**Kingston University** London

# Performance of Concrete Cured Using a Curing Compound and Treated with Admixture or Surface Treatment

**By**

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# Declaration

I declare that all material contained in the thesis is my own original work, and that any references to or use of other sources have been clearly acknowledged within the text and in the list of references provided in the bibliography.

**Sirwan Kamal**

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# Publications

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# Abstract

Water curing is widely used to maintain sufficient moisture content within concrete. However, curing process could be challenging and difficult in regions suffering from clean water scarcity, or improper curing could occur due to poor site practices. Another method of curing is applying curing compounds (CC) on concrete surface, which creates a protective layer on the concrete surface to prevent or mitigate moisture evaporation from concrete surface. Thus, it retains the amount of water needed for the hydration process. Efficiency of using curing compounds for concrete curing have been investigated by numerous researchers. However, the majority of previous studies focused on the impact of curing compounds on the compressive strength development, rather than transport and durability properties. It is well known that failures in concrete mostly occur due to durability problems such as steel corrosion rather than strength issues. Moreover, many researches have been conducted to evaluate the influence of using protective materials such as waterproofing admixtures (Admix) and water repellent surface treatment (ST) to improve concrete performance. Nevertheless, all previous studies were performed on concrete conventionally cured in water.

This study investigates performance of concrete cured using a water-based curing compound and protected by means of waterproofing admixtures or surface treatments compounds. Moreover, mineral admixtures such as fly ash (FA), ground granulated blast furnace slag (GGBS) and silica fume (SF) were added to the mixes to further enhance concrete performance while exposed to aggressive environment. Equal strength plain (CEM I) and binary blended cements were prepared by replacing 20%, 40% and 10% of cement mass (PC) with FA, GGBS and SF respectively, to produce CEM II/A-V, CEM III and CEM II/A-D according to BS EN 197-1. Ultimately, concrete performance was enhanced by the combined effects of waterproofing admixtures or surface treatments along with mineral admixtures. In this study, two set of protective materials in the form of waterproofing admixtures and surface treatments were used. Admixtures were added directly to the concrete batch during mixing, whereas surface treatment agents were applied on concrete surface after curing. Both set of materials provide protection by means of crystalline pore blockers actions, or by hydrophobic effects.

This study was conducted in three phases, Phase 1 involved evaluation of engineering properties of concrete specimens cured using the curing compound. To assess efficiency of the CC, compressive strength, flexural strength and drying shrinkage tests were conducted and results were compared to two set of control samples cured in air (AC) and in water (WC). Phase 2 involved assessing transport properties of concrete specimens cured with CC, and treated either with waterproofing admixtures or surface treatment agents to improve resistance to water ingress. Short-term and long-term water penetration due to capillary absorption and applied pressure were assessed through initial surface absorption test (ISAT), sorptivity (capillary absorption) and depth of water penetration under pressure tests. In Phase 3, durability properties were investigated by conducting carbonation, resistance to scaling and resistance to chloride penetration tests.

Results have shown that cubes cured using the curing compound developed more than 93% and 96% of the target compressive strength at 28 and 90 days respectively. Strength development due to pozzolanic reactions was more evident beyond 28 days. Moreover, incorporation of mineral admixtures reduced shrinkage strains under all curing conditions compared to CEM I prisms. In addition, the study has demonstrated that treatment with protective materials particularly those governed by hydrophobic effects, significantly reduced sorptivity due to capillary absorption, and considerably improved resistance to scaling and chloride penetration.

Furthermore, the research has established that application of surface treatment agents provided better protection for concrete than addition of waterproofing admixtures. The study has indicated that using a curing compound along with an appropriate protective treatment and mineral admixtures, can safeguard concrete exposed to harsh conditions, for instance, concrete pavements, marine structures and bridges. In addition, producing such concretes can reduce the environmental impact of the construction industry, such as carbon dioxide emissions, and excessive consumption of fresh water during curing, while maintaining the essential properties of concrete.

# List of Abbreviations

| | |
|---|---|
| CC | Curing compound |
| AC | Air curing |
| WC | Water curing |
| IC | Internal curing |
| Admix1 | Admixture 1 |
| Admix2 | Admixture 2 |
| Admix3 | Admixture 3 |
| ST1 | Surface treatment 1 |
| ST2 | Surface treatment 2 |
| ST3 | Surface treatment 3 |
| PC | Portland cement |
| SCM | Supplementary cementitious materials |
| FA | Fly ash |

|  |  |
|---|---|
| GGBS | Ground granulated blast furnace slag |
| SF | Silica fume |
| MK | Metakaolin |
| CEM I | 100% Portland cement |
| CEM II/A-V | 80% Portland cement + 20% Fly ash |
| CEM III/A | 60% Portland cement + 40% Ground granulated blast furnace slag |
| CEM II/A-D | 90% Portland cement + 10% Silica fume |
| BS | British Standard |
| ISAT | Initial surface absorption test |
| $C_3S$ | Tricalcium silicate |
| $C_2S$ | Dicalcium silicate |
| $C_3A$ | Tricalcium aluminate |
| $C_4AF$ | Tetracalcium aluminoferrite |
| C-S-H | Calcium silicate hydrate |
| w/c ratio | Water/cement ratio |
| HCP | Hydrated cement paste |

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# Chapter 1: Introduction

## 1.1 Background

Concrete is the most widely used material in the construction industry, it is the second most consumed man-made material after water. Commonly produced by mixing Portland cement with sand, crushed rock, and water to form concrete (CEM I). It is clearly a major component of the construction industry due to its versatility, durability, and cost. It plays a crucial role in many aspects of everyday life, from general buildings to infrastructure such as roads, bridges, and dams. Nowadays, the rate at which concrete is consumed is much higher than it was 40 years ago. It is estimated that the current consumption of concrete in the world is roughly 25 billion tonnes each year (WBCSD, 2009). Furthermore, nearly 2 tonnes of concrete is produced per person worldwide (Desai and Limbachiya 2006). However, the massive production of cement and concrete has huge environmental impacts, it is estimated that production of concrete contributes for around 5-8% of $CO_2$ emissions (Scrivener and Kirkpatrick 2008), and the cement industry is being the third largest causes of global pollution (Olivier et al., 2017). Furthermore, concrete industry is the highest consumer of fresh water as it consumes nearly 1 billion cubic of water (Asadollahfardi et al. 2016).

Typical service lives of concrete structures are between 50 to 100 years with minimal maintenance (Mehta and Monteiro, 2006). Cost of maintenance and repair of concrete structures suffering deterioration is relatively high, thus producing a durable concrete to prolong lifespan and reduce maintenance cost is of great importance for construction industry. Concrete can suffer deterioration and degradation due to physical factors such as cavitation, erosion and cracking, or caused by chemical factors such as sulfate attack, acid attack and corrosion of reinforcing bars (Neville, 1996; Soutsos, 2010; Mehta et al., 2006). Another cause of deterioration is inadequate curing; therefore, proper concrete curing is important to produce a durable concrete. Providing good curing is essential to promote the cement hydration process and hence, ensure strength development. The main purpose of curing is to prevent the evaporation of moisture content in the concrete (ACI 308R, 2016). Generally, water curing is an effective way for curing, and it is used widely through water ponding, spraying, covering concrete with wet sand or with wetted hessian. However, adequate curing could be challenging in regions suffering from clean water shortage, or improper curing could occur due to poor site practices.

Moreover, curing can also be done by applying membrane-forming curing compounds (CC) or using internal curing (IC). Curing compounds are liquid materials that can be sprayed, rolled, or brushed on the concrete surface. Once the curing compound is applied, it seals the concrete surface by forming a continuous film, thus retard, or reduce moisture evaporation from concrete. Using curing compounds as a way of curing has increased and received additional interest due to its ease of application, cost effectiveness, convenience and water saving (Lamond and Pielert, 2006). Curing compounds can be used in larger concrete applications such as pavements, runways, dams as well as standard concrete slabs, beams, and columns. According to Neville and Brooks (2010), the hydration of all cement particles is rarely achieved in the field and it is not necessary to develop satisfactory strength. Furthermore, concrete cured in controlled environment such as in the laboratory hardly has the same properties compared with same concrete cured in the field. Many factors would impact the curing condition such as air temperature, relative humidity, wind speed, and human factor. For instance, concrete specimens produced in the laboratory are usually cured by immersing in water tank or in a controlled temperature and humidity environment, whereas actual structures are never cured in this way.

Many studies have been conducted to assess the efficiency of using various types of curing compounds (acrylic-based, paraffin-based, silicate-based, composite-based and water based) for concrete curing (Xue *et al.*, 2015; Dang *et al.*, 2013; Al-Gahtani, 2010; Wasserman and Bentur, 2013). Generally, results obtained showed that using curing compounds were effective in concrete curing and improved concrete performance. The majority of previous researches focused on the evaluation of curing conditions and short-term performance of concrete cured using CC. Therefore, insufficient results have been reported on the long-term durability properties where concrete is exposed to aggressive conditions, such as freeze and thaw and long exposure to water and chloride.

Concrete is widely used in structures exposed to aggressive environmental conditions such as marine structures, tunnels and bridges exposed to chloride through de-icing salt. Hence, using concrete in aggressive environment condition increases concern over its durability and the actual service lives of concrete structures (Monteiro and Kurtis 2003). Durability of Portland cement concrete is defined as its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration. In other words, a durable concrete will retain its original form, quality, and serviceability when exposed to its intended service environment. (Mehta & Monteiro, 2006).

Previous investigations have been conducted to overcome durability related problems in concrete such as carbonation, sulphate attack, reinforcing bar corrosion and freezing-thawing**.** Studies have shown that concrete performance can be improved by using water repellent components or chemical admixtures, which tend to safeguard concrete from chloride ingress to prolong lifespan of concrete exposed to aggressive environment (Zheng et al., 2012; Shen et al., 2014; Al-Zahrani et al., 2002; De Muynck et al., 2009; Almusallam et al., 2003; Medeiros and Helene, 2008; Baltazar et al., 2014; Tang et al., 2015). These materials usually provide protection either by hydrophobic impregnation or crystalline effect. Results showed that some materials were successful in protecting concrete. However, all previous researches were carried out on concrete cured with water. In other words, durability of concrete cured using curing compounds, and treated with admixtures or surface treatment agents is yet to be evaluated. This necessitates the need for this investigation and forms the basis of this research study. Additionally, it is essential to assess compatibility and efficiency of applying curing compounds followed by surface treatment materials on the concrete surface.

Previous investigations have examined the efficacy of the partial replacement of cement with mineral admixtures, such as fly ash (FA), ground granulated blast furnace slag (GGBS), silica fume (SF) and metakaolin (MK) to improve concrete performance (Ismail et al., 2013; Bjegovic et al., 2012; Githachuri and Alexander, 2013). The replacement of cement with finer particle size tends to refine the pore structure of concrete and increases its chloride binding capacity, thus reducing permeability and heat of hydration. Therefore, the incorporation of these by-products tends to improve the overall durability of concrete. Furthermore, using blended cement has environmental benefit by reducing $CO_2$ emissions which is vital for a sustainable concrete industry. Nowadays, use of blended cement in construction industry is widely preferred and recommended by design standards (BSI EN 197-1, 2011; BS EN 206, 2013, ASTM C595, 2020). Nevertheless, little results are presented on the performance of blended cement cured using CC rather than conventional water curing.

This study has been devised in response to the need of investigating the effectiveness of using curing compounds on concrete which has been treated with admixture or surface treatment agents.

It will also examine the contribution of adding mineral admixtures to improve its overall performance including transport and durability properties while exposed to harsh environment. Another aspect of this study is to produce durable concretes with less environmental impact to be used in various applications, such as concrete pavements, marine structures and bridges.

## 1.2 Aims and Objectives

The main aim of this research is to investigate performance and properties of concrete cured using a water-based curing compound and treated with admixtures or water repellents agents while exposed to aggressive environment. Ultimately, producing concretes using curing compounds, protective materials and mineral admixtures, without compromises in the important properties such as engineering, transport and durability properties. Subsequently, contributing to the sustainable development of the industry while maintaining essential properties of concrete.

The objectives of this study are listed below:

- To assess the effect of using CC on engineering properties of concrete.
- To investigate the effect of using CC on the performance of blended cement concrete.
- To investigate the efficiency and compatibility of using CC in conjunction with surface treatments components.
- To evaluate the effect of adding various waterproofing admixtures on the performance of the concrete.
- To evaluate the effect of applying different surface treatments materials characterized by hydrophobic effects or crystalline pore blockers on concrete performance.

- To investigate the contribution of adding mineral admixtures to improve overall performance of concrete cured using CC and treated with admixtures or surface treatments.

## 1.3 Scope of Research

To accomplish the objectives established in this research, this study was divided into three phases.

### Phase 1- Engineering Properties of Concrete

In this phase, engineering properties of concrete cured using the CC were determined. The tests included compressive strength, flexural strength, and drying shrinkage tests. Cubes, beams, and prisms were produced in the laboratory to undergo the stated tests at specific ages. Results were compared with two set of controls. The first set of control samples were cured in the air, whereas the second set were cured in water. Four concrete mixes were prepared namely, CEM I, CEM II/AV, CEM III and CEM II/ A-D.

### Phase 2- Transport Properties

This phase involved assessing resistance of concrete cubes to water penetration under capillary absorption and applied pressure. For this purpose, concrete cubes were cast in the laboratory and cured using the CC. Like Phase 1, four concrete mixes were prepared involving CEM I, CEM II/AV, CEM III/A and CEM II/ A-D. The cubes were treated either with admixtures or water repellent agent to improve performance against water ingress. Short term exposure resistance was assessed through initial surface absorption test, whereas long term resistance was evaluated through sorptivity test. On the other hand, penetration depth of water under pressure was determined according to BS EN 12390-8 (2019). Results were compared with control cubes cured in air and water to evaluate performance.

### Phase 3- Exposure to Carbonation, Calcium Chloride and Sodium Chloride

In this phase, durability properties were examined by conducting (i) carbonation test, (ii) resistance to scaling and (iii) resistance to chloride penetration. Cubes and slabs were cast and cured with CC, and treated with admixtures or surface treatment. Four concrete mixes were prepared including CEM I, CEM II/A-V, CEM III/A and CEM II/A-D. Slabs were exposed to sodium chloride and calcium chloride during chloride penetration and resistance to scaling tests respectively. Results were compared to control slabs to determine performance of treated slabs. In terms of carbonation test, cubes of all mixes were exposed to carbon dioxide for 150 days. Depth of carbon penetration was determined and a comparison was carried out to assess performance.

## 1.4 Outline of Thesis

The structure of the thesis is outlined in 7 chapters as presented below:

Chapter 1 (Introduction): Presents a background of the research and problem statement. It also includes scope and layout of the study.

Chapter 2 (Literature review): Presents a review of the literature, including

- Cement types and mineral admixtures
- Hydration of cement, chemistry and mechanism of hydration
- Effect of different curing method on the hydration of cement
- Effect of using different types of curing compounds on concrete performance
- Microstructure of the hydrated cement paste
- Transport mechanisms in concrete
- Factors causing deterioration in concrete such as durability related issues
- Corrosion of steel reinforcement and measures to protect concrete
- Approaches to mitigate and prolong the lifespan of concrete exposed to aggressive environment such as chloride attack
- The role of mineral admixtures (FA, GGBS and SF) to increase the chloride binding capacity of concrete and decrease permeability.
- Efficiency of using admixtures to improve durability of concrete

- Efficiency of using water repellent agents to improve durability of concrete

Chapter 3 (Experimental programme): Provides comprehensive description of materials used and experimental programme of the research.

Chapter 4 (Assessment of engineering properties): Presents results and discussion of Phase 1, showing influence of using CC on the mechanical properties of various concrete types. The role of mineral admixtures on these properties.

Chapter 5 (Evaluation of transport properties): Presents results and discussion of Phase 2, reporting the role of different admixtures and surface treatments agents on reducing water uptake by concrete due to capillary absorption and permeability under applied pressure.

Chapter 6 (Investigating durability properties): Presents results and discussion of Phase 3, showing the combined effect of using admixtures or surface treatments agents along with mineral admixtures to enhance performance of specimens subjected to chloride and carbonation.

Chapter 7 (Conclusions and recommendations): Presents the main findings concluded from this study and recommendations for future researches.

# Chapter 2: Literature Review

## 2.1 Introduction

Concrete is the main component of the construction industry which employs around 7% of the global workforce and more than half in some countries (Soutsos 2010). It is used in almost all forms of structures, from buildings and dams to bridges and highways. This high demand for concrete is attributed to its versatility, relatively low cost, and energy efficiency (Mehta et al. 2006). Producing a durable concrete is important to prolong the service life of concrete structures and reduce maintenance cost. The ACI committee 201 (2001) defines concrete durability as "its resistance to deteriorating influences which may through inadvertence or ignorance reside in the concrete itself, or which are inherent in the environment to which it is exposed". This means that degradation in concrete can occur due to exposure to harsh environment such as chemical attack, or from internal causes within the concrete itself such as alkali-aggregate reaction. Moreover, another factor causing issues in concrete is the workmanship, for instance, inadequate curing due to skilled labour or water scarcity (Krishna et al., 2016; Filian and Montero, 2016).

A series of fundamental changes is currently happening in the concrete industry. These changes have been led partially by cost but mainly by environmental concerns. It is estimated that the cement production contributes for around 5-8 % of the world's carbon dioxide emissions (Dyer, 2014; Alexander et al., 2017). Thus, replacing cement with mineral admixtures is highly encouraged and recommended in concrete practice. Another environmental concern facing the industry is the huge consumption of fresh water as it consumes approximately 1 billion cubic of water (Asadollahfardi et al. 2016). Therefore, using curing compounds instead of water for curing should be considered in specific places and applications.

This chapter presents a comprehensive review of the available literature related to types of cement and mineral admixtures, hydration process of cement, the effect of various curing methods on concrete performance, efficiency of using different types of curing compounds on concrete durability, materials used to enhance concrete performance while exposed to water and chloride, such as surface treatment agents and chemical admixtures, effect of partial replacement of cement with mineral admixtures on durability properties, durability related deterioration such as carbonation and chloride ingress.

## 2.2 Concrete

According to BS EN 206 (2013), concrete is a material formed by mixing cement, coarse and fine aggregate, and water, with or without the incorporation of admixtures, additions or fibres, which develops its properties by hydration. It has been the most used material in the construction industry over the past 100 years, and this demand is unlikely to change in the foreseeable future. It is estimated that approximately 10 billion cubic meters of concrete is produced worldwide every year. In fact, production of reinforced concrete is more than half of the other materials and manufactured products combined together in the world as shown in Table 2.1 (Alexander et al., 2017). This high demand for concrete is attributed to its versatility, adaptability, cost effectiveness and availability of its constituents.

Another factor contributing to this high consumption of concrete is its durability. Lifespan of concrete structures can be up to 100 years if the concrete is properly made, and this can be achieved by selecting right proportions of materials, followed by proper mixing, placing, and curing. Moreover, other factors contributing to this huge consumption of concrete and favoring it over steel are less maintenance cost compared to steel structures and excellent fire resistance (Mehta & Monteiro, 2006). Furthermore, cements that are produced through chemical interaction with water are called hydraulic cements, and Portland cement (PC) is the most widely used and important member of the family of hydraulic cements (Mindess, 2008).

**Table 2.1** Annual worldwide production of materials, 2014 (tonnes) (Alexander et al., 2017)

| Material | Production in 2014 (tonnes) |
|---|---|

| | |
|---|---|
| Portland cement | 4.3 billion |
| Concrete (estimated) | ≈23 billion |
| Coal | ≈7.8 billion |
| Steel | 1.66 billion |
| Wood | ≈2.2 billion |
| Crude oil | ≈4.2 billion |
| Wheat | 709 million |
| Salt | 270 million |
| Sugar | 173 million |
| Gold | 2860 |

## 2.3 Portland Cement

According to BS EN 197-1 (2011), “cement is a hydraulic binder, i.e., a finely ground inorganic material which, when mixed with water, forms a paste which sets and hardens by means of hydration reactions and processes and which, after hardening, retains its strength and stability even under water”. PC is the most common type used to produce concrete worldwide. Typical PC clinker contains about 55-65% tricalcium silicate ($C_3S$), 15-25% dicalcium silicate ($C_2S$), 8-12 tricalcium aluminate ($C_3A$) and 8-12% Tetracalcium aluminoferrite ($C_4AF$) (Kurdowski 2014). PC clinker is produced by burning a mix of calcium carbonate (limestone or chalk) and an aluminosilicate (clay or shale) at a temperature of up to 1450 °C, and then grinding the product with approximately 5% gypsum to produce cement (Bye 1999). The raw materials contain elements, usually represented as oxides, CaO, $SiO_2$, $Al_2O_3$, $Fe_2O_3$ and small quantities of other materials. The inclusion of gypsum which is a form of calcium sulfate is to control rate of setting and to influence the rate of strength development. Taylor (1997) reported PC clinker involves four main phases which are summarized as following:

- Alite or tricalcium silicate ($C_3S$): it is by far the most significant constituent of Portland cement clinkers as it contributes to the strength development at ages up to 28 days. In normal Portland cements, the $C_3S$ is the most important of the constituent phases due to its relatively rapid reaction with water.

- Belite or dicalcium silicate ($C_2S$): it reacts slowly with water, thus contributing little to the early strength development during the first 28 days. However, it contributes significantly to the strength development process at later ages.
- Aluminate or tricalcium aluminate ($C_3A$): this constituent can cause an undesirable rapid setting due to its fast reaction with water. Therefore, gypsum is added which acts as a setcontrolling agent.
- Ferrite or tetracalcium aluminoferrite ($C_4AF$): its reaction rate with water appears to be somewhat variable, perhaps due to differences in composition or other characteristics. Generally, the reaction is high initially and low or very low at later ages.

In addition to the above major phases, several other phases are also present such as, alkali sulfates and calcium oxide but in minor amounts. Table 2.2 shows the chemical composition in terms of oxide of the various elements that are present in Portland cement.

**Table 2.2** Shorthand notation for the oxides in Portland Cement (Mindess, 2008).

| Oxide | Shorthand Notation | Common Name | Typical Weight Percent in Cement |
|---|---|---|---|
| $CaO$ | C | Lime | 63 |
| $SiO_2$ | S | Silica | 22 |
| $Al_2O_3$ | A | Alumina | 6 |
| $Fe_2O_3$ | F | Ferric oxide | 2.5 |
| $MgO$ | M | Magnesia | 2.5 |
| $K_2O$ | K | Alkalis | 0.6 |
| $Na_2O$ | N | Alkalis | 0.4 |
| $SO_3$ | $\bar{S}$ | Sulfur trioxide | 2.0 |
| $CO_2$ | $\bar{C}$ | Carbon dioxide | — |
| $H_2O$ | H | Water | — |

### 2.3.1 Types of Portland Cement

Different types of cements are produced by changing the amounts of the phases present in PC. For instance, altering the amount of $C_3A$ and fineness can alter the properties of the cements. Therefore, various cement types are produced for use in different applications and exposure conditions (Gani, 1997; Imbabi et al., 2012).

According to ASTM C150 (2011), PC are designated into five main types and are classified as following:

- Type I: it is the most common type of Portland cement used worldwide in general construction applications where there is exposure to sulfates.
- Type II: it contains low $C_3A$ (<8%) and preferred for applications where moderate sulfate resistance and low heat of hydration are required.
- Type III: its chemical composition is similar to type I but it is ground more finely and may contain slightly more $C_3S$, and it is suitable for applications where high early strength is required.
- Type IV: it contains lower amount of $C_3S$ and $C_3A$, it is used in massive concrete structures such as dams where a low heat of hydration and slow strength development is desired.
- Type V: it contains very low amount of $C_3A$ (<5%) and used specifically when high sulfate resistance is required.

On the other hand, BS EN 197-1 (2011) designate 27 products as shown in Table 2.3 in the family of common cements and grouped into five main types as following:

- CEM I – Portland cement
- CEM II – Portland-composite cement
- CEM III – Blastfurnace cement
- CEM IV – Pozzolanic cement
- CEM V – Composite cement

**Table 2.3** Products in the family of common cements (BS EN 197-1, 2011)

| Main Types | Notation of the 27 products (Types of common cement) | | Main constituents (Percentage by mass) |
|---|---|---|---|
| CEM I | Portland cement | CEM I | 95-100 % clinker |

| | | | |
|---|---|---|---|
| CEM II | Portland-slag cement | CEM II/A-S | 80-94 % clinker and 6-20% GGBS |
| | | CEM II/B-S | 65-79 % clinker and 21-35 % GGBS |
| | Portland-silica fume cement | CEM II/A-D | 90-94 % clinker and 6-10 % GGBS |
| | Portlandpozzolana cement | CEM II/A-P | 80-94 % clinker and 6-20 % natural pozzolana |
| | | CEM II/B-P | 65-79 % clinker and 21-35 % natural pozzolana |
| | | CEM II/A-Q | 80-94 % clinker and 6-20 % natural calcined pozzolana |
| | | CEM II/B-Q | 65-79 % clinker and 21-35 % natural calcined pozzolana |
| | Portland-fly ash cement | CEM II/A-V | 80-94 % clinker and 6-20 % siliceous fly ash |
| | | CEM II/B-V | 65-79 % clinker and 21-35 % siliceous fly ash |
| | | CEM II/A-W | 80-94 % clinker and 6-20 % calcareous fly ash |
| | | CEM II/B-W | 65-79 % clinker and 21-35 % calcareous fly ash |
| | Portland-burnt shale cement | CEM II/A-T | 80-94 % clinker and 6-20 % burnt shale |
| | | CEM II/B-T | 65-79 % clinker and 21-35 % burnt shale |
| | Portland-limestone cement | CEM II/A-L | 80-94 % clinker and 6-20 % limestone L |
| | | CEM II/B-L | 65-79 % clinker and 21-35 % limestone L |
| | | CEM II/A-LL | 80-94 % clinker and 6-20 % limestone LL |
| | | CEM II/B-LL | 65-79 % clinker and 21-35 % limestone LL |
| | Portlandcomposite cement | CEM II/A-M | 80-94 % clinker and 6-20 % combination of the materials stated above |
| | | CEM II/A-M | 65-79 % clinker and 21-35 % combination of the materials stated above |
| CEM III | Blast furnace cement | CEM III/A | 35-64 % clinker and 36-65 % GGBS |
| | | CEM III/B | 20-34 % clinker and 66-80 % GGBS |
| | | CEM III/C | 5-19 % clinker and 81-95 % GGBS |
| CEM IV | Pozzolanic cement | CEM IV/A | 65-89 % clinker and 11-35 % combination of SF, natural pozzolana, natural calcined pozzolana, siliceous FA & calcareous FA |
| | | CEM IV/B | 45-64 % clinker and 36-55 % combination of SF, natural pozzolana, natural calcined pozzolana, siliceous FA & calcareous FA |
| CEM V | Composite cement | CEM V/A | 40-64 % clinker and 18-30 % GGBS and 1830% of a combination of natural pozzolana, natural calcined pozzolana and siliceous FA |
| | | CEM V/B | 20-38 % clinker and 31-50 % GGBS and 3150% of a combination of natural pozzolana, natural calcined pozzolana and siliceous FA |

## 2.4 Mineral admixtures

Partial replacement of cement with finely divided silicious materials is an established practice in modern concrete technology. Usually, this replacement is large and can reach 70 % by mass of total cement in concrete (Sanjuán and Argiz 2012). These materials are called mineral admixtures or supplementary cementitious materials (SCMs), and act either as pozzolans or latent hydraulic materials. These materials can be natural pozzolanas which are still being used in some parts of the world, or industrial by-products which are the main source of mineral admixtures used widely in concrete industry nowadays, due to environmental and economic benefits as well as improving durability of hardened concrete (Mindess et al., 2003; Mehta et al., 2006). Producing one ton of Portland cement releases approximately 0.9 ton of $CO_2$ into atmosphere (Tokyay 2016). Therefore, replacement of PC cement with SCMs is significant to reduce carbon emission. The main types of mineral admixtures used in blending PC are: Fly ash (FA), ground granulated blast furnace slag (GGBS), silica fume or microsilica (SF) and metakaolin (MK).

### 2.4.1 Fly ash (FA)

Fly ash is a byproduct obtained from the combustion of pulversied coal in thermal power plants. It is removed as a fine particulate residue from combustion gases through a dust collection system before releasing the gases into the atmosphere. Chemical composition of fly ash depends on types and relative amounts of incomputable matter in the coal. More than 85% of most fly ashes consist of chemical compounds and glasses formed from silica ($SiO_2$), alumina ($Al_2O_3$), iron oxide ($Fe_2O_3$), calcium (CaO), and magnesia (MgO). Generally, fly ash collected from the combustion of subbituminous coals contains more calcium and less iron than fly ash from bituminous coal. Fly ash is grey in colour and spherical, with typical particles diameter ranging from <1 µm to up to 150 µm. The specific gravity of fly ashes ranges from 1.9 for a subbituminous ash to 2.96 for an iron-rich bituminous ash. Adding FA in concrete can have one or more of the following benefits (Malhotra, 2008; Ramezanianpour, 2014) :

- Reducing costs by reducing quantity of cement in the mixture
- Reducing heat of hydration
- Improving durability and workability

Based on the source of mineral coal, ASTM C 618 (2019) classifies FA into Class F and Class C. These two classes of FA have identical physical characteristics, but they have different chemical compositions. Class F has pozzolanic properties as it contains more than 70% of silica, alumina, and iron oxide collectively. This class usually results from burning of anthracite or bituminous coal and more used in cement and concrete production. On the other hand, class C contains high amount of calcium oxide (between 10-30%), thus giving it both pozzolanic and cementitious properties. This class usually results from burning of lignite or subbituminous coal (Bapat, 2012; Tokyay, 2016). Based on the proportion of reactive calcium oxide content in FA, BS EN 197-1 (BS EN197-1, 2011) groups FA as called CEM II into siliceous when calcium oxide content is < 10% by mass, or calcareous when calcium oxide is > 10% (Soutsos 2010).

### 2.4.2 Ground granulated blast furnace slag (GGBS)

The American Society for Testing and Materials (ASTM C989, 2018) defines blast furnace slag (BFS) as “the non-metallic product consisting essentially of calcium silicates and other bases, developed in a molten condition simultaneously with pig iron in a blast furnace”. GGBS is a latent hydraulic material which forms stable hydrate when combined with water. It is widely used in concrete practice to improve durability, reduce cost and reduce $CO_2$ emission (Connell, 2010). Slag is a byproduct of iron manufacture consisting of silicates and aluminosilicates of calcium. It develops its latent hydraulic property when it is rapidly quenched with water to a glassy state and finely ground. Most of the slags produced using rapid water cooling develop cementitious properties to a certain degree. On the other hand, slags cooled gradually using ambient air temperature do not develop satisfactory cementitious properties and are mainly used as base materials for road construction or as aggregates in special concrete productions. It should be stressed that, slag used in concrete industry is produced from iron production which is different from steel production. In terms of chemical composition of slag, calcium (CaO), silicon ($SiO_2$) and aluminum ($Al_2O_3$) are the main components of slag used in concrete. Moreover, typical fineness of GGBS used in cementitious systems lies between 350 and 600 $m^2/kg$ Blaine, and particle size of slag is similar to that of CEM I Portland cement (Li, 2011; Lewis et al., 2003; Malhorta, 2008; Bapat, 2012). According to BS EN 197-1 (2011), PC blended with GGBS is referred to as CEM III.

### 2.4.3 Silica fume (SF)

Silica fume, also known as condensed silica fume or microsilica is a byproduct obtained from the exhaust gases of silicon, ferrosilicon, and other metal alloy smelting furnaces. It is formed during the high temperature reduction of quartz in an electric arc furnace, where the main product is silicon or ferrosilicon. SiO vapors which is produced during reduction of quartz to silicon at high temperatures, oxidize and condense in the low temperature zone of the furnace to very fine spherical particles consisting of noncrystalline silica. The material is collected by filtering the outgoing gases in bag filters (Lewis, 2010; Mehta et al., 2006). SF is available in different forms namely, (a) undensified, (b) densified, (c) pelletized and (d) slurry. SF is amorphous, glassy and its colour varies from pale to dark grey depending mainly on the carbon content. Due to its amorphous nature, SF takes part in the pozzolanic reactions happening during the hydration of cement. SF in uncondensed form is an ultrafine powder with at least 85% $SiO_2$ content, thus highly pozzolanic. Generally, SF particles are spherical with mean particle diameter between 0.1 and 0.2 µm, and minimum surface area of 15000 $m^2$/kg. Generally, the specific gravity of SF is 2.20 compared to specific gravity of PC which is 3.15 (Bapat, 2012; Lewis et al., 2003; Malhorta, 2008). Inclusion of SF in concrete mixtures, increases compressive strength and reduces workability, thus adding high range water-reducing admixtures are used to increase workability (Mehta et al., 2006).

### 2.4.4 Metakaolin (MK)

Unlike FA, GGBS and SF, metakaolin is not a byproduct of an industrial process nor it is completely natural, it is a relatively new type of mineral admixtures in cement and concrete industry (Bapat 2012). It is produced under carefully controlled condition, by heating kaolin clay, which is a soft, white clay at temperatures typically between 650 and 800. Increasing the temperature leads to dihydroxylation and breakdown of kaolin structure. Thus, formation of a metakaolin takes place which is a highly reactive white powder, amorphous with pozzolanic and latent hydraulic properties. Generally, MK particles size is less than 2 µm which is substantially smaller than that of cement particles, but not as fine as SF. Typically, silicon dioxide (50-55%) and aluminum oxide (40-45%) are the main component of the chemical composition of MK (Ramezanianpour, 2014; Lewis et al., 2003; Malhorta, 2008). The large specific surface area of

MK particles which is about 12000-18000 $m^2/kg$, leads to an increase in quantity of water required in the concrete mix. Thus, inclusion of MK reduces workability of the concrete mix (Shvarzman and Shamoon, 2010). Furthermore, adding MK to the mix, improves concrete performance by decreasing permeability and increasing strength. This improvement is attributed to the reaction of MK with calcium hydroxide leading to formation of secondary calcium silicate hydarte C-S-H (Z. Li 2011).

## 2.5 Hydration of Cement

Hydration refers to the chemical reactions taking place when cement particles mixed with water and it occurs immediately once the cement is brought into contact with water. Figure 2.1 illustrates the development of hydrate structure in cement paste. The primarily outcome of the hydration reactions is the calcium silicate hydrate which is the main constituent of the hydrated cement (Neville and Brooks, 2010; Taylor, 1997; Shafiq, 2010). It is reported that up to 50% of a typical cement hydrates within the first 24 hours once mixed with water, and the degree of hydration continues to increase reaching around 80% by 28 days (Scrivener and Nonat 2011). The reaction between both calcium silicates $C_3S$ and $C_2S$ with water leads to the formation of calcium silicate hydrate. The two calcium silicates are the main cementitious compounds in cement, and major contributor to strength development as shown in Table 2.4 and 2.5.

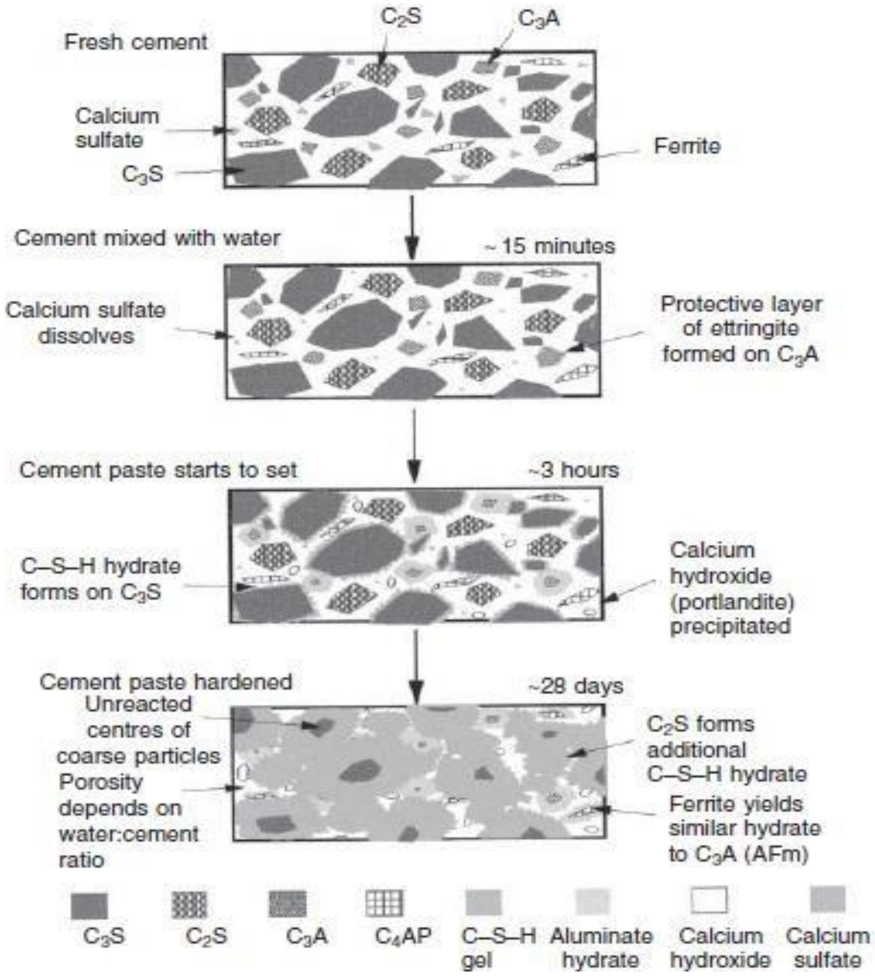


**Figure 2.1** Simplified illustration of hydration of cement paste (Newman and Choo, 2003b)

According to Mindess (2008), the main characteristics of the hydration of Portland cement are summarized as following:

- The cement paste stays in fluid form when water continues to separate cement particles from each other.
- Volume filled by products formed from hydration reactions is greater than that occupied by initial cement particles.
- Setting happens once the hydration products starts to intergrow.
- Additional bonds are developed within cement particles due to continuation of hydration reactions, resulting in strengthening the system.

Beaudoin and Odler (2019) identified a range of factors affecting the progress of hydration and its kinetics, particularly:

- Phase composition of the cement and presence of foreign ions within the crystalline lattices of the individual clinker phases.
- Fineness of the cement, especially its particle size distribution and specific surface.
- Water-cement ratio of the mix.
- Curing temperature
- Adding chemical admixtures to modify the hydration rate and properties of the cement paste.
- Partial replacement of cement with mineral admixtures such as GGBS and FA.

**Table 2.4** Typical Compound Composition of Ordinary Portland Cement (Mindess, 2008)

| Chemical Name | Chemical Formula | Shorthand Notation | Weight Percent |
|---|---|---|---|
| Tricalcium silicate | $3CaO.SiO_2$ | $C_3S$ | 50 |
| Dicalcium silicate | $2CaO.SiO_2$ | $C_2S$ | 25 |
| Tricalcium aluminate | $3CaO.Al_2O_3$ | $C_3A$ | 12 |
| Tetracalcium aluminoferrite | $3CaO.Al_2O_3.Fe_2O_3$ | $C_4AF$ | 8 |
| Calcium sulfate dihydrate | $CaSO_4.2H_2O$ | $CSH_2$ | 3.5 |

**Table 2.5** Contribution of Cement Compounds to the hydration of Portland Cement (Mindess, 2008)

| Compound | Reaction Rate | Heat Liberated | Contribution to strength |
|---|---|---|---|
| $C_3S$ | Moderate | High | High |
| $C_2S$ | Slow | Low | Low initially, high later |
| $C_3A + CSH_2$ | Fast | Very high | Low |
| $C_4AF + CSH_2$ | Moderate | Moderate | Low |

### 2.5.1 Mechanism of Hydration

Hydration of cement begins the minute cement is mixed with water, the chemical reactions involved in this process are responsible for setting and hardening of mortar and concrete.

Hydration of the calcium silicates has a major role in strength development. Most of the early strength comes from the rapid hydration of $C_3S$ compared with $C_2S$. Despite the quick hydration of the aluminate and ferrite phases, they provide little contribution in strength gain. During cement hydration, several chemical processes take place where each occurs at a rate that is influenced by the nature of the process and the state of the system. Numerous authors (Bullard et al., 2011; Kurdowski, 2014; Moses and Perumal, 2016) have explained the hydration processes as following:

- Dissolution: this process involves the separation of molecular units from the surface of a solid when mixed with water.
- Diffusion: this process refers to the movement of solution components through the pore volume in cement paste or along the surfaces of solids in the adsorption layer.
- Growth: this process describes the incorporation of molecular units into the structure of a crystalline or amorphous solid within its self-adsorption layer.
- Nucleation: this process occurs when solids are precipitated heterogeneously on solid surfaces or homogeneously in solution.
- Complexation: this process refers to the formation of complex ion or adsorbed molecular complexes on solid surfaces due to reactions between simple ions.
- Adsorption: in this process, ions or other molecular units accumulate on the surface of a solid particle in a liquid.

The above processes may take place in series, in parallel or in more complex combination and occur during five hydration stages based on the amount of heat released as shown in Figure 2.2. The first stage starts immediately once cement is in contact with water and lasts only few minutes. This period is characterized by the rapid reaction between $C_3S$ and water which begins instantly upon wetting. Thus, significant heat is released due to the dissolution of $C_3S$. In the second stage, the hydration activity drops considerably, and the cement paste remains fluid, thus very little heat is released during this period which may last for several hours. Substantial heat is liberated during the third stage due to the hydration of $C_3S$ which leads to the formation of hydration products. Followed by stage four where hydration of $C_3A$ takes place after depletion of the gypsum. In final stage, the rate of hydration continues to slow in the presence of water (Mindess, 2008; Gartner et al., 2002; Bullard et al., 2011; Scrivener and Nonat, 2011; Beaudoin and Odler, 2019).

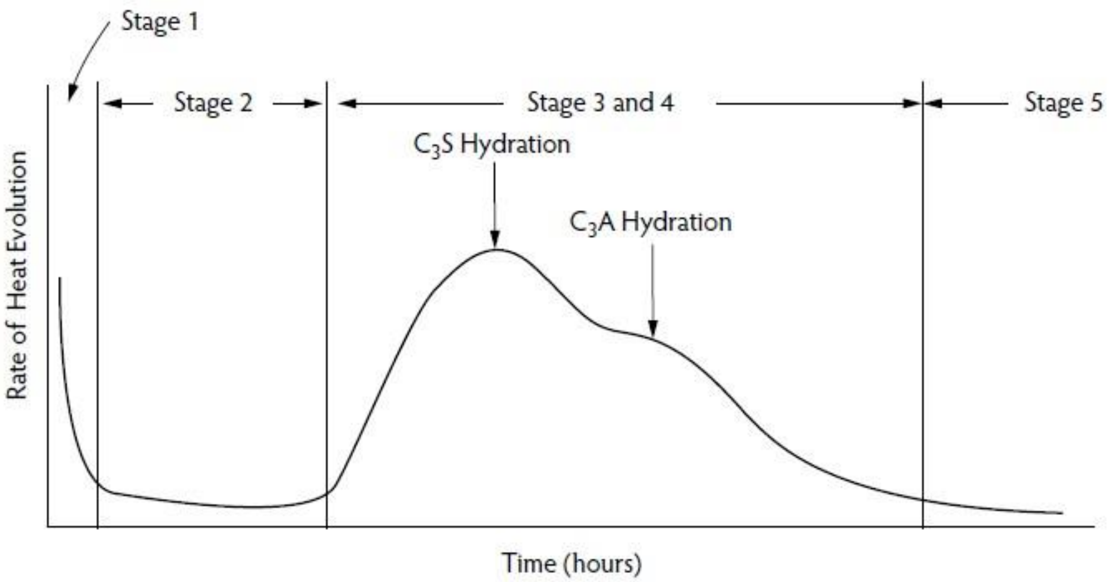


**Figure 2.2** Rate of heat evolution during the hydration of Portland cement (Mindess, 2008)

## 2.6 Curing of Concrete

Curing is defined “action taken to maintain moisture and temperature conditions in a freshlyplaced cementitious mixture to allow hydraulic cement hydration and (if applicable) pozzolanic reactions to occur so that the potential properties of the mixture may develop” (ACI 116R, 2000; ASTM C125, 2020). In other words, curing is the procedure carried out to ensure continuation of cement hydration process to maintain adequate moisture content and temperature in concrete immediately after placing, until it develops required properties. Inadequate curing can lead to a weak and porous material near the surface of the concrete, causing ingress of harmful substances from the environment (Gowripalan et al. 1990). In addition, Basheer et al. (2001) reported that inadequate curing is a major factor for deterioration and reduction in the lifespan of structures, leading to massive costly repairs.

Taylor (2013) reported that only outer 30 to 50 mm of the concrete element surface is influenced by the moisture curing. Therefore, controlling moisture is not aimed solely to ensure compressive strength development. Likewise, permeability and hardness of concrete surface is significantly affected by moisture curing, so it plays a major role in the longevity of a system, especially those exposed to sever environments. Furthermore, mixtures with water to cement ratio below 0.4 is very common nowadays, which are highly susceptible to risk of self-desiccation (chemical reactions of cement hydration). Therefore, providing external water to such mixtures is essential to the outer surface of such mixtures. Nevertheless, only up to 30 mm of the outer surface will benefit from this water curing, thus other techniques may be considered such as internal curing (P. C. Taylor 2014). According to Neville (2011), in order to ensure ongoing hydration process in concrete, it is important to keep the relative humidity at a minimum of 80% inside the concrete, provided that the relative humidity of the ambient air is at least that high as shown in Figure 2.3. Thus, movement of water between concrete and ambient air is little, and no active curing is required to promote the hydration process. It should be emphasized, the previous statement is valid only if no other factors get involved, for example, there is no difference in temperature between the concrete and the air, and there is no wind as shown in Figure 2.4 and 2.5 respectively. Therefore, active curing is not required in practice only in very humid climate with a steady temperature.

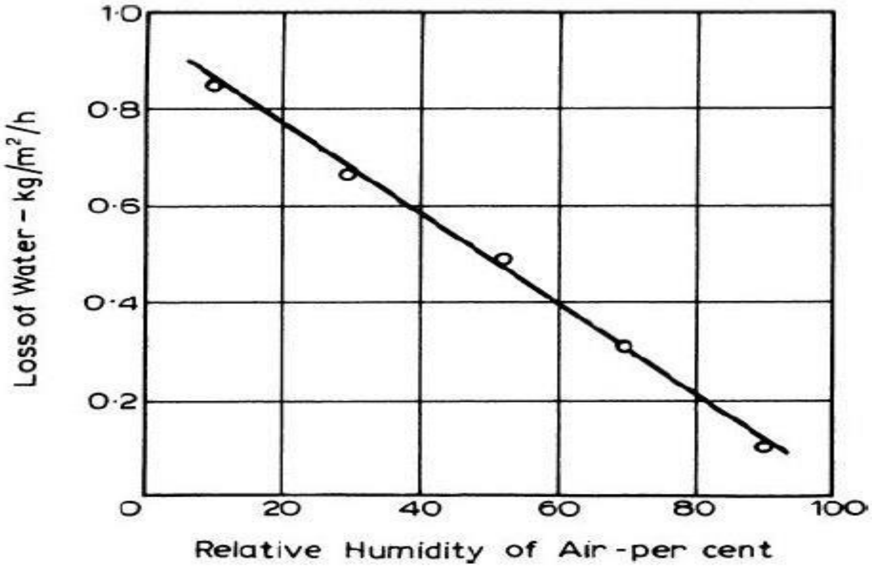


**Figure 2.3** Influence of relative humidity of air on the loss of water from concrete in the early stages after placing (air temperature 21 °C) (Johnston, 1998)

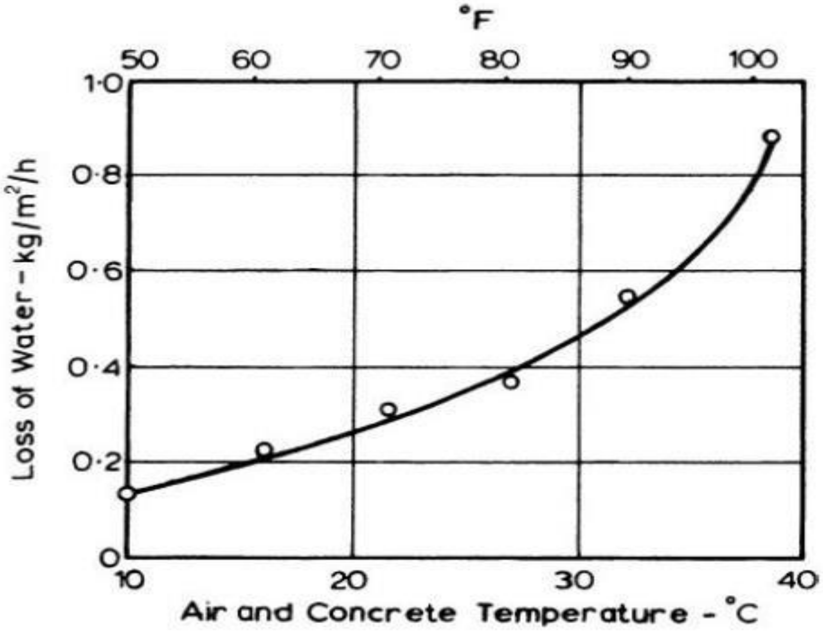


**Figure 2.4** Influence of temperature of air and concrete on the loss of water from concrete in the early stages after placing (relative humidity of air 70 percent, wind velocity 4.5 m/s) (Johnston, 1998)

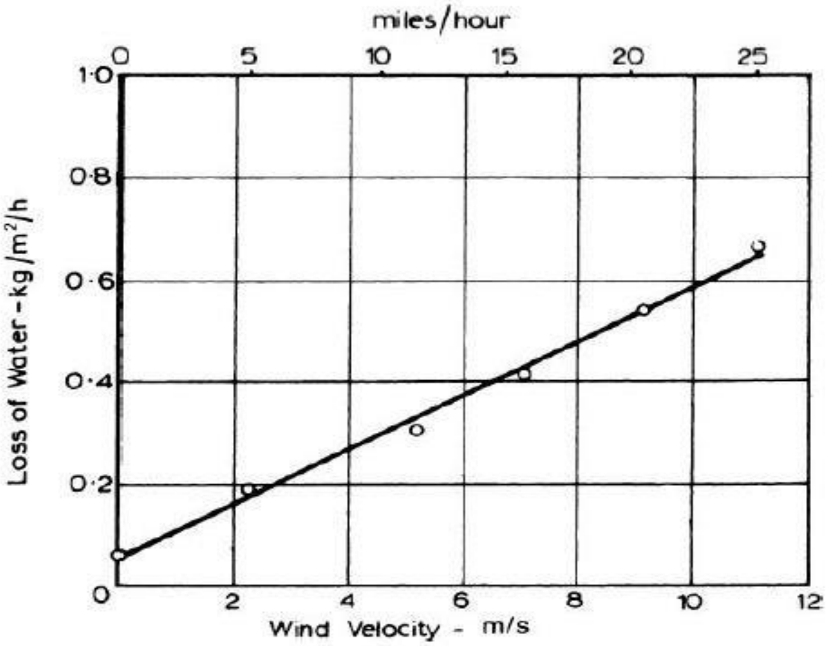


**Figure 2.5** Influence of wind velocity on the loss of water from concrete in the early stages after placing (relative humidity of air 70 percent, temperature 21 °C) (Johnston, 1998)

When the water/cement ratio is over 0.5, preventing loss of moisture from the concrete is adequate to ensure continuation of hydration process. On the other hand, ingress of water into concrete is desirable in mixtures with water/cement ration below 0.5 to promote the hydration of cement (Johnston 1998). Moreover, Basheer et al. (2010) and Mather (2004) wrote that concrete mixtures with water/cement ratio greater than 0.42 contain enough water to complete the hydration process without supplying additional water.

Newman and Choo (2003) stated concrete curing provides protections against the following:

- Premature drying out, particularly by solar radiation and wind
- Leaching out by rain and flowing water
- Rapid cooling during the first few days after placing
- High internal thermal gradients
- Low temperature or frost
- Vibration and impact which may disrupt the concrete and interfere with bond to reinforcement

### 2.6.1 Curing Methods

Selecting adequate curing methods and materials for concrete curing depends on (i) type of concrete, (ii) type of the structure including orientation of the structural member, (iii) the weather and (iv) need for construction access during curing. Normally, curing starts immediately after placing and consolidating the concrete, and it continues during subsequent operations such as finishing and texturing (Lamond and Pielert, 2006).

To control moisture loss from the concrete surface, three basic approaches are available for this purpose: adding water to the concrete surface after final set, preventing moisture evaporation or supplying water internally. Generally, the first and second methods are widely used in practice. The first one involves providing water, which can be absorbed by concrete. This is conducted by continuous spraying, ponding, or by covering the concrete with materials such as sand, burlap, or straw that are kept constantly wet. This method is very effective in achieving all the requirements of curing, namely, continuing hydration process and elimination of shrinkage. This approach will prevent moisture evaporation from the concrete surface and supply additional moisture to the surface as mixing water is consumed in the cement hydration process. However, the disadvantages of this method involve the effort to maintain the concrete wet constantly, availability of a sufficient source of water, and providing for suitable drainage of excess water during continuous spraying. Moreover, this approach may be impractical for specific type of structure and structural elements that are vertical or inclined.

The second method of curing is based on preventing moisture loss from the surface of concrete. This technique could be named a water barrier method. It involves covering the concrete surface with overlapping plastic sheet laid flat, reinforced waterproof paper or membrane-forming curing compounds. The use of plastic sheets and waterproof paper can be challenging as more labor is required and keeping the materials in place could be difficult especially in windy conditions. Therefore, use of membrane-forming curing compounds is preferred over plastic sheet and waterproof paper in such circumstances (Lamond and Pielert, 2006; Taylor, 2013).

Curing compounds (CC) are liquid materials with different chemical compositions and can be water or solvent based. They are applied on the concrete surface by spraying, rolling, or brushing. Once applied, it entirely seals the concrete surface and retards moisture evaporation by forming a continuous film. It is recommended to apply the CC on the surface of fresh concrete once the bleed water evaporates from the surface of concrete, with coverage rate of about 5 $m^2$/L. Moreover, CC are also used for further curing of concrete after removal of form work or after initial water curing for one or two days. The bases of CC are (i) Synthetic resin, (ii) Wax, (iii) Acrylic and (iv) Chlorinated rubber (Lamond and Pielert, 2006; Shetty, 2008).

The common ones are solutions of synthetic hydrocarbon resins in high-volatility solvents, sometimes including a fugitive bright colour dye. The dye makes obvious the areas not properly sprayed. A white or alumina pigment can be included to reduce the solar heat gain; this is very effective. Other resin solutions are available: acrylic, vinyl or styrene butadiene and chlorinated rubber. Wax emulsions can also be used, but they result in a slippery finish, which is not easy to remove, whereas the hydrocarbon resins have poor adhesion to concrete and are degraded by ultraviolet light (Johnston 1998).

CC are usually used for curing concrete in regions suffering from water shortage, where the excess application of water is not possible due to availability and economic reasons. Also, curing concrete placed in in some inaccessible, difficult, or far off places cannot be adequately maintained.

Furthermore, increase in construction volume, necessity for water conservation, increase in cost of labour have encouraged the use of CC in practice. CC is a preferred option for curing in specific applications such as canal lining, sloping roofs, and textured surface of concrete pavements (Shetty, 2008).

According to Neville (2011), wet curing should be used for concrete with a water-cement ration lower than 0.5, particularly lower than 0.4, provided it can be conducted continuously and thoroughly. If such measures are not possible to maintain, then well-executed membrane curing is preferable. Moreover, Taylor (2013) stated that mixtures with water-cement ratio greater than 0.4 contain enough water to hydrate all the cement, thus no added water is needed.

### 2.6.2 Influence of Curing on Concrete Properties

Effects of curing methods and curing compounds on concrete properties have been broadly investigated by numerous researchers as summarized in Table 2.6.

**Table 2.6** Effects of curing compounds on concrete properties

| Reference | Curing method | Comments/Results |
|---|---|---|
| Cabrera et al. (1989) | Curing compounds (CC) (Acrylic emulsion, Solventborne acrylic, Wax emulsion, and Solvent-borne resin) | Moisture loss due to evaporation in specimens cured using CC was higher than specimens cured in water |
| Dang et al. (2013) | Coating shrinkage reducing admixture (SRA) followed by a curing compound (CC) on the surface of the concrete | Specimens cured with SRA + CC had a minimum drying shrinkage and moisture loss, and this method of curing could significantly improve the chloridepenetration resistance and reduce water absorption of concrete |
| Xue et al. (2015) | Four different types of CC (acrylic-based, paraffin-based, silicate-based and compositebased) | They concluded that curing compounds could be used for curing the cement concrete without any negative effect on the mechanical and durability properties and microstructure |
| Ibrahim *et al.* (2013) | Specimens were covered with wet burlap for 2 days before applying the CC. Four types of curing compounds were used, namely water, acrylic, bitumen-based and coal tar epoxy | Strength and durability properties of specimens cured using the selected curing compounds were similar or better than that of concrete specimens covered with wet burlap |
| Al-Gahtani (2010) | Covering with wet burlap or by applying two types of curing compounds, namely waterbased and acrylic-based | Both types of CC were effective in decreasing the plastic and drying shrinkage strain in plain and blended cement concrete. Curing with wet burlap developed higher strength than applying CC |
| Wasserman and Bentur (2013) | CC, wet fabric and water curing | Performance of CC was less effective in terms of strength and penetration characteristics compared with other curing methods |
| Nancy et al. (2003) | Six different types of curing compounds | Curing compounds performed better than air cured, however none of the CC performed as well as specimens cured with water and or plastic sheeting |
| Wang et al. (2006) | Curing compounds | applications of CC improved moisture content retention, degree of cement hydration and decreased sorptivity of the near surface layer concrete. |

Cabrera et al. (1989) investigated curing efficiency of four different types of CC (Acrylic emulsion, Solvent-borne acrylic, Wax emulsion, and Solvent-borne resin), by measuring oxygen permeability of specimens cured using CC and compared with non-cured and water-cured specimens. They demonstrated that moisture loss due to evaporation in specimens cured using CC was higher than specimens cured in water. Dang et al. (2013) examined the performance of concrete specimens cured by coating shrinkage reducing admixture (SRA) followed by a curing compound (CC) on the surface of the concrete. The authors reported that specimens cured with SRA + CC had a minimum drying shrinkage and moisture loss, and this method of curing could significantly improve the chloride-penetration resistance and reduce water absorption of concrete. Moreover, Xue et al. (2015) investigated the effect of CC on mechanical properties and durability aspects of concrete cured using four different types of CC (acrylic-based, paraffin-based, silicatebased and composite-based). Results indicated that CC were effective in increasing the compressive, flexural strength and the impermeability of concrete. Also, the composite-based and the acrylic-based curing compound performed better than the paraffin-based and the silicate-based curing compound. They concluded that curing compounds could be used for curing the cement concrete without any negative effect on the mechanical and durable properties and microstructure.

The effect of curing methods on strength and durability of concrete under field condition in hot climate was studied by Ibrahim et al. (2013). In the investigation, concrete specimens were cured by covering them with wet burlap or applying a curing compound under field conditions. Concrete specimens were cured using four types of curing compounds, namely water, acrylic, bitumen-based and coal tar epoxy. Specimens were covered with wet burlap for 2 days before applying the CC. Results showed that strength and durability properties of specimens cured using the selected curing compounds were similar or better than that of concrete specimens covered with wet burlap. In addition, best performance was reported in samples cured by applying the bitumen-based CC. Moreover, Al-Gahtani (2010) investigated the effect of curing methods on the properties of plain and blended cement concretes. Cement specimens type I, silica fume and fly ash were prepared and cured either by covering with wet burlap or by applying two types of curing compounds, namely water-based and acrylic-based. Results showed that both types of CC were effective in decreasing the plastic and drying shrinkage strain in plain and blended cement concrete. In terms of strength development, specimens cured by covering with wet burlap developed higher strength than specimens cured by applying both types of CC. Also, acrylic-based CC performed better than water-based CC.

Furthermore, Wasserman and Bentur (2013) studied the efficiency of curing technologies on strength and durability of concrete. They concluded the performance of CC was less effective in terms of strength and penetration characteristics as compared with other curing methods, namely wet fabric and water curing. Also, they stated strength cannot be effectively used as a means for assessing curing performance with respect to durability characteristics. Additionally, Nancy et al. (2003) examined the efficiency of six different types of curing compounds in terms of water retaining to sustain the hydration process required to develop strength, and reducing permeability. Results were compared to samples cured using water, plastic-sheet curing, and air cured. Results showed that all samples cured using the curing compounds performed better than air cured, however none of the CC performed as well as specimens cured with water and or plastic sheeting. Moreover, Wang et al. (2006) investigated the effects of curing compounds on concrete properties. They reported applications of CC improved moisture content retention, degree of cement hydration and decreased sorptivity of the near surface layer concrete.

According to Gowripalan *et al.* (1990), a good quality CC is capable of retaining sufficient relative humidity in the pores of the concrete near the surface for the hydration reactions to continue. They also stated that evaluating efficiency of CC based on compressive strength measurements could be misleading, as it ignores other parameters related to durability such as porosity and permeability. Moreover, Kholia *et al.* (2013) concluded that conventional water curing is the most efficient method of curing, and CC can achieve 90% of efficiency compared to water curing. This efficiency percentage was confirmed in a study conducted by Nahata et al. (2014). They demonstrated that using CC can achieve up to 90% compressive strength as compared with conventional water curing. It is clear from previous studies that water curing is the preferred method of curing followed by CC. However, based on strength measurements, these results were obtained in the laboratory. In other words, tests were conducted in controlled humidity and temperature environment with continuous water curing which are different from actual site conditions. Moreover, durability properties of concrete should be considered in addition to compressive strength to assess overall concrete performance.

## 2.7 Transport processes in concrete

The integrity of concrete can change directly or indirectly when gases, liquids and ions penetrate the concrete. This causes interactions between penetrated substances with concrete constituents or the pore water, thus leading to deterioration and degradation of structures. This ingress is attributed to various combinations of air or water pressure differentials, humidity differentials and concentration or temperature differences of solutions. Different transport mechanisms are identified depending on nature of the transported substance and the operating force of the process (Basheer et al., 2001). The term penetrability refers to the extent in which concrete allows liquids, gases, or ionic species to move through its pore structure. This penetration initiates deterioration mechanisms such as leaching, chemical attack, chloride ingress and carbonation (Alexander et al., 2017). Therefore, concrete durability is directly connected to the transport properties of cementitious materials. Moreover, the amount of pores, pore size distribution and cracks on the microclimate at the concrete surface, substantially influence the rate, extent and effect of the transport processes (COMITÉ EURO-INTERNATIONAL DU BÉTON, 1991). The main transport processes in concrete namely absorption, diffusion, permeation, and migration are illustrated in Figure 2.6, which represents the different penetrability processes in a typical sea wall structure (excluding migration).

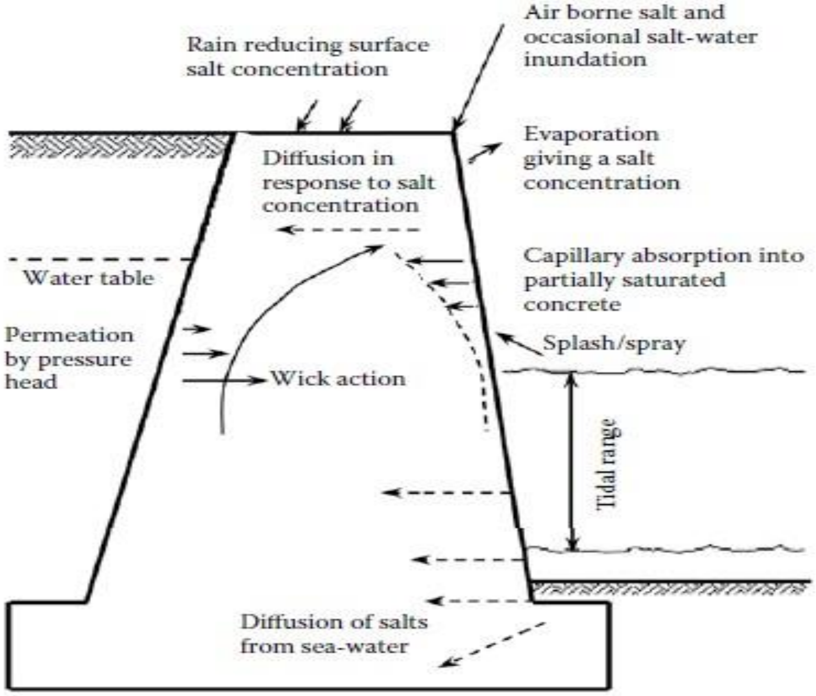


**Figure 2.6** Penetrability processes illustrated by way of a sea wall (Alexander et al., 2017)

## 2.8 Influence of transport mechanisms on concrete durability (Relations between transport characteristics and durability)

According to ACI Committee 201(2008), durability of Portland cement concrete is defined as its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration. In other words, durable concrete will maintain its original quality, form and serviceability while exposed to its environment. This means that concrete can lasts for decades with minimum or no maintenance provided it has been appropriately designed, proportioned, placed, finished, tested, inspected, and cured (ACI, 2009). Moreover, durability relates to the concept of material performance and cannot be considered as an intrinsic material property, thus a concrete that is durable in one environment may not be durable in another (Alexander et al., 2017; Ballim et al., 2009). Li (2011) stated that concrete, particularly reinforced concrete structures have been specified primarily based on compressive strength at 28 days after casting, and always designed with a high safety factor. Therefore, failures in concrete structures are rarely attributed to lack of inherent strength. Nevertheless, lack of durability in concrete structures causing gradual deterioration, subsequently leading to structure failure earlier than its intended lifespan is increasing.

Detwiler et al. (2005) wrote that durability not strength is the most important characteristic of concrete. Strength is indirectly associated to durability in many cases as measures needed to enhance durability also lead to an increase in strength. Nonetheless, the two are different and in some instances, actions taken to increase strength are detrimental to durability. For instance, to improve durability of concrete exposed to cycles of freezing and thawing, the concrete should be air entrained, however presence of air in concrete adversely affects the strength. Similarly, increasing cement content in concrete usually increases strength, but this action increases the risk of shrinkage-related cracking (P. C. Taylor 2014). Furthermore, Bentur and Jaegermann (1991) suggested that evaluation of concrete skin properties based on compressive strength is inadequate, and can be misleading when durability properties are investigated.

Moreover, Bentz et al. (1999) reported that description of compressive strength without consideration to durability is insufficient to ensure proper durability of concrete. The authors stated the compressive strength is more of a bulk property, whereas properties of the surface and nearsurface layers greatly influence durability of concrete. In addition, strength is influenced by flaw (pore) size whereas transport is typically governed by the overall connectivity of the pore network. They concluded that a significant indication of durability of concrete can be measured through the assessment of the transport properties of the surface layer because it is exposed to the external environment, thus it initiates many degradation processes such as ingress of chloride and sulfates and carbonation. Therefore, it is essential to differentiate between durability and strength, and to assess concrete durability by means of its transport mechanisms. Transport mechanisms greatly influence degradation in concrete, thus testing of transport parameters for concrete, such as gas permeability, absorption and chloride diffusivity are more relevant to assess durability of concrete (Kropp and Hilsdorf, 1995; Zhang and Zhang, 2014).

According to Powers (1958), cement paste is intrinsically porous and permeable, and the densest possible completely hydrated cement paste has a porosity of about 26%. Porosity depends on the initial w/c ratio and on curing conditions, whereas permeability depends on porosity and on the size and shape of the pores. Previous studies (Roy et al., 1993; Odler and Rößler, 1985; Kumar and Bhattacharjee, 2003; Bentz et al., 1999; R.F.Feldman, 1986) have concluded that transport properties such as permeability of concrete, significantly influence strength and durability of concrete. Furthermore, Mindess et al. (2003) stated that durability of concrete is greatly influenced by its permeability because it controls the rate of entry of moisture that may contain aggressive chemicals and the movement of water during freezing or heating. The authors singled out w/c ratio as the main parameter affecting durability, because decreasing the w/c ratio leads to a reduction in the porosity of the paste, thus concrete becomes impermeable. Moreover, the significant influence of w/c ratio and degree of hydration on permeability was also reported by (Kosmatka, 2008; Lin et al., 2012). Furthermore, Yu et al. (2018) demonstrated that connectivity of the capillary pores in blended cement significantly influences water permeability of cement paste in addition to capillary pores. It is clear from previous studies that reducing w/c is imperative to produce a durable concrete as it directly affects porosity and permeability.

Deterioration in concrete such as carbonation and chloride ingress, which are caused by the movement of a gas or ion into concrete microstructure, are associated to the transport processes of concrete. Hence, transport mechanisms are of great importance in the evaluation of durability.

## 2.9 Factors influencing concrete durability

According to Ballim et al. (2009), concrete durability involves the interaction between concrete as a system and its environment, and both need to be taken into account in durability evaluation. Ability of the concrete to resist deterioration is influenced by factors related to concrete system, whereas extent of aggressiveness that concrete must withstand is influenced by environmental factors.

Causes of concrete deterioration can be categorized into three groups: physical, chemical, and mechanical causes. These factors may act alone or occur simultaneously (Mehta et al., 2006; Li, 2011; Tang et al., 2015; Bertolini et al., 2013). According to Mehta et al. (2006), concrete deterioration and degradation due to physical factors can be grouped into two categories as illustrated in Figure 2.7:

i. Surface wear or loss of mass due to abrasion, erosion, and cavitation.

ii. Cracking due to normal temperature and humidity gradients, crystallisation of salts. in pores, structural loading, and exposure to temperature extremes, for instance freezing or fire.

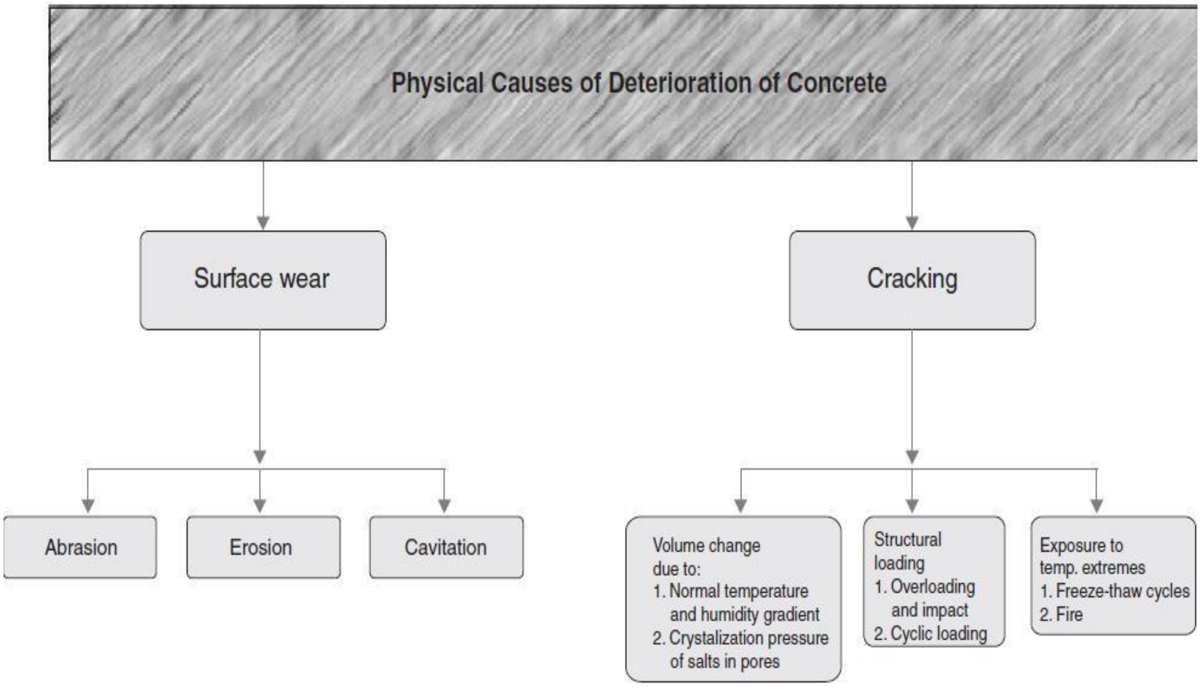


**Figure 2.7** Physical causes of concrete deterioration (Mehta et al., 2006)

On the other hand, external or internal chemical attack on the cement matrix causes chemical deterioration. Since PC is alkaline, it will react with acids and chlorides in the presence of moisture. Consequently, the matrix may suffer degradation and its components may be leached out. The most common chemical causes of concrete deterioration are i) alkali-aggregate reactions, ii) sulfate attack, iii) acid attack and iv) attack by pure water. Moreover, mechanical deteriorations are caused by impact and overloading (Li, 2011; Bertolini *et al.*, 2013). Generally, concrete structures suffer degradation due to the combined effect of loading and environmental factors. It should be noted that aggressiveness of agent attacking the concrete is the most important environmental factor. Moreover, durability of concrete is largely influenced by intrinsic factors such as water/binder (w/b) ratio and binder type, as well as extrinsic factors such as curing (Ballim et al., 2009; Alexander et al., 2017). Figure 2.8 shows main factors influencing durability of concrete.

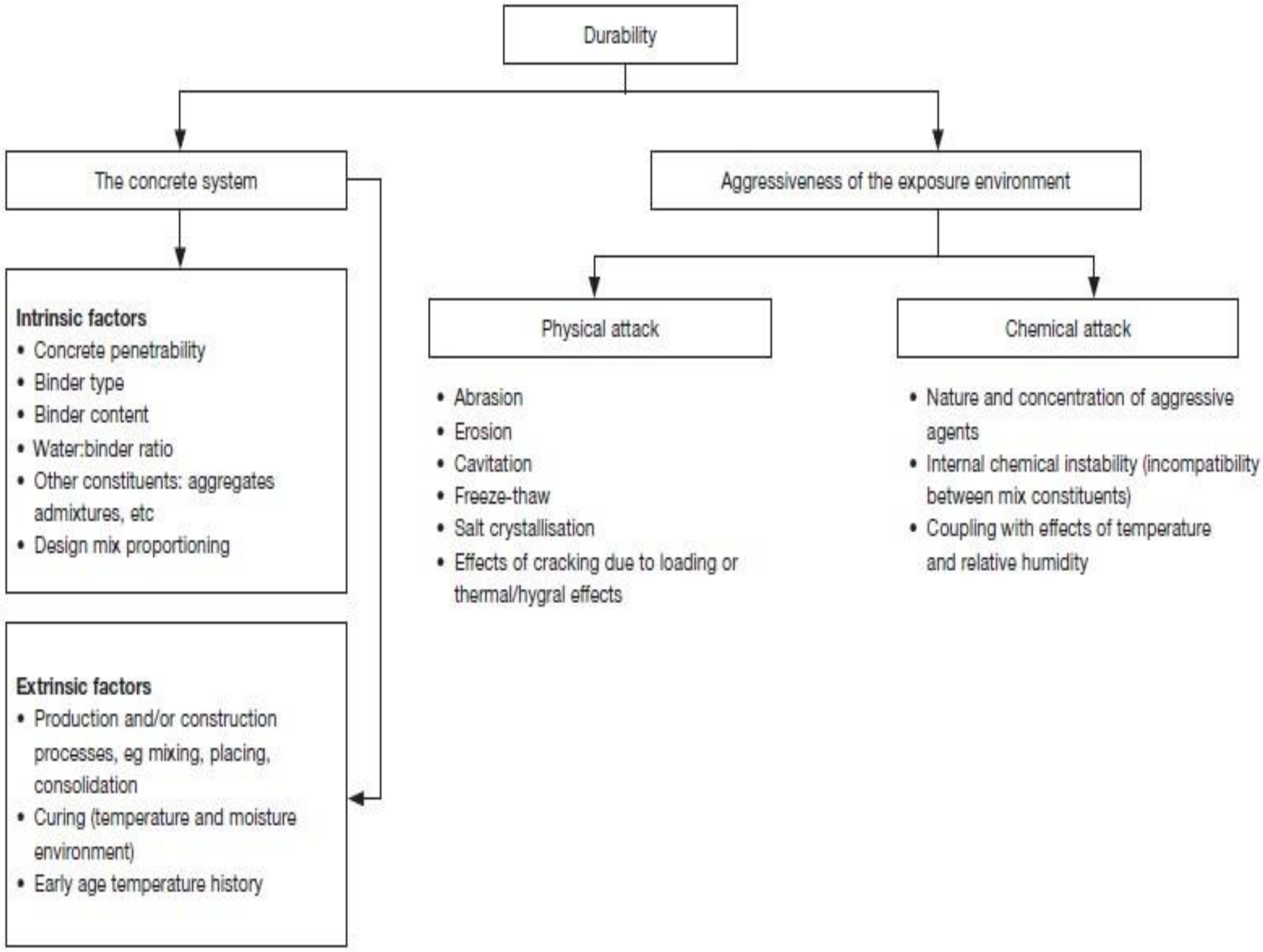


**Figure 2.8** Factors influencing the durability of concrete (Owens, 2009)

## 2.10 Durability related deterioration of concrete

As mentioned previously, deterioration of concrete is mainly caused by physical and chemical Factors. Concrete is widely used in structures exposed to aggressive environmental conditions such as marine structures, tunnels and bridges exposed to chloride through de-icing salt. Hence, using concrete in aggressive environment conditions increases concern over its durability and the actual service lives of concrete structures (Mehta et al. 2006). Deterioration of concrete structures can occur due to various processes such as alkali-aggregate reaction and freezing and thawing. However, corrosion of embedded steel reinforcement is the predominant cause of deterioration in practice, thus it is regarded as the most serious and demanding challenge facing the construction industry worldwide (Gjørv, 2014; Richardson, 2002; Broomfield, 2011; Broomfield, 2007). The main purpose of concrete cover is to protect concrete from the environment by providing a coating. In fact, concrete cover provides both physical and chemical protection against corrosion. The physical protection includes its total porosity, its pore size distribution and the extent to which pores are interconnected. On the other hand, chemical protection is achieved through the high alkalinity of the concrete pore solution (Bentur et al., 1997). However, concrete cover exposed to ingress of aggressive species such as carbon dioxide and chloride ions causes loss of this protective cover (Glass, 2003).

Ordinary steel bars used for concrete reinforcement is susceptible to corrosion in humid conditions in the air. Nevertheless, excellent protection from corrosion is provided by the alkaline environment in the concrete, with a pH > 12. In hardened PC, the pore water usually has a pH in the range 12.5-13.5. This is due to large reserves of calcium hydroxide $Ca(OH)_2$, supplemented by far smaller amounts of sodium and potassium oxides and hydroxides. This alkaline environment safeguards steel bars by creating a passive layer on the steel surface. This passive layer or passivity is a thin stable layer of iron oxide at the surface of the steel, and it is firmly protected by the surrounding concrete. However, this passive layer can be broken by two processes namely, i) carbonation and ii) chloride attack (Nilsson, 2019; Broomfield, 2010).

Corrosion of steel reinforcement has two detrimental consequences on the structural performance of the concrete. The first is that corroded steel suffers a loss of rebar cross-section area, which undermines its ability to withstand tensile stress. The second is the formation and buildup of rust at the steel surface. Corrosion products occupy a larger volume than the original metal from which they were derived. As a result, tensile stresses are formed causing deterioration such as cracking and spalling of the concrete cover as shown in Figure 2.9 (Mather, 2004; Glass, 2003).

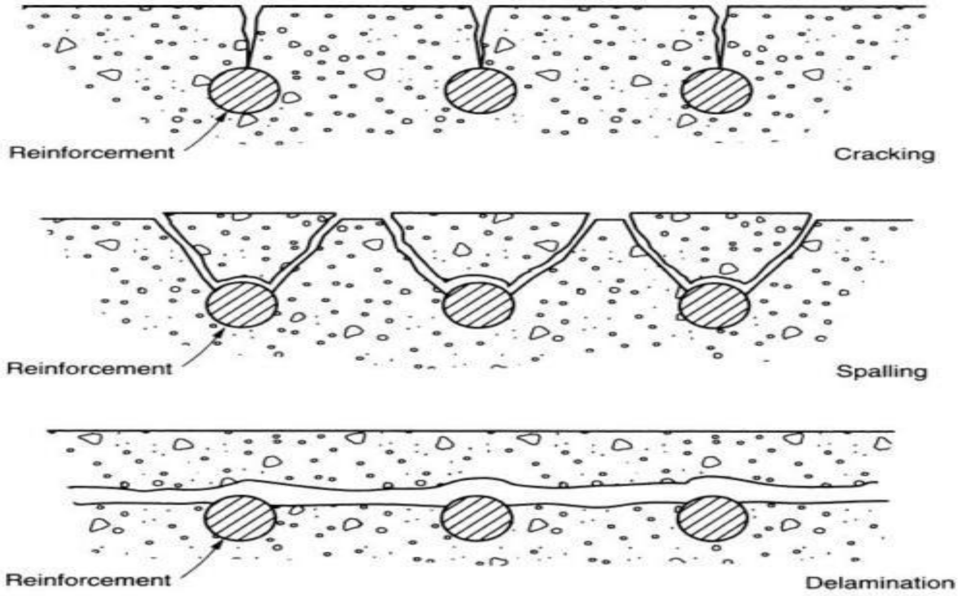


**Figure 2.9** Diagrammatic representation of damage induced by corrosion (Johnston, 1998)

It is estimated the global cost of corrosion is around US$2.5 trillion, which is equivalent to 3.4% of the global Gross Domestic Product (GDP) (NACE International, 2016). It is believed that savings of between 15 and 35% cost of corrosion could be achieved by using available corrosion control measures. In other words, an immense savings of US$375 to $875 could be realized annually. It should be noted that these substantial costs typically do not include environmental consequences and individual safety (Bowman et al., 2016; NACE International, 2016; Mazumder, 2020). Moreover, according to the National Association of Corrosion Engineers (NACE International 2016) the direct cost of corrosion for highway bridges in the USA is estimated to be $13.6 billion annually. This figure included replacement of deficient bridges, maintenance, and capital cost for concrete bridges decks as well as maintenance of substructures. On the other hand, indirect costs such as lost productivity and traffic delays were estimated to be 10 times higher than direct corrosion costs (Ueli M Angst 2018).

Furthermore, repair and maintenance cost caused by corrosion in the United Arab Emirates mainly in the energy industry is estimated at 14.26 billion US$ in 2011, which is about 5.2% of the country’s GDP in three years 2009-2011 (Lim 2012). The above examples of repair and maintenance cost due to corrosion in concrete structures and other industries show the magnitude of this problem within all industries worldwide. It should be noted that all forms of deterioration of concrete involve the presence of water in the surrounding environment and in the internal pore structure of the concrete (Owens, 2009; Mehta et al., 2006). Additionally, the corrosion of steel reinforcement in concrete affects the structural performance and safety of the structure, as well as its serviceability or the external condition as shown in Figure 2.10 (Bertolini *et al.*, 2013; Cabrera, 1996). It is well known that the two most significant causes of corrosion of reinforcing steel in concrete are carbonation and chloride ingress. Chloride contamination affects structures that are exposed to de-icing salts or marine environments, whereas carbonation problem is mainly related to buildings. These two mechanisms do not attack the integrity of the concrete, it is the effect of aggressive chemical species pass through the pores and attack the steel. Other less common causes of corrosion are aggressive ions such as sulfates, acidic gases like sulphur dioxide, fluorides, bromides and straying electrical currents. (Glass, 2003; Broomfield, 2011; El-Reedy, 2017).

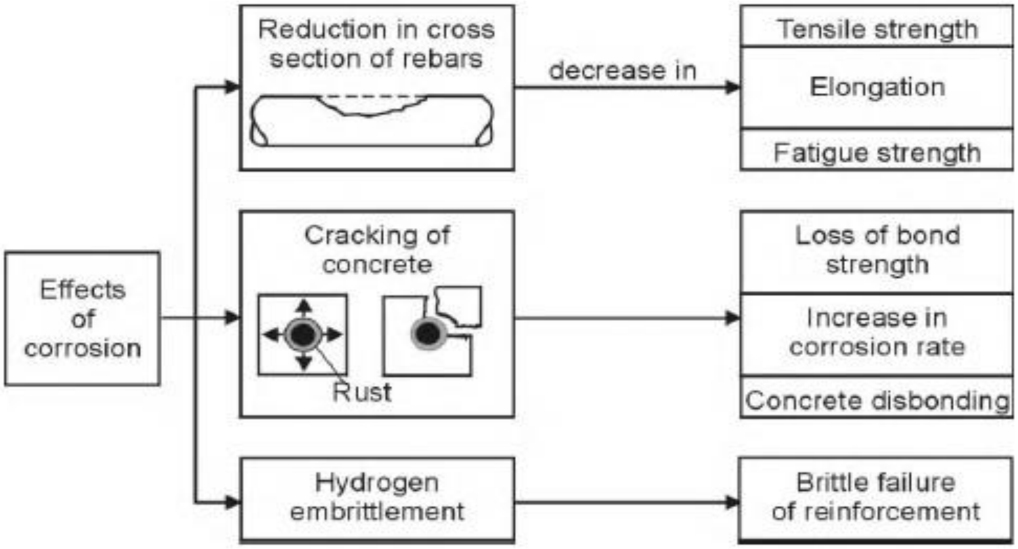


**Figure 2.10** Structural consequences of corrosion in reinforced concrete structures (Bertolini et al., 2013)

### 2.10.1 Chloride binding capacity

Chloride binding is defined (Glass and Buenfeld 2000) as interaction between the porous concrete matrix and chloride ions leading to effective removal of mobile chloride from the pore solution of concrete. According to Dyer (2014), the chloride binding process in concrete involves mainly two mechanisms: the formation of Friedel's salt and the immobilization of the ions that come into contact with C-S-H gel. Chloride binding could have a major impact on the lifespan of many concrete structures as it may influence the rate of chloride ingress, the chloride threshold level, and the subsequent corrosion rate. Regardless of the chloride source, the content of $C_3A$ and $C_4AF$ influences chloride binding in cementitious system. Chlorides can be chemically bound by reacting with the aluminate phases ($C_3A$ and $C_4AF$) to form calcium chloroaluminates, or physically adsorbed to the cement paste and dissolved in the pore solution. Moreover, bound chlorides are in chemical equilibrium with the free chlorides. It should be stressed that in particular circumstances, such as carbonated cement paste or intruded by sulfates, bound chlorides can be released and become free chlorides again (Justnes, 1998; Alexander et al., 2017; Poulsen and Mejlbro, 2014) (Montemor et al., 2003). Therefore, bound chloride could play a role in the steel corrosion process. Moreover, the influence of incorporating various SCMs including metakaolin, FA, GGBS and SF on the chloride binding capacity of PC pastes was examined by Thomas et al. (2012). Results showed that inclusion of SCMs with high content of alumina increased the binding capacity of cement paste. Highest chloride binding capacity was measured in pastes with metakaolin containing 45% $Al_2O_3$, and least binding capacity was in silica fume paste containing less than 0.5% $Al_2O_3$. According to the authors, the chemical binding capacity in solutions containing high concentration of chloride is mainly due to the formation of Friedel's salt $C_3A \cdot CaCl_2 \cdot 10H_2O$.

## 2.11 Carbonation of concrete

Interaction of carbon dioxide gas present in the atmosphere with the alkaline hydroxides in the concrete leads to formation of carbonates (Kropp and Hilsdorf, 1995; Broomfield, 2007; Kosmatka, 2008). Initially, carbon dioxide diffuses through the surface of concrete and dissolves in water to form a carbonic acid, which neutralizes the alkalies in the pore water rather than affecting the cement paste. After the penetration of $CO_2$ into the concrete, the chemical reactions take place in two phases. The first one occurs when $CO_2$ dissolves in water, and the second phase involves reaction of dissolution products with hydration products within cement paste (Mather 2004b).

Carbonic acid $H_2CO_3$ is formed when $CO_2$ meets water as following:

$$CO2 + H2O \longrightarrow H_2CO_3 \qquad \text{Equation 2.1}$$

Followed by the reaction of the carbonic acid with Portlandite to form calcium carbonate:

$$Ca(OH)_2 + H_2CO_3 \longrightarrow CaCO_3 + 2H_2O \qquad \text{Equation 2.2}$$

It should be stressed that, calcium silicate hydrate (C-S-H) gel will also be affected during carbonation. It is well known that the alkaline nature of the concrete is mainly due to the presence of calcium hydroxide $Ca(OH)_2$ which is formed during the hydration of cement. Typical pH value of concrete pore water is about 12.6. However, consumption of calcium hydroxide $Ca(OH)_2$ drops pH value to below 9 in completely carbonated concrete, thus destroying the passive film which protects steel surface from corrosion. Consequently, corrosion of embedded steel reinforcement will occur in the presence of oxygen and moisture (Beushausen and Luco, 2015; True, 1993; Richardson, 2002). Another consequence of carbonation in terms of corrosion is its ability to release bound chloride ions into the pore solution phase of concrete, thus increasing the aggressiveness of the pore solution (Bertolini et al., 2013; Tuutti, 1982; Page and Page, 2007; Wang et al., 2017).

Moreover, carbonation rate in concrete is influenced by several parameters including permeability of concrete, its moisture content, $CO_2$ concentration and the relative humidity of the ambient medium. Typically concrete with a high water-cement ratio and poorly cured will be more susceptible to carbonation (Neville & Brooks, 2010; Kosmatka, 2008). It should be noted that, carbonation does not occur in a totally dry or wet environment and the carbonation rate may be associated to the humidity of the environment. Typical value of relative humidity in the environment to promote carbonation in concrete is from 60 to 70% (Li, 2011; Poursaee, 2016). It should be emphasized that carbonation of concrete is a very slow process due to the small amounts of $CO_2$ available in the air approximately 0.04% by volume (Nilsson, 2019).

BS EN 206 (2013) identifies four exposure classes where reinforced concrete is exposed to environmental actions namely air and moisture, and corrosion induced by carbonation is likely to occur as shown in Table 2.7.

**Table 2.7** Corrosion induced by carbonation based on exposure classes (BS EN 206, 2013)

| Class designation | Description of the environment | Informative examples where exposure classes may occur |
|---|---|---|
| XC1 | Dry or permanently wet | Concrete inside buildings with low air humidity; Concrete permanently submerged in water |
| XC2 | Wet, rarely dry | Concrete surfaces subject to long-term water contact; Many foundations |
| XC3 | Moderate humidity | Concrete inside buildings with moderate or high air humidity; External concrete sheltered from rain |
| XC4 | Cyclic wet and dry | Concrete surfaces subject to water contact, not within exposure class XC2 |

Carbonation of concrete have been investigated and described widely by researchers and authors. In a study conducted by Turcry et al. (2014) to assess the influence of preconditioning on the accelerated carbonation kinetics. It was demonstrated that concrete samples exhibited less carbonation near the surface, and more carbonation was detected in depth during the first days of the test. This was attributed to the effect of preconditioning which highly dries the first mm. Therefore, carbonation occurred at deeper depth where water content is sufficient to promote carbonation reaction. This shows that presence of water which is available within the concrete is vital to initiates carbonation. Furthermore, the effect of porosity and water content on the diffusivity of $CO_2$ through hardened cement paste was examined by (Houst and Wittmann 1994). Results showed that diffusion coefficients of $CO_2$ increased more than ten times when w/c ratio increased from 0.4 to 0.8. On the other hand, effect of relative humidity between 50-90% was insignificant on samples in adsorption equilibrium as shown in Figure 2.11. This finding was consistent with results obtained in a study conducted by Wang et al., (2019). The authors concluded that carbonation depths and rate increased with increase in w/c ratios, porosity, and carbonation time.

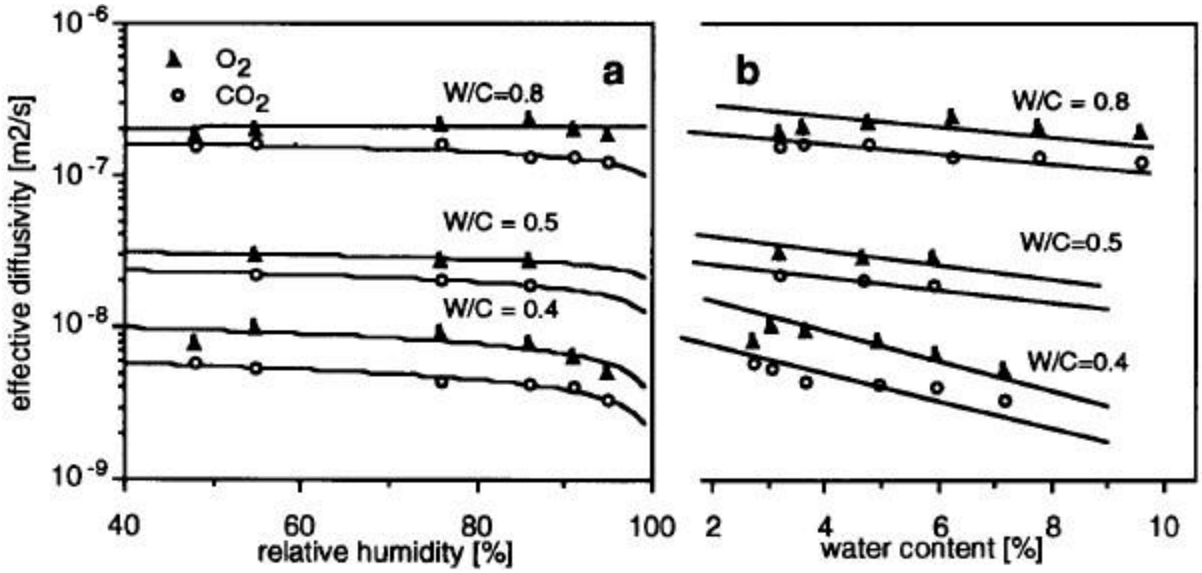


**Figure 2.11** Effective diffusivity versus: (a) relative humidity, (b) water content (Houst and Wittmann, 1994)

Moreover, Marques et al. (2013) investigated modelling of long term performance of concrete compositions with different proportions of clinker with respect to the diffusion of $CO_2$ in concrete. In the study, CEM I samples were used as well blended cements including limestone filler and low calcium fly ash. It was demonstrated that at 28 days of age, only CEM I reached the target periods of 50 and 100 years of design requirements. It was concluded that blended cements did not meet the estimated design target. However, the performance of blended cements tested at 90, 180 and 365 days improved and reached the target design. Nevertheless, this performance was inferior to CEM I.

Ghahari et al., (2016) assessed durability of concrete containing silica fume exposed to carbonation and chloride ingress simultaneously. They reported that presence of silica fume in the concrete, physically and chemically filled the pores of specimens and reduced carbonation depth. In addition, carbonation of concrete specimens containing GGBS produced with different waterbinder ratios (w/b) and different binder contents was investigated by Alhassan and Balim (2017). They demonstrated that lower w/b ratio and prolonged moist curing age of concrete resulted in slower rate of carbonation due to pore structure densification. Also, it was observed that the pore structure of GGBS concrete was denser than that of CEM I concrete. However, the carbonation coefficients of GGBS mixtures were higher than that of the plain concrete. They concluded that pore structure is not the main influential factor in carbonation control as the amount of CH present within concrete is significant in the carbonation process.

The influence of mineral admixtures namely FA, GGBS and SF on carbonation of concrete was studied by (Peethamparan et al., 2003). They reported that better carbonation resistance was observed in mixes with reduced water to binder ratio and replacement level of FA, GGBS or SF, or an increase in GGBS fineness and curing age in water. However, inclusion of mineral admixtures (except GGBS with greater fineness and SF) reduced resistance to carbonation compared to reference specimens (CEM I). This is likely due to the reduction in calcium hydroxide over pore refinement. These results were confirmed in another study conducted by Czarnecki, Woyciechowski and Adamczewski (2018). They concluded that using mineral by-products such as FA, GGBS and SF increased the rate and depth of carbonation, and using the lowest possible w/c ratio and extended initial water curing time were imperative to increase carbonation resistance of blended cement concrete.

In a review conducted by Lye et al. (2016) on carbonation resistance of GGBS concrete, it was reported that the inclusion of GGBS led to a rise in the carbonation of concrete, and the rate increased as GGBS content was increased. Moreover, increases in carbonation rate is higher in GGBS concrete designed on an equal w/c ratio basis to the corresponding CEM I concrete than on equal strength basis. The authors concluded that carbonation of concrete containing 20% GGBS is similar to corresponding CEM I. In addition, effects of curing on carbonation of concrete was studied by Lo and Lee (2002). The authors concluded that w/c ratio and age of concrete are influential factors, as an increase in the w/c ratio led to a rise in the carbonation depth. They also reported that the initial water curing period of concrete was critical in the carbonation process, and carbonation depth varied between water-cured and air-cured specimens, but the differences diminished with time.

Furthermore, the durability behavior of fly ash concrete against combined effect of carbonation and chloride aerosol ingress was investigated by Liu et al. (2016). It was demonstrated that carbonation substantially affected the chloride ingress profile as it reduced the chloride binding capacity and accelerates diffusion rate of chloride ion. It was also observed that the presence of chloride aerosol reduced the carbonation rate of fly ash concrete. Geng et al. (2016) examined the effect of carbonation on releasing bound chlorides in chloride-contaminated cement paste specimens. Results showed that carbonation of cement paste led to a release of bound chlorides, which was attributed to the decomposition of C-S-H gel as well as decomposition of Friedel's salt.

Moreover, the influence of carbonation of C-S-H on the pore structure of cement paste blended with different SCMs such as FA and GGBS was investigated by Wu and Ye (2017). Results showed that carbonation of most of the species of C-S-H led to an increase in the porosity of the cement paste. Also, carbonation of cement paste with high content of GGBS caused an increase in the total and effective capillary porosity. They concluded carbonation of blended cement concrete adversely affects durability properties. In addition, durability of blended cement concrete (SF, low and high calcium FA) against carbonation and chloride ingress was studied by Papadakis (2000). Results showed that replacement of cement by SCM increased carbonation depth, but significantly extended the chloride-induced corrosion initiation stage. Ye et al. (2016) showed that incorporation of GGBS and low calcium FA in concrete exposed to chloride and carbonation environment, makes concrete more susceptible to carbonation-induced chloride movements due to its less amount of portlandite. Furthermore, McPolin et al., (2009) investigated carbonation of mortars produced with OPC, FA, GGBS, MK and MS. The authors concluded that replacement of PC with FA and GGBS had damaging effect on carbonation, and MK had little influence on carbonation. On the other hand, rate of carbonation was decreased in MS specimens as shown in Figure 2.12.

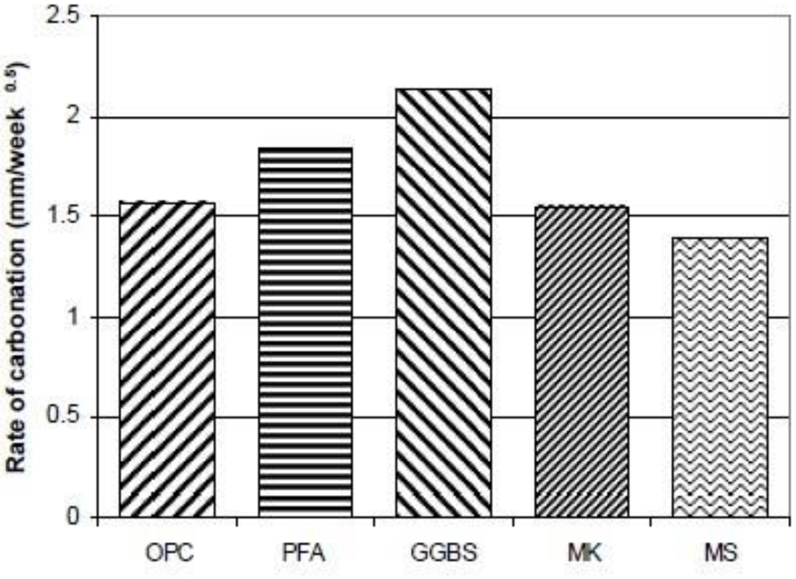


**Figure 2.12** Rate of carbonation (McPolin et al., 2009)

Replacement of PC with FA, GGBS, SF and MK leads to a reduction in $Ca(OH)_2$ content. The amount of $Ca(OH)_2$ in concrete is significant to control the rate of carbonation, as larger quantity of $CO_2$ is needed when higher level of $Ca(OH)_2$ is present. Therefore, when the level of $Ca(OH)_2$ is reduced due to replacement of PC with mineral admixtures, this means that amount of $CO_2$ required to cause carbonation is reduced (Dyer, 2014).

According to Glass (2003), reaction between $CO_2$ and all major components of hydrated cement, including calcium hydroxide and C-S-H gel will release hydroxyl ions as the pH drops. The alkaline reserve in hydrated cement is influenced by the cement type. Thus, resistance of blended cement with FA or GGBS against carbonation may significantly decrease the alkaline reserves in the hydrated paste, subsequently reduces carbonation resistance of concrete.

Furthermore, Chi et al. (2002) assessed influence of carbonation on durability and mechanical properties of CEM I concrete. It was demonstrated that higher $CO_2$ concentration and longer exposure period led to an increase in the depth of carbonation of concrete. In addition, slightly higher compressive strength and splitting strength were measured in carbonated concrete at the age of 28 days compared to concrete specimens without carbonation. Moreover, the influence of carbonation on the pore structure and permeability of concrete was evaluated by Claisse et al.

(1999). Results showed that carbonation caused considerable reduction in porosity and permeability of concrete, and the extent of the reduction was highest in poor quality concrete. Furthermore, Visser (2014) investigated the effect of $CO_2$ concentration on the resistance of concrete to carbonation. It was reported that a change in the $CO_2$ concentration would not change the carbonation process. Additionally, it was concluded that all unhydrated and hydrated cement eventually carbonates. Moreover, the influence of limestone fillers on changes in microstructure and permeability of cement paste due to carbonation was investigated by Phung et al. (2015). The authors established that carbonation caused a substantial decrease in water permeability due to changes in microstructure and mineralogy. This permeability reduction was attributed to portlandite carbonation and partially from C-S-H carbonation.

It is clear from the literature review that carbonation is a major cause of corrosion in reinforced concrete structure, particularly aged buildings. Another major consequence of carbonation is the release of bind chloride, which is detrimental in structures exposed to chloride ingress. Various factors influence carbonation process in concrete namely, w/c ratio, curing period, concrete composition, concrete cover, relative humidity, temperature, concentration of $CO_2$ and exposure period. Moreover, inclusion of mineral admixtures in concrete especially FA and GGBS reduced carbonation resistance of concrete. Thus, limiting amount of cement to be replaced with mineral admixtures in structures which are exposed to high and constant $CO_2$ is recommended. Moreover, based on literature review, carbonation causes a slight increase in compressive strength and reduction in porosity and permeability. It should be emphasized that to provide a proper protection from carbonation-induced corrosion, low w/c ratio and adequate concrete cover depth as well as appropriate curing are significant to prevent or mitigate carbonation.

## 2.12 Chloride ingress

Chloride penetration into concrete causes major threats to reinforcement steel in concrete, as it is one of the major causes of steel corrosion. The main sources of chlorides can be external or internal. It can enter concrete externally from the environment such as seawater and de-icing salts on highways through different mass transport mechanisms, or internally incorporated into concrete as contaminants in constituent materials such as aggregate or as calcium chloride used as an accelerating admixture. Therefore, the use of latter compound is no longer permitted in reinforced and prestressed concrete due to its corrosive nature (Dyer 2014).

According to Neville and Brooks (2010), PC itself is another source of chloride in the mix, as it contains a very small amount, usually, no more than 0.01% by mass. On the other hand, GGBS may contain a significant chloride content if its processing involved quenching with sea water. Also, drinking water may also contain 250 parts per million of chloride ions. For instance, at a w/c ratio of 0.4, the water would contribute the same amount of chloride ions as PC. Moreover, the chloride content of the aggregate should not exceed 0.05% by mass of the total aggregates. This is reduced to 0.03% when sulphate resisting cement is used. Nevertheless, the major sources of chloride ingress can usually occur from external sources such as de-icing salts and seawater mainly as sodium, magnesium, and calcium chloride.

Moreover, chloride ions can penetrate concrete through diffusion, permeation or capillary suction (Poulsen and Mejlbro, 2014; Mather, 2004). It should be noted that, depending on the concentration of the chloride in the pore water, the free chloride ions will be physically bound to the inner pore surfaces and will chemically react with some of the solids, particularly $C_3A$. Thus, only free chloride in the pore water influences the corrosion of the reinforcement. Moreover, carbonation of concrete considerably increases the risk of corrosion as some of the bound chloride will be released again in the pore water (Mindess 2019). Resistance of concrete to chloride penetration depends mainly on the following factors (Nilsson, 2019; Richardson, 2002):

- Resistance to movement of chloride ions by diffusion through narrow and very tortuous pores.
- The binding capacity of the concrete due to the interaction between ions and the solids. This binding capacity tends to retard the ingress of chloride as it will stop further movement of the ions.
- Sorptivity of the concrete
- Water/cement ratio
- Extent of exposure to chloride source
- Temperature
- carbonation

Modelling deterioration in reinforced concrete structures exposed to corrosive environments was well illustrated by Tuutti (1982). The model represents the service life of a concrete structure exposed to the action of carbonation and/or chloride ingress as shown in Figure 2.13. Based on the model, the service life of a structure is divided to an initiation stage during which aggressive agents such as chloride and $CO_2$ penetrates the concrete cover until reaching concentration level at the surface of steel bars required to cause depassivation. The second stage is a propagation phase during which the depassivated steel starts corroding until a limit state being reached leading to formation and buildup of rust, subsequently causing cracking, and spalling of the concrete cover.

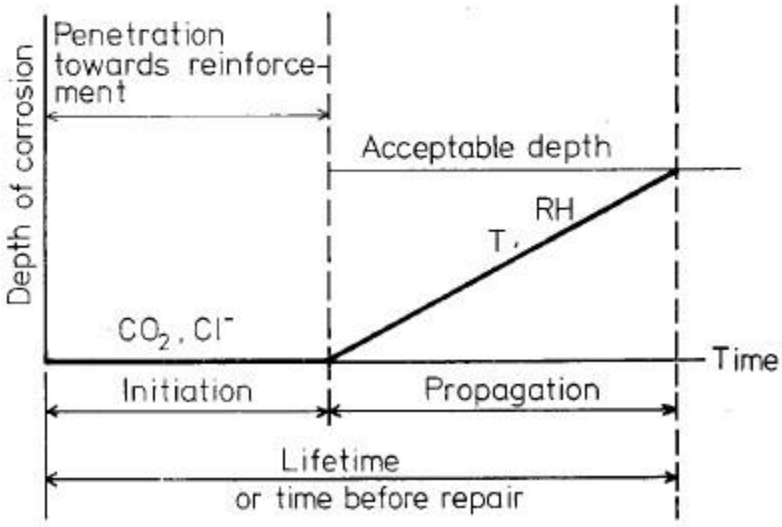


**Figure 2.13** Service life model of a reinforced concrete structure exposed to a corrosive environment (Tuutti, 1982)

In terms of chloride attack mechanism, the chloride ion attacks the passive layer surrounding steel reinforcement, but unlike carbonation there is no drop in pH. During the corrosion process, chlorides act as catalysts and they are not consumed in the process. Chlorides promote and accelerate the corrosion process by helping the breakdown of the passive layer of oxide on the steel (Broomfield, 2011; Broomfield, 2007).

Once chloride concentration at the steel bar depth exceeds chloride threshold level (Critical level $C_{cc}$), corrosion process initiates at the steel bar surfaces. The critical chloride level can be defined as the chloride content required for the breakdown of the passive layer around steel bars (Schissl and Raupach, 1990; Kropp and Hilsdorf, 1995). In other words, depassivation of the steel surface occur when the chloride concentration exceeds the critical level. Moreover, the chloride threshold level is influenced by numerous parameters such as moisture content, concrete quality (chloride binding capacity), concrete cover (availability of oxygen, pH level) and w/c ratio (Böhni 2005). In addition, steel-concrete interface and the steel potential are also extremely influential factors on the $C_{cc}$ (Angst et al., 2009; Ann and Song, 2007). Moreover, the critical chloride level is usually represented as total chloride content relevant to the weight of the cement. This is preferred due to availability of simple approaches to determine chloride content which are well documented in standards (Glass and Buenfeld, 1997; Angst et al., 2009; ASTM C1218, 2020; BS 1881-124, 2015; ASTM C1152, 2020). BS EN 206 (2013) limits the maximum chloride content of a concrete represented as the percentage of chloride ions by mass of cement in concrete without steel reinforcement to 1%. This limit is reduced to 0.2% for reinforced concrete and 0.4% for reinforced concrete containing CEM III cement. Moreover, this restriction of chloride content is further reduced in concrete containing prestressing steel reinforcement to 0.1% as shown in Table 2.8.

**Table 2.8** Maximum chloride content of concrete (BS EN 206, 2013)

| **Concrete use** | **Maximum chloride content by mass of cement %** |
|---|---|
| Concrete without steel reinforcement or other embedded metal | 1,00 |
| Containing steel reinforcement or other embedded metal | 0,20 |
| | 0,40 (CEM III) |
| Containing prestressing steel reinforcement in direct contact with concrete | 0,10 |
| | 0,20 |

In addition, BS EN 206 (2013) identifies three exposure classes where reinforced concrete is exposed to water containing chlorides, including de-icing salts and corrosion induced by chloride other than sea water is likely to occur as shown in Table 2.9.

**Table 2.9** Corrosion induced by chlorides other than from sea water (BS EN 206, 2013)

| Class designation | Description of the environment | Informative examples where exposure classes may occur |
|---|---|---|
| XD1 | Moderate humidity | Concrete surfaces exposed to airborne chlorides |
| XD2 | Wet, rarely dry | Swimming pools;<br>Concrete exposed to industrial waters containing chlorides |
| XD3 | Cyclic wet and dry | Parts of bridges exposed to spray containing chlorides. Pavements, Car park slabs |

On the other hand, corrosion of reinforced concrete exposed to chlorides from sea water or air carrying salt originating from sea water, are classified differently as shown in table 2.10.

**Table 2.10** Corrosion induced by chlorides from see water (BS EN 206, 2013)

| Class designation | Description of the environment | Informative examples where exposure classes may occur |
|---|---|---|
| XS1 | Exposed to airborne salt but not in direct contact with sea water | Structures near to or on the coast |
| XS2 | Permanently submerged | Parts of marine structures |
| XS3 | Tidal, splash and spray zones | Parts of marine structures |

As mentioned previously, chloride penetration into concrete can take place through diffusion, which is driven by a concentration difference. In crack- free concrete, the role of porosity plays an important role on chloride diffusion through concrete. In other words, when the total volume fraction of porosity is low, a low diffusion rate is achieved. The impact of porosity on chloride diffusion in concrete is clearly illustrated in terms of the w-c ratio in Figure 2.14. The value of chloride diffusion coefficient increases as w-c ratio increases. Likewise, the total volume of porosity declines as the degree of cement hydration increases, leading to a reduction in the diffusion coefficient. It should be stressed that, the volume of porosity declines in outer layer of the concrete as chloride penetration continues. This could be attributed to the formation of

Friedel's salt within the pores. On the other hand, the presence of cracks in concrete will significantly increase the diffusion coefficient and the rate of flow through concrete as shown in Figure 2.15. This increase is because cracks provide a relatively unhindered path for chlorides through the concrete cover (Dyer 2014). In addition, a high diffusion coefficient occurs when the maximum pore size approaches the minimum pore size. Therefore, pore size distribution significantly influences chloride diffusion coefficients (Moukwa 1989).

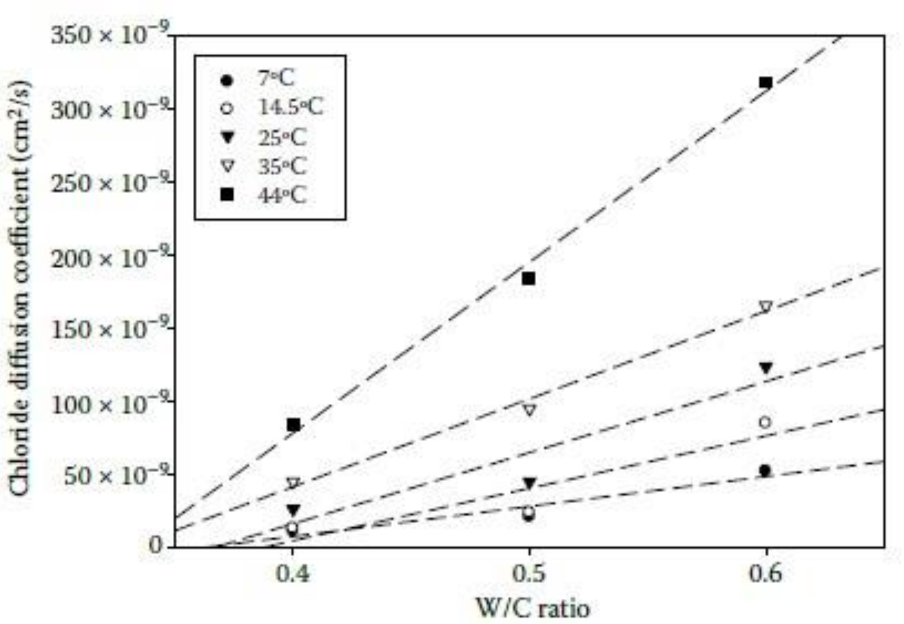


**Figure 2.14** Influence of w/c ratio on chloride diffusion coefficients of hardened PC pastes (Page et al., 1981)

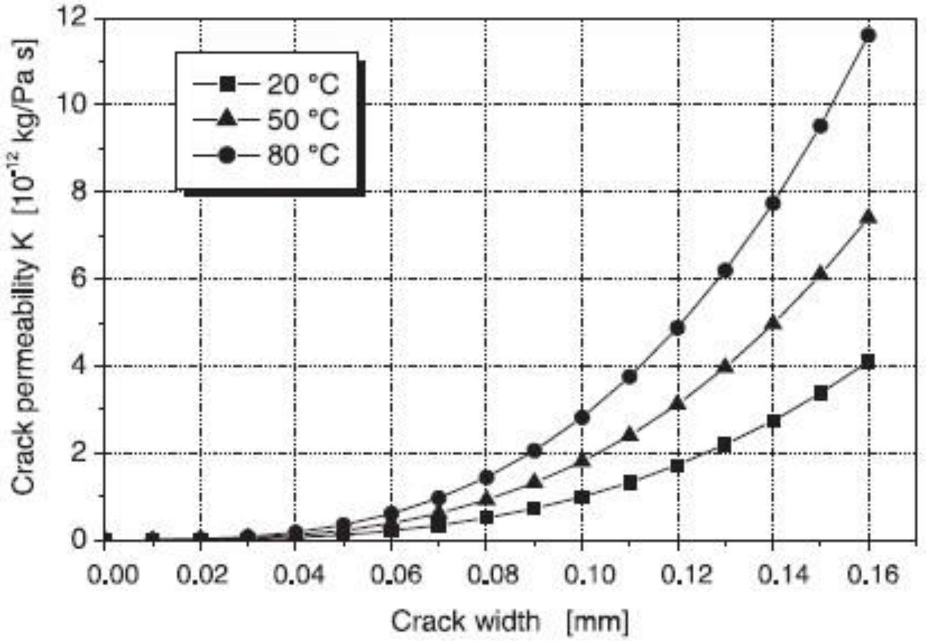


**Figure 2.15** Influence of crack width on the flow of water through damaged concrete specimens (Reinhardt and Jooss, 2003)

Resistance of blended cements to chloride ingress have been studied and reported by many researchers and authors. Bai et al. (2003) investigated the effect of the composition of PC-PFAMK binders on the chloride ingress and strength retardation of PC-PFA-MK concrete exposed to seawater. They established that partial replacement of PC with PFA and MK substantially reduced chloride ingress depths in concrete specimens. They reported that inclusion of MK had significant contribution in terms of chloride concentration and penetration depth. The authors attributed this reduction in chloride ingress to the relative changes in intrinsic diffusivity and chloride binding capacity. In addition, durability of CEM III (GGBS cement concrete) was studied by Osborne (1999). The author reported that higher level of slag (70%) can be used in applications where resistance to chloride, sulfates and seawater is required. Nonetheless, this level should be limited to 50% in circumstances where there is a risk of excessive carbonation.

Moreover, the corrosion resistance of concrete containing GGBS and type I and type V concrete produced according to ASTM was examined by Yeau and Kim (2005). Results showed that all concrete mixes containing GGBS exhibited lower diffusion coefficient compared to GGBS-free concrete. The authors concluded that higher corrosion resistance can be achieved in type I cement by increasing the amount of GGBS in concrete. This finding was consistent with results obtained from a study conducted by Topçu and Boĝa (2010). The authors reported that replacement of 25% PC with GGBS in concrete specimens considerably improved corrosion resistance of concrete. In addition, Divsholi, Lim and Teng (2014) reported that partial replacement of PC with GGBS improved the pore structure of concrete and significantly reduced chloride penetration. However, specimens prepared with 30 and 50% GGBS exhibited an increase in the rate of carbonation.

Additionally, the influence of mineral admixtures namely FA, SF, MK and GGBS on strength and corrosion properties of blended cements mortar and concrete was evaluated by Shi *et al.* (2011). The authors concluded that blended cements with 10% MK and 50% GGBS were more effective in reducing chloride diffusivity followed by 10% SF and 25% FA.

Durability and strength of Portland limestone cement (PLC) concrete (CEM II A-L) mixtures blended with GGBS and/or FA was investigated by Githachuri and Alexander (2013). Results showed that incorporating SCMs such as GGBS and FA reduced chloride penetration and gas permeability. Also, it was reported inclusion of slag in CEM II A-L did not adversely affect the strength properties of the mixture. On the other hand, blending with FA caused reduction in strength. The authors emphasized on the importance of adequate curing for such concrete mixes. Moreover, in a recent review carried out by Elgalhud et al. (2018) to evaluate performance of PLC based on chloride ingress and chloride-induced corrosion resistance. The authors reported that chloride ingress of concrete increases as the LS content increases in CEM II/A (6-20% LS) and CEM II/B (21-35% LS) cements specified in BS EN 197-1 (2011). The authors concluded that concrete containing up to 15% LS would not adversely affect the performance against chloride ingress.

Based on previous researches, it is evident that adequate resistance to chloride penetration can be achieved through a low w/c ratio and selection of an appropriate cement or binder system. In CEM I concrete, the w/c ratio should not exceed 0.4 to ensure low porosity and permeability. Also, incorporating SCMs such as FA, GGBS and SF considerably reduces chloride diffusivity (Gjørv 2014).

## 2.13 Measures to combat chloride ingress and improve durability

### 2.13.1 Mix proportions (Mineral admixtures) (SCMs)

As a measure to reduce the risk of chloride induced corrosion in reinforced concrete, several approaches in formulating concrete mixes can be used. Based on chloride ingress mechanism, it can be assumed that the following course of actions will limit the rate at which chlorides penetrate concrete:

- Reducing the volume of capillary porosity
- Reducing the pore diameter
- Increasing the tortuosity, surface area and/or constrictivity of the porosity

Reducing the w/c ratio is an effective way of reducing the capillary porosity of concrete. For instance, in CEM I concrete, the w/c ratio should not exceed 0.4 to ensure low porosity and permeability. The action will also reduce pore diameters and increase tortuosity to a limited extent. The last two strategies are best accomplished through the combination of cement fraction particle sizes that reduces a refined porosity. This is usually achieved by blending PC with SCMs (FA, GGBS, SF and MK) which undergo either pozzolanic or latent hydraulic reactions. Influence of improved packing of the materials in the cement and the production of cement hydration products produce a reduction in pore diameter and constrictivity and usually an increased tortuosity and surface area. Inclusion of mineral admixtures in the mix tend to increase the chloride binding capacity of the concrete. This is because mineral admixtures (GGBS, MK and FA) containing high level of alumina ($Al_2O_3$) forms higher level of Friedel's salt (Dyer, 2014; Gjørv, 2014; Thomas et al., 2012).

Previous studies (Dhir et al., 1997; Dhir et al., 1996; Luo et al., 2003; Chen et al., 2012) have demonstrated that air permeability, chloride binding capacity and chloride diffusion coefficient of concrete change with increasing levels of FA and GGBS as shown in Figure 2.16 and 2.17 respectively.

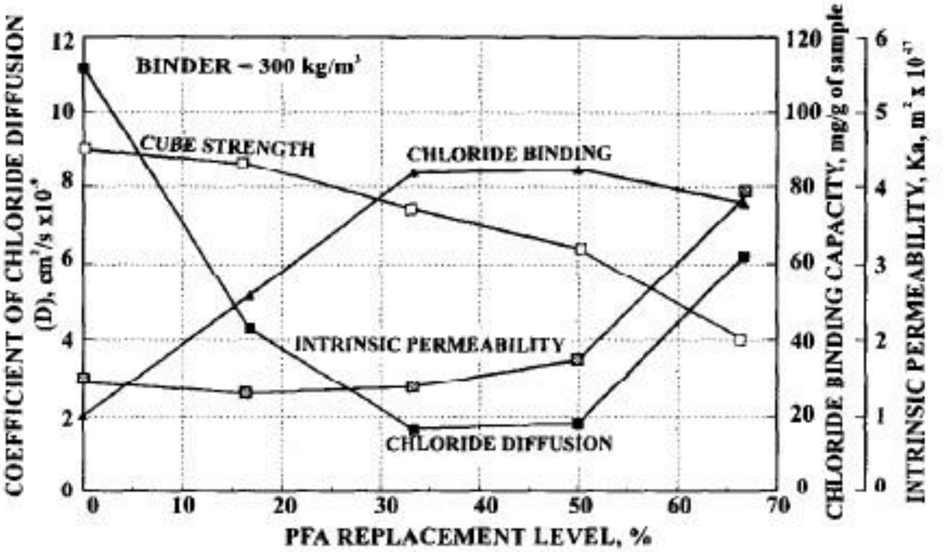


**Figure 2.16** Influence of FA content on chloride binding capacity, air permeability and chloride diffusion coefficient of concrete with a fixed w/c ratio of 0.55 (Dhir et al., 1997)

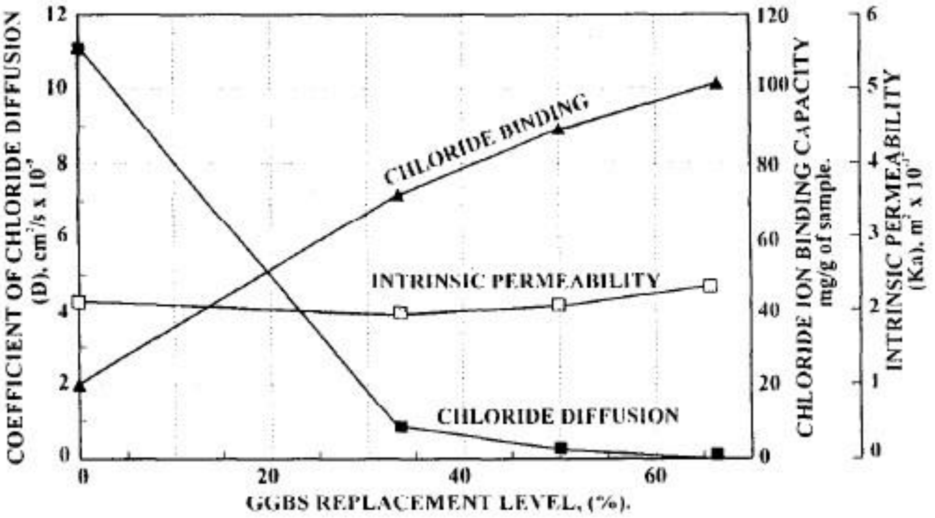


**Figure 2.17** Influence of GGBS content on chloride binding capacity, air permeability and chloride diffusion coefficient of concrete with a fixed w/c ratio of 0.55 (Dhir et al., 1996)

As shown in Figure 2.16 and 2.17, increasing the level of FA leads to an increase in the levels of chloride binding and a reduction in the diffusion coefficient up to about 40% of the total mass of cement. Beyond this point, chloride binding decreases and permeability increases; as a result, the diffusion coefficient increases. On the other hand, increasing GGBS leads to an increase in chloride binding and a decrease in permeability and this continues to much higher levels, subsequently reducing the diffusion coefficient. It is clear from both figures that the role of chloride binding is significant in reducing the rate of chloride ingress.

Another example of the influence of GGBS on reducing the chloride diffusion is shown in Figure 2.18. Results showed that blending cement with GGBS significantly reduced chloride content at different w/c ratios. In fact, blended cement with GGBS even at high w/c ratio of 0.7 performed better than PC at lowest w/c ratio of 0.5.

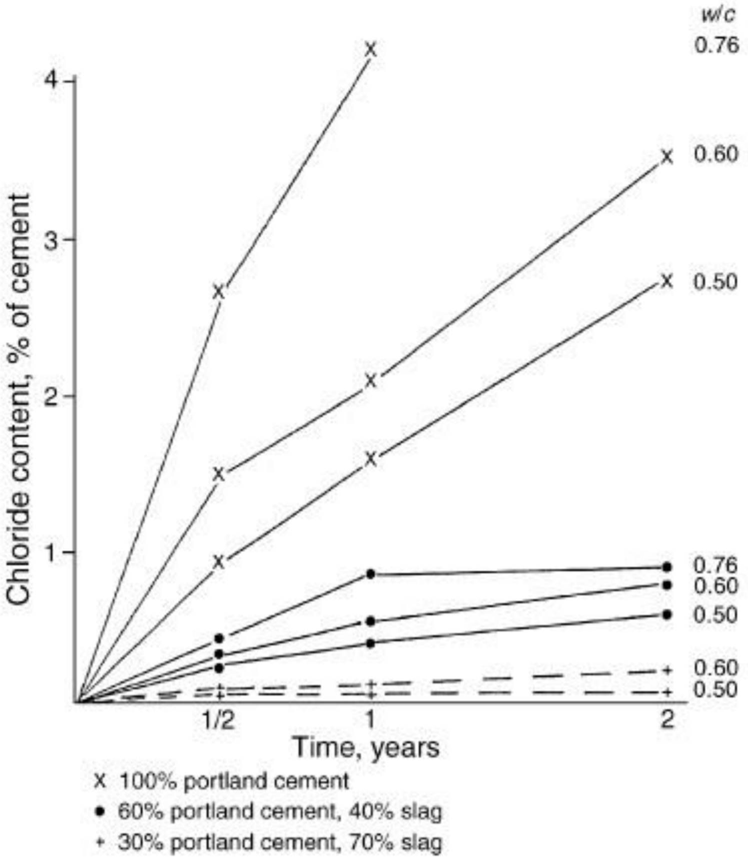


**Figure 2.18** Influence of GGBS on chloride diffusion (Smolczyk, 1977)

In terms of silica fume, previous studies (Page and Vennesland, 1983; Rasheeduzzafar et al., 1991) have demonstrated that the capacity to bind chloride ions declines as the silica fume content increases. This could be due to the high content of $SiO_2$ in SF, which can cause reduction in the formation of Friedel's salt and the Ca/Si ratio of any CSH gel formed. Another reason could be the reduction of $Al_2O_3$ in cement fraction caused by partial replacement of cement with SF.

Therefore, reducing the chloride binding capacity of CSH. Nonetheless, introduction of SF improves concrete performance against chloride-induced corrosion through the refinement of porosity and reducing the rates of chloride ingress (Dyer, 2014).

It should be stressed that, undoubtedly reinforced concrete exposed to aggressive environment such as harmful species, the chloride will ultimately reach the steel bars. Therefore, providing adequate concrete cover is one of the simplest and most effective measures to prolong the lifespan of concrete structures before corrosion initiation.

### 2.13.2 Chemical Admixtures

According to ASTM C125 (2020) and ACI 116R (2000) admixture is defined as “a material other than water, aggregates, hydraulic cement, and fiber reinforcement used as an ingredient of concrete or mortar, and added to the batch immediately before or during its mixing”. Despite the fact the admixtures are not key constituent of a concrete mix, they are important and widespread component. Nowadays, a concrete mix without admixtures is rare in many countries (A M Neville 2011). For instance, in Canada and Japan, approximately 100% of concrete contains at least a water reducer and an air-entraining agent. Whereas more than 50% of concrete contains admixtures in France and the United States. Nevertheless, the use of admixtures in concrete mixes is rising constantly (Aïtcin and Flatt 2015). The reason for the large growth in the use of admixture is its capability to enhance the properties of concrete and mortar in the plastic and hardened state, in addition to its economic benefits (Neville, 2011; ACI 212, 2010). Admixtures can be added as a single chemical or a blend of several chemicals able to produce a variety range of properties. Chemical admixtures are supplied in liquid or solid forms. Nevertheless, aqueous solution form is preferred because it is easier to thoroughly dispense it in the concrete mix (Dransfield, 2003; Marais, 2009).

Admixtures are usually categorized based on their influence on concrete. According to ASTM C494 (2015), admixtures are classified as following:

- Type A: Water reducing admixtures
- Type B: Retarding admixtures
- Type C: Accelerating admixtures
- Type D: Water reducing and retarding admixtures

- Type E: Water reducing and accelerating admixtures
- Type F: Water reducing, high range admixtures
- Type G: Water reducing, high range and retarding admixtures

Moreover, ASTM C260 (2013) standard covers materials for use as air-entraining admixtures to be added to concrete mixtures to provide protection against freezing and thawing. In addition, ASTM C1582 (2017) standard covers specification for admixtures to inhibit chloride-induced corrosion of steel reinforcement in concrete.

In terms of European standards, BS EN 934-2 (2012) defines admixtures as materials added during the mixing process of concrete in a quantity not more than 5% by mass of the cement content of the concrete, to modify the properties of the mix in the fresh and/or hardened state. It classifies admixtures according to their functions as following:

- Water reducing/plasticizing admixture
- High range water reducing/superplasticizing admixture
- Water retaining admixture
- Air entraining admixture
- Set accelerating admixture
- Hardening accelerating admixture
- Set retarding admixture
- Water resisting admixture
- Set retarding/water reducing/plasticizing admixture
- Set retarding/high range water reducing/ superplasticizing admixture
- Set accelerating/water reducing/plasticizing admixture
- Viscosity modifying admixture

Other types of admixtures which are not covered by BS EN 934 and available on the market are (Dransfield, 2003; Marais, 2009; Aïtcin and Flatt, 2015):

- Foamed concrete and low-density fill material
- Corrosion inhibiting admixtures
- Pumping aids

- Self-compacting concrete
- Polymer dispersions
- Precast semi-dry concrete
- Underwater/anti-washout
- Washwater
- Shrinkage- reducing admixture

Generally, water-resisting (waterproofing), also called damp proofers and corrosion inhibitors admixtures are used widely in the construction industry to protect reinforced concrete from water penetration and chloride-induced corrosion.

#### 2.13.2.1 Damp proofers or waterproofing admixtures (water resisting admixtures)

BS EN 934 (2012) defines it as admixtures which reduces the capillary absorption of hardened concrete. They act as permeability reducing admixtures by reducing the passage of water through the concrete under a pressure head by one or more of the following (Dransfield, 2003; Marais, 2009):

- Reducing the size, number and continuity of the capillary pore structure
- Blocking the pore structure
- Prevent water penetration into concrete due to absorption/capillary suction by lining the capillaries with a hydrophobic material

Waterproofing admixtures improve concrete performance by reducing water permeability and surface absorption through acting on the capillary structure of the cement paste. Nevertheless, adding waterproofing admixtures to poorly compacted or cracked concrete will not significantly reduce water penetration due to water leakage through concrete. Waterproofing admixtures can be supplied in two forms namely, hydrophobic and pore blockers. Generally, dosage of admixture depends on the type of and performance required. For example, typical percent for the hydrophobic type is 2% of cement weight or volume per cubic meter, whereas up to 5% or more can be used for the pore blockers.

Pore blockers are more effective if used in combination with high-range water-reducing admixtures. On the other hand, hydrophobic water resisting admixtures are not efficient against water with a constant pressure head. Generally, hydrophobic admixtures are effective against:

- Rain
- Surface water
- Low-pressure heads in structures
- Water penetration in tidal and splash zone
- Build-up of absorbed chloride at concrete surface by reducing the chloride diffusion

Hydrophobic (damp proofers) provide protection from water ingress by changing the concrete surface to become water repellent, or less wettable. It should be stressed that, converting the surface to water repellency is only efficient against water penetration when the applied pressure is low (Dransfield, 2003; Marais, 2009; Dyer, 2014).

Changing concrete surface to hydrophobic water repellent is achieved through different mechanisms. The most common type of damp proofers contains fatty acids such as stearic and oleic acids. These materials react with hydration products at pore surfaces, leaving a layer of hydrophobic hydrocarbon chains at the surface. This leads to formation of a high contact angle when water comes into contact with concrete surface as illustrated in Figure 2.19. Moreover, water repellent surface can also be achieved by the introduction of admixtures consisting of emulsions of waxes water. Once wax emulsions come into contact with the alkaline environment of concrete, the emulsion breaks down and forms a hydrophobic layer (Rixom and Mailvaganam, 1999; Dyer, 2014; Dransfield, 2003).

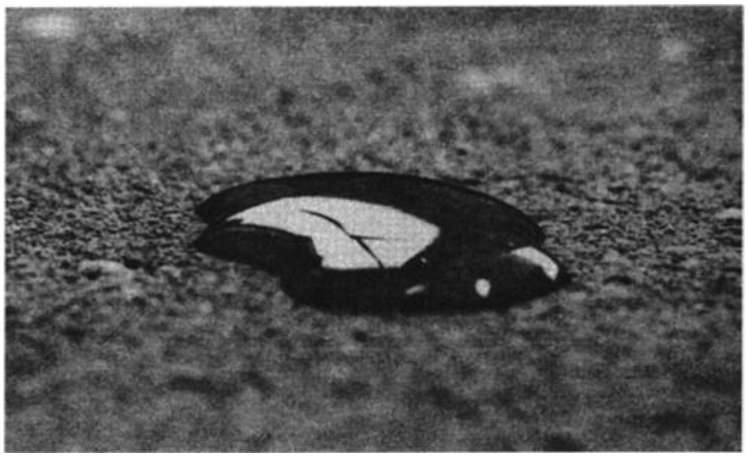


**Figure 2.19** Dampproofed concrete exhibits a high contact angle to water (Rixom and Mailvaganam, 1999)

The effect of admixtures on concrete properties have been investigated by many researchers, (Dao et al. 2010) studied the performance of permeability reducing admixtures in improving chloride penetration characteristics of concrete exposed to coastal envirronments. Two types of admixtures used for this purpose, the first type was characterised by crystalissation activity, whereas the second type was characterised by hydrophobic and pore blocking effects. They concluded that the inclusion of an admixture governed by hydrophobic and pore blocking effects significantly improved concrete durability in terms of chloride induced corrosion by reducing diffusion coifficient. On the other hand, the incorporation of an admixture charactrised by crystallisation mechanism had insignificant effect. Furthermore, Muynck et al. (2009) investigated the effectiveness of different surface treatments (Polyurea lining, Epoxy coating and Cementitious coating) and admixtures (Silicate admixture) against biogenic sulfuric acid corrosion of concrete. It was demonstrated that the best protective performance was achieved with the epoxy coating as no deterioration was detected on the treated surface of concrete. Moreover, the use of cementitious coating and the addition of the silicate admixture did not improve the performance as strong degradation was observed.

Moreover, the influence of different water-repellent admixtures (sodium oleate and calcium stearate) on the performance of lime-based mortars was evaluated by Izaguirre et al. (2009). The authors reported that performance of mortars was improved in terms of capillary absorption and resistance to freezing-thawing when sodium oleate was added. On the other hand, inclusion of calcium stearate was less effective. In addition, Pazderka and Hájková (2016) examined the influence of crystalline admixtures on concrete properties. They reported that incorporation of crystalline admixtures was insignificant as they only reduced the water vapor permeability of concrete by 16-20%. In studies conducted by Tittarelli and Moriconi (2008), it was demonstrated that silane-based hydrophobic admixture improved performance of reinforced concrete against corrosion by blocking the corrosion process in uncracked concrete. However, the admixture was ineffective to protect the steel reinforcement in cracked concrete. In terms of galvanized steel reinforcement, the authors (2010) concluded that silane-based admixture was effective in protecting galvanized steel reinforcement from corrosion even in the presence of cracks in the concrete cover.

#### 2.13.2.2 Corrosion Inhibitors Admixtures

According to BS EN ISO 8044 (2020), a corrosion inhibitor is a “chemical substance that, when present in the corrosion system at a suitable concentration, decreases the corrosion rate without significantly changing the concentration of any corrosive agent”. In reinforced concrete structures, they act to increase the critical chloride threshold level required to cause depassivation and slow down the rate of corrosion after breakdown of the passive layer around steel bars (Dyer, 2014; Marais, 2009). Corrosion inhibitor admixtures can effectively delay the onset of chloride-induced corrosion if appropriate dosage of admixture is added to the mixture (Raupach et al., 2007). Typical dosage rate of corrosion inhibitors used in concrete is 1-4% based on the weight of the cement. As mentioned previously, corrosion inhibitors are not covered in BS EN 934 and generally grouped into three classes (Aïtcin and Flatt, 2015; Rixom and Mailvaganam, 1999; Whitney, 2008; Söylev and Richardson, 2008):

- Anodic or active corrosion inhibitors: calcium and sodium nitrite based are the most common types which act to strengthen the passive protective layer on the steel surface by converting it into a more stable and less reactive state. Thus, when the chloride ions reach the layer, no reaction takes place.
- Cathodic or passive corrosion inhibitors: they are usually highly alkaline materials that render the ferrous ions at the surface of the reinforcing steel. They indirectly retard the corrosion process by slowing down the cathodic reactions by serving as proton acceptors, therefore impeding the corrosion current, and the most common type is amino alcohols.
- Mixed or passive-active corrosion inhibitors: They act simultaneously on both anodic and cathodic sites, therefore preferred over the previous types as they are more involved in the corrosion process before it can start. They coat the metal surface with a monomolecular layer that keeps the chloride ions away from the reinforcement steel. Moreover, they inhibit the reaction of oxygen and water at the cathodic sites on the steel. Furthermore, amino alcohol blended with inorganic inhibitors is a common type of this admixture.

Usually, corrosion inhibitors improves performance against corrosion through one or more of the following mechansims (Dariva et al., 2014):

- Formation of a protectve and inhibitave thin film by chemical adsorption of the inhibitor on the metal surface or by combination between inhibitor ions and metallic surface.
- Formation of a film by oxide of the base metal.
- Reaction between the inhibitor and a potential corrosive component present in aqueous media and the product is a complex.

Effect of corrosion inhibitors admixtures on concrete durability have been investigated and reported by many researchers (Muralidharan et al., 2004; Saraswathy and Song, 2007; Ann et al., 2006; Królikowski and Kuziak, 2011; Rakanta, Zafeiropoulou and Batis, 2013; Tang et al., 2012; Angst et al., 2016). Results showed incorporation of this type of admixtures in the mixture increased the chloride threshold level and reduced the rate of corrosion in concrete. Therefore, using this type of admixtures can extend the service life of reinforced concrete structures exposed to aggressive environment.

### 2.13.3 Concrete surface treatment

Another measure to protect concrete exposed to aggressive environments and prevent ingress of harmful substances such as chloride, $CO_2$, oxygen and water into concrete is applying surface treatments on concrete surface. This applied layer will act as a protective barrier, thus improve durability performance and prolong the lifespan of concrete structures exposed to detrimental species (Bentur et al, 1997; Bertolini et al., 2013; Elsener, 2008; Böhni, 2005). Surface protection can be applied on new, existing and repaired structures. Nevertheless, applying protective surface treatment on new concrete structures is more effective before onset of deteriorations. This is because concrete exhibiting chloride induced corrosion contains enough oxygen and moisture to produce small amount of rust needed to cause cracks, subsequently allowing oxygen and water move towards steel surface (Broomfield 2007).

According to Pan et al. (2017), performance of surface treatments is influenced by the following factors:

- Air permeability: it plays a major role in the performance of surface treatments. Reduced air permeability is essential to protect concrete from $CO_2$ penetration, thus preventing or reducing rate of carbonation. On the other hand, sufficient permeability is required to allow water vapor as concrete needs breathability to a certain extent.

- Bonding strength: good adhesion is vital between concrete substrate and surface treatments to ensure long term performance and protection of concrete.
- Coating thickness / penetration depth: to ensure appropriate performance and long-term durability, impregnation surface treatment compounds should be deeply penetrated into the substrate as much as possible.
- Cracking resistance: concrete is susceptible to cracking, thus protection provided by the protective layer will be lost soon after applying a surface treatment system that does not have sufficient crack resistance or crack healing capacity.
- Method of application and substrate properties: The efficiency of surface treatment is influenced by age and moisture content of the concrete substrate, application methods and the amount of treatment agent.

Protection of concrete using surface treatments is covered by a single standard BS EN 1504-2 (2004). As shown in Figure 2.20, the standard classifies surface treatments materials based on performance characteristics into three types: (i) coatings, (ii) impregnation and (iii) hydrophobic impregnation. Moreover, the standard specifies the following principles for protection of concrete:

- Protection from ingress
- Moisture control
- Increasing physical resistance
- Resistance to chemicals
- Increasing resistivity

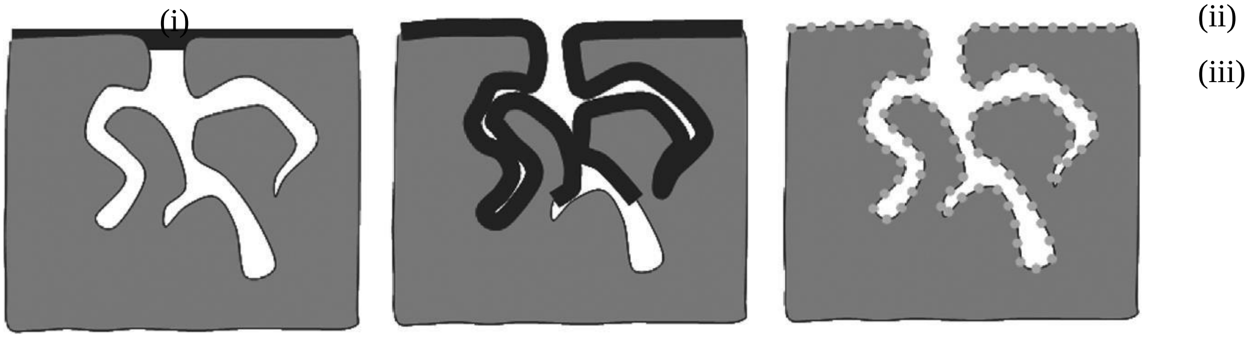


**Figure 2.20** Schematic of different types of concrete surface treatments, (i) coatings, (i) impregnation and (iii) hydrophobic impregnation (Dyer, 2014)

#### 2.13.3.1 Coating

Coating materials applied on the concrete surface form a continuous protective layer to prevent ingress of harmful species available in the external environment. Average thickness of such layers varies from 0.1 to 0.5 mm, and it could reach 5.0 mm in specific applications. Surface coatings are generally grouped into three types: traditional polymer coatings such as epoxy resin and acrylic, polymer nanocomposite compounds, and polymer modified cementitious coatings (BS EN 15042, 2004) (Pan et al. 2017). Previous studies have reported that concrete substrate could affect adhesion and performance of coatings (Sadowski et al., 2016; Garbacz et al., 2006). Moreover, presence of cracks on the concrete surface reduces efficiency of surface coatings. Previous studies (Almusallam et al., 2003; Medeiros and Helene, 2009; Liu and Vipulanandan, 2001; Dang et al., 2014; Ibrahim et al., 1997; De Muynck et al., 2009) have demonstrated that using surface coating improves performance of concrete exposed to aggressive environment and prolong lifespan of reinforced concrete structures. Moreover, Khanzadeh et al. (2012) reported that surface coating continuously exposed to chloride could lose efficiency. Therefore, the authors suggested reapplication of coating agents on concrete surface before deterioration of the protective film. Furthermore, Al-Zahrani et al. (2002) demonstrated that polymer-based coatings showed better performance against water and chloride penetration than cement-based polymer-modified and cement-based coatings.

In addition, many of polymer coatings such as epoxy and polyurethane have very low air permeability, which can hinder drying of concrete if it is wet. Consequently, causing formation of bubbles and deterioration in the protective layer due to the vapour pressure of the internal humidity (Pan et al., 2017; Medeiros et al., 2012). Therefore, influence of surface coating agents on air permeability of concrete should be carefully considered when selecting such materials for concrete protection.

#### 2.13.3.2 Impregnation (surface sealers or pore blockers)

Unlike coating agents, impregnation materials penetrate beneath the surface of hardened concrete, thus partially or completely filling the pores as shown in Figure 2.29 (ii). This penetration blocks pores and capillaries beneath the surface, leading to a reduction in surface porosity by increasing hardness and impermeability of the concrete’s protective surface film. Typical compounds of impregnates materials are organic polymers and silicate-based solutions (calcium silicate and sodium silicate). Formulations of such materials are similar to coating agents but with much lower viscosity to increase the depth of penetration (BS EN 1504-2, 2004; Pan et al., 2017; Dyer, 2014).

Previous studies have reported that using ethyl silicate for protection of concrete surface is effective in decreasing water and chloride penetration into concrete (Pigino et al., 2012; Franzoni et al., 2013; Parashar et al., 2001). Moreover, the substrate roughness and moisture content of the surface prior to the application of the impregnant material, significantly influence the performance of the impregnant material (Baltazar et al., 2014). In addition, Moon et al. (2007) studied the effect of applying inorganic surface treatment agents, including calcium-silicate compound to improve concrete resistance against chloride ingress. They reported that lower chloride concentration was measured in treated specimens compared to non-treated ones. The authors attributed this improvement in concrete performance to the hydration of calcium silicate which is the main component of inorganic coating. This caused formation of insoluble silicate compound and creation of a micro-structure after reaction with components present at the surface of mortar. Moreover, Jiang et al. (2015) demonstrated that applying inorganic sodium silicate-based impregnant improved waterproofing of treated concrete specimens. However, Dai et al. (2010) showed that sodium silicate-based pore blockers did not significantly reduce ingress of water and chloride ions compared to hydrophobic water repellent agents.

#### 2.13.3.3 Hydrophobic impregnation

Hydrophobic impregnates are liquids applied on the concrete to produce a water repellent surface, which means that the contact angle with water is greater than 90°. They are able to penetrate into concrete and internally coat the pores and capillaries, but do not fill them. It prevents the capillary intake of water, including entrained harmful substances. Hydrophobic agents do not change the surface appearance of the concrete, and do not form a physical barrier between concrete and external environment, thus allowing concrete to feely breathe. In other words, they allow water vapour to escape from the concrete interior through the surface. Typical active compounds are silanes or siloxanes (BS EN 1504-2, 2004; Pan et al., 2017; Dyer, 2014; Böhni, 2005).

Improving resistance of concrete to water and chloride ingress using hydrophobic impregnation agents have been widely investigated. Ibrahim et al. (1997) showed that treatment of concrete surface with silane and siloxane was effective in reducing chloride-induced corrosion rate. Dai et al. (2010) reported that using silane as hydrophobic impregnation in uncracked concrete significantly reduced water and chloride ingress. However, efficiency of such materials on existing cracked concrete, depends largely on agent's penetration depth. Additionally, Formation of cracks after applying silane could not prevent chloride ingress in cracks wider than 0.08 mm. They suggested a second layer of surface impregnation is recommended in such cases. In a review conducted by Basheer et al. (1997), they stated that silane treatment had insignificant effect in reducing carbonation depth, but it was effective in reducing chloride ingress in the treated specimens. Furthermore, Mckenzie and Calder (2009) investigated the effectiveness of eight hydrophobic pore lining impregnants and two crystal growth pore blockers in reducing chloride ions ingress into concrete. They demonstrated that the ingress of chloride ions by ponding and water by sorptivity was significantly reduced by treatment with the pore lining impregnants. On the other hand, the pore blockers were ineffective in protection against water and chloride penetration. In studies carried out by Medeiros and Helene (2008) (2009), it was demonstrated that treatment with hydrophobic agents significantly reduced water penetration in concrete. However, minor reduction in chloride diffusion coefficient was measured in treated specimens. In addition, Zhang et al. (2017) showed treatment with water repellent agents significantly reduced water absorption and chloride penetration. They concluded that selecting appropriate water repellent agents with increased impregnation depth can prolong service life of reinforced structures exposed to chloride. Long term field studies were carried out to assess efficacy of hydrophobic impregnation agents on concrete structures exposed to aggressive environment (Schueremans et al., 2007; Christodoulou et al., 2013; Raupach and Wolff, 2005). Results showed using such materials provided effective protection against water ingress even after 12 and 20 years of exposure.

## 2.14 Summary

This chapter has reviewed the importance of using concrete as a vital component of the construction industry, the main constituents in concrete such as cement and mineral admixtures, types of cement in American and European standards, hydration process of cement, different curing methods used for concrete curing, microstructure of hydrated cement paste, transport mechanisms and their influence on concrete degradation, corrosion due to carbonation and chloride attack, measures to improve durability and prolong lifespan of concrete exposed to aggressive environment. The review has also looked at different materials such as chemical admixtures and surface treatment used to protect reinforced steel from corrosion. Previous studies have shown that concrete curing is essential to develop strength and durability of concrete, and the main objective of curing is to ensure continuation of the hydration process. Generally, there are two main methods of curing, the first involves adding water to concrete surface to ensure concrete is wet particularly for mixes designed with w/c ratio below 0.4. Whereas the other method involves prevention of moisture loss in concrete by covering with sheets or applying curing compounds to form a thin film which seals the concrete surface.

The literature review has revealed that water curing carried out in controlled environment such as laboratory is more effective than curing compounds (Kholia et al. 2013; Nahata et al. 2014). However, such ideal conditions only exist in the laboratory and are different from actual site conditions. Moreover, previous studies have focused on assessing efficiency of CC method largely by evaluating compressive strength and little results and data are available with respect to long term durability properties. It is important to investigate durability properties more than compressive strength as most types of deteriorations and failures in concrete are attributed to durability rather than strength. The literature has shown that concrete mixes designed with w/c ratio over 0.42 should contain sufficient water to promote the hydration process without supplying of external water. Thus, performance of such concrete mixes cured using CC should be investigated based on durability properties such as carbonation and chloride penetration in addition to engineering and permeation properties. Moreover, the review has shown that durability of concrete is mainly influenced by transport properties of cementitious materials. It is clear that penetration of gases and chloride through pores from the surface can cause detrimental deterioration such as corrosion in embedded steel due to carbonation or chloride ingress. Previous studies have demonstrated that adding chemical admixtures or using surface treatment agents can prevent or retard penetration of harmful species into concrete, thus extending service life of concrete structures. Nevertheless, all previous investigations involved adding admixtures or applying surface treatment materials on concrete specimens conventionally cured in water. Almost no data and information are available on performance of concrete cured using CC and treated with admixture or surface treatment to improve performance in severe conditions. Furthermore, partial replacement of cement with SCMs has shown to have environmental and technical benefits. Nonetheless, little results are available on performance of blended cement cured using CC rather than traditional water curing.

Therefore, this study is conducted to examine engineering, transport and durability properties of concrete cured using CC, followed by treatment with chemical admixtures or surface treatment agents to enhance performance against water and chloride ingress. It will also examine the influence of using blended cement to improve overall durability and performance. The study will evaluate the performance of different types of cement concrete (CEM I, CEM II/A-V, CEM III/A and CEM II/A-D) cured with CC and treated with protective materials (admixtures and surface treatments). Moreover, the study will examine effectiveness of CC for curing blended cements as inclusion of mineral admixtures usually requires longer water curing periods. Therefore, suitability of using CC as an alternative for water curing in blended cements.

# Chapter 3: Experimental Programme

This chapter presents materials used and experimental methodology employed in this study. The chapter is divided into two sections, the first section covers characterization of different materials used such as curing compound, chemical admixtures, surface treatment agents, cement, FA, GGBS and SF. The second section includes concrete mix design, preparation of specimens, concrete casting, curing conditions and tests carried out to evaluate performance of concrete specimens. It is worth noting that, the experimental work is carried out in three phases as illustrated in Figure 3.1 and outlined below:

> Phase 1: The engineering properties of specimens cured using CC are evaluated and compared with control counterpart cured in different curing conditions, (i.e. air and water). The assessed engineering properties include compressive strength, flexural strength, and drying shrinkage.
>
> Phase 2: The transport properties are investigated based on short- and long-term permeability parameters. This includes initial surface absorption test, sorptivity and depth of water penetration under pressure of specimens.
>
> Phase 3: The durability properties are investigated including carbonation, resistance to scaling and chloride penetration.

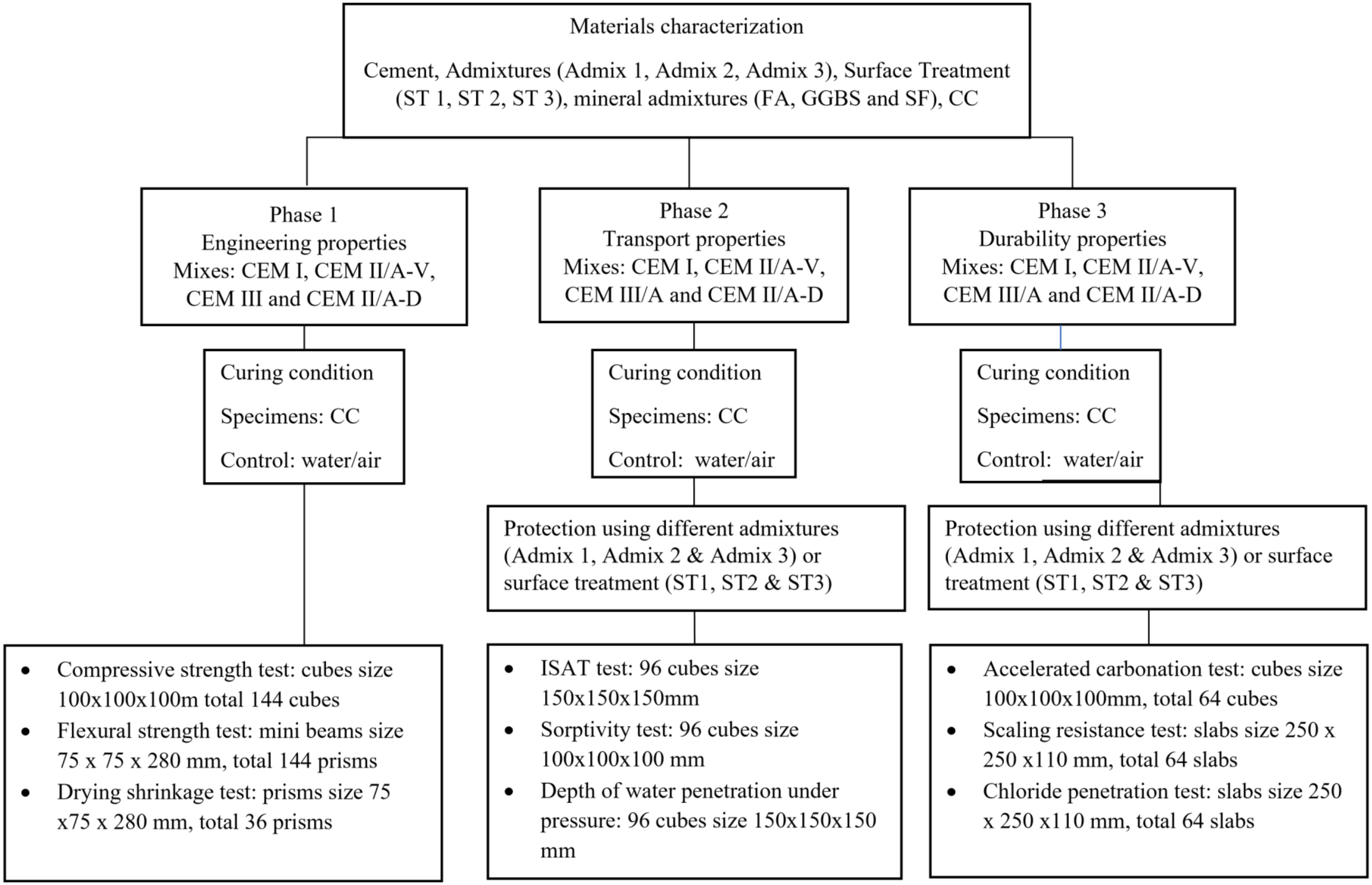

Materials characterization
Cement, Admixtures (Admix 1, Admix 2, Admix 3), Surface Treatment (ST 1, ST 2, ST 3), mineral admixtures (FA, GGBS and SF), CC
Phase 1
Engineering properties
Mixes: CEM I, CEM II/A-V, CEM III and CEM II/A-D
Phase 2
Transport properties
Mixes: CEM I, CEM II/A-V, CEM III/A and CEM II/A-D
Phase 3
Durability properties
Mixes: CEM I, CEM II/A-V, CEM III/A and CEM II/A-D
Curing condition
Specimens: CC
Control: water/air
Curing condition
Specimens: CC
Control: water/air
Curing condition
Specimens: CC
Control: water/air
Protection using different admixtures (Admix 1, Admix 2 & Admix 3) or surface treatment (ST1, ST2 & ST3)
Protection using different admixtures (Admix 1, Admix 2 & Admix 3) or surface treatment (ST1, ST2 & ST3)
Compressive strength test: cubes size 100x100x100m total 144 cubes
Flexural strength test: mini beams size 75 x 75 x 280 mm, total 144 prisms
Drying shrinkage test: prisms size 75 x75 x 280 mm, total 36 prisms
ISAT test: 96 cubes size 150x150x150mm
Sorptivity test: 96 cubes size 100x100x100 mm
Depth of water penetration under pressure: 96 cubes size 150x150x150 mm
Accelerated carbonation test: cubes size 100x100x100mm, total 64 cubes
Scaling resistance test: slabs size 250 x 250 x110 mm, total 64 slabs
Chloride penetration test: slabs size 250 x 250 x110 mm, total 64 slabs

**Figure 3.1** Schematic of research experimental programme

## 3.1 Materials Characteristics

The materials used in this research study were:

- Portland cement (CEM I), FA (CEM II/A-V), GGBS (CEM III/A) and SF (CEM II/A-D).
- Curing compound (CC).
- Chemical admixtures (Admix1, Admix2 and Admix3).
- Surface treatments agents (ST1, ST2 and ST3).
- Fine aggregate and coarse aggregate.
- Water
- Superplasticizer

### 3.1.1 Portland cement (CEM I)

The type of Portland cement used in this research study was CEM I 52,5 N and it was manufactured by Blue Circle cement company. Cement specifications were conforming to the requirements of BS EN 197-1 (2011). The same type and strength of cement was used throughout the experimental programme to maintain consistency in chemical composition and physical properties. The required amount of cement needed for the experimental programme was obtained from the same supplier and source, and cement bags were stored in sealed plastic containers to avoid exposure to humidity. The chemical composition and physical properties of the cement provided by the manufacturer are listed in Table 3.1. Four types of concrete mixes were cast based on BS EN 197-1 cements as shown in Table 3.2.

### 3.1.2 Fly ash (CEM II/A-V)

Fly ash used in this research to produce CEM II/A-V was supplied by CEMEX company and was according to BS EN 450-1 (2012). Like PC, the quantity needed for this study was obtained at the start of the experimental programme from the same supplier to ensure consistency in chemical composition and stored in sealed plastic containers to avoid exposure to humidity. The chemical composition and physical properties were provided by the manufacturer and are given in Table 3.1.

### 3.1.3 Ground granulated blast furnace slag (CEM III/A)

GGBS used in this study to produce CEM III/A was supplied by Hanson company and it was complying to BS EN 15167-1 (2006). Similarly, the quantity required for the entire research project was obtained at the start of the study from the same supplier and stored in sealed plastic containers to prevent exposure to humid environment. The chemical and physical properties are listed in table 3.1.

### 3.1.4 Silica fume (CEM II/A-D)

SF used in this study to produce CEM II/A-D was supplied by ELKEM company and it was conforming to BS EN 13263-1 (2009). The amount required for the study was obtained and stored in sealed plastic containers to prevent exposure to moisture. It was provided in uncondensed powder form with bulk density of 0.305 g/cm$^3$ and specific gravity of 2.2 and specific surface area of 26.8 m$^2$/g. The mean particle size was about 0.15 µm with less than 1.5% content of primary coarse particles greater than 45 µm. The chemical and physical properties which were provided by the manufacturer are listed in table 3.1.

**Table 3.1** Chemical composition of cementitious materials provided by manufacturers (See Appendix E)

| Compound | PC Percentage % | FA Percentage % | GGBS Percentage % | SF Percentage % |
|---|---|---|---|---|
| $SiO_2$ | 19.44 | 50.4 | 33.57 | 95.3 |
| $Al_2O_3$ | 4.89 | 28.1 | 15 | 0.36 |
| $Fe_2O_3$ | 3.25 | 8.8 | 0.29 | 0.11 |
| CaO | 63.63 | 6.2 | 38.86 | 0.2 |
| MgO | 1.02 | 1.4 | 9 | 0.33 |
| $SO_3$ | 3.08 | 0.5 | 0.6 | 0.33 |
| $K_2O$ | 0.62 | 2.6 | 0.52 | 1.19 |
| $Na_2O$ | 0.12 | 0.8 | 0.74 | 0.24 |
| Loss on ignition | 2.09 | 4.4 | 0.55 | 0.92 |
| Fineness(m$^2$/kg) | 373 | 281 | 502 | 22701 |
| Density (g/cm$^3$) | 3.14 | 2.29 | 2.9 | 0.305 |

**Table 3.2** Cement types used in this research study (BS EN197-1, 2011)

| Type and annotation of cements used | Cement and binder composition |
|---|---|

| | |
|---|---|
| CEM I | 100%PC |
| CEM II/A-V | 80 %PC + 20%FA |
| CEM III/A | 60 %PC + 40%GGBS |
| CEM II/A-D | 90%PC + 10%SF |

### 3.1.5 Curing Compound (CC)

Concrete specimens were cured using a water-based sodium silicate curing compound. It was applied on specimens approximately 3-4 hours after casting, and it acts to prevent or retard moisture loss through evaporation by forming a microscopic crystalline structure in the concrete pores of the surface layer. It can be applied on concrete which is expected to receive further surface treatments as it does not affect adhesion between concrete surface and applied surface treatment agents. The CC is water white liquid with a specific gravity of 1.09 at 20 °C. It is important to ensure that surface water has dissipated before spraying the CC on freshly laid horizontal concrete surfaces. Based on manufacturer's recommendation, the application rate is usually 5.5 to 6.0 $m^2$ per litre.

### 3.1.6 Chemical admixtures

Three types of waterproofing admixtures used in this study to improve permeability of concrete against water and chloride penetration, characteristics of the admixtures are described below and shown in Table 3.3. These waterproofing admixtures are the most common types and widely used in the industry nowadays to improve impermeability through crystalline pore blocking and hydrophobic effects. The last type was water reducer superplasticizer liquid used in CEM II/A-D concrete mix to provide slump retention as addition of SF reduces workability of the mix. Data sheet of materials are given in Appendix F.

**Table 3.3** Waterproofing admixtures used in the study

| Material | Form | Protection mechanism | Category |
|---|---|---|---|
| Admix 1 waterproofing | Powder | - Formation of crystalline pore blockers | Non-toxic cement based |
| Admix 2 waterproofing | Liquid | - Hydrophobic pore blocking | Non- toxic water based |
| Admix 3<br>corrosion-inhibiting and waterproofing admixture | Liquid | - Hydrophobic pore blocking<br>- Corrosion-inhibiting surface coating | Non- toxic water based |

### 3.1.6.1 Admix1 (SUPERSHIELD ADMIX 100)

This is a cement based chemical admixture with active ingredient (DPC system) added to concrete during batching to provide waterproofing, thus extending life span of the concrete. It is supplied in grey colour dry powder form and conforms to BS EN 934-2 (2012) as water resisting admixtures. It provides protection by forming insoluble crystalline structures when the chemical composition of ADMIX 1 reacts with the moisture and products formed during cement hydration process. It forms a waterproof barrier to prevent or retard penetration of water and harmful agents. Based on manufacturer's recommendations, dosage added to the mix at the time of batching was 1.5% of cement by weight.

### 3.1.6.2 Admix2 (Hycrete W1000)

It is a water based waterproofing admixture which is added to the concrete mix at the time of batching. It is supplied in liquid form with a specific gravity of 1.05 and the recommended dosage to include in the concrete is 5 l/m$^3$. It complies with ISO 14021(ISO 14021, 2006) and it is compatible with most types of cement such as CEM II and CEM III. It provides protection by reducing water absorption and forming a protective coating around steel reinforcement.

### 3.1.6.3 Admix3 (Hycrete X1000)

It is a water based, non-toxic dual action corrosion-inhibiting and waterproofing concrete admixture. It is added to the concrete mix at the time of batching with a recommended dosage of 10 l/m$^3$. It is supplied in liquid form with a specific gravity of 1.05. It is compatible with most types of cement such as CEM II and CEM III. It provides dual protection by reducing water absorption by means of hydrophobic pore blocking and acts a corrosion-inhibiting by forming a protective passivating layer on the surface of the embedded steel reinforcement to reduce corrosion initiation and propagation.

### 3.1.6.4 Admix 4 (ADVA 650)

It is a high range water reducer superplasticizer liquid supplied by Grace Construction Company and it is based on modified synthetic carboxylated polymers. It is used to provide slump retention in concrete mixes designed with low w/c ratio. It conforms to BS EN 934-2 and it is effective in mixes containing mineral admixtures particularly SF. It was used in this study to obtain required slump value for mixes containing SF as slump value significantly dropped due to the small particle size of SF. The specific gravity of the admixture is 1.06 at 20°C with zero chloride content.

According to manufacturer's recommendations, it has no adverse effects on mixes containing other admixtures such as waterproofing as long they are not premixed together. The dosage rate was 500 ml per 100 kg of cement. Trials mixes were conducted to determine precise dosage for the required slump value.

### 3.1.7 Surface treatment (ST)

Three types of surface treatment agents used in this study to improve permeability of concrete against water and chloride penetration, characteristics of these materials are described below and shown in Table 3.4. Similarly, these types of materials are the most popular ones and widely used in the industry to enhance impermeability of the concrete via crystalline and water repellent for hydrophobic effects. Data sheet of materials are given in Appendix G.

**Table 3.4** Surface treatments used in the study

| Material | Diluted with water | Protection mechanism | Category |
|---|---|---|---|
| Surface treatment 1 (liquid) | No | Water repelling technology with impregnation (Hydrated crystals) and DPC crystallization (Hygroscopic crystals) | Non- toxic water based |
| Surface treatment 2 (liquid) | No | Silane based hydrophobic impregnation without blocking any pores or capillaries | Non- toxic water based |
| Surface treatment 3 (liquid) | Yes | Silanes and siloxanes based hydrophobic impregnation without blocking any pores or capillaries | Non- toxic water based |

#### 3.1.7.1 ST1 (SUPERSHIELD MULTISEAL 100)

It is a water based, non-toxic liquid crystalline forming waterproofing treatment for concrete conforming to BS EN 1504-2 (BS EN 1504-2, 2004). It provides protection via three different mechanisms that combines water repelling technology with impregnation and deep penetrating capillary crystallization. Once sprayed on the concrete surface, it will seep into the pores and capillaries, thus produce a protection system by forming a water repelling substrate with two distinctive crystal formation (Hydrated and Hygroscopic) deep inside the concrete. It will fill all the pores, capillaries, and voids from all directions. It is colourless with a specific gravity of about 1.06 kg/litre and it is applied in a single layer. Based on manufacturer's recommendations, a dosage rate of 4.9 m$^2$/L should be applied evenly in a single coat by means of spraying or brushing.

#### 3.1.7.2 ST2 (SILRES BS 1701)

It is a silane based colourless solvent free liquid used in undiluted form for the hydrophobic priming and impregnation of concrete. It penetrated deep into pores and capillaries in the concrete (≥ 10 mm) and significantly reduces water and chloride ingress. It provides protection by means of hydrophobic impregnation with no loss in concrete breathability. Once applied on concrete surface, it reacts with atmospheric moisture and/or moisture content in concrete to form a substance that greatly reduces concrete absorption in the active zone, but without blocking any pores or capillaries. Thus, the impregnated surface retains very high water-vapor permeability. The silane content of this ST is about 99.0 % and it conforms to BS EN 1504-2 (BS EN 1504-2:2004).

According to manufacturer's recommendations, the material should be applied after four weeks of casting to ensure that setting of cement is not affected. Also, the moisture content of concrete surface should not exceed 4%. Therefore, moisture content of concrete specimens was measured using a moisture meter device before applying the agent as shown in Figure 3.2. Moreover, it was evenly applied on dry concrete surface in two coats, wet-on-wet by means of spraying or brushing.

#### 3.1.7.3 ST3 (SILRES BS SMK 2101)

It is a solvent free liquid, based on a mixture of silane and siloxanes which is diluted with water to form microemulsion concentrate. It provides protection for concrete by means of hydrophobic impregnation as it penetrates deep into pores and capillaries (≤ 10 mm) without blocking them. Once applied on the surface of concrete, it reacts with atmospheric moisture and / or moisture content in concrete to form a substance that significantly delays water and chloride penetration. Thus, the impregnated surface retains very high water-vapor permeability. The silane content of this ST is approximately 100.0 % and it conforms to BS EN 1504-2 (BS EN 1504-2:2004).

According to manufacturer's recommendations, the material should be applied after four weeks of casting to ensure that setting of cement is not affected. Also, the moisture content of concrete surface was measured to ensure it does not exceed 4 wt%. It was evenly applied on dry concrete surface in two coats, wet-on-wet by means of spraying or brushing. Based on manufacturer's recommendation, the dilution rate is carried out by mixing 1 part of the agent with 3 parts of water.

**Figure 3.2** Moisture content measurement of specimens

### 3.1.8 Aggregates

Fine and coarse aggregates used to produce concrete mixes with gradation conforming to the requirements specified in BS EN 12620 (2013). Results of particle size distribution of fine and coarse aggregates determined according to BS EN 933-1 (2012) are shown in Table 3.3. Particle density and water absorption tests were carried out according to BS EN 1097-6 (2013) as shown in Table 3.4. Grading curves of fine and coarse aggregates are shown in Figure 3.2 and 3.3, respectively. Details of test results are given in Appendix A.

#### 3.1.8.1 Fine aggregates

Natural sand with nominal size ranging between 0-5 mm was used as fine aggregates in this study. Tests conducted to determine physical characteristics such as grading based on the cumulative percentage passing by weight using sieving method as set out in BS EN 933-1 (2012). Particle density and water absorption tests were carried out according to BS EN 1097-6 (2013).

### 3.1.8.2 Coarse Aggregates

Natural uncrushed Thames Valley gravel with nominal sizes ranging from 5 to 20 mm was used as coarse aggregates in this study. Similarly, tests were carried out according to relevant BS and EN standards to determine physical properties including particle size distribution, density, and water absorption as shown in Table 3.5 and 3.6.

**Table 3.5** Particle size distribution of fine and coarse aggregates

| Fine Aggregates | | Coarse Aggregates | |
|---|---|---|---|
| **Sieve size** | **Cumulative percentage passing (%)** | **Sieve size** | **Cumulative percentage passing (%)** |
| 8 | 100.00 | 31.5 | 100.00 |
| 5 | 98.57 | 20 | 96.28 |
| 4 | 95.65 | 16 | 81.14 |
| 2 | 85.83 | 12.5 | 62.93 |
| 1 | 75.40 | 8 | 27.26 |
| 0.6 | 61.85 | 4 | 0.57 |
| 0.25 | 19.61 | 2 | 0.17 |
| 0.063 | 0.80 | Pan | 0.05 |
| Pan | 0.69 | | |

**Table 3.6** Physical properties of fine and coarse aggregates used in this study

| Physical properties | Fine aggregates | Coarse aggregates |
|---|---|---|
| $\rho_a$ $(Mg/m^3)$ | 2.74 | 2.52 |
| $\rho_{rd}$ $(Mg/m^3)$ | 2.72 | 2.48 |
| $\rho_{ssd}$ $(Mg/m3)$ | 2.73 | 2.52 |
| $WA_{24}$ (%) | 0.36 | 1.69 |
| FM | 2.62 | 3.32 |
| MC | 4.1 | 1.3 |

Where:

$\rho_a$: Apparent particle density

$\rho_{rd}$: Oven-dried particle density

$\rho_{ssd}$: Saturated surface dry particle density

$WA_{24}$: 24 hours water absorption

FM: Fineness modulus

MC: moisture content

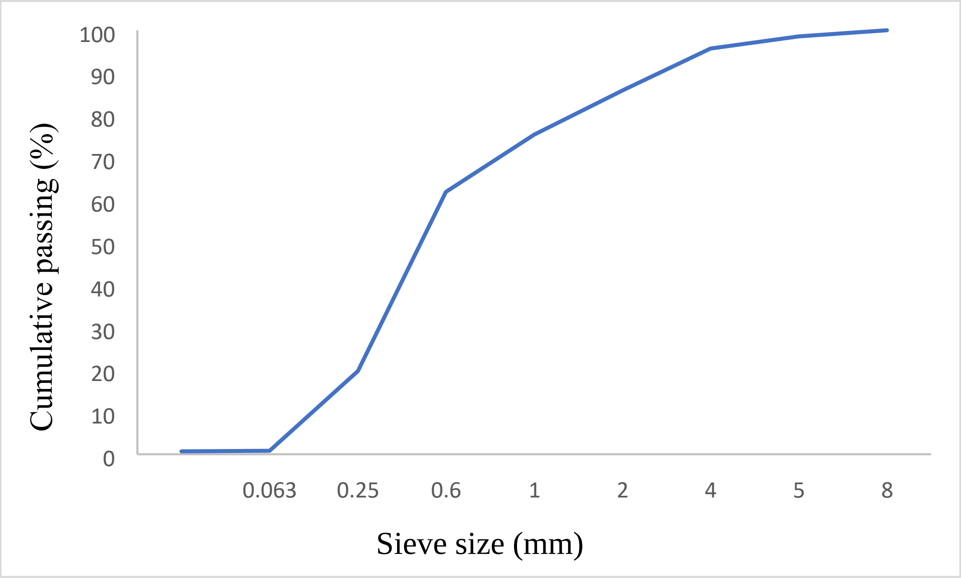


**Figure 3.3** Grading of fine aggregates

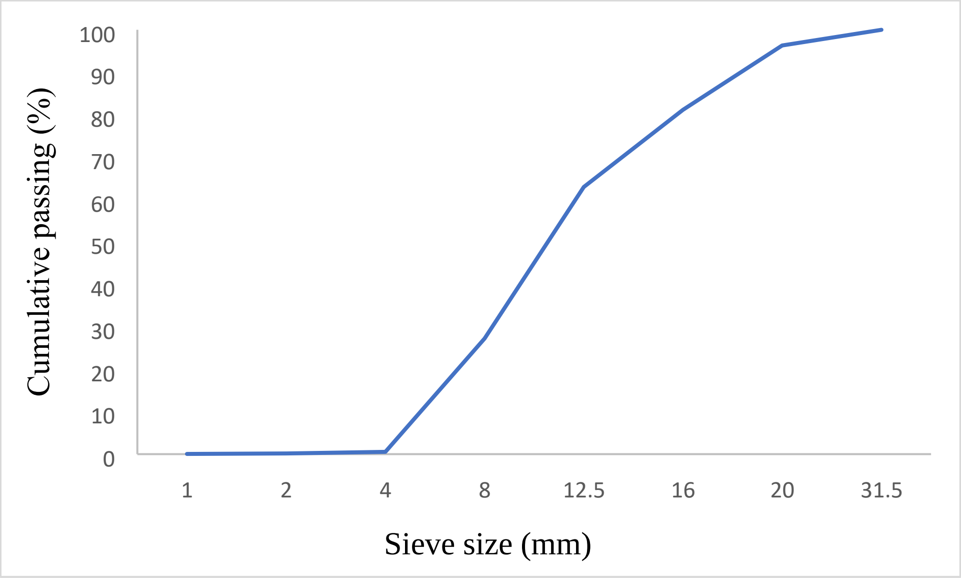


**Figure 3.4** Grading of coarse aggregates

### 3.1.9 Water

Standard tap water was used to produce all concrete mixes prepared in the laboratory. On the other hand, de-ionised water was used to conduct ISAT and sorptivity tests in Phase 2 as recommended by relevant standards BSI 1881-208 (1996) and BS EN 13057 (2002).

### 3.1.10 Sodium chloride solution

Sodium chloride solution with 3 percent concentration (30g/L) was prepared and used in chloride ponding test which was carried out in Phase 3 of this study to subject the slabs to a continuous ponding.

### 3.1.11 Calcium chloride solution

Calcium chloride solution with 4 percent concentration (40gm/L) was prepared and used in scaling resistance of concrete surface test which was conducted in Phase 3 to expose specimens to the solution while undergoing freezing and thawing in the environmental chamber room.

## 3.2 Concrete mix design

Concrete mixes were designed according to Building Research Establishment instructions and guidelines (BRE, 1997). Concrete cubes with strength of 40 N/mm$^2$ was selected in this study as it is widely used in the construction industry. The mixes were designed with a workability value between 30-60 mm. water content of the mix was specified according to the coarse aggregate type, specified slump value and cementitious binder. Initially, the free water content of 180 kg/m$^3$ was specified for CEM I mix. However, the water content and w/c ratio were modified in concrete mixes containing FA (CEM II/A-V) and GGBS (CEM III/A) based on cement replacement percentage to develop required strength at 28 days age.

It should be stressed that, all mixes were designed without adding high range water reducing admixture. However, mixes produced with SF in powder uncondensed form suffered significant reduction in the specified slump value due to the extremely fine particle size. Thus, a high range superplasticizer was added to trial mixes according to manufacturer's recommended dosage to establish appropriate dosage required for the specified slump value. Moreover, the water content of the mixes was adjusted according to calculated water absorption and moisture content. For instance, the moisture contents of fine and coarse aggregates were determined to be 4.1% and 1.3% respectively, thus the total amount of free water content was decreased accordingly to take into account these values in the mix. Overall, four concrete mixes were produced namely CEM I, CEM II/A-V (80%PC-20%FA), CEM III/A (60%PC-40%GGBS) and CEM II/A-D (90%PC-10%SF). Details of all concrete mix design are given in Appendix B.

**Table 3.7** Concrete mix proportions for Phase 1- Engineering Properties

| **Mix No.** | **Cement type** | **Water ($kg/m^3$)** | **Cementitious binder ($kg/m^3$)** | | | | **Aggregates ($kg/m^3$)** | | **w/b ratio** | **Superplasticizer 5 ml/kg PC** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | **PC** | **FA** | **GGBS** | **SF** | **Fine** | **Coarse** | | |
| 1 | CEM I | 180 | 400 | – | – | – | 543 | 1256 | 0.45 | – |
| 2 | CEM II/A-V | 170 | 352 | 88 | – | – | 534 | 1246 | 0.38 | – |
| 3 | CEM III/A | 175 | 240 | – | 160 | – | 543 | 1256 | 0.43 | – |
| 4 | CEM II/A-D | 180 | 360 | – | – | 40 | 543 | 1256 | 0.45 | 5 |

- All mixes were designed to achieve strength of 40 $N/mm^2$ at 28 days.
- All mixes were designed to have a slump test value between 30-60 mm.
- The high range water reducing admixture was used only in mixes containing SF.
- SF was in uncondensed powder form.

**Table 3.8** Mix proportions for Phase 2 – Transport Properties and Phase 3 – Durability Properties

| Mix No | Cement type | water (kg/m$^3$) | Cementitious binder (kg/m$^3$) | | | | Aggregates (kg/m$^3$) | | w/b ratio | Treatment with Waterproofing Admix | Treatment with ST | Water reducer admixture 5 ml/kg PC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | PC | FA | GGBS | SF | Fine | Coarse | | | | |
| 5 | CEM I | 180 | 400 | – | – | – | 543 | 1256 | 0.45 | – | ST 1 | – |
| 6 | CEM I | 180 | 400 | – | – | – | 543 | 1256 | 0.45 | – | ST 2 | – |
| 7 | CEM I | 180 | 400 | – | – | – | 543 | 1256 | 0.45 | – | ST 3 | – |
| 8 | CEM I | 180 | 400 | – | – | – | 543 | 1256 | 0.45 | Admix 1 | – | – |
| 9 | CEM I | 180 | 400 | – | – | – | 543 | 1256 | 0.45 | Admix 2 | – | – |
| 10 | CEM I | 180 | 400 | – | – | – | 543 | 1256 | 0.45 | Admix 3 | – | – |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11 | CEM II/A-V | 170 | 352 | 88 | – | – | 534 | 1246 | 0.38 | – | ST 1 | – |
| 12 | CEM II/A-V | 170 | 352 | 88 | – | – | 534 | 1246 | 0.38 | – | ST 2 | – |
| 13 | CEM II/A-V | 170 | 352 | 88 | – | – | 534 | 1246 | 0.38 | – | ST 3 | – |
| 14 | CEM II/A-V | 170 | 352 | 88 | – | – | 534 | 1246 | 0.38 | Admix 1 | – | – |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15 | CEM II/A-V | 170 | 352 | 88 | – | – | 534 | 1246 | 0.38 | Admix 2 | – | – |
| 16 | CEM II/A-V | 170 | 352 | 88 | – | – | 534 | 1246 | 0.38 | Admix 3 | – | – |
| 17 | CEM III/A | 175 | 240 | – | 160 | – | 543 | 1256 | 0.43 | – | ST 1 | – |
| 18 | CEM III/A | 175 | 240 | – | 160 | – | 543 | 1256 | 0.43 | – | ST 2 | – |
| 19 | CEM III/A | 175 | 240 | – | 160 | – | 543 | 1256 | 0.43 | – | ST 3 | – |
| 20 | CEM III/A | 175 | 240 | – | 160 | – | 543 | 1256 | 0.43 | Admix 1 | – | – |
| 21 | CEM III/A | 175 | 240 | – | 160 | – | 543 | 1256 | 0.43 | Admix 2 | – | – |
| 22 | CEM III/A | 175 | 240 | – | 160 | – | 543 | 1256 | 0.43 | Admix 3 | – | – |
| 23 | CEM II/A-D | 180 | 360 | – | – | 40 | 543 | 1256 | 0.45 | – | ST 1 | 5 |
| 24 | CEM II/A-D | 180 | 360 | – | – | 40 | 543 | 1256 | 0.45 | – | ST 2 | 5 |
| 25 | CEM II/A-D | 180 | 360 | – | – | 40 | 543 | 1256 | 0.45 | – | ST 3 | 5 |
| 26 | CEM II/A-D | 180 | 360 | – | – | 40 | 543 | 1256 | 0.45 | Admix 1 | – | 5 |
| 27 | CEM II/A-D | 180 | 360 | – | – | 40 | 543 | 1256 | 0.45 | Admix 2 | – | 5 |
| 28 | CEM II/A-D | 180 | 360 | – | – | 40 | 543 | 1256 | 0.45 | Admix 3 | – | 5 |

## 3.3 Concrete mixing, casting and specimen preparation

Concrete constituents such as cement, SCMs and aggregates were stored in appropriate laboratory environment at 20 C and 45-55% relative humidity before production of concrete. Concrete mixing procedure was carried as specified in BS EN 206 (BSI, 2016) and BS 1881-125 (BSI, 2013) as following:

- Fine and coarse aggregates were mixed in the pan mixer for 1 minute.
- Approximately half of the total mixture water was added and mixed for 1 more minute.
- The aggregates were left 8 minutes to absorb water added while covering the mixer to minimize water loss.
- Cementitious materials (cement or blended cement) were added and mixed for 1 minute.
- The remaining water was added (and admixture if appropriate) and mixed for further 2 minutes.

Once mixing process was completed, slump test was conducted in accordance with BS EN 123502 (2019) to determine workability of fresh concrete. Then, fresh concrete was cast into cube (size 100x100x100mm and 150x150x150mm), mini beams (size 75x75x280mm) and slabs specimens (size 250x250x110mm) in multi layers as specified in BS EN 12390-2 (2019). Each filled layer of fresh concrete was compacted using a vibrating table to ensure removal of entrapped air after pouring. For example, cube specimens were filled with three equal layers, whereas mini beam and slab specimens were filled with two layers while being compacted using the vibrating table. The moulds were then covered with a plastic sheet to prevent moisture evaporation.

It should be stressed that, all cube specimens of size 100x100x100mm and 150x150x150mm were cast into polystyrene moulds as shown in Figure 3.5, this is recommended by Standards to avoid applying oil releasing agent because it affects permeability of concrete surface. Therefore, specimens which cured using CC were demoulded approximately three to four hours after casting and cured by applying the CC on the freshly cast concrete as shown in Figure 3.6. On the other hand, control cubes which cured in water or in air were demoulded after 24 hours from casting and labeled accordingly, before being transferred to the specific curing regime.

**Figure 3.5** Casting concrete in polystyrene moulds

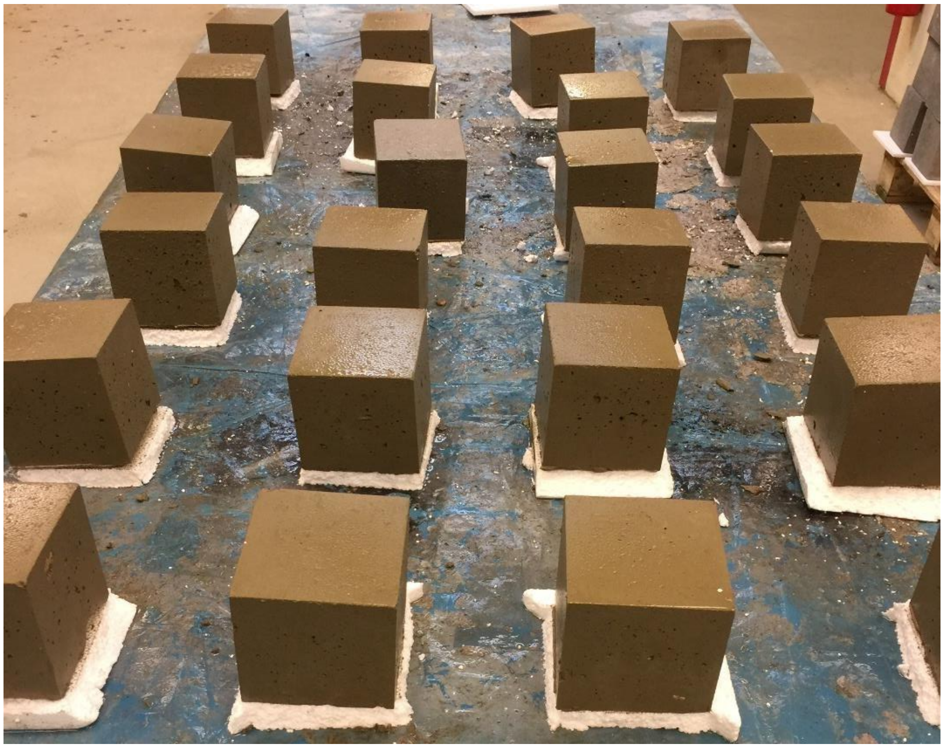


**Figure 3.6** Demoulding and applying curing compound

## 3.4 Curing regimes

As mentioned previously, specimens cast into polystyrene cube moulds were demoulded 3-4 hours after casting and cured by spraying the CC. On the other hand, control samples in Phase 1 were cast into similar moulds but demoulded after 24 hours, followed by water curing (WC) at 20 °C for 28 days and air cured (AC) for 28 days in the laboratory environment. In Phase 2, specimens were cured using the CC, followed by treatment with admixture or surface treatment to improve impermeability. Whereas control cubes were cured in air (AC) and water (WC). Similar to Phase 2, specimens in Phase 3 were cured using the CC, followed by treatment with admixture or surface treatment to improve performance, while reference samples were cured in AC and WC. Generally, performance of concrete specimens was assessed by comparing with two sets of control samples cured in different curing conditions as shown in Table 3.9.

**Table 3.9** Curing conditions for Phase 1 – Engineering Properties, Phase 2 – Transport Properties and Phase 3 – Durability Properties of experimental programme

| **Phase** | **Tests** | **Curing methods** | | |
|---|---|---|---|---|
| | | **Specimen (cc)** | **Control (wc)** | **Control (ac)** |
| 1 | • Compressive strength | Curing compound | Water curing | Air curing |
| | • Flexural strength | Curing compound | Water curing | Air curing |
| | • Drying shrinkage | Curing compound | Water curing | Air curing |
| 2 | • ISAT | CC + Admix / ST | Water curing | Air curing |
| | • Sorptivity | CC + Admix / ST | Water curing | Air curing |
| | • Permeability | CC + Admix / ST | Water curing | Air curing |
| 3 | • Carbonation | CC + Admix / ST | Water curing | Air curing |
| | • Resistance to scaling | CC + Admix / ST | Water curing | Air curing |
| | • Chloride ponding | CC + Admix / ST | Water curing | Air curing |

## 3.5 Slump test

After mixing the concrete according to procedures previously stated, slump test of fresh concrete was carried out to determine workability and consistency of freshly casted concrete in accordance with BS EN 12350-2 (2019). Slump test was conducted to ensure that workability of concrete mixes was within the range specified in the mix design process. All mixes were designed to have a workability value between 30-60 mm after compaction. The test was conducted on all mixes before casting into moulds and results are presented in Table 3.10. Complete mix information is provided in Table 3.7 and 3.8.

**Table 3.10** Slump test value for all mixes (mm)

| Mix No. | Slump | Mix No. | Slump | Mix No. | Slump | Mix No. | Slump |
|---|---|---|---|---|---|---|---|
| 1 | 56 | 8 | 56 | 15 | 53 | 22 | 64 |
| 2 | 54 | 9 | 52 | 16 | 57 | 23 | 58 |
| 3 | 53 | 10 | 49 | 17 | 56 | 24 | 62 |
| 4 | 55 | 11 | 51 | 18 | 56 | 25 | 61 |
| 5 | 52 | 12 | 48 | 19 | 55 | 26 | 62 |
| 6 | 54 | 13 | 50 | 20 | 67 | 27 | 63 |
| 7 | 52 | 14 | 52 | 21 | 65 | 28 | 62 |

## 3.6 Tests

A range of tests were carried out on concrete specimens and control samples in hardened state at different ages to establish engineering properties (compressive strength, flexural strength and drying shrinkage) in Phase 1, permeation properties (ISAT, sorptivity and depth of water penetration under pressure) in Phase 2, and durability properties (carbonation, resistance to scaling and resistance to chloride penetration) in Phase 3. These tests were conducted in accordance with relevant standard at different ages as shown in Table 3.11. For each test, three samples were tested and averaged to determine the specific test result. Results of resistance to scaling and chloride ponding tests were based on the mean of two samples for each test.

**Table 3.11** Age of samples at specified tests

| Phase | Test | Standard | Test ages |
|---|---|---|---|
| 1 (Engineering Properties) | • Compressive strength<br>• Flexural strength<br>• Drying shrinkage | • BS EN 12390-3:2019<br>• BS EN 12390-5:2019<br>• BS ISO 1920-8:2009 | 7, 28, 56 and 90 days<br>7, 28 and 56 days<br>7, 14, 21, 28, 56 and 112 days |
| 2 (Transport Properties) | • ISAT<br>• Sorptivity<br>• Permeability under pressure | • BS 1881-208:1996<br>• BS EN 13057:2002<br>• BS EN 12390-8:2019 | After 28 days<br>After 28 days<br>After 28 days |
| 3 (Durability Properties) | • Carbonation<br>• Resistance to scaling<br>• Chloride ponding | • BS 1881-210:2013<br>• ASTM C672-12<br>• AASHTO T 259-02 (2017) | 150 days<br>28 days<br>28 days |

### 3.6.1 Phase 1 (Engineering properties)

#### 3.6.1.1 Compressive strength

Compressive strength test was conducted on concrete specimens cast into polystyrene moulds size 100 mm and resistance of the cube to applied load until failure was measured to determine strength as specified in BS EN 12390-3 (2019). Strength of specimens cured using the CC was evaluated by comparing results with control cubes cured in water and control cubes air cured in the laboratory environment at 20 °C and 50-60% relative humidity. Cubes were tested at 7, 28, 56 and 90 days as shown in Table 3.9. Three samples were tested for compressive strength and the results averaged.

#### 3.6.1.2 Flexural strength

Flexural strength of concrete specimens was determined using the two-point loading method applied on mini beams size 75 x 75 x 280 mm in accordance with BS EN 12390-5 (2019). Flexural strength results of specimens cured using the CC was compared to two set of control samples cured in different curing conditions (AC and WC) as specified in Table 3.9. Three samples were tested for flexural strength and the results averaged.

#### 3.6.1.3 Drying shrinkage

Nine concrete prisms of size 75 mm x 75 mm x 280 mm of each concrete mix were cast to determine drying shrinkage as described in BS ISO 1920-8 (2009). Prisms were fitted with stainless steel gauge studs at both ends to measure shrinkage over times. All prisms were demoulded after approximately 24 hours from casting and cured according to the curing regime outlined in table 3.9. After demoulding, prisms were split into two groups according to the specified curing method. The first group involved prisms cured using the CC and another three control prisms air cured in the laboratory environment. Immediately after demoulding, measurements of length were taken as a reference with an accuracy of 0.001 mm and 0.1 gm respectively. Followed by applying the CC on the three prisms cast to be cured using the CC.

The remaining group involved three prisms cured in water for 7 days, then removed to a dry room in the laboratory to wipe the surface dry using a damp cloth. Immediately after drying the surfaces, accurate measurements of length were taken as a reference. To provide accuracy and consistency in readings, one end of the cast face of each specimen was marked as top and this marked side was set as the front face during measurements as shown in Figure 3.7. Changes in lengths measurements were recorded after total periods of air drying at 7, 14, 21, 28, 56 and 112 days as shown in Table 3.11. Length measurements of prisms were converted to microstrain and plotted against time.

**Figure 3.7** Drying shrinkage comparator

### 3.6.2 Phase 2 (Transport Properties)

#### 3.6.2.1 Initial surface absorption test (ISAT)

Initial surface absorption test was carried out on concrete cubes size 150 mm in accordance with BS 1881-208 (BSI, 1996) to assess uniaxial water penetration of concrete surface under applied pressure of 200 mm head of water. Concrete cubes were cast into polystyrene moulds to avoid applying oil releasing agent as it can affect surface permeability. Specimens were demoulded about 3-4 after casting and cured using the CC. To improve impermeability, specimens were treated either with admixture by adding it directly into the mix during batching or treated with surface treatment after 28 days from casting by means of brushing or spraying. Performance of specimens were assessed by comparing results with two set of control cubes. The first set was demoulded after 24 from casting and cured in water at 20 °C for 28 days. Whereas the second set was demoulded after 24 from casting and air-cured in the laboratory environment at 20 °C and 50-60% relative humidity. ISAT test as shown in Figure 3.8 was conducted after 28 days from casting on all cubes and readings were taken at 10, 30 and 60 minutes from the start of the test. All samples were conditioned in the laboratory environment at 20 °C for 48 hours before testing. ISAT values were calculated by determining the average value of three specimens for each curing condition, recorded in ml/($m^2$.s) and plotted against time in minutes.

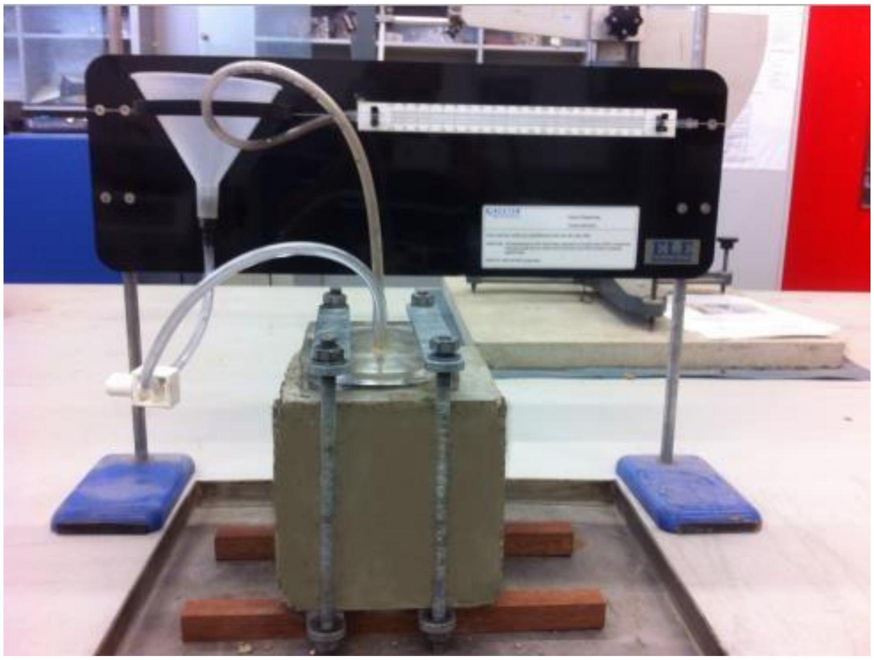


**Figure 3.8** ISAT apparatus test

### 3.6.2.2 Sorptivity

Sorptivity test was conducted on concrete cubes size 100 mm as specified in BS EN 13057-02 (2002) and ASTM C1585 (2020). The test was slightly modified to be similar to the method used by Mckenzie and Calder (2009). This method is more appropriate to accurately determine water absorption of concrete at surface rather than the interior as exterior surface is usually exposed to potentially adverse conditions. In this method, bottom sides of cubes were immersed in water and rate of water absorption by capillary suction was determined by measuring mass increase of the specimen over time. Concrete cubes were cast into polystyrene moulds to avoid applying oil releasing agent as it can affect surface permeability. Specimens were demoulded about 3-4 after casting and cured using the CC. To improve impermeability, these specimens were treated either with admixture by adding it directly into the mix during batching or treated with surface treatment after 28 days from casting by means of brushing or spraying. Performance of specimens were evaluated by comparing results with two set of control cubes. The first set was demoulded after 24 from casting and cured in water at 20 °C for 28 days. While the second set of control cubes was demoulded after 24 from casting and air-cured in the laboratory environment at 20 °C and 50-60% relative humidity.

Cube sides except top and bottom were sealed with epoxy paint to control moisture evaporation through uncoated sides. Weight measurements of coated cubes were taken to the nearest 0.01 gm and recorded as initial mass before exposure to water. Samples were exposed to approximately 3 mm depth of water above the top of the supports as shown in Figure 3.9. To evaluate mass gain of cubes, samples were removed from the pan and surface water was dried with a dampened paper towel, and weight measurements were recorded at different time intervals up to 7 days after first contact with water. Mass gain was calculated at each time interval by subtracting initial mass from the recorded mass. Water uptake was calculated by dividing the absorbed water (kg) by the surface area of the cube face ($m^2$). Water uptake was plotted against the square root of the time of immersion (h), and gradient of the resulting line represents the sorption coefficient (kg/( $m^2.h^{0.5}$)).

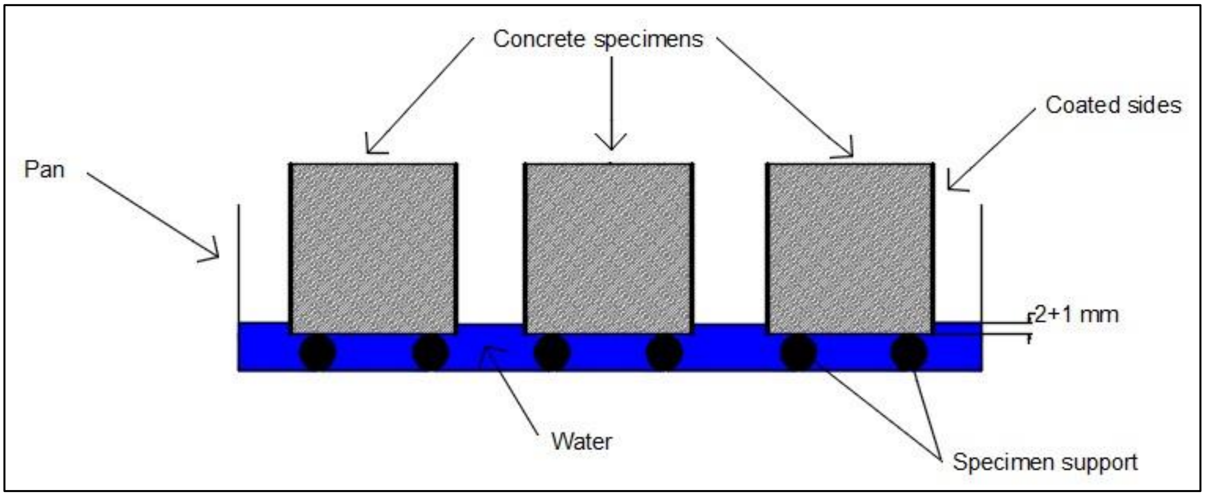


**Figure 3.9** Schematic of sorptivity test

### 3.6.2.3 Depth of water penetration under pressure

Permeability of concrete cubes size 150 mm under applied pressure was conducted as described in BS EN 12390-8 (2019). In this test, the bottom sides of concrete cubes were exposed to water under applied pressure of 5 bar (500 KPa) for 72 hours, then samples were split in half and depth of penetration of water was measured to the nearest mm. Concrete cubes were cast into polystyrene moulds to avoid applying oil releasing agent as it can affect surface permeability. Specimens were demoulded about 3-4 after casting and cured using the CC. To improve impermeability, specimens were treated either with admixture by adding it directly into the mix during batching or treated with surface treatment after 28 days from casting, by means of brushing or spraying. Performance of specimens were evaluated by comparing results with two set of control cubes. The first set was demoulded after 24 from casting and cured in water at 20°C for 28 days. Whereas the second set was air cured (AC) in the laboratory environment at 20 °C and 50-60% relative humidity. The test was conducted at least 28 days from casting, three cubes were placed in the apparatus at a time and exposed to water under the specified pressure as shown in Figure 3.10. After 72 hours, specimens were removed from apparatus and wiped to remove excess water, samples were split in half and depth of water penetration was measured to the nearest mm.

**Figure 3.10** Water permeability apparatus

### 3.6.3 Phase 3 (Durability Properties)

#### 3.6.3.1 Carbonation resistance of concrete

Resistance of concrete to carbonation penetration was evaluated using cubes size 100 mm casted and tested as described in BS 1881-210 (2013). Concrete cubes were cast into polystyrene moulds to avoid applying oil releasing agent as it can influence the carbonation depth. Cubes were demoulded about 3-4 after casting and cured using the CC. To improve performance, the specimens were treated either with admixture by adding it directly into the mix during batching or treated with surface treatment after 28 days from casting. Performance of specimens were evaluated by comparing results with the two set of control samples. The first set was demoulded after 24 from casting and cured in water at 20°C for 28 days and conditioned in the laboratory environment for 14 days. On the other hand, the second set of control samples was demoulded after 24 from casting and air-cured in the laboratory environment at 20 °C and 50-60% relative humidity.

The top, bottom and two opposite side faces of all cubes were coated with bitumen to allow $CO_2$ penetration only through the sides. All cubes were placed in the carbonation test chamber with $CO_2$ level of 4.0 ± 0.5% at 20 °C and 55% relative humidity as shown in Figure 3.11. Specimens were exposed to $CO_2$ in the carbonation chamber for 150 days. To measure depth of carbonation in the specimens, an indicator solution was prepared in the laboratory by dissolving 1 gm of phenolphthalein powder in a solution produced by mixing 70 ml of ethanol with 30 ml of deionized water. After completion of test, specimens were split in half using a diamond saw and the solution indicator was sprayed on the exposed surface. Carbonated section of the specimen remained colourless as the pH value dropped below 9, whereas non-carbonated section turned pink due to the alkalinity. Carbonation depth was determined by measuring the depth at five points on each exposed side using a ruler and the final depth was calculated as the mean value of these five readings.

**Figure 3.11** Carbonation chamber apparatus

#### 3.6.3.2 Scaling resistance of concrete surface exposed to deicing chemical

This test was carried out to assess resistance of concrete slabs size 250mm x 250mm x 110 mm deep, exposed to freezing and thawing cycles in the presence of deicing chemical as outlined in ASTM C672 (2012). For each combination of variables, six concrete slabs were cast upside down with an insert in the base of the mould to form a recess for subsequent ponding. All slabs were demoulded after 24 hours from casting and cured differently according to the research methodology. After demoulding, two slabs were cured using the CC and treated either with admixture by adding it directly into the mix during batching or treated with surface treatment after 28 days from casting.

Performance of the treated slabs were evaluated by comparing results with the remaining four untreated slabs. Two of the control slabs were cured in water for 14 days and conditioned in the laboratory environment for 14 days. Whereas the remaining two slabs were air cured in the laboratory environment for 28 days at 20 °C and 50-60% relative humidity. After completion of air and water curing as shown in Figure 3.12, the flat surface of each slab was covered with approximately 6 mm of a chemical solution which was prepared by dissolving 4 gm of anhydrous calcium chloride in 100 ml of water. All slabs were placed in the environmental chamber to undergo exposure to freezing environment (-18 °C) for 16 hours as shown in Figure 3.13, followed by exposure to laboratory environment at 23 °C and a relative humidity of 50-60% for 8 hours. This cycle was repeated for 50 days and water was added between each cycle as necessary to maintain the required depth of solution. The slab surface was thoroughly flushed off at the end of each 5 cycles, followed by visual examination and collection of loose material to determine scaled weight over 50 cycles, and the mass loss due to freezing and thawing was calculated as the average cumulative scaled weight.

**Figure 3.12** Slabs after air and water curing

**Figure 3.13** Slabs placed in freeze-thaw chamber

### 3.6.3.3 Resistance of concrete to chloride penetration

This test was conducted to determine resistance of concrete slabs size 250mm x 250mm x 110mm deep to the penetration of sodium chloride solution in accordance to ASTM C1543 (2010). This American standard was used as this method is more relevant and widely used in laboratory conditions to determine chloride penetration. For each case, six concrete slabs were cast upside down with an insert in the base of the mould to form a recess for subsequent ponding. All slabs were demoulded after 24 hours from casting and cured differently according to the research methodology. After demoulding, two slabs were cured using the CC and treated either with admixture by adding it directly into the mix during batching or treated with surface treatment after 28 days from casting.

Performance of the treated slabs were evaluated by comparing results with the remaining four untreated slabs. Two of the control slabs were cured in water for 14 days and conditioned in the laboratory environment for 14 days. Whereas the remaining two slabs were air cured in the laboratory environment for 28 days at 20 °C and 50-60% relative humidity. After completion of air and water curing, the flat surface of each slab was ponded with approximately 8 mm of a chemical solution which was prepared by dissolving 3 gm of sodium chloride in 100 ml of water. All specimens were covered with a glass plate to retard evaporation of water from the solution and stored in the laboratory environment at 20 °C and 50 -60 % relative humidity as shown in Figure 3.14. Specimens were ponded for four months and fresh solution was added accordingly to maintain the specified level of solution. The solution was replaced with fresh solution at twomonth intervals.

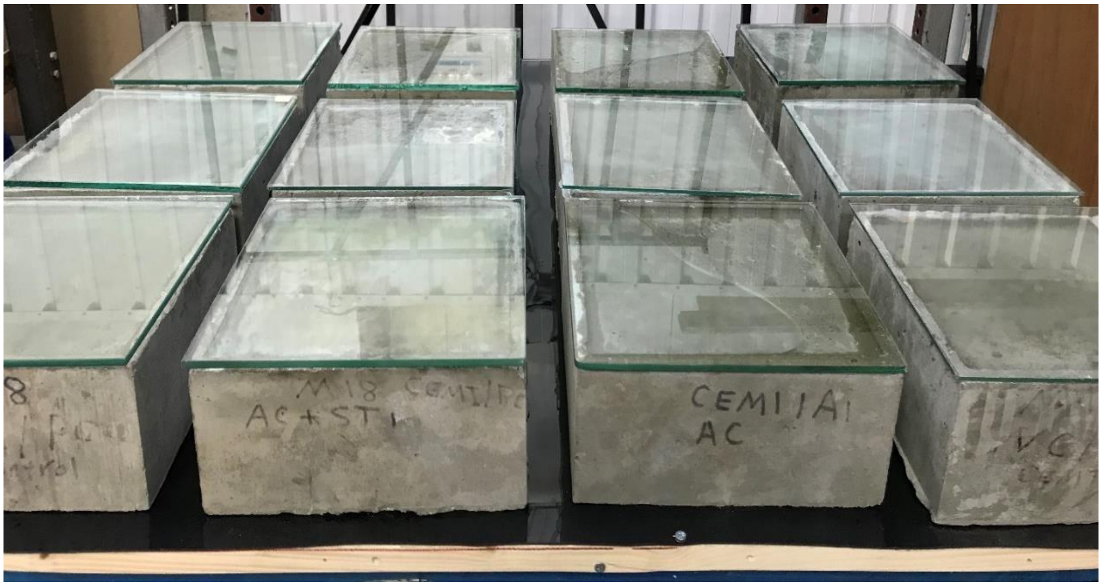


**Figure 3.14** Chloride ponding test

After completion of the test, the solution was removed, and specimens were left to dry completely in the laboratory. After drying, the salt crystals were removed from the slab surface using a wire brush. Powdered samples at 8mm and 16mm depths were obtained from specimens using a drilling device shown in Figure 3.15. The collected samples were sieved (size 0.300 mm) to ensure the entire sample is finer than 0.300 mm and mixed in approximately 20 ml of deionized water in small tubes for 24 hours. Samples were chemically analysed using an inductively coupled plasma (ICP) spectroscopy machine to detect and measure the sodium ion in parts per million as shown in Figure 3.16. The final concentration was calculated by averaging results obtained from two slabs.

**Figure 3.15** Drilling device used to obtain powdered samples

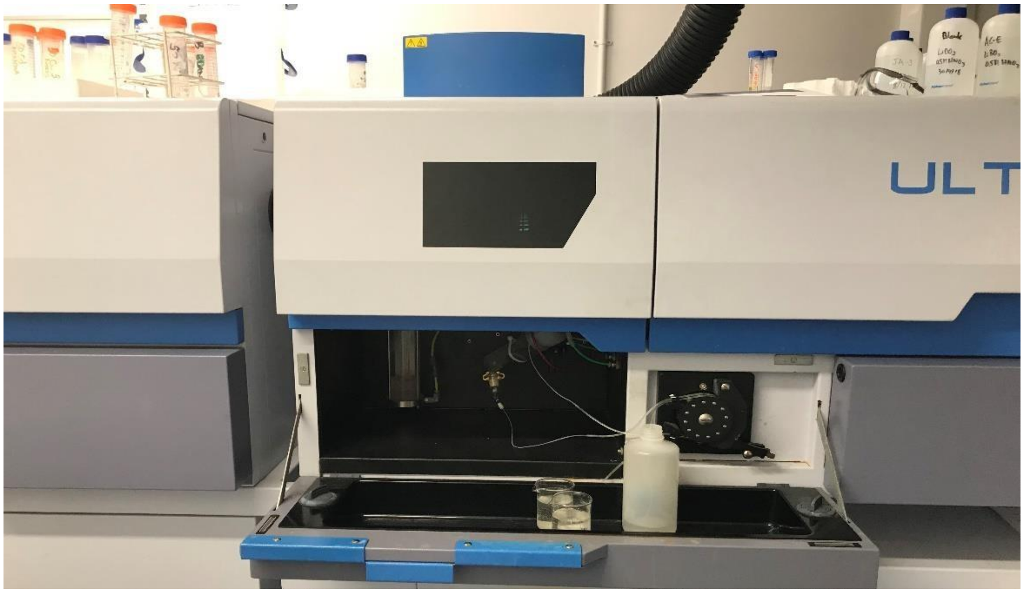


**Figure 3.16** Apparatus used to chemically analyse the samples

# Chapter 4: Engineering Properties

## 4.1 Introduction

In this Chapter, the influence of applying a curing compound along with incorporation of mineral admixtures on engineering properties of concrete namely, compressive and flexural strength were assessed and evaluated as these properties play an important role in the structural design of concrete structures. Moreover, drying shrinkage is also examined as presence of cracks due to moisture loss could make concrete susceptible to water and chloride ingress. Therefore, formation of cracks could cause deterioration such as steel corrosion, consequently decreasing long-term durability of concrete. As a result, these parameters are thoroughly investigated as shown in the programme of work in Figure 4.1.

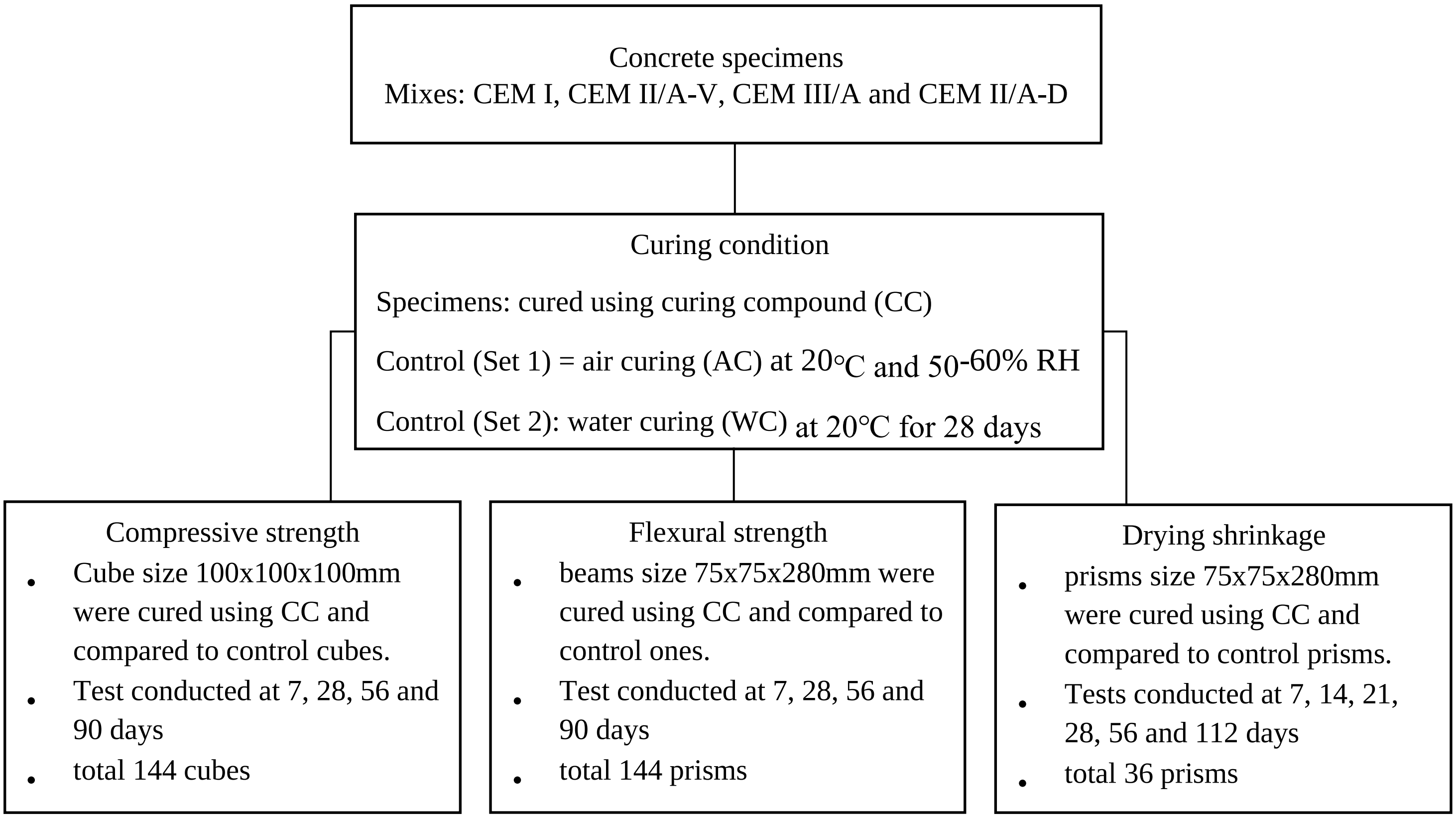


**Figure 4.1** Experimental work of phase 1 – Engineering Properties

As shown in Figure 4.1, concrete specimens were prepared using different types of cement CEM I, CEM II/A-V, CEM III/A and CEM II/A-D, while a curing compound (CC) was applied for curing. The CC is a water-based sodium silicate liquid applied on specimens approximately 3-4 hours after casting, and it acts to prevent or retard moisture loss through evaporation by forming a microscopic crystalline structure in the concrete pores of the surface layer. Performance of concrete specimens was compared to two set of control samples as shown in Chapter 3 (Table 3.9). The first set was air cured (AC) in the laboratory at 25°C and 50-60% RH, whereas the second set of control samples was cured in water (WC) at 20°C for 28 days. Short- and long-term impact of CC on compressive and flexural strength development was investigated as specimens were tested at 7, 28, 56 and 90 days as shown in Chapter three (Table 3.11). Since incorporation of mineral admixtures such as FA and GGBS tend to delay strength development, therefore, it was important to observe strength gain after 28 days. Similarly, drying shrinkage test was conducted at 7, 14, 21, 28, 56 and 112 days to examine influence of CC on concrete moisture loss due to drying. Concrete mixes were prepared with equal design strength as shown in Chapter 3 (Table 3.7) to evaluate the engineering properties and compare the performance of all mixes.

## 4.2 Experimental programme

## 4.3 Compressive Strength

### 4.3.1 Compressive strength of CEM I (100%PC) concrete mix

Concrete specimens were cast into 100 mm cube mould according to BS EN 12390-3 (BSI, 2019) to investigate the strength development of cubes cured using the CC. For this purpose, polystyrene mould was used instead of metal or plastic moulds to demould the cubes approximately 3 hours after casting and apply the CC on specimens. Compressive strength of cubes was compared with two set of control samples. The first set was air cured in the laboratory environment at 25°C and 50-60% RH, whereas the second set of control cubes was cured in the water tank at 20°C for seven days. Three cubes were tested and averaged at 7, 28, 56 and 90 days to determine strength development under different curing conditions at each specific age. Results showed that CEM I concrete cubes developed significant strength at early ages of 7 days. Nevertheless, strength gain beyond 28 days was trivial as maximum strength gain between 28 and 90 days was 1.34 MPa in control cubes cured in water. The early strength development in CEM I is primarily due to two reasons, the primary reason is the high content of $C_3S$ which is the main contributor to the early strength gain, and the secondary reason is the role of $C_3A$ which reacts quickly with water causing rapid setting Taylor (1997). Specimens cured using the CC developed 94.21%, 91.98%, 91.21% and 91.40% strength compared with control cubes cured in water and tested at 7, 28, 56 and 90 days respectively. This shows that efficiency of CC was more than 90% when compared to corresponding control cubes cured in water. In fact, compressive strength of CEM I specimens cured using the CC achieved 97.93% of design strength at 28 days as the measured compressive strength was 39.17 MPa as shown in Figure 4.2. Moreover, compressive strength of specimens and control cubes was 40.15 and 43.93 MPa respectively at 90 days. Maximum difference in strength was measured at 56 days which was 3.82 MPa between specimen cured using the CC and control cube cured in water. Results showed that the hydration process continued beyond 28 days as it was observed in the strength development. Furthermore, minimum compressive strength was measured in control cubes air cured in the laboratory environment as the hydration process was negatively affected due to lack of a curing source and moisture loss under ambient condition. See Appendix B1 for complete results of compressive strength.

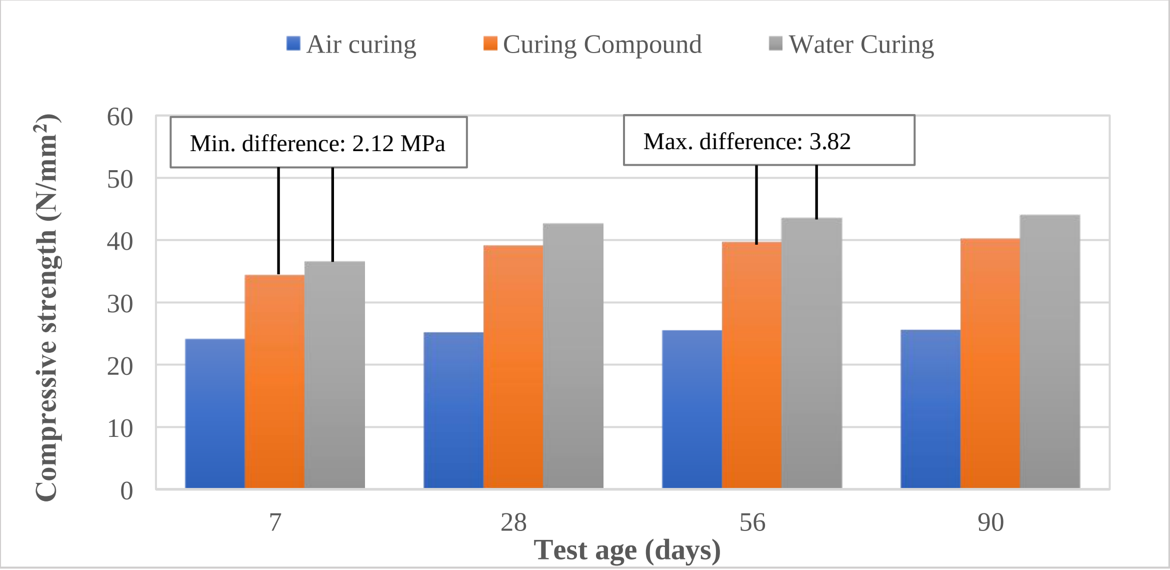


**Figure 4.2** Compressive strength results of CEM I concrete

### 4.3.2 Compressive strength of CEM II/A-V (80%PC+20%FA) concrete mix

Compressive strength results of CEM II/A-V mix are presented in Figure 4.3. Results obtained show that partial replacement of 20 % of PC with FA reduced strength development at early ages up to 28 days under all curing conditions. However, hydration process continued beyond 28 days as strength development between 28 and 90 days were 2.93 and 2.95 in specimens cured using the CC and control cubes cured in water respectively. Specimens cured with CC developed more than 90% strength compared to control cubes cured in water at 7, 28, 56 and 90 days. Specimens treated with CC achieved 91.58% and 98.90% of the design strength at 28 and 90 days respectively. Control cubes air cured in the laboratory environment suffered significant reduction in strength due to discontinuation of the hydration process. In terms of strength differences between specimens treated with CC and control samples cured in water, minimum strength difference was 1.23 MPa measured at 7 days and maximum difference was 3.37 MPa observed at 56 days. This reduction in early age compressive strength in mixes containing FA is attributed to the pozzolanic reaction – a reaction with $Ca(OH)_2$ produced during the hydration of PC. Partial replacement of PC with FA reduces the amount of CaO which contributes to the formation of C-S-H gel, thus causing reduction in early age strength. As a result, the $Ca(OH)_2$ will be lower due to the dilution of PC and consumption of $Ca(OH)_2$ in the pozzolanic reaction (Dyer, 2014; Megat Johari et al., 2011; Shi et al., 2009).

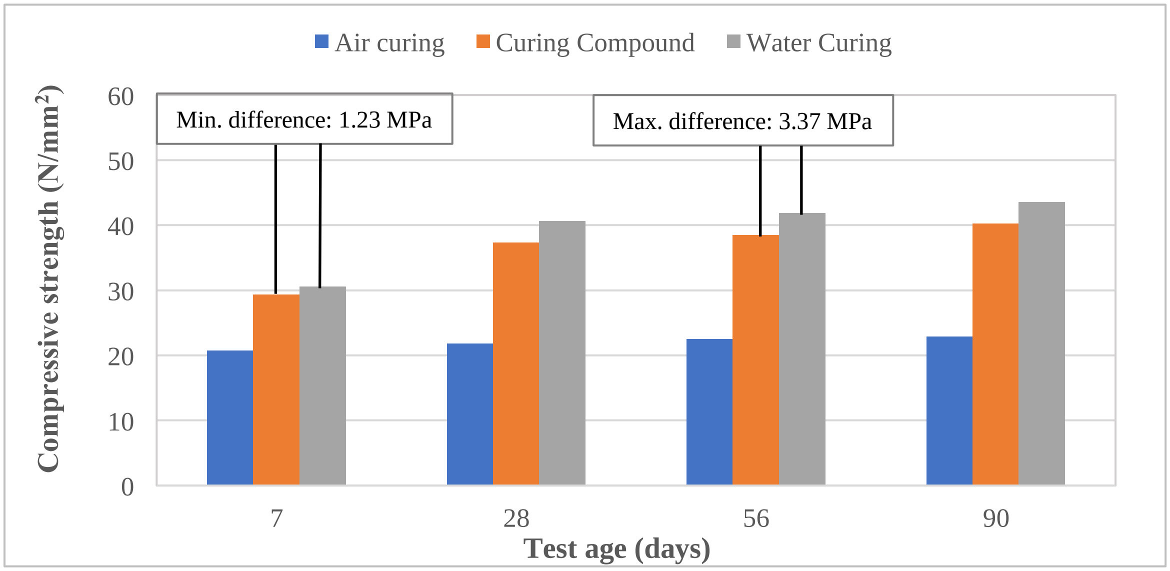


**Figure 4.3** Compressive strength results of CEM II/A-V concrete

### 4.3.3 Compressive strength of CEM III/A (60%PC+40%GGBS) concrete mix

Compressive strength results of CEM III/A concrete mix are shown in Figure 4.4. Results showed that 40% replacement of PC with GGBS reduced strength development at early ages up to 7 days under all curing conditions. Nevertheless, strength development continued beyond 28 days as strength increased by 4.47 MPa and 3.2 MPa in specimens cured using the CC and control cubes cured in water respectively. It was observed that treated specimens with CC developed more than 90% strength compared to corresponding control cubes cured in water. It was noted that cubes under both curing conditions (applying CC and water curing) kept gaining reasonable strength up to 90 days age and minimum strength difference was 2.64 MPa at 90 days. This shows that hydration process continued up to 90 days age. On the other hand, maximum strength difference was 3.91 MPa at 28 days. Mixes containing GGBS suffers reduction in early age compressive strength because GGBS hydrates slower than CEM I, thus the rate of strength development will be slower (Michael Connell, Concrete Durability Book by Soutsos, 2010). However, at later ages usually after 28 days, the strength will typically be similar to PC (Dyer, 2014). Moreover, control cubes cured in the laboratory environment exhibited huge reduction in strength development at all ages due to termination of the hydration process. This is due to the fact that incorporation of mineral admixtures in the concrete needs longer curing period to ensure continuation of the hydration process, thus developing required strength.

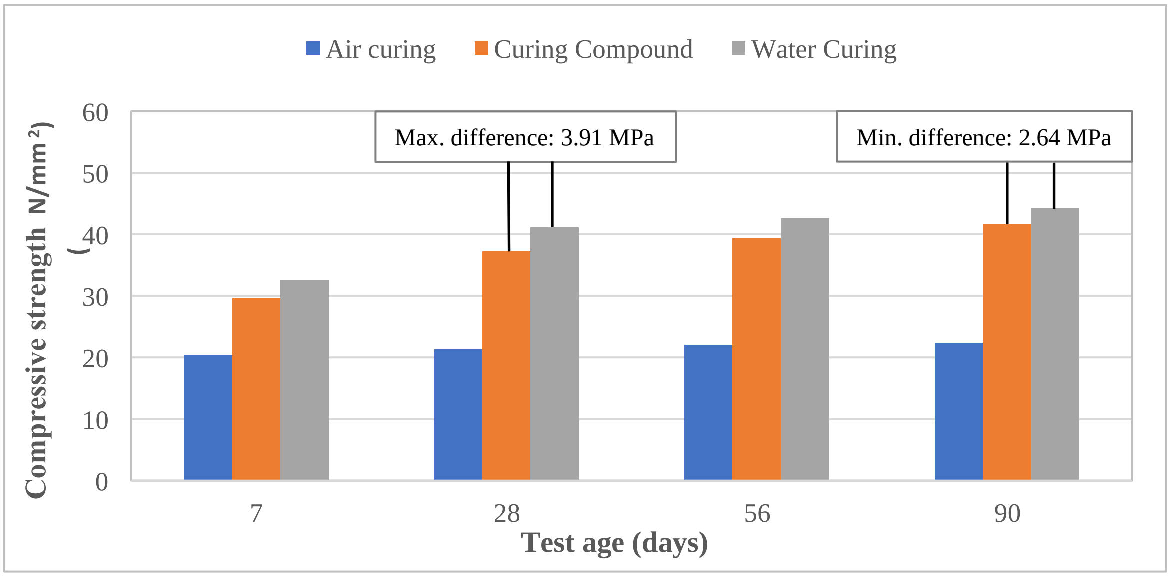


**Figure 4.4** Compressive strength results of CEM III/A concrete

### 4.3.4 Compressive strength of CEM II/A-D (90%PC+10%SF) concrete mix

Compressive strength results of CEM II/A-D concrete mix are shown in Figure 4.5. Results demonstrated that 10% replacement of PC with SF significantly increased strength development at early ages up to 28 days under all curing conditions. However, strength development beyond 28 days was relatively insignificant as strength of specimens cured using the CC increased by 0.9 MPa and control cubes cured in water and in air by 1.59 MPa and 0.56 MPa respectively.

Moreover, specimens cured with CC developed more than 90% strength of control cubes cured in water. It was observed that minimum strength difference between cubes under both curing conditions (applying CC and water curing) was 2.59 MPa at 7 days and maximum was 5.18 MPa at 90 days. On the other hand, control cubes air cured in the laboratory environment developed sensible strength at early ages up to 7 days. Nonetheless, strength development was relatively insignificant at later ages particularly beyond 28 days which was more likely due to the termination of the hydration process. This significant improvement in compressive strength of mixes containing SF is attributed to the reaction between SF and the liberated calcium hydroxide during the hydration process which forms additional cementitious compound, mainly calcium silicate hydrates (CSH) (Roy et al., 2001; Mazloom et al., 2004; Soutsos, 2010).

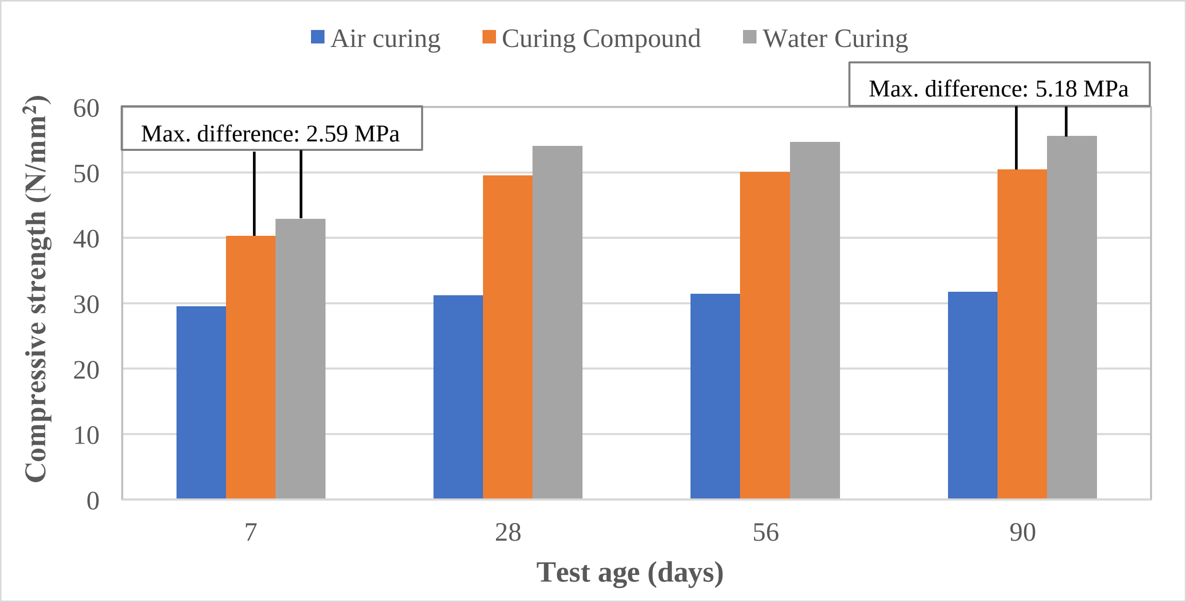


**Figure 4.5** Compressive strength results of CEM II/A-D concrete

### 4.3.5 Comparison of CEM II/A-V, CEM III/A and CEM II/A-D with CEM I

**Table 4.1** Results of all cement types (CEM I, CEM II/A-V, CEM III/A and CEM II/A-D)

| **Cement type** | **Strength (MPa) Air Curing (AC)** | | | | **Strength (MPa) Curing Compound (CC)** | | | | **Strength (MPa) Water Curing (WC)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **7 days** | **28 days** | **56 days** | **90 days** | **7 days** | **28 days** | **56 days** | **90 days** | **7 days** | **28 days** | **56 days** | **90 days** |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CEM I | 24.11 | 25.16 | 25.50 | 25.60 | 34.45 | 39.17 | 39.63 | 40.15 | 36.57 | 42.59 | 43.45 | 43.93 |
| CEM II/A-V | 20.68 | 21.81 | 22.47 | 22.84 | 29.35 | 37.30 | 38.47 | 40.23 | 30.58 | 40.60 | 41.84 | 43.54 |
| CEM III/A | 20.30 | 21.32 | 22.06 | 22.42 | 29.62 | 37.20 | 39.39 | 41.67 | 32.59 | 41.11 | 42.59 | 44.31 |
| CEM II/A-D | 29.54 | 31.20 | 31.4 | 31.76 | 40.29 | 49.54 | 50.01 | 50.44 | 42.88 | 54.03 | 54.65 | 55.62 |

Strength comparisons between all cement types with respect to reference mix (CEM I) at 7, 28, 56 and 90 days of age are given Figures 4.6, 4.7, 4.8 and 4.9 respectively. It was observed that replacement of PC with FA and GGBS in CEM II/A-V and CEM III/A mixes, reduced early ages strength up to 28 days due to the pozzolanic and latent hydraulic reactions of FA and GGBS respectively. Therefore, strength development in CEM II/A-V and CEM III/A mixes were slower than that of CEM I mix because of the reduction of C-S-H formation as a result of the pozzolanic reaction in mixes containing FA, and retardation of the hydration process in mixes containing GGBS. Nonetheless, at later ages usually after 28 days, the strength will typically be similar to that of PC as these reactions become dominant after 28 days of age (Gonen and Yazicioglu, 2007; Wesche, 1991; Dyer, 2014; Oner and Akyuz, 2007). Results obtained show that early ages strength up to 28 days of CEM II/A-V, CEM III/A samples cured using the CC and cured in the air were almost identical. However, a slight difference of approximately 2 MPa at 7 days age was observed between cubes of both cement types cured in water which was later reduced to 1.5 MPa at 28 days as shown in Figure 4.6 and 4.7. Maximum strength difference at early ages 7 days was measured as 5.99 MPa for CEM II/A-V. However, this difference was decreased to 1.99 MPa at 28 days age.

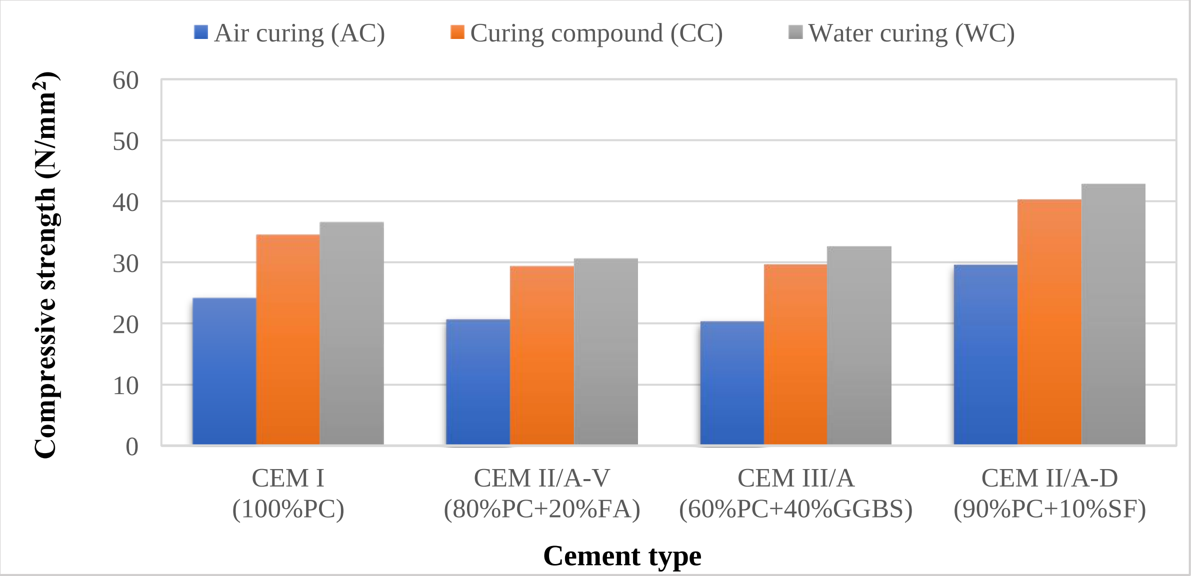


**Figure 4.6** Compressive strength results of all cement types at 7 days age

Moreover, compressive strength of CEM II/A-V and CEM III/A mixes beyond 28 days and up to 90 days kept developing under both curing conditions (CC and WC). It was observed that compressive strengths of both mixes were comparable to strength of CEM I. In fact, CEM III/A cubes cured using CC and cured in water developed higher strength than that of CEM I and CEM II/A-V at later ages 90 days. These results are in agreement with findings of previous studies (Johari *et al.*, 2011; Oner and Akyuz, 2007).

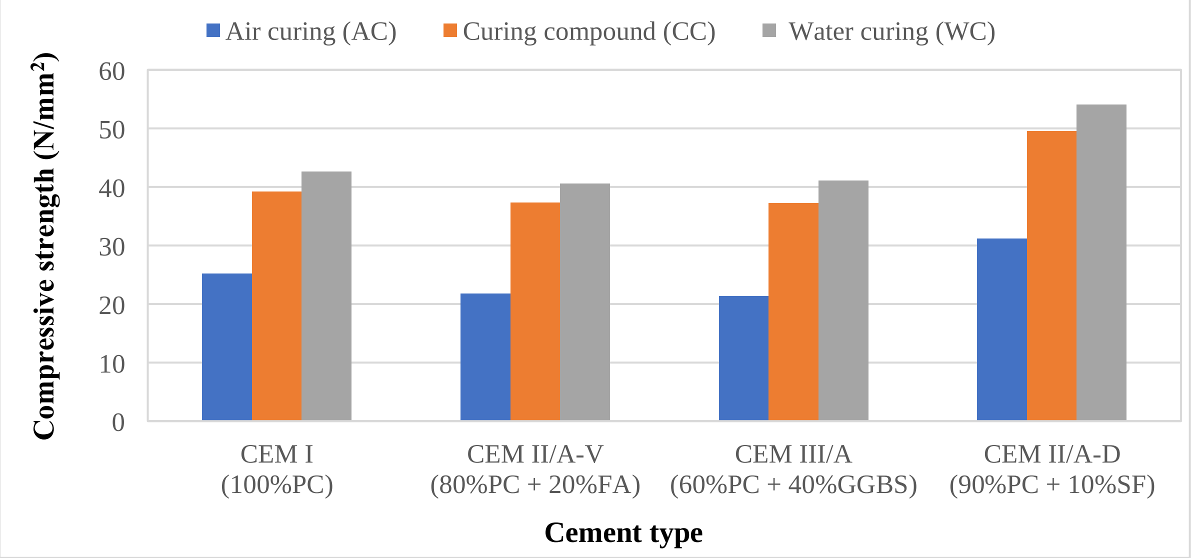


**Figure 4.7** Compressive strength results of all cement types at 28 days age

In terms of SF mix, 10% replacement of PC with SF significantly increased strength development at early ages up to 28 days under all curing conditions. However, strength gain diminished after 28 days under all curing conditions. In fact, incorporation of SF increased strength development of cubes cured using the CC and cured in water by approximately 26% at 28 days age compared to reference control cubes CEM I. Maximum strength difference between CEM II/A-D and CEM I was recorded as 11.2 and 11.69 MPa in cubes cured in water at 56 and 90 days respectively. However, the substantial strength development was observed at early ages up to 28 days which 11.15 MPa. This improvement in compressive strength is believed to be due to the chemical and physical impact of SF. This is in agreement with previous studies which state the chemical effect is attributed to the pozzolanic reaction between SF and calcium hydroxide to form additional C-SH. Whereas the physical effect is mainly due to the very fine particle size of SF which acts as filler to fill the spaces between the cement grains. Thus, forming a more dense and compacted concrete matrix (Erdem and Kirca, 2008; Roy et al., 2001; Mazloom et al., 2004). It was observed that results of strength development of all cement types under all curing conditions were in agreement with previous studies (Al-Gahtani, 2010; Xue et al., 2015; Whiting and Snyder, 2003; Surana et al., 2017).

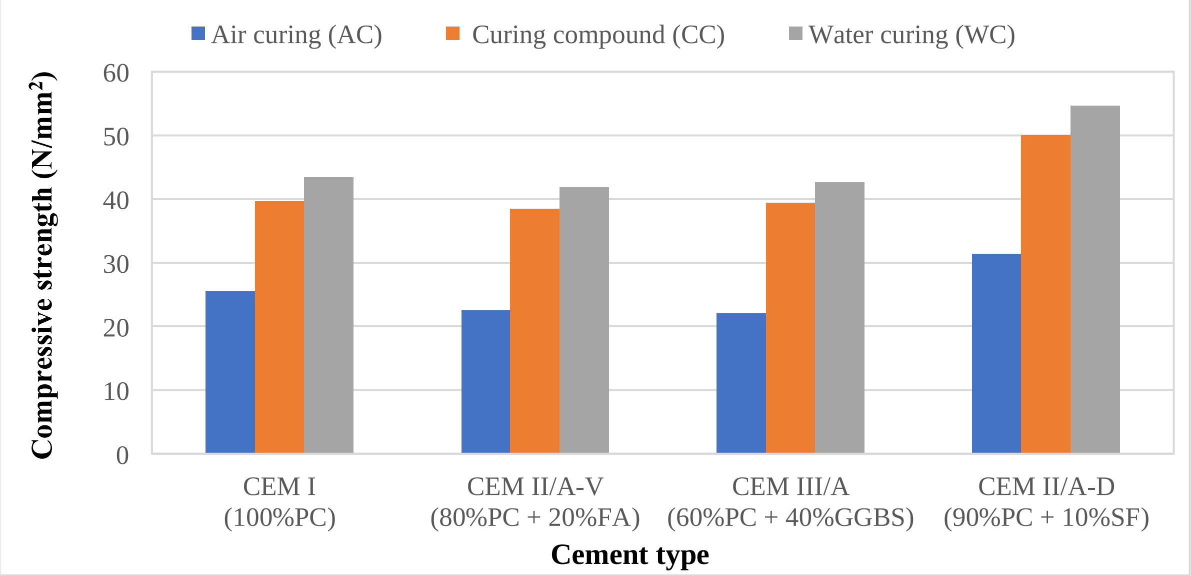


**Figure 4.8** Compressive strength results of all cement types at 56 days age

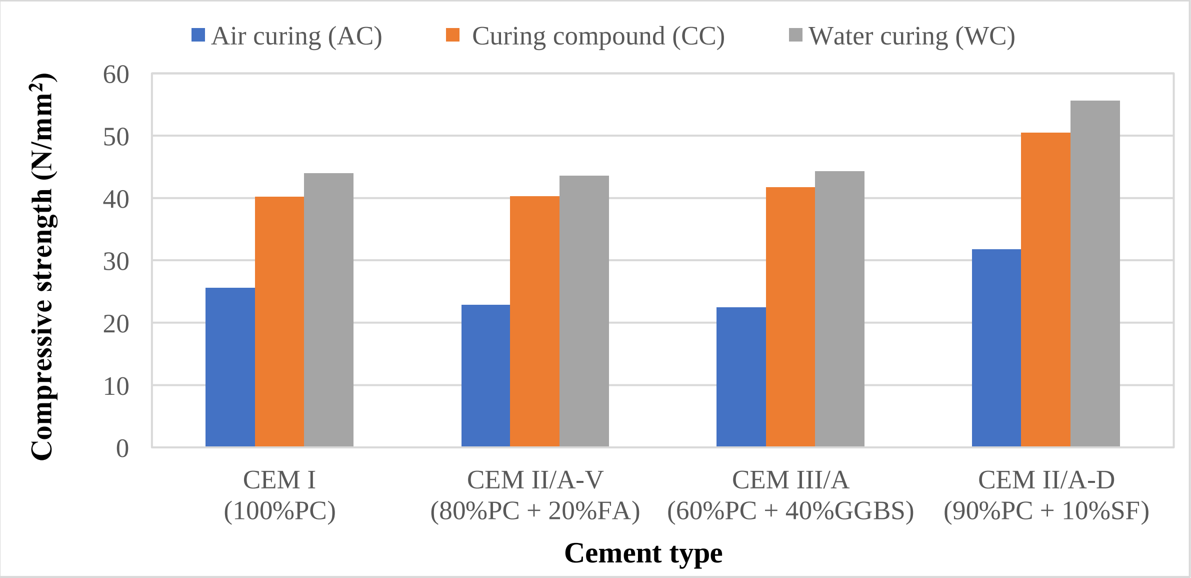


**Figure 4.9** Compressive strength results of all cement types at 90 days age

## 4.4 Flexural Strength

Flexural strength of concrete mixes was determined by subjecting prisms size 75mm x75mm x 280mm to four-point loading in accordance with BS EN 12390-5 (2019). Three prisms were tested and the average value was determined for each mix at 7, 28, 56 and 90 days. Performance of specimens cured with CC was evaluated by comparing results with two set of reference samples cured in air and in water.

### 4.4.1 Flexural strength of CEM I (100%PC) concrete mix

Results show that CEM I specimens cured using the CC developed higher flexural strength than that of control samples air cured in the laboratory, and lower strength than control prisms cured in water as shown in Figure 4.10. Nevertheless, flexural strength of specimens cured using the CC achieved more than 91% strength of reference ones cured in water at all ages (7, 28, 56 and 90 days). It was observed that the majority of strength development of CEM I specimens occurred at early ages up to 7 days. In fact, strength development beyond 28 days was insignificant. Minimum and maximum strength differences between specimens cured with CC and control samples cured in water were 0.3 and 0.47 MPa at 7 and 90 days age respectively. Results of flexural strength test are given in Appendix B2.

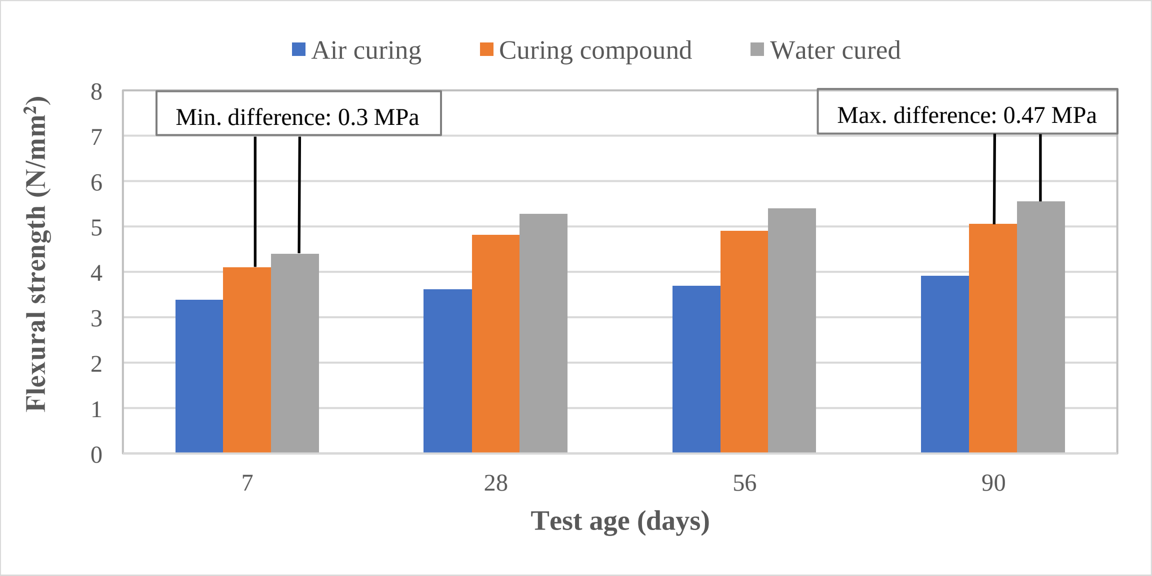


**Figure 4.10** Flexural strength results of CEM I concrete

### 4.4.2 Flexural strength of CEM II/A-V (80%PC+20%FA) concrete mix

Results show that highest flexural strength was developed in control cubes cured in water, followed by specimens cured using the CC and finally reference prisms cured in air as shown in Figure 4.11. It was observed that strength gain in CEM II/A-V specimens at early ages up to 28 days was slow under all curing conditions. However, results show that strength development continued post 28 days age. Moreover, flexural strength of specimens cured using the CC reached more than 90% strength of reference ones cured in water at all ages (7, 28, 56 and 90 days). It is evident that replacement of 20% PC with FA slowed down they hydration process, thus affected short term strength development up to 28 days age. Minimum and maximum strength differences between specimens cured with CC and control samples cured in water were 0.4 and 0.53 MPa at 7 and 90 days age respectively.

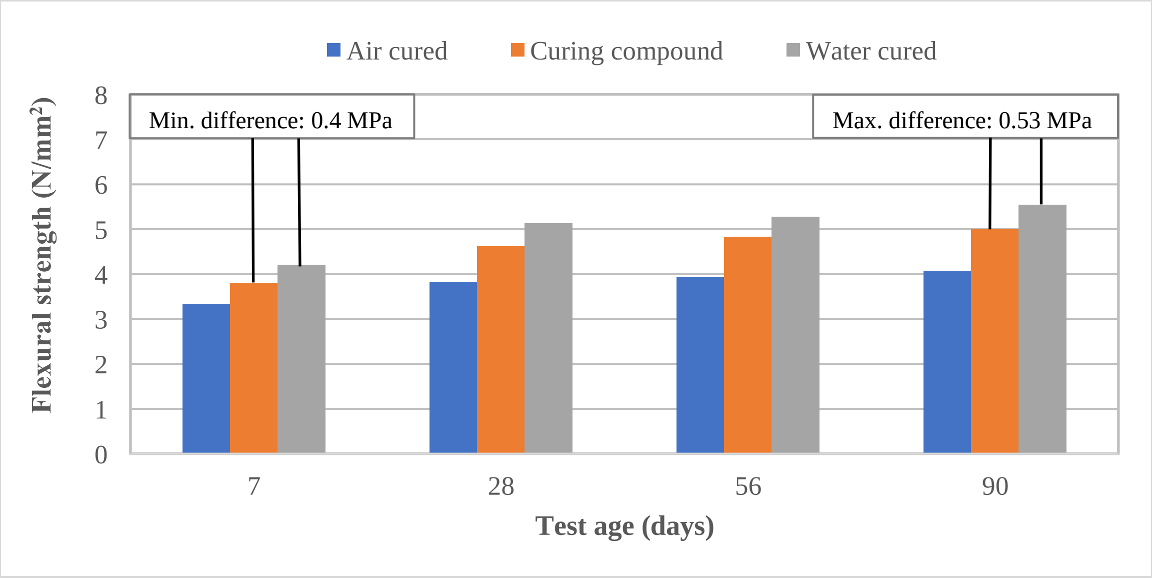


**Figure 4.11** Flexural strength results of CEM II/A-V concrete

### 4.4.3 Flexural strength of CEM III/A (60%PC+40%GGBS) concrete mix

Results show highest flexural strength was developed in reference samples cured in water, followed by specimens cured using the CC and control prisms cured in the air as shown in Figure 4.12. Similar to CEM II/A-V specimens, it was observed that strength development in CEM III/A specimens at early ages up to 28 days was slow under all curing conditions. However, results show that strength growth continued post 28 days age. Furthermore, flexural strength of specimens cured using the CC reached more than 91% strength of reference ones cured in water at all ages (7, 28, 56 and 90 days). It is evident that replacement of 40% PC with GGBS slowed down they hydration process, thus affected short term strength development up to 28 days age. Nevertheless, ultimate strength development at later ages was important as strength increased by 0.75 and 0.89 MPa at 90 days in specimens cured using the CC and control prisms cured in water respectively. Minimum and maximum strength differences between specimens cured with CC and control samples cured in water were 0.37 and 0.43 MPa at 7 and 90 days age respectively.

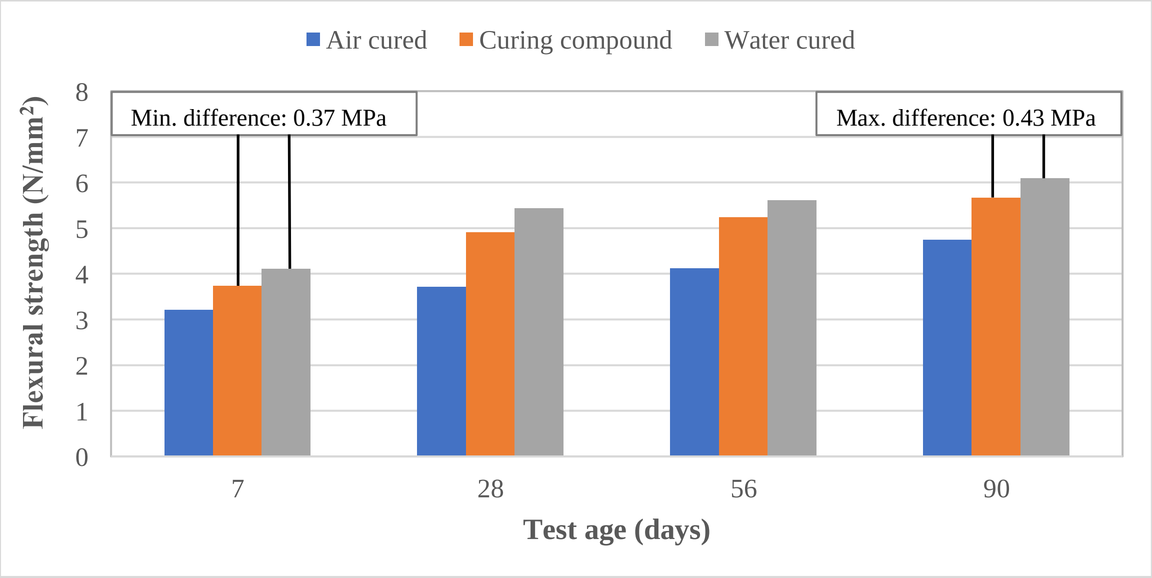


**Figure 4.12** Flexural strength results of CEM III/A concrete

### 4.4.4 Flexural strength of CEM II/A-D (90%PC+10%SF) concrete mix

Results show that control prisms cured in water developed highest flexural strength than specimens cued using the CC and reference samples cured in the air as shown in Figure 4.13. Moreover, it was observed that flexural strength of specimens cured using the CC achieved more than 92% strength of reference ones cured in water at all ages (7, 28, 56 and 90 days). Results indicate that the majority of strength development of CEM II/A-D specimens occurred at early ages up to 28 days under all curing conditions. In addition, ultimate strength development beyond 28 days was insignificant as strength increased by 0.24 and 0.3 MPa at 90 days in specimens cured with CC and control prisms cured in water respectively. It is apparent that 10% replacement of PC with SF increased strength gain at early ages up to 28 days. However, the effect was less significant post 28 days. Minimum and maximum strength differences between specimens cured with CC and control samples cured in water were 0.29 and 0.49 MPa at 7 and 90 days age respectively.

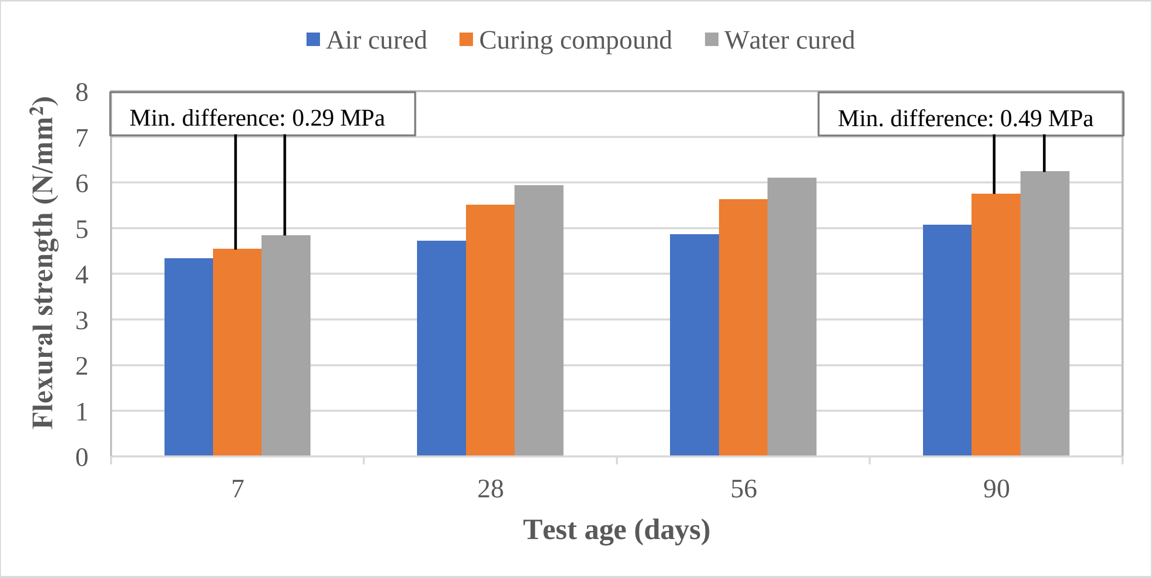


**Figure 4.13** Flexural strength results of CEM II/A-D concrete

### 4.4.5 Comparison of CEM II/A-V, CEM III/A and CEM II/A-D with CEM I

Comparisons of flexural strength of blended cement mixes (CEM II/A-V, CEM III/A and CEM II/A-D) with respect to reference mix (CEM I) at different ages 7, 28, 56 and 90 days are presented in Figure 4.14, 4.15, 4.16 and 4.17. The comparison was conducted between specimens cured using the CC and reference samples cured in water. This is because the other reference samples which were cured in the air developed minimum strength. Therefore, it was excluded from the comparisons.

Results indicate that CEM I and CEM II/A-D mixes developed higher early ages strength than CEM II/A-V and CEM III/A at 7 and 28 days as shown in Figure 4.14, 4.15. It was observed that flexural strength development mainly occurred at early ages up to 28 days of age. Strength development beyond 28 days was 0.26 MPa in CEM I concrete under both curing conditions. Whereas strength development post 28 days age was 0.24 and 0.30 MPa in CEM II/A-D concrete cured using the CC and cured in water respectively. Results show that strength gain was insignificant in both cement mixes after 28 days age. Moreover, highest flexural strength was 6.24 MPa measured in CEM II/A-D concrete samples cured in water which is attributed to the chemical and physical impact of SF.

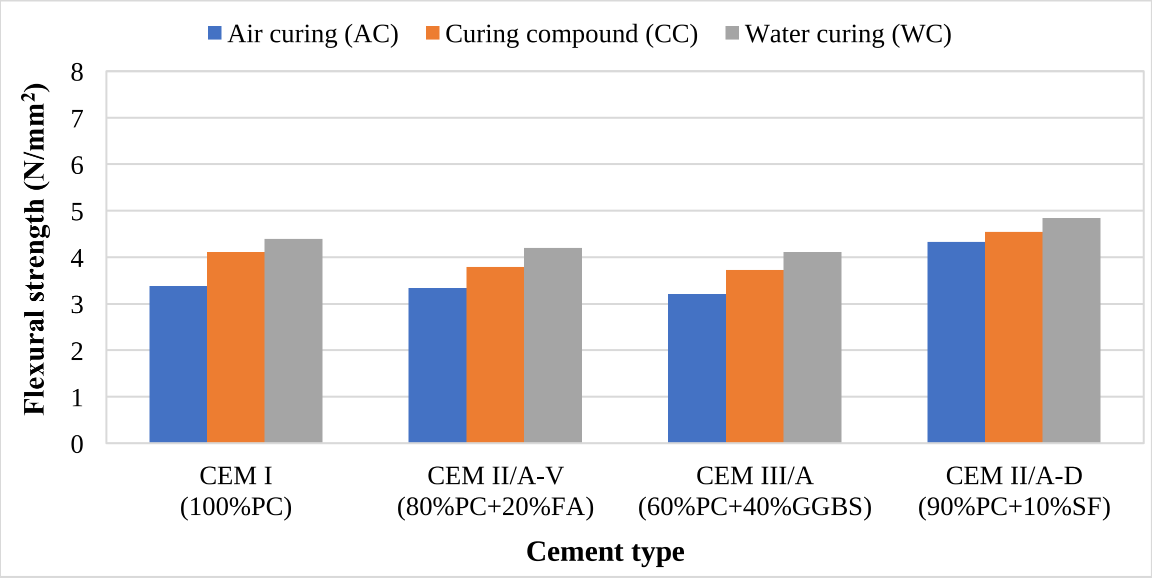


**Figure 4.14** Flexural strength results of all cement types at 7 days age

In terms of CEM II/A-V, CEM III/A mixes, it was noticed that partial replacement of PC with FA and GGBS reduced early age strength up to 28 days due to the pozzolanic and latent hydraulic reactions of FA and GGBS. Therefore, rate of strength development in CEM II/A-V and CEM III/A mixes was slower than that of CEM I mix. However, strength gain continued after 28 days as strength increased by 0.39 and 0.41 MPa in CEM II/A-V specimens cured with CC and in water respectively.

On the other hand, CEM III/A mix exhibited maximum strength development after 28 days as strength increased by 0.75 and 0.89 MPa in samples cured with CC and in WC respectively. Replacement of PC with GGBS in CEM III/A mix delayed the hydration process at early ages up to 28 days. However, at later ages after 28 days, the strength increased and was higher than PC as the latent hydraulic reactions become dominant after 28 days of age. It was noticed that performance of CEM II/A-V and CEM III/A was comparable at early ages up to 28 days age. Furthermore, maximum flexural strength difference between specimens cured using the CC and reference sample cured in water was 0.53 MPa recorded in CEM II/A-V at 90 days age. Whereas minimum difference was 0.29 MPa measured in CEM II/A-D mix at 7 days age. These results are in agreement with previous findings (Gonen and Yazicioglu, 2007; Wesche, 1991; Dyer, 2014; Oner and Akyuz, 2007; Al-Gahtani, 2010; Xue et al., 2015).

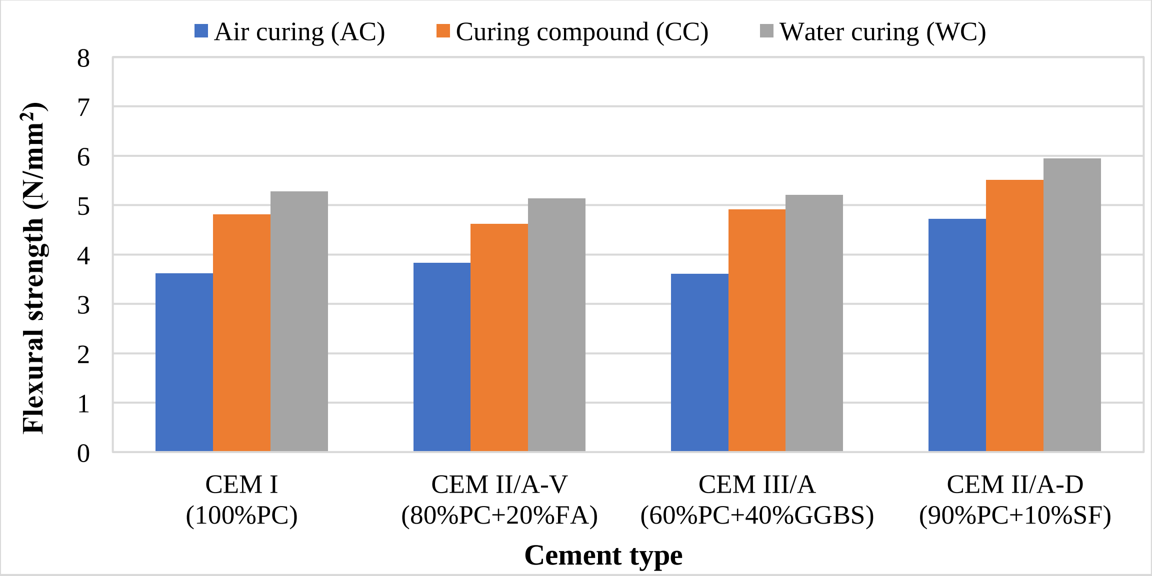


**Figure 4.15** Flexural strength results of all cement types at 28 days age

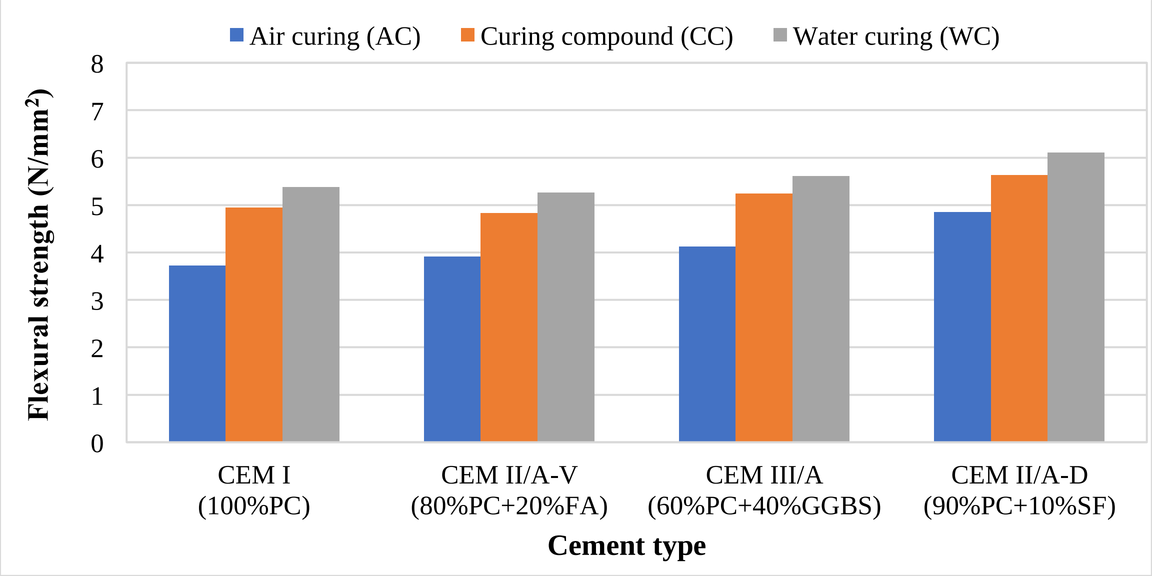


**Figure 4.16** Flexural strength results of all cement types at 56 days age

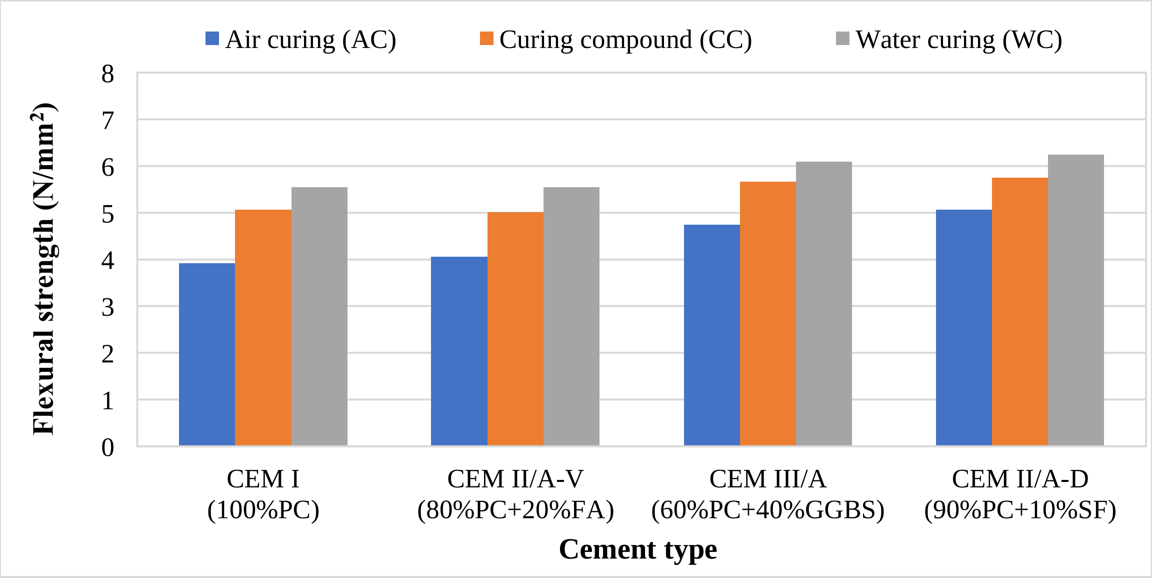


**Figure 4.17** Flexural strength results of all cement types at 90 days age

## 4.5 Drying shrinkage

Drying shrinkage is an important parameter of concrete elements such as slabs, beams, columns and foundations. It occurs as capillary water evaporates from the hardened cement mixture, causing contraction and formation of cracks within concrete. The presence of cracks on the surface of the concrete makes it vulnerable to water and chloride ingress. Therefore, formation of cracks could cause deterioration and negatively affect the long-term durability of concrete.

Drying shrinkage test was conducted according to BS ISO 1920-8 (BSI ISO, 2009) at 7, 14, 21, 28, 56 and 112 days to evaluate the effectiveness of applying the curing compound (CC) on the retardation of moisture loss due to drying. Performance of specimens were compared to two set of control samples; the first set was air cured (AC) in the laboratory environment and the second set was cured in water (WC) for 7 days. For each cement type, three prisms were tested under all curing regimes (AC, CC and WC) at specific ages and the average value was calculated to determine the drying shrinkage.

### 4.5.1 Drying shrinkage of CEM I (100%PC) concrete mix

Drying shrinkage results of CEM I mix under all curing regimes (AC, CC and WC) are presented in Figure 4.18. Results indicate that shrinkage values initially increased up to 28 days age under all curing conditions, and then stabilized consistently. Minimum shrinkage values measured at 7 days were 276, 182 and 160 με for prisms cured in AC, CC and WC respectively. Whereas maximum strain values were 586, 464 and 388 με obtained at 112 days age.

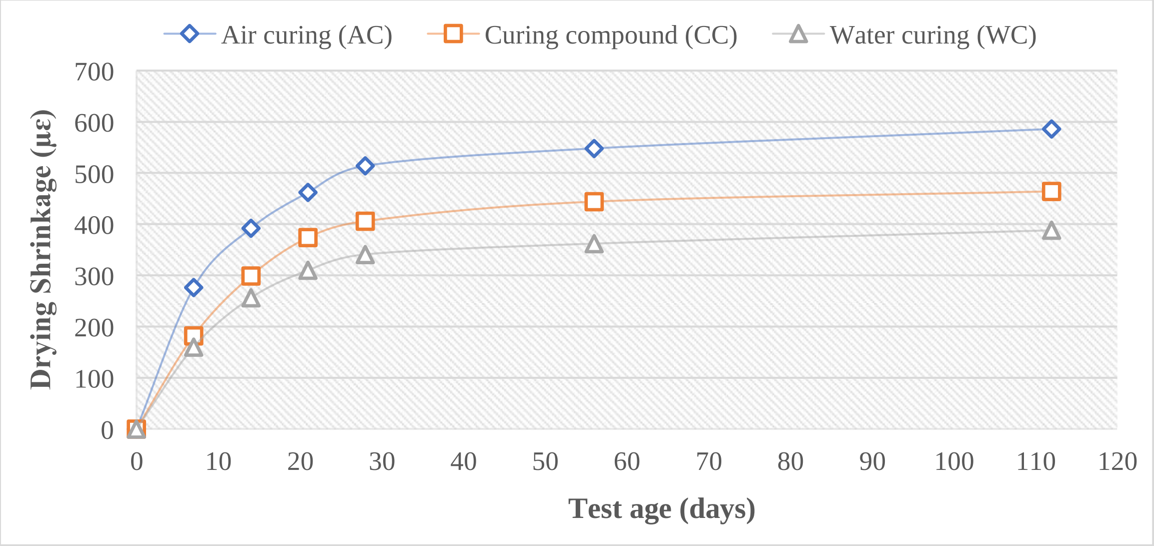


**Figure 4.18** Drying shrinkage values of CEM I concrete

It is apparent that prisms cured with CC performed better than corresponding control ones cured in the air, but not as good as reference prisms cured in water. In terms of shrinkage value difference between prisms cured with CC and control prisms cured in water, maximum value was 82 με measured at 56 days age, and minimum value was 22 με recorded at 7 days age. Furthermore, overall shrinkage value was reduced by approximately 23% in specimens treated with CC compared to reference prisms cured in the air. Results demonstrated that moisture evaporation rate was highest in reference samples cured in the air as there was no compensation for the water evaporating from the prisms. Therefore, highest shrinkage strains were recorded in this curing condition.

In comparison to reference prisms cured in WC, results show that overall shrinkage values of control prisms cured in air and specimens cured with CC increased by 54% and 18% respectively.

Moreover, the overall efficiency of the CC compared to control prisms cured in water was 84%. In addition, it was observed that trend of shrinkage in specimens cured with CC and corresponding controls cured in WC was comparable up to 7 days age.

### 4.5.2 Drying shrinkage of CEM II/A-V (80%PC+20%FA) concrete mix

Figure 4.19 shows results of CEM II/A-V mix under all curing regimes (AC, CC and WC). Similar to CEM I mix, results demonstrate that shrinkage values progressively increased up to 28 days age under all curing conditions, then gradually stabilized. Minimum shrinkage values were 270, 154 and 148 με for prisms cured in AC, CC and WC respectively measured at 7 days. Whereas maximum strain values were 562, 395 and 322 με obtained at 112 days age. It was observed that the overall shrinkage value was decreased by 30% in specimens cured by applying the CC in comparison to reference samples cured in air.

It is clear that minimum shrinkage strains were observed in samples cured in water, followed by prisms cured with CC and finally air cured control samples. In terms of shrinkage value difference between prisms cured with CC and control prisms cured in water, maximum value was 97 με measured at 28 days age, and minimum value was 6 με recorded at 7 days age. In comparison to reference prisms cured in WC, results show that overall shrinkage values of control samples cured in AC and specimens cured with CC increased by 80% and 24% respectively. Moreover, the overall efficiency of the CC compared to control prisms cured in WC was more than 80%. In addition, it was observed that shrinkage trend of specimens cured with CC and corresponding controls cured in WC was almost identical up to 7 days age.

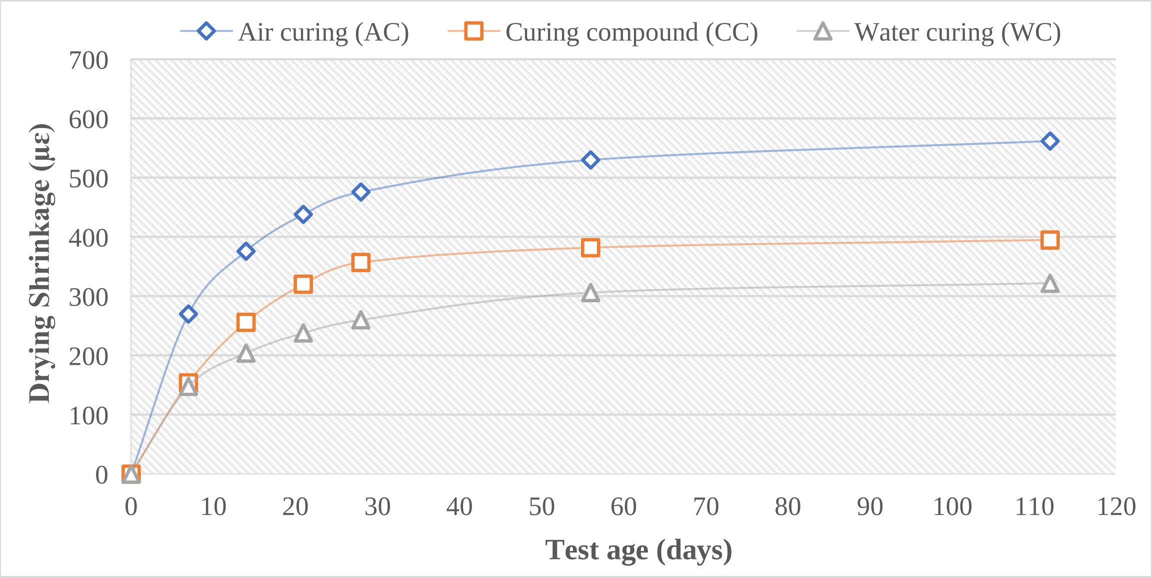


**Figure 4.19** Drying shrinkage values of CEM II/A-V concrete

### 4.5.3 Drying shrinkage of CEM III/A (60%PC+40%GGBS) concrete mix

Values of drying shrinkage test of CEM III/A concrete under all curing conditions are shown in Figure 4.20. Similar to previous mixes, drying shrinkage increased up to 28 days age, then steadily stabilized. Minimum shrinkage values were 230, 138 and 130 με for prisms cured AC, CC and WC respectively measured at 7 days. On the other hand, maximum strain values were 516, 368 and 304 με obtained at 112 days age. Results show that minimum shrinkage values were measured in samples cured in water, followed by prisms cured with CC and finally air cured control samples. Moreover, applying the CC led to 30% reduction in the overall shrinkage values compared to reference samples cured in air.

With respect to shrinkage value difference between CC and WC, minimum value was 8 με measured at 7 days age, and maximum value was 64 με at 112 days age. Comparing to reference prisms cured in WC, results show that overall shrinkage values of control samples cured in AC and curing with CC increased by 75% and 21% respectively. Moreover, the overall efficiency of the CC compared to control prisms cured in WC was more than 82%. Furthermore, similar shrinkage trend was observed in specimens cured with CC and corresponding controls cured in WC up to 7 days age.

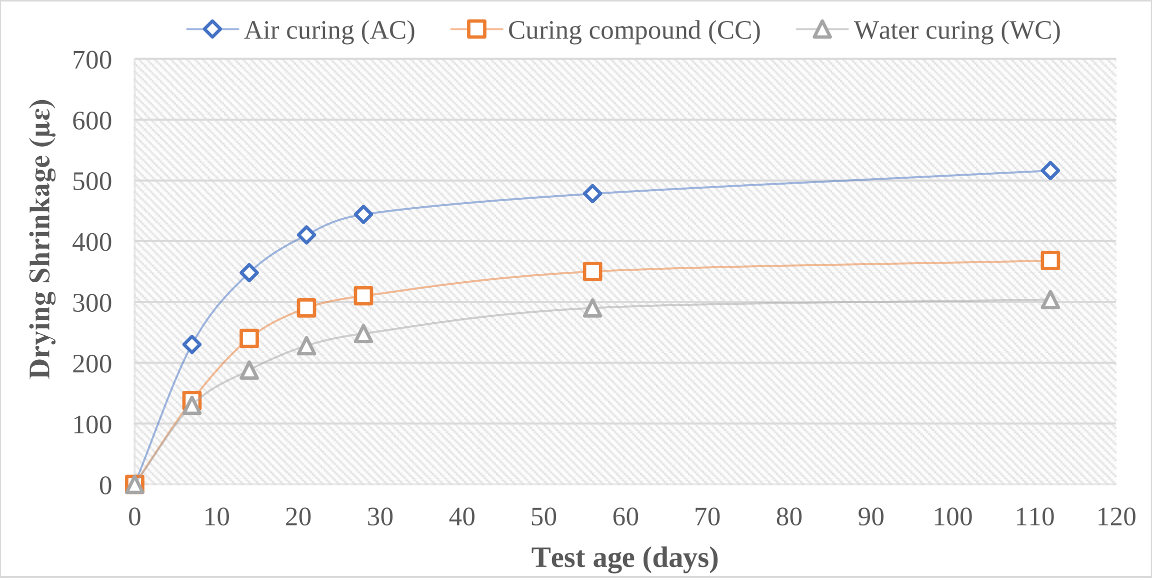


**Figure 4.20** Drying shrinkage values of CEM III/A concrete

### 4.5.4 Drying shrinkage of CEM II/A-D (90%PC+10%SF) concrete mix

Drying shrinkage results of CEM II/A-D mix under all curing regimes (AC, CC and WC) are presented in Figure 4.21. Similar to previous mixes, shrinkage values initially increased up to 28 days age under all curing conditions, and then gradually stabilized. Minimum shrinkage values measured at 7 days were 194, 130 and 118 με for prisms cured in AC, CC and NC respectively. On the other hand, maximum strain values were 358, 274 and 238 με obtained at 112 days age. Results show applying the CC led to approximately 25% reduction in overall shrinkage values compared to reference samples cured in air.

As far as shrinkage difference between CC and WC is concerned, minimum value was 12 με measured at 7 days age, and maximum value was 44 με at 28 days age. Comparing to reference prisms cured in WC, results show that overall shrinkage values of control samples cured in AC and CC increased by 57% and 18% respectively. Moreover, the overall efficiency of the CC compared to control prisms cured in WC was approximately 85%. Additionally, shrinkage trend of specimens cured with CC and corresponding controls cured in WC was comparable up to 7 days age.

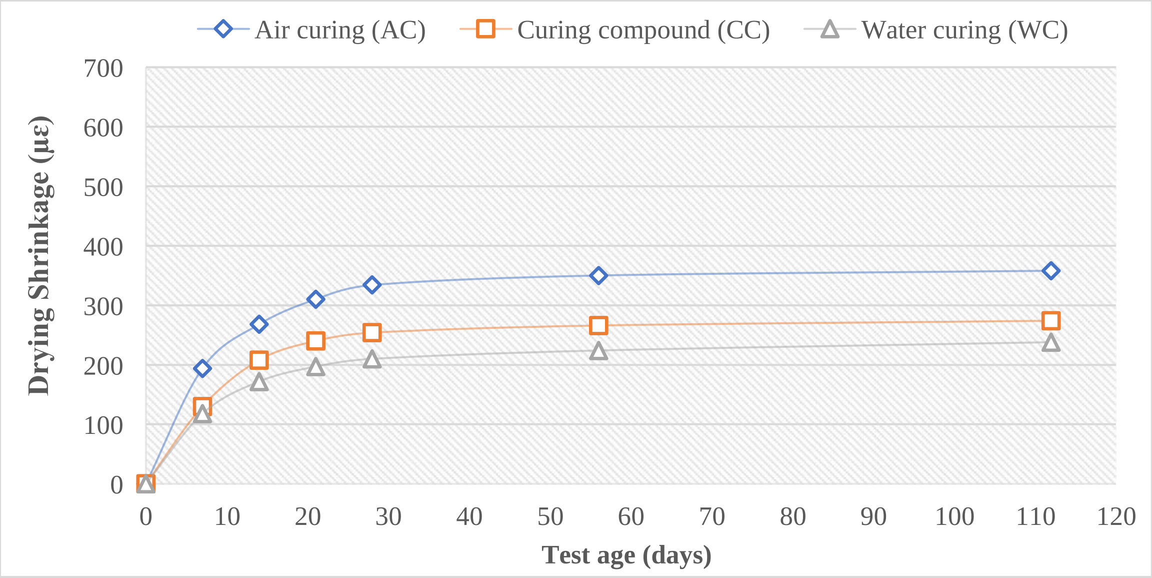


**Figure 4.21** Drying shrinkage values of CEM II/A-D concrete

### 4.5.5 Comparison of CEM II/A-V, CEM III/A and CEM II/A-D with CEM I

Comparisons of drying shrinkage of blended cement mixes (CEM II/A-V, CEM III/A and CEM II/A-D) with respect to reference mix (CEM I) according to curing regimes (AC, CC and WC) are presented in Figure 4.22, 4.23 and 4.24. Results indicate that prisms cured in air exhibited highest shrinkage due to drying. Nevertheless, blended cements particularly CEM II/A-D showed less shrinkage than reference mix (CEM I).

Shrinkage values of CEM I, CEM II/A-V, CEM III/A and CEM II/A-D prisms cured in air were 276, 270, 230 and 194 με respectively at 7 days. These values increased to 586, 562, 516 and 358 με at 112 days. Results demonstrate that shrinkage strain kept increasing consistently over time in all cement types except CEM II/A-D, which showed slower shrinkage development beyond 28 days as shown in Figure 4.22. Partial replacement of PC in CEM I with FA (20%), GGBS (40%) and SF (10%) in CEM II/A-V, CEM III/A and CEM II/A-D resulted in an average reduction in shrinkage by 4.4%, 12.9% and 34.1% respectively.

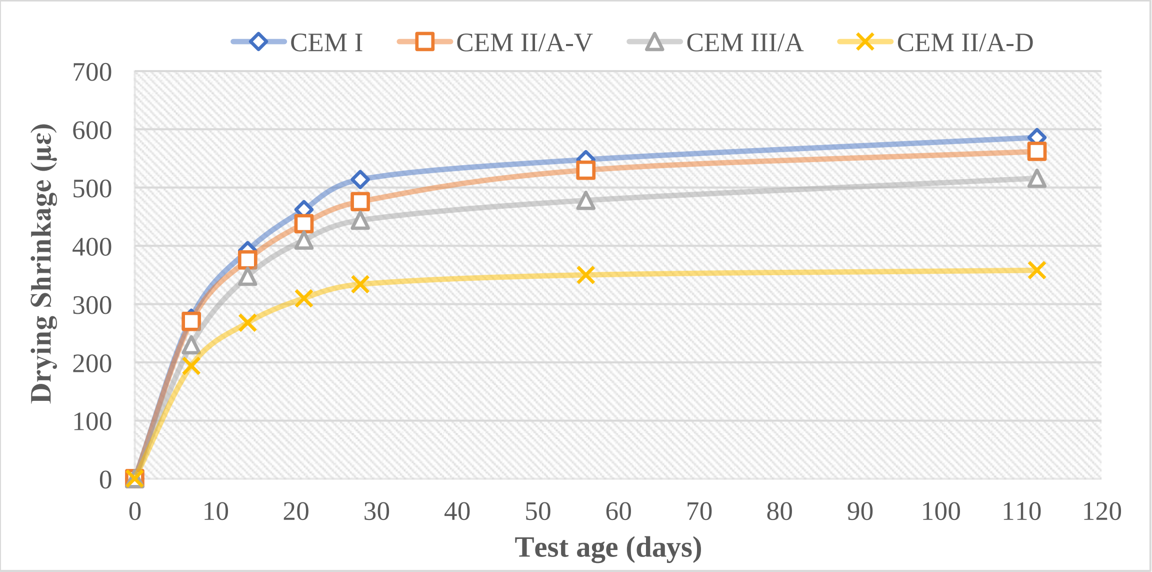


**Figure 4.22** Drying shrinkage results of all cement types cured in air (AC)

In terms of specimens cured with CC, it was observed that applying the CC reduced shrinkage strains in all cement types. Similarly, inclusion of mineral admixtures especially SF contributed positively in reducing shrinkage values as shown in Figure 4.23. Shrinkage values of 182, 154, 138 and 130 με were measured in CEM I, CEM II/A-V, CEM III/A and CEM II/A-D prisms at 7 days. These values increased to 464, 395, 368 and 274 με at 112 days. It was observed that shrinkage development slowed down beyond 28 days in CEM II/A-D concrete. The overall reduction in shrinkage values due to applying CC and inclusion of mineral admixtures reduced by 14.2%, 22% and 35.6% in CEM II/A-V, CEM III/A and CEM II/A-D respectively.

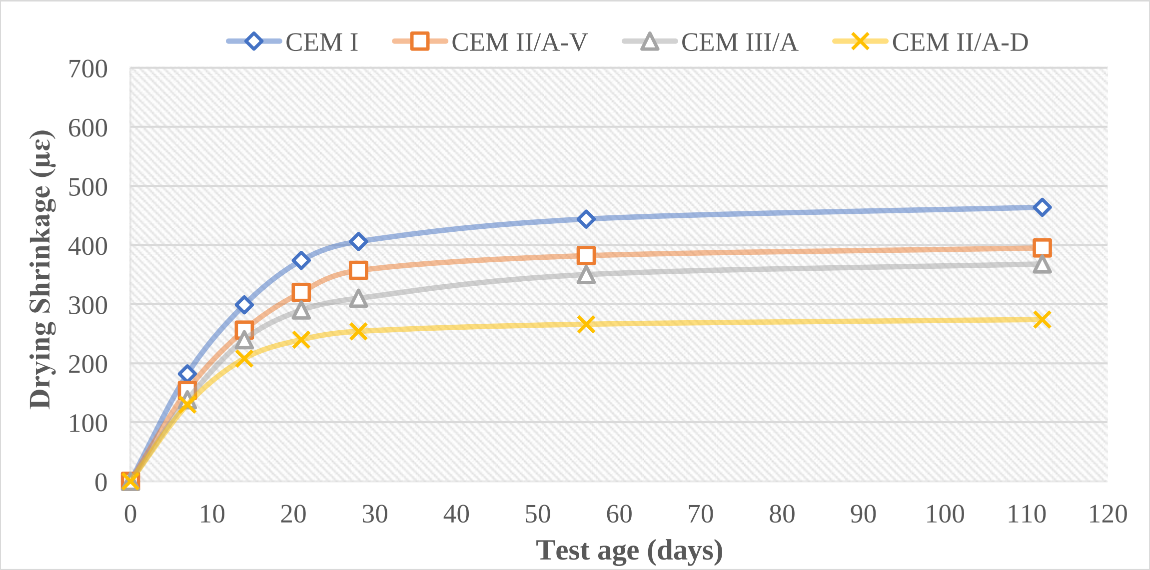


**Figure 4.23** Drying shrinkage results of all cement types cured using the curing compound (CC)

On the other hand, minimum shrinkage strains were observed in prisms of all cement types cured in water. Similar shrinkage trend was observed as minimum shrinkage was reported in CEM II/AD, followed by CEM III/A, CEM II/A-V and CEM I as shown in Figure 4.24. It is evident that the curing condition and incorporation of mineral admixtures significantly reduced shrinkage due to drying. Moreover, results show that performance of samples containing FA and GGBS were comparable.

Shrinkage values of CEM I, CEM II/A-V, CEM III/A and CEM II/A-D prisms were 160, 148, 130 and 118 με respectively at 7 days. These values increased to 388, 322, 304 and 238 με at 112 days. The combined effect of curing and mineral admixtures reduced shrinkage by 17.9%, 23.4% and 35.1% in CEM II/A-V, CEM III/A and CEM II/A-D respectively.

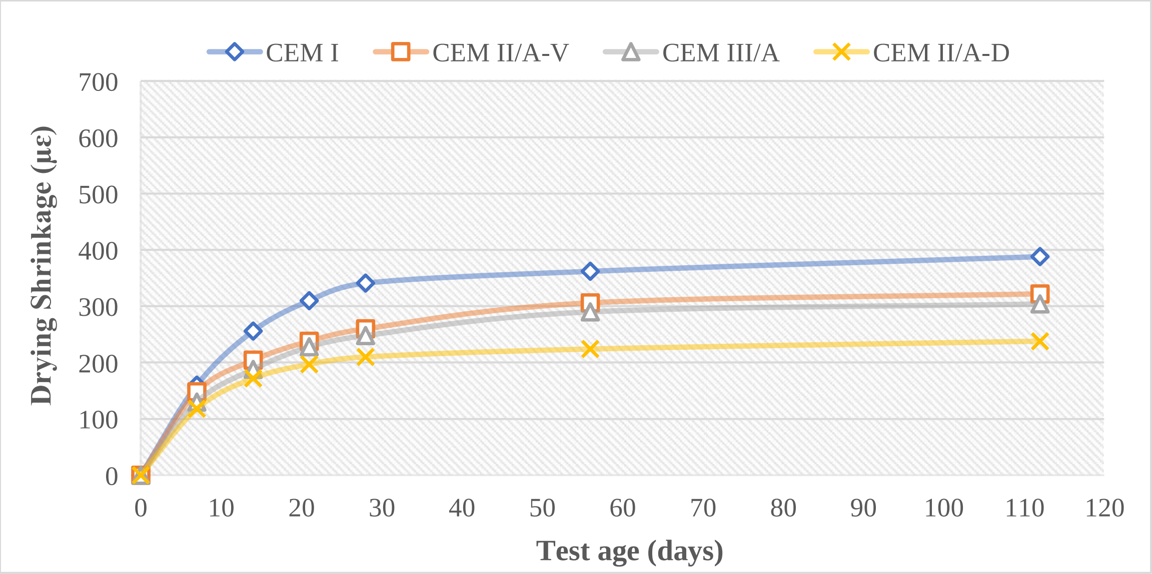


**Figure 4.24** Drying shrinkage results of all cement types cured in water (WC)

Results show that addition of mineral admixtures reduced shrinkage strains in all curing conditions. It is well known that incorporation of FA and GGBS slows down the hydration process in concrete. In other words, longer period required for reaction between calcium hydroxide and mineral admixtures which leads to a reduction in internal water loss as it is mainly consumed during the delayed hydration process. Moreover, blended cement improves pore refinement of concrete, thus increases densification of concrete (Kou et al., 2008)(Güneyisi et al., 2010). As a result, blended cement with FA and GGBS tend to decrease permeability, hence it becomes more difficult for internal moisture to evaporate. Furthermore, blended cements containing FA and GGBS requires less water in the w/c ratio which is a primary factor for causing drying shrinkage. Zhang and Canmet (1995) reported that another mechanism for shrinkage reduction is the unhydrated FA particles which serve as fine aggregates to restrain the shrinkage deformation.

Results also show that shrinkage of CEM II/A-V and CEM III/A cements cured in WC were comparable. However, overall reduction in shrinkage was higher in CEM III/A than CEM II/A-V cement due to higher replacement of PC with the mineral admixture. In other words, shrinkage decreased as the replacement of PC with the mineral admixture increased.

The overall shrinkage trend of blended cements was consistent with previous investigations (Zhou et al., 2012; Chindaprasirt et al., 2004; Nath and Sarker, 2011; Yang et al., 2017; Li and Yao, 2001).

Results also demonstrated that partial replacement of PC with SF significantly reduced shrinkage strains in all curing conditions. It was observed that rate of shrinkage development decreased post 28 days. The reduction in shrinkage strains could be attributed to the pozzolanic reaction of SF with calcium hydroxide during the hydration process leading to formation of extra C-S-H. Also, inclusion of SF increases the density of concrete due to pore size refinement, thus reduces internal moisture evaporation. Moreover, Jianyong and Yan (2001) stated that inclusion of ultrafine SF can increase the amount of AFt crystal hydrates and C-S-H gel hydrates in cement paste, which offers hardened concrete a stronger structure and higher resistance to deformation caused by applied force. Results obtained were in agreements with previous findings (Mazloom et al., 2004; Alsayed, 1998; Afroughsabet and Teng, 2020). However, contradictory findings reported in previous studies (Al-Amoudi et al., 2007; Rao, 2001) stating that inclusion of SF increases shrinkage due to pozzolanic reaction and pore size refinement mechanism. Nevertheless, results obtained showed that addition of SF has positive effect in reducing drying shrinkage in all curing conditions. Moreover, drying shrinkage of concrete containing SF was less than those containing GGBS and FA.

## 4.6 Concluding remarks

- Compressive strength of control mix CEM I and blended cements CEM II/A-V, CEM III/A and CEM II/A-D cured in water reached the design strength at 28 days. However, cubes of control mix and blended cements except CEM II/A-D cured using the CC did not reach the design strength at 28 days. Nonetheless, the difference was marginal as CEM I, CEM II/AV and CEM III/A achieved 97.93%, 93.25%, and 93% of the target strength.

- At later age 56 days, compressive strength of CEM I, CEM II/A-V and CEM III/A cubes cured using the CC increased and achieved 99%, 96% and 98% of design strength respectively. It was observed that strength development continued up to 90 days as strength of all cements reached target strength.

- The inclusion of FA and GGBS in CEM II/A-V and CEM III/A cements reduced early ages strength development up to 28 days in all curing conditions. It was observed that strength development due to pozzolanic reactions was more evident beyond 28 days particularly CEM III/A as specimens cured in water developed higher strength than control samples in same curing condition at 90 days. This means that higher replacement of PC with GGBS increased the strength at later ages post 28 days.

- The inclusion of SF in CEM II/A-D significantly improved strength development up to 28 days under all curing conditions. Results show that strength increased by approximately 26% in both curing conditions (CC and WC) at 28 days compared to control mix CEM I. However, strength development diminished beyond 28 days as strength gain was insignificant. This means that effect of the pozzolanic reaction mainly occurs within 28 days after casting. All samples surpassed design strength at 28 days except cubes cured in air which did not achieve required strength.

- Similar trend was observed in flexural strength, results show that CEM I and CEM II/A-D specimens exhibited strength development mainly at early ages as strength gain was insignificant after 28 days. Highest flexural strength was measured in CEM II/A-D which demonstrate that addition of SF increases strength development in all curing conditions.

- Inclusion of FA and GGBS in CEM II/A-V, CEM III/A mixes respectively, reduced early age strength development up to 28 days. However, strength of CEM II/A-V was comparable to CEM I in all curing conditions at later ages (56 and 90 days). On the other hand, CEM III/A specimens developed higher strength than control mix at later ages (56 and 90 days) in all curing conditions.

- Samples cured in WC developed higher flexural strength than those cured with CC and in AC. Nevertheless, prisms of the control and blended cements cured with CC achieved more than 90% strength of corresponding ones cured in WC.

- Mixes containing SF and GGBS developed higher strength than those containing FA and control mix (CEM I). Furthermore, performance of CEM II/A-V and CEM III/A was comparable at early ages up to 28 days.

- Generally, incorporation of mineral admixtures reduced shrinkage strains under all curing conditions compared to reference cement CEM I. Minimum shrinkage was observed in CEM II/A-D cement followed by CEM III/A and CEM II/A-V. This demonstrate that inclusion of mineral admixtures was effective in reducing shrinkage.

- Shrinkage strains kept increasing consistently over time in all cement types except CEM II/A-D, which showed slower shrinkage development beyond 28 days. This demonstrate that effect of pozzolanic reaction continued beyond 28 days.

- Drying shrinkage of CEM II/A-V and CEM III/A cements cured in WC were comparable. However, CEM III/A cement exhibited less shrinkage than CEM II/A-V cement as replacement of PC with mineral admixture in CEM III/A was 40%. In other words, shrinkage decreased as the replacement of PC with the mineral admixture increased.

- Specimens cured in WC exhibited less shrinkage than prisms cured with CC and AC. Nevertheless, applying CC improved performance as shrinkage of specimens cured in AC were reduced from 586, 562, 516 and 358 με to 464, 395, 368 and 274 με in CEM I, CEM II/A-V, CEM III/A and CEM II/A-D respectively at 112 days. Whereas shrinkage values of CEM I, CEM II/A-V, CEM III/A and CEM II/A-D cured in WC were 388, 322, 304 and 238 με respectively at 112 days. Results suggest that applying CC did not cause a substantial increase in shrinkage strain particularly in blended cements.

# Chapter 5: Transport Properties

## 5.1 Introduction

Transport properties of concrete is one of the important parameters of concrete, it has significant impact on durability and service life of concrete. Permeation parameters of concrete such as capillary absorption and permeability, are significantly influenced by transport mechanisms, subsequently permeable concrete exhibits severe deterioration such as corrosion of reinforced steel bars when concrete exposed to aggressive environment. In phase 2, concrete specimens were comprehensively investigated by conducting Initial Surface Absorption Test (ISAT), sorptivity and depth of water penetration under pressure as shown in Figure 5.1.

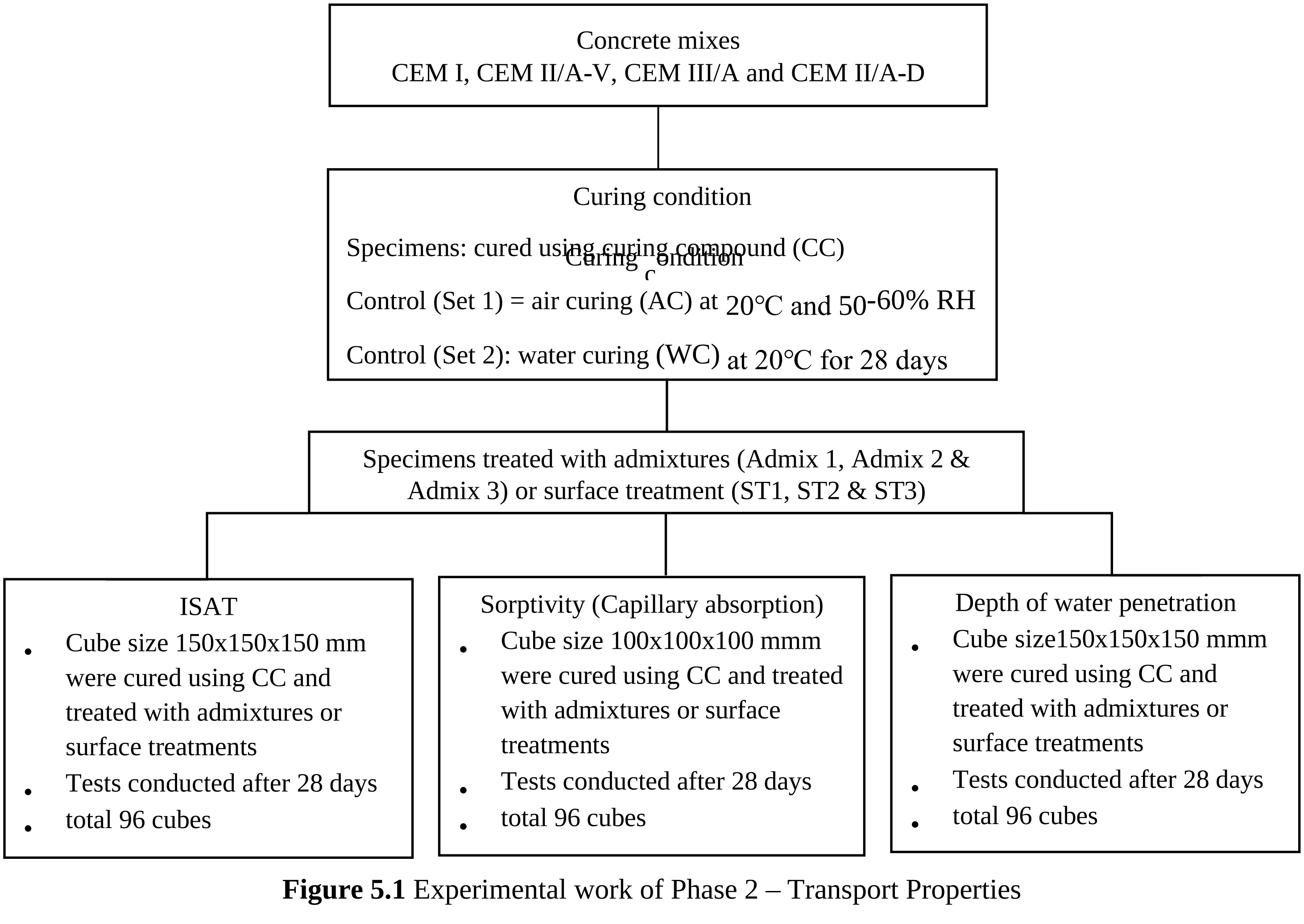


**Figure 5.1** Experimental work of Phase 2 – Transport Properties

In Phase 2, water absorption via capillary action was examined during short term exposure to water by conducting ISAT to determine absorption rate after 10, 30 and 60 minutes of exposure to water, whereas long term water intake was determined through sorptivity to determine water absorption rate up to 7 days after contact with water.

On the other hand, water ingress due to applied pressure (5 bar) for 72 hours was determined by measuring depth of water penetration. It should be stressed that for each case in phase 2, three cubes were tested and averaged to determine the mean value. Specimens were cured using the curing compound (CC) and treated either with admixture or ST to improve impermeability. Performance of treated specimens was compared to two set of control cubes cured in air (AC) and in water (WC). Plain and blended cement mixes were prepared with equal design strength to evaluate influence of admixtures and surface treatment along with mineral admixtures on permeation properties of the mixes.

## 5.2 Experimental programme

## 5.3 Initial surface absorption test (ISAT)

### 5.3.1 ISAT of CEM I (100%PC) concrete mix

In order to determine ISAT values, concrete cubes were cast in accordance with BS 1881-208 (BSI 1881-208, 1996) as shown in Figure 5.2. To improve impermeability, specimens were treated either with waterproofing admixture added directly to the mix during batching, or treated with surface treatment agents applied on the surface after 28 days. Performance of specimens was compared to reference cubes cured in AC and WC as illustrated in Table 5.1. ISAT values were calculated by determining the average value of three specimens for each case.

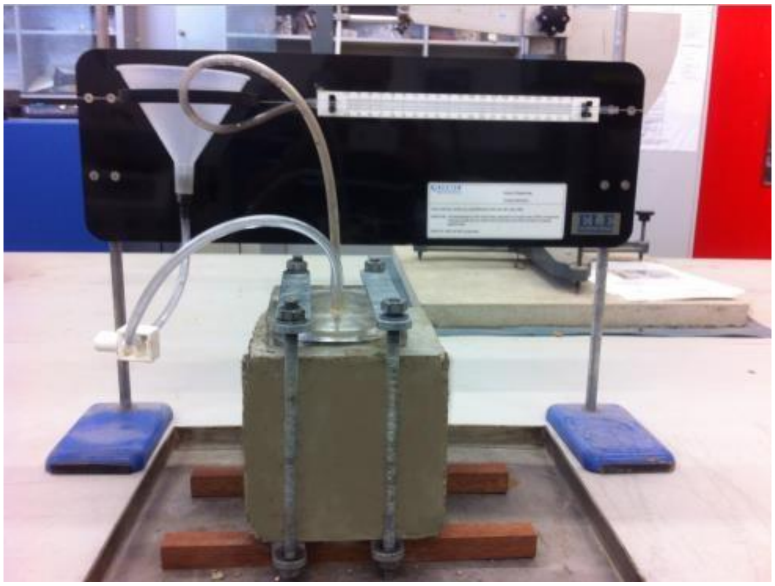


**Figure 5.2** ISAT apparatus test

**Table 5.1** Concrete cubes used for ISAT

| Cement type | Control cubes (AC) | Control cubes (WC) | Specimen CC + Admixtures | | | Specimen CC +Surface Treatments | | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | | | **Admix1** | **Admix2** | **Admix3** | **ST 1** | **ST 2** | **ST 3** | |
| CEM I | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 24 |
| CEM II/A-V | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 24 |
| CEM III/A | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 24 |
| CEM II/A-D | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 24 |
| Grand total | 96 | | | | | | | | |

AC = air curing, WC = water curing, CC = curing compound, Admix1 = admixture 1, Admix2 = admixture 2, Admix3 = admixture 3, ST1 = surface treatment 1, ST2 = surface treatment 2, ST3 = surface treatment 3

ISAT results of CEM I specimens along with reference cubes are presented in Table 5.2 and Figure 5.3. Results show that ISAT values deceased over time as highest absorption rate was recorded at 10 min and lowest rate was measured at 60 min. This is due to the fact that absorption decreases as concrete becomes saturated. Thus, less water will be absorbed by concrete surface as test progresses over time.

**Table 5.2** ISAT results of CEM I concrete

| Time (min) | ISAT (ml/m²/sec) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | AC | WC | CC+ Admix1 | CC+ Admix2 | CC+ Admix3 | CC+ ST1 | CC+ ST2 | CC+ ST3 |
| 10 | 0.68 | 0.34 | 0.32 | 0.21 | 0.19 | 0.26 | 0.16 | 0.18 |
| 30 | 0.53 | 0.24 | 0.22 | 0.16 | 0.15 | 0.2 | 0.12 | 0.13 |
| 60 | 0.41 | 0.16 | 0.16 | 0.12 | 0.11 | 0.13 | 0.08 | 0.09 |

Moreover, it was observed that highest absorption rate measured in control cubes cured in AC, followed by reference samples cured in WC. In contrast, specimens cured with CC and treated with admixtures and surface treatments experienced less water absorption compared to control samples. In terms of surface treatments agents, results show that ST2 was more effective in reducing water absorption than ST3 and ST1, as reduction were 51%, 46% and 20% in cubes treated with ST2, ST3 and ST1 respectively compared to reference cubes in WC.

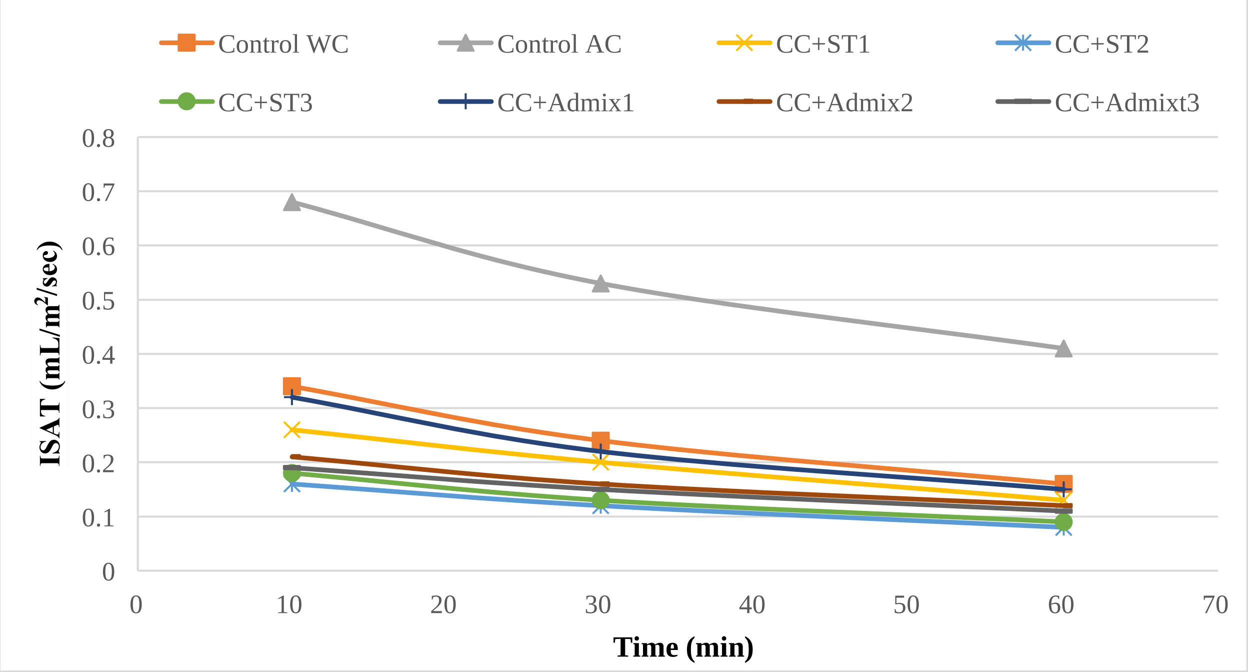


**Figure 5.3** ISAT results of CEM I concrete

On the other hand, treatment with Admix3, Admix2 and Admix1 decreased absorption by 38%, 32% and 7% respectively. This shows that treatments with treatment agents governed by hydrophobic action was more effective than crystallization. Additionally, results indicate a relation between ISAT-10 values measured at 10 min and compressive strength at 28 days. It was observed that absorption rate decreased as compressive strength increased in CEM I samples as shown in Figure 5.4. ISAT values at 10 min were selected and plotted against compressive strength as the majority of water absorption occurred during this period. This relationship between compressive strength and permeability has also been reported by previous researches (Wongpa et al., 2010; Liu et al., 2018). They stated the higher the compressive strength, the lower the permeability of concrete as shown in Figure 5.5 and 5.6 respectively.

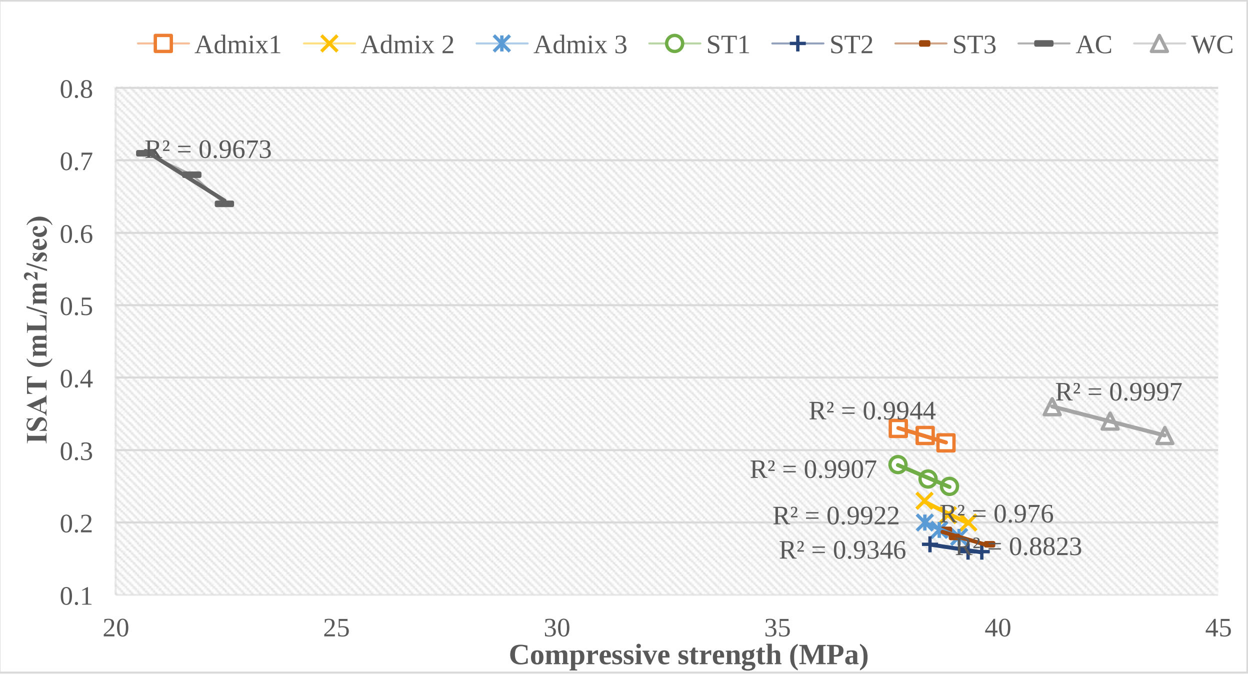


**Figure 5.4** Relationship between ISAT-10 values and compressive strength of CEM I cubes at 28 days

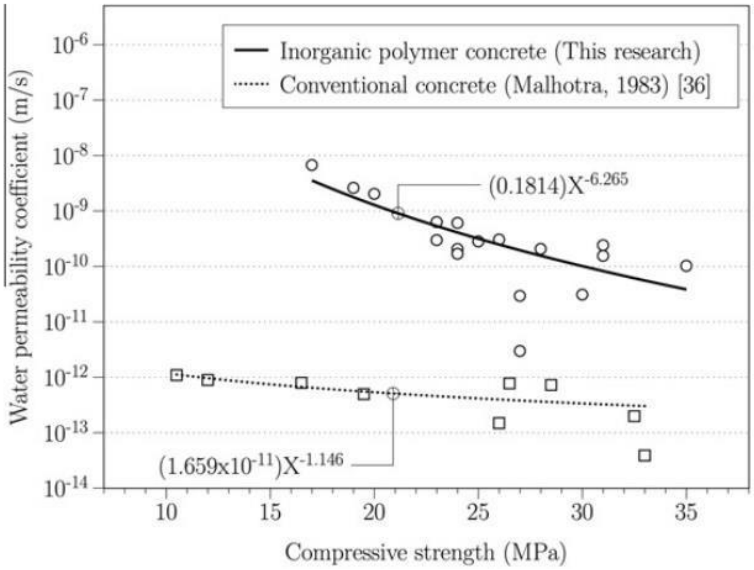


**Figure 5.5** Relationship between water permeability coefficient and compressive strength (Wongpa et al., 2010)

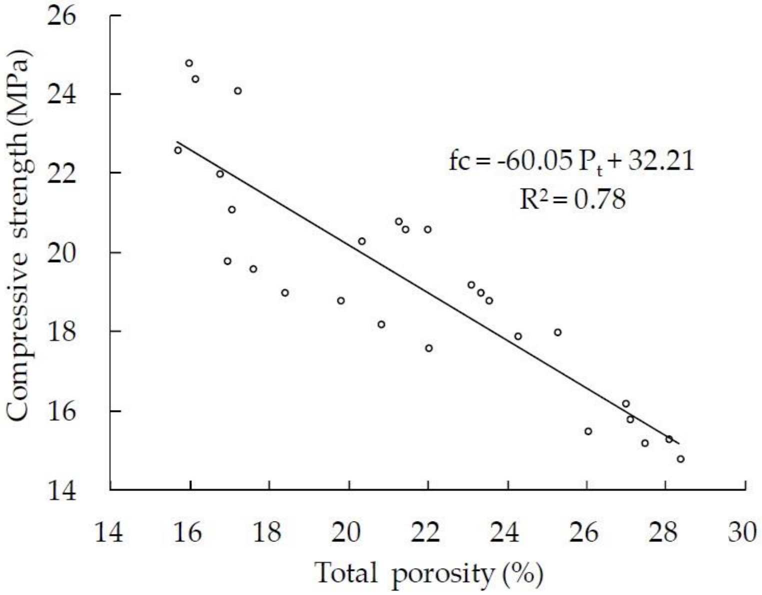


**Figure 5.6** Relationship between compressive strength and total porosity (Liu et al., 2018)

### 5.3.2 ISAT of CEM II/A-V (80%PC+20%FA) concrete mix

ISAT results of CEM II/A-V cubes along with control samples are shown in Table 5.3 and Figure 5.7. Similar trend was observed in treated and untreated cubes as absorption rate decreased over time due to saturation of concrete surface. Highest absorption was measured in control samples cured in AC, followed by reference samples cured in WC. It was observed that specimens cured with CC and treated with ST agents experienced less water absorption. Reduction in water absorption due to treatment with ST2, ST3 and ST1 agents were 54%, 48% and 26% respectively compared to corresponding control cubes cured in WC. On the other hand, treatment with Admix3, Admix2 and Admix1 reduced absorption by 41%, 35% and 7% respectively.

**Table 5.3** ISAT results of CEM II/A-V concrete

| **Time (min)** | **ISAT (ml/m$^2$/sec)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **AC** | **WC** | **CC+ Admix1** | **CC+ Admix2** | **CC+ Admixt3** | **CC+ ST1** | **CC+ ST2** | **CC+ ST3** |
| 10 | 0.67 | 0.32 | 0.28 | 0.18 | 0.16 | 0.2 | 0.12 | 0.14 |
| 30 | 0.51 | 0.22 | 0.18 | 0.13 | 0.12 | 0.14 | 0.08 | 0.1 |
| 60 | 0.38 | 0.14 | 0.13 | 0.09 | 0.08 | 0.1 | 0.05 | 0.07 |

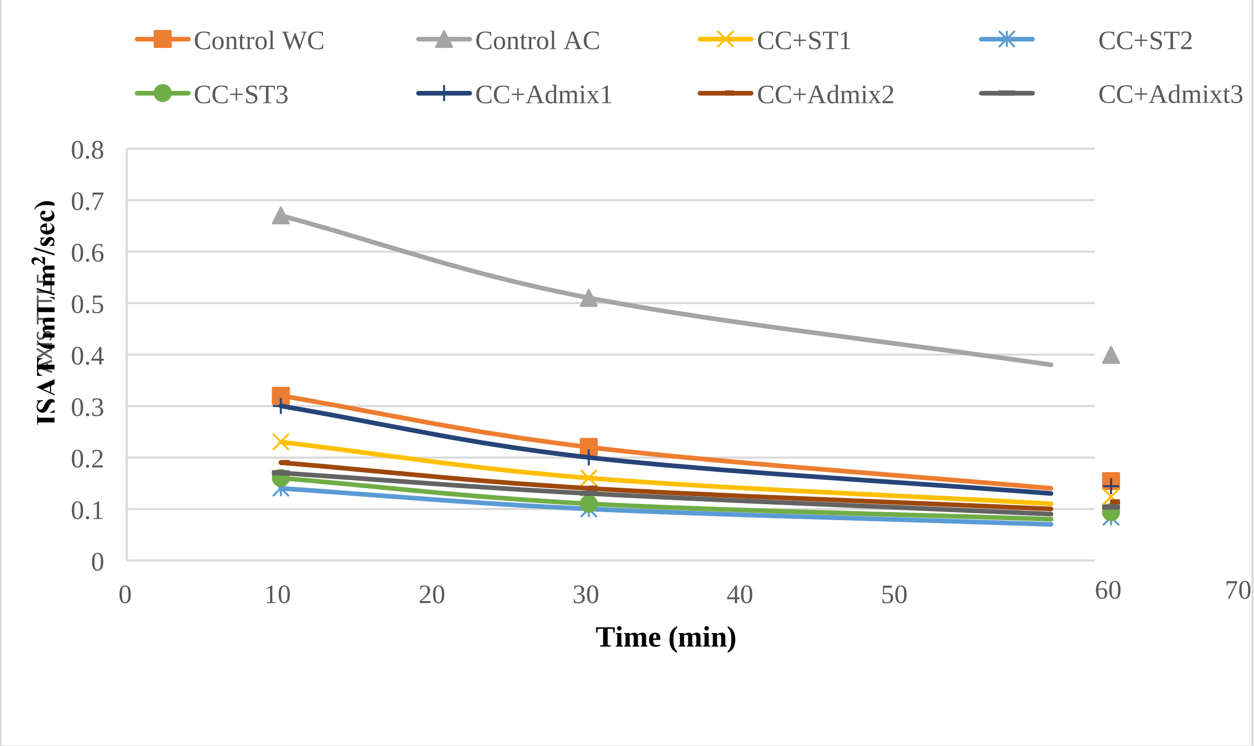


**Figure 5.7** ISAT results of CEM II/A-V concrete

Similar trend was observed in relationship between ISAT-10 values and compressive strength at 28 days as shown in Figure 5.8. It can be seen that absorption rate decreased as compressive strength increased. It should be stressed that although CEM II/A-V treated cubes did not develop higher compressive strength than CEM I samples, they experienced lower absorption rate due to the effect of FA particles which tend to improve pore structure of concrete.

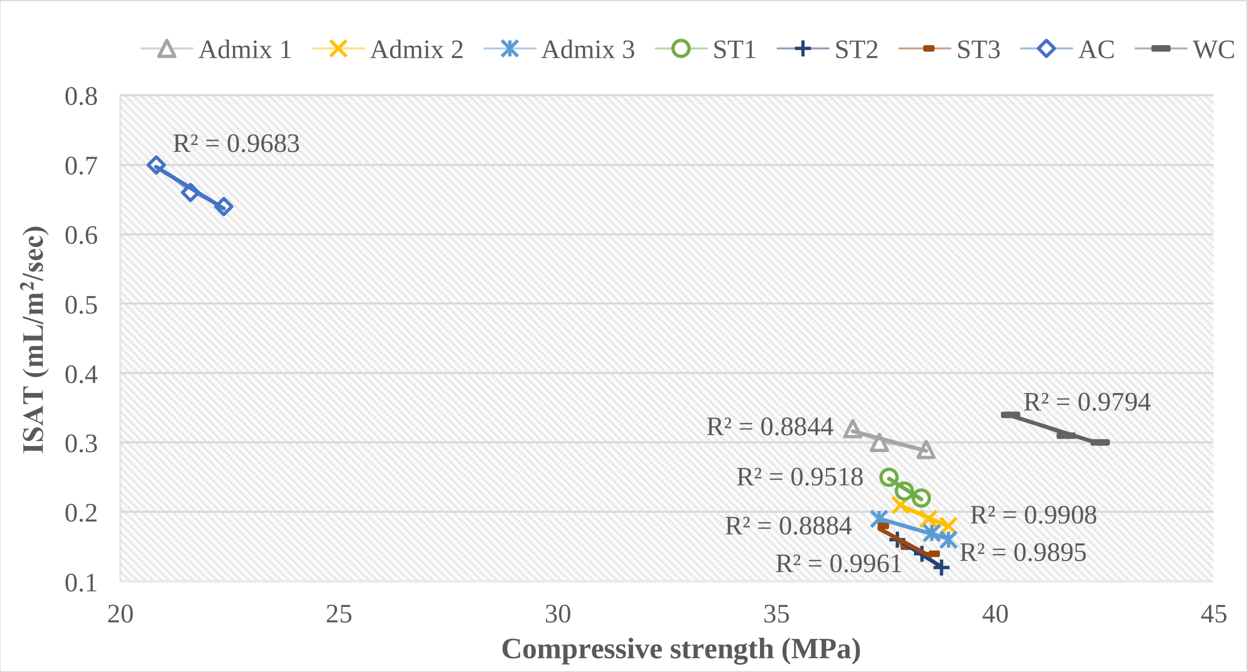


**Figure 5.8** Relationship between ISAT-10 values and compressive strength of CEM II/A-V cubes at 28 days

### 5.3.3 ISAT of CEM III/A (60%PC+40%GGBS) concrete mix

ISAT results of CEM III/A cubes with control samples under both curing conditions are presented in table 5.4 and Figure 5.9. Similar trend was observed in control and treated specimens as ISAT values decreased over time. Reduction in water absorption due to combined effect of treatment and blended cement were 23%, 60% and 50% in ST1, ST2 and ST3 respectively compared to control samples cured in WC. On the other hand, inclusion of Admix1, Admix2 and Admix 3 in the mixes reduced absorption by 6%, 35% and 44% respectively.

**Table 5.4** ISAT results of CEM III/A concrete

| Time (min) | ISAT (ml/$m^2$/sec) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | AC | WC | CC+ Admix1 | CC+ Admix2 | CC+ Admixt3 | CC+ ST1 | CC+ ST2 | CC+ ST3 |
| 10 | 0.59 | 0.28 | 0.27 | 0.17 | 0.14 | 0.2 | 0.1 | 0.13 |
| 30 | 0.45 | 0.18 | 0.17 | 0.11 | 0.1 | 0.14 | 0.07 | 0.09 |
| 60 | 0.34 | 0.11 | 0.10 | 0.08 | 0.07 | 0.09 | 0.05 | 0.06 |

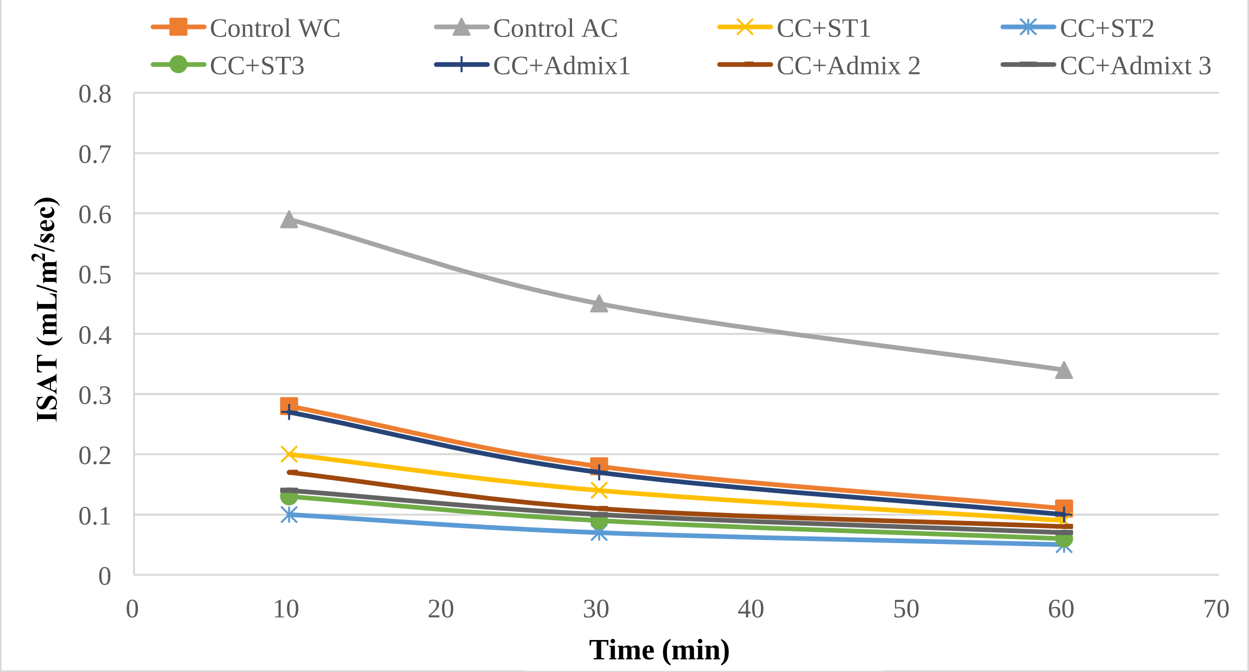


**Figure 5.9** ISAT results of CEM III/A concrete

In terms of relationship between ISAT-10 and compressive strength at 28 days, similar trend was observed as ISAT-10 values decreased when compressive strength increased as shown in Figure 5.10. Moreover, the influence of replacing PC with GGBS on absorption was more evident in CEM III/A as control cubes under both conditions experienced less water absorption compared to previous cement types. This reduction could be attributed to the higher binder content which improves refinement of pore structure of concrete and to the low w/c.

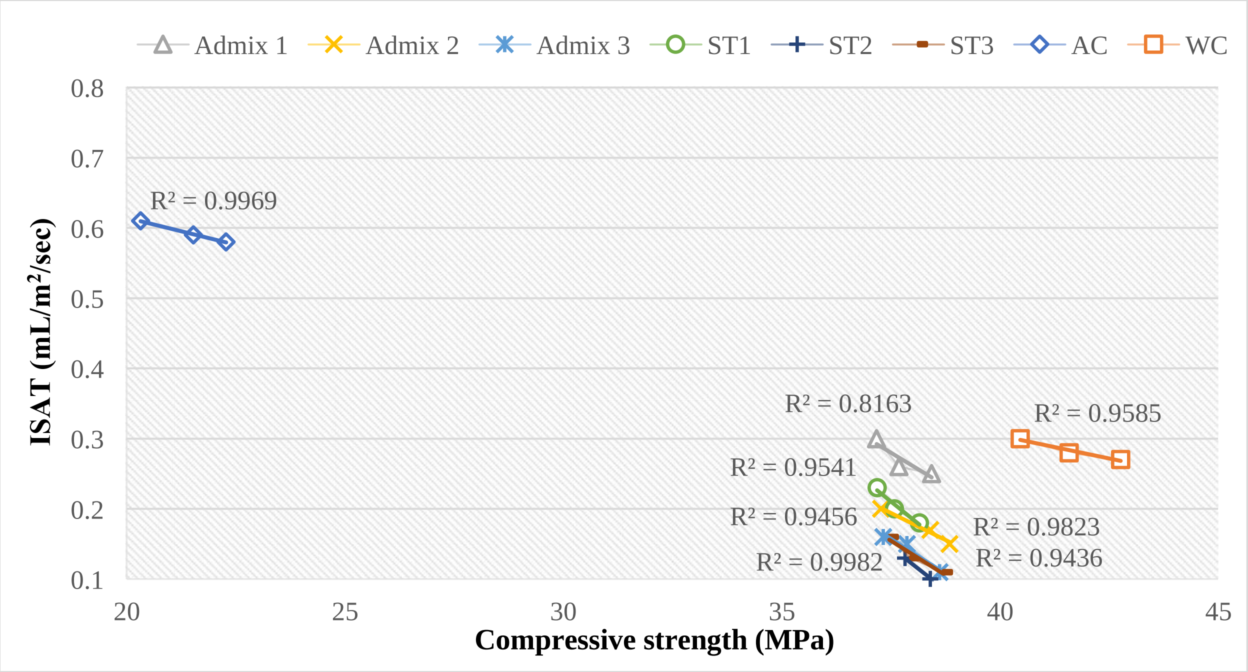


**Figure 5.10** Relationship between ISAT-10 values and compressive strength of CEM III/A cubes at 28 days

### 5.3.4 ISAT of CEM II/A-D (90%PC+10%SF) concrete mix

ISAT results of CEM II/A-D specimens with reference samples in both curing regimes are presented in table 5.5 and Figure 5.11. Similar to previous cement types, a comparable trend was observed in untreated and treated specimens as ISAT values decreased over time. Reduction in water absorption due to the combined effect of treatment and binder addition were 25%, 66% and 55% in ST1, ST2 and ST3 respectively compared to control samples cured in WC. On the other hand, inclusion of Admix1, Admix2 and Admix 3 in the mixes reduced absorption by 4%, 39% and 48% respectively.

**Table 5.5** ISAT results of CEM II/A-D concrete

| Time (min) | ISAT ($ml/m^2/sec$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | AC | WC | CC+ Admix1 | CC+ Admix2 | CC+ Admixt3 | CC+ ST1 | CC+ ST2 | CC+ ST3 |
| 10 | 0.55 | 0.2 | 0.19 | 0.12 | 0.1 | 0.15 | 0.07 | 0.09 |
| 30 | 0.41 | 0.14 | 0.13 | 0.09 | 0.08 | 0.11 | 0.05 | 0.07 |
| 60 | 0.32 | 0.1 | 0.1 | 0.06 | 0.05 | 0.07 | 0.03 | 0.04 |

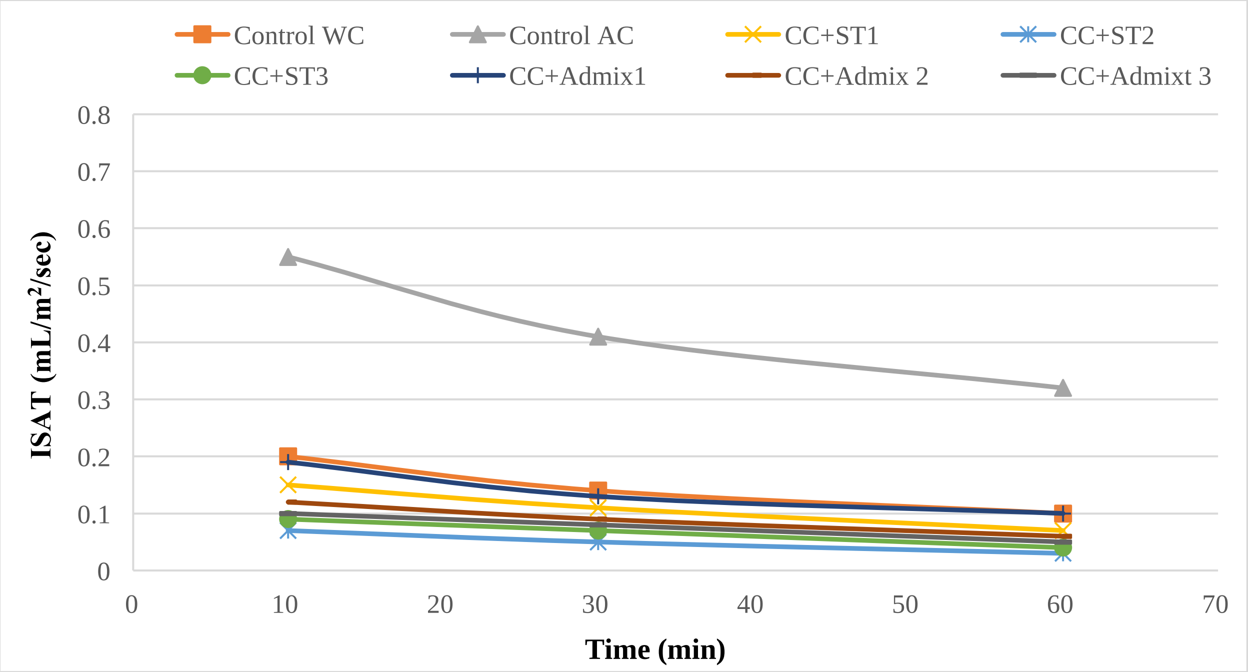


**Figure 5.11** ISAT results of CEM II/A-D concrete

With respect to relationship between ISAT-10 values and compressive strength at 28 days, similar trend was observed as ISAT-10 values decreased when compressive strength increased as shown in Figure 5.12. Furthermore, results demonstrated that replacement of PC with SF significantly reduced water absorption rate as untreated reference cubes in both curing regimes experienced the least water absorption in comparison to previous concrete mixes. This reduction is due to the very fine particles of SF which substantially improves pore structure of concrete, thus forming an impermeable dense matrix.

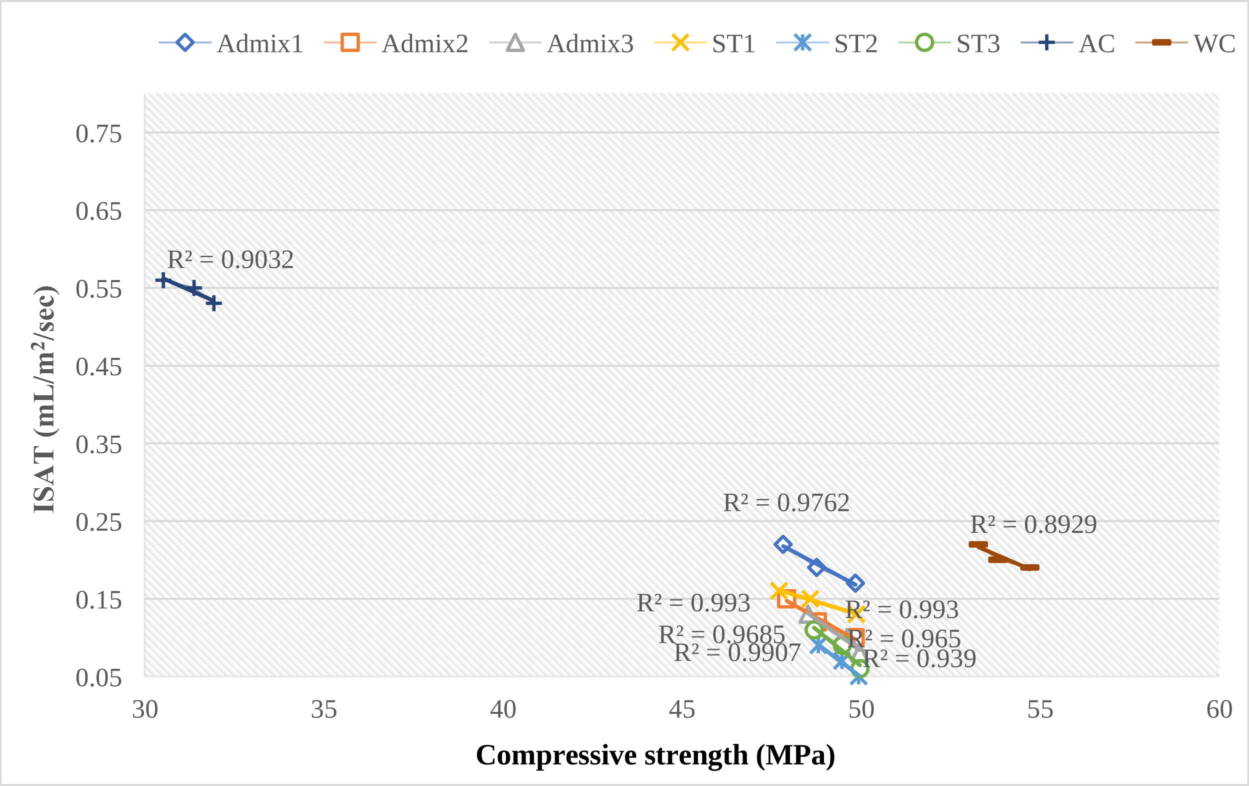


**Figure 5.12** Relationship between ISAT-10 values and compressive strength of CEM II/A-D cubes at 28 days

### 5.3.5 Comparison of CEM II/A-V, CEM III/A and CEM II/A-D with CEM I

ISAT results of all cement control cubes cured in AC and WC are shown in Figure 5.13. It can be seen that inclusion of GGBS and SF significantly improved refinement of concrete, thus reduced capillary water abortion in comparison to control mixes. Impermeability improvement could be due to the larger binder content involved in the latent hydraulic reaction and to the reduced w/c in CEM III/A concrete. Whereas reduction in capillary water absorption in CEM II/A-D concrete could be attributed to reduction in porosity due to the effect of the extreme particle size of SF which increases density and improves pore structure as a result of the pozzolanic reactions of SF with calcium hydroxide which leads to additional formation of C-S-H. Results are consistent with findings of previous investigations (Razak et al., 2004; Liu et al., 2018; Megat Johari *et al.*, 2011)

Moreover, it was observed that replacement of PC with FA also reduced water uptake but to less extent than GGBS and SF. This could be due to the lower binder content in comparison to the higher binder content of GGBS, or could be attributed to presence of FA in the mix which tend to require longer time to have beneficial effects as reported by Hassan et al. (2000) and Naik et al. (1994). Nevertheless, the incorporation of FA improved impermeability in both curing conditions compared to control CEM I mix. This may be due to the effect of the pozzolanic reaction which reduces porosity of concrete as stated in previous studies (Nath and Sarker, 2011; Kou et al., 2007; Saha, 2018; Tasdemir, 2003). Generally, results demonstrated that untreated control cubes cured in WC experienced less water absorption than cubes cured in AC in all cement types. Moreover, best performance was observed in CEM II/A-D cement, followed by CEM III/A and CEM II/AV. Furthermore, results showed that ISAT values decreased when compressive strength increased regardless of the cement type, curing regime and type of protective material used for treatment.

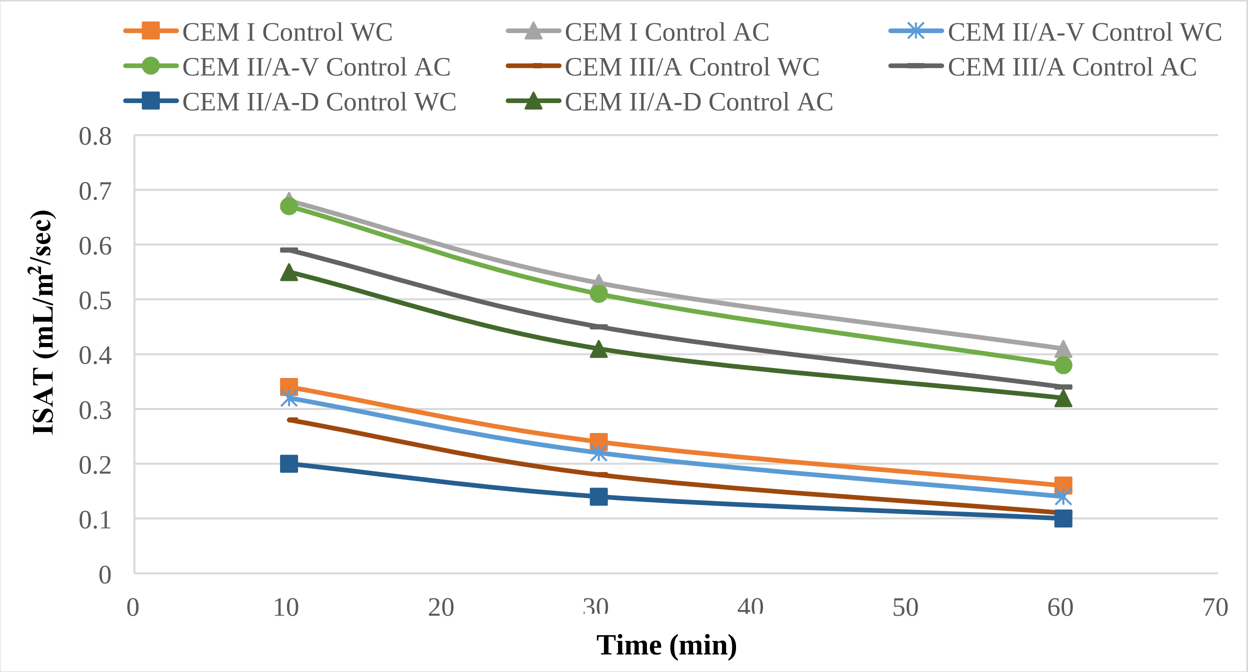


**Figure 5.13** ISAT values of control cubes cured in air and water

Figure 5.14 presents results of specimens treated with CC and different admixtures to enhance performance in control and blended cements. Generally, it can be seen that reduction of water absorption in specimens treated with Admix3 and Admix2 was far more than those treated with Admix1in all cement types. In fact, absorption reduction due to treatment with Admix1 was insignificant based on performance of reference cube cured in WC. This shows that treatment with materials governed by hydrophobic mechanism (Admix2 and Admix3) was more effective than compounds influenced by crystallization activity (Admix1). Results demonstrated that cubes treated with CC and Admix2 or Admix3 performed better than control cubes in both curing conditions. Maximum reduction in water absorption was 48% measured in CEM II/A-D cubes treated with Admix3, whereas minimum value was 4%. Results are in agreement with findings of previous studies (García-Vera *et al.*, 2018; Dao *et al.*, 2010; De Muynck et al., 2009; Izaguirre et al., 2009; Pazderka and Hájková, 2016; Tittarelli and Moriconi, 2008).

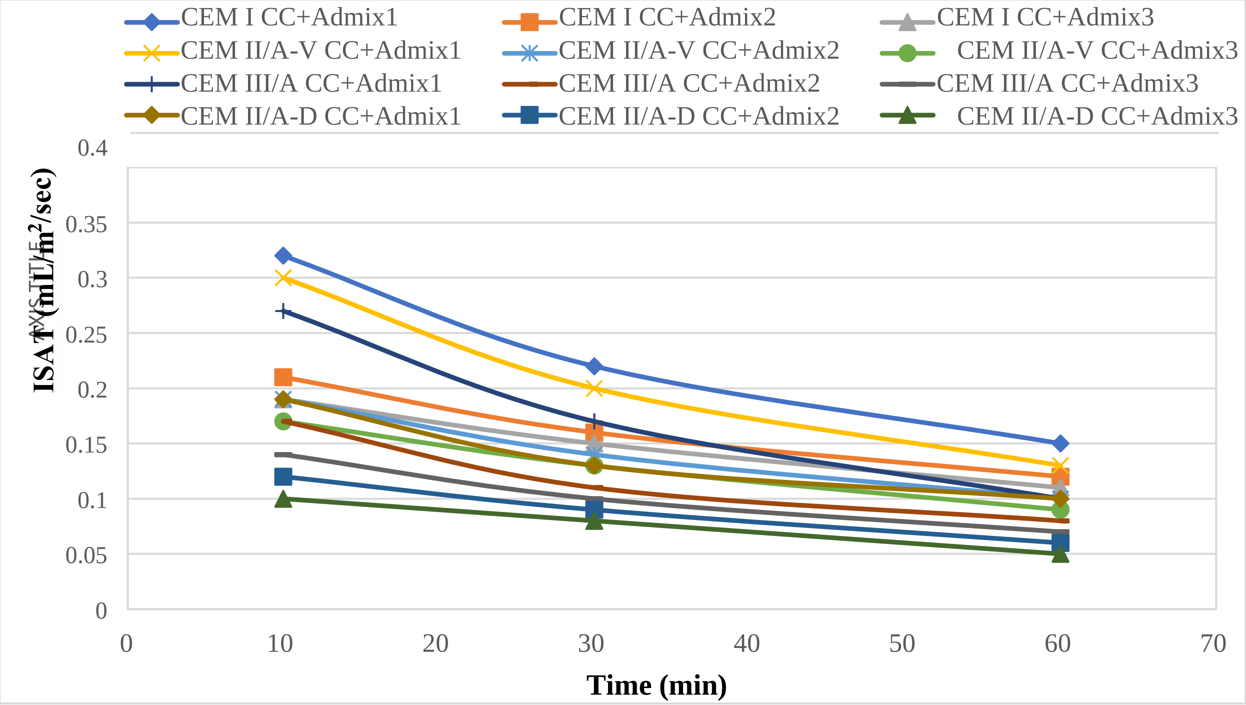


**Figure 5.14** ISAT values of specimens treated with CC and admixtures

Performance of cubes treated with CC and various surface treatments to improve impermeability of all cement types are shown in Figure 5.15. Results demonstrated that treatment with ST2 and ST3 significantly reduced surface water absorption in comparison to control cubes. On the other hand, treatment with ST1 was less effective than ST2 and ST2 as reduction was between 20-26% in control and blended cements. Maximum reduction was 66% observed in CEM II/A-D cubes treated with ST2, whereas minimum value was 20% measured in CEM I samples treated with ST1. Overall, performance of cubes treated with ST2 and ST3 was superior to ST1 in all cement types under both curing conditions. Likewise, treatment with water repellent agents (ST2 and ST3) influenced by hydrophobic effect was more efficient than materials governed by crystalline mechanism (ST1). Results are consistent with findings of previous researches (Mckenzie and

Calder, 2009; Cappellesso *et al.*, 2016; Zhang *et al.*, 2017; Dai *et al.*, 2010; Medeiros and Helene, 2008; Christodoulou *et al.*, 2013).

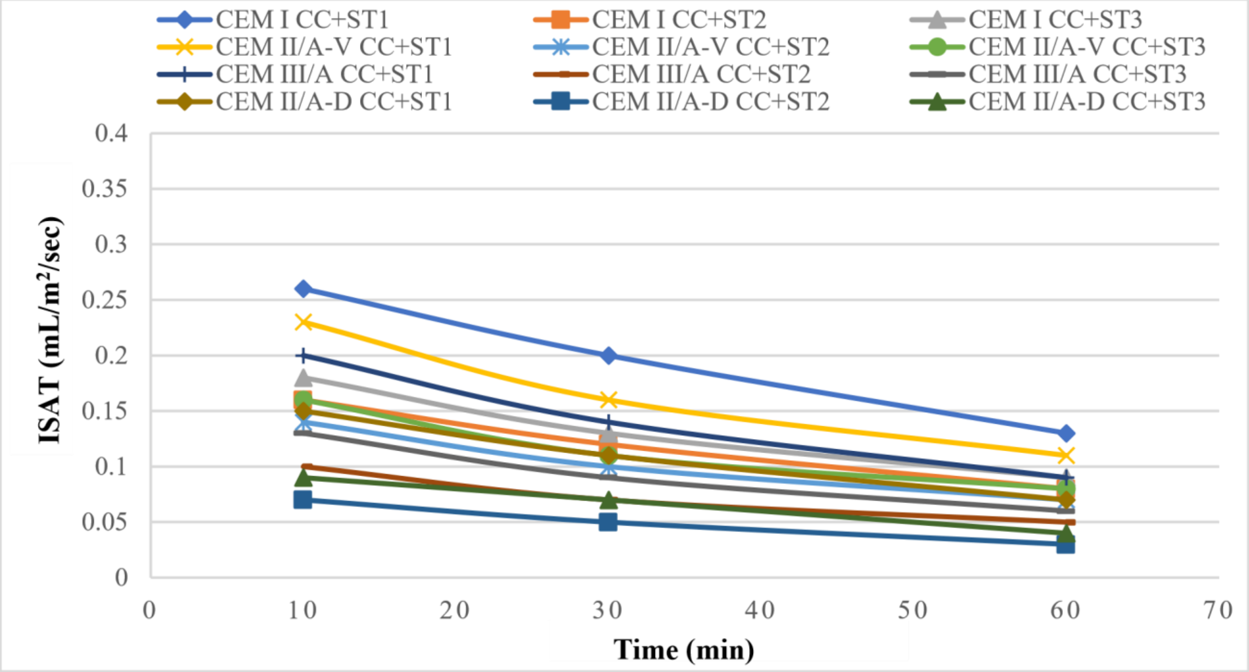


**Figure 5.15** ISAT values of specimens treated with CC and surface treatments

Based on Brook and Hanstead (1990) summary of typical ISAT values with respect to water absorption shown in Table 5.6, it was found that cubes treated with Admix2, Admix3, ST2 and ST3 achieved low absorption rate, whereas cubes treated with ST1, Admix1 and control samples cured in WC and CC can be categorized as average absorption rate, while reference samples cured in AC are considered high absorption rate.

**Table 5.6** Typical values for ISAT (after Brook and Hanstead, 1990)

| Concrete Absorption | ISAT values at time t (mL/m$^2$/sec) | | | |
|---|---|---|---|---|
| | 10 min | 30 min | 1-hour | 2-hour |
| low | < 0.25 | < 0.17 | < 0.10 | < 0.07 |
| average | 0.50-0.25 | 0.35-0.17 | 0.20-0.10 | 0.15-0.07 |
| High | > 0.50 | > 0.35 | > 0.20 | > 0.15 |

## 5.4 Sorptivity test (Resistance of Capillary Absorption)

### 5.4.1 Sorptivity of CEM I (100%PC) concrete mix

Sorptivity test was conducted to determine the increase of weight in concrete cubes due to capillary absorption of water in accordance with ASTM C1585 (2020) and BS EN 13057-02 (BSI, 2002) as shown in Figure 5.16. Performance was compared to controls cubes cured in air (AC) and in water (WC) as shown in Table 5.7. Test was carried out on three specimens for each case and average value was determined to represent sorptivity of each case.

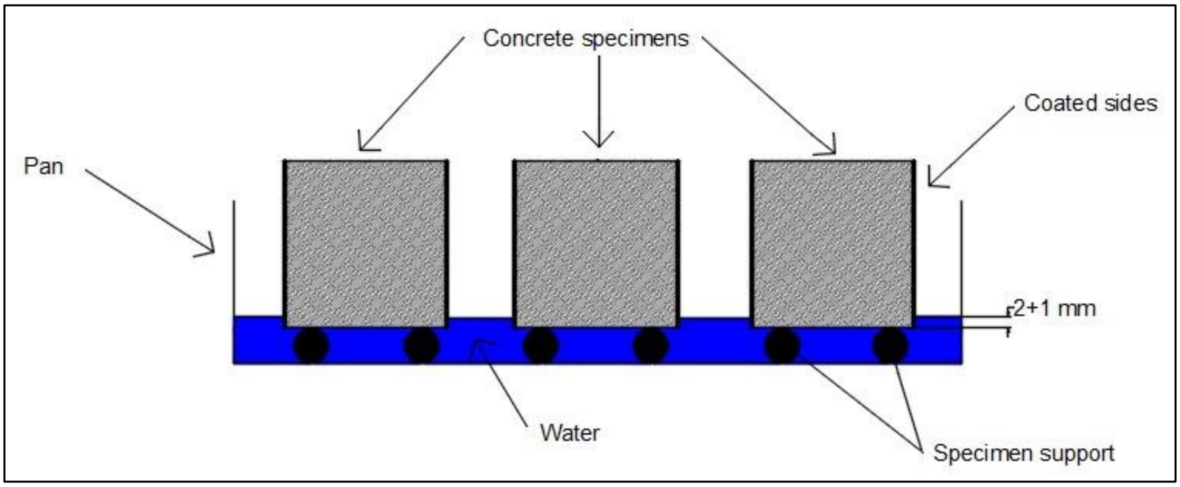


**Figure 5.16** Schematic of sorptivity test

**Table 5.7** Concrete cubes used for sorptivity test

| Cement type | | | Specimen<br>CC + Admixtures | Specimen CC +Surface Treatments | Total |
|---|---|---|---|---|---|

| | Control cubes (AC) | Control cubes (WC) | Admix1 | Admix2 | Admix3 | ST 1 | ST 2 | ST 3 | |
|---|---|---|---|---|---|---|---|---|---|
| CEM I | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 24 |
| CEM II/A-V | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 24 |
| CEM III/A | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 24 |
| CEM II/A-D | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 24 |
| Grand total | 96 | | | | | | | | |

AC = air curing, WC = water curing, CC = curing compound, Admix1 = admixture 1, Admix2 = admixture 2, Admix3 = admixture 3, ST1 = surface treatment 1, ST2 = surface treatment 2, ST3 = surface treatment 3

Sorptivity results of CEM I specimens along with control cubes cured in WC and AC are shown in Figure 5.17. Results show absorption kept increasing over time and highest cumulative water absorption was measured in control samples cured in AC, followed by specimens treated with CC and Admix1. Results indicate that performance of specimens cured with CC and treated with Admix2 and Admix3 were comparable as both materials reduced average capillary absorption by 17% and 22% respectively in comparison to control cubes cured in WC.

On the other hand, counterpart specimens treated with surface treatments exhibited less water absorption. Treatment with ST1, ST2 and ST3 decreased average water absorption by 49%, 85% and 79% respectively. However, the graph shows that sorptivity of cubes treated with ST1, Admix2 and Admix3 kept increasing over time. In other word, treatment with these materials became less effective as exposure to water continued. In contrast, cubes treated with ST2 and ST3 experienced minimum absorption during the entire period of exposure. Results showed that treatment with ST compounds improved impermeability of concrete more than admixtures. Moreover, materials governed by hydrophobic effects performed far better than agents influenced by crystalline mechanism.

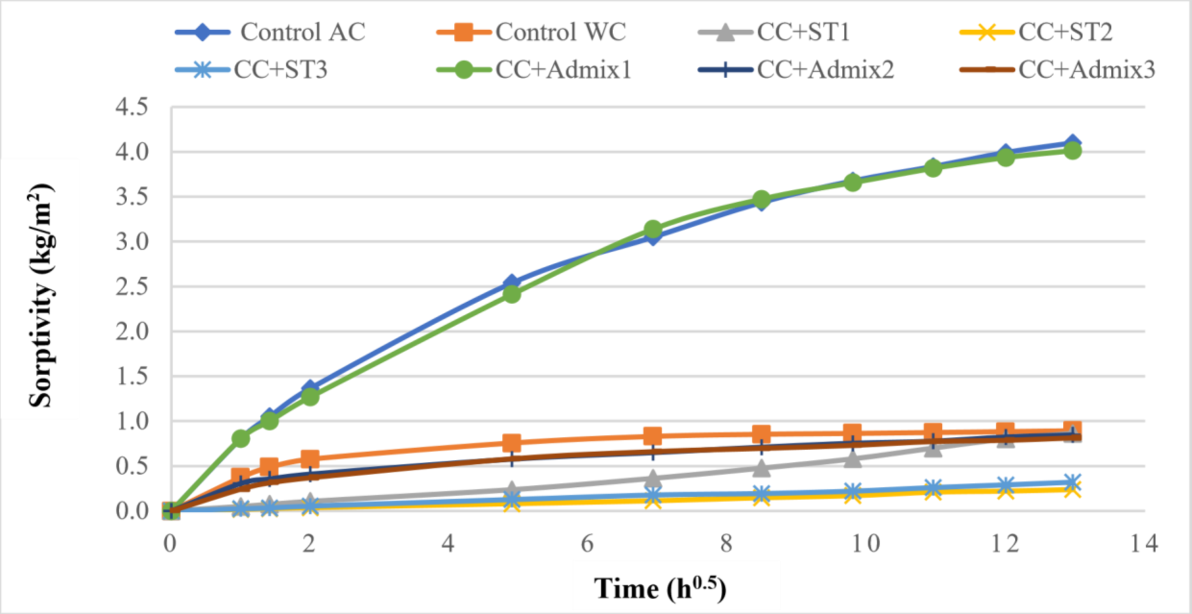


**Figure 5.17** Sorptivity results of CEM I concrete

### 5.4.2 Sorptivity of CEM II/A-V (80%PC+20%FA) concrete mix

Sorptivity results of CEM II/A-V specimens with control cubes in both curing conditions are presented in Figure 5.18. Similar trend was observed as maximum cumulative absorption was measured in control cubes cured in AC, followed by specimens treated with Admix1. Results indicated that performance of cubes treated with Admix2 and Admix3 was comparable as average absorption was decreased by 16% and 19% respectively in comparison to control cubes cured in WC. In contrast, treatment with ST1, ST2 and ST3 was more effective as average water absorption decreased by 43%, 81% and 70% respectively. It should be stressed that performance of cubes treated with ST1, Admix2 and Admix3 declined over time. In other word, treatment with these materials became less effective as exposure to water continued.

On the other hand, cubes treated with ST2 and ST3 experienced minimum absorption during the entire period of exposure. Similar to CEM I, results showed that treatment with ST compounds improved impermeability of concrete more than admixtures. Furthermore, materials governed by hydrophobic effects performed far better than agents influenced by crystalline mechanism. Moreover, results showed that inclusion of FA in the mix reduced rate of water absorption in comparison to CEM I mix which could be attributed to the low w/c and the effect of the pozzolanic reaction which reduces porosity of concrete as stated in previous studies (Nath and Sarker, 2011; Kou et al., 2007; Saha, 2018).

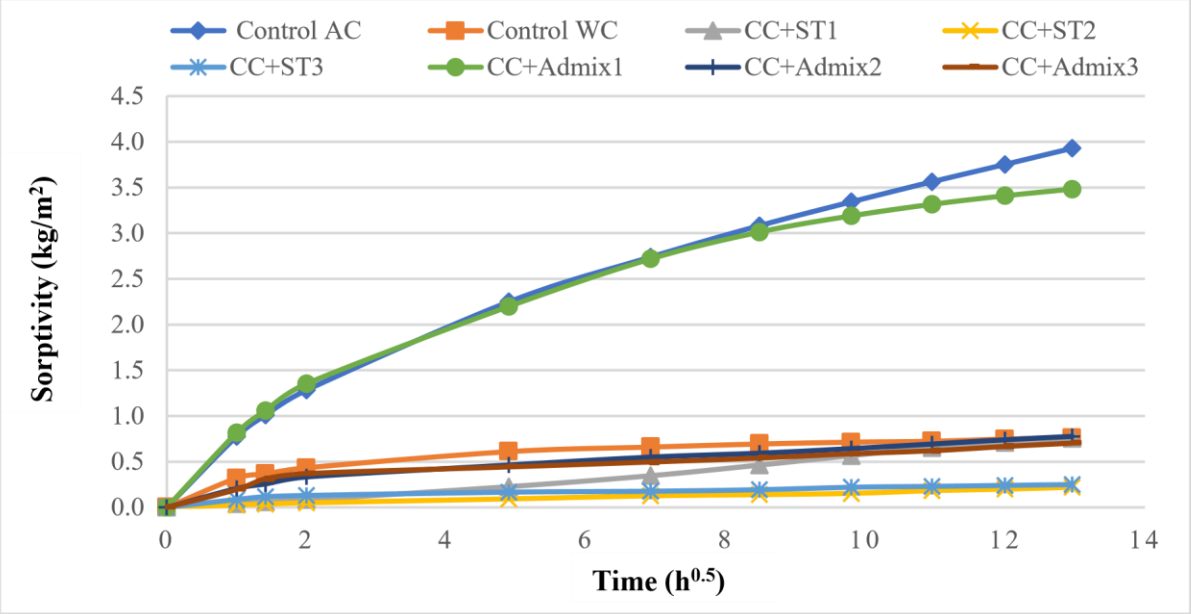


**Figure 5.18** Sorptivity results of CEM II/A-V concrete

### 5.4.3 Sorptivity of CEM III/A (60%PC+40%GGBS) concrete mix

Sorptivity results of CEM III/A specimens and control cubes in both curing regimes are shown in Figure 5.19. It can be seen that reference samples cured in AC and specimens cured with CC and treated with Admix1 exhibited highest water abortion. Similar to previous cement types, performance of cubes treated with Admix2 and Admix3 was comparable as average absorption was decreased by 20% and 29% respectively in comparison to control cubes cured in WC. Results indicated that treatment with Admix2 and Admix3 performed better than corresponding cubes in previous cement types (CEM I and CEM II/A-V). In terms of ST agents, treatment with ST1, ST2 and ST3 reduced average water absorption by 50%, 83% and 76% respectively. However, results demonstrated that efficiency of ST1 declined over time as absorption kept increasing. This means that continuous exposure to water decreased resistance of materials to water absorption, thus increased water absorption.

In contrast, results showed that cubes treated with ST2 and ST3 experienced minimum absorption during entire exposure period. In terms of effectiveness of materials used to improve impermeability, similar trend was observed as results demonstrated that treatment with ST compounds performed better than admixtures. Furthermore, agents governed by hydrophobic effects performed better than compounds influenced by crystalline mechanism. Moreover, results showed that inclusion of GGBS in the mix improved overall performance by decreasing water absorption rate in comparison to CEM I and CEM II/A-V.

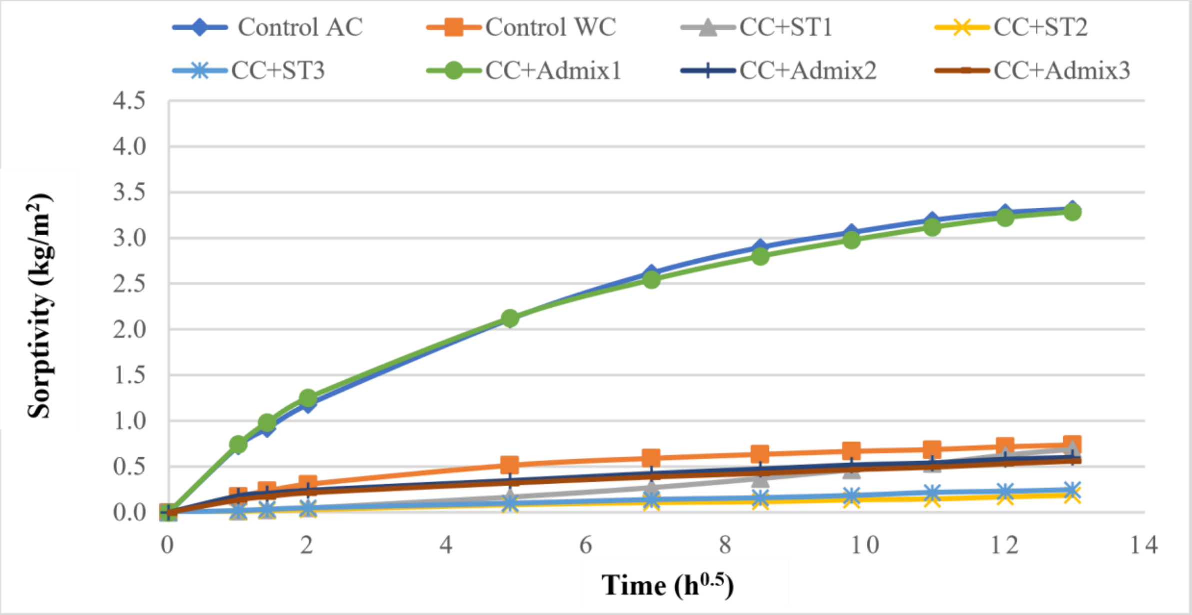


**Figure 5.19** Sorptivity results of CEM III/A concrete

### 5.4.4 Sorptivity of CEM II/A-D (90%PC+10%SF) concrete mix

Sorptivity results of CEM II/A-D specimens and control samples in both curing conditions are shown in Figure 5.20. Similar to previous mixes, reference samples cured in AC and specimens cured with CC and treated with Admix1 experienced highest water abortion. Results indicated that average reduction in water absorption due to treatment with Admix2 and Admix3 were 19% and 24% respectively in comparison to control cubes cured in WC. It was observed that performance of cubes treated with Admix2 and Admix3 was comparable to corresponding cubes in CEM III/A as resistance to water absorption did not decrease with time.

With respect to performance of ST agents, treatment with ST1, ST2 and ST3 reduced average water absorption by 62%, 80% and 81% respectively. Results showed that all treatment agents except Admix1 were effective in reducing water absorption particularly ST2 and ST3. A similar trend was observed as materials influenced by hydrophobic actions were more effective in reducing water absorption. Moreover, the addition of SF in the mix contributed positively in the overall performance improvement by densifying the concrete matrix and reducing porosity as mentioned previously due to the pozzolanic reaction and the impact of the fine particle size.

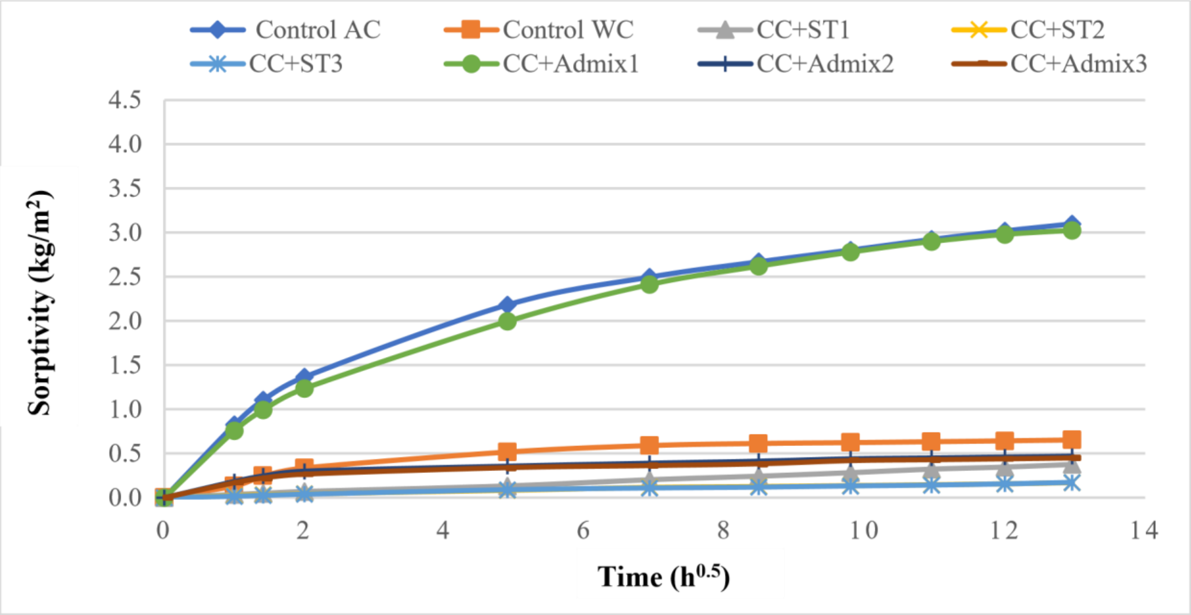


**Figure 5.20** Sorptivity results of CEM II/A-D concrete

### 5.4.5 Comparison of CEM II/A-V, CEM III/A and CEM II/A-D with CEM I

Sorptivity results of control cubes of all cement types cured in AC and WC are shown in Figure 5.21. It is clear that addition of mineral admixtures particularly GGBS and SF reduced water absorption in comparison to reference mix CEM I. As mentioned previously, improvement in CEM III/A mix could be attributed to the reduced w/c and to the larger binder content involved in the pozzolanic reaction. Inclusion of SF in the CEM II/A-D mix leads to formation of additional C-SH due to the reaction between SF and calcium hydroxide, subsequently improving refinement of pore structure of concrete matrix and reducing porosity.

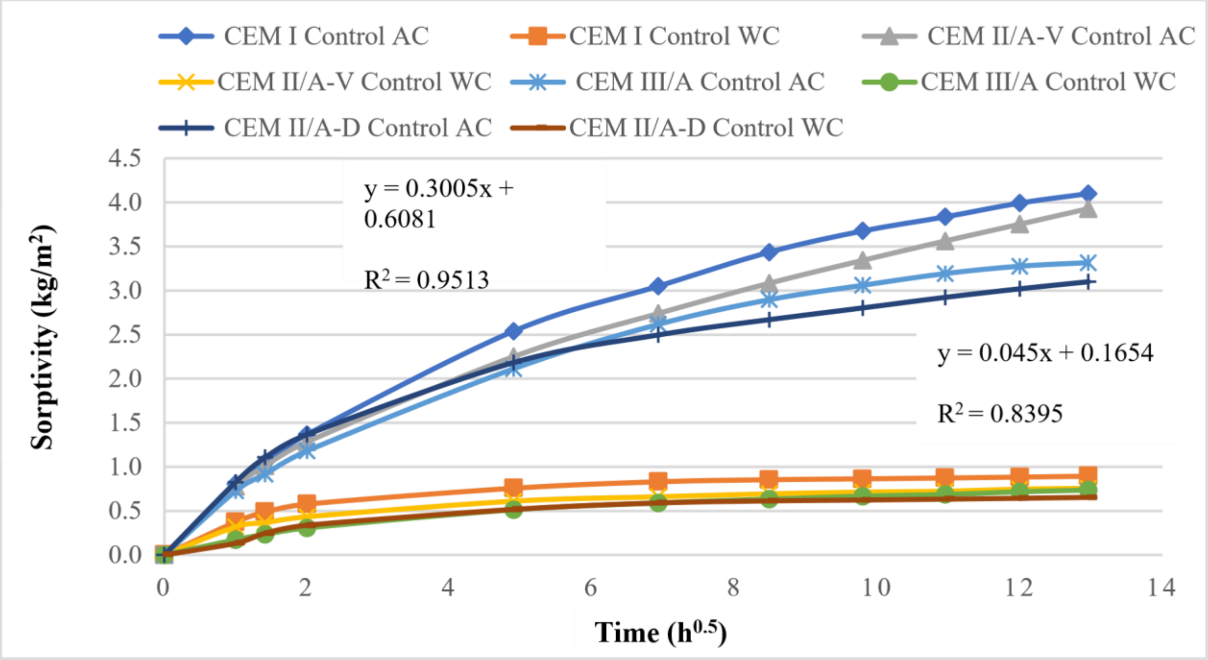
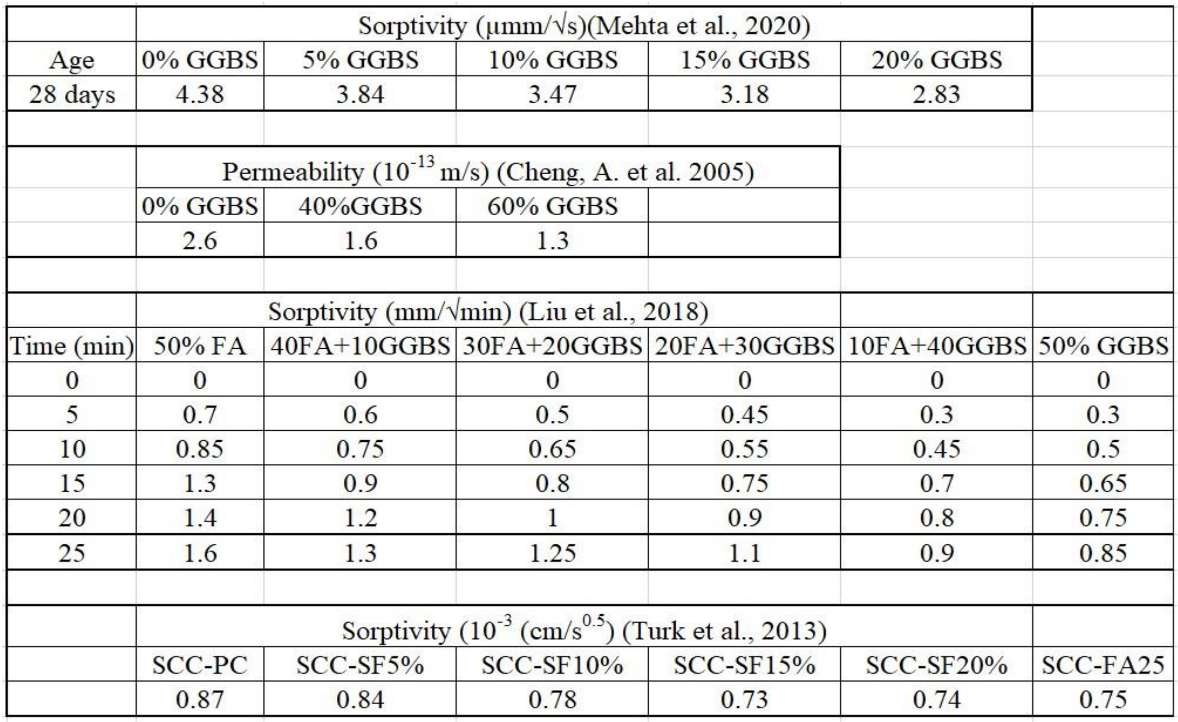


**Figure 5.21** Capillary absorption results of control cubes cured in air and water

Furthermore, results indicated that incorporation of FA in CEM II/A-V mix reduced absorption rate but reduction was less than mixes containing GGBS and SF. This could be due to the lower binder content in comparison to the higher binder content of GGBS, or could be attributed to presence of FA in the mix which tend to require longer time to have beneficial effects as reported by Hassan et al. (2000) and Naik et al. (1994). Nonetheless, incorporation of FA improved performance of blended cement compared to plain control CEM I mix. This may be due to the low w/c and effect of the pozzolanic reaction which reduces porosity of concrete as stated in previous studies (Nath and Sarker, 2011; Kou et al., 2007; Saha, 2018; Kurda et al., 2019; Gopalan, 1996). Results demonstrated that control cubes cured in WC experienced less water absorption than corresponding cubes cured in AC in plain and blended cements.

Moreover, Figure 5.21 shows that maximum sorptivity coefficient was (0.3005) measured in CEM I cubes cured in AC, whereas minimum value was (0.045) measured in CEM II/A-D cured in WC. Results demonstrated that blended cements performed better than plain cement in both curing conditions. Results are consistent with previous findings (Mehta et al., 2020; Cheng et al., 2005; Khan and Lynsdale, 2002; Liu et al., 2018; Megat Johari et al., 2011; Turk et al., 2013) as shown in Table 5.8.

**Table 5.8** Influence of mineral admixtures on sorptivity



|  | Sorptivity (μmm/√s)(Mehta et al., 2020) |  |  |  |  |  |
|---|---|---|---|---|---|---|
| Age | 0% GGBS | 5% GGBS | 10% GGBS | 15% GGBS | 20% GGBS |  |
| 28 days | 4.38 | 3.84 | 3.47 | 3.18 | 2.83 |  |

|  | Permeability ($10^{-13}$ m/s) (Cheng, A. et al. 2005) |  |  |  |
|---|---|---|---|---|
|  | 0% GGBS | 40%GGBS | 60% GGBS |  |
|  | 2.6 | 1.6 | 1.3 |  |

|  | Sorptivity (mm/√min) (Liu et al., 2018) |  |  |  |  |  |
|---|---|---|---|---|---|---|
| Time (min) | 50% FA | 40FA+10GGBS | 30FA+20GGBS | 20FA+30GGBS | 10FA+40GGBS | 50% GGBS |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0.7 | 0.6 | 0.5 | 0.45 | 0.3 | 0.3 |
| 10 | 0.85 | 0.75 | 0.65 | 0.55 | 0.45 | 0.5 |
| 15 | 1.3 | 0.9 | 0.8 | 0.75 | 0.7 | 0.65 |
| 20 | 1.4 | 1.2 | 1 | 0.9 | 0.8 | 0.75 |
| 25 | 1.6 | 1.3 | 1.25 | 1.1 | 0.9 | 0.85 |

|  | Sorptivity ($10^{-3}$ (cm/$s^{0.5}$) (Turk et al., 2013) |  |  |  |  |  |
|---|---|---|---|---|---|---|
|  | SCC-PC | SCC-SF5% | SCC-SF10% | SCC-SF15% | SCC-SF20% | SCC-FA25 |
|  | 0.87 | 0.84 | 0.78 | 0.73 | 0.74 | 0.75 |

Results of specimens treated with CC and different admixtures to reduce water absorption in plain and blended cements are shown in Figure 5.22. It can be seen that performance of cubes treated with Admix2 and Admix3 is significantly better than Admix1 in plain and blended cements. In fact, results show that treatment with Admix1 did not contribute to absorption reduction. It was observed that reduction in water absorption due to treatment with Admix2 and Admix3 was higher and more consistent in CEM III/A and CEM II/A-D than CEM II/A-V and CEM I mixes. Generally, performance of both admixtures was comparable in all cement types. Maximum reduction due to treatment with Admix2 and Admix3 were 20% and 29% respectively measured in CEM III/A. Results showed that cubes treated with CC and Admix2 or Admix3 performed better than control cubes in both curing conditions.

Results demonstrated that treatment with materials governed by hydrophobic mechanism (Admix2 and Admix3) was more effective than compounds influenced by crystalline activity (Admix1).

Moreover, Figure 5.22 shows that maximum sorptivity coefficient was (0.3003) measured in CEM I cubes treated with Admix1, while minimum value was (0.0266) measured in CEM II/A-D cubes treated with Admix3.

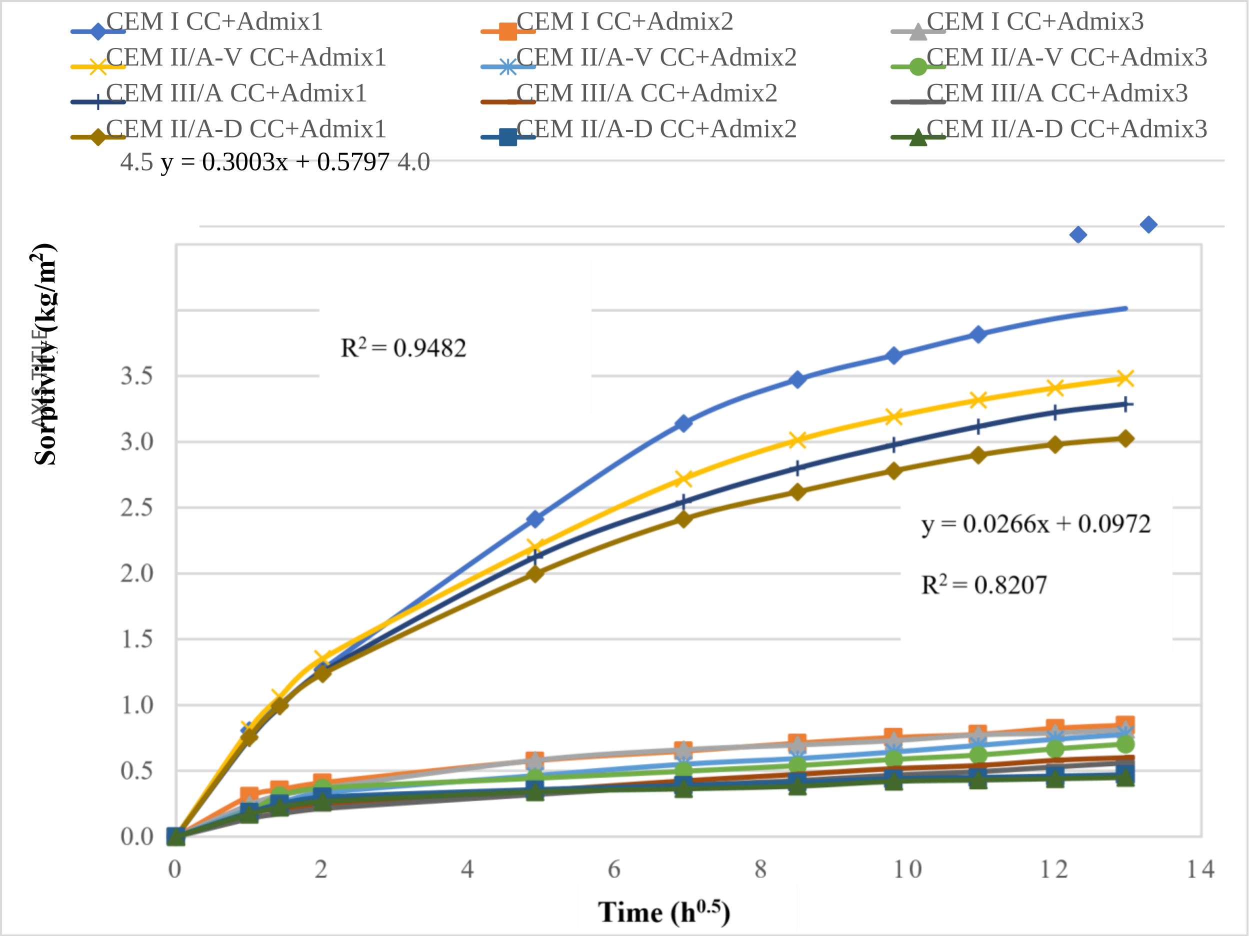
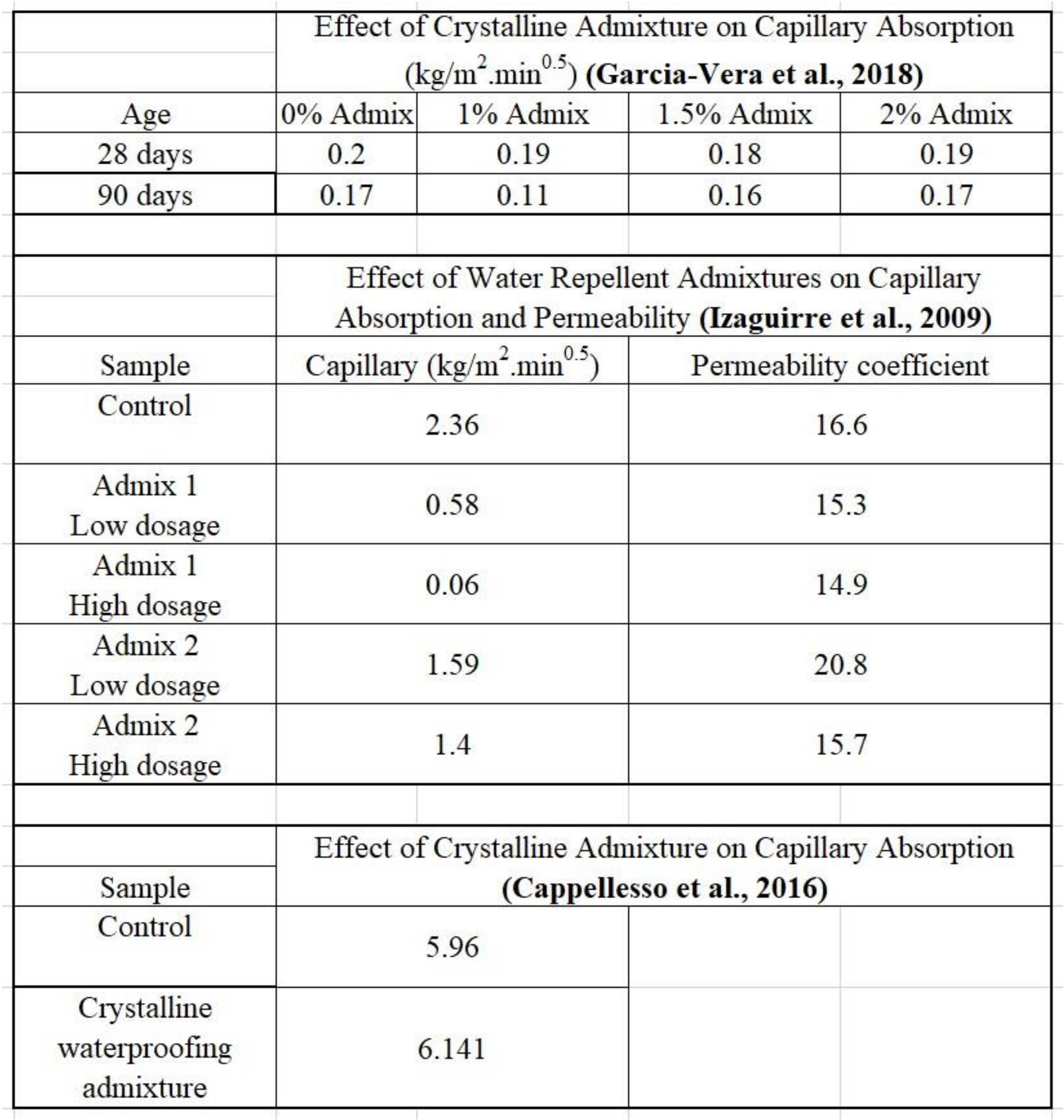


**Figure 5.22** Capillary absorption results of specimens treated with CC and admixtures

Results are in agreement with findings of previous studies (García-Vera et al., 2018; Dao et al., 2010; De Muynck et al., 2009;  et al., 2009; Pazderka and Hájková, 2016; Tittarelli and Moriconi, 2008; Cappellesso et al., 2016) as shown in Table 5.9.

**Table 5.9** Influence of waterproofing admixtures on sorptivity (capillary absorption)



| | Effect of Crystalline Admixture on Capillary Absorption ($kg/m^2.min^{0.5}$) **(Garcia-Vera et al., 2018)** | | | |
|---|---|---|---|---|
| Age | 0% Admix | 1% Admix | 1.5% Admix | 2% Admix |
| 28 days | 0.2 | 0.19 | 0.18 | 0.19 |
| 90 days | 0.17 | 0.11 | 0.16 | 0.17 |

| | Effect of Water Repellent Admixtures on Capillary Absorption and Permeability **(Izaguirre et al., 2009)** | |
|---|---|---|
| Sample | Capillary ($kg/m^2.min^{0.5}$) | Permeability coefficient |
| Control | 2.36 | 16.6 |
| Admix 1 Low dosage | 0.58 | 15.3 |
| Admix 1 High dosage | 0.06 | 14.9 |
| Admix 2 Low dosage | 1.59 | 20.8 |
| Admix 2 High dosage | 1.4 | 15.7 |

| Sample | Effect of Crystalline Admixture on Capillary Absorption **(Cappellesso et al., 2016)** |
|---|---|
| Control | 5.96 |
| Crystalline waterproofing admixture | 6.141 |

Capillary absorption of cubes treated with CC and various surface treatments to improve impermeability of plain and blended cements are shown in Figure 5.23. Results show that treatment with surface treatments agents, particularly ST2 and ST3 were effective in reducing water absorption. Treatment with ST2 and ST3 reduced absorption by more than 80% and 70% respectively in all cement types compared to control cubes cured in WC. On the other hand, treatment with ST1 was less effective as highest reduction was 62% measured in CEM II/A-D specimens.

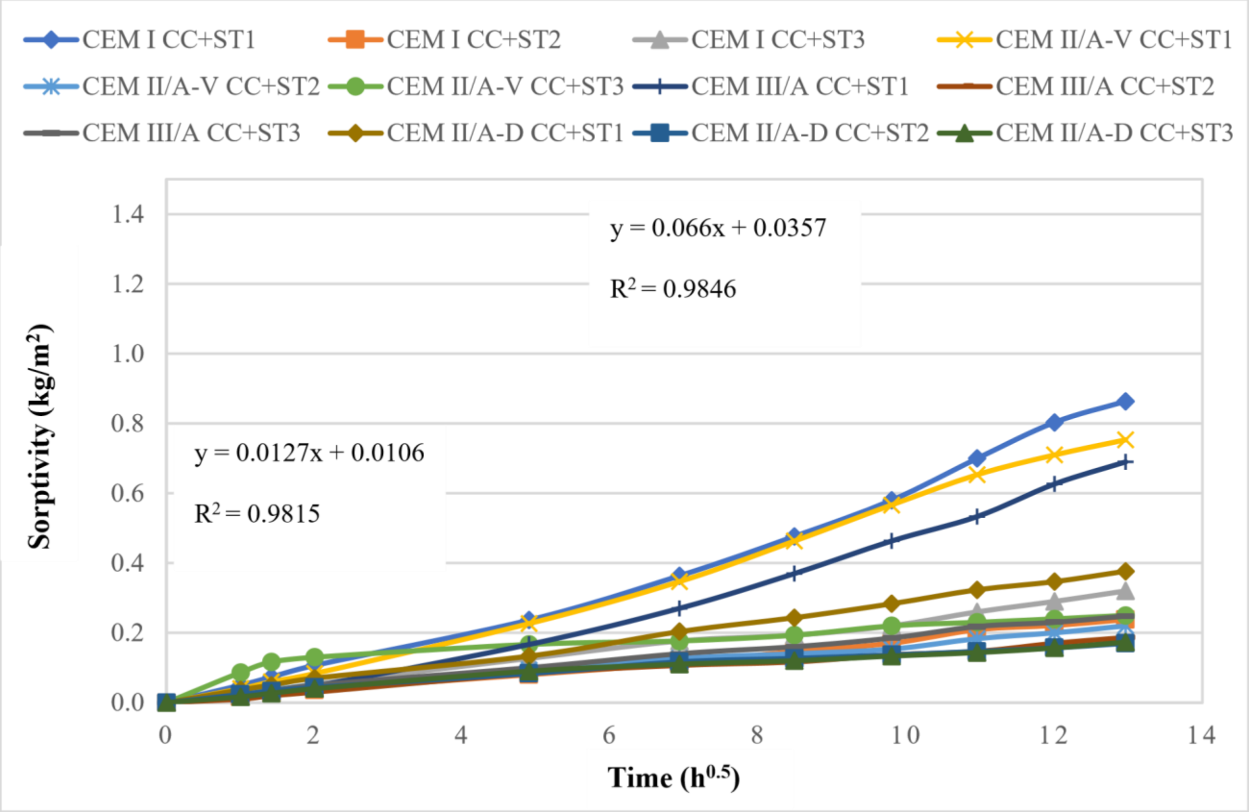
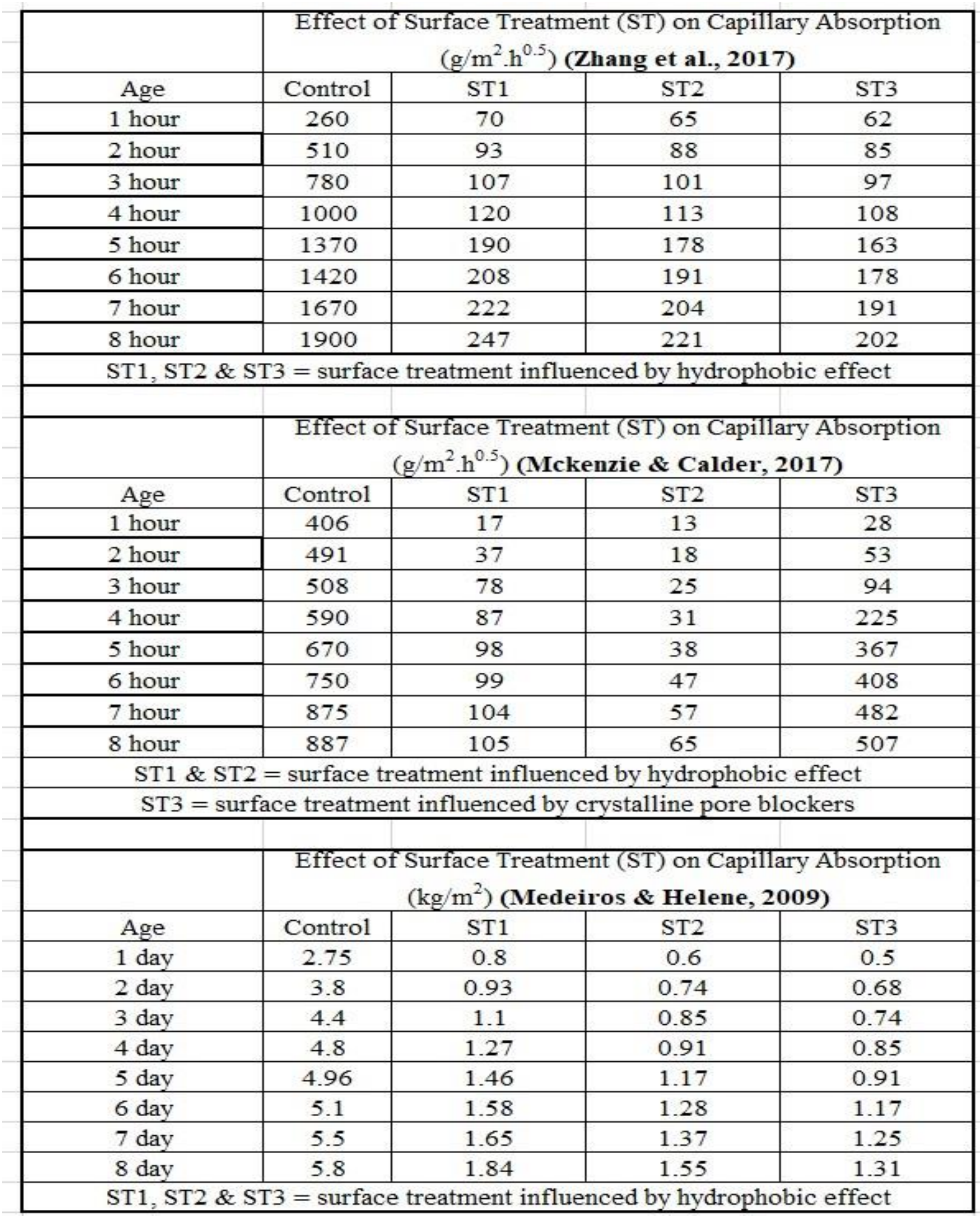


**Figure 5.23** Capillary absorption results of specimens treated with CC and surface treatments

It was observed the efficiency of cubes treated with ST1 diminished over time due to constant exposure to water. Nevertheless, it reduced capillary absorption during initial exposure period. In addition, maximum sorptivity coefficient was (0.066) measured in CEM I cubes treated with ST1, whereas minimum value was (0.0127) measured in CEM II/A-D cubes treated with ST2. Moreover, treatment with water repellent agents (ST2 and ST3) influenced by hydrophobic effects was more effective than materials governed by crystalline mechanism (ST1). Results are consistent with findings of previous studies (Mckenzie and Calder, 2009; Cappellesso et al., 2016; Zhang et al., 2017; Dai et al., 2010; Medeiros and Helene, 2008; Christodoulou et al., 2013; Medeiros and Helene, 2009) as shown in Table 5.10.

**Table 5.10** Influence of surface treatment on sorptivity (capillary absorption)



| | Effect of Surface Treatment (ST) on Capillary Absorption ($g/m^2.h^{0.5}$) **(Zhang et al., 2017)** | | | |
|---|---|---|---|---|
| Age | Control | ST1 | ST2 | ST3 |
| 1 hour | 260 | 70 | 65 | 62 |
| 2 hour | 510 | 93 | 88 | 85 |
| 3 hour | 780 | 107 | 101 | 97 |
| 4 hour | 1000 | 120 | 113 | 108 |
| 5 hour | 1370 | 190 | 178 | 163 |
| 6 hour | 1420 | 208 | 191 | 178 |
| 7 hour | 1670 | 222 | 204 | 191 |
| 8 hour | 1900 | 247 | 221 | 202 |
| ST1, ST2 & ST3 = surface treatment influenced by hydrophobic effect | | | | |

| | Effect of Surface Treatment (ST) on Capillary Absorption ($g/m^2.h^{0.5}$) **(Mckenzie & Calder, 2017)** | | | |
|---|---|---|---|---|
| Age | Control | ST1 | ST2 | ST3 |
| 1 hour | 406 | 17 | 13 | 28 |
| 2 hour | 491 | 37 | 18 | 53 |
| 3 hour | 508 | 78 | 25 | 94 |
| 4 hour | 590 | 87 | 31 | 225 |
| 5 hour | 670 | 98 | 38 | 367 |
| 6 hour | 750 | 99 | 47 | 408 |
| 7 hour | 875 | 104 | 57 | 482 |
| 8 hour | 887 | 105 | 65 | 507 |
| ST1 & ST2 = surface treatment influenced by hydrophobic effect | | | | |
| ST3 = surface treatment influenced by crystalline pore blockers | | | | |

| | Effect of Surface Treatment (ST) on Capillary Absorption ($kg/m^2$) **(Medeiros & Helene, 2009)** | | | |
|---|---|---|---|---|
| Age | Control | ST1 | ST2 | ST3 |
| 1 day | 2.75 | 0.8 | 0.6 | 0.5 |
| 2 day | 3.8 | 0.93 | 0.74 | 0.68 |
| 3 day | 4.4 | 1.1 | 0.85 | 0.74 |
| 4 day | 4.8 | 1.27 | 0.91 | 0.85 |
| 5 day | 4.96 | 1.46 | 1.17 | 0.91 |
| 6 day | 5.1 | 1.58 | 1.28 | 1.17 |
| 7 day | 5.5 | 1.65 | 1.37 | 1.25 |
| 8 day | 5.8 | 1.84 | 1.55 | 1.31 |
| ST1, ST2 & ST3 = surface treatment influenced by hydrophobic effect | | | | |

## 5.5 Depth of penetration of water under pressure

### 5.5.1 Water penetration depth of CEM I (100%PC) concrete mix

Concrete cubes were tested in accordance with BS EN 12390-8 (BSI 12390, 2019) to determine depth of penetration of water under applied pressure as shown in Figure 5.24. After completion of test, cubes were split in half to measure depth of water penetration to the nearest mm. Results were compared to controls cubes cured in air (AC) and in water (WC) as shown in Table 5.11. Test was conducted on three specimens for each case and average value was determined to represent depth of water penetration of each case.

**Figure 5.24** Water permeability under pressure apparatus

**Table 5.11** Concrete cubes used for water penetration depth test

| Cement type | Control cubes (AC) | Control cubes (WC) | Specimen CC + Admixtures | | | Specimen CC +Surface Treatments | | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | | | Admix1 | Admix2 | Admix3 | ST 1 | ST 2 | ST 3 | |
| CEM I | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 24 |
| CEM II/A-V | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 24 |
| CEM III/A | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 24 |
| CEM II/A-D | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 3 Cubes | 24 |
| Grand Total | 96 | | | | | | | | |

AC = air curing, WC = water curing, CC = curing compound, Admix1 = admixture 1, Admix2 = admixture 2, Admix3 = admixture 3, ST1 = surface treatment 1, ST2 = surface treatment 2, ST3 = surface treatment 3

Results of water penetration depth under pressure of CEM I specimens along with control cubes in both curing conditions are shown in Figure 5.25. It can be seen that control cubes cured in AC and specimens treated with Admix1 and ST1 experienced highest penetration depth. Results indicated that treatment with admixtures and surface treatments were not highly effective in reducing water penetration depth. The graph shows that performance of specimens treated with ST3 and Admix2 was comparable to some extent to reference samples cured in WC. It was observed that lowest penetration depths were 27 and 31 mm measured in specimens treated with ST2 and Admix3 respectively, compared to depth of control cubes cured in WC (32 mm). Results showed that maximum reduction in penetration depth was 15% measured in specimens treated with ST2 in comparison to control samples cured in WC. Moreover, results demonstrated that treatment with hydrophobic agents was more effective than compounds governed by crystalline actions. It should be stressed that although treatment with ST2 and Admix3 did not reduce water penetration depth significantly, nevertheless they performed better than control cubes cured in WC.

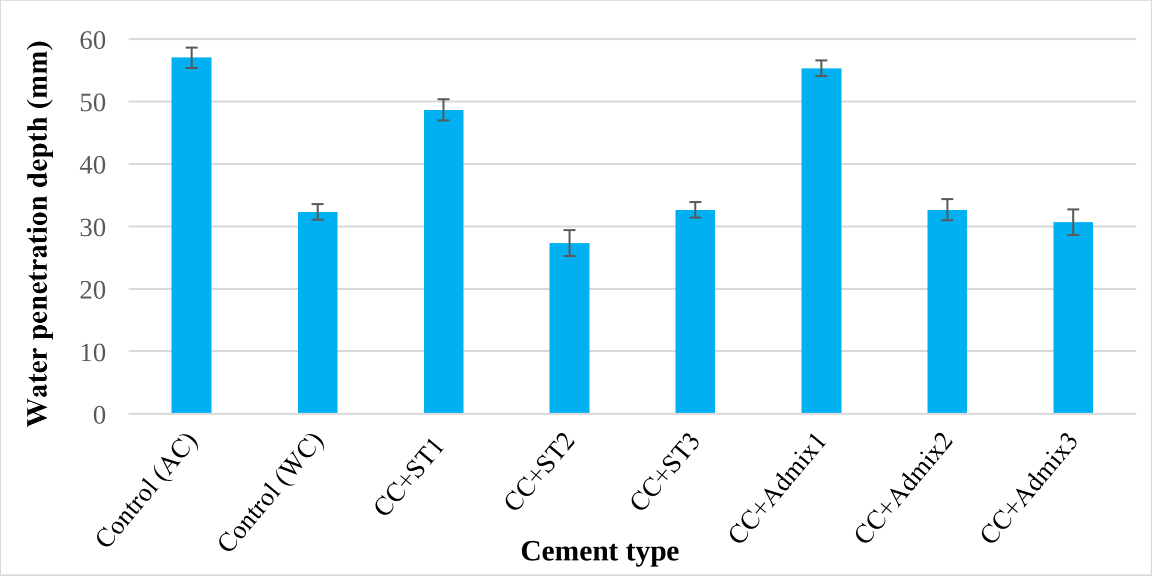


**Figure 5.25** Water penetration depth results of CEM I concrete

### 5.5.2 Water penetration depth of CEM II/A-V (80%PC+20%FA) concrete mix

Results of water penetration depth under pressure of CEM II/A-V specimens as well as control cubes in both curing conditions are shown in Figure 5.26. Similar trend was observed as reference cubes cured in AC and specimens treated with Admix1 and ST1 exhibited highest penetration depth. Similar to CEM I, performance of specimens treated with ST3 and Admix2 was comparable to some extent to reference samples cured in WC. Results showed that minimum penetration depths were 25mm and 26mm measured in specimens treated with ST2 and Admix3 respectively, compared to control cubes cured in WC (27 mm).

Results indicated that treatment with admixtures and surface treatments was not very effective in reducing water penetration depth. However, inclusion of FA in the mix improved performance as penetration depth was decreased from 57mm and 32mm in CEM I control cubes to 47mm and 27mm in CEM II/A-V control cubes cured in AC and WC respectively. This improvement could be due to the pozzolanic reaction taking place during cement hydration and to the low w/c of the mix. Furthermore, results showed that treatment with hydrophobic agents was more effective than compounds influenced by crystalline mechanism. It is noteworthy that although treatment with ST2 and Admix3 did not significantly reduce water penetration depth, nonetheless they performed better than control cubes cured in WC.

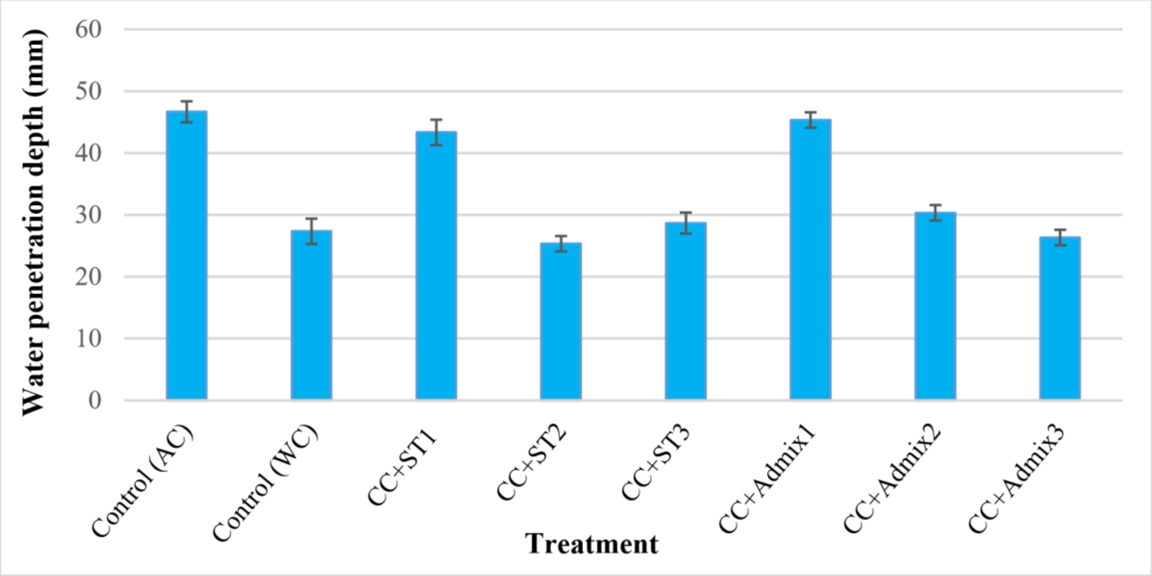


**Figure 5.26** Water penetration depth results of CEM II/A-V concrete

### 5.5.3 Water penetration depth of CEM III/A (60%PC+40%GGBS) concrete mix

Results of water penetration depth under pressure of CEM III/A specimens and control cubes cured in both curing regimes are presented in Figure 5.27. Similar to previous mixes, it was observed that cubes cured in AC and specimens treated with Admix1 and ST1 showed highest penetration depth. It can be seen that treatment with Admix1 and ST1 did not improve performance as effects were insignificant. On the other hand, performance of specimens treated with ST3 and Admix2 was identical and comparable to some extent to reference samples cured in WC. Minimum penetration depths were 27mm and 28mm measured in specimens treated with ST2 and Admix3 respectively, compared to control cubes cured in WC (29 mm).

Results showed that treatment with admixtures and surface treatments was not very effective in reducing water penetration depth. Similar to CEM II/A-V concrete, inclusion of GGBS in the mix improved performance as penetration depths were decreased from 57mm and 32mm in CEM I control cubes to 50mm and 29mm in CEM III/A control cubes cured in AC and WC respectively. This improvement is largely attributed to the pozzolanic reaction taking place during cement hydration and to the low w/c of the mix. Additionally, results showed that treatment with hydrophobic agents was more effective than compounds influenced by crystalline mechanism. It is noteworthy that although treatment with ST2 and Admix3 did not significantly reduce water penetration depth, nevertheless they performed better than control cubes cured in WC.

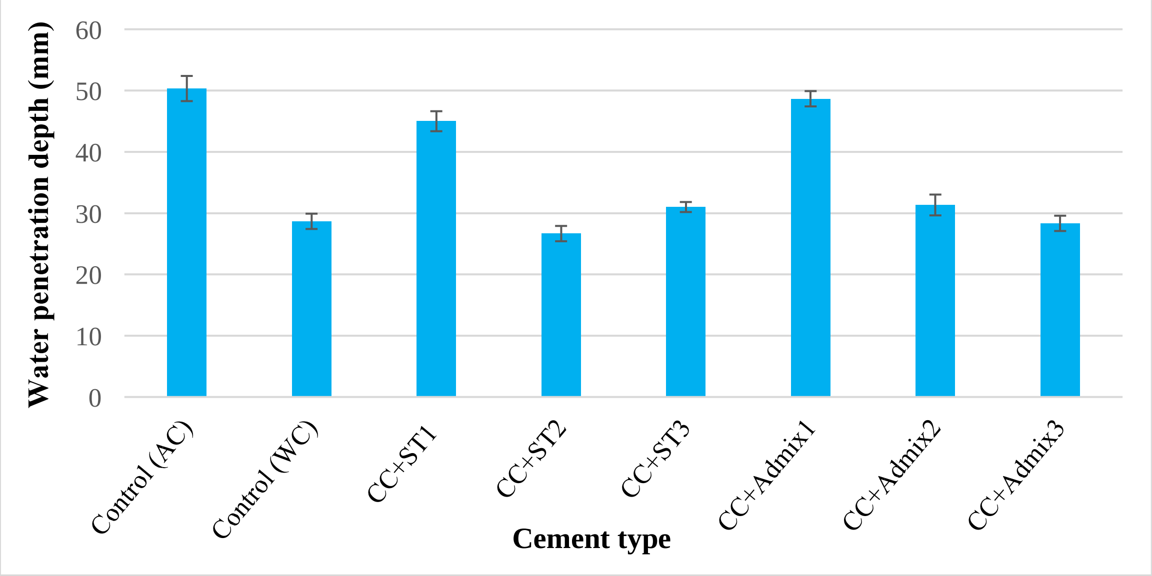


**Figure 5.27** Water penetration depth results of CEM III/A concrete

### 5.5.4 Water penetration depth of CEM II/A-D (90%PC+10%SF) concrete mix

Results of water penetration depth under pressure of CEM II/A-D specimens as well as control cubes cured in both curing regimes are presented in Figure 5.28. Similar trend was observed as control cubes cured in AC and treatment with agents Admix1 and ST1which are influenced by crystalline effects experienced highest penetration depth. On the other hand, performance of specimens treated with ST3 and Admix2 which are governed by hydrophobic effects was better than Admix1 and ST1 and comparable to some extent to reference samples cured in WC.

Results show that minimum penetration depths were 14mm and 16mm measured in specimens treated with ST2 and Admix3 respectively, compared to control cubes cured in WC (17mm). Results showed that treatment with ST2 and Admix3 managed to decrease depth of penetration, but the reduction was not significant. However, incorporation of SF in the mix significantly improved performance as penetration depths were decreased from 57mm and 32mm measured in control mix (CEM I) to 31mm and 17mm in CEM II/A-D control cubes cured in AC and WC respectively. This reduction in penetration depth is primarily attributed to the pozzolanic reaction occurring between SF and calcium hydroxide during the hydration of cement which leads to refinement in the pore structure of the matrix, thus reducing porosity and permeability of concrete.

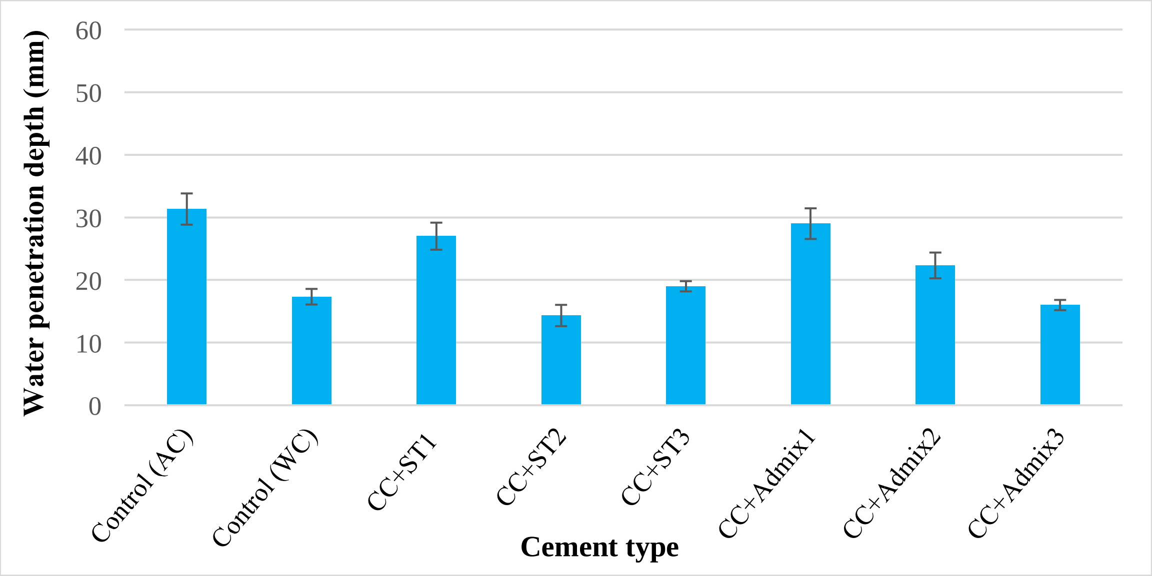


**Figure 0.28** Water penetration depth results of CEM II/A-D concrete

### 5.5.5 Comparison of CEM II/A-V, CEM III/A and CEM II/A-D with CEM I

Results of water penetration depth of control cubes of all cement types cured in AC and WC are shown in Figure 5.29. It can be seen that inclusion of mineral admixtures reduced capillary absorption compared to reference mix CEM I in both curing regimes. It was observed that addition of FA in CEM II/A-V reduced capillary absorption more than incorporation of GGBS in CEM III/A, nevertheless the difference was not substantial as performance was comparable. This enhancement of capillary absorption could be due to the low w/b ratio 0.39 and 0.41 in CEM II/AV and CEM III/A respectively, and the pozzolanic reaction between mineral admixtures and calcium hydroxide during the hydration process as mentioned previously. The graph shows that maximum reduction in penetration depth occurred in CEM II/A-D cured in AC and WC. The graph illustrates that inclusion of SF in the mix resulted in maximum reduction in penetration depth of specimens cured in WC. In fact, addition of SF reduced water penetration in both curing conditions by more than 45% in comparison to reference mix CEM I as shown in Figure 5.30. As stated previously, this improvement is mainly due to the pozzolanic reaction during the hydration process which leads to the formation of extra C-S-H, subsequently improving refinement of pore structure of concrete matrix and reducing porosity. Overall, results show that blended cements performed better than plain cement. Results are in agreement with previous findings (Baghabra et al., 2009; Uysal et al., 2012; Cappellesso et al., 2016)) as shown in Table 5.12.

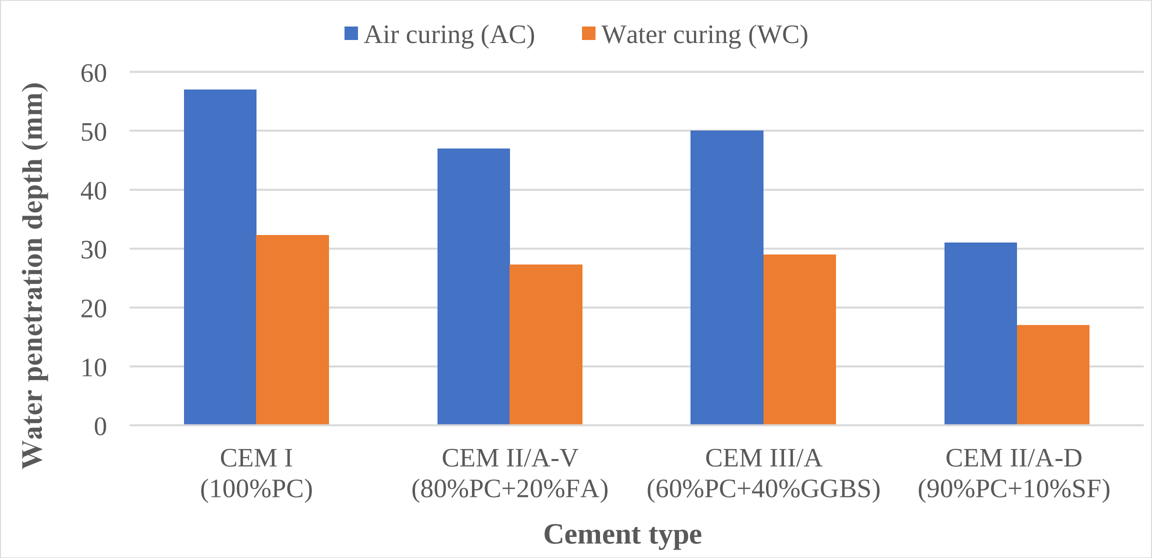


**Figure 5.29** Water penetration depth results of control cubes cured in air and water

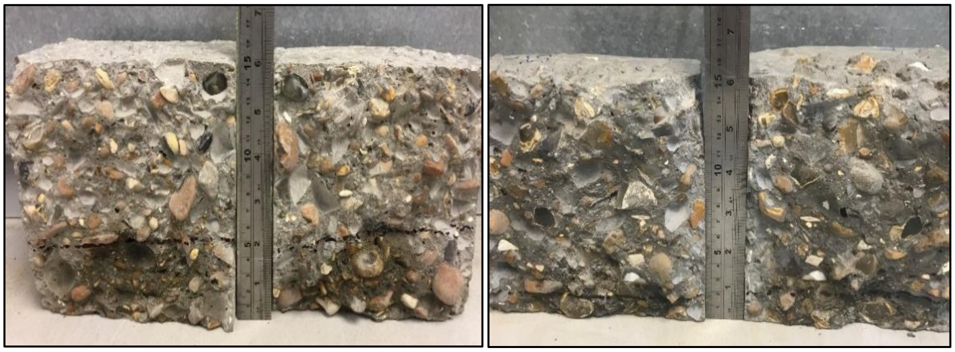
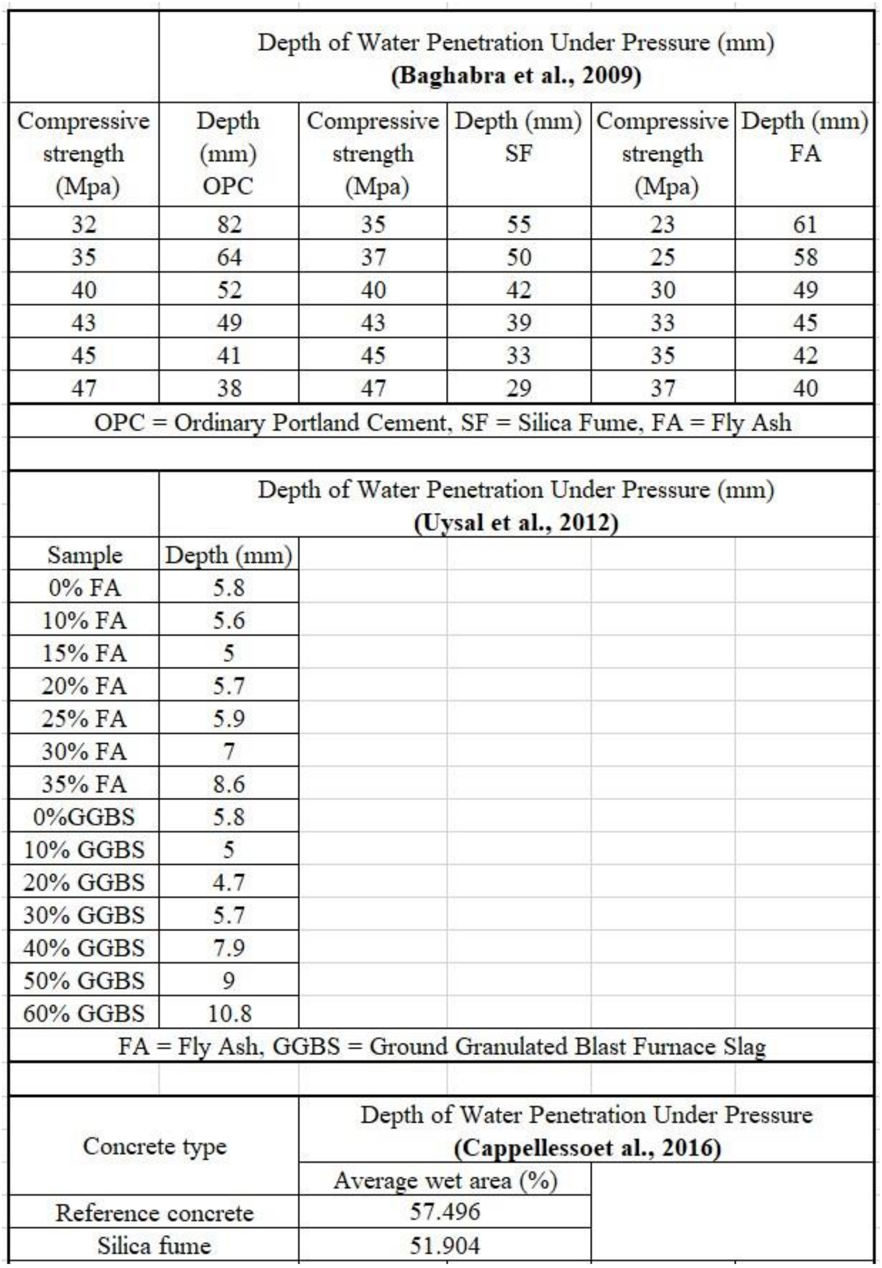


**Figure 5.30** Reduction in water penetration depth in CEM II/A-D due to inclusion of SF

**Table 5.12** Influence of mineral admixtures on depth of water penetration under pressure



| | Depth of Water Penetration Under Pressure (mm)<br>**(Baghabra et al., 2009)** | | | | |
|---|---|---|---|---|---|
| Compressive strength (Mpa) | Depth (mm) OPC | Compressive strength (Mpa) | Depth (mm) SF | Compressive strength (Mpa) | Depth (mm) FA |
| 32 | 82 | 35 | 55 | 23 | 61 |
| 35 | 64 | 37 | 50 | 25 | 58 |
| 40 | 52 | 40 | 42 | 30 | 49 |
| 43 | 49 | 43 | 39 | 33 | 45 |
| 45 | 41 | 45 | 33 | 35 | 42 |
| 47 | 38 | 47 | 29 | 37 | 40 |

OPC = Ordinary Portland Cement, SF = Silica Fume, FA = Fly Ash

| | Depth of Water Penetration Under Pressure (mm)<br>**(Uysal et al., 2012)** |
|---|---|
| Sample | Depth (mm) |
| 0% FA | 5.8 |
| 10% FA | 5.6 |
| 15% FA | 5 |
| 20% FA | 5.7 |
| 25% FA | 5.9 |
| 30% FA | 7 |
| 35% FA | 8.6 |
| 0%GGBS | 5.8 |
| 10% GGBS | 5 |
| 20% GGBS | 4.7 |
| 30% GGBS | 5.7 |
| 40% GGBS | 7.9 |
| 50% GGBS | 9 |
| 60% GGBS | 10.8 |

FA = Fly Ash, GGBS = Ground Granulated Blast Furnace Slag

| Concrete type | Depth of Water Penetration Under Pressure<br>**(Cappellessoet al., 2016)** |
|---|---|
| | Average wet area (%) |
| Reference concrete | 57.496 |
| Silica fume | 51.904 |

Results of specimens treated with CC and different admixtures to decrease water penetration depth in plain and blended cements are shown in Figure 5.31. Generally, results showed that treatment with Admixtures did not contribute to water penetration depth under pressure as reduction was insignificant. However, it was observed that specimens treated with Admix3 which is governed by hydrophobic effects performed better than corresponding cubes treated with Admix1 and Admix2 in plain and blended cement.

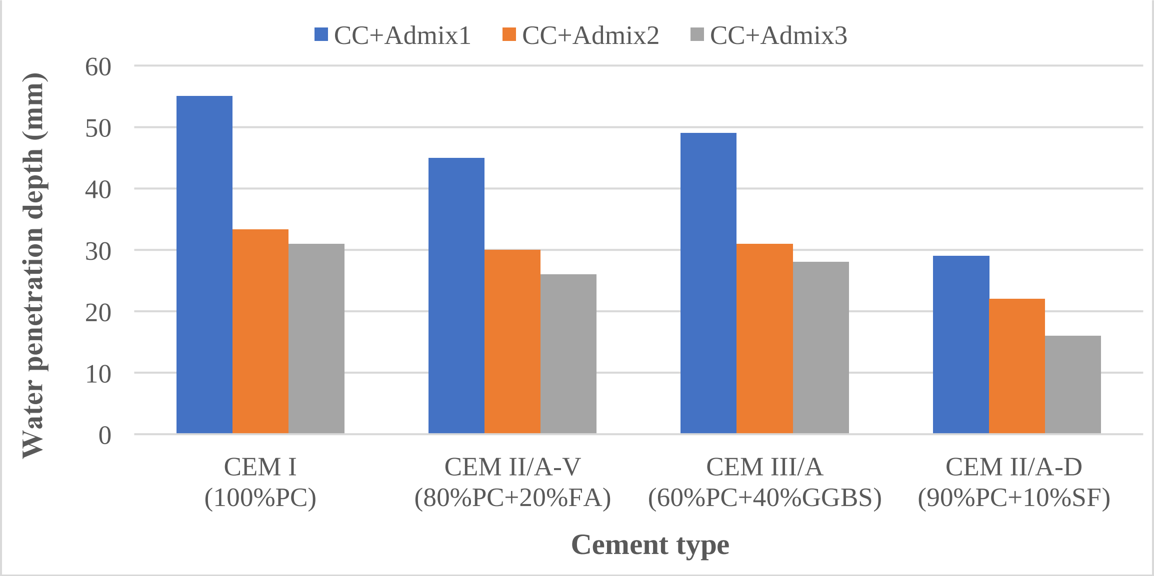
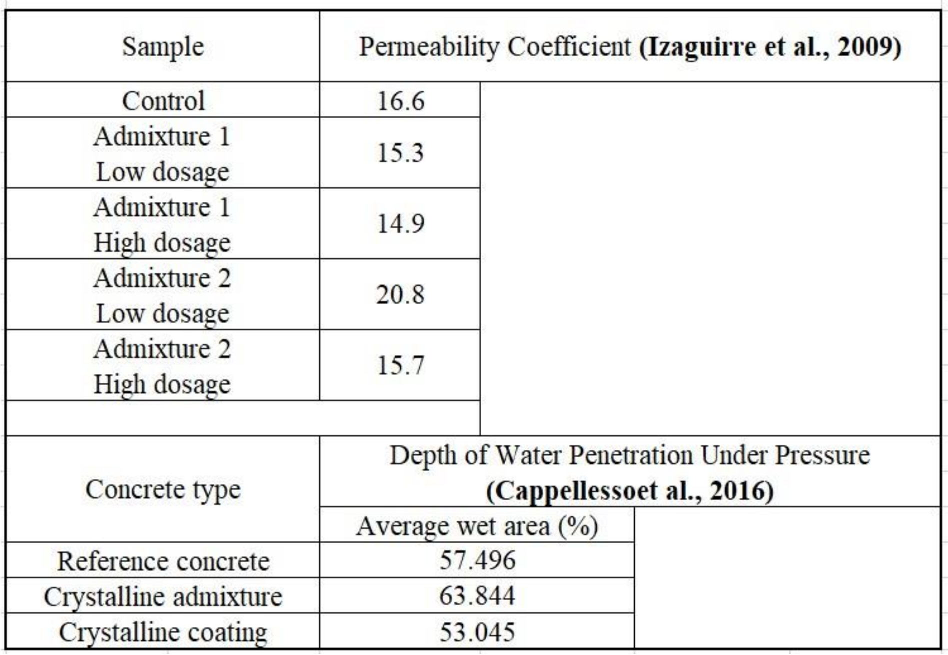


**Figure 5.31** Water penetration depth results of specimens treated with CC and admixtures

It should be stressed that although Admix2 is also influenced by hydrophobic effects, but its performance was not as good as Admix3. This could be due to the low dosage used in the mix which was half of the amount of Admix3. Generally, results indicated that treatment with admixtures governed by hydrophobic effects was more effective than crystalline actions. Nevertheless, it was observed that treatment with admixtures in cases where water under pressure is the main transport mechanism was ineffective as reduction percentage was small. Results are consistent with previous studies (Cappellesso et al., 2016; Izaguirre et al., 2009) as shown in Table 5.13.

**Table 5.13** Influence of waterproofing admixtures on depth of water penetration under pressure



| Sample | Permeability Coefficient **(Izaguirre et al., 2009)** |
|---|---|
| Control | 16.6 |
| Admixture 1<br>Low dosage | 15.3 |
| Admixture 1<br>High dosage | 14.9 |
| Admixture 2<br>Low dosage | 20.8 |
| Admixture 2<br>High dosage | 15.7 |

| Concrete type | Depth of Water Penetration Under Pressure **(Cappellessoet al., 2016)** |
|---|---|
| | Average wet area (%) |
| Reference concrete | 57.496 |
| Crystalline admixture | 63.844 |
| Crystalline coating | 53.045 |

Results of specimens treated with CC and different surface treatment to decrease water penetration depth in plain and blended cements are shown in Figure 5.32. Similar trend was observed as treatment with surface treatments did not reduce water penetration depth except treatment with ST2 which led to an insignificant reduction in comparison to control cubes cured in WC. It was observed that performance of cubes treated with ST3 was not as good as ST2 which could be attributed to reduction in concentration as it was diluted with water (ratio 1:3). Nevertheless, treatment with ST2 and ST3 agents acting as water repellent for hydrophobic impregnation performed greatly better than ST1 which provides protection by crystalline actions. Similar to admixtures, results showed that treatment with surface treatment did not achieve adequate efficiency in cases where water under pressure is the primary cause of transport mechanism. Results are in agreement with previous findings (Medeiros and Helene, 2008; Cappellesso et al., 2016) as shown in Table 5.14.

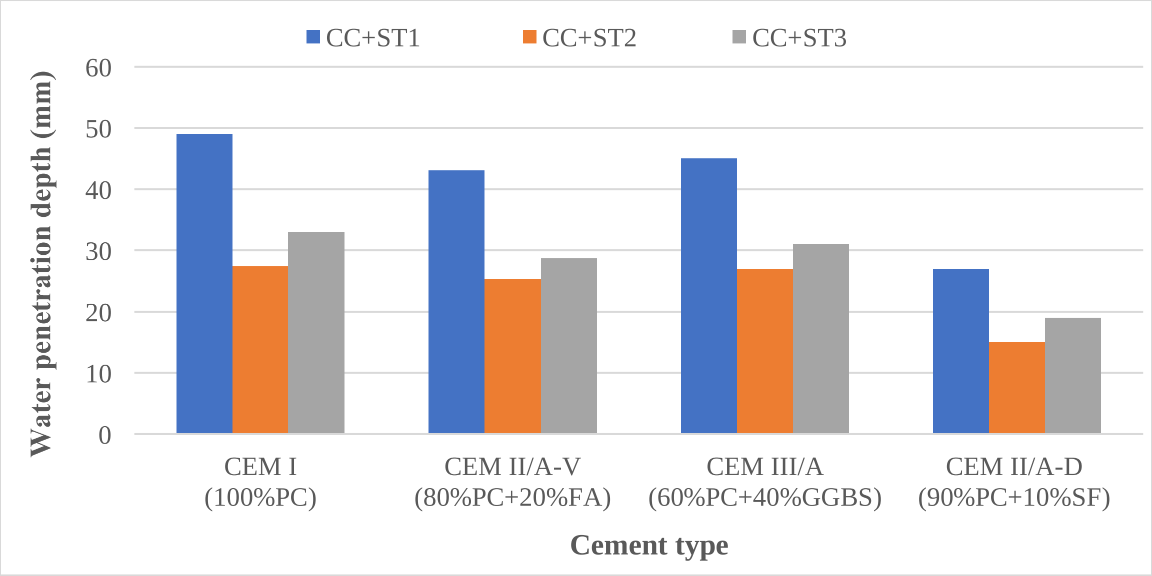
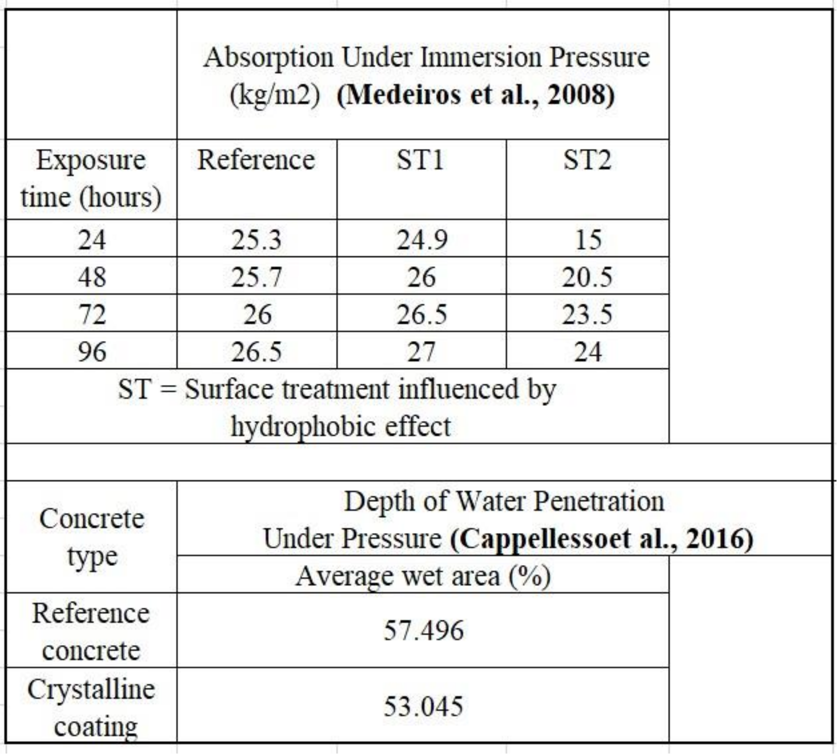


**Figure 5.32** Water penetration depth results of specimens treated with CC and surface treatments

**Table 5.14** Influence of surface treatment on depth of water penetration under pressure



| | Absorption Under Immersion Pressure (kg/m2) **(Medeiros et al., 2008)** | | |
|---|---|---|---|
| Exposure time (hours) | Reference | ST1 | ST2 |
| 24 | 25.3 | 24.9 | 15 |
| 48 | 25.7 | 26 | 20.5 |
| 72 | 26 | 26.5 | 23.5 |
| 96 | 26.5 | 27 | 24 |
| ST = Surface treatment influenced by hydrophobic effect | | | |

| Concrete type | Depth of Water Penetration Under Pressure **(Cappellessoet al., 2016)** |
|---|---|
| | Average wet area (%) |
| Reference concrete | 57.496 |
| Crystalline coating | 53.045 |

## 5.6 Concluding remarks

- Results showed that inclusion of mineral admixtures particularly SF and GGBS reduced initial surface absorption in both curing conditions (AC and WC). Maximum reduction was measured in CEM II/A-D, followed by CEM III/A and CEM II/A-V, this shows that surface absorption rate was influenced by the type and quantity of the cementitious material used in the mix.

- Irrespective of cement type, curing regime and type of protective material used for treatment, it was found that ISAT-10 values decreased as compressive strength of cubes increased. For instance, CEM II/A-D specimens cured in AC and WC experienced minimum surface absorption and developed highest compressive strength. Thus, an inverse relation was found between surface absorption and compressive strength.

- Treatment with admixtures influenced by hydrophobic effects (Admix2 and Admix3) showed more effectiveness than corresponding compounds governed by crystalline actions (Admix1). In fact, protection provided by crystallization mechanism did not inhibit surface water absorption. Therefore, use of this type of admixture did not contribute to performance improvement.

- Application of water repellent agents (ST2 and ST3) for hydrophobic impregnation of concrete surface significantly reduced surface water absorption. On the other hand, application of compounds governed by crystalline water proofing was less effective in reducing surface water absorption.

- Generally, treatment with curing compound and protective materials influenced by hydrophobic effects achieved low surface absorption rate.

- In terms of sorptivity, similar trend was found as incorporation of supplementary cementitious materials reduced capillary water absorption as minimum sorptivity coefficient was measured in blended cements whereas maximum coefficient was measured in plain cement.

- Maximum sorptivity reduction was measured in specimens treated with agents influenced by hydrophobic effects, particularly ST2 and ST3 as they caused significant reduction in capillary water absorption compared to counterpart admixtures.

- Efficiency of treatment with agent (ST1) governed by crystalline actions reduced with continuous exposure to water.

- Overall, application of surface treatments for hydrophobic impregnation was more effective than treatment with admixtures in reducing capillary water absorption.

- Permeability under pressure of blended cements was lower than plain cement. Maximum reduction was approximately 45% measured in CEM II/A-D mix compared to reference CEM I cubes cured in water.

- Treatment with admixtures and surface treatment to reduce water penetration depth under pressure was insignificant as reduction due to treatment mainly with agents influenced by hydrophobic effects was trivial. This shows that treatment with protective materials to improve impermeability of concrete exposed to water under pressure was ineffective. Nevertheless, it should be noted that treatment with hydrophobic agents was efficient in decreasing capillary suction which is considered as one of the main transport mechanism in non-saturated conditions (Kropp and Hilsdorf 1995) .

- Hydrophobic impregnation treatment achieved capillary absorption criteria ($< 0.1$ kg/m$^2$. h$^{0.5}$ in 24 hours) stated in BS EN 1504-2 (2004) and German Committee for Reinforced Concrete Guidelines (absorption reduction > 50%) in cases where capillary absorption is the main transport mechanism.

# Chapter 6: Durability Properties

## 6.1 Introduction

Having established the influence of transport properties on permeation properties of concrete as discussed in previous Chapter 5, this chapter investigates durability properties of concrete. As described previously, durability is the ability of concrete to resist weathering actions such as chemical and physical attacks or any other process causing deterioration. This means that properly designed, proportioned, placed, finished and cured concrete will maintain its form and quality with minimum maintenance. Lack of durability could potentially cause significant deterioration in concrete such as corrosion of reinforcing steel bars due to exposure to carbonation and chloride penetration in aggressive environment. In Phase 3, durability properties were thoroughly examined by carrying out accelerated carbonation test, resistance to scaling and chloride ponding tests as shown in Figure 6.1.

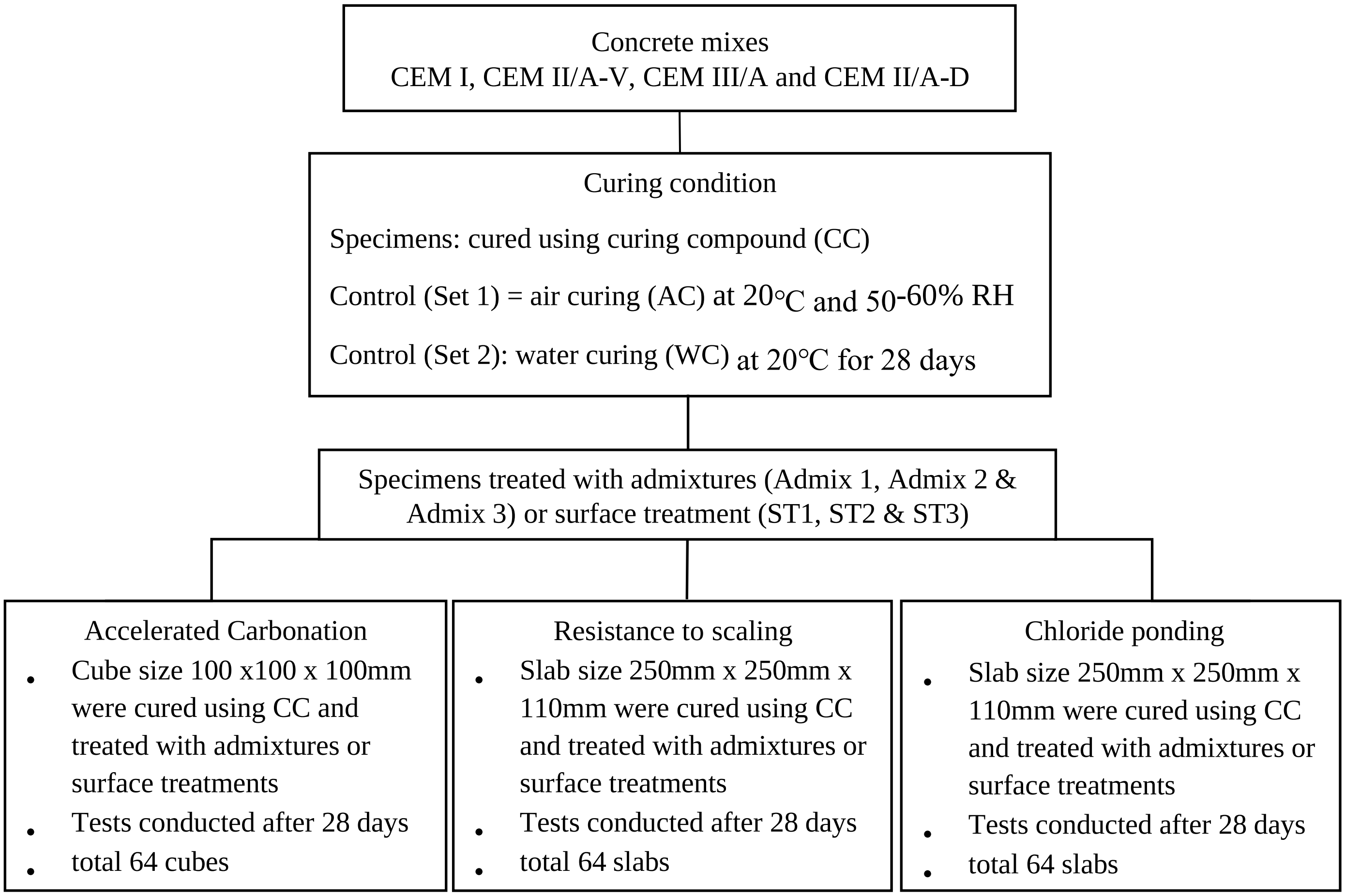


**Figure 6.1** Experimental work of Phase 3 – Durability Properties

In this phase, accelerated carbonation method was conducted to determine carbonation resistance of concrete cubes exposed to $CO_2$ for 150 days. At the end of exposure period, specimens were split and depth of carbonation was measured in mm using a phenolphthalein solution sprayed on the freshly split concrete surface. Resistance to scaling was conducted on concrete slabs to determine scaling resistance of concrete surface exposed to freezing and thawing cycles in the presence of deicing chemicals. Two slabs were casted and treated for each case and exposed to freezing and thawing conditions in the presence of 4% calcium chloride for 50 cycles in the environmental chamber. Performance of slabs was evaluated by comparing results with untreated control slabs exposed to same conditions.

On the other hand, to determine resistance of concrete to chloride ion penetration, slabs of similar size were casted and treated with CC and waterproofing admixtures or surface treatments and subjected to continuous ponding with 3% sodium chloride solution for 90 days. After completion of exposure period, slabs were left to dry and samples were collected at different depths (8 and 16mm) from all slabs to compare results of chemical analysis with untreated control samples cured in air and in water.

## 6.2 Experimental programme

## 6.3 Carbonation resistance

### 6.3.1 Carbonation resistance of CEM I (100%PC) concrete

Accelerated carbonation test was conducted using cube size 100mm as described in BS 1881-210 (2013). Performance of specimens were evaluated by comparing results with two sets of control cubes as shown in Table 6.1. The top, bottom and two opposite side faces of all cubes were coated with bitumen to allow $CO_2$ penetration only through the sides. All cubes were placed in the carbonation test chamber with $CO_2$ level of 4.0 ± 0.5% at 20 °C and 55% relative humidity for 150 days. Carbonation depth was determined by measuring the depth at five points on each exposed side using a ruler and the final depth was calculated as the mean value.

**Table 6.1** Concrete cubes used for carbonation test

| Cement type | Control cubes (AC) | Control cubes (WC) | Specimen CC + Admixtures | | | Specimen CC +Surface Treatments | | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | | | Admix1 | Admix2 | Admix3 | ST 1 | ST 2 | ST 3 | |
| CEM I | 2 Cubes | 2 Cubes | 2Cubes | 2 Cubes | 2 Cubes | 2 Cubes | 2 Cubes | 2 Cubes | 16 |
| CEM II/A-V | 2 Cubes | 2 Cubes | 2 Cubes | 2 Cubes | 2 Cubes | 2 Cubes | 2 Cubes | 2 Cubes | 16 |
| CEM III/A | 2 Cubes | 2 Cubes | 2 Cubes | 2 Cubes | 2 Cubes | 2 Cubes | 2 Cubes | 2 Cubes | 16 |
| CEM II/A-D | 2 Cubes | 2 Cubes | 2 Cubes | 2 Cubes | 2 Cubes | 2 Cubes | 2 Cubes | 2 Cubes | 16 |
| Grand total | 64 | | | | | | | | |

AC = air curing, WC = water curing, CC = curing compound, Admix1 = admixture 1, Admix2 = admixture 2, Admix3 = admixture 3, ST1 = surface treatment 1, ST2 = surface treatment 2, ST3 = surface treatment 3

Carbonation results of CEM I specimens with control cubes in both curing conditions are presented in Figure 6.2. It can be seen that highest carbonation depths were measured in untreated control cubes cured in AC and specimens treated with Admix1. On the other hand, minimum carbonation depth was 4.5 mm measured in specimens treated with ST2. The graph shows that performance of specimens treated ST3 was comparable to control samples cured in WC. Results show that treatment with ST1 did not improve performance against carbonation. It is clear from the graph that surface treatment with water repellent agents (ST2 and ST3) for hydrophobic impregnation of concrete surface contributed to carbonation resistance compared to control samples cured in WC. Moreover, performance of specimens cured with CC and treated with ST2 improved in comparison to specimens treated with other protective materials. Regardless of protection mechanisms (crystalline pore blockers and hydrophobic effects), admixtures did not provide protection against carbonation. Results are in agreement with previous findings (Basheer et al., 1997; Aguiar and Júnior, 2013; Zhu et al., 2013; Zhang et al., 2017) as shown in Table 6.2.

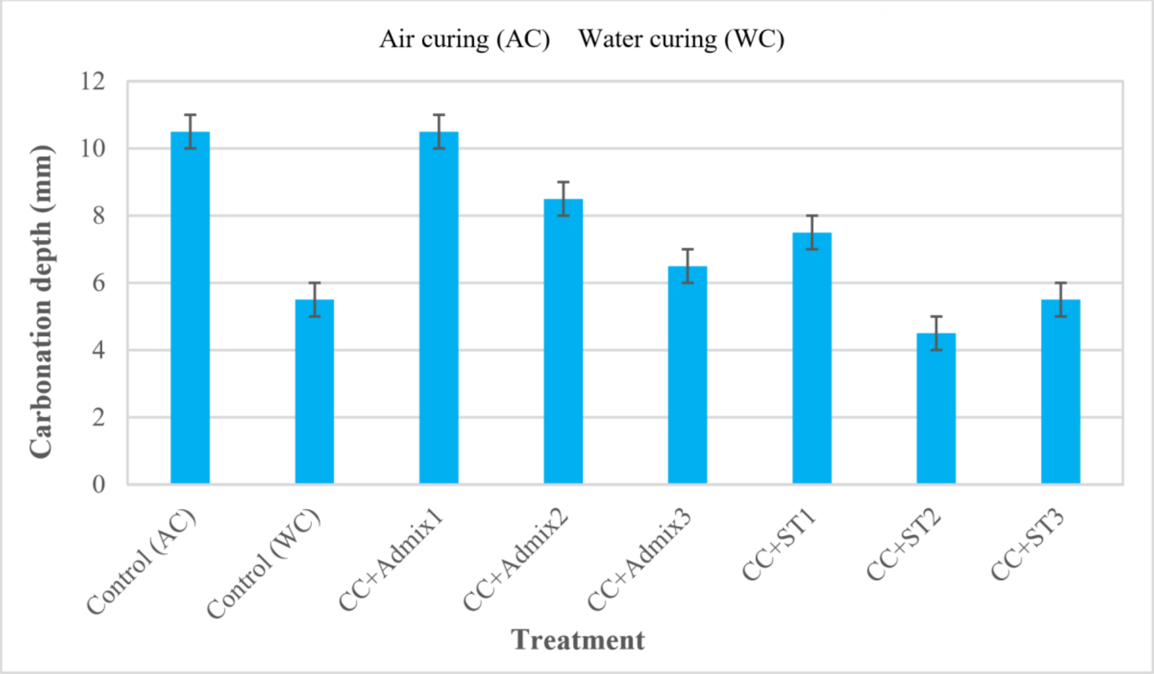
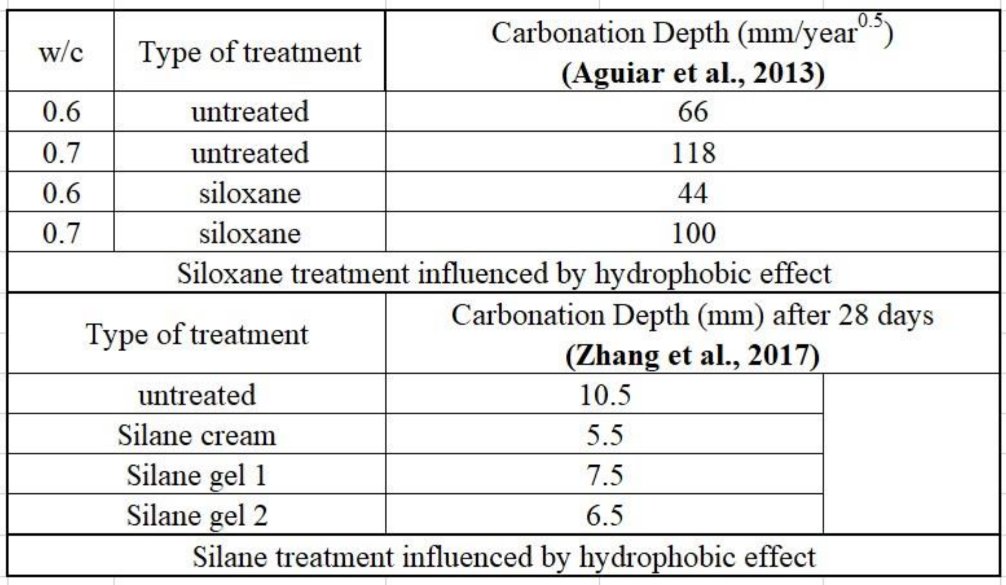


**Figure 6.2** Carbonation depths of CEM I concrete cubes

**Table 6.2** Influence of treatment on carbonation



| w/c | Type of treatment | Carbonation Depth (mm/year$^{0.5}$) **(Aguiar et al., 2013)** |
|---|---|---|
| 0.6 | untreated | 66 |
| 0.7 | untreated | 118 |
| 0.6 | siloxane | 44 |
| 0.7 | siloxane | 100 |
| Siloxane treatment influenced by hydrophobic effect | | |

| Type of treatment | Carbonation Depth (mm) after 28 days **(Zhang et al., 2017)** |
|---|---|
| untreated | 10.5 |
| Silane cream | 5.5 |
| Silane gel 1 | 7.5 |
| Silane gel 2 | 6.5 |
| Silane treatment influenced by hydrophobic effect | |

### 6.3.2 Carbonation resistance of CEM II/A-V (80%PC+20%FA) concrete

Carbonation depth results of CEM II/A-V specimens and control cubes in both curing regimes are shown in Figure 6.3. Similar trend was observed as maximum carbonation depths (17.5mm) were measured in untreated control cubes cured in AC and specimens treated with Admix1, whereas minimum depth was 8.5mm measured in in control cube cured in WC. Results show that treatment with admixtures and surface treatment did not improve carbonation resistance of cubes.

Moreover, results showed that inclusion of FA in the mix increased depth of carbonation in control cubes and treated specimens compared to reference concrete mix CEM I. It is well documented that the alkaline nature of concrete is mainly attributed to the presence of calcium hydroxide $Ca(OH)_2$. Replacement of PC with FA causes a reduction in $Ca(OH)_2$ content. The amount of $Ca(OH)_2$ in concrete is significant to control the rate of carbonation, as larger quantity of $CO_2$ is needed when higher level of $Ca(OH)_2$ is present. Thus, reduction in $Ca(OH)_2$ content leads to a decrease in the alkaline reserve (Mather, 2004; Newman and Choo, 2003; Ye et al., 2016; Khunthongkeaw et al., 2006). Results are consistent with previous researches (Marques et al., 2013; Sideris et al., 2006; Shi et al., 2009; Papadakis, 2000; Turk et al., 2013; Khan and Lynsdale, 2002) as shown in Table 6.3.

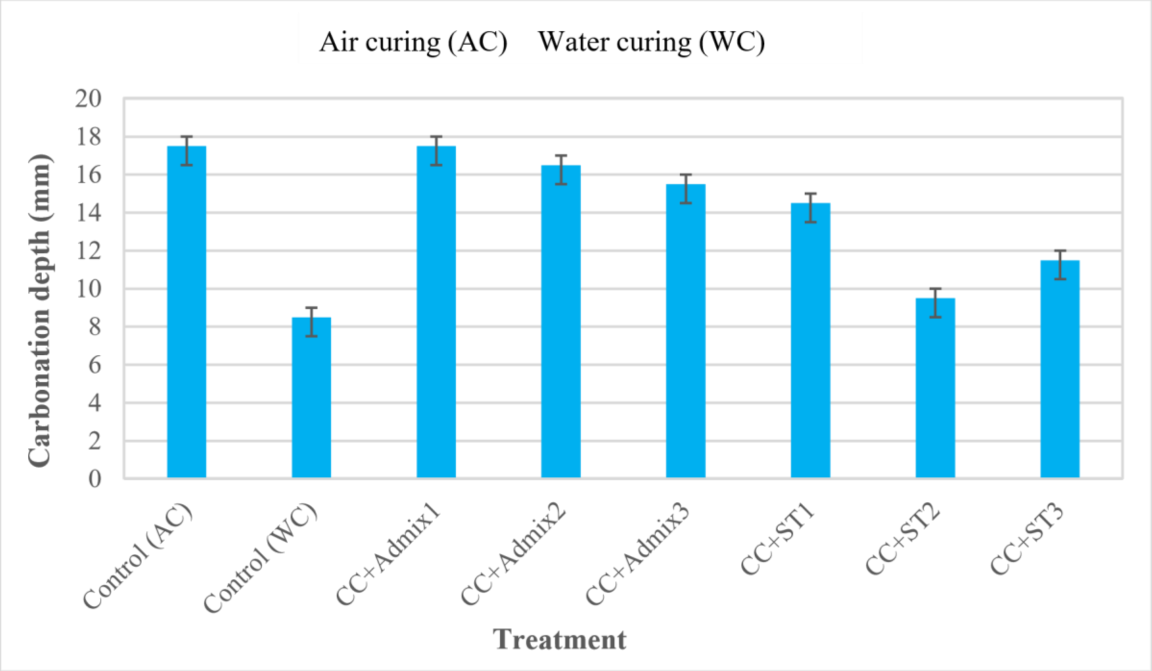
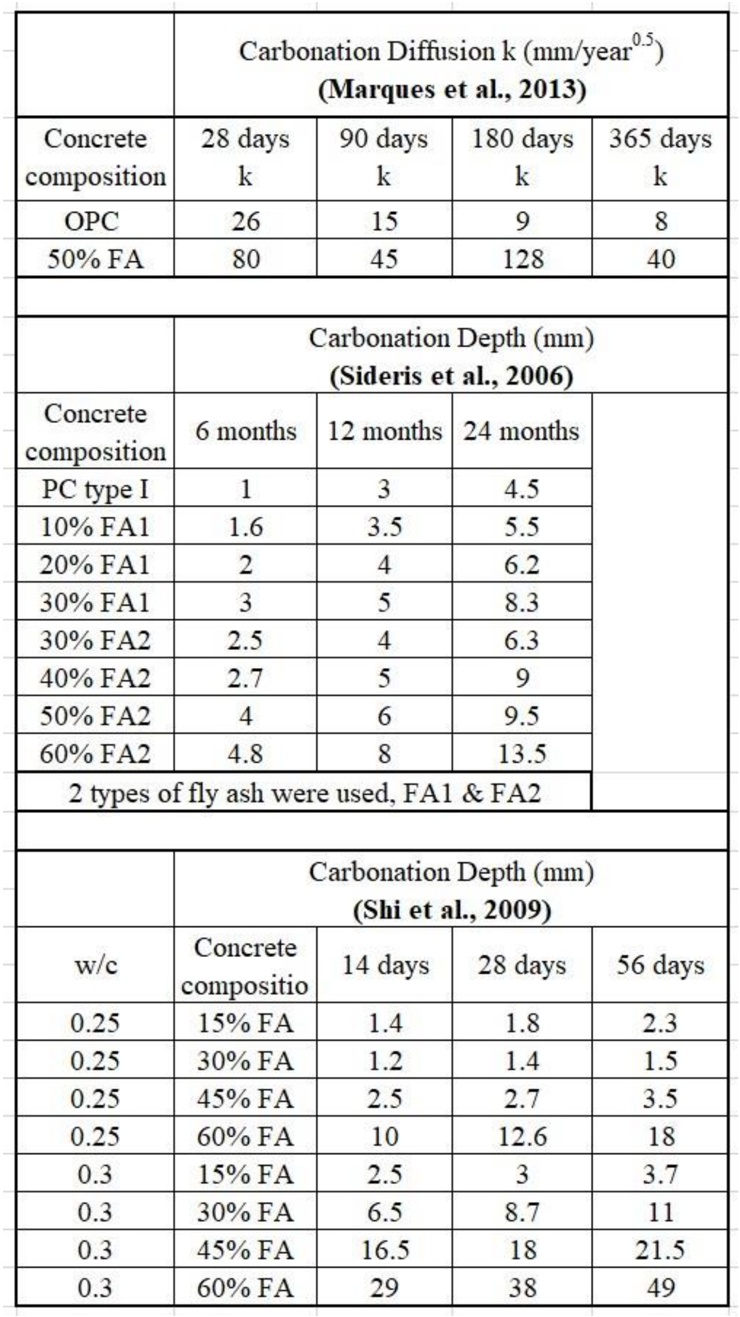


**Figure 6.3** Carbonation depths of CEM II/A-V concrete cubes

**Table 6.3** Influence of fly ash on carbonation depth



| | Carbonation Diffusion k (mm/year$^{0.5}$)<br>**(Marques et al., 2013)** | | | |
|---|---|---|---|---|
| Concrete composition | 28 days k | 90 days k | 180 days k | 365 days k |
| OPC | 26 | 15 | 9 | 8 |
| 50% FA | 80 | 45 | 128 | 40 |

| | Carbonation Depth (mm)<br>**(Sideris et al., 2006)** | | |
|---|---|---|---|
| Concrete composition | 6 months | 12 months | 24 months |
| PC type I | 1 | 3 | 4.5 |
| 10% FA1 | 1.6 | 3.5 | 5.5 |
| 20% FA1 | 2 | 4 | 6.2 |
| 30% FA1 | 3 | 5 | 8.3 |
| 30% FA2 | 2.5 | 4 | 6.3 |
| 40% FA2 | 2.7 | 5 | 9 |
| 50% FA2 | 4 | 6 | 9.5 |
| 60% FA2 | 4.8 | 8 | 13.5 |
| 2 types of fly ash were used, FA1 & FA2 | | | |

| | Carbonation Depth (mm)<br>**(Shi et al., 2009)** | | | |
|---|---|---|---|---|
| w/c | Concrete compositio | 14 days | 28 days | 56 days |
| 0.25 | 15% FA | 1.4 | 1.8 | 2.3 |
| 0.25 | 30% FA | 1.2 | 1.4 | 1.5 |
| 0.25 | 45% FA | 2.5 | 2.7 | 3.5 |
| 0.25 | 60% FA | 10 | 12.6 | 18 |
| 0.3 | 15% FA | 2.5 | 3 | 3.7 |
| 0.3 | 30% FA | 6.5 | 8.7 | 11 |
| 0.3 | 45% FA | 16.5 | 18 | 21.5 |
| 0.3 | 60% FA | 29 | 38 | 49 |

### 6.3.3 Carbonation resistance of CEM III/A (60%PC+40%GGBS) concrete

Carbonation penetration depths of CEM III/A specimens and control samples cured in both curing conditions are presented in Figure 6.4. Similar trend was observed as maximum carbonation depths (16.5mm and 15.5mm) were measured in untreated control cubes cured in AC and specimens treated with Admix1 respectively, whereas minimum depth was 7.5mm measured in in control cube cured in WC and specimens treated with ST2. Apart from ST2 whose performance was comparable to control samples cured in WC, results show that treatment with admixtures and surface treatments did not improve carbonation resistance of cubes. Furthermore, incorporation of GGBS in the mix adversely affected performance as depth of carbonation increased in comparison to reference concrete mix (CEM I). This is probably due to reduction in the alkaline reserve of the mix as replacement of PC with GGBS leads to a decrease in the amount of $Ca(OH)_2$ in concrete, which is important to control rate of carbonation. Results indicated that addition of GGBS in the mix slightly reduced carbonation depth compared to inclusion of FA in CEM II/A-V. Nevertheless, both mineral admixtures increased carbonation depths in comparison to CEM I reference mix. Results are in agreement with findings of previous studies (Shi et al., 2009; Peethamparan et al., 2003; Lye et al., 2016; Ye et al., 2016; Divsholi et al., 2014;Ayub et al. 2013) as shown in Table 6.4.

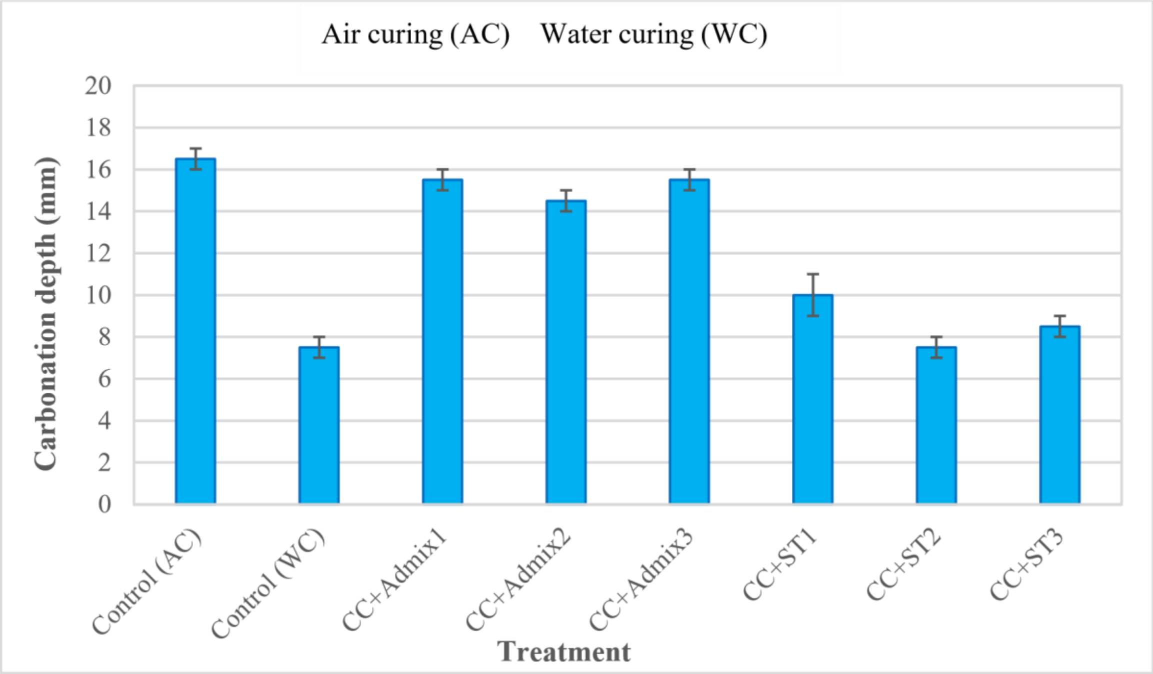
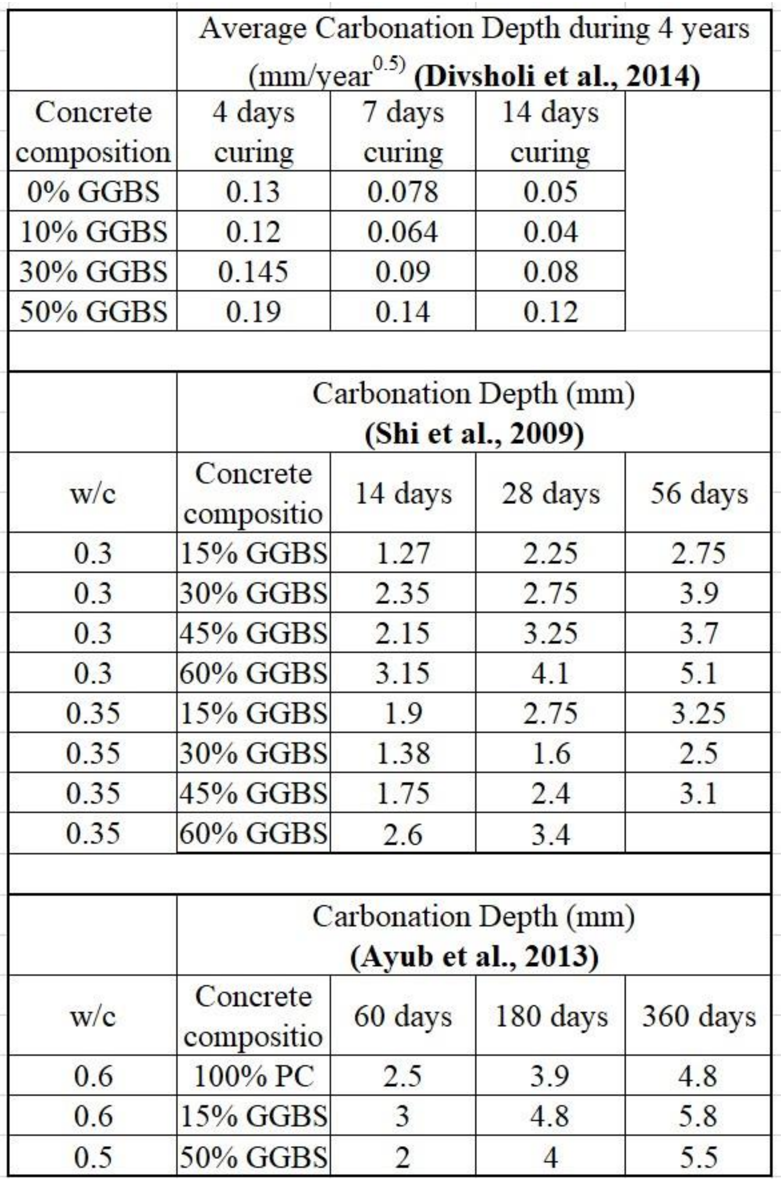


**Figure 6.4** Carbonation depths of CEM III/A concrete cubes

**Table 6.4** Influence of GGBS on carbonation depth



| | Average Carbonation Depth during 4 years (mm/year$^{0.5)}$ **(Divsholi et al., 2014)** | | | |
|---|---|---|---|---|
| Concrete composition | 4 days curing | 7 days curing | 14 days curing | |
| 0% GGBS | 0.13 | 0.078 | 0.05 | |
| 10% GGBS | 0.12 | 0.064 | 0.04 | |
| 30% GGBS | 0.145 | 0.09 | 0.08 | |
| 50% GGBS | 0.19 | 0.14 | 0.12 | |

| | Carbonation Depth (mm) **(Shi et al., 2009)** | | | |
|---|---|---|---|---|
| w/c | Concrete compositio | 14 days | 28 days | 56 days |
| 0.3 | 15% GGBS | 1.27 | 2.25 | 2.75 |
| 0.3 | 30% GGBS | 2.35 | 2.75 | 3.9 |
| 0.3 | 45% GGBS | 2.15 | 3.25 | 3.7 |
| 0.3 | 60% GGBS | 3.15 | 4.1 | 5.1 |
| 0.35 | 15% GGBS | 1.9 | 2.75 | 3.25 |
| 0.35 | 30% GGBS | 1.38 | 1.6 | 2.5 |
| 0.35 | 45% GGBS | 1.75 | 2.4 | 3.1 |
| 0.35 | 60% GGBS | 2.6 | 3.4 | |

| | Carbonation Depth (mm) **(Ayub et al., 2013)** | | | |
|---|---|---|---|---|
| w/c | Concrete compositio | 60 days | 180 days | 360 days |
| 0.6 | 100% PC | 2.5 | 3.9 | 4.8 |
| 0.6 | 15% GGBS | 3 | 4.8 | 5.8 |
| 0.5 | 50% GGBS | 2 | 4 | 5.5 |

### 6.3.4 Carbonation resistance of CEM II/A-D (90%PC+10%SF) concrete

Carbonation depth results of CEM II/A-D specimens and control samples cured in both curing regimes are shown in Figure 6.5. It can be seen that similar trend was observed as control cubes cured in AC, followed by specimens treated with admixtures exhibited highest carbonation depths. On the other hand, lowest carbonation depths were 4 and 4.5mm measured in control cubes cured in WC and specimens treated with ST2 respectively. Results show that treatment with admixtures and surface treatments did not improve carbonation resistance of cubes except treatment with ST2 which was to some extent comparable to control samples cured in WC. Nevertheless, no reduction in carbonation depth was observed in specimens treated with admixtures and surface treatment agents. It should be stressed that inclusion of SF in the mix improved resistance to carbonation as penetration depths were reduced in comparison to mixes containing FA and GGBS. Moreover, results showed addition of SF reduced carbonation depths of control cubes cured in WC compared to corresponding cubes of CEM I cubes cured in water. This reduction in carbonation depth could be associated to the pozzolanic reaction in the presence of SF which leads to pore refinement of concrete matrix, thus causing reduction in permeability and gas diffusivity. Moreover, lower replacement level of PC with SF compared to FA and GGBS, means more amount of calcium hydroxide $Ca(OH)_2$ present in concrete which is responsible for the alkaline nature of concrete. Results are in agreement with findings of previous studies (Ghahari et al., 2016; Kulakowski et al., 2009; McPolin et al., 2009; Turk et al., 2013) as shown in Table 6.5.

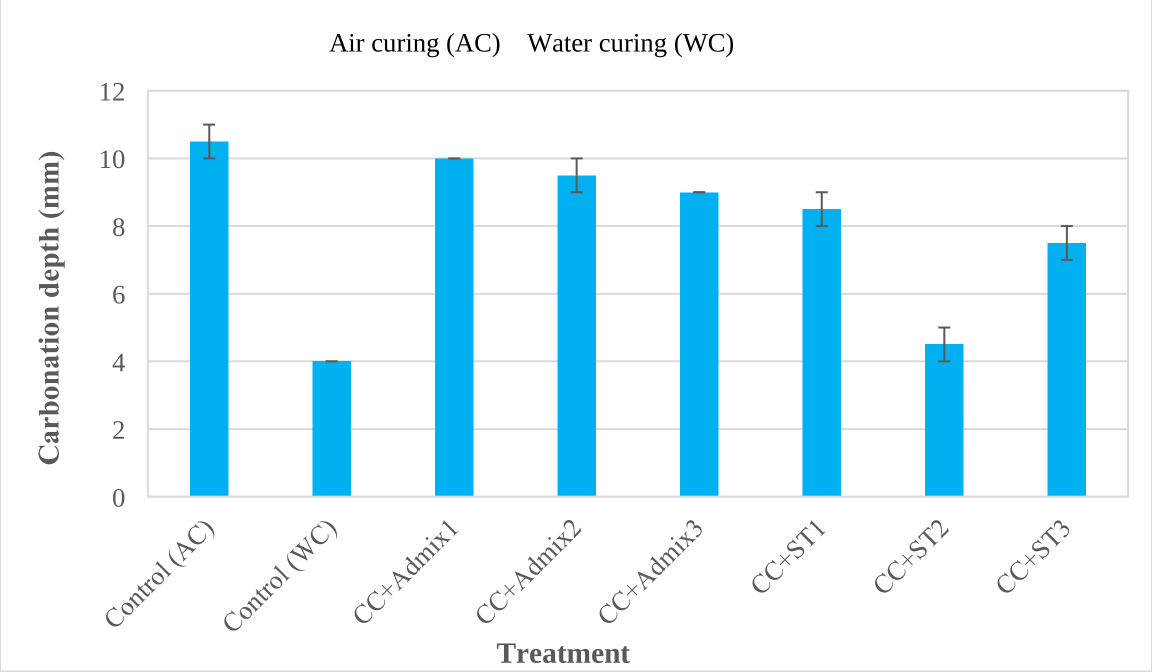
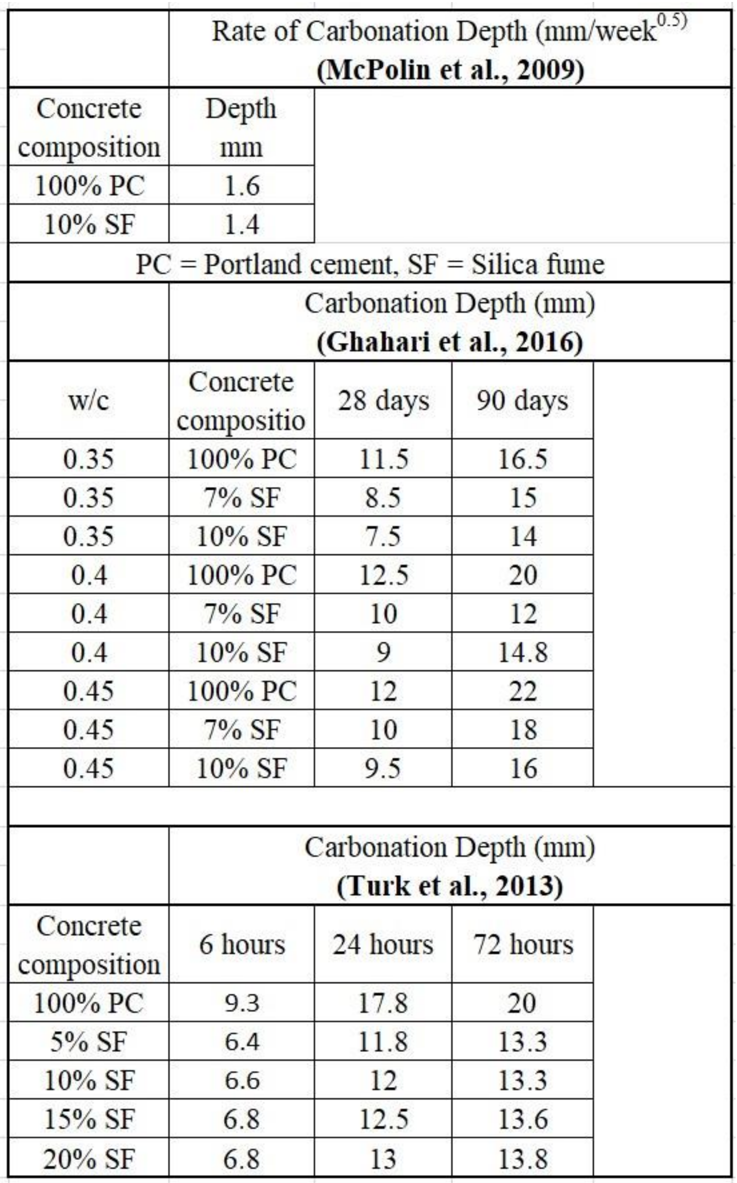


**Figure 6.5** Carbonation depths of CEM II/A-D concrete cubes

**Table 6.5** Influence of silica fume on carbonation depth



| | Rate of Carbonation Depth (mm/week$^{0.5)}$ **(McPolin et al., 2009)** |
|---|---|
| Concrete composition | Depth mm |
| 100% PC | 1.6 |
| 10% SF | 1.4 |
| PC = Portland cement, SF = Silica fume | |

| | Carbonation Depth (mm) **(Ghahari et al., 2016)** | | |
|---|---|---|---|
| w/c | Concrete compositio | 28 days | 90 days |
| 0.35 | 100% PC | 11.5 | 16.5 |
| 0.35 | 7% SF | 8.5 | 15 |
| 0.35 | 10% SF | 7.5 | 14 |
| 0.4 | 100% PC | 12.5 | 20 |
| 0.4 | 7% SF | 10 | 12 |
| 0.4 | 10% SF | 9 | 14.8 |
| 0.45 | 100% PC | 12 | 22 |
| 0.45 | 7% SF | 10 | 18 |
| 0.45 | 10% SF | 9.5 | 16 |

| | Carbonation Depth (mm) **(Turk et al., 2013)** | | |
|---|---|---|---|
| Concrete composition | 6 hours | 24 hours | 72 hours |
| 100% PC | 9.3 | 17.8 | 20 |
| 5% SF | 6.4 | 11.8 | 13.3 |
| 10% SF | 6.6 | 12 | 13.3 |
| 15% SF | 6.8 | 12.5 | 13.6 |
| 20% SF | 6.8 | 13 | 13.8 |

### 6.3.5 Comparison of CEM II/A-V, CEM III/A and CEM II/A-D with CEM I

Carbonation depths of all cement types treated with admixtures and surface treatments along with control cubes cured in both curing conditions are presented in Figure 6.6. It can be seen that control cubes produced from CEM II/A-D cement and cured in WC exhibited minimum carbonation depth (4mm), followed by control cubes of CEM I cubes cured in water (5.5mm) as shown in Figure 6.7. On the other hand, highest carbonation depths were measured in control cubes cured in AC and specimens treated with Admix1. This shows that control cubes cured in water experienced better hydration process than corresponding cubes cured in air, thus experienced less permeability and diffusivity.

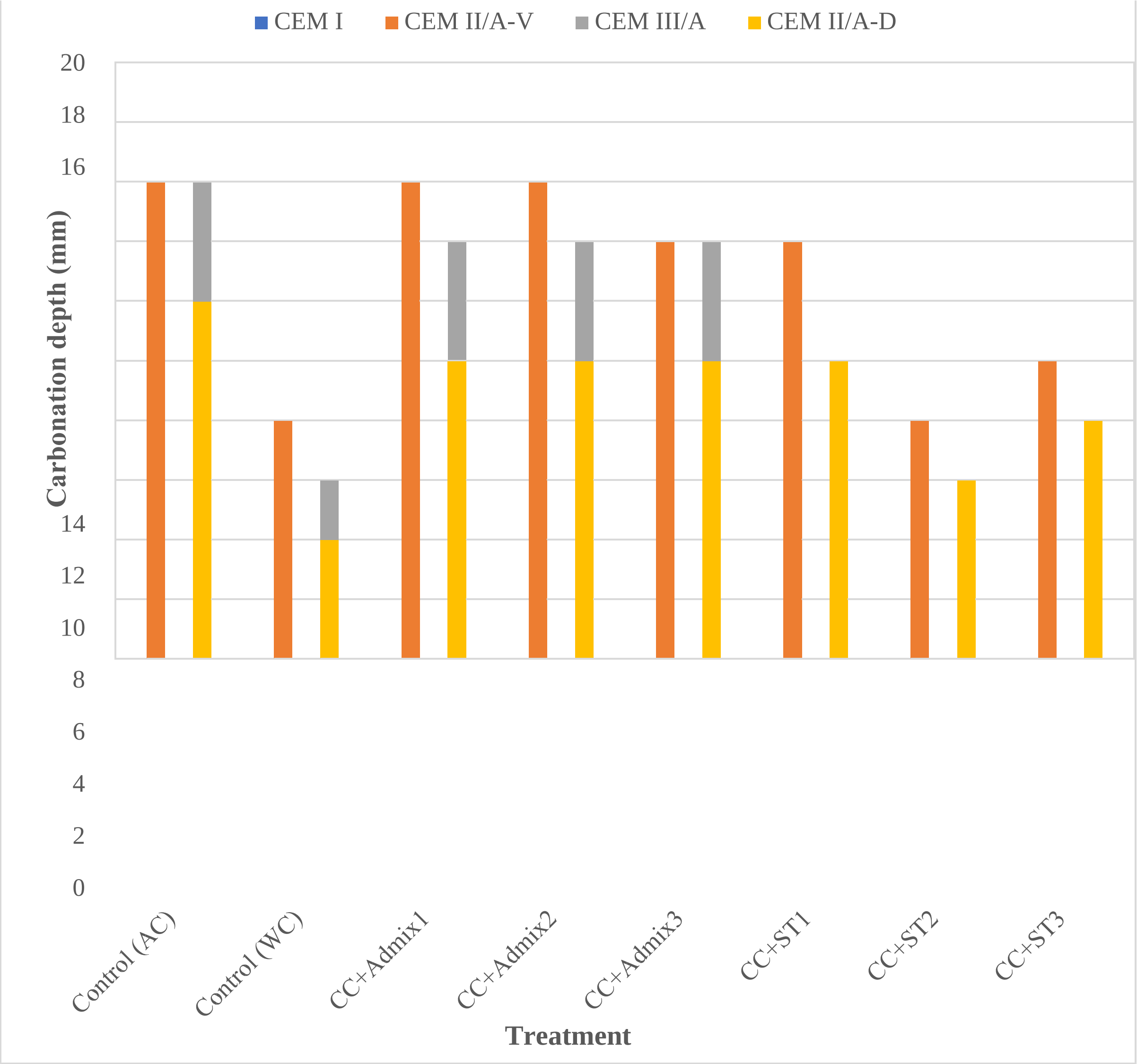
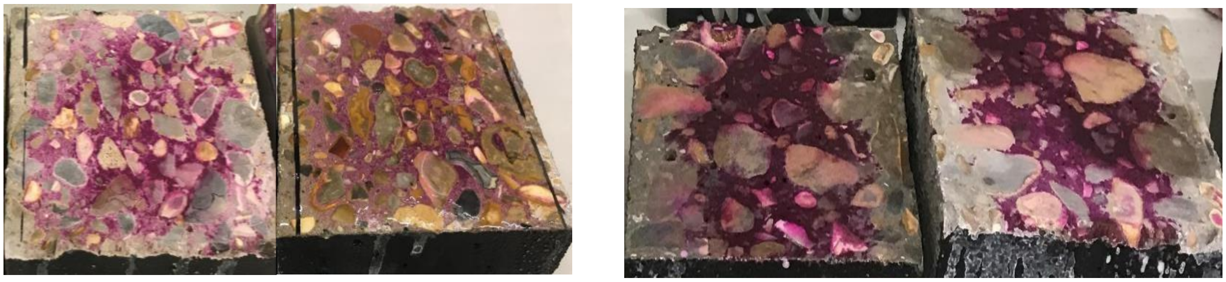


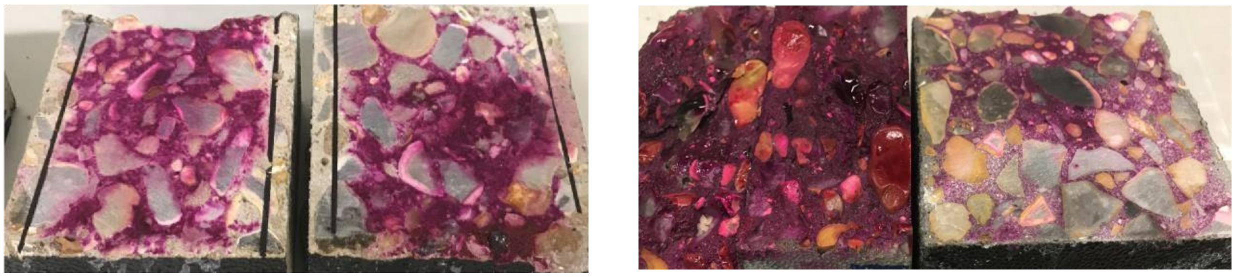
**Figure 6.6** Carbonation depths of all cement types

It was found that inclusion of SF in the mix, increased carbonation resistance due to refinement in the pore structure of concrete matrix, hence reduced permeability and diffusivity. In contrast, addition of FA and GGBS reduced carbonation resistance of concrete as replacement of PC with FA and GGBS decreased the amount of calcium hydroxide in concrete which is significant to control carbonation rate as it is vital for the alkaline nature of concrete. Moreover, results showed that treatment with admixtures and surface treatments did not improve carbonation resistance of treated specimens. Nevertheless, performance of cubes treated with ST2 slightly reduced carbonation depth in CEM I specimens and was comparable to some extent to control cubes of blended cements cured in WC.



CEM I

CEM II/A-V



CEM III/A

CEM II/A-D

**Figure 6.7** Carbonated samples of all cement types cured in water

## 6.4 Scaling resistance of concrete surface exposed to deicing chemical

### 6.4.1 Scaling resistance of CEM I (100%PC) concrete mix

Scaling resistance of concrete surface subjected to freezing and thawing cycles in the presence of a solution of calcium chloride acting as a deicing chemical was carried out on slab size 250mm x 250mm x 110mm in accordance with ASTM C672 (2012). Performance of treated slabs was evaluated by comparing results with two set of control samples as shown in Table 6.6. Slabs were placed in the environmental chamber to undergo freezing and thawing for 50 cycles. Visual examination and collection of loose material to determine scaled weight over 50 cycles, and mass loss was calculated as the average cumulative scaled weight.

**Table 6.6** Concrete slabs used for surface scaling resistance test

| Cement type | Control cubes (AC) | Control cubes (WC) | Specimen CC + Admixtures | | | Specimen CC +Surface Treatments | | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | | | Admix1 | Admix2 | Admix3 | ST 1 | ST 2 | ST 3 | |
| CEM I | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 16 |
| CEM II/A-V | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 16 |
| CEM III/A | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 16 |
| CEM II/A-D | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 16 |
| Grand total | 64 | | | | | | | | |

AC = air curing, WC = water curing, CC = curing compound, Admix1 = admixture 1, Admix2 = admixture 2, Admix3 = admixture 3, ST1 = surface treatment 1, ST2 = surface treatment 2, ST3 = surface treatment 3

Results of scaling resistance of CEM I specimens with control samples in both curing conditions are presented in Figure 6.8. It can be seen that the majority of scaling occurred from cycle 20 onward and scaling increased with time. The graph shows that curing in air (AC) significantly reduced scaling resistance of concrete surface. Results show that resistance of slabs treated with Admix1 was slightly lower than control samples cured in water (WC). Whereas resistance of slabs treated with Admix3 was higher than corresponding specimens treated with Admix2 as scaling was reduced by 53% and 49% respectively compared to reference slabs cured in WC. This may be attributed to the higher dosage of Admix3 which is double the amount of Admix2. On the other hand, application of surface treatment agents, particularly ST2 and ST3 on concrete surface was effective in improving scaling resistance of concrete surface. Results demonstrated that treatment with ST1, ST2 and ST3 reduced surface scaling by 57%, 70% and 64% respectively in comparison to control samples cured in WC.

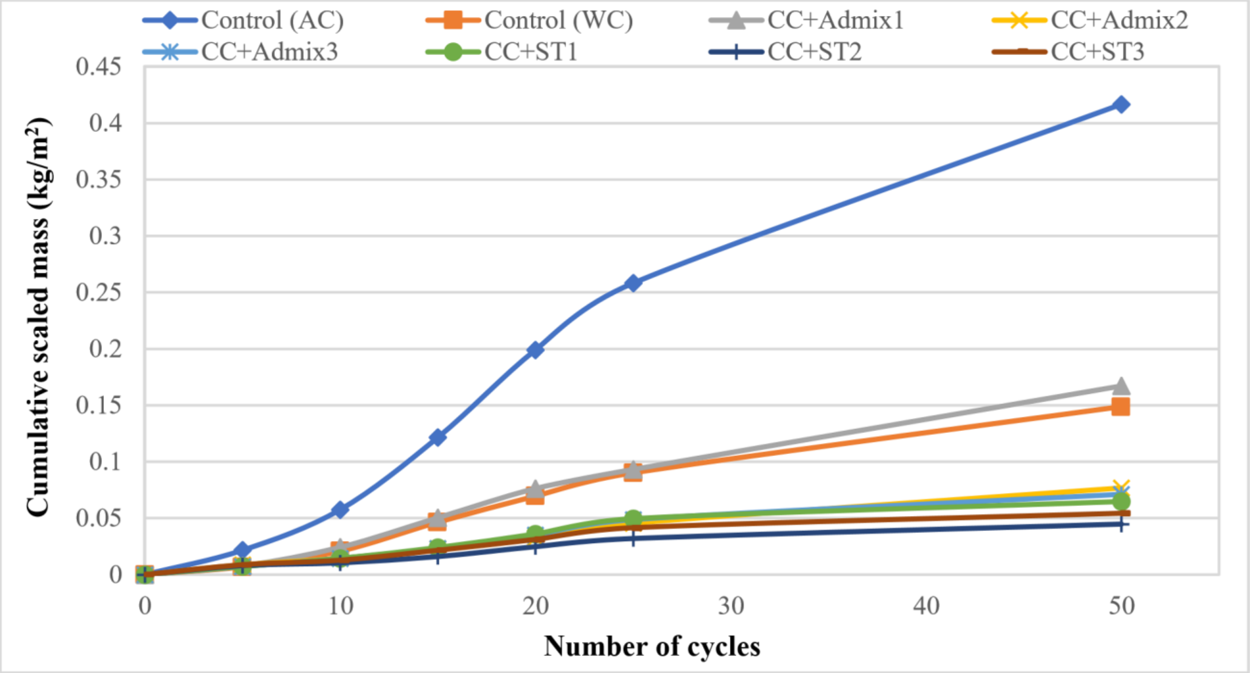


**Figure 6.8** Scaling resistance of CEM I concrete slabs

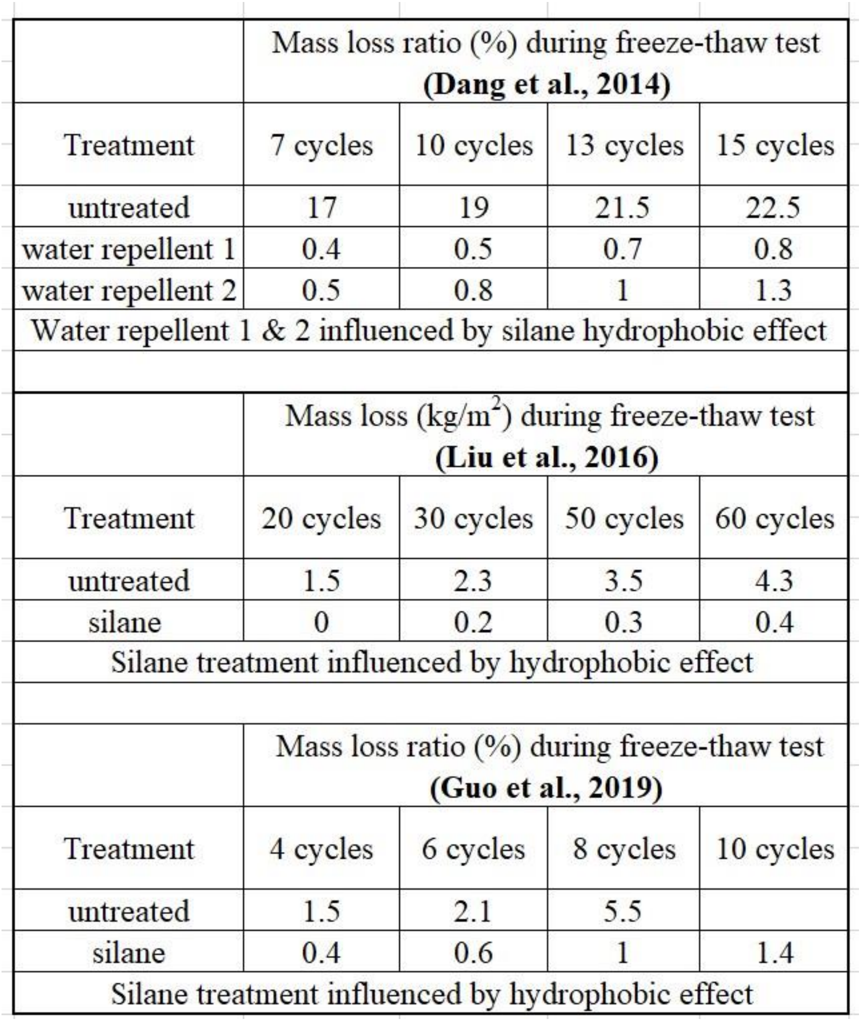
Based on scaling rating specified in ASTM C672 presented in Table 6.7, visual observation showed that treated slabs (except treatment with Admix1) did not exhibit severe scaling compared to untreated control samples cured in AC and WC as shown in Figure 6.9. In fact, slabs treated with ST2 and ST3 remained almost intact. Results indicated that application of surface treatment agents (ST1, ST2 and ST3) was more effective than inclusion of admixtures (Admix1, Admix2 and Admix3) to improve scaling resistance of concrete. Moreover, treatment with water repellent agents (ST2 and ST3) for hydrophobic impregnation was more efficient than compounds governed by crystalline pore blocking compounds (ST1). Numerous studies (Liu et al., 2016; Dang et al., 2014; Basheer and Cleland, 2006) reported that improvement in scaling resistance of concrete surface is attributed to the hydrophobic impregnation treatment which acts as a barrier on the surface preventing penetration of external liquid containing chloride.

Results are in agreement with previous researches (Zhao et al., 2010; Guo and Weng, 2019; Liu et al., 2016; Dang et al., 2014; Basheer and Cleland, 2006) as shown in Table 6.8.

**Table 6.7** Surface scaling rating according to ASTM C 672

| Visual Rating | Surface Condition |
|---|---|
| 0 | No scaling |
| 1 | Very slight scaling (3 mm depth, max, no coarse aggregate visible) |
| 2 | Slight to moderate scaling |
| 3 | Moderate scaling (some coarse aggregate visible) |
| 4 | Moderate to severe scaling |
| 5 | Severe scaling (coarse aggregate visible over entire surface) |

**Table 6.8** Influence of surface treatment on scaling resistance



| | Mass loss ratio (%) during freeze-thaw test<br>**(Dang et al., 2014)** | | | |
|---|---|---|---|---|
| Treatment | 7 cycles | 10 cycles | 13 cycles | 15 cycles |
| untreated | 17 | 19 | 21.5 | 22.5 |
| water repellent 1 | 0.4 | 0.5 | 0.7 | 0.8 |
| water repellent 2 | 0.5 | 0.8 | 1 | 1.3 |
| Water repellent 1 & 2 influenced by silane hydrophobic effect | | | | |

| | Mass loss (kg/m$^2$) during freeze-thaw test<br>**(Liu et al., 2016)** | | | |
|---|---|---|---|---|
| Treatment | 20 cycles | 30 cycles | 50 cycles | 60 cycles |
| untreated | 1.5 | 2.3 | 3.5 | 4.3 |
| silane | 0 | 0.2 | 0.3 | 0.4 |
| Silane treatment influenced by hydrophobic effect | | | | |

| | Mass loss ratio (%) during freeze-thaw test<br>**(Guo et al., 2019)** | | | |
|---|---|---|---|---|
| Treatment | 4 cycles | 6 cycles | 8 cycles | 10 cycles |
| untreated | 1.5 | 2.1 | 5.5 | |
| silane | 0.4 | 0.6 | 1 | 1.4 |
| Silane treatment influenced by hydrophobic effect | | | | |

Control (AC) Control (WC)

Admix1 Admix2

Admix3 ST1

ST2 ST3

**Figure 6.9** Visual evaluation of CEM I concrete slabs before (left) and after (right) test

### 6.4.2 Scaling resistance of CEM II/A-V (80%PC+20%FA) concrete mix

Results of surface scaling of CEM II/A-V specimens treated with admixtures and surface treatments along with reference slabs are shown in Figure 6.10 and 6.11 respectively. It can be seen that control slabs cured in AC exhibited significant scaling, while performance of control samples cured in WC and specimens treated with Admix1 was comparable to some extent. Similar trend was observed as scaling resistance of slabs treated with Admix3 was higher than corresponding slabs treated with Admix2. In terms of treatment with admixtures, results show that treatment with Admix3 significantly improved scaling resistance in comparison to control slabs in both curing conditions. On the other hand, treatment with surface treatment agents, particularly ST2 and ST3 significantly improved scaling resistance of concrete surface. Results indicated that optimum performance was observed in slabs treated with ST2, followed by slabs treated with ST3, ST1, Admix3 and Admix 2.

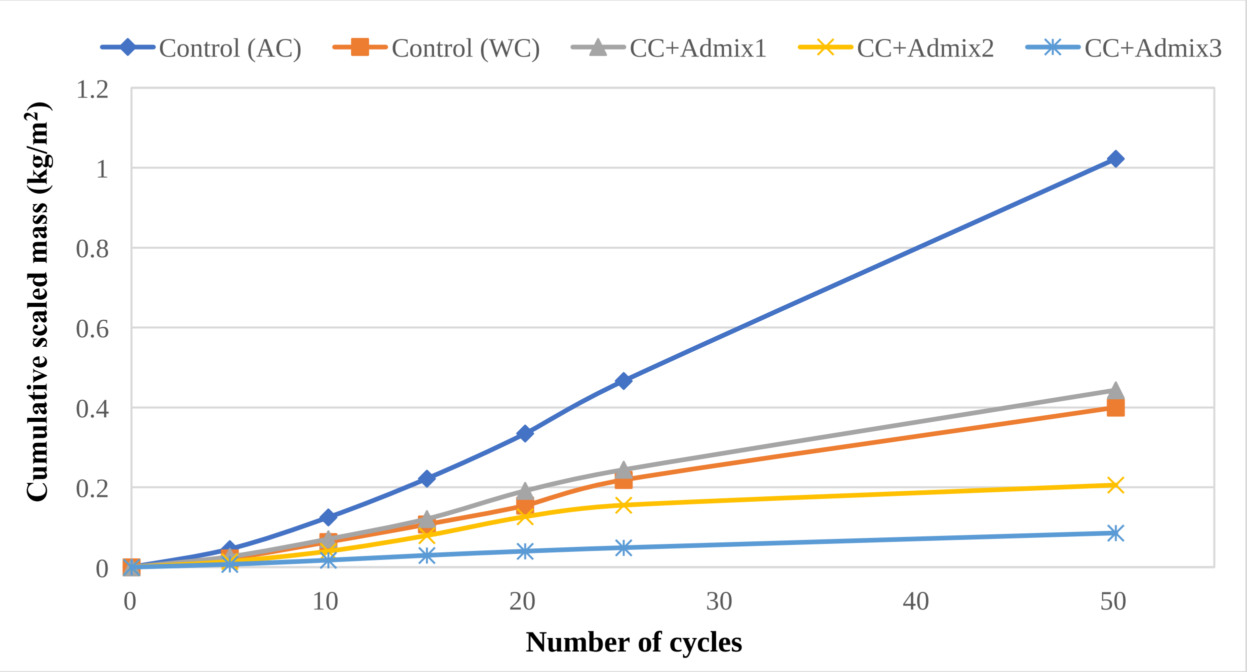


**Figure 6.10** Scaling resistance of CEM II/A-V slabs treated with admixtures

Results demonstrated that treatment with agents governed by hydrophobic effects (ST2, ST3 and Admix3) was more efficient than materials influenced by crystalline mechanism (ST1 and Admix1). It was observed that inclusion of FA in the mix reduced scaling resistance of untreated control slabs in both curing conditions compared to control slabs in CEM I mix. Bouzoubaâ et al., (2011) and Pigeon et al., (1996) reported that poor performance of mixes containing FA could be attributed to the characteristic of the surface layer as presence of FA in the mix tend to increase porosity of the surface layer and increase bleeding of concrete. Bilodeau et al. (1991) and Bilodeau and Malhotra (1992) suggested that reduced scaling resistance of mixes containing FA could be due to lower compressive strength when the strength is less than 40 MPa or when w/c ratio is more than 0.5. Nevertheless, results of compressive strength of CEM II/A-V mix which was performed in Phase 1 (Chapter 4) showed that strength of cubes cured in water developed more than 40 MPa at 28 days. Thus, poor scaling resistance of FA mixes could be due to porosity of the surface layer as stated by Bouzoubaâ et al. (2011) and Pigeon et al. (1996). Results are in good agreement with findings of previous investigations (Gebler, et al., 1986; Whiting, 1989; Glinicki and Zielinski, 2009; Bouzoubaâ et al., 2011; Pigeon et al., 1996; Bouzoubaǎ et al., 2002) as shown in Table 6.9.

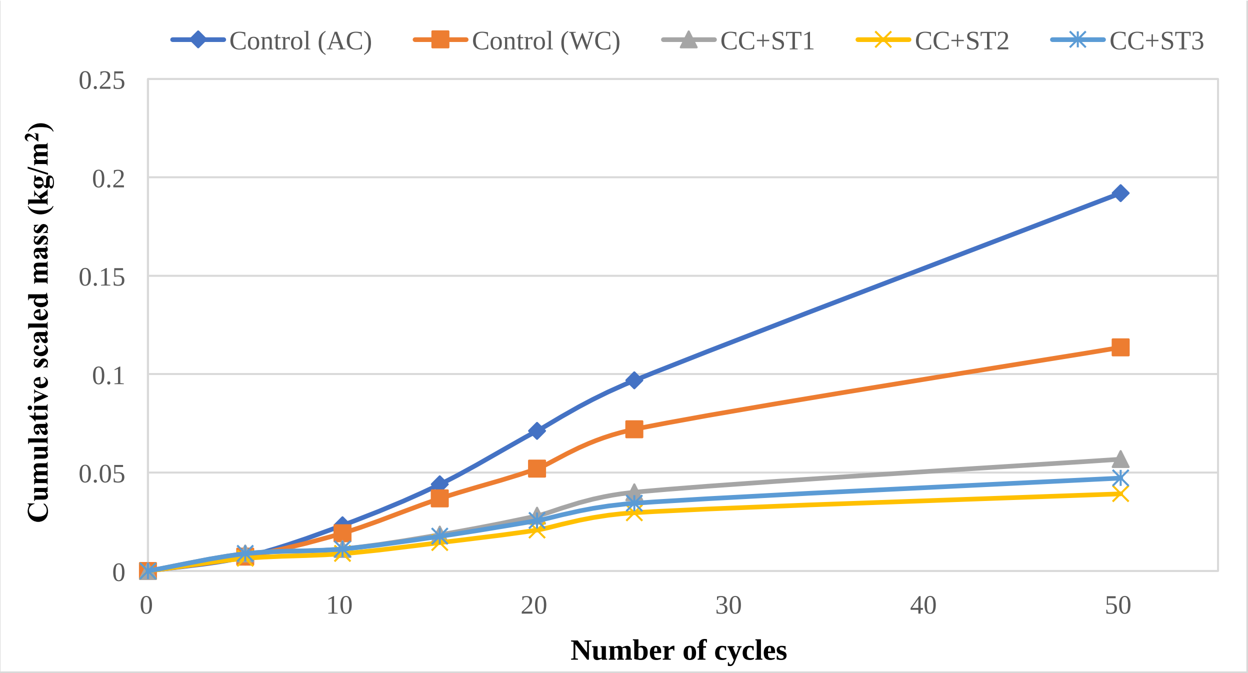
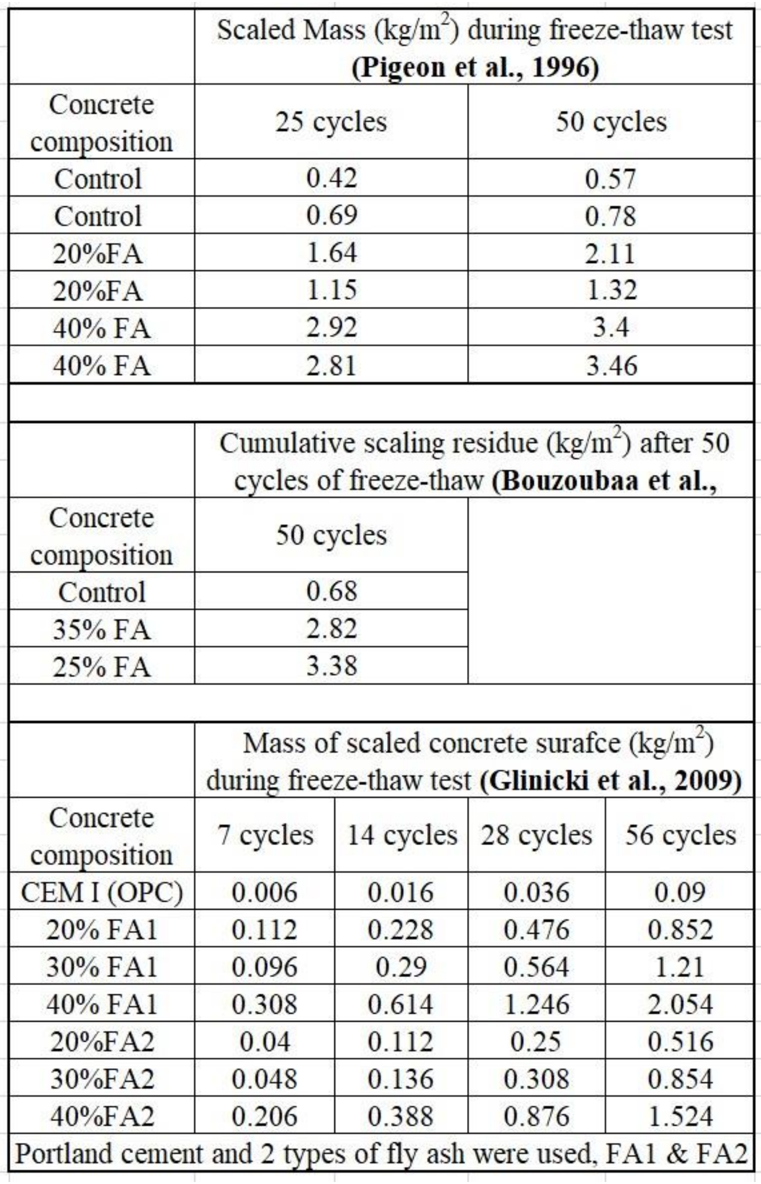


**Figure 6.11** Scaling resistance of CEM II/A-V slabs treated with surface treatments

**Table 6.9** Influence of fly ash on scaling resistance



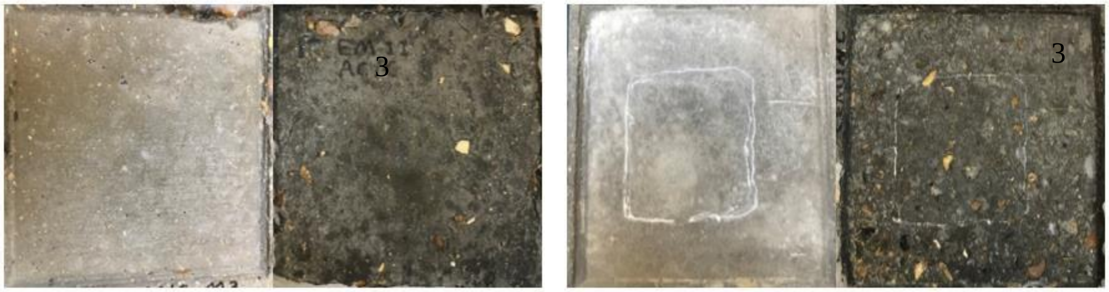
| | Scaled Mass (kg/m$^2$) during freeze-thaw test **(Pigeon et al., 1996)** | |
|---|---|---|
| Concrete composition | 25 cycles | 50 cycles |
| Control | 0.42 | 0.57 |
| Control | 0.69 | 0.78 |
| 20%FA | 1.64 | 2.11 |
| 20%FA | 1.15 | 1.32 |
| 40% FA | 2.92 | 3.4 |
| 40% FA | 2.81 | 3.46 |

| | Cumulative scaling residue (kg/m$^2$) after 50 cycles of freeze-thaw **(Bouzoubaa et al.,** |
|---|---|
| Concrete composition | 50 cycles |
| Control | 0.68 |
| 35% FA | 2.82 |
| 25% FA | 3.38 |

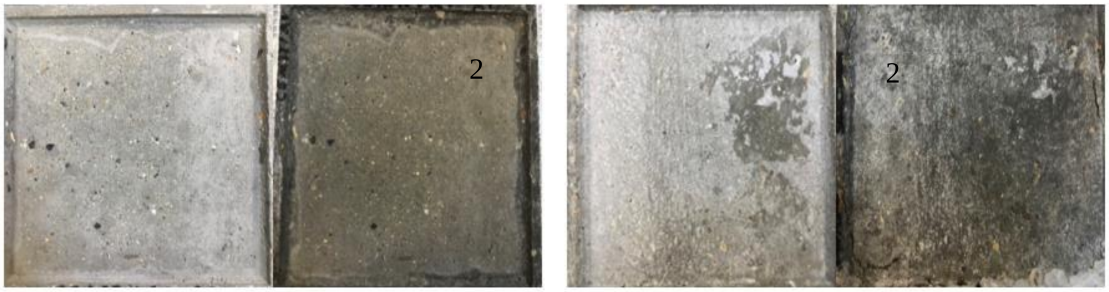
| | Mass of scaled concrete surafce (kg/m$^2$) during freeze-thaw test **(Glinicki et al., 2009)** | | | |
|---|---|---|---|---|
| Concrete composition | 7 cycles | 14 cycles | 28 cycles | 56 cycles |
| CEM I (OPC) | 0.006 | 0.016 | 0.036 | 0.09 |
| 20% FA1 | 0.112 | 0.228 | 0.476 | 0.852 |
| 30% FA1 | 0.096 | 0.29 | 0.564 | 1.21 |
| 40% FA1 | 0.308 | 0.614 | 1.246 | 2.054 |
| 20%FA2 | 0.04 | 0.112 | 0.25 | 0.516 |
| 30%FA2 | 0.048 | 0.136 | 0.308 | 0.854 |
| 40%FA2 | 0.206 | 0.388 | 0.876 | 1.524 |
| Portland cement and 2 types of fly ash were used, FA1 & FA2 | | | | |

Visual observation revealed severe scaling occurred in control slabs cured in AC and moderate scaling in control samples cured in WC and specimens treated with Admix1 and Admix2. On the other hand, slabs treated with Admix3 and ST1 exhibited slight scaling, whereas slabs treated with ST2 and ST3 showed very slight scaling as shown in Figure 6.12.

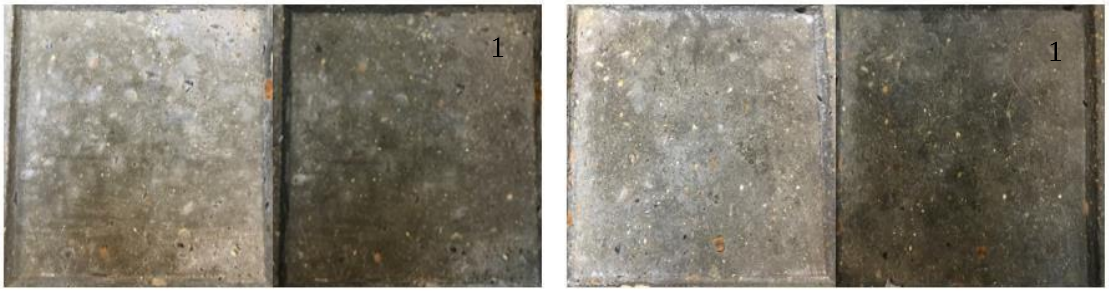
Control (AC) Control (WC)



Admix1 Admix2



Admix3 ST1



ST2 ST3

**Figure 6.12** Visual evaluation of CEM II/A-V slabs before (left) and after (right) test

### 6.4.3 Scaling resistance of CEM III/A (60%PC+40%GGBS) concrete mix

Surface scaling results of CEM III/A specimens treated with admixtures and surface treatments as well as reference cured in AC and WC slabs are shown in Figure 6.13 and 6.14 respectively. Similar trend was observed as control slabs cured in air suffered substantial deterioration due to scaling, whereas less scaling occurred in control samples cured in water and specimens treated with Admix1. Results show that control samples cured in WC performed better than specimens treated with Admix1. It can be seen that slabs treated with Admix3 exhibited less scaling than corresponding specimens treated with Admix2. It was observed that treatment with admixtures, particularly Admix3 improved scaling resistance of concrete surface.

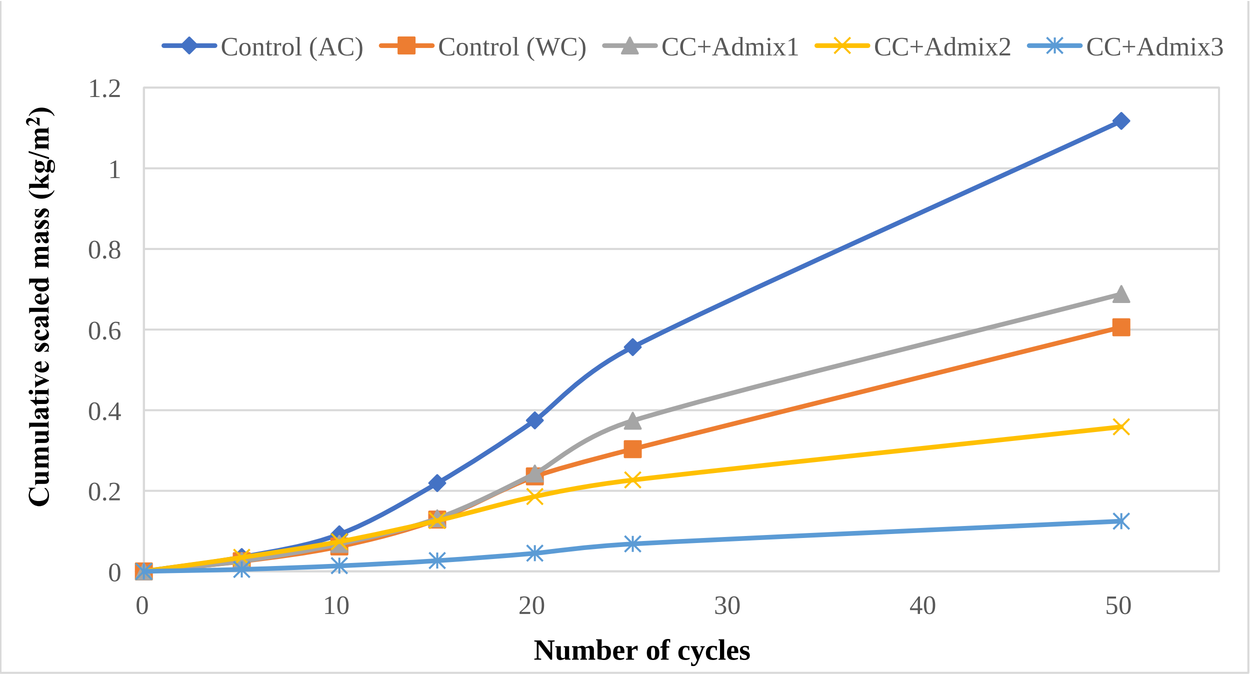


**Figure 6.13** Scaling resistance of CEM III/A slabs treated with admixtures

Moreover, application of surface treatment agents significantly improved scaling resistance of concrete surface. Results indicated that application of surface treatment agents provided more protection for concrete surface than addition of admixtures to the mix. Moreover, treatment with hydrophobic impregnation agents (ST2 and ST3) was more effective than compounds governed by crystalline effects (ST1). Similarly, admixtures influenced by hydrophobic mechanism (Admix2 and Admix3) performed better than counterpart governed by crystalline actions (Admix1). It was observed that addition of GGBS in the mix caused reduction in scaling resistance of untreated control slabs in both curing conditions compared to control slabs in CEM I mix. Valenza and Scherer (2007) and Bleszynski et al. (2002) suggested that reduction in scaling resistance of mixes containing GGBS could be attributed to the weak surface of the concrete and increased period of bleeding due to delayed setting time. Results are consistent with findings of previous studies (Tavasoli et al., 2018; Bleszynski et al., 2002; Chidiac and Panesar, 2008; Panesar and Chidiac, 2007; Wawrzeńczyk et al., 2016; Correia et al., 2020).

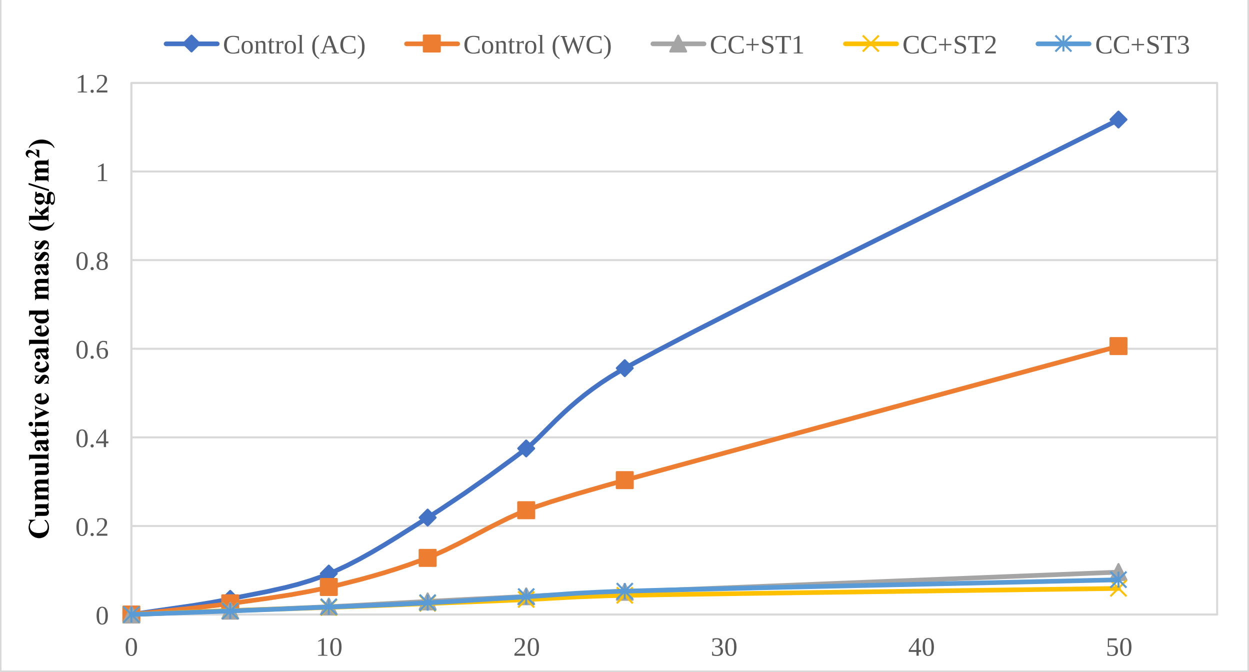
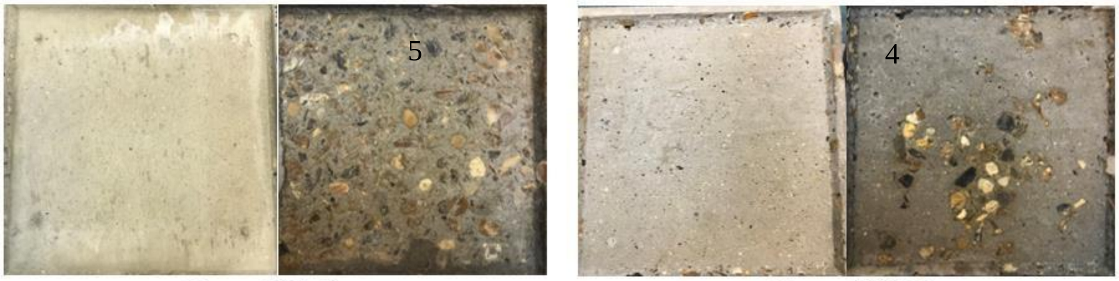
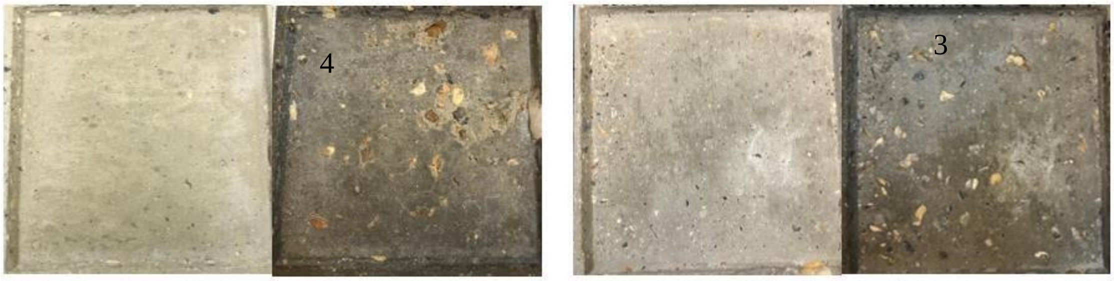


**Figure 6.14** Scaling resistance of CEM III/A slabs treated with surface treatments

Based on visual observation, it can be seen that control samples cured in AC exhibited severe scaling, while moderate to severe scaling was observed in control slabs cured in WC and slabs treated with Admix1. Slabs treated with Admix2 and Admix3 exhibited moderate and slight scaling respectively. On the other hand, treatment with ST1 and ST3 showed very slight scaling and treatment with ST2 exhibited no scaling as illustrated in Figure 6.15.



Control (AC) Control (WC)



Admix1 Admix2

Admix3 ST1

ST2 ST3

**Figure 6.15** Visual evaluation of CEM III/A slabs before (left) and after (right) test

### 6.4.4 Scaling resistance of CEM II/A-D (90%PC+10%SF) concrete mix

Surface scaling results of CEM II/A-D specimens treated with admixtures and surface treatments along with control samples in both curing conditions are presented in Figure 6.16. It can be seen that minimum scaling resistance was observed in control samples cured in AC, followed by control slabs cured in WC. Results show that treatment with Admix1, Admix2 and Admix3 improved scaling resistance of concrete surface and performance of all admixtures was comparable. Similarly, slabs treated with surface treatments protected the surface from scaling. In fact, specimens treated with ST2 and ST3 which are influenced by hydrophobic impregnation remained intact.

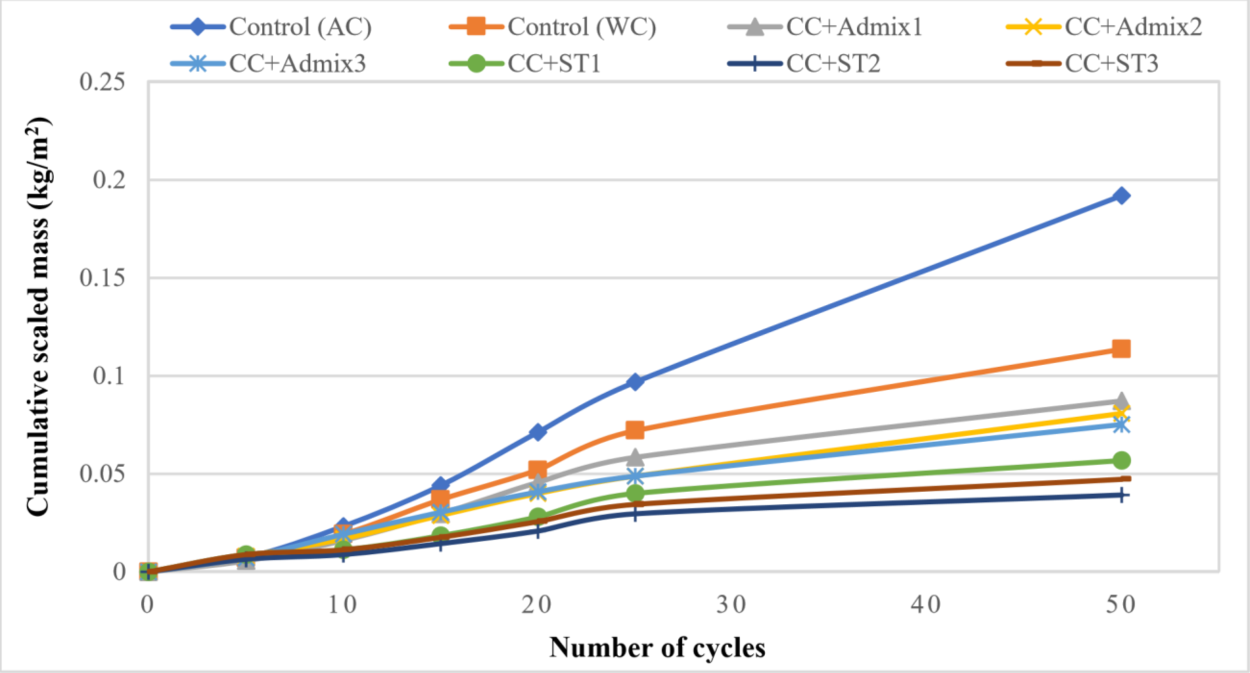
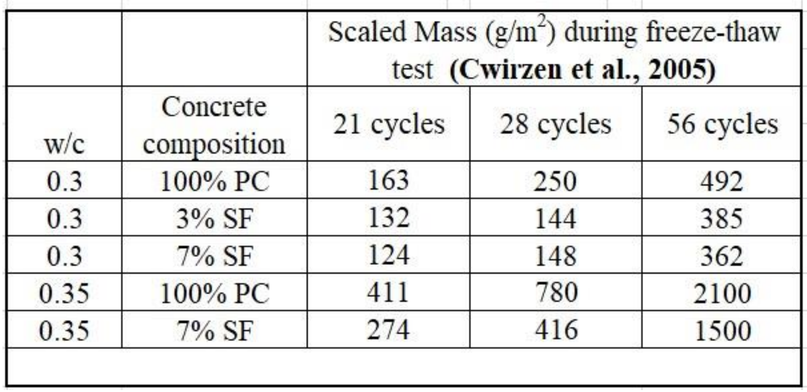


**Figure 6.16** Scaling resistance of CEM II/A-D concrete slabs

Overall, the significant improvement in scaling resistance of CEM II/A-D slabs is largely due to the inclusion of SF in the mix. Valenza et al., (2007) and Jacobsen et al. (1991) reported that improved scaling resistance of mixes containing SF could be attributed to the increased compressive strength. Results are in agreement with previous investigations (Hooton, 1993; Pigeon et al., 1986; Cwirzen et al., 2005) as shown in Table 6.10.

**Table 6.10** Influence of silica fume on scaling resistance

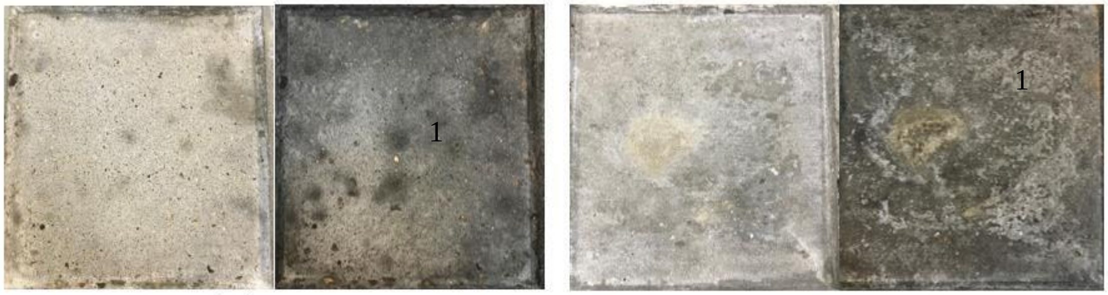


| | | Scaled Mass (g/m$^2$) during freeze-thaw test **(Cwirzen et al., 2005)** | | |
|---|---|---|---|---|
| w/c | Concrete composition | 21 cycles | 28 cycles | 56 cycles |
| 0.3 | 100% PC | 163 | 250 | 492 |
| 0.3 | 3% SF | 132 | 144 | 385 |
| 0.3 | 7% SF | 124 | 148 | 362 |
| 0.35 | 100% PC | 411 | 780 | 2100 |
| 0.35 | 7% SF | 274 | 416 | 1500 |

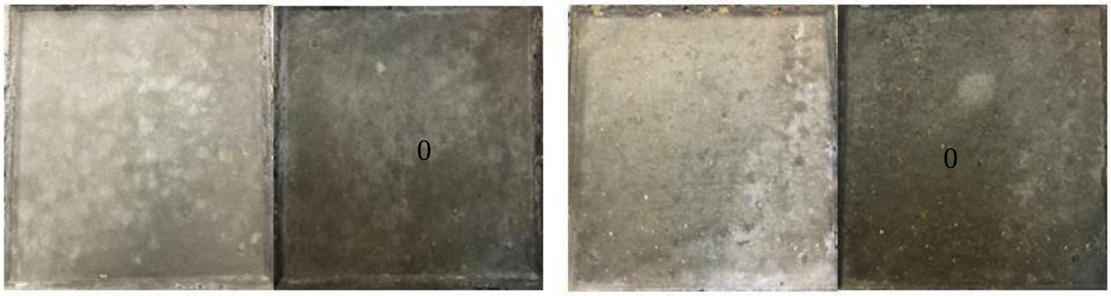
Visual evaluation reveals that reference samples in both curing regimes exhibited moderate scaling, whereas slabs treated with admixtures (Admix1, Admix2 and Admix3) experienced very slight scaling. On the other hand, slabs treated with ST1 experienced very slight scaling while no scaling was observed in slabs treated with ST2 and ST3 as shown in Figure 6.17.

Control (AC) Control (WC)

Admix1 Admix2



Admix3 ST1



ST2 ST3

**Figure 6.17** Visual evaluation of CEM II/A-D slabs before (left) and after (right) test

### 6.4.5 Comparison of CEM II/A-V, CEM III/A and CEM II/A-D with CEM I

Scaling resistance of control samples cured in both curing regimes of all cement types are presented in Figure 6.18. It can be seen that inclusion of mineral admixtures namely FA and GGBS reduced scaling resistance of concrete slabs in comparison to reference mix CEM I. As mentioned previously, addition of these supplementary cementitious materials tends to increase bleeding and weaken the concrete surface. Consequently, concrete surface becomes more prone to scaling. Visual evaluation indicated that increasing the partial replacement of PC with the mineral admixture (GGBS) to 40% in CEM III/A caused more surface scaling. In contrast, incorporation of SF significantly improved scaling resistance of slabs in both curing conditions. This improvement could be attributed to the increased strength and pore structure refinement in CEM II/A-D concrete. Moreover, it was observed that CEM I slabs performed better than corresponding specimens produced from CEM II/A-V and CEM III/A cements. Results indicated that slabs cured in AC poorly performed against scaling.

Furthermore, treatment with surface treatments agents, particularly ST2 and ST3 which provide protection through hydrophobic impregnation, considerably improved performance against scaling in all cement types. Overall, it was observed that application of surface treatment agents was more effective than addition of admixtures to concrete mixes as results demonstrated that scaling was reduced by 70% and 64% in CEM I slaps treated with ST2 and ST3 respectively in comparison to control samples cured in WC. Performance improvement due to application of ST2 and ST3 was more evident in CEM II/A-V and CEM III/A slabs as deterioration in untreated control slabs due to scaling was substantial compared to reference mix CEM I slabs. This is mainly due to presence of FA and GGBS in CEM II/A-V and CEM III/A respectively. Therefore, it was clearly visible that treated slabs performed better than corresponding control samples cured in AC and WC.

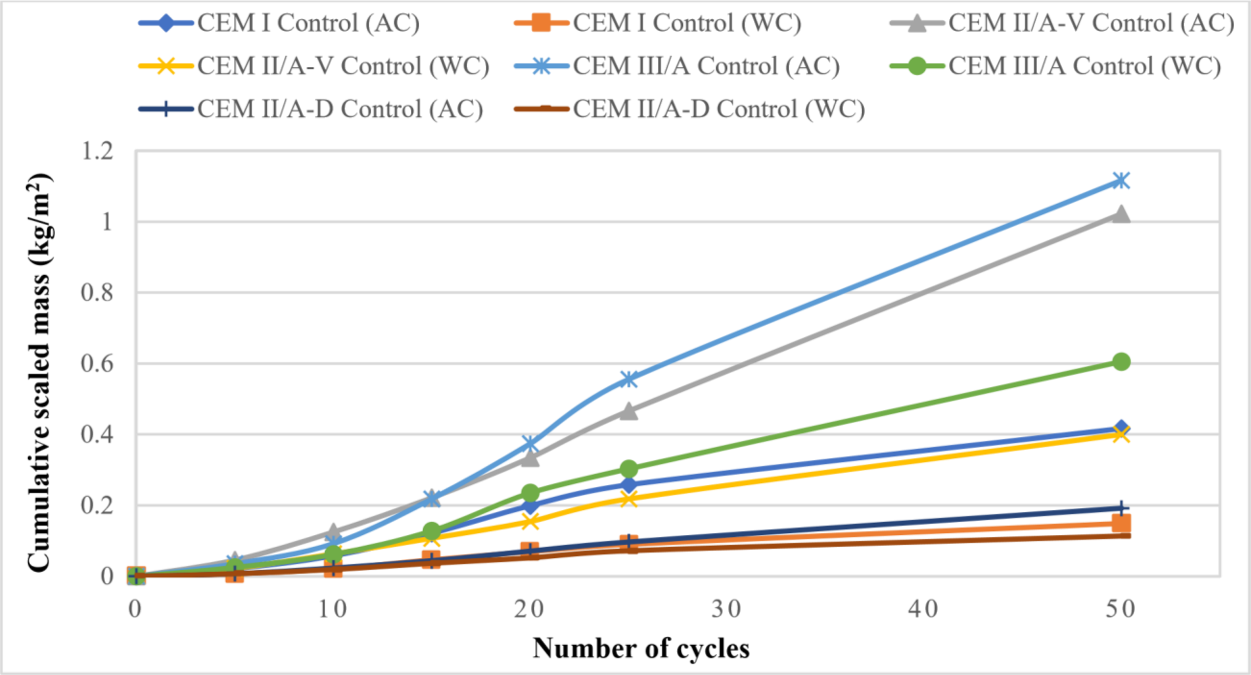


**Figure 6.18** Scaling resistance of control slabs cured in air and water

## 6.5 Resistance of concrete to chloride penetration

### 6.5.1 Chloride penetration of CEM I (100%PC) concrete mix

Resistance of concrete slabs size 250mm x 250mm x 110mm to the penetration of sodium chloride solution was performed as specified in ASTM C1543 (ASTM, 2010). Performance of slabs treated with admixtures and surface treatments was assessed by comparing results with two set of control samples cured in air (AC) and water (WC) as shown in Table 6.11. After completion of exposure period, powdered samples at 8mm and 16 mm depths were obtained from slabs using a drilling device. Chemical analysis of collected samples was carried out using an inductively coupled plasma (ICP) spectroscopy machine to detect and measure the sodium ion in parts per million. The final concentration was calculated by averaging results obtained from two slabs.

**Table 6.11** Concrete slabs used for chloride penetration test

| Cement type | Control cubes (AC) | Control cubes (WC) | Specimen CC + Admixtures | | | Specimen CC +Surface Treatments | | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | | | Admix1 | Admix2 | Admix3 | ST 1 | ST 2 | ST 3 | |
| CEM I | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 16 |
| CEM II/A-V | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 16 |
| CEM III/A | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 16 |
| CEM II/A-D | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 2 slabs | 16 |
| Grand total | 64 | | | | | | | | |

AC = air curing, WC = water curing, CC = curing compound, Admix1 = admixture 1, Admix2 = admixture 2, Admix3 = admixture 3, ST1 = surface treatment 1, ST2 = surface treatment 2, ST3 = surface treatment 3

Results of chloride penetration of CEM I specimens at 8 and 16mm depth along with untreated control slabs in both curing conditions are presented in Figure 6.19 and 6.20 respectively. Chemical analyses of dust concrete samples collected at both depths show that untreated control slabs exhibited highest chloride penetration, followed by slabs treated with Admix1 and ST1. Treatment with Admix1and ST1 reduced chloride penetration by 16% and 30% respectively compared to control samples cured in WC. On the other hand, specimens treated with Admix2 and Admix3 reduced chloride ingress by approximately 60% and 70% respectively. It can be seen that treatment with ST2 and ST3 significantly decreased chloride concentration as chloride reductions were 82% and 75% respectively in comparison to control samples cured in water. Results showed that treatment with hydrophobic agents (Admix2, Admix3, ST2 and ST3) was more effective than crystalline materials (Admix1 and ST1) in protecting concrete surface from chloride ingress. Furthermore, results demonstrated that application of surface treatment agents characterized by hydrophobic impregnation was more effective than adding admixtures in reducing chloride diffusion.

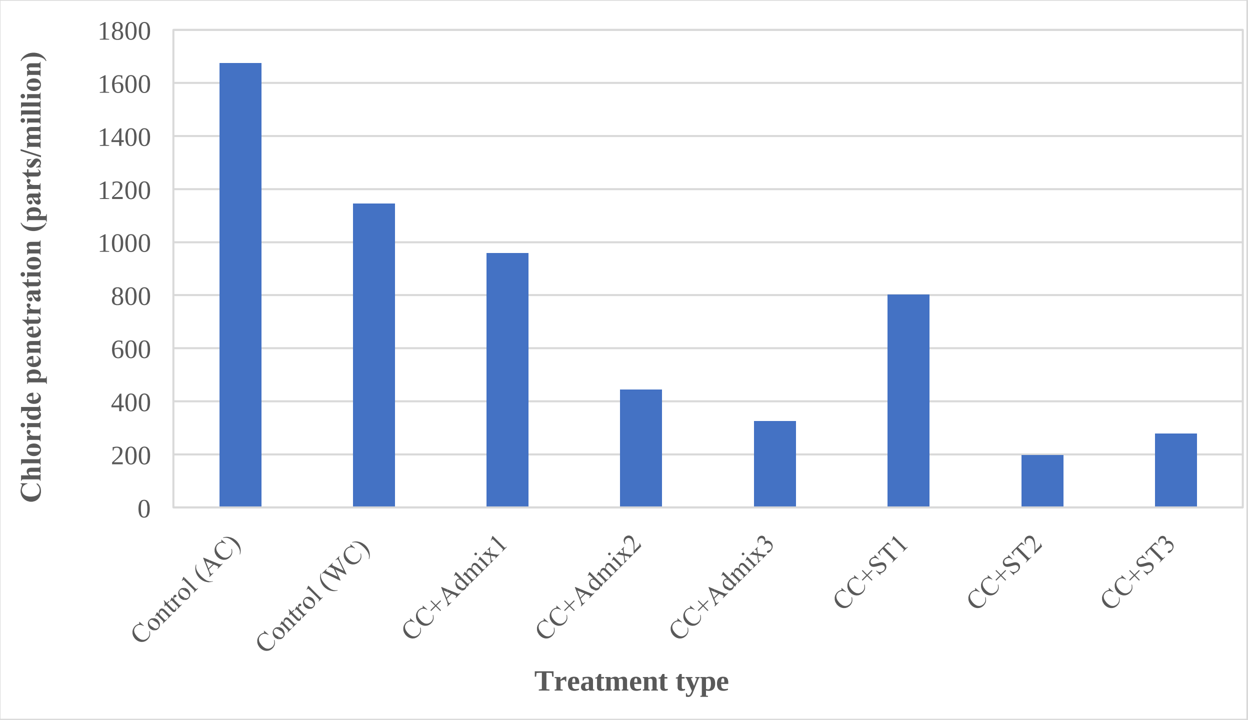


**Figure 6.19** Chloride concentration of CEM I specimens at 8 mm depth

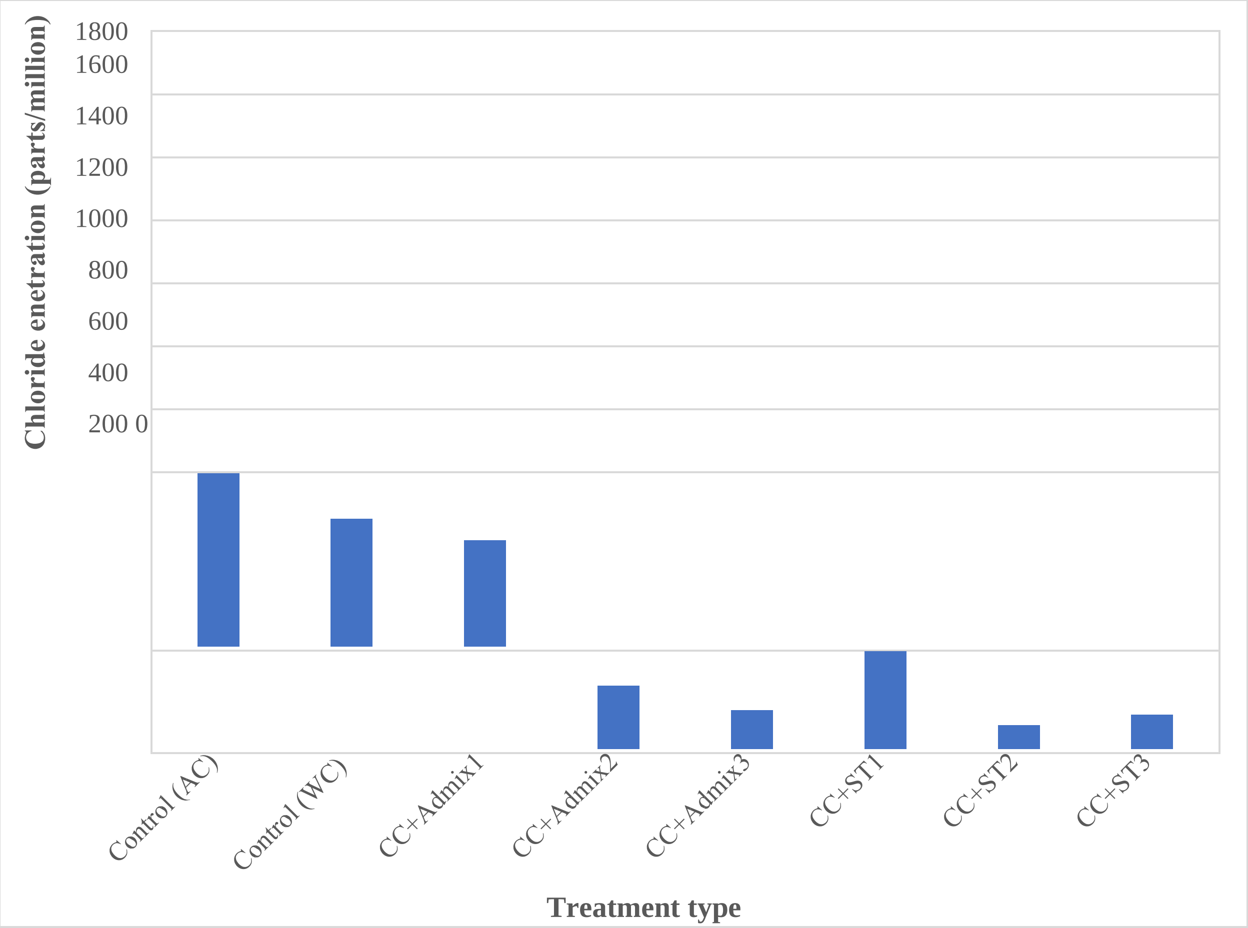
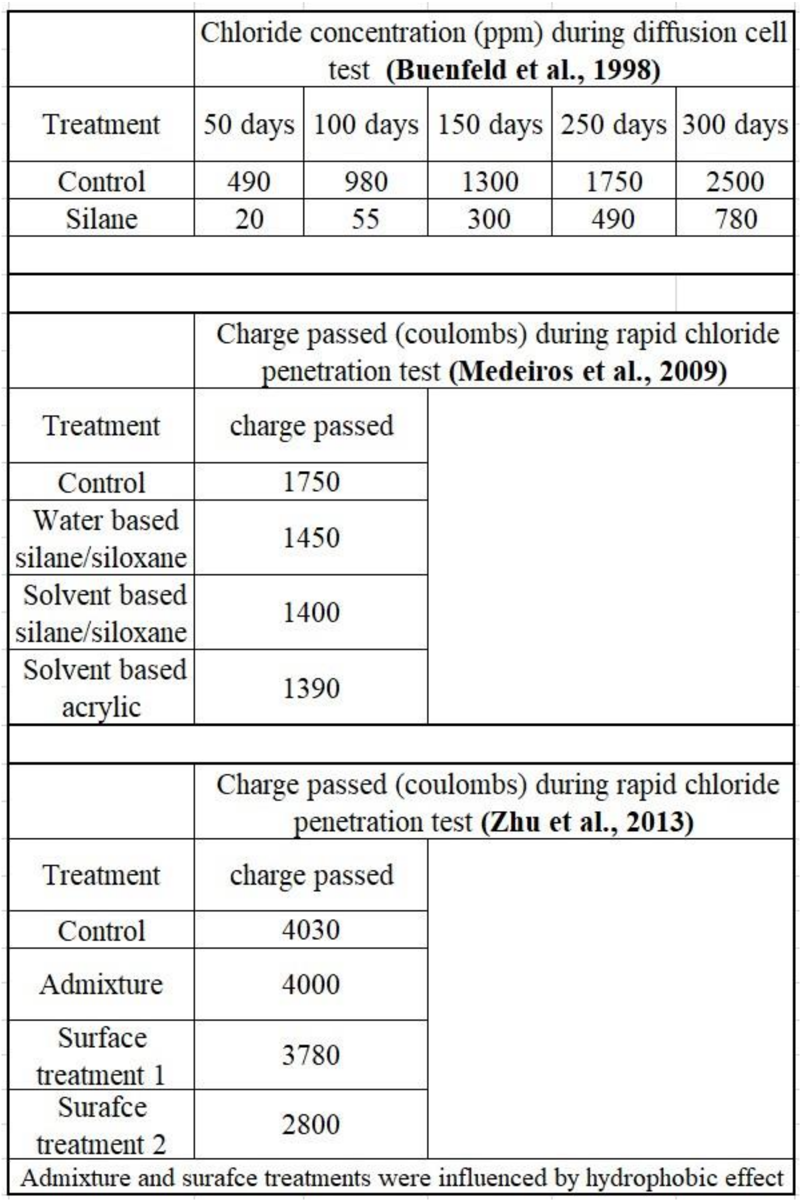


**Figure 6.20** Chloride concentration of CEM I specimens at 16 mm depth

Moreover, results demonstrated that chloride concentration was reduced in dust samples collected at deeper depth (16mm). In other words, chloride concentration decreases when depth increases. Results are in agreement with previous studies (Buenfeld and Zhang, 1998; Jones et al., 1995; Medeiros et al., 2009; Liu et al., 2019; Zhu et al., 2013; Angst et al., 2016; Mckenzie et al., 2009) as shown in Table 6.12.

**Table 6.12** Influence of treatment on chloride penetration



|  | Chloride concentration (ppm) during diffusion cell test **(Buenfeld et al., 1998)** |  |  |  |  |
|---|---|---|---|---|---|
| Treatment | 50 days | 100 days | 150 days | 250 days | 300 days |
| Control | 490 | 980 | 1300 | 1750 | 2500 |
| Silane | 20 | 55 | 300 | 490 | 780 |

|  | Charge passed (coulombs) during rapid chloride penetration test **(Medeiros et al., 2009)** |
|---|---|
| Treatment | charge passed |
| Control | 1750 |
| Water based silane/siloxane | 1450 |
| Solvent based silane/siloxane | 1400 |
| Solvent based acrylic | 1390 |

|  | Charge passed (coulombs) during rapid chloride penetration test **(Zhu et al., 2013)** |
|---|---|
| Treatment | charge passed |
| Control | 4030 |
| Admixture | 4000 |
| Surface treatment 1 | 3780 |
| Surafce treatment 2 | 2800 |

Admixture and surafce treatments were influenced by hydrophobic effect

### 6.5.2 Chloride penetration of CEM II/A-V (80%PC+20%FA) concrete mix

Results of chloride ingress of CEM II/A-V specimens obtained at different depths (8 and 16mm) with control samples in both curing conditions are shown in Figure 6.21 and 6.22 respectively. It can be seen that highest chloride concentration were measured in control samples cured in AC and WC measured at 8 mm depth. Similar trend was observed as treatment with Admix1 and ST1 was ineffective as reduction in chloride ingress was insignificant, whereas treatment with Admix2 and Admix3 improved chloride penetration resistance as chloride concentration was reduced by more than 70% in comparison to control samples cured in WC. On the other hand, results showed that treatment with ST2 and ST3 significantly reduced chloride concentration by more than 80%. Results showed that treatment with agents governed by hydrophobic effects was more efficient than compounds influenced by crystalline mechanism. Moreover, applications of surface treatment agents governed by hydrophobic impregnation reduced chloride concentration more than inclusion of admixtures in the mixes. It was observed that inclusion of FA in the mix reduced chloride concentration of untreated control samples cured in both curing conditions in comparison to control slabs in CEM I mix. Leng et al. (2000) reported that inclusion of FA and GGBS in the concrete improve resistance to chloride penetration and they attributed the improvement to the following reasons:

- Partial replacement of PC with FA and GGBS tends to improve pore size and pore shape of concrete matrix.
- Formation of extra C-S-H gel in blended cement concrete containing FA and GGBS during the hydration process, thus increasing chloride ions adsorption and blocking diffusion paths.
- Blended cements containing FA and GGBS contain more $C_3A$ which can adsorb more chloride ions to form Friedel's salt.

Furthermore, Mather (2004), Gjørv (2014), Dyer (2014) and Thomas et al. (2012) stated that inclusion of FA and GGBS containing high level of alumina ($Al_2O_3$) tend to increase the chloride binding capacity of concrete due to the formation of extra Friedel's salt. . Therefore, adding FA in the mix increases resistance to chloride ingress. Similar results were reported by numerous researches (Wang et al., 2018; Yazici, 2008; Uysal et al., 2012; Oh et al., 2002; Chindaprasirt et al., 2007; Naik et al., 1994).

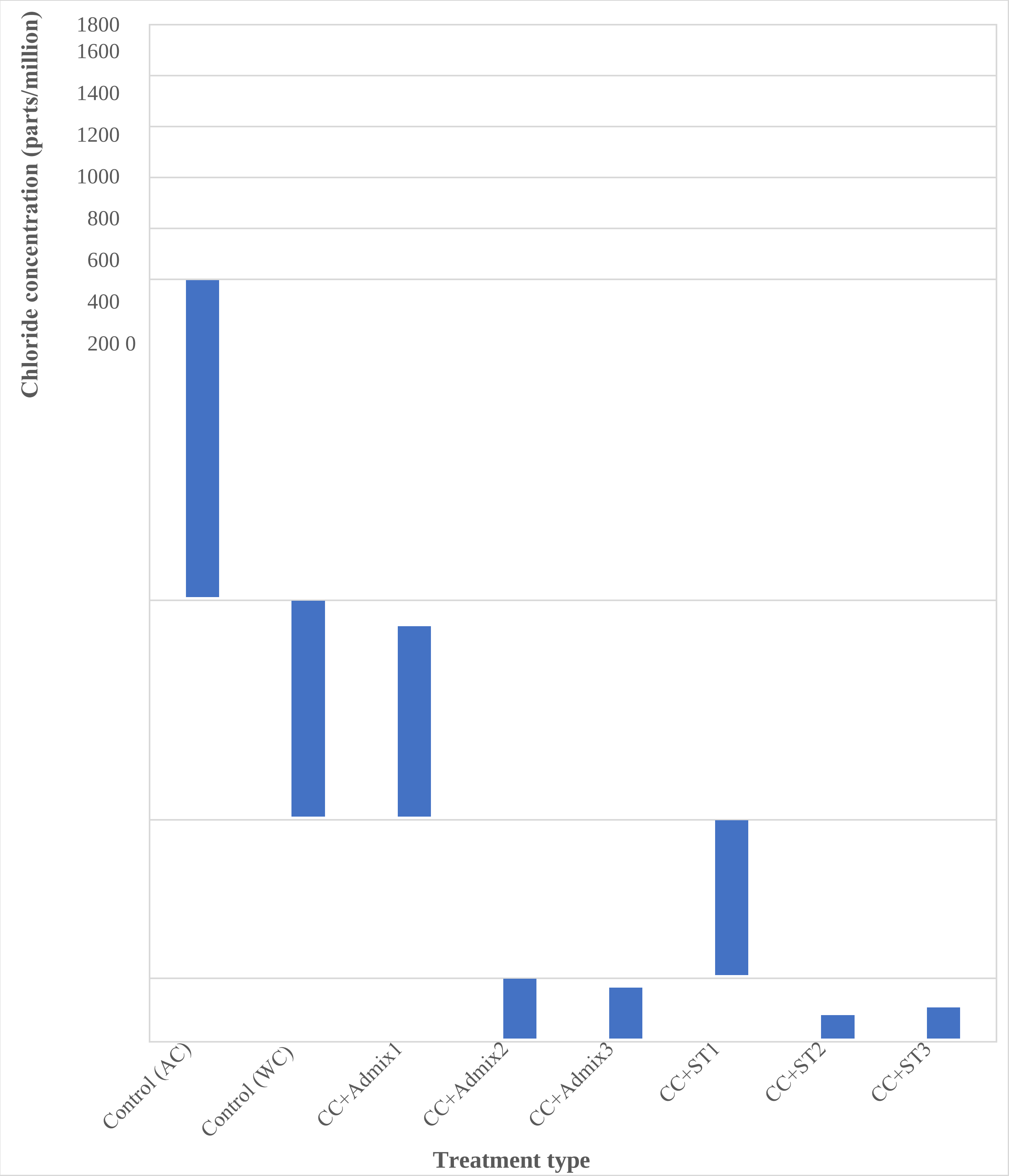


**Figure 6.21** Chloride concentration of CEM II/A-V specimens at 8 mm depth

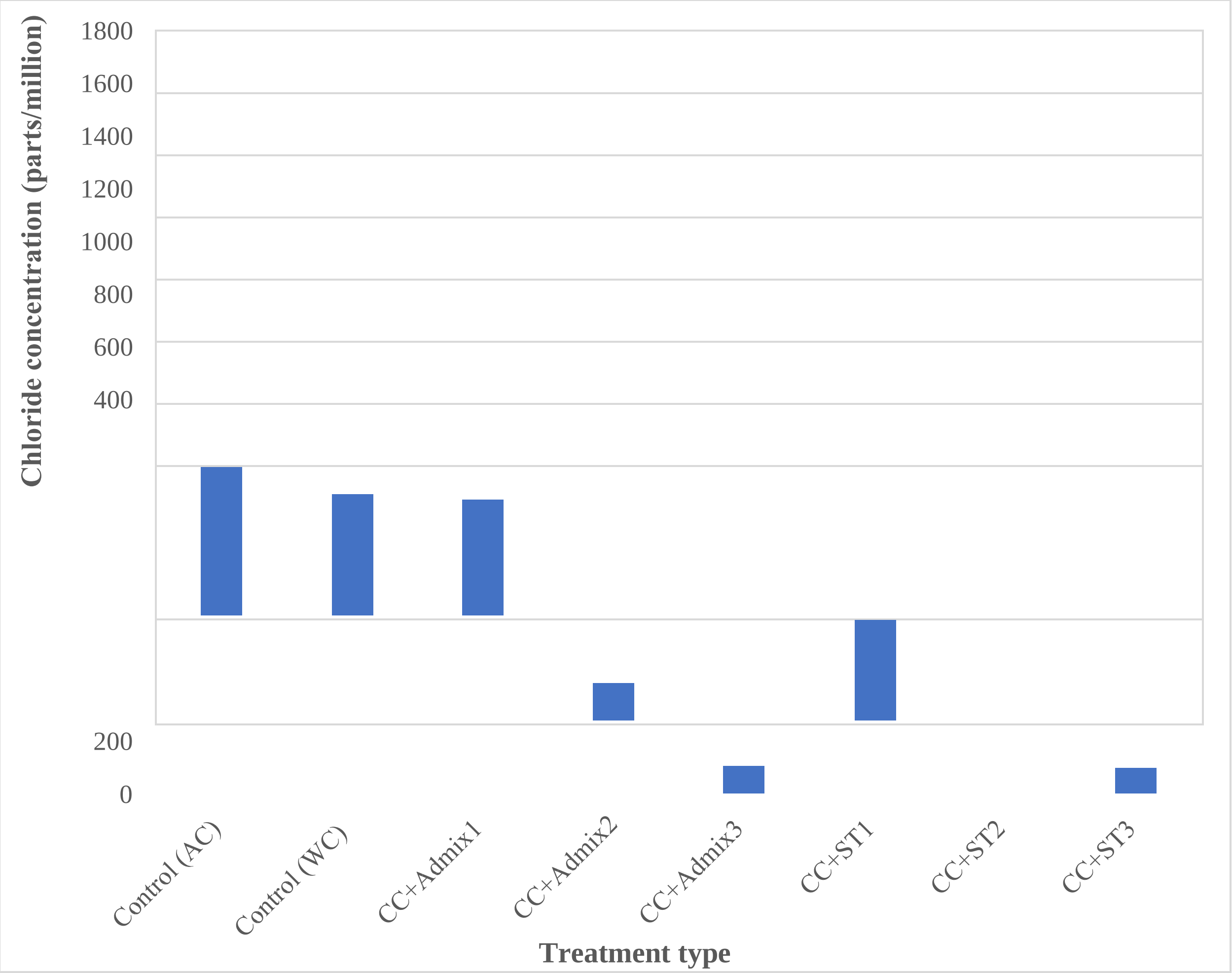


**Figure 6.22** Chloride concentration of CEM II/A-V specimens at 16 mm depth

### 6.5.3 Chloride penetration of CEM III/A (60%PC+40%GGBS) concrete mix

Results of chloride penetration of CEM III/A specimens collected at different depths (8 and 16mm) with control samples in both curing conditions are illustrated in Figure 6.23 and 6.24 respectively. Similar to previous cement types, highest chloride concentrations were measured in control samples cured in AC and WC measured at 8 mm depth. Results showed that treatment with Admix1 and ST1 had the least influence on reducing chloride penetration compared to other treatment types. In contrast, treatment with Admix2, Admix3, ST2 and ST3 considerably reduced chloride concentration in comparison to control samples cured in WC. Maximum reduction was 84% measured in specimens treated with ST2. In terms of treatment with protective materials, similar trend was observed as materials governed by hydrophobic effects was far more effective than compounds influenced by crystalline mechanism. Furthermore, applications of surface treatment agents influenced by hydrophobic impregnation reduced chloride concentration more than inclusion of admixtures in the mixes.

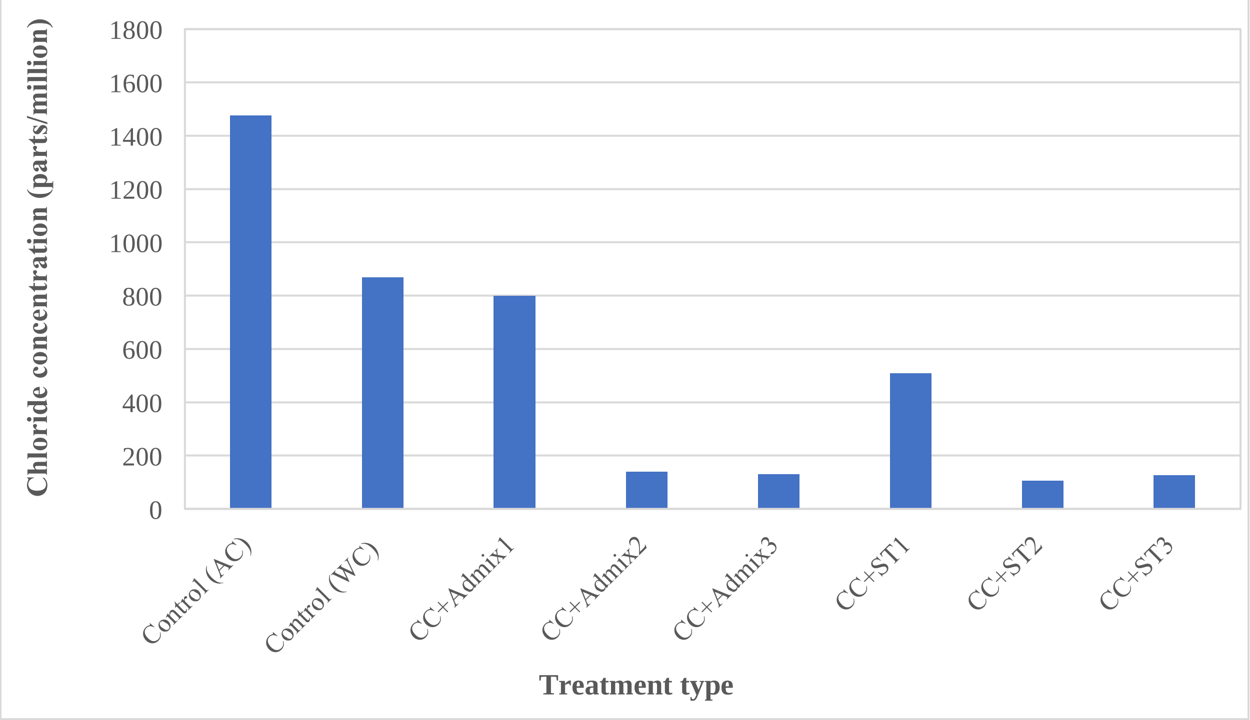


**Figure 6.23** Chloride concentration of CEM III/A specimens at 8 mm depth

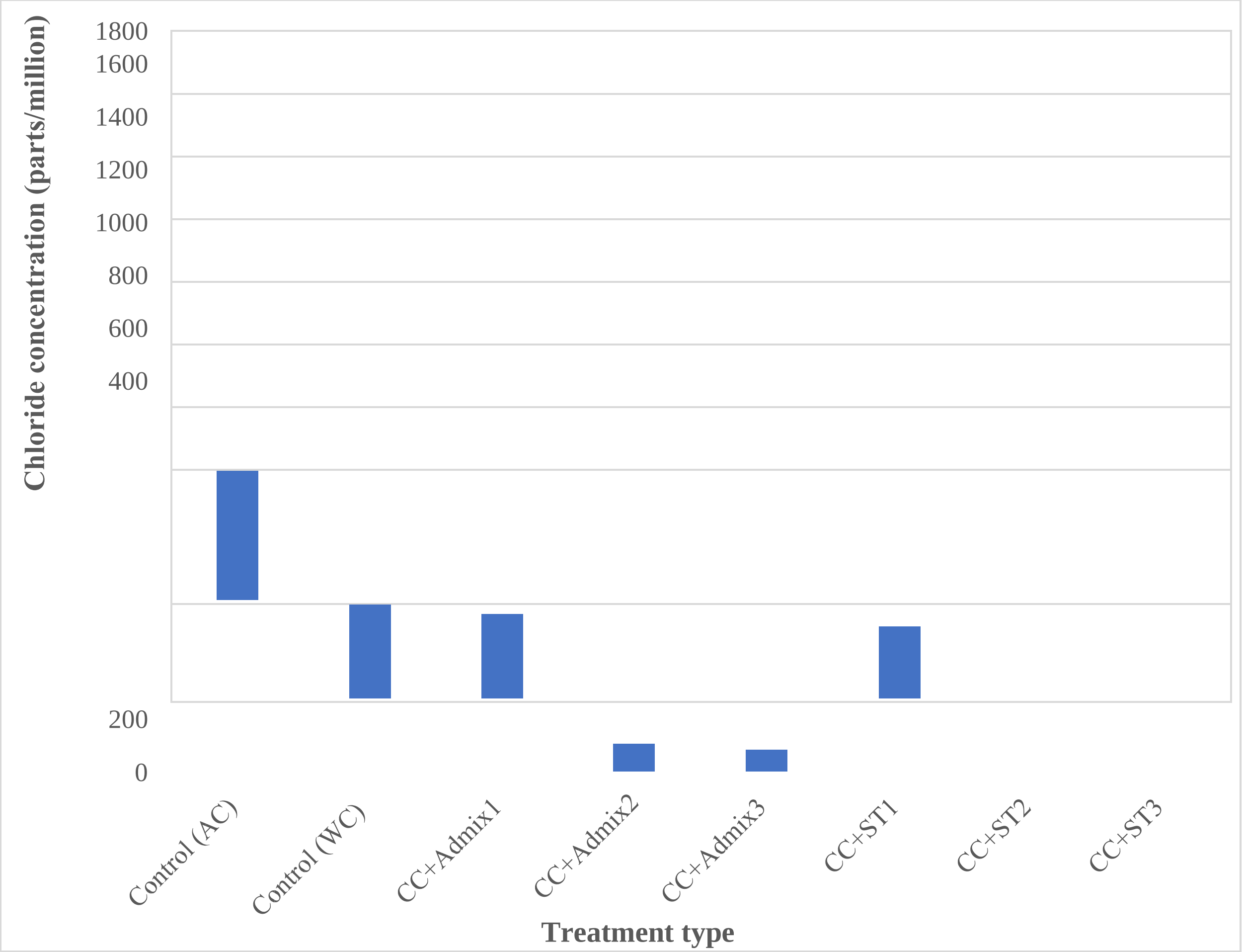
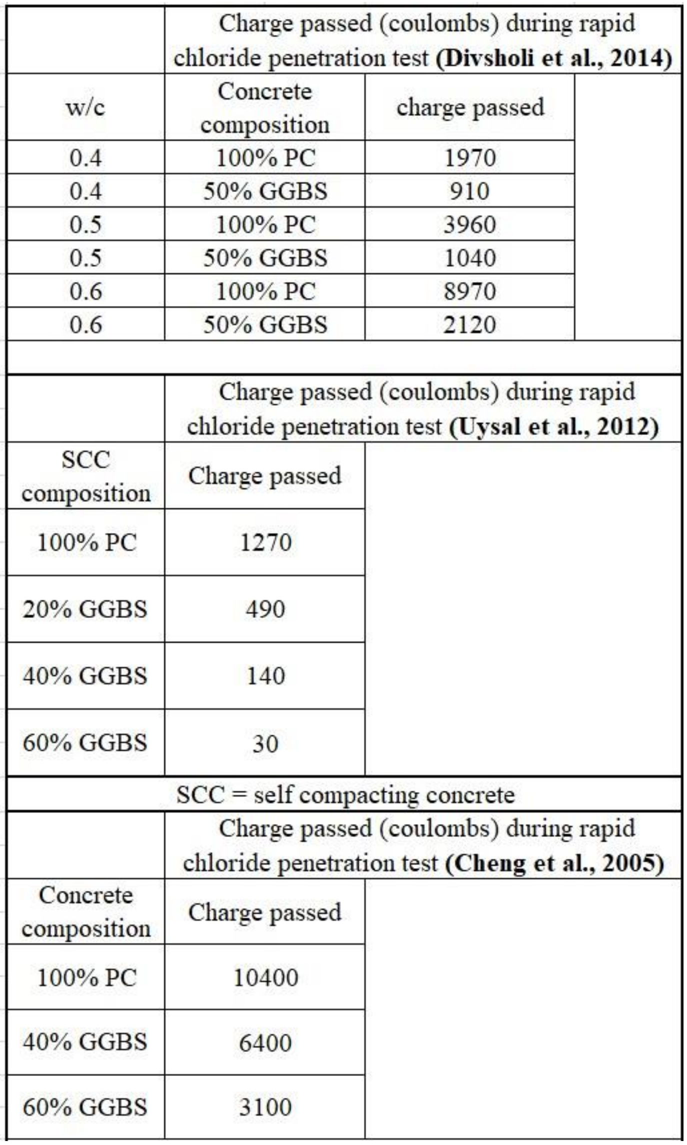


**Figure 6.24** Chloride concentration of CEM III/A specimens at 16 mm depth

It can be seen that presence of GGBS in the mix reduced chloride concentration of untreated control samples cured in water by approximately 27% compared to corresponding reference mix CEM I. As mentioned previously, reduction of chloride penetration in concrete mix containing GGBS could be attributed to many factors, namely, improvement of pore size and pore shape of concrete mix, increased chloride adsorption due to formation of the additional C-S-H gel and formation of Friedel's salt which increases chloride binding capacity of the concrete mix. (Leng et al., 2000; Mather, 2004; Gjørv, 2014; Thomas et al., 2012). Moreover, results showed that presence of GGBS in the mix increased chloride penetration resistance more than inclusion of FA. This could be due to the fact that GGBS particle size is finer than FA, thus better pore structure refinement in CEM III/A mix. In addition, many studies (Dhir et al., 1997; Dhir et al., 1996; Luo et al., 2003; Chen et al., 2012) stated that increasing the partial replacement level of PC with GGBS increases the chloride binding capacity and reduces permeability of concrete. Results are consistent with findings of previous studies (Uysal et al., 2012; Cheng et al., 2005; Dhir et al., 1996; Divsholi et al., 2014; Basheer et al., 2002) as shown in Table 6.13.

**Table 6.13** Influence of GGBS on chloride penetration



| | Charge passed (coulombs) during rapid chloride penetration test **(Divsholi et al., 2014)** | | |
|---|---|---|---|
| w/c | Concrete composition | charge passed | |
| 0.4 | 100% PC | 1970 | |
| 0.4 | 50% GGBS | 910 | |
| 0.5 | 100% PC | 3960 | |
| 0.5 | 50% GGBS | 1040 | |
| 0.6 | 100% PC | 8970 | |
| 0.6 | 50% GGBS | 2120 | |

| | Charge passed (coulombs) during rapid chloride penetration test **(Uysal et al., 2012)** | |
|---|---|---|
| SCC composition | Charge passed | |
| 100% PC | 1270 | |
| 20% GGBS | 490 | |
| 40% GGBS | 140 | |
| 60% GGBS | 30 | |

SCC = self compacting concrete

| | Charge passed (coulombs) during rapid chloride penetration test **(Cheng et al., 2005)** | |
|---|---|---|
| Concrete composition | Charge passed | |
| 100% PC | 10400 | |
| 40% GGBS | 6400 | |
| 60% GGBS | 3100 | |

### 6.5.4 Chloride penetration of CEM II/A-D (90%PC+10%SF) concrete mix

Results of chloride concentration of CEM II/A-D specimens collected at 8 and 16mm depths with control samples in both curing conditions are shown in Figure 6.25 and 6.26 respectively. It can be seen that highest chloride concertation were measured in control samples cured in AC and WC at

8mm depth. Similar to previous mixes, chloride concentration was reduced in specimens collected at 16mm depth. Results show that treatment with Admix1 and ST1 did not provide adequate protection against chloride ingress in comparison to other treatment materials. On the other hand, treatment with Admix2, Admix3, ST2 and ST3 significantly reduced chloride penetration compared to control samples cured in air and water. Maximum reduction was approximately 70% measured in specimens treated with ST2. Similar trend was observed as materials influenced by hydrophobic effects was more efficient than compounds governed by crystalline actions.

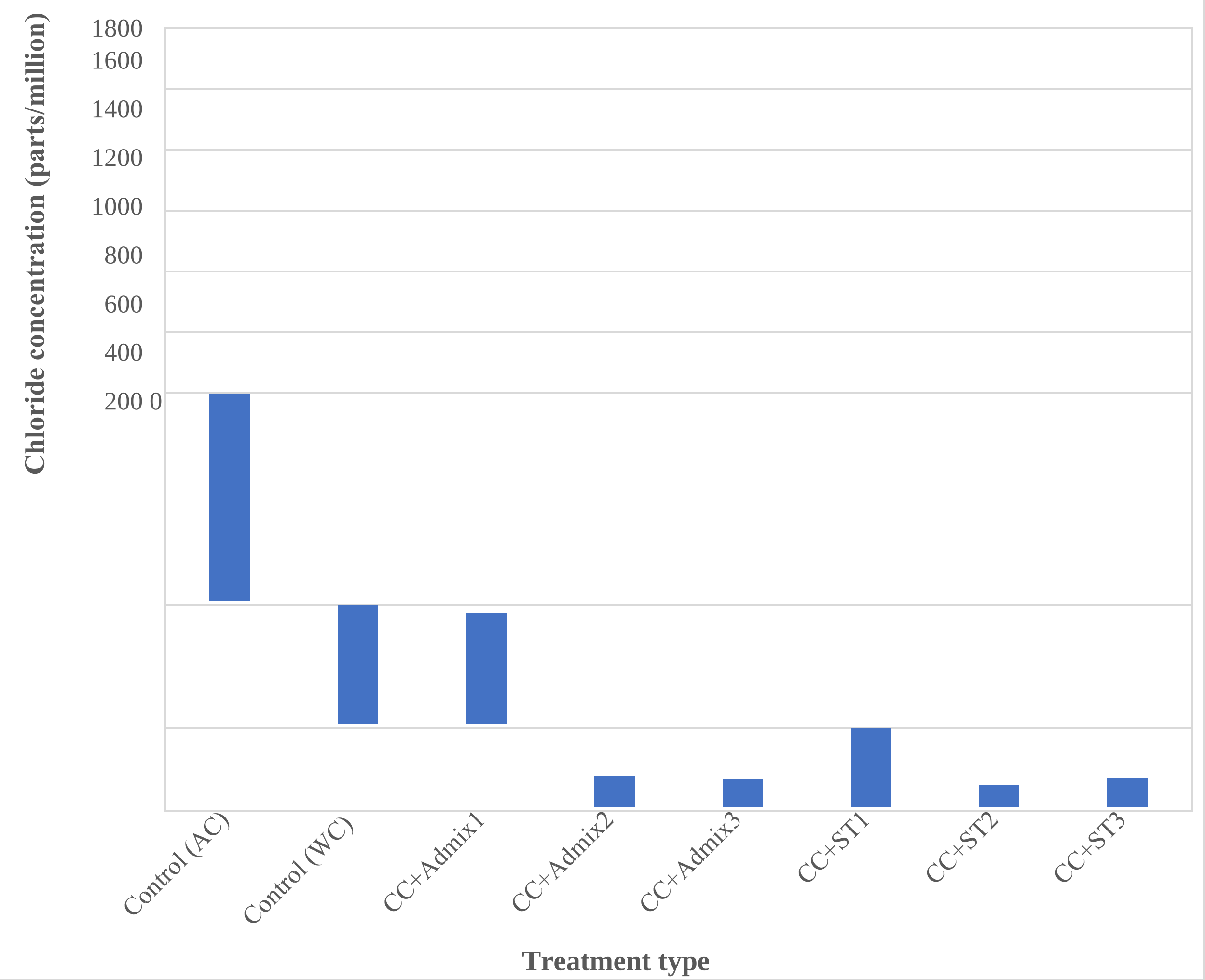
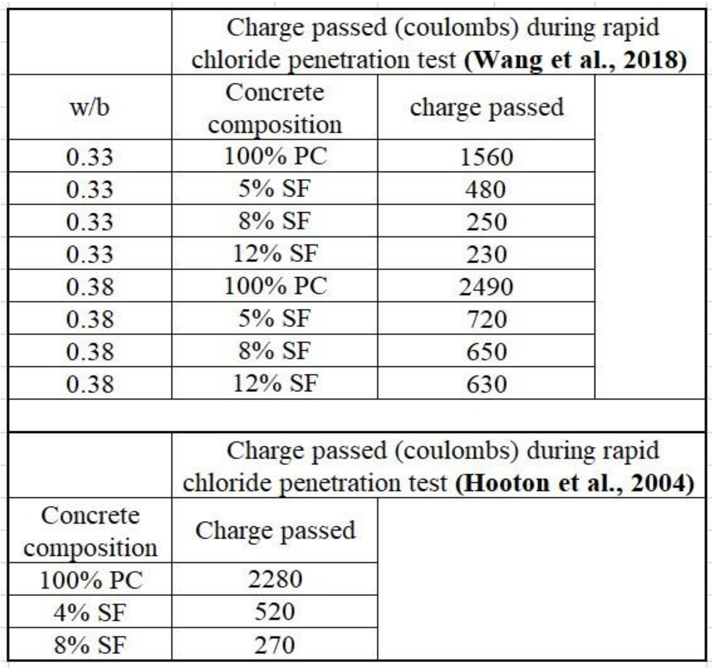


**Figure 6.25** Chloride concentration of CEM II/A-D specimens at 8 mm depth

Moreover, applications of surface treatment agents influenced by hydrophobic impregnation was more effective in reducing chloride penetration than incorporation of waterproofing admixtures. Results showed that partial replacement of PC with SF in the mix, reduced chloride concentration of untreated control samples cured in water by approximately 63% compared to corresponding reference mix CEM I. Results demonstrated that inclusion of SF significantly improved chloride penetration resistance of the concrete mix. Mather (2004) and Oh et al. (2002) reported that presence of SF in the mix improves pore size refinement of the concrete matrix due to the extreme fine particles, leading to a dense and impermeable structure. Furthermore, it is evident that performance of concrete containing SF improved chloride penetration resistance of the mix more than inclusion of GGBS and FA. This is mainly due to the pore structure refinement as SF particle is much finer than GGBS and FA particles (Erdem and Kirca 2008). Results are in agreement with previous studies stating that addition of SF in the mix significantly reduces chloride diffusion and porosity of the concrete (Wang et al., 2018; Hooton and Titherington, 2004; Yazici, 2008; Zhang et al., 2017) as shown in Table 6.14.

**Table 6.14** Influence of silica fume on chloride penetration



| | Charge passed (coulombs) during rapid chloride penetration test **(Wang et al., 2018)** | |
|---|---|---|
| w/b | Concrete composition | charge passed |
| 0.33 | 100% PC | 1560 |
| 0.33 | 5% SF | 480 |
| 0.33 | 8% SF | 250 |
| 0.33 | 12% SF | 230 |
| 0.38 | 100% PC | 2490 |
| 0.38 | 5% SF | 720 |
| 0.38 | 8% SF | 650 |
| 0.38 | 12% SF | 630 |

| | Charge passed (coulombs) during rapid chloride penetration test **(Hooton et al., 2004)** |
|---|---|
| Concrete composition | Charge passed |
| 100% PC | 2280 |
| 4% SF | 520 |
| 8% SF | 270 |

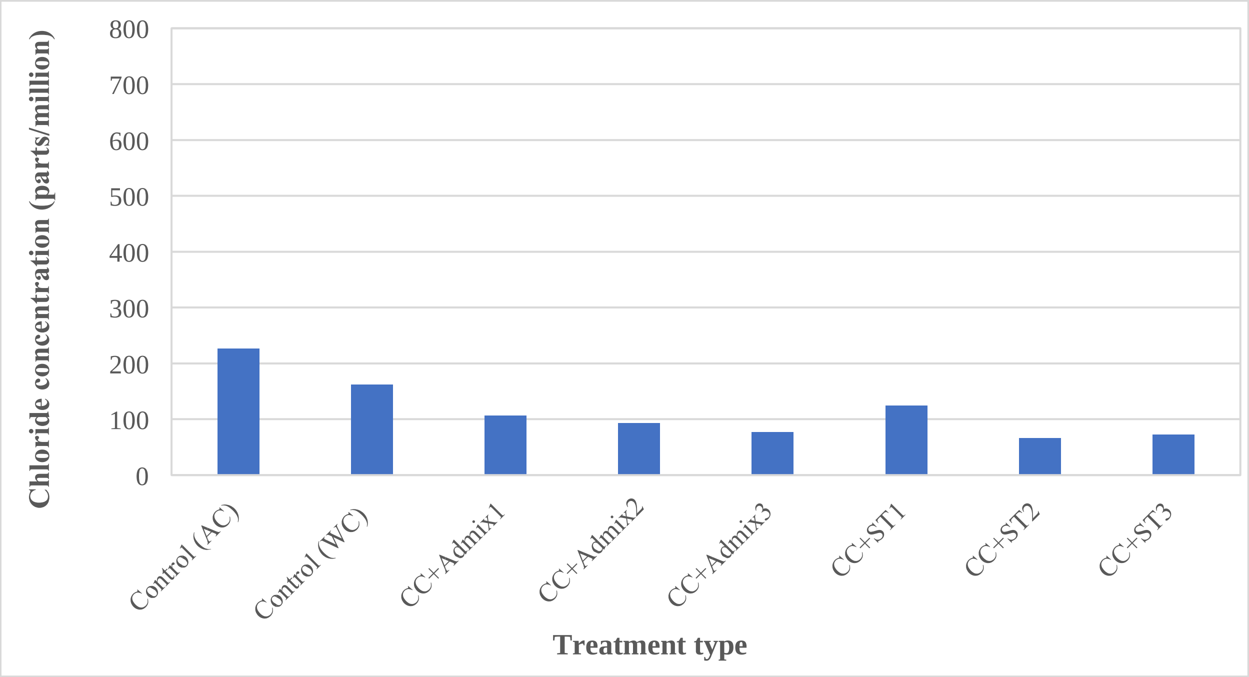


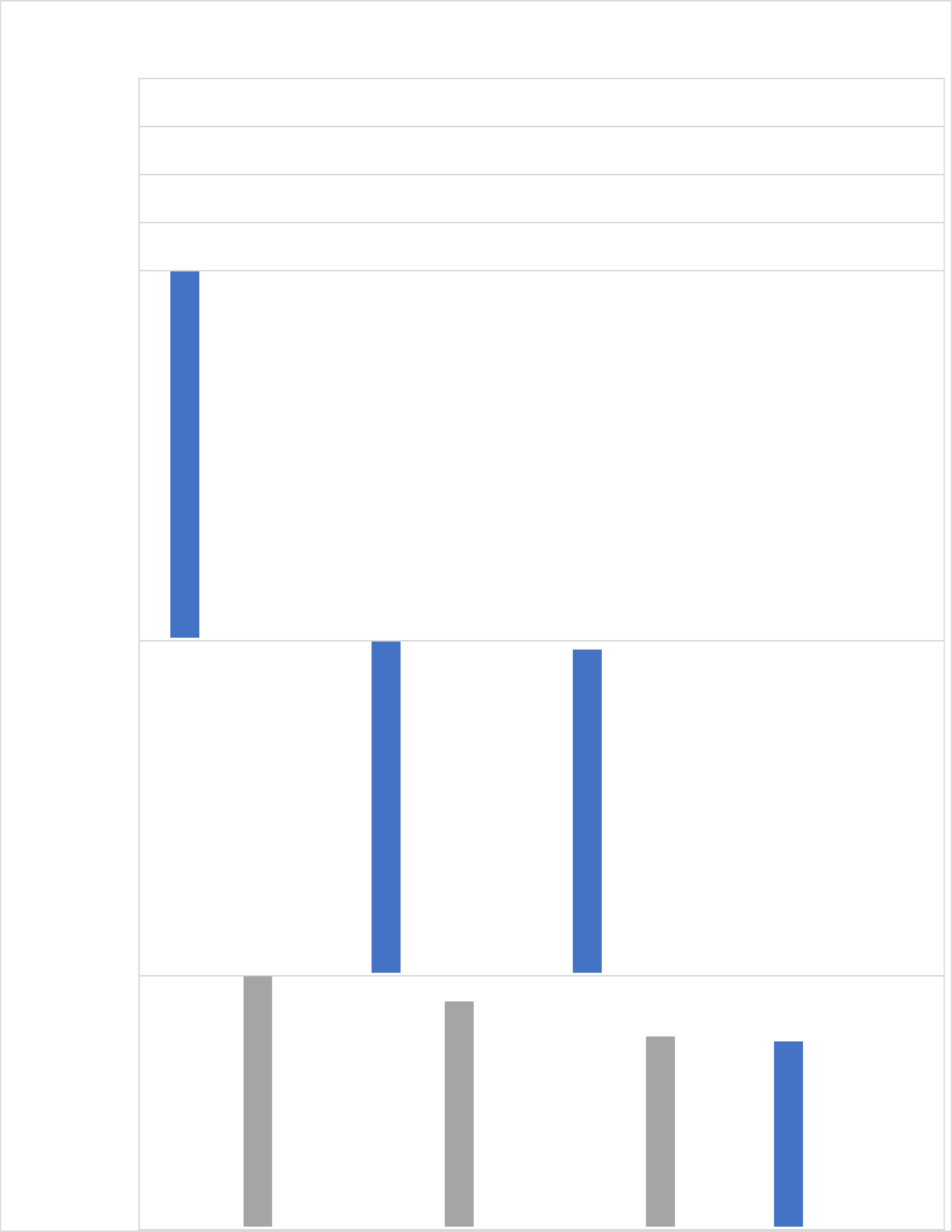
**Figure 6.26** Chloride concentration of CEM II/A-D specimens at 16 mm depth

### 6.5.5 Comparison of CEM II/A-V, CEM III/A and CEM II/A-D with CEM I

Chloride concentration results of untreated control samples cured in both curing conditions of all cement types and collected at 8 and 16mm depths are presented in Figure 6.27. Generally, it can be seen that adding mineral admixtures improves chloride penetration resistance of concrete.

Nevertheless, 20% replacement of PC with FA in CEM II/A-V reduced chloride concentration by approximately 10% in comparison to reference samples (CEM I) cured in water. This could be attributed to the low replacement level of PC with FA as numerous previous studies (Dhir et al., 1997; Dhir et al., 1996; Luo et al., 2003; Chen et al., 2012) reported that replacement of PC with FA up to 40% reduces chloride diffusion coefficient and increases chloride binding capacity. On the other hand, results showed that increasing the replacement level of PC with GGBS to 40% in CEM III/A, V reduced chloride concentration by approximately 27% compared to reference mix (CEM I) cured in water. This improvement could be due to the higher level of replacement which increases chloride binding capacity, and better refinement of concrete structure due to the finer particle size of GGBS as mentioned previously. Moreover, results indicated that inclusion of SF in the mix significantly improved chloride penetration resistance as chloride concentration was reduced by around 63% compared to corresponding reference mix CEM I cured in water. Presence of SF in the mix improves performance against chloride ingress through refinement of porosity and reduction in the rates of chloride penetration (Mather, 2004).

Furthermore, results showed that treatment with protective materials influenced by crystalline effects (Admix1 and ST1) was not as effective as protective agents (Admix2, Admix3, ST2 and ST3) governed by hydrophobic effects. Maximum reduction in chloride penetration due to treatment with protective materials was measured in specimens treated with ST2 and ST3, followed by specimens treated with Admix3 and Admix2. This shows that application of surface treatment was more effective than addition of admixtures to concrete mixes in combating chloride ions ingress.



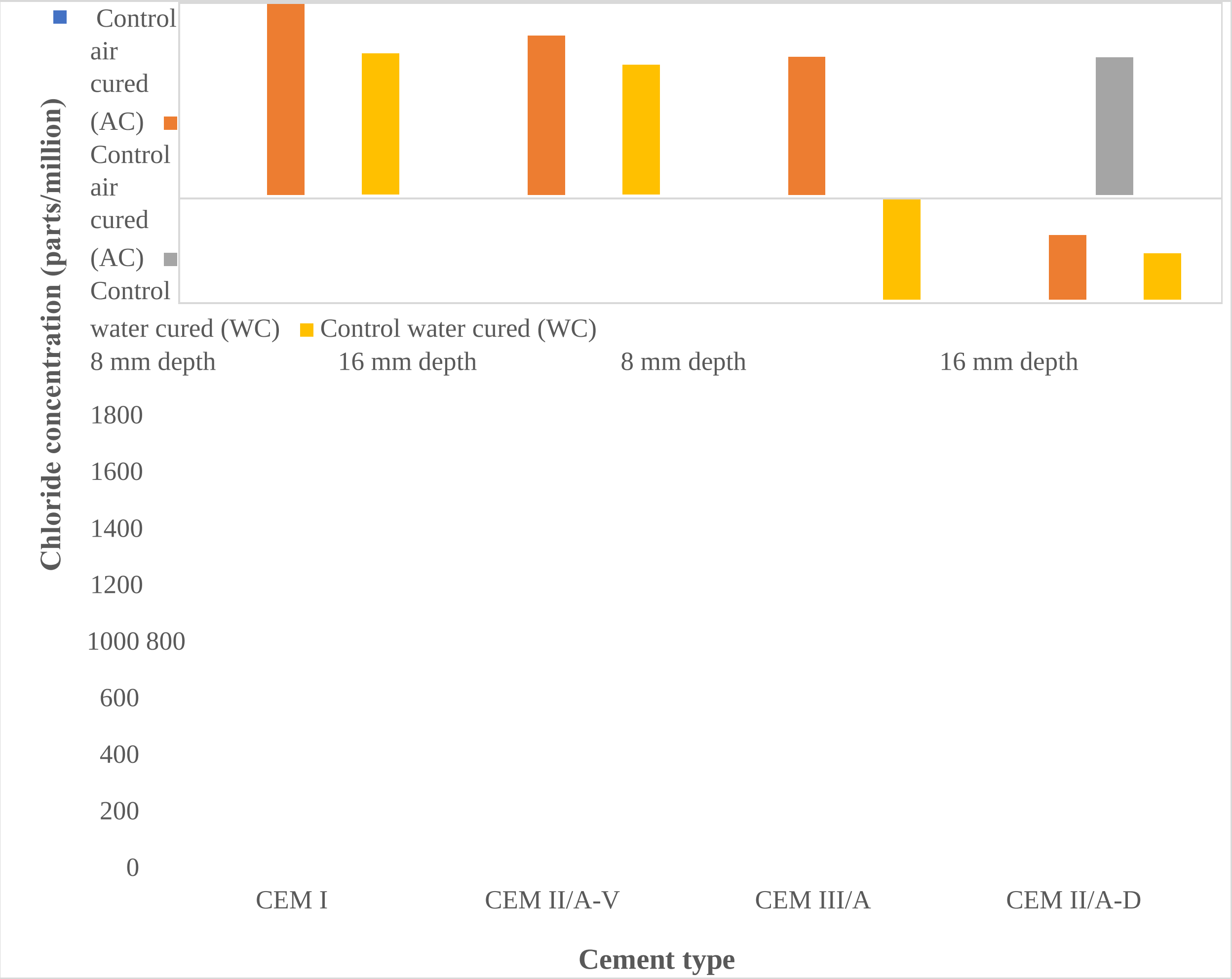


**Figure 6.27** Chloride concentration of control samples cured in air and water

## 6.6 Concluding remarks

- Treatment with protective materials (admixtures and surface treatment agents) did not improve carbonation resistance of concrete cubes. However, performance of cubes treated with ST2 was comparable to some extent to control samples cured in water.

- Overall, control cubes cured in water experienced less carbonation than control samples cured in air and specimens treated with curing compound and protective materials. This shows that water curing is important to provide adequate carbonation resistance.

- Minimum carbonation depths were measured in CEM II/A-D and CEM I sample cured in water, whereas maximum carbonation depths were measured in control cubes cured in air.

- Inclusion of SF in the mix increased carbonation resistance of concrete cubes cured in water. On the other hand, replacement of PC with FA and GGBS in CEM II/A-V and CEM III/A respectively, decreased carbonation resistance. In other words, cement blended with FA and GGBS is more susceptible to carbonation.

- CEM I specimens cured with CC and treated with protective materials performed better than corresponding cubes produced from blended cement. This indicates that the amount of calcium hydroxide which is higher in CEM I concrete is vital for the alkaline nature of concrete, thus better control of carbonation rate in concrete.

- In terms of scaling resistance, results shows that treatment with admixtures influenced by hydrophobic effect (Admix2 & Admix3) was more effective than admixtures governed by crystalline actions (Admix1). In fact, treatment with Admix1 was ineffective in providing protection against scaling.

- Similarly, treatment with surface treatment agents characterized by hydrophobic impregnation (ST2 & ST3) was more effective than agent influenced by crystalline mechanism (ST1).

- Application of surface treatment agents particularly ST2 & ST3 provided far more protection for concrete surface than inclusion of admixtures. In other words, external protection mechanism was more efficient than internal protection mechanism.

- Best performance was observed in specimens treated with ST2 and ST3 as slabs remained almost intact after completion of test.

- Inclusion of supplementary cementitious materials namely, FA and GGBS reduced scaling resistance of concrete surface in comparison to reference mix CEM I. This could be attributed to presence of mineral admixtures which tends to increase bleeding and weaken the concrete surface.

- Increasing the replacement level of PC with mineral admixtures (GGBS) in CEM III/A caused more scaling and deterioration compared to CEM II/A-V cement where only 20% of PC was replaced with FA.

- Addition of SF in the mix significantly improved scaling resistance of concrete surface. This could be due to the increased compressive strength and pore structure refinement in CEM II/A-D cement.

- With respect to chloride penetration, results indicated that presence of mineral admixtures improved chloride penetration resistance of concrete. Nevertheless, 20% replacement of PC with FA reduced chloride concentration by only 10% in comparison to reference mix CEM I cured in water. This shows that replacement level of PC in CEM II/A-V was not sufficient to reach optimum performance.

- Partial replacement of 40% PC with GGBS in CEM III/A reduced chloride concentration by 27%. This indicates that increasing replacement level improved chloride penetration resistance of concrete specimens compared to reference mix CEM I cured in water.

- Inclusion of SF in the mix significantly reduced chloride penetration as results showed that chloride concentration was decreased by 63%. Results demonstrate that using blended cements increases chloride ingress resistance of concrete and replacement level directly influences concrete performance.

- Results showed that treatment with protective materials influenced by crystalline effects (Admix1 and ST1) was not as effective as protective agents (Admix2, Admix3, ST2 and ST3) governed by hydrophobic effects.

- Application of surface treatment was more effective than addition of admixtures to concrete mixes in combating chloride ions ingress. This means that external protection mechanism was more effective than internal protection mechanism.

- Maximum reduction in chloride concentration was more than 75% measured in specimens treated with ST2 and ST3. This emphasizes that external treatment mechanism provided adequate protection for concrete exposed to chloride penetration.

# Chapter 7: Conclusions and Recommendations

## 7.1 Concluding Remarks

This study was conducted to evaluate performance of plain and blended cements concrete cured using a water-based curing compound, and treated either with waterproofing admixture or surface treatment agents to improve overall performance. The performance was based on investigating engineering, transport and durability properties of concrete. Conclusions drawn from all phases (Phase 1, 2 and 3) are presented at the end of individual chapters (Chapter 4, 5 and 6). This chapter presents findings and novelty of the study based on the objectives identified in Chapter 1.

### 7.1.1 Phase 1 (Engineering Properties)

- Water curing was more efficient than applying the curing compound as specimens of plain and blended cements cured in water reached design strength at 28 days age. On the other hand, specimens cured using the curing compound achieved more than 93% of the design strength at 28 days age. However, results showed that strength development of cubes cured using the curing compound continued beyond 28 days as target strength was achieved in specimens of all cement types at 90 days age.

- In terms of mineral admixtures impact on strength development, results showed that inclusion of SF in CEM II/A-D significantly contributed to strength development within 28 days age. In contrast, presence of FA and GGBS in CEM II/A-V and CEM III/A respectively was more influential on strength gain beyond 28 days age.

- Results show that flexural strength of specimens cured in water developed higher strength than specimens cured with the curing compound. Nevertheless, plain and blended cement specimens cured using the curing compound achieved more than 90% strength of corresponding ones cured in water.

- Similar trend was observed as strength development in CEM I and CEM II/A-D mainly occurred within 28 days. Whereas strength gain in CEM II/A-V and CEM III/A continued up to 90 days. This indicates that applying the curing compound was effective in curing plain and blended cements.

- Results show that inclusion of SF and GGBS developed higher flexural strength than FA and plain cement. Overall, results suggest that incorporating SF and GGBS in the mixes improved strength development more than addition of FA.

- Minimum drying shrinkage were measured in prisms cured in water, followed by curing compound and air curing. Moreover, minimum shrinkage was observed in CEM II/A-D cement followed by CEM III/A and CEM II/A-V.

- Results indicate that the combined effects of applying the curing compound and presence of mineral admixtures was efficient in decreasing drying shrinkage, as it did not cause a large increase in drying shrinkage particularly in blended cements.

- Generally, curing plain and blended cement concrete with the curing compound achieved more than 90% at 28 days with respect to compressive and flexural strength. This percentage was increased to more than 96% at 90 days due to the continuous pozzolanic reactions of the mineral admixtures. This shows that using the curing compound in blended cement was effective in strength development beyond 28 days. Moreover, results suggest that inclusion of GGBS and SF was more effective in improving engineering properties. Moreover, results show that that drying shrinkage of samples cured in water performed better than prisms cured using the curing compound. Therefore, the objectives outlined in Phase 1 were not entirely achieved. Nevertheless, taking into account the overall results of plain and blended cement concrete, it can be concluded that the majority of the objectives were accomplished.

### 7.1.2 Phase 2 (Transport Properties)

- Results show that type and replacement level of PC with cementitious materials was important in reducing initial surface absorption as maximum reduction was measured in CEM II/A-D, followed by CEM III/A and CEM II/A-V.

- Compressive strength of specimens was influential on reducing absorption rate as an inverse relation was established between surface absorption and compressive strength. It was found that absorption rate decreased as compressive strength increased.

- Generally, treatment with admixtures and surface treatment agents influenced by hydrophobic effects was more effective than corresponding compounds influenced by crystalline pore blockers. Moreover, maximum sorptivity reduction was measured in specimens treated with surface treatment agents governed by hydrophobic impregnation. This demonstrates that selecting appropriate protective materials is essential to provide adequate protection for concrete.

- Protection through external mechanism (application of surface treatment agents) was more effective than internal mechanism (addition of waterproofing admixtures). This indicates that providing a suitable protection for concrete surface (skin) is more efficient than internal protection mechanism in combating water penetration.

- Inclusion of supplementary cementitious materials reduced capillary absorption as minimum sorptivity coefficient was measured in blended cements whereas maximum coefficient was measured in plain cement.

- Regardless of treatment type and mechanism, it was found that treatment did not improve impermeability of concrete subjected to water under pressure. Nevertheless, treatment with hydrophobic agents was highly effective in reducing water ingress due to capillary suction, as hydrophobic surface treatment achieved absorption criteria specified in BS EN 1504-2 (2004) and German Committee for Reinforced Concrete Guidelines.

- Although results of water penetration under pressure were not promising, the majority of the objectives specified in Phase 2 were achieved successfully. This is because sorptivity due to capillary absorption was significantly reduced in blended cement, treated with protective materials (particularly surface treatment agents). It is well known that water ingress due to capillary absorption is the main mechanism for water and chloride ions penetration, causing major deterioration in concrete. Therefore, the combined effect of protective treatment and inclusion of mineral admixtures was effective in improving transport properties.

### 7.1.3 Phase 3 (Durability Properties)

- Treatment with the curing compound and protective materials did not improve resistance of specimens against carbonation. Results show that specimens cured in water performed better than corresponding cubes cured with the curing compound and cured in air.

- Inclusion of SF increased carbonation resistance of cubes in water. In contract, addition of FA and GGBS reduced carbonation resistance and made the concrete more prone to carbonation. This indicates that the amount of calcium hydroxide which is less in blended cements due to replacement of PC with mineral admixtures is essential for the alkaline nature of concrete.

- Addition of SF significantly increased scaling resistance of specimens, whereas inclusion of FA and GGBS reduced scaling resistance. Nevertheless, treatment with the protective materials particularly ST2 and ST3 provided adequate safeguard for concrete surface.

- In terms of chloride penetration, replacement of PC with mineral admixtures was effective in reducing chloride ingress. Highest reduction in chloride concentration was measured in CEM II/A-D mix, followed by CEM III/A and CEM II/A-V.

- Similar trend was observed as treatment with protective materials influenced by crystalline actions was not as effective as protective agents governed by hydrophobic effects. Moreover, applying surface treatment agents was more efficient than adding waterproofing admixtures. This emphasizes that external protection mechanism is more effective than internal protection mechanism in combating chloride ingress.

- Results of Phase 3 have shown that inclusion of FA and GGBS was ineffective in terms of carbonation and scaling resistance. Nonetheless, inclusion of SF and treatment with protective materials influenced by hydrophobic effect, provided excellent resistance and protection. In fact, FA and GGBS slabs treated with ST2 and ST3 remained almost intact after 50 cycles of freeze and thaw. On the other hand, inclusion of mineral admixtures and treatment with ST2 and ST3 were highly effective in reducing chloride penetration. Overall, it can be concluded that objectives outlined in Phase 3 were achieved to a great extent.

## 7.2 Key findings and novelty of the research

- Results indicate that applying the curing compound led to continuation of the hydration process particularly in blended cements (CEM II/A-V and CEM III/A) up to 90 days age. This implies that strength development due to the pozzolanic reactions was more evident beyond 28 days in blended cements. In other words, using the curing compound was effective in curing blended cements as they usually require longer water curing periods to develop the target strength.

- Results show that applying the curing compound on plain and blended cements was effective in strength development, as specimens achieved more than 93% of the design strength at 28 days age. However, results suggest that other properties such as water penetration due to capillary absorption requires treatment with adequate protective material (surface treatment or waterproofing admixture) to improve impermeability. Thus, it is advisable for concrete cured with curing compounds to receive further protective treatment.

- The study demonstrated that using curing compound followed by application of surface treatment agents on plain and blended cements is effective in improving engineering and transport properties. In other words, both materials (curing compounds and surface treatment) are compatible and jointly contribute to overall performance improvement.

- The study showed that using a suitable curing compound along with an appropriate protective material and mineral admixtures can improve overall properties of concrete. In other words, combined effects of protective materials and mineral admixtures can produce a durable concrete while exposed to aggressive environment.

- Treatment with protective materials influenced by hydrophobic effects was more effective than compounds governed by crystalline mechanism. Furthermore, application of surface treatment provided better protection for concrete surface than addition of waterproofing admixtures. This establishes that external protection mechanism is more efficient than internal protection mechanism.

## 7.3 Practical Implications

The findings from this research study present technical data and suggestions on the efficiency of using various environmentally friendly (water based) substances, and byproduct materials to produce durable concrete. Producing such concrete can be useful and important in applications exposed to harsh conditions, for instance, concrete pavement, marine structures and bridges exposed to deicing salt. Moreover, utilising byproduct materials enhance the overall cost effectiveness of the concrete while maintaining its important properties. Subsequently, contributing to sustainable benefits of the industry by reducing its environmental impacts such as, embodied carbon and excessive consumption of clean water. Results of this investigation can give the industry incentive and vision on adequate approaches for concrete curing and protection.

## 7.4 Recommendations for Future Works

This research has demonstrated that using a curing compound along with treatment of adequate protective materials on plain and blended cements concrete, can improve performance and produce a durable concrete. The study has achieved the majority of the goals and objectives initially identified in Chapter 1. However, as the study progressed, further aspects and areas have risen for consideration and exploration. Therefore, further investigations are recommended on the following fields:

- This study focused on investigating the influence of binary cement combination on mechanical, transport and durability properties. It was found that inclusion of SF and GGBS improved performance of blended cement (binary blended cement). Therefore, further research should be conducted to evaluate the impact of ternary blended cement, for instance a combination of 60% PC with 35% GGBS and 5% SF. Moreover, increasing the replacement level of PC with FA to 30% and inclusion of 5% SF to form another type of ternary blended cement for additional investigation.

- Different partial replacement of Portland cement with mineral admixtures could be investigated further. For instance, up to 50% replacement of PC with GGBS and FA to produce ternary blended cement.

- In this research, specimens were demoulded approximately 3-4 hours after casting, and sprayed with the curing compound. Demoulding the specimens after 24 hours, followed by spraying the curing compound would be another matter to investigate in future works as this action would allow samples to retain more moisture content.

- Another aspect recommended for further investigation is the influence of partial replacement of normal aggregate with lightweight aggregate to provide an internal source for curing along with the external curing (spraying curing compound). Performance should

0be compared to control samples cured in water to determine efficiency of the combined curing sources.

- In this study, treated concrete specimens of plain and binary blends performed well when exposed to chloride ions penetration and resistance to scaling tests. It would be useful to evaluate performance of binary and ternary blends specimens while subjected to combined solution of sulphate and chloride in the environmental chamber.

- Various conventional protective materials which are commonly used in the construction industry, were used in this research based on manufacturers recommended dosages. It would be helpful to change the dosage, for example increasing the dosage of waterproofing admixtures added to the concrete, and assessing its impact on overall performance.

- In the current study, a fixed water to binder ratio and compressive strength were adopted as numerous variables were present in this research. It would be beneficial to investigate the impact of different water to binder ratio and compressive strength on the performance of concrete.

- Another area to investigate is the temperature, for instance curing the samples in high, ambient and low temperatures to evaluate concrete properties and assess effectiveness of the protective materials and the curing method.

- Cost of using CC and protective materials should be investigated further and compared to cost of conventional concrete production (water curing without protective materials) to establish the economy aspect. Taking into account lifespan and repair cost due to potential deterioration of both types of concrete.

- Speed of construction using CC can be investigated further and compared to conventional water curing to establish the most cost-effective method for construction practice.

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# Appendices

## Appendix A: Aggregates Characterization

### A1. Particle Size Distribution: BS EN 933-1

#### Coarse Aggregate with nominal size D 20mm

Table A1. Particle Size Distribution of Specimen 1

| | | | |
|---|---|---|---|
| | | Specimen 1 | |
| | | Mi (gm) | Mf (gm) |
| | | 2515.6 | 2514.4 |
| | | | |
| SIEVE (mm) | Mass retained (g) | Percentage retained (%) | Cumulative percentage passing (%) |
| 31.5 | 0 | 0 | 100 |
| 20 | 118.4 | 4.71 | 95.29 |
| 16 | 297.6 | 11.83 | 83.46 |
| 12.5 | 416.7 | 16.56 | 66.90 |
| 8 | 933.7 | 37.12 | 29.78 |
| 4 | 733.1 | 29.14 | 0.64 |
| 2 | 11.3 | 0.45 | 0.19 |
| Pan | 3.6 | 0.14 | 0.05 |
| | | | |
| | 2514.4 | | |
| Error checking | [(Mi-Mf)/Mi] * 100 < 1% | [(2515.6 - 2514.3)/ 2515.6] * 100 | 0.05 |

Table A2. Particle Size Distribution of Specimen 2

| | | | |
|---|---|---|---|
| | | Specimen 2 | |
| | | Mi (gm) | Mf (gm) |
| | | 2525.8 | 2524.40 |
| SIEVE (mm) | Mass retained (g) | Percentage retained (%) | Cumulative percentage passing (%) |
| 31.5 | 0 | 0 | 100 |
| 20 | 102.6 | 4.06 | 95.94 |
| 16 | 377.5 | 14.95 | 80.99 |
| 12.5 | 470.4 | 18.62 | 62.37 |
| 8 | 900.8 | 35.66 | 26.70 |
| 4 | 658.1 | 26.06 | 0.65 |
| 2 | 11.7 | 0.46 | 0.19 |
| Pan | 3.3 | 0.13 | 0.06 |
| | | | |
| | 2524.4 | | |
| Error checking | [(Mi-Mf)/Mi] * 100 < 1% | [(2515.6 - 2514.3)/ 2515.6] * 100 | 0.06 |

Table A3. Particle Size Distribution of Specimen 3

| | | | |
|---|---|---|---|
| | | Specimen 3 | |
| | | Mi (gm) | Mf (gm) |
| | | 2550.50 | 2549.50 |
| SIEVE (mm) | Mass retained (g) | Percentage retained (%) | Cumulative percentage passing (%) |
| 31.5 | 0 | 0 | 100 |

| | | | |
|---|---|---|---|
| 20 | 61.1 | 2.40 | 97.60 |
| 16 | 475.2 | 18.63 | 78.97 |
| 12.5 | 496.1 | 19.45 | 59.52 |
| 8 | 872.8 | 34.22 | 25.30 |
| 4 | 634.3 | 24.87 | 0.43 |
| 2 | 7.8 | 0.31 | 0.13 |
| Pan | 2.2 | 0.09 | 0.04 |
| | | | |
| | 2549.5 | | |
| Error checking | [(Mi-Mf)/Mi] * 100 < 1% | [(2515.6 - 2514.3)/ 2515.6] * 100 | 0.04 |

Table A4. Average of specimens

| SIEVE (mm) | Cumulative percenta passing (%) Specimen 1 | Cumulative percentage passing (%) Specimen 2 | Cumulative percentage passing (%) Specimen 3 | Average |
|---|---|---|---|---|
| 31.5 | 100.00 | 100.00 | 100.00 | 100.00 |
| 20 | 95.29 | 95.94 | 97.60 | 96.28 |
| 16 | 83.46 | 80.99 | 78.97 | 81.14 |
| 12.5 | 66.90 | 62.37 | 59.52 | 62.93 |
| 8 | 29.78 | 26.70 | 25.30 | 27.26 |
| 4 | 0.64 | 0.65 | 0.43 | 0.57 |
| 2 | 0.19 | 0.19 | 0.13 | 0.17 |
| Pan | 0.05 | 0.06 | 0.04 | 0.05 |
| | | | | |
| | | | | 368.40 |
| Fineness modulus (FM) = | N(100) - sume of total percentage passing / 100<br>N = number of sieves | | | **3.32** |

**Fine Aggregate with nominal size D 5mm**

Table A5. Particle Size Distribution of Specimen 1

| | | Specimen 1 | |
|---|---|---|---|
| | | Mi (gm) | Mf (gm) |
| | | 505.5 | 504.6 |
| SIEVE (mm) | Mass retained (g) | Percentage retained (%) | Cumulative percentage passing (%) |
| 8 | 1.2 | 0 | 100 |
| 5 | 7.5 | 1.48 | 98.52 |
| 4 | 15.1 | 2.99 | 95.53 |
| 2 | 47.5 | 9.40 | 86.13 |
| 1 | 48.2 | 9.54 | 76.60 |
| 0.6 | 66.5 | 13.16 | 63.44 |
| 0.25 | 223.6 | 44.23 | 19.21 |
| 0.063 | 94.5 | 18.69 | 0.51 |
| Pan | 0.5 | 0.10 | 0.42 |
| | | | |
| Error checking | [(Mi-Mf)/Mi] * 100 < 1% | [(505.7 - 506.2)/ 505.7] * 100 | **0.18** |

Table A6. Particle Size Distribution of Specimen 2

| | | Specimen 2 | |
|---|---|---|---|
| | | Mi (gm) | Mf (gm) |
| | | 506.8 | 504.2 |
| SIEVE (mm) | Mass retained (g) | Percentage retained (%) | Cumulative percentage passing (%) |
| 8 | 1.4 | 0 | 100 |
| 5 | 6.3 | 1.24 | 98.76 |
| 4 | 12.7 | 2.51 | 96.25 |
| 2 | 52.8 | 10.42 | 85.83 |
| 1 | 52.4 | 10.34 | 75.49 |
| 0.6 | 69.5 | 13.71 | 61.78 |
| 0.25 | 216.6 | 42.74 | 19.04 |
| 0.063 | 92.1 | 18.17 | 0.87 |
| Pan | 0.4 | 0.08 | 0.79 |
| | 504.2 | | |
| Error checking | [(Mi-Mf)/Mi] * 100 < 1% | [(505.7 - 506.2)/ 505.7] * 100 | **0.51** |

Table A7. Particle Size Distribution of Specimen 3

| | | Specimen 3 | |
|---|---|---|---|
| | | Mi (gm) | Mf (gm) |
| | | 502.4 | 500.9 |
| SIEVE (mm) | Mass retained (g) | Percentage retained (%) | Cumulative percentage passing (%) |
| 8 | 2.9 | 0 | 100 |
| 5 | 7.8 | 1.55 | 98.45 |
| 4 | 16.5 | 3.28 | 95.16 |
| 2 | 48.4 | 9.63 | 85.53 |
| 1 | 57.4 | 11.43 | 74.10 |
| 0.6 | 69.2 | 13.77 | 60.33 |
| 0.25 | 199.7 | 39.75 | 20.58 |
| 0.063 | 98.3 | 19.57 | 1.02 |
| Pan | 0.7 | 0.14 | 0.88 |
| | 500.9 | | |
| Error checking | [(Mi-Mf)/Mi] * 100 < 1% | [(505.7 - 506.2)/ 505.7] * 100 | **0.30** |

Table A8. Average of specimens

| SIEVE (mm) | Cumulative percentage passing (%) Specimen 1 | Cumulative percentage passing (%) Specimen 2 | Cumulative percentage passing (%) Specimen 3 | Average |
|---|---|---|---|---|
| 8 | 100.00 | 100.00 | 100.00 | 100.00 |
| 5 | 98.52 | 98.76 | 98.45 | 98.57 |
| 4 | 95.53 | 96.25 | 95.16 | 95.65 |
| 2 | 86.13 | 85.83 | 85.53 | 85.83 |
| 1 | 76.60 | 75.49 | 74.10 | 75.40 |
| 0.6 | 63.44 | 61.78 | 60.33 | 61.85 |
| 0.25 | 19.21 | 19.04 | 20.58 | 19.61 |
| 0.063 | 0.51 | 0.87 | 1.02 | 0.80 |
| Pan | 0.42 | 0.79 | 0.88 | 0.69 |

| | | | |
|---|---|---|---|
| | | | 538.41 |
| Fineness modulus (FM) | = | N(100) - sume of total percentage passing / 100 | **2.62** |
| | | N = number of sieves | |

## A2. Determination of particle density and water absorption.

**Standard:** BS EN 1097-6 (2013),

**Sample**: Coarse aggregate with nominal particle size D: 20 mm. **Sample condition**: oven dried at 110 °C, saturated surface dry.

### Specimen 1

$M_1 = 1360.3$ gm, $M_2 = 3010.4$ gm, $M_3 = 2185.7$ gm, $M_4 = 1333.5$ gm

Apparent density $\rho_a = \rho_w \times \frac{M4}{M4-(M2-M3)} = 1 \times \frac{1333.5}{1333.5-(3010.4-2185.7)} = 2.62\ \text{Mg/m}^3$

Oven-dried density $\rho_{rd} = \rho_w \text{ x } \frac{M4}{M1 - (M2-M3)} = 1 \text{ x } \frac{1333.5}{1360.3 - (3010.4-2185.7)} = 2.49 \text{ Mg/m}^3$

Saturated surface dry density $\rho_{ssd} = \rho_w \text{ x } \frac{M1}{M1 - (M2-M3)} = 1 \text{ x } \frac{1360.3}{1360.3 - (3010.4-2185.7)} = 2.54 \text{ Mg/m}^3$

24-hour water absorption $WA_{24} = \frac{100}{M_4} \quad \frac{}{1333.5} \text{ x } (M_1 - M_4) = 100 \text{ x } (1360.3-1333.5) = 2.01 \%$

**Specimen 2**

$M_1$ = 1355.5 gm, $M_2$ = 2975.8 gm, $M_3$ = 2155.4 gm, $M_4$ = 1336.3 gm

Apparent density $\rho_a = \rho_w \text{ x } \frac{M4}{M4 - (M2-M3)} = 1 \text{ x } \frac{1336.3}{1336.3-(2975.8-2155.4)} = 2.59 \text{ Mg/m}^3$

Oven-dried density $\rho_{rd} = \rho_w \text{ x } \frac{M4}{M1 - (M2-M3)} = 1 \text{ x } \frac{1336.3}{1355.5 - (2975.8 - 2155.4)} = 2.5 \text{ Mg/m}^3$

Saturated surface dry density $\rho_{ssd} = \rho_w \text{ x } \frac{M1}{M1 - (M2-M3)} = 1 \text{ x } \frac{1355.5}{1355.5 - (2975.8 - 2155.4)} = 2.53 \text{ Mg/m}^3$

24-hour water absorption $WA_{24} = \frac{100}{M_4} \quad \frac{}{1336.3} \text{ x } (M_1 - M_4) = 100 \text{ x } (1355.5-1336.3) = 1.44 \%$

**Specimen 3**

$M_1$ = 1365.2 gm, $M_2$ = 2989.6 gm, $M_3$ = 2169.5 gm, $M_4$ = 1343.3 gm

Apparent density $\rho_a = \rho_w \text{ x } \frac{M4}{M4 - (M2-M3)} = 1 \text{ x } \frac{1343.3}{1343.3-(2989.6 - 2169.5)} = 2.57 \text{ Mg/m}^3$

Oven-dried density $\rho_{rd} = \rho_w \text{ x } \frac{M4}{M1 - (M2-M3)} = 1 \text{ x } \frac{1343.3}{1365.2 - (2989.6 - 2169.5)} = 2.46 \text{ Mg/m}^3$

Saturated surface dry density $\rho_{ssd} = \rho_w \text{ x } \frac{M1}{M1 - (M2-M3)} = \frac{1365.2}{1365.2 - (2989.6 - 2169.5)} \quad 1 \text{ x } = 2.50 \text{ Mg/m}^3$

24-hour water absorption $WA_{24} = 100 \quad \frac{100 \text{ x } (1365.2 - 1343.3)}{1343.3} \quad \frac{}{} \text{ x } (M1 - M4) = \quad = 1.63 \%$

M4

Table A9. Particle densities and water absorption test results of coarse aggregates used in this study

| Specimen | Apparent $\rho_a$ dens (Mg/m$^3$) | Oven-dried density (Mg/m$^3$) | Saturated surface d density $\rho_{ssd}$ (Mg/m$^3$) | 24-hour wat absorption $WA_{24}$ |
|---|---|---|---|---|
| 1 | 2.62 | 2.49 | 2.54 | 2.01 |
| 2 | 2.59 | 2.5 | 2.53 | 1.44 |
| 3 | 2.57 | 2.46 | 2.50 | 1.63 |
| **Average** | **2.59** | **2.48** | **2.52** | **1.69** |

**Standard:** BS EN 1097-6 (2013), determination of particle density and water absorption.
**Sample**: Fine aggregate with nominal particle size D: 5 mm.
**Sample condition**: oven dried at 110 °C, saturated surface dry.

**Specimen 1**

$M_1$ = 650.4 gm, $M_2$ = 1671.3, gm, $M_3$ = 1261.2 gm, $M_4$ = 648.1 gm

Apparent density $\rho_a = \rho_w \text{ x } \frac{M4}{M4-(M2-M3)} = \frac{648.1}{648.1-(1671.3-1261.2)}$ 1 x = 2.72 Mg/m$^3$

Oven-dried density $\rho_{rd} = \rho_w \text{ x } \frac{M4}{M1-(M2-M3)} = \frac{648.1}{650.4-(1671.3-1261.2)}$ 1 x = 2.70 Mg/m$^3$

Saturated surface dry density $\rho_{ssd} = \rho_w \text{ x } \frac{M1}{M1-(M2-M3)} = \frac{650.4}{650.4-(1671.3-1261.2)}$ 1 x = 2.71 Mg/m$^3$

24-hour water absorption $WA_{24}$ = 100 $\frac{100 \text{ x } (650.4-648.1)}{648.1}$ $\frac{}{M_4}$ x (M1- M4) = = 0.35 %

**Specimen 2**

$M_1$ = 665.5 gm, $M_2$ = 1676.7, gm, $M_3$ = 1254.6 gm, $M_4$ = 663.1 gm

Apparent density $\rho_a = \rho_w \text{ x } \frac{M4}{M4-(M2-M3)} = \frac{663.1}{663.1-(1676.7-1254.6)}$ 1 x = 2.75 Mg/m$^3$

Oven-dried density $\rho_{rd} = \rho_w$ x $\frac{M4}{M1 -(M2-M3)}$ = $\frac{663.1}{665.5 -(1676.7 -1254.6)}$ 1 x = 2.72 Mg/m$^3$

Saturated surface dry density $\rho_{ssd} = \rho_w$ x $\frac{M1}{M1 -(M2-M3)}$ = $\frac{665.5}{665.5 -(1676.7 -1254.6)}$ 1 x = 2.73 Mg/m$^3$

24-hour water absorption $WA_{24} = \frac{100}{M_4}$ x (M1- M4) = $\frac{100 \times (665.5 - 663.1)}{663.1}$ = 0.36 %

**Specimen 3**

$M_1$ = 677 gm, $M_2$ = 1688.5, gm, $M_3$ = 1258.4 gm, $M_4$ = 674.5 gm

Apparent density $\rho_a = \rho_w$ x $\frac{M4}{M4 -(M2-M3)}$ = $\frac{674.5}{674.5 -(1688.5 -1258.4)}$ 1 x = 2.76 Mg/m$^3$

Oven-dried density $\rho_{rd} = \rho_w$ x $\frac{M4}{M1 -(M2-M3)}$ = $\frac{674.5}{677 -(1688.5 -1258.4)}$ 1 x = 2.74 Mg/m$^3$

Saturated surface dry density $\rho_{ssd} = \rho_w$ x $\frac{M1}{M1 -(M2-M3)}$ = $\frac{677}{677 -(1688.5 -1258.4)}$ 1 x = 2.74 Mg/m$^3$

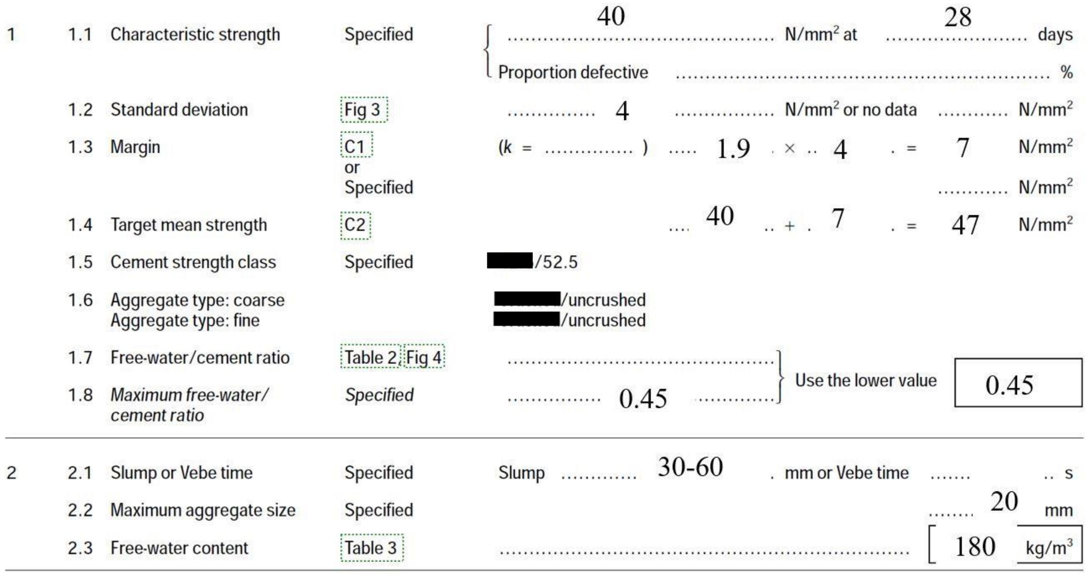
24-hour water absorption $WA_{24} = \frac{100}{M_4}$ x (M1- M4) = $\frac{100 \times (677 - 674.5)}{674.5}$ = 0.37 %

Table A10. Particle densities and water absorption test results of fine aggregate used in this study

| **Specimen** | **Apparent $\rho_a$ dens** (Mg/m$^3$) | **Oven-dried density** (Mg/m$^3$) | **Saturated surface d density** $\rho_{ssd}$ (Mg/m$^3$) | **24-hour wat absorption $WA_{24}$** |
|---|---|---|---|---|
| 1 | 2.72 | 2.70 | 2.71 | 0.35 |
| 2 | 2.75 | 2.72 | 2.73 | 0.36 |
| 3 | 2.76 | 2.74 | 2.74 | 0.37 |
| **Average** | **2.74** | **2.72** | **2.73** | **0.36** |

# Appendix B: Concrete Mix Design According to BRE

## 1. CEM I Concrete



| | | | | |
|---|---|---|---|---|
| 1 | 1.1 | Characteristic strength | Specified | 40 N/mm² at 28 days<br>Proportion defective ……… % |
| | 1.2 | Standard deviation | Fig 3 | ……… 4 ……… N/mm² or no data ……… N/mm² |
| | 1.3 | Margin | C1<br>or<br>Specified | (k = ……… ) ….. 1.9 × 4 = 7 N/mm²<br>……… N/mm² |
| | 1.4 | Target mean strength | C2 | 40 + 7 = 47 N/mm² |
| | 1.5 | Cement strength class | Specified | [redacted]/52.5 |
| | 1.6 | Aggregate type: coarse<br>Aggregate type: fine | | [redacted]/uncrushed<br>[redacted]/uncrushed |
| | 1.7 | Free-water/cement ratio | Table 2, Fig 4 | ……… } Use the lower value 0.45 |
| | 1.8 | *Maximum free-water/ cement ratio* | *Specified* | ……… 0.45 ……… } |
| 2 | 2.1 | Slump or Vebe time | Specified | Slump ……… 30-60 mm or Vebe time ……… s |
| | 2.2 | Maximum aggregate size | Specified | 20 mm |
| | 2.3 | Free-water content | Table 3 | ……… 180 kg/m³ |

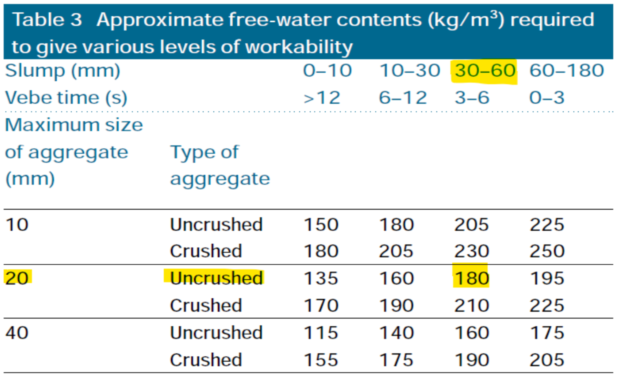
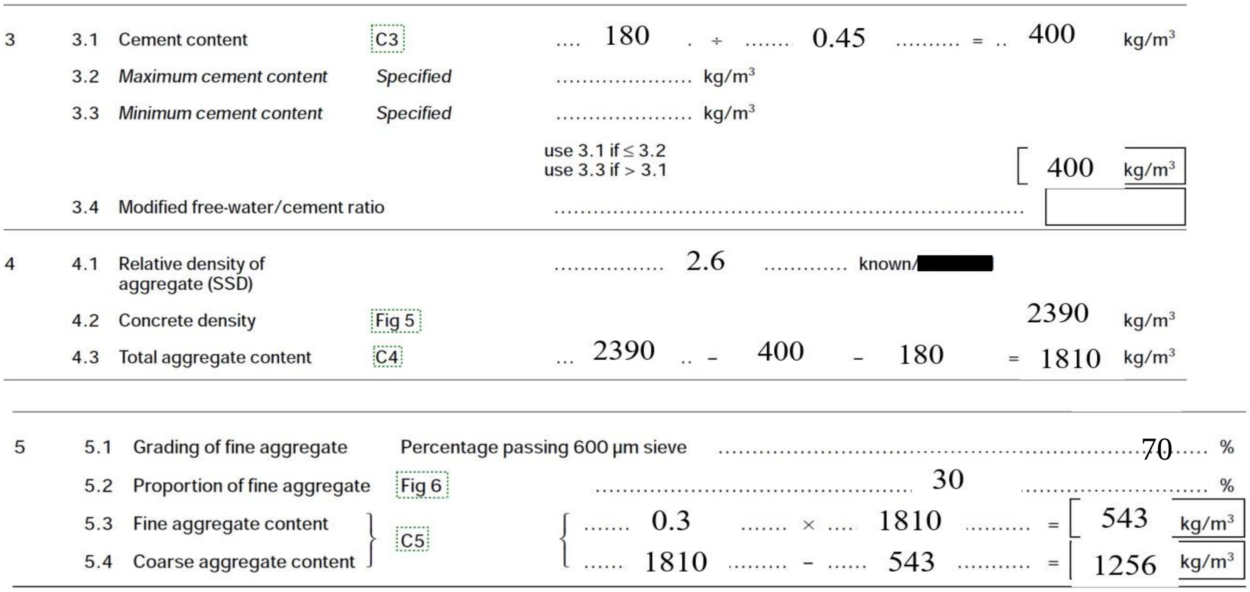


**Table 3** Approximate free-water contents (kg/m³) required to give various levels of workability

| Slump (mm) | | 0–10 | 10–30 | 30–60 | 60–180 |
|---|---|---|---|---|---|
| Vebe time (s) | | >12 | 6–12 | 3–6 | 0–3 |
| Maximum size of aggregate (mm) | Type of aggregate | | | | |
| 10 | Uncrushed | 150 | 180 | 205 | 225 |
| | Crushed | 180 | 205 | 230 | 250 |
| 20 | Uncrushed | 135 | 160 | 180 | 195 |
| | Crushed | 170 | 190 | 210 | 225 |
| 40 | Uncrushed | 115 | 140 | 160 | 175 |
| | Crushed | 155 | 175 | 190 | 205 |

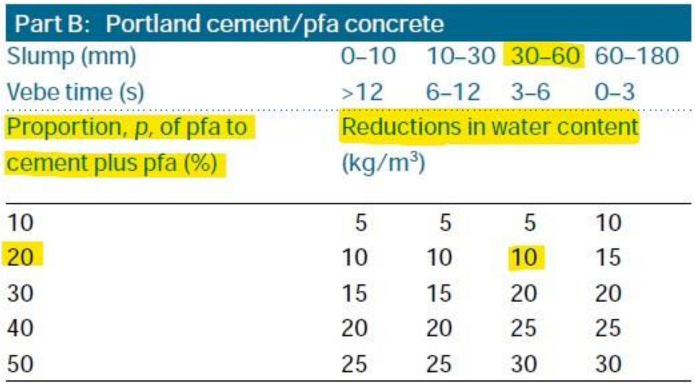


| | | | | |
|---|---|---|---|---|
| 3 | 3.1 | Cement content | C3 | …. 180 ÷ ……. 0.45 ……… = .. 400 kg/m³ |
| | 3.2 | *Maximum cement content* | *Specified* | ……… kg/m³ |
| | 3.3 | *Minimum cement content* | *Specified* | ……… kg/m³ |
| | | | | use 3.1 if ≤ 3.2<br>use 3.3 if > 3.1   400 kg/m³ |
| | 3.4 | Modified free-water/cement ratio | | ……… |
| 4 | 4.1 | Relative density of aggregate (SSD) | | ……… 2.6 ……… known/[redacted] |
| | 4.2 | Concrete density | Fig 5 | 2390 kg/m³ |
| | 4.3 | Total aggregate content | C4 | … 2390 – 400 – 180 = 1810 kg/m³ |
| 5 | 5.1 | Grading of fine aggregate | | Percentage passing 600 μm sieve ……… 70 ….. % |
| | 5.2 | Proportion of fine aggregate | Fig 6 | ……… 30 ……… % |
| | 5.3 | Fine aggregate content | C5 | ……. 0.3 ……. × …. 1810 ……… = 543 kg/m³ |
| | 5.4 | Coarse aggregate content | | …… 1810 ……… – …… 543 ……… = 1256 kg/m³ |

## 2. CEM II/A-V Concrete

$$\frac{W}{\phantom{xxxx}} = 0.45\ (C$$
$$+\ 0.3F)$$

From table 9 (Part B), free water content = 180 – 10 = 170 kg/m$^3$



| Part B: Portland cement/pfa concrete | | | | |
|---|---|---|---|---|
| Slump (mm) | 0–10 | 10–30 | 30–60 | 60–180 |
| Vebe time (s) | >12 | 6–12 | 3–6 | 0–3 |
| Proportion, *p*, of pfa to cement plus pfa (%) | Reductions in water content (kg/m$^3$) | | | |
| 10 | 5 | 5 | 5 | 10 |
| 20 | 10 | 10 | 10 | 15 |
| 30 | 15 | 15 | 20 | 20 |
| 40 | 20 | 20 | 25 | 25 |
| 50 | 25 | 25 | 30 | 30 |

For a specified proportion of pfa of 20%, p = 20

$$\text{Portland cement content } (C) = \frac{(100\text{-}p)Ww}{(100\text{-}0.7p)\left[\frac{\phantom{xx}}{C+0.3F}\right]}$$

$$C = \frac{(100\text{-}20)*170}{(100\text{-}0.7*20)*0.45} = 352\ kg/m^3$$

$$\text{Pfa content} = \frac{\phantom{xx}}{100\text{-}p}{}^{PC} \quad \frac{20*352}{100\text{-}20} \quad = \quad = 88\ kg/m^3$$

Then combined cement content and pfa content = 352 + 88 = 440 kg/m$^3$

$$\frac{W}{C+F}\ \text{ratio} = \frac{170}{352+88} = 0.38$$

Total aggregate content = D – (C+F) – W = 2390 – 440 – 170 = 1780 kg/m$^3$

Fine aggregate content = 0.3 * 1780 = 534 kg/m$^3$

Coarse aggregate content 1780 – 534 = 1246 kg/m$^3$

## 3. CEM III/A Concrete

According to BRE, when ggbs is used as a replacement for Portland cement in a mix it normally acts as a water-reducing agent. The workability of the concrete can be obtained with a lower water content, the reduction depending on the characteristics of the materials used. As a rough guide the water contents given in Table 3 should be reduced by about 5 kg/m$^3$.

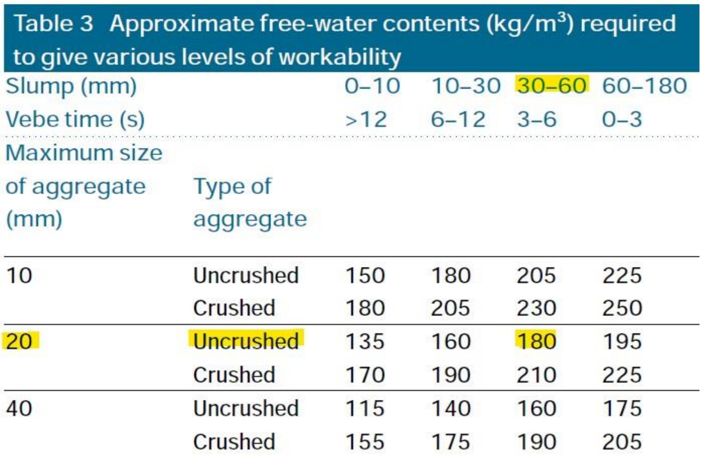


Table 3 Approximate free-water contents (kg/m$^3$) required to give various levels of workability

| Slump (mm) | | 0–10 | 10–30 | 30–60 | 60–180 |
|---|---|---|---|---|---|
| Vebe time (s) | | >12 | 6–12 | 3–6 | 0–3 |
| Maximum size of aggregate (mm) | Type of aggregate | | | | |
| 10 | Uncrushed | 150 | 180 | 205 | 225 |
| | Crushed | 180 | 205 | 230 | 250 |
| 20 | Uncrushed | 135 | 160 | 180 | 195 |
| | Crushed | 170 | 190 | 210 | 225 |
| 40 | Uncrushed | 115 | 140 | 160 | 175 |
| | Crushed | 155 | 175 | 190 | 205 |

**Free water content = 180-5 = 175 kg/m$^3$**

When ggbs is used as a replacement for some of the Portland cement in the mix it is generally done on the basis of a direct mass for mass replacement of Portland cement by ggbs. Generally, replacements are in the order of from 30 to 50% by mass, although higher replacements of 70% or more are required for some purposes. The replacement of Portland cement by ggbs generally improves the workability of the concrete allowing for a small reduction in the water content.
Since the CEM I mix contains 400 kg/m$^3$, so replacing 40% of cement with ggbs in CEM III/A changed mix quantities to the following:

Water content = 180 – 5 = 175 kg/m$^3$

Cement = 400 – 40% = 240 kg/m$^3$

GGBS = 160 kg/m$^3$ w/b = 0.43

### 4. CEM II/A-D Concrete

Similarly, direct mass for mass replacement of Portland cement by silica fume in CEM II/A-D mix was carried out. To compensate for the reduction in the workability due to the extreme fine particle size of silica fume, Superplasticizer was added to the mix according to manufacturer recommended dosage. The mix contents were as following:

Water content = 180 kg/m$^3$

Cement content = 360 kg/m$^3$

Silica fume = 40 kg/m$^3$ w/b

= 0.45

Superplasticizer = 5 ml/kg PC

# Appendix C: Engineering Properties

## C1. Compressive Strength (MPa)

Table C1. Compressive strength of all cement types

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **CEM I** | | | | | |
| 7 days (MPa) | | 28 days (MPa) | | 56 days (MPa) | | 90 days (MPa) | |
| Curing Compound | | Curing Compound | | Curing Compound | | Curing Compound | |
| cube 1 | 33.84 | cube 1 | 38.88 | cube 1 | 39.23 | cube 1 | 39.66 |
| cube 2 | 34.73 | cube 2 | 38.97 | cube 2 | 39.46 | cube 2 | 40.2 |
| cube 3 | 34.79 | cube 3 | 39.66 | cube 3 | 40.2 | cube 3 | 40.6 |
| average | 34.45 | average | 39.17 | average | 39.63 | average | 40.15 |
| Water Curing | | Water Curing | | Water Curing | | Water Curing | |
| cube 1 | 36.85 | cube 1 | 43.15 | cube 1 | 43.34 | cube 1 | 43.61 |
| cube 2 | 35.47 | cube 2 | 42.22 | cube 2 | 43.54 | cube 2 | 44.2 |
| cube 3 | 37.39 | cube 3 | 42.39 | cube 3 | 43.47 | cube 3 | 43.98 |
| average | 36.57 | average | 42.59 | average | 43.45 | average | 43.93 |
| Air Curing | | Air Curing | | Air Curing | | Air Curing | |
| cube 1 | 23.75 | cube 1 | 24.53 | cube 1 | 24.75 | cube 1 | 24.92 |
| cube 2 | 22.84 | cube 2 | 24.62 | cube 2 | 24.87 | cube 2 | 24.93 |
| cube 3 | 25.73 | cube 3 | 26.34 | cube 3 | 26.87 | cube 3 | 26.96 |
| average | 24.11 | average | 25.16 | average | 25.50 | average | 25.60 |
| | | **CEM II/A-V** | | | | | |
| 7 days | | 28 days | | 56 days | | 90 days | |
| Curing Compound | | Curing Compound | | Curing Compound | | Curing Compound | |
| cube 1 | 29.83 | cube 1 | 37.34 | cube 1 | 38.84 | cube 1 | 40.93 |
| cube 2 | 29.81 | cube 2 | 37.33 | cube 2 | 38.12 | cube 2 | 39.92 |
| cube 3 | 28.41 | cube 3 | 37.23 | cube 3 | 38.44 | cube 3 | 39.83 |
| average | 29.35 | average | 37.30 | average | 38.47 | average | 40.23 |
| Water Curing | | Water Curing | | Water Curing | | Water Curing | |
| cube 1 | 30.62 | cube 1 | 40.42 | cube 1 | 41.46 | cube 1 | 42.88 |
| cube 2 | 30.62 | cube 2 | 40.66 | cube 2 | 41.83 | cube 2 | 43.86 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| cube 3 | 30.50 | cube 3 | 40.71 | cube 3 | 42.23 | cube 3 | 43.89 |
| average | 30.58 | average | 40.60 | average | 41.84 | average | 43.54 |
| Air Curing | | Air Curing | | Air Curing | | Air Curing | |
| cube 1 | 20.43 | cube 1 | 21.76 | cube 1 | 22.45 | cube 1 | 22.75 |
| cube 2 | 19.86 | cube 2 | 20.87 | cube 2 | 21.66 | cube 2 | 21.93 |
| cube 3 | 21.76 | cube 3 | 22.79 | cube 3 | 23.31 | cube 3 | 23.83 |
| average | 20.68 | average | 21.81 | average | 22.47 | average | 22.84 |

**CEM III/A**

| 7 days | | 28 days | | 56 days | | 90 days | |
|---|---|---|---|---|---|---|---|
| Curing Compound | | Curing Compound | | Curing Compound | | Curing Compound | |
| cube 1 | 29.72 | cube 1 | 37.28 | cube 1 | 39.76 | cube 1 | 41.43 |
| cube 2 | 29.62 | cube 2 | 36.66 | cube 2 | 38.84 | cube 2 | 41.89 |
| cube 3 | 29.51 | cube 3 | 37.65 | cube 3 | 39.56 | cube 3 | 41.69 |
| average | 29.62 | average | 37.20 | average | 39.39 | average | 41.67 |
| Water Curing | | Water Curing | | Water Curing | | Water Curing | |
| cube 1 | 33.28 | cube 1 | 40.78 | cube 1 | 42.34 | cube 1 | 43.62 |
| cube 2 | 31.92 | cube 2 | 40.67 | cube 2 | 41.87 | cube 2 | 43.78 |
| cube 3 | 32.57 | cube 3 | 41.88 | cube 3 | 43.56 | cube 3 | 45.54 |
| average | 32.59 | average | 41.11 | average | 42.59 | average | 44.31 |
| Air Curing | | Air Curing | | Air Curing | | Air Curing | |
| cube 1 | 19.54 | cube 1 | 20.74 | cube 1 | 21.67 | cube 1 | 21.73 |
| cube 2 | 20.62 | cube 2 | 21.55 | cube 2 | 22.21 | cube 2 | 22.83 |
| cube 3 | 20.73 | cube 3 | 21.68 | cube 3 | 22.31 | cube 3 | 22.69 |
| average | 20.30 | average | 21.32 | average | 22.06 | average | 22.42 |

**CEM II/A-D**

| 7 days | | 28 days | | 56 days | | 90 days | |
|---|---|---|---|---|---|---|---|
| Curing Compound | | Curing Compound | | Curing Compound | | Curing Compound | |
| cube 1 | 40.49 | cube 1 | 49.82 | cube 1 | 50.23 | cube 1 | 51.1 |
| cube 2 | 40.93 | cube 2 | 49.88 | cube 2 | 50.05 | cube 2 | 50.2 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| cube 3 | 39.46 | cube 3 | 48.93 | cube 3 | 49.74 | cube 3 | 50.02 |
| average | 40.29 | average | 49.54 | average | 50.01 | average | 50.44 |
| Water Curing | | Water Curing | | Water Curing | | Water Curing | |
| cube 1 | 43.08 | cube 1 | 54.56 | cube 1 | 55.06 | cube 1 | 55.35 |
| cube 2 | 43.24 | cube 2 | 53.6 | cube 2 | 54.12 | cube 2 | 55.2 |
| cube 3 | 42.33 | cube 3 | 53.93 | cube 3 | 54.78 | cube 3 | 56.32 |
| average | 42.88 | average | 54.03 | average | 54.65 | average | 55.62 |
| Air Curing | | Air Curing | | Air Curing | | Air Curing | |
| cube 1 | 29.62 | cube 1 | 31.37 | cube 1 | 31.69 | cube 1 | 32.13 |
| cube 2 | 28.58 | cube 2 | 30.34 | cube 2 | 30.54 | cube 2 | 30.91 |
| cube 3 | 30.42 | cube 3 | 31.88 | cube 3 | 31.97 | cube 3 | 32.24 |
| average | 29.54 | average | 31.20 | average | 31.40 | average | 31.76 |

## C2. Flexural Strength (MPa)

Table C2. Flexural strength of CEM I

| **Age (days)** | **Air curing (AC)** | **Curing compound (CC)** | **Water curing (WC)** |
|---|---|---|---|
| 7 | 3.38 | 4.1 | 4.4 |
| 28 | 3.62 | 4.81 | 5.28 |
| 56 | 3.7 | 4.9 | 5.4 |
| 90 | 3.91 | 5.06 | 5.55 |

Table C3. Flexural strength of CEM II/A-V

| **Age (days)** | **Air curing (AC)** | **Curing compound (CC)** | **Water curing (WC)** |
|---|---|---|---|
| 7 | 3.34 | 3.8 | 4.2 |
| 28 | 3.82 | 4.62 | 5.13 |
| 56 | 3.92 | 4.83 | 5.27 |
| 90 | 4.07 | 5.01 | 5.54 |

Table C4. Flexural strength of CEM III/A

| **Age (days)** | **Air curing (AC)** | **Curing compound (CC)** | **Water curing (WC)** |
|---|---|---|---|

| | | | |
|---|---|---|---|
| 7 | 3.21 | 3.73 | 4.1 |
| 28 | 3.71 | 4.91 | 5.43 |
| 56 | 4.12 | 5.24 | 5.61 |
| 90 | 4.74 | 5.66 | 6.09 |

Table C5. Flexural strength of CEM II/A-D

| **Age (days)** | **Air curing (AC)** | **Curing compound (CC)** | **Water curing (WC)** |
|---|---|---|---|
| 7 | 4.33 | 4.55 | 4.84 |
| 28 | 4.72 | 5.51 | 5.94 |
| 56 | 4.86 | 5.63 | 6.11 |
| 90 | 5.07 | 5.75 | 6.24 |

## C3. Drying Shrinkage ($10^{-6}$)

Table C6. Drying shrinkage of CEM I

| **Age (days)** | **Air curing (AC)** | **Curing compound (CC)** | **Water curing (WC)** |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 7 | 276 | 182 | 160 |
| 14 | 392 | 299 | 256 |
| 21 | 462 | 374 | 310 |
| 28 | 514 | 406 | 341 |
| 56 | 548 | 444 | 362 |
| 112 | 586 | 464 | 388 |

Table C7. Drying shrinkage of CEM II/A-V

| **Age (days)** | **Air curing (AC)** | **Curing compound (CC)** | **Water curing (WC)** |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 7 | 270 | 154 | 148 |
| 14 | 376 | 256 | 204 |
| 21 | 438 | 320 | 238 |
| 28 | 476 | 357 | 260 |
| 56 | 530 | 382 | 306 |
| 112 | 562 | 395 | 322 |

Table C8. Drying shrinkage of CEM III/A

| **Age (days)** | **Air curing (AC)** | **Curing compound (CC)** | **Water curing (WC)** |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 7 | 230 | 138 | 130 |
| 14 | 348 | 240 | 188 |
| 21 | 410 | 290 | 228 |
| 28 | 444 | 310 | 248 |
| 56 | 478 | 350 | 290 |
| 112 | 516 | 368 | 304 |

Table C9. Drying shrinkage of CEM II/A-D

| **Age (days)** | **Air curing (AC)** | **Curing compound (CC)** | **Water curing (WC)** |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 7 | 194 | 130 | 118 |
| 14 | 268 | 208 | 172 |
| 21 | 310 | 240 | 197 |
| 28 | 334 | 254 | 210 |
| 56 | 350 | 266 | 224 |
| 112 | 358 | 274 | 238 |

# Appendix D: Transport Properties

## D1. Sorptivity

Table D1. Sorptivity results of CEM I concrete

| **Time ($h_{0.5}$)** | **Sorptivity (kg/m$^2$)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **CC** | **WC** | **CC + Admix1** | **CC + Admix2** | **CC + Admixt3** | **CC + ST1** | **CC + ST2** | **CC + ST3** |
| 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 1.00 | 0.807 | 0.373 | 0.807 | 0.307 | 0.243 | 0.050 | 0.017 | 0.023 |
| 1.41 | 1.050 | 0.487 | 1.000 | 0.357 | 0.313 | 0.073 | 0.027 | 0.033 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2.00 | 1.367 | 0.577 | 1.270 | 0.410 | 0.370 | 0.107 | 0.037 | 0.053 |
| 4.90 | 2.540 | 0.757 | 2.413 | 0.577 | 0.580 | 0.237 | 0.080 | 0.127 |
| 6.93 | 3.050 | 0.830 | 3.140 | 0.650 | 0.660 | 0.363 | 0.113 | 0.177 |
| 8.49 | 3.437 | 0.853 | 3.473 | 0.710 | 0.697 | 0.477 | 0.147 | 0.193 |
| 9.80 | 3.677 | 0.863 | 3.657 | 0.753 | 0.730 | 0.580 | 0.170 | 0.220 |
| 10.95 | 3.837 | 0.873 | 3.817 | 0.777 | 0.773 | 0.700 | 0.209 | 0.260 |
| 12.00 | 3.993 | 0.883 | 3.937 | 0.823 | 0.787 | 0.803 | 0.221 | 0.290 |
| 12.96 | 4.100 | 0.893 | 4.013 | 0.847 | 0.813 | 0.864 | 0.238 | 0.320 |

Table D2. Sorptivity results of CEM II/A-V concrete

| **Time (h$_{0.5}$)** | **Sorptivity (kg/m$^2$)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **AC** | **WC** | **CC + Admix1** | **CC + Admix2** | **CC + Admixt3** | **CC + ST1** | **CC + ST2** | **CC + ST3** |
| 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 1.00 | 0.777 | 0.320 | 0.817 | 0.207 | 0.197 | 0.040 | 0.027 | 0.087 |
| 1.41 | 1.010 | 0.367 | 1.060 | 0.257 | 0.313 | 0.060 | 0.037 | 0.117 |
| 2.00 | 1.283 | 0.433 | 1.353 | 0.333 | 0.370 | 0.083 | 0.050 | 0.130 |
| 4.90 | 2.250 | 0.610 | 2.200 | 0.463 | 0.443 | 0.227 | 0.093 | 0.167 |
| 6.93 | 2.740 | 0.660 | 2.720 | 0.550 | 0.497 | 0.347 | 0.127 | 0.177 |
| 8.49 | 3.083 | 0.693 | 3.013 | 0.593 | 0.540 | 0.463 | 0.140 | 0.193 |
| 9.80 | 3.343 | 0.713 | 3.190 | 0.643 | 0.587 | 0.567 | 0.153 | 0.220 |
| 10.95 | 3.563 | 0.723 | 3.317 | 0.693 | 0.620 | 0.653 | 0.183 | 0.230 |
| 12.00 | 3.753 | 0.747 | 3.410 | 0.740 | 0.667 | 0.710 | 0.200 | 0.240 |
| 12.96 | 3.930 | 0.757 | 3.483 | 0.777 | 0.703 | 0.753 | 0.220 | 0.250 |

Table D3. Sorptivity results of CEM III/A concrete

| **Time (h$_{0.5}$)** | **Sorptivity (kg/m$^2$)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **AC** | **WC** | **CC + Admix1** | **CC + Admix2** | **CC + Admixt3** | **CC + ST1** | **CC + ST2** | **CC + ST3** |
| 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 1.00 | 0.727 | 0.173 | 0.743 | 0.180 | 0.137 | 0.013 | 0.010 | 0.020 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1.41 | 0.917 | 0.233 | 0.983 | 0.207 | 0.173 | 0.027 | 0.020 | 0.033 |
| 2.00 | 1.180 | 0.307 | 1.253 | 0.240 | 0.213 | 0.047 | 0.030 | 0.050 |
| 4.90 | 2.113 | 0.513 | 2.123 | 0.347 | 0.320 | 0.167 | 0.083 | 0.100 |
| 6.93 | 2.617 | 0.590 | 2.543 | 0.423 | 0.387 | 0.270 | 0.107 | 0.140 |
| 8.49 | 2.897 | 0.633 | 2.800 | 0.473 | 0.427 | 0.370 | 0.117 | 0.160 |
| 9.80 | 3.060 | 0.667 | 2.977 | 0.517 | 0.467 | 0.463 | 0.137 | 0.185 |
| 10.95 | 3.193 | 0.687 | 3.117 | 0.540 | 0.493 | 0.533 | 0.147 | 0.218 |
| 12.00 | 3.277 | 0.717 | 3.223 | 0.580 | 0.530 | 0.627 | 0.170 | 0.230 |
| 12.96 | 3.317 | 0.737 | 3.287 | 0.600 | 0.560 | 0.690 | 0.187 | 0.248 |

Table D4. Sorptivity results of CEM II/A-D concrete

| **Time ($h_{0.5}$)** | **Sorptivity (kg/m$^2$)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **AC** | **WC** | **CC + Admix1** | **CC + Admix2** | **CC + Admixt3** | **CC + ST1** | **CC + ST2** | **CC + ST3** |
| 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 1.00 | 0.827 | 0.133 | 0.757 | 0.183 | 0.170 | 0.037 | 0.023 | 0.017 |
| 1.41 | 1.107 | 0.247 | 0.993 | 0.247 | 0.223 | 0.050 | 0.033 | 0.027 |
| 2.00 | 1.367 | 0.337 | 1.237 | 0.300 | 0.267 | 0.070 | 0.043 | 0.040 |
| 4.90 | 2.183 | 0.517 | 1.997 | 0.357 | 0.340 | 0.133 | 0.083 | 0.090 |
| 6.93 | 2.497 | 0.590 | 2.413 | 0.390 | 0.363 | 0.203 | 0.117 | 0.110 |
| 8.49 | 2.670 | 0.613 | 2.620 | 0.413 | 0.383 | 0.243 | 0.127 | 0.120 |
| 9.80 | 2.803 | 0.623 | 2.780 | 0.440 | 0.420 | 0.283 | 0.137 | 0.133 |
| 10.95 | 2.923 | 0.633 | 2.900 | 0.450 | 0.430 | 0.323 | 0.147 | 0.143 |
| 12.00 | 3.020 | 0.643 | 2.980 | 0.460 | 0.440 | 0.347 | 0.157 | 0.157 |
| 12.96 | 3.100 | 0.653 | 3.027 | 0.470 | 0.450 | 0.377 | 0.170 | 0.173 |

## D2. Depth of penetration of water under pressure

Table D5. Depth of water penetration of CEM I specimens

| Specimen | Average Penetration depth (mm) | cube 1 | cube 2 | cube 3 |
|---|---|---|---|---|
| Control (AC) | 57 | 57 | 59 | 55 |
| Control (WC) | 32 | 32 | 31 | 34 |
| CC+ST1 | 49 | 48 | 47 | 51 |
| CC+ST2 | 27 | 25 | 30 | 27 |
| CC+ST3 | 33 | 31 | 34 | 33 |
| CC+Admix1 | 55 | 55 | 57 | 54 |
| CC+Admix2 | 33 | 31 | 32 | 35 |
| CC+Admix3 | 31 | 28 | 31 | 33 |

Table D6. Depth of water penetration of CEM II/A-V specimens

| Specimen | Average Penetration depth (mm) | cube 1 | cube 2 | cube 3 |
|---|---|---|---|---|
| Control (AC) | 47 | 46 | 49 | 45 |
| Control (WC) | 27 | 30 | 25 | 27 |
| CC+ST1 | 43 | 41 | 43 | 46 |
| CC+ST2 | 25 | 24 | 25 | 27 |
| CC+ST3 | 29 | 31 | 27 | 28 |
| CC+Admix1 | 45 | 44 | 47 | 45 |
| CC+Admix2 | 30 | 32 | 29 | 30 |
| CC+Admix3 | 26 | 26 | 25 | 28 |

Table D7. Depth of water penetration of CEM III/A specimens

| Specimen | Average Penetration depth (mm) | cube 1 | cube 2 | cube 3 |
|---|---|---|---|---|
| Control (AC) | 50 | 53 | 50 | 48 |
| Control (WC) | 29 | 29 | 30 | 27 |
| CC+ST1 | 45 | 47 | 43 | 45 |
| CC+ST2 | 27 | 27 | 28 | 25 |
| CC+ST3 | 31 | 32 | 30 | 31 |
| CC+Admix1 | 49 | 47 | 50 | 49 |
| CC+Admix2 | 31 | 32 | 29 | 33 |
| CC+Admix3 | 28 | 28 | 30 | 27 |

Table D8. Depth of water penetration of CEM II/A-D specimens

| Specimen | Average Penetration depth (mm) | cube 1 | cube 2 | cube 3 |
|---|---|---|---|---|
| Control (AC) | 31 | 34 | 28 | 32 |
| Control (WC) | 17 | 17 | 19 | 16 |
| CC+ST1 | 27 | 25 | 26 | 30 |
| CC+ST2 | 14 | 15 | 12 | 16 |
| CC+ST3 | 19 | 18 | 20 | 19 |
| CC+Admix1 | 29 | 26 | 29 | 32 |
| CC+Admix2 | 22 | 20 | 22 | 25 |
| CC+Admix3 | 16 | 15 | 17 | 16 |

# Appendix E: Durability Properties

## E1. Accelerated Carbonation

Table E1. Carbonation of CEM I specimens

| Specimen | Average carbonation depth (mm) | cube 1 | cube 2 |
|---|---|---|---|
| Control (AC) | 10.5 | 11 | 10 |
| Control (WC) | 5.5 | 5 | 6 |
| CC+Admix1 | 10.5 | 11 | 10 |
| CC+Admix2 | 8.5 | 9 | 8 |
| CC+Admix3 | 6.5 | 6 | 7 |
| CC+ST1 | 7.5 | 7 | 8 |
| CC+ST2 | 4.5 | 4 | 5 |
| CC+ST3 | 5.5 | 5 | 6 |

Table E2. Carbonation of CEM II/A-V specimens

| Specimen | Average carbonation depth (mm) | cube 1 | cube 2 |
|---|---|---|---|
| Control (AC) | 17.5 | 17 | 18 |
| Control (WC) | 8.5 | 9 | 8 |
| CC+Admix1 | 17.5 | 17 | 18 |
| CC+Admix2 | 16.5 | 17 | 16 |
| CC+Admix3 | 15.5 | 16 | 15 |
| CC+ST1 | 14.5 | 14 | 15 |
| CC+ST2 | 9.5 | 9 | 10 |
| CC+ST3 | 11.5 | 12 | 11 |

Table E3. Carbonation of CEM III/A specimens

| Specimen | Average carbonation depth (mm) | cube 1 | cube 2 |
|---|---|---|---|
| Control (AC) | 16.5 | 17 | 16 |
| Control (WC) | 7.5 | 8 | 7 |
| CC+Admix1 | 15.5 | 15 | 16 |
| CC+Admix2 | 14.5 | 14 | 15 |

| | | | |
|---|---|---|---|
| CC+Admix3 | 15.5 | 15 | 16 |
| CC+ST1 | 10 | 9 | 11 |
| CC+ST2 | 7.5 | 8 | 7 |
| CC+ST3 | 8.5 | 9 | 8 |

Table E4. Carbonation of CEM II/A-D specimens

| Specimen | Average carbonation depth (mm) | cube 1 | cube 2 |
|---|---|---|---|
| Control (AC) | 10.5 | 11 | 10 |
| Control (WC) | 4 | 4 | 4 |
| CC+Admix1 | 10 | 10 | 10 |
| CC+Admix2 | 9.5 | 10 | 9 |
| CC+Admix3 | 9 | 9 | 9 |
| CC+ST1 | 8.5 | 8 | 9 |
| CC+ST2 | 4.5 | 5 | 4 |
| CC+ST3 | 7.5 | 7 | 8 |

## E2. Resistance to Scaling

Table E5. Cumulative scaled mass of CEM I specimens (kg/m$^2$)

| Cycle | Control (AC) | Control (WC) | CC+Admix1 | CC+Admix2 | CC+Admix3 | CC+ST1 | CC+ST2 | CC+ST3 |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0.0216 | 0.0069 | 0.0077 | 0.0088 | 0.0072 | 0.0072 | 0.008 | 0.0088 |
| 10 | 0.0576 | 0.0208 | 0.0242 | 0.0144 | 0.0144 | 0.0144 | 0.0104 | 0.0128 |
| 15 | 0.1216 | 0.0465 | 0.0504 | 0.0232 | 0.0232 | 0.024 | 0.016 | 0.0216 |
| 20 | 0.1992 | 0.0696 | 0.0763 | 0.0328 | 0.0352 | 0.036 | 0.0248 | 0.0312 |
| 25 | 0.2583 | 0.0902 | 0.0932 | 0.0456 | 0.0488 | 0.0496 | 0.032 | 0.0416 |
| 50 | 0.4168 | 0.1489 | 0.1672 | 0.0768 | 0.0712 | 0.0648 | 0.0448 | 0.0544 |

Table E6. Cumulative scaled mass of CEM II/A-V specimens (kg/m$^2$)

| Cycle | Control (AC) | Control (WC) | CC+Admix1 | CC+Admix2 | CC+Admix3 | CC+ST1 | CC+ST2 | CC+ST3 |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 5 | 0.0456 | 0.0224 | 0.0264 | 0.0144 | 0.0072 | 0.012 | 0.0088 | 0.0096 |
| 10 | 0.1248 | 0.0632 | 0.0704 | 0.04 | 0.0176 | 0.0184 | 0.012 | 0.0144 |
| 15 | 0.2216 | 0.1072 | 0.1208 | 0.0792 | 0.0296 | 0.0272 | 0.0192 | 0.0216 |
| 20 | 0.3344 | 0.1544 | 0.1912 | 0.1264 | 0.04 | 0.0376 | 0.028 | 0.0296 |
| 25 | 0.4664 | 0.2184 | 0.244 | 0.1552 | 0.0488 | 0.0528 | 0.0392 | 0.0416 |
| 50 | 1.0224 | 0.4 | 0.4432 | 0.2056 | 0.0856 | 0.0792 | 0.0544 | 0.0608 |

Table E7. Cumulative scaled mass of CEM III/A specimens (kg/m$^2$)

| Cycle | Control (AC) | Control (WC) | CC+Admix1 | CC+Admix2 | CC+Admix3 | CC+ST1 | CC+ST2 | CC+ST3 |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0.0352 | 0.0248 | 0.0256 | 0.0344 | 0.0048 | 0.0088 | 0.0088 | 0.008 |
| 10 | 0.092 | 0.0616 | 0.068 | 0.0736 | 0.0136 | 0.0176 | 0.016 | 0.0168 |
| 15 | 0.2184 | 0.128 | 0.1312 | 0.1256 | 0.0264 | 0.0296 | 0.0248 | 0.0264 |
| 20 | 0.3744 | 0.2352 | 0.2424 | 0.1856 | 0.0448 | 0.0408 | 0.0336 | 0.04 |
| 25 | 0.556 | 0.3032 | 0.3736 | 0.2264 | 0.068 | 0.0512 | 0.0432 | 0.0528 |
| 50 | 1.1168 | 0.6056 | 0.6877 | 0.3584 | 0.1244 | 0.0957 | 0.059 | 0.0784 |

Table E8. Cumulative scaled mass of CEM II/A-D specimens (kg/m$^2$)

| Cycle | Control (AC) | Control (WC) | CC+Admix1 | CC+Admix2 | CC+Admix3 | CC+ST1 | CC+ST2 | CC+ST3 |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0.0072 | 0.0072 | 0.0056 | 0.008 | 0.0072 | 0.0088 | 0.0064 | 0.0088 |
| 10 | 0.0232 | 0.0192 | 0.016 | 0.0168 | 0.0192 | 0.0112 | 0.0088 | 0.0112 |
| 15 | 0.044 | 0.0368 | 0.0296 | 0.0288 | 0.0304 | 0.0184 | 0.0144 | 0.0176 |
| 20 | 0.0712 | 0.052 | 0.0456 | 0.04 | 0.0408 | 0.028 | 0.0208 | 0.0256 |
| 25 | 0.0968 | 0.072 | 0.0584 | 0.0488 | 0.0488 | 0.04 | 0.0296 | 0.0344 |
| 50 | 0.192 | 0.1136 | 0.0872 | 0.0808 | 0.0752 | 0.0568 | 0.0392 | 0.0472 |

## E3. Resistance to Chloride Penetration

Table E9. Chloride penetration of CEM I specimens (parts/million)

| | **Slab 1** | | | | | **Slab 2** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Slab** | **Water (ml)** | **Weight (gm)** | **Depth (mm)** | **Dilution factor** | **Parts per million (PPM)** | **Water (ml)** | **Weight (gm)** | **Depth (mm)** | **Dilution factor** | **Parts per million PPM)** | **Average (PPM)** |
| Control (AC) | 20.0 | 1.7 | 8.0 | 140.6 | 1613.9 | 20.0 | 1.7 | 8.0 | 145.3 | 1732.5 | 1673.21 |
| Control (AC) | 20.0 | 1.8 | 16.0 | 60.7 | 679.6 | 20.0 | 1.7 | 16.0 | 57.4 | 666.1 | 672.85 |
| Control (WC) | 20.0 | 1.8 | 8.0 | 99.5 | 1128.1 | 20.0 | 1.7 | 8.0 | 97.0 | 1159.3 | 1143.69 |
| Control (WC) | 20.0 | 1.7 | 16.0 | 40.8 | 468.2 | 20.0 | 1.7 | 16.0 | 43.5 | 526.6 | 497.38 |
| CC+Admix1 | 20.0 | 1.8 | 8.0 | 86.7 | 972.6 | 20.0 | 1.8 | 8.0 | 82.8 | 945.0 | 958.84 |
| CC+Admix1 | 20.0 | 1.3 | 16.0 | 31.8 | 492.0 | 20.0 | 1.6 | 16.0 | 27.5 | 333.9 | 412.94 |
| CC+Admix2 | 20.0 | 1.8 | 8.0 | 37.3 | 417.6 | 20.0 | 1.7 | 8.0 | 39.8 | 471.9 | 444.76 |
| CC+Admix2 | 20.0 | 1.8 | 16.0 | 20.2 | 225.1 | 20.0 | 1.7 | 16.0 | 23.4 | 267.7 | 246.41 |
| CC+Admix3 | 20.0 | 1.8 | 8.0 | 29.7 | 337.6 | 20.0 | 1.6 | 8.0 | 25.5 | 313.7 | 325.66 |
| CC+Admix3 | 20.0 | 1.7 | 16.0 | 13.8 | 166.7 | 20.0 | 1.7 | 16.0 | 11.5 | 133.4 | 150.06 |
| CC+ST1 | 20.0 | 1.7 | 8.0 | 73.1 | 840.6 | 20.0 | 1.8 | 8.0 | 68.2 | 764.8 | 802.73 |
| CC+ST1 | 20.0 | 1.7 | 16.0 | 33.4 | 395.0 | 20.0 | 1.7 | 16.0 | 31.5 | 363.3 | 379.16 |
| CC+ST2 | 20.0 | 1.7 | 8.0 | 18.9 | 216.7 | 20.0 | 1.8 | 8.0 | 15.6 | 177.0 | 196.85 |
| CC+ST2 | 20.0 | 1.8 | 16.0 | 7.3 | 81.7 | 20.0 | 1.7 | 16.0 | 8.5 | 100.9 | 91.31 |
| CC+ST3 | 20.0 | 1.7 | 8.0 | 22.7 | 264.7 | 20.0 | 1.8 | 8.0 | 25.8 | 290.8 | 277.74 |
| CC+ST3 | 20.0 | 1.8 | 16.0 | 10.7 | 121.6 | 20.0 | 1.7 | 16.0 | 12.1 | 144.6 | 133.12 |

Table E10. Chloride penetration of CEM II/A-V specimens (parts/million)

| | **Slab 1** | | | | | **Slab 2** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Slab** | **Water (ml)** | **Weight (gm)** | **Depth (mm)** | **Dilution factor** | **Parts per million (PPM)** | **Water (ml)** | **Weight (gm)** | **Depth (mm)** | **Dilution factor** | **Parts per million (PPM)** | **Average** |
| Control (AC) | 20.0 | 1.7 | 8.0 | 130.7 | 1523.5 | 20.0 | 1.7 | 8.0 | 125.8 | 1503.1 | 1513 |
| Control (AC) | 20.0 | 1.7 | 16.0 | 45.7 | 533.7 | 20.0 | 1.8 | 16.0 | 51.5 | 587.8 | 561 |
| Control (WC) | 20.0 | 1.8 | 8.0 | 86.7 | 977.7 | 20.0 | 1.7 | 8.0 | 90.5 | 1081.6 | 1030 |
| Control (WC) | 20.0 | 1.8 | 16.0 | 42.1 | 473.4 | 20.0 | 1.8 | 16.0 | 39.2 | 442.4 | 458 |
| CC+Admix1 | 20.0 | 1.7 | 8.0 | 77.5 | 886.6 | 20.0 | 1.8 | 8.0 | 81.8 | 933.6 | 910 |
| CC+Admix1 | 20.0 | 1.8 | 16.0 | 40.6 | 459.1 | 20.0 | 1.8 | 16.0 | 36.5 | 415.4 | 437 |
| CC+Admix2 | 20.0 | 1.8 | 8.0 | 23.4 | 264.9 | 20.0 | 1.7 | 8.0 | 25.6 | 304.1 | 285 |
| CC+Admix2 | 20.0 | 1.8 | 16.0 | 13.3 | 150.6 | 20.0 | 1.7 | 16.0 | 11.4 | 130.4 | 140 |
| CC+Admix3 | 20.0 | 1.8 | 8.0 | 21.7 | 244.1 | 20.0 | 1.6 | 8.0 | 19.7 | 242.4 | 243 |
| CC+Admix3 | 20.0 | 1.8 | 16.0 | 8.4 | 93.8 | 20.0 | 1.7 | 16.0 | 9.7 | 113.2 | 103 |
| CC+ST1 | 20.0 | 1.8 | 8.0 | 64.2 | 714.2 | 20.0 | 1.8 | 8.0 | 68.2 | 764.8 | 740 |
| CC+ST1 | 20.0 | 1.8 | 16.0 | 31.4 | 353.8 | 20.0 | 1.7 | 16.0 | 27.3 | 326.3 | 340 |
| CC+ST2 | 20.0 | 1.8 | 8.0 | 10.6 | 119.5 | 20.0 | 1.7 | 8.0 | 8.6 | 102.4 | 111 |
| CC+ST2 | 20.0 | 1.8 | 16.0 | 7.3 | 82.7 | 20.0 | 1.7 | 16.0 | 6.1 | 72.4 | 78 |
| CC+ST3 | 20.0 | 1.8 | 8.0 | 13.7 | 156.4 | 20.0 | 1.8 | 8.0 | 12.3 | 138.7 | 148 |
| CC+ST3 | 20.0 | 1.5 | 16.0 | 8.4 | 108.4 | 20.0 | 1.8 | 16.0 | 7.2 | 81.3 | 95 |

Table E11. Chloride penetration of CEM III/A specimens (parts/million)

| | **Slab 1** | | | | | **Slab 2** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Slab** | **Water (ml)** | **Weight (gm)** | **Depth (mm)** | **Dilution factor (mg/l)** | **Parts per million (PPM)** | **Water (ml)** | **Weight (gm)** | **Depth (mm)** | **Dilution factor** | **Parts per million (PPM)** | **Average** |
| Control (AC) | 20.0 | 1.7 | 8.0 | 124.9 | 1429.8 | 20.0 | 1.7 | 8.0 | 127.3 | 1520.9 | 1475.4 |
| Control (AC) | 19.0 | 1.7 | 16.0 | 44.8 | 499.4 | 20.0 | 1.8 | 16.0 | 41.5 | 473.7 | 486.6 |
| Control (WC) | 20.0 | 1.8 | 8.0 | 72.7 | 819.8 | 20.0 | 1.7 | 8.0 | 76.8 | 917.9 | 868.8 |
| Control (WC) | 20.0 | 1.8 | 16.0 | 33.5 | 376.7 | 20.0 | 1.8 | 16.0 | 29.2 | 329.6 | 353.1 |
| CC+Admix1 | 20.0 | 1.7 | 8.0 | 68.5 | 783.6 | 20.0 | 1.8 | 8.0 | 71.5 | 816.1 | 799.9 |
| CC+Admix1 | 20.0 | 1.8 | 16.0 | 27.6 | 312.1 | 20.0 | 1.8 | 16.0 | 28.5 | 324.4 | 318.2 |
| CC+Admix2 | 20.0 | 1.8 | 8.0 | 11.1 | 124.7 | 20.0 | 1.8 | 8.0 | 13.6 | 154.9 | 139.8 |
| CC+Admix2 | 20.0 | 1.8 | 16.0 | 8.2 | 93.4 | 20.0 | 1.7 | 16.0 | 9.8 | 113.2 | 103.3 |
| CC+Admix3 | 20.0 | 1.8 | 8.0 | 11.4 | 128.4 | 20.0 | 1.6 | 8.0 | 10.8 | 132.9 | 130.6 |
| CC+Admix3 | 20.0 | 1.8 | 16.0 | 6.7 | 76.0 | 20.0 | 1.7 | 16.0 | 7.5 | 87.5 | 81.7 |
| CC+ST1 | 20.0 | 1.8 | 8.0 | 46.8 | 526.3 | 20.0 | 1.8 | 8.0 | 43.6 | 490.6 | 508.5 |
| CC+ST1 | 20.0 | 1.8 | 16.0 | 22.6 | 255.0 | 20.0 | 1.7 | 16.0 | 24.1 | 287.1 | 271.1 |
| CC+ST2 | 20.0 | 1.7 | 8.0 | 9.8 | 112.1 | 20.0 | 1.7 | 8.0 | 8.7 | 99.5 | 105.8 |
| CC+ST2 | 20.0 | 1.8 | 16.0 | 5.8 | 66.1 | 20.0 | 1.8 | 16.0 | 6.7 | 76.5 | 71.3 |
| CC+ST3 | 20.0 | 1.7 | 8.0 | 11.2 | 128.1 | 20.0 | 1.7 | 8.0 | 10.6 | 126.2 | 127.1 |
| CC+ST3 | 20.0 | 1.7 | 16.0 | 6.4 | 73.4 | 20.0 | 1.7 | 16.0 | 7.2 | 82.7 | 78.0 |

Table E12. Chloride penetration of CEM II/A-D specimens (parts/million)

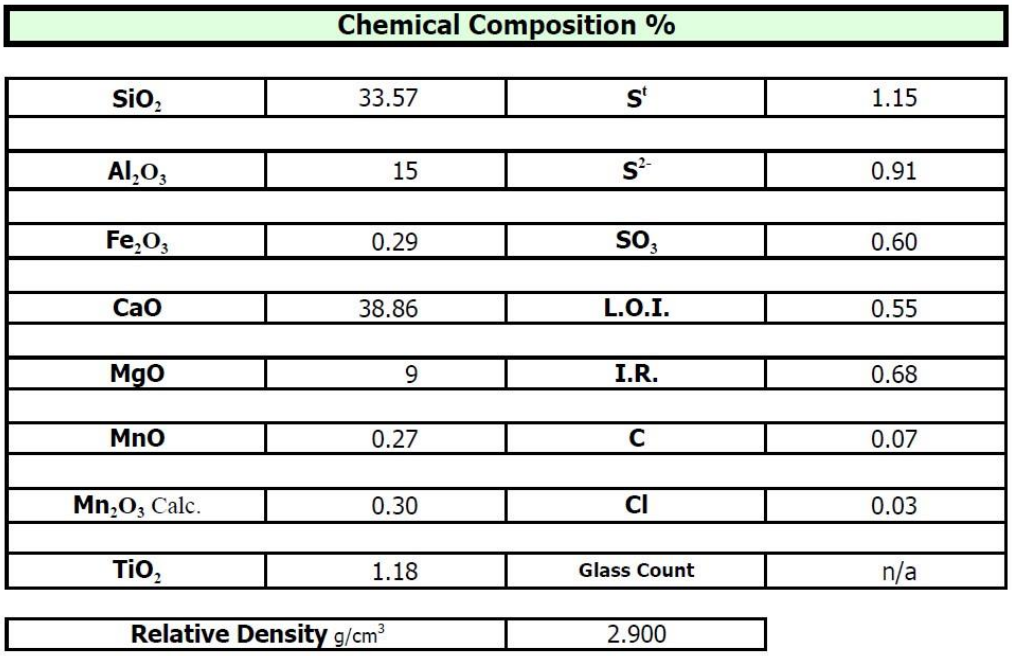
| | **Slab 1** | | | | | **Slab 2** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Slab** | **Water (ml)** | **Weight (gm)** | **Depth (mm)** | **Dilution factor (mg/l)** | **Parts per million (PPM)** | **Water (ml)** | **Weight (gm)** | **Depth (mm)** | **Dilution factor** | **Parts per million (PPM)** | **Average** |
| Control (AC) | 20.0 | 1.7 | 8.0 | 72.3 | 835.5 | 20.0 | 1.8 | 8.0 | 76.3 | 855.2 | 845.3 |
| Control (AC) | 20.0 | 1.7 | 16.0 | 18.5 | 211.7 | 20.0 | 1.8 | 16.0 | 21.5 | 242.0 | 226.9 |
| Control (WC) | 20.0 | 1.8 | 8.0 | 39.6 | 445.4 | 20.0 | 1.7 | 8.0 | 45.5 | 524.0 | 484.7 |
| Control (WC) | 20.0 | 1.8 | 16.0 | 13.5 | 150.2 | 20.0 | 1.8 | 16.0 | 15.3 | 174.0 | 162.1 |
| CC+Admix1 | 20.0 | 1.7 | 8.0 | 37.1 | 429.8 | 20.0 | 1.7 | 8.0 | 40.8 | 475.3 | 452.6 |
| CC+Admix1 | 20.0 | 1.7 | 16.0 | 8.4 | 95.8 | 20.0 | 1.8 | 16.0 | 10.4 | 117.3 | 106.6 |
| CC+Admix2 | 20.0 | 1.7 | 8.0 | 10.5 | 120.5 | 20.0 | 1.7 | 8.0 | 11.2 | 132.9 | 126.7 |
| CC+Admix2 | 20.0 | 1.7 | 16.0 | 7.5 | 87.4 | 20.0 | 1.8 | 16.0 | 8.7 | 98.1 | 92.8 |
| CC+Admix3 | 20.0 | 1.7 | 8.0 | 9.6 | 111.5 | 20.0 | 1.8 | 8.0 | 10.3 | 116.5 | 114.0 |
| CC+Admix3 | 20.0 | 1.7 | 16.0 | 7.3 | 83.8 | 20.0 | 1.7 | 16.0 | 6.2 | 70.9 | 77.3 |
| CC+ST1 | 20.0 | 1.8 | 8.0 | 27.6 | 312.4 | 20.0 | 1.8 | 8.0 | 29.5 | 335.4 | 323.9 |
| CC+ST1 | 20.0 | 1.8 | 16.0 | 12.4 | 140.2 | 20.0 | 1.7 | 16.0 | 9.4 | 108.0 | 124.1 |
| CC+ST2 | 20.0 | 1.6 | 8.0 | 8.1 | 100.0 | 20.0 | 1.8 | 8.0 | 7.7 | 85.9 | 92.9 |
| CC+ST2 | 20.0 | 1.6 | 16.0 | 5.1 | 63.5 | 20.0 | 1.8 | 16.0 | 6.2 | 69.7 | 66.6 |
| CC+ST3 | 20.0 | 1.8 | 8.0 | 9.4 | 106.0 | 20.0 | 1.8 | 8.0 | 11.3 | 128.9 | 117.4 |
| CC+ST3 | 20.0 | 1.8 | 16.0 | 6.5 | 73.0 | 20.0 | 1.7 | 16.0 | 6.2 | 71.2 | 72.1 |

# Appendix F: Chemical Composition of Cementitious Materials

Table F1. Analysis of cement - Tunstead CEM I 52,5N (Bulk/Packed)

| Date | SiO2 | Al2O3 | Fe2O3 | CaO | MgO | SO3 | K2O | Na2O | EqNa2O | LOI950 |
|---|---|---|---|---|---|---|---|---|---|---|
| 2015 | 19.51 | 4.79 | 3.13 | 63.92 | 0.96 | 3.17 | 0.60 | 0.15 | 0.55 | 2.38 |
| 2016 | 19.41 | 4.86 | 3.19 | 63.76 | 0.97 | 3.11 | 0.60 | 0.17 | 0.56 | 2.24 |
| 2017 | 19.44 | 4.89 | 3.25 | 63.63 | 1.02 | 3.08 | 0.62 | 0.12 | 0.53 | 2.09 |
| 2018 | 19.68 | 4.79 | 3.24 | 63.53 | 1.04 | 3.11 | 0.62 | 0.11 | 0.52 | 2.07 |
| 2019 | 19.89 | 4.91 | 3.29 | 63.67 | 1.06 | 3.12 | 0.61 | 0.12 | 0.52 | 1.92 |

Table F2: Chemical composition of GGBS provided by Hanson Cement Company



**Chemical Composition %**

| | | | |
|---|---|---|---|
| **$SiO_2$** | 33.57 | **$S^t$** | 1.15 |
| **$Al_2O_3$** | 15 | **$S^{2-}$** | 0.91 |
| **$Fe_2O_3$** | 0.29 | **$SO_3$** | 0.60 |
| **CaO** | 38.86 | **L.O.I.** | 0.55 |
| **MgO** | 9 | **I.R.** | 0.68 |
| **MnO** | 0.27 | **C** | 0.07 |
| **$Mn_2O_3$** Calc. | 0.30 | **Cl** | 0.03 |
| **$TiO_2$** | 1.18 | **Glass Count** | n/a |

| | |
|---|---|
| **Relative Density** g/cm$^3$ | 2.900 |

Table F3: Chemical composition of SF provided by Elkem Company

| | | % | % | % | | % | % | % | % | % | m2/g |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Free | | | | | Na2O- | | | Specific |
| DATE | | SiO2 | Silicon | CaO | S03 | Na2O | K2O | equiv. | Cl | LOI | surface area |
| 30-12-19 | | 95.3 | | 0.20 | 0.33 | 0.24 | 1.19 | 1.02 | 0.12 | 0.92 | |
| 07-01-20 | | 95.5 | 0.09 | 0.22 | 0.27 | 0.21 | 1.07 | 0.91 | 0.09 | 0.94 | 26.8 |
| 13-01-20 | | 95.2 | | 0.28 | 0.23 | 0.20 | 0.96 | 0.83 | 0.06 | 0.85 | |
| 20-01-20 | | 94.8 | | 0.27 | 0.23 | 0.23 | 1.14 | 0.98 | 0.11 | 0.89 | |
| 27-01-20 | | 95.3 | | 0.29 | 0.20 | 0.17 | 0.88 | 0.75 | 0.03 | 0.95 | |
| 03-02-20 | | 95.4 | 0.09 | 0.23 | 0.25 | 0.20 | 1.05 | 0.90 | 0.09 | 0.91 | 26.8 |
| 10-02-20 | | 95.4 | | 0.24 | 0.25 | 0.20 | 1.04 | 0.88 | 0.08 | 0.84 | |
| 17-02-20 | | 96.2 | | 0.23 | 0.27 | 0.21 | 1.08 | 0.92 | 0.09 | 1.05 | |

# Appendix G: Data Sheet of Waterproofing Admixtures and Surface Treatment Materials

[This Appendix has been removed due to copyright reasons.]