SOUMELA FOTIADOU

Use of Foamed Glass Gravel for Sustainable Concrete Construction

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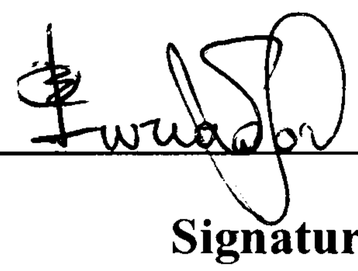
The Thesis is being submitted in fulfillment of the requirements of Kingston University, Faculty of Engineering, for the Degree of Doctor of Philosophy.

February 2007

DECLARATION

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any university or other institution of tertiary education. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given.



06 FEBRUARY 2007

Signature **Date**

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ABSTRACT

With the introduction of waste legislation, in the form of regulations and directives, in many parts of the world a significant move towards sustainable waste management is becoming a legal requirement. Emphasis is now being placed on increasing recycling and promoting more sustainable practices for waste materials, including glass. The present research, therefore, aimed at examining the feasibility of Foamed Glass Gravel (FGG) as construction material, in particular Geofil Foamed Glass Gravel (GFGG), a manufactured lightweight secondary aggregate, for use as a primary aggregate substitute in concrete production. Comparison is made at all times with other FGG material, namely Hasopor, and other lightweight by-product manufactured material namely Lytag. In the main, research was carried out in three distinct parts; Part 1 examining the key characteristics of GFGG (following relevant BS and BS EN standards), Part 2 assessing its suitability for use in concrete applications, and Part 3 providing practical implications of the findings. The programme of work was designed to establish benchmarking level for coarse and fine GFGG and to provide simple practical guidelines for its use in concrete. The research has identified some of the key practical and application issues for utilising GGFG in concrete.

The physical characteristics of GFGG were found to be comparable, and in some cases superior, to those obtained for currently available manufactured lightweight secondary aggregates. The grading of GFGG was found to be almost within the limits of lightweight aggregates with similar voids ratio as that of NA. Typically, GFGG, rough in it's texture, could create better mechanical interlocking with cement paste than smooth aggregates. GFGG had 60- 65% lower bulk density, 40-50% lower apparent particle density and water absorption 3 to 5 times higher than natural Thames Valley Gravel but still performed comparable to other lightweight aggregates. However it was found to have slightly higher density than Hasopor, but also higher heat and crushing resistance. Overall, characterisation test results showed that GFGG has a potential for use as quality lightweight aggregate in concrete production. However, it was noted that the precautions may be necessary to take account of bubble densities and water absorption characteristics to guarantee suitable fresh properties of concrete.

In order to determine the practical upper limit of GFGG content for a range of applications and to assess the performance of GFGG concrete, mixes were proportioned using Natural Aggregate (NA) and GFGG bubbles blends with up to 60% coarse or 15% fine bubbles- by volume. The general trends observed indicate comparable workability with inclusion of GFGG in concrete mixes and slump loss with time was not adversely affected. Results of compressive strength testing showed that up to 30% coarse or 15% fine GFGG had negligible effect on the cube and cylinder strength of concrete and using up to 15% fine GFGG caused a slight increase in cube, cylinder and other engineering properties. Moreover, within 3-days 30% coarse GFGG and (5-15%) fine GFGG concrete mixes achieved on average 73% of 28-day compressive strength. This increased to 85% within 7 days, regardless of GFGG content when compared to NA (Control) concrete mixes. However, results show gradual reduction in strength with an increase in GFGG content beyond 30% coarse in the mix. Indeed, the results showed that such reduction in strength with high GFGG proportions can be compensated for by adjusting the mix water/cement ratio. The results also showed that the original glass source had a negligible effect on fresh and key bulk engineering properties of resulting concrete.

The subject of GFGG concrete durability study included initial surface absorption, carbonation rates and alkali-silica reaction testing. In general, GFGG concrete mixes were found to posses near surface absorption properties similar to the corresponding NA concrete mixes, providing GFGG content was restricted to 30% coarse or 15% fine. Carbonation rates for up to 60% GFGG mixes were comparable to NA mixes. Results of accelerated ASR testing of 30-100% fine GFGG mortar prisms indicated that none of the tested samples expanded significantly during the test and that damaging deleterious expansion due to ASR did not occurred during testing. The practical implications of the study to the construction industry are also discussed.

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LIST OF PUBLICATIONS

Based on this research work, the following three technical papers are prepared and/ or under preparation.

FOTIADOU S, LIMBACHIYA M.C, FRIED, A.N. and ROBERTS, J. J, Use of Foamed Glass Gravel in Construction. Proceedings of the International Conference "Sustainable Waste Management and Recycling", September 2004. Thomas Telford, London, ISBN 0-7277-3284-6, p (306-312)

FOTIADOU S, LIMBACHIYA M.C, Foamed Glass Gravel - Scientific and Microscopy Study of Alkali Silica Reaction (ASR), 2006. ***(In preparation)***

FOTIADOU S, LIMBACHIYA M.C, Foamed Glass Gravel - A Novel Sustainable Concrete Construction Material, 2006. ***(In preparation)***

CHAPTER 1

INTRODUCTION

1.1 Background

The necessity for adopting sustainable practices is becoming increasingly clear, and the recovery of maximum value from surplus glass cullet is a key component in this. Since the introduction of public bottle banks in the late 1970s, container glass recovery in the UK has grown steadily [1]. Waste glass is generated from a number of sources, glass packaging (containers), architectural flat glass, lamp glass and electrical equipment such as televisions and computers. The majority of the recovered glass is re-melted and formed into new bottles and containers for the food industry. In 2003, a total of 3.4 million tones (Mt) of glass waste were generated in the UK, and of this some 1.1 Mt was recycled or reused and the remaining ended up at landfill. In 2005, the recycling rate increased to 37%, which is still significantly less than levels obtained in many countries in mainland Europe. In the UK, at present there are currently 150,000 tones of recovered waste glass containers that are available annually for use in alternative applications.

UK government has set target for post consumer glass recycling rate to increase from current 37% to 60% by 2008. There is now, therefore, a clear and urgent need to identify alternative uses for surplus cullet. The glass particles strength and its granular nature have given rise to its consideration as a secondary or manufactured aggregate in concrete and construction related industry.

On the other hand, with the introduction of Aggregate Levy, in 2002, the UK aggregate supply market has been changed quite evidently. The government introduced this levy to encourage effective restrictive use of primary aggregates and thereby reducing demand on them, so that the construction industry becomes more sustainable. In other words, not using up assets today that future generation may need. At the same time, many governments throughout the world, including the UK, have introduced policies/ legislations to encourage maximum recycling and reuse of waste, including glass. Moreover, due to both the environmental and economical pressures, the necessity for

adopting sustainable practices is becoming increasingly clear, and the recovery of maximum value from waste glass is a key component in this.

Against this background, a comprehensive research work was undertaken at Kingston University to assess the feasibility of using foamed glass gravel **(FGG)**, manufactured aggregate, as a primary aggregate substitute in a range of concrete applications and thereby to develop a high volume value-added outlet for glass waste in a way that is innovative, yet sound. In this study, FGG produced using mixed bottle glass and television / PC cathode ray tube waste, were used in two size fractions, 20-5 mm (as coarse aggregate) and less than 5 mm (as fine aggregate). FGG was developed and pioneered by a Hungarian Company, Geofil Ltd, specifically designed and manufactured to meet the requirements of modern construction products. In essence, **Geofil-FGG (GFGG)** technology utilizes waste glass (from a variety of sources) as the main feedstock with additions of a clay mineral to assist adhesion and chemical additives to optimize viscosity and to control water absorbency. The product has been promoted in Hungary for a number of applications including post insulation for buildings, heat and sound insulation, frost resistance on motorways, roof products and fire resistant systems for buildings. Another FGG material which was examined in the research was Hasopor and another lightweight manufactured material from fly ash namely Lytag.

1.2 Objectives

The prime objective of the research was to examine high value outlets for exploiting the beneficial properties of glass surplus, which at present go to landfill or are stockpiled, in the form of FGG. Specific objectives were to:

i) Establish the history and current scene of glass waste and review published work.

ii) Investigate and compare key fundamental physical, chemical and mechanical characteristics including thermal conductivity of FGG and assess its suitability for use as lightweight aggregate in concrete products.

iii) Assess the influence of FGG, when used as an aggregate, on the fresh properties of concrete.

iv) Examine the effect of FGG on concrete density, engineering properties (compressive strengths, flexural strength, modulus of elasticity-stiffness and stress/strain relationship and Shrinkage and Swelling) and main durability related performance (near surface absorption, carbonation and alkali-silica reaction).

v) Establish fire resistance and sound insulation of FGG wall panels

vi) Measure and compare the performance of FGG concrete with those produced using other key manufactured lightweight aggregates, such as Hasopor and Lytag.

vii) Assess the practical implications of FGG in concrete production.

1.3 Scope of the Research

Scope of the research was to identify and propose sustainable value-added outlets for waste glass in concrete construction industry. Successfully using FGG in concrete will be a major breakthrough in dealing with one of the largest waste streams and so promote Government initiatives on sustainable development and environmental protection via recycling and the reuse of waste glass.

In order to meet the above objectives, the research programme was divided into four distinct phases as follows:

Phase 1: Desk Study/ Literature Review
Phase 2: Obtaining Sample Materials and Characterisations of FGG
Phase 3: FGG Concrete: Production and Performance
Phase 4: Practical Implications and Dissemination of Findings

Phase 1-Desk Study/ Literature Review

The main aims of this section were to understand the FGG granulation process, from production techniques through to resources required, and so establish practical, as well as application issues relating glass waste generation to recycling. Current and developing European and British standards were reviewed and the existing test methods for manufactured secondary aggregates were studied. Technical information and other published literature from a range of sources were obtained for this exercise. These

included research/academic technical journals, British and European standards, industrial reports, trade associations' data, worldwide web sites and data available from the key researchers working in this area.

Phase 2- Obtaining Sample Materials and Characterisations

To ensure that the project covered a range of materials of density and quality currently used in industry materials from two different types of glass surplus were used. These include mixed bottles and television / PC cathode ray tubes. The main physical, mechanical, chemical and thermal characteristics were determined following procedures described in recently developed/adopted standards or widely used common test procedures. These were then compared with those obtained for natural gravel and commercially available lightweight FGG aggregate such as Hasopor and another manufactured lightweight aggregate named Lytag.

Phase 3- FGG Concrete: Production and Performance

To develop suitable mix proportions, trial mixes were proportioned with between 0.40-0.77 water/cement ratios using GFGG/natural aggregate blends, with up to 100% coarse GFGG or up to 15% fine GFGG-by volume. These trial mixes were tested to ensure that both requirements for fresh properties and hardened concrete were satisfied. Based on the test results obtained, a practical upper limit on coarse and fine GFGG content for use in a range of concrete applications was established. A series of tests to assess concrete performance aspects known to influence by GFGG were undertaken. These included a range of fresh (slump, compacting factor, retention of workability), engineering (compressive cube strength, cylinder strength, modulus of elasticity, flexural strength and shrinkage) and durability (near surface absorption, carbonation and ASR resistance) related properties. Much importance was placed on fresh properties to ensure that the GFGG concrete could be effectively produced, handled and placed in practical applications. Tests therefore were carried out for cohesion, consistence, bleeding, compactability, handling and finish ability of GFGG. Similar procedures were followed for Hasopor and Lytag concrete production and performance.

Phase 4- Practical Implications and Dissemination of Findings

The final phase of the study aimed at providing practical guidance associated with the use of FGG concrete and to disseminate project findings to other researchers.

1.4 Thesis Layout

A desk study was carried out to review previously related investigations in this subject area. This included glass production, waste generation, recovery rate, recycling for reuse, and published technical information assessing suitability of recycled glass for use as aggregate or cement in concrete production. The information on using manufactured glass for lightweight aggregate production, included pre-separation, granulation, size distribution, characteristics and its influence on fresh and hardened concrete properties. This information is given in **Chapter 2**.

Chapter 3 briefly describes the FGG production processes and its characteristics. A brief description of the research programme and experimental details are included in **Chapter 4**, which includes details of the materials, mix proportions, specimen preparations and test procedures used in the current study.

In **Chapter 5**, the characteristics of FGG aggregates are presented and include physical, mechanical, chemical and thermal properties. These were then compared with Hasopor (FGG-commercially available light-weight aggregate) and Lytag (Fly ash-commercially available light-weight aggregate).

The work reported in **Chapter 6** was carried out to establish the effect of FGG (mainly GFGG) characteristics on the fresh properties of concrete established through workability (slump and compacting factor) and stability (bleeding and segregation) tests. In order to assess the effect of GFGG on changes to workability with time, further tests were carried out. Comparison of results was made with Hasopor and Lytag fresh concrete properties.

Results of the work examining the effect of substituting coarse and fine FGG, for natural aggregates, on compressive strength development and other bulk engineering properties are discussed in **Chapter 7**. Tests were carried out to assess the influence of GFGG content, original glass source and curing conditions on strength development. Other bulk engineering properties, namely flexural strength, modulus of elasticity and drying shrinkage of natural aggregate (NA) and GFGG concretes were also established. In this, initial GFGG concrete test series was based on equal cement and water content (in order to examine the effect of GFGG content) and thereafter performance at

equivalent design strength was considered. Comparison of results was made with Hasopor and Lytag concrete engineering properties.

In **Chapter 8** results from Durability related performance of NA and GFGG concretes are provided and analyzed. Durability tests such as Initial Surface Absorption (ISA), carbonation and Alkali-Silica Reaction (ASR) were carried out at various replacement levels of coarse or fine GFGG and conclusions were drawn. Again, comparison of results was made with Hasopor and Lytag concrete durability properties.

The results of a feasibility study examining the use of washed glass sand (WGS), as a fine aggregate substitute in concrete production are given in **Chapter 9**. The work was devised to establish benchmark replacement level of WGS and to provide simple practical guidelines for its use in concrete.

A summary of practical implications drawn from the research findings, together with recommendations for further study are given in **Chapter 10**.

Information about the references used throughout the research can be found in section **11**, while section **12** includes Appendices from data and results from fire resistance and sound insulation testing of GFGG wall panels and additional aspects from literature review.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

In many parts of the world, the production of waste glass is increasing annually, but current recovery and recycling rates are unable to keep up with the ever increasing amount. At the same time, there is a growing awareness of environmental and economic considerations to minimise the disposal of glass waste. The quantities of arisings are likely to increase considerably as a result of the implementation of a series of European Directives aiming to reduce glass waste [1]. Quantities of glass remaining after recycling due to colour imbalance have the potential to act as a barrier for increased recovery in both economic and environmental terms. Especially for green glass, there is a vast surplus, which may amount to 424,000 tonnes by 2008 as a result of increased recycling (according to European Directives). Given the situation, there is an urgent need to develop alternative outlets for recycled glass, which can utilise all types and colour of glass.

It is now widely accepted that the recycling of surplus glass for use as aggregate in concrete products offers an environmentally responsible and economically viable route to convert the wastes to a valuable resource. However, successful usage of glass aggregate is partially obstructed by the potential reaction between silica in glass and alkali in cement (Alkali Silica Reaction-ASR) resulting in deleterious expansion and durability related problems of concrete. One of the environmentally friendly and economically sustainable outputs of glass waste could be formation of lightweight foamed gravel for use in construction. This chapter reviews current UK glass scene only, while technical and practical issues associated with foamed glass gravel production, characterisation and its use in concrete are covered in the next chapters.

Literature collected from a variety of sources has been summarised into different sections, namely (i) glass production and recycling, (ii) legislative directives, (iii) current outlets for waste glass, and (iv) recycling for reuse in concrete.

2.2 Glass Production and Recycling

2.2.1 Current production of glass-chemical composition

The main constituent of all commercial glass is sand. Sand by itself can be fused to produce glass but the temperature at which this can be achieved is about 1700°C. The addition of different minerals and chemicals to sand has considerably reduced the melting temperature. The addition of sodium carbonate (Na_2CO_3), known as soda ash, to produce a mixture of 75% silica (SiO_2) and 25% of sodium oxide (Na_2O), can reduce the temperature of fusion to about 800°C. However, a glass of this composition is water-soluble and is known as water glass. In order to give the glass stability, other chemicals like calcium oxide (CaO) and magnesium oxide (MgO) are needed. These are obtained by adding limestone, which results in a pure inert glass. This is known as Commercial Glass or Soda Lime Glass [3].

Other forms of glass that exist in industry are flat glass, used for windows of buildings or windscreens for cars, and other types of glass as briefly outlined below [3]:

1. Lead glass is used to make a wide variety of decorative glass objects. It is made by using lead oxide instead of calcium oxide, and potassium oxide instead of all or most of the sodium oxide.
2. Borosilicate glass (Pyrex) is in the form of ovenware and other heat-resisting ware. This type of glass has chemical durability, low alkali content and good thermal shock resistance. It is used extensively in the chemical industry.
3. Glass fibre has many uses from roof insulation to medical equipment and its composition varies depending on its applications.
4. Types of special glasses are: Vitreous Silica, Alumino-silicate Glass. Alkali-Barium Silicate Glass, Glass ceramics, Optical glass and Technical Glass.

Chemical compositions of all types of commercial glass are given in Table 2.1, where the main constituent is silica (SiO_2) and sodium oxide (Na_2O). According to Table 2.1, most commercial glasses (container, flat and domestic) have roughly similar chemical compositions of silica (70-74%), sodium oxide (12-16%), calcium oxide (5-11%), magnesium oxide (1-3%), and aluminium oxide (1-3%).

Glass also forms the cathode-ray tube (CRT) in Television and PC Monitors. The CRT represents about two thirds of the weight of a television or a computer monitor and is

composed of 85% glass. The average weight of the CRT glass for TV sets is 11 kg, while for computers it is 3.8 kg. The CRT is made up of four main glass parts namely: Panel (front part), Funnel (part hidden inside the TV set), Frit (joint between panel and funnel) and Neck. Table 2.2 gives typical chemical composition of CRT.

Table 2.1 Composition of Various Glasses [4]

Component	Container glass	Flat glass	Domestic glass	Heat resistant (Pyrex)	Glass fibre
SiO_2	74.0	71.0	71.0	80.0	54.5
CaO	11.0	9.0	5.0	-	22.0
Na_2O	14.0	16.0	16.0	4.5	0.5
Al_2O_3	1.0	1.0	3.0	4.5	14.5
MgO	-	3.0	3.0	-	-
B_2O_3	-	-	1.0	12.0	8.5

Table 2.2 Typical Chemical Compositions for Cathode Ray Tubes in PC and TV [1]

Oxide	TV		PC	
	TV panel	TV funnel	PC panel	PC funnel
Na_2O	**8.0-9.0**	**6.5-7.0**	**7.0**	**5.5**
K_2O	**7.0-7.5**	**8.0-10.0**	**7.5**	**8.0**
Mg0	0.5-1.5	8.0-10.0	0.5	8.0
CaO	0.5-2.5	1.5-4.0	1.0	3.5
SrO	**1.5-8.5**	**0.15-0.5**	**9.0**	**0.5**
BaO	**10.0-12.0**	**1.0-2.0**	**1.0**	**3.5**
Al_2O_3	2.0-3.0	3.0-4.0	2.0	4.0
ZrO_2	0.5-1.5	1.0	1.0	0
PbO	**0-0.5**	**15.0-22.5**	**0**	**20.5**
SiO_2	60.0-62.0	50.0-60.0	60.0	55.0
CeO_2	0.25	-	-	-
TiO_2	0.5	0	1.0	0
Sb_2O_3	0.5	0	0.5	-
As_2O_3	0	0	0	-
Fe_2O_3	0	0	0	-
ZnO	-	-	1.0	0

It is obvious from Table 2.2 that there are small differences between TV and PC panels, and that of TV and PC Funnel. There are also differences in the percentages of elements when comparing container and CRT glass. The glass from CRT contains heavy metals at percentages of (10.0-12.0%) of barium oxide (BaO) and 9% of strontium oxide (SrO) in the TV/PC panel, and (15.0-25.0%) of lead oxide (PbO) in the TV/PC funnel. The SiO_2 percentage for CRT is around 60% while for container glass, according to Table 2.1, is around 75%. Percentage of alkalies such as Na_2O and K_2O are (7.0–10.0%) in CRT's respectively, while for container glass are ranging around 14%. It is probable that these different percentages have an effect on the composition of the final product. Since the research into FGG concentrates on two sources of glass, container and TV/PC CRT, the glass chemical composition of it is of high importance.

2.2.2 Waste glass-UK scene

There are no published statistics relating to the volume of production from the UK glass industry but in 2003 the total output was estimated to be 3.6 million tonnes; of this, the flat and container sectors accounted for over 85% as shown in Figure 2.1 [4].

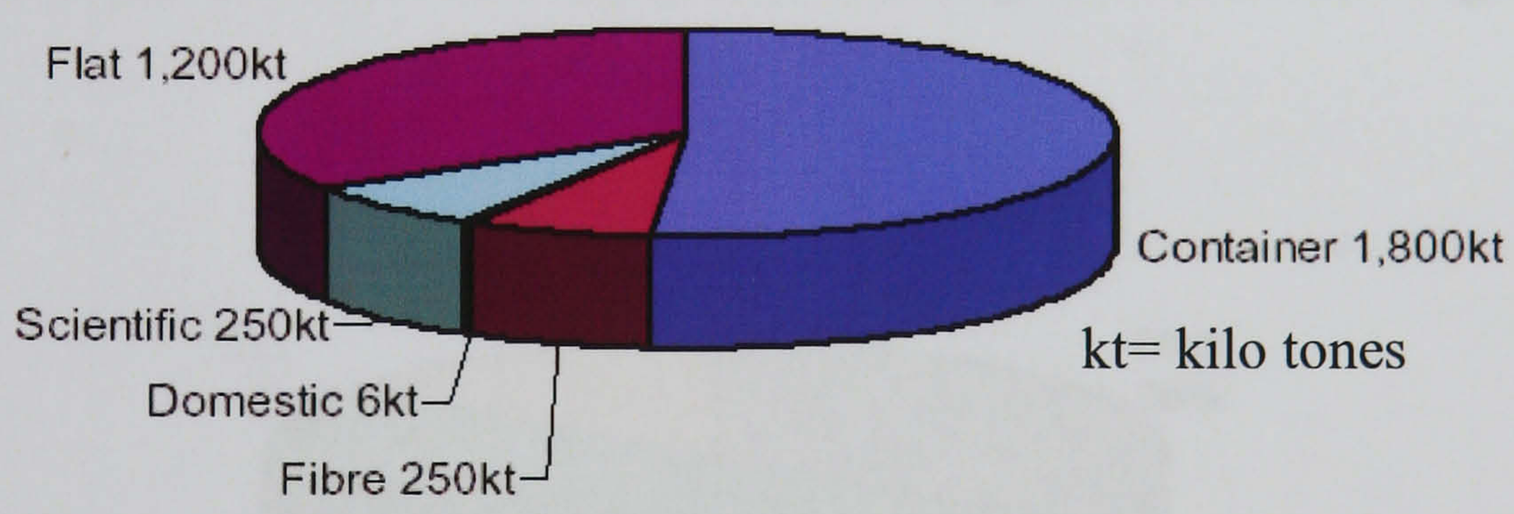

Figure 2.1 Estimated Annual UK Glass Production in 2003 [4]

In 2003, 3.4 million tonnes of glass waste were generated in the UK [4]. A summary of the statistics in 2003 from each glass source is presented in Table 2.3. According to Table 2.3, 1.1 million tonnes of waste glass were recycled which comprised 875,000 tonnes of container glass along with 230,000 tonnes of flat glass, representing a 33% recycling rate. To meet the Legislative Targets set by the Government, total recycling (container, flat, CRT, fibre etc) should have increased from 33% to 49% in 2004 and should be further increased to 51% in 2006 and 60% in 2008 [4].

Table 2.3 Estimated Waste Glass Arisings and Recycling by Type (2003) [4]

Glass type	Estimated arisings (tonnes/year)	Collection (tonnes/year)	Recycling rate (%)
Container	**2,400,000**	**875,000**	**36**
Flat	**760,000**	**230,000**	**30**
Fiber	60,000	0	0
Lighting	15,000	0	0
Cathode ray tube	**100,000**	**0**	**0**
Tableware	40,000	0	0
Heat resistant	20,000	0	0
Total / Average	**3,395,000**	**1,105,000**	**33**

Container glass

Container glass, which forms the bulk of recycled glass, is collected through bottle banks, Local Authority kerbside collection schemes and collections from licensed premises. The reason glass bottles and jars are collected in green, brown and clear banks, is so that they can be easily recycled back into packaging material of the same colour [4]. The colour breakdown of recycled container glass is shown in Figure 2.2.

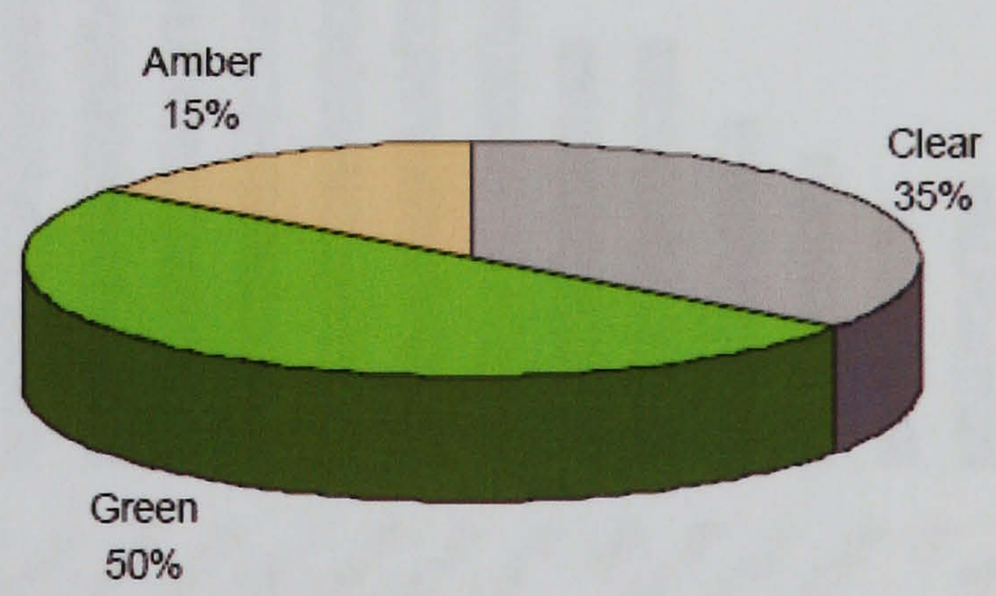

Figure 2.2 Estimated Colour Breakdown of Recycled Glass (2003) [4]

In 2003, the UK glass container industry used approximately 616,700 tonnes of the 875,000 tonnes of recycled container glass as a feedstock for new container manufacture. In the following year, this amount further increased by 60,000 tonnes [6], indicating a significant increase on the recycling rate from 2002 (of 494,800 tonnes).

British Glass findings for 2005 showed that 1.272 million tonnes of glass was recycled from which 742,000 tonnes have been used as new container manufacture, 250,000 tonnes were exported and 280,000 tonnes were used for aggregate manufacturing [5]. There has been a progressing increase in recycling rate from 33% in 2003 to 37% at 2005. Such increase in rate was largely due to advances in technology and the investments made by glass processors in colour-sorting and contaminant detection systems to obtain glass of sufficient quality for reuse in container manufacture. In 2008, the UK must achieve a recycling level of 1.6 million tonnes annually (60% recycling rate) [6].

Figure 2.3 presents data from container recycling rates in European Countries in 2004 and shows with clarity that promoting recycling is important in the UK. As seen from Figure 2.3, in 2004 the rate of container glass recycling in UK increased from 36 to 37% while other countries such as Switzerland, Finland, Norway and Germany recycled around 90% of waste glass. The UK's waste management scheme is poor and scores badly on recycling compared with the rest of Europe.

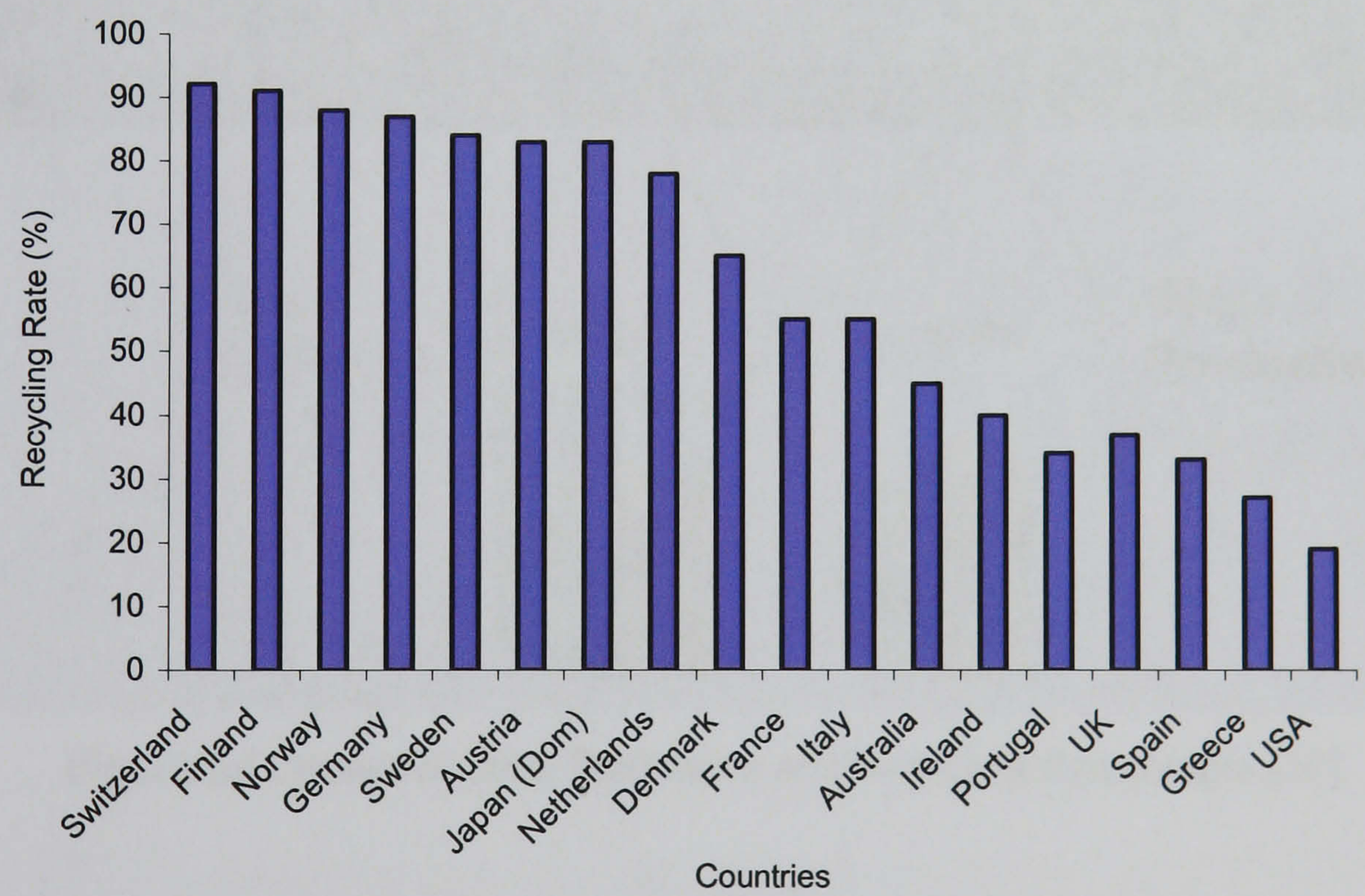

Figure 2.3 Recycling Rates of Container Glass in European Countries In 2004 [7]

With an annual production of some 1.8 million tonnes/year the container manufacturers could in theory consume up to 1.6 million tonnes/year (88% of produced glass). However the consumption was limited to (41%) 742,000 tonnes in 2005, by the quantities available [5]. The ability of the industry to achieve the higher levels of

recycling of 65% in 2008 is compromised by three factors that make the UK glass recycling market unique.

Firstly, the UK is a net importer of glass packaging while most other major European countries are net exporters. Secondly, UK Industry produces mainly clear glass while most European countries produce much more green. As collection rates increase, the amount of green glass in the waste stream will outstrip the capacity of the container manufacturers to utilise it (92% in 2003). Green glass accounts for 50% of waste glass but only 16.5% is produced in the UK (Figure 2.4). Currently green glass furnaces in the UK operate with an average 92% recycled glass in their feedstock compared to 30% for clear and 42% for amber. Therefore there is very limited scope for additional green glass consumption by container manufacturers, which are currently using around the maximum quantity of recycled glass. This produces a surplus of green cullet, which will be increased to 424,000 tonnes by 2008 since recycling rates of container glass will reach 65%. A surplus of amber cullet of about 26,000 tonnes will not be used, while there is still a furnace capacity for clear cullet [4].

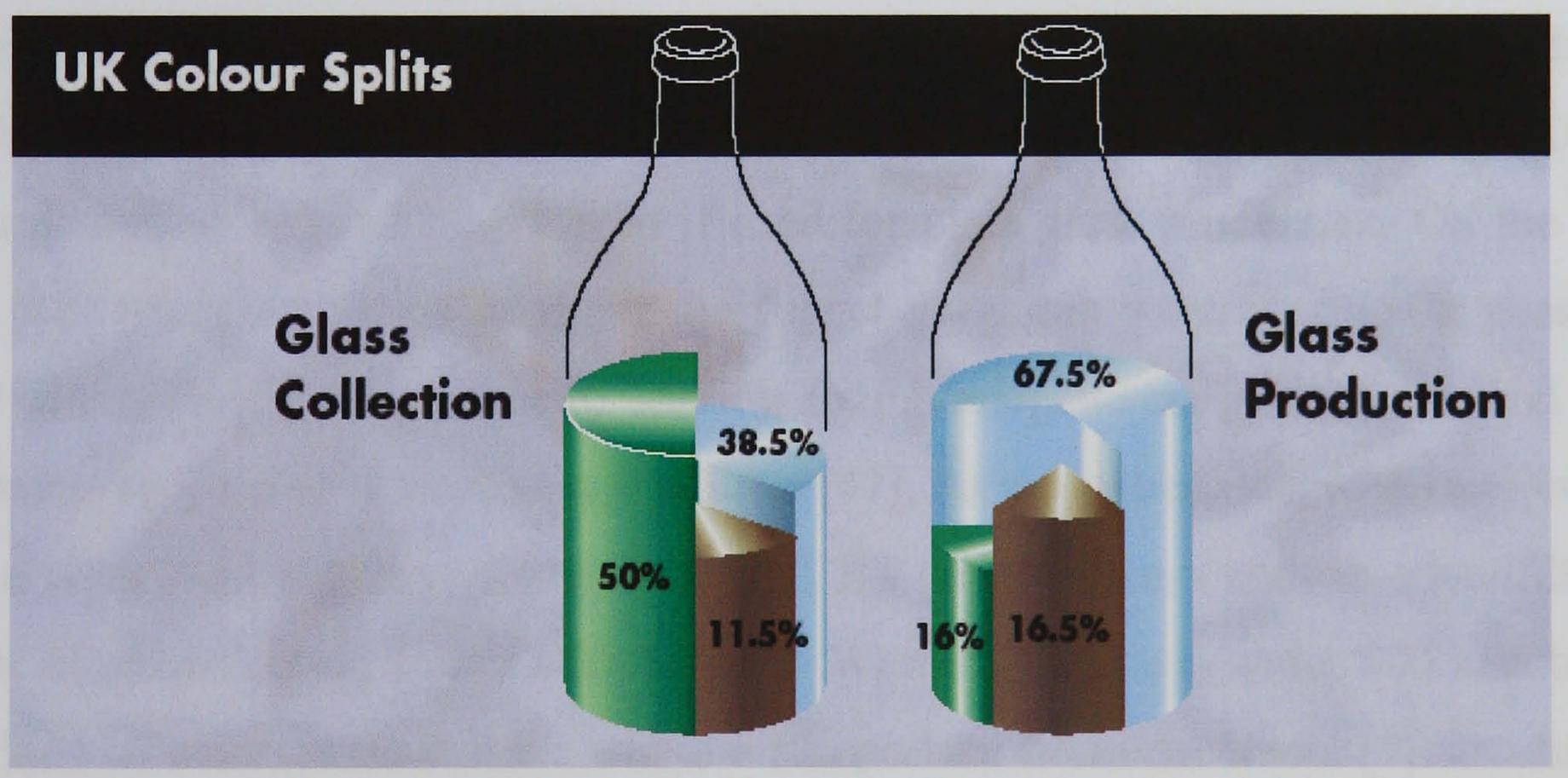

Figure 2.4 Container Glass Production and Recycling Percentages [10]

Thirdly UK's collection infrastructure is significantly different [5]. Mixed collection is compounding the UK's colour imbalance. For glass collected mixed and then colour separated, three tonnes of extra green arise for every tonne of additional clear. UK glass packaging production is predominantly clear, with high exports, mainly in the form of filled spirits bottles. There is limited green production and with high imports of green glass, mainly in the form of filled wine bottles, the result is a shortage of clear and

brown glass for recycling and greener glass than container makers alone can recycle [5]. However, it is going to get tougher to maintain progress. It is vitally important for container manufacturers that the move to mixed collection is halted and the amount of glass that is collected colour separated is maximised. This will ensure that the glass packaging industry, which delivers the highest environmental benefit and best value market for glass will be able to maximise the amount of glass it recycles.

Cathode Ray Tubes (CRT)

It has been estimated that in 2003 CRT glass sources were giving rise to some 100,000 tonnes/year of waste. If CRTs are crushed and mixed together, they cannot be recycled as cullet, for instance for industrial glass production such as container glass, tableware glass and TV glass due to heavy metal content (Lead-Pb, Barium-Ba and Strontium-Str). The heavy metals are essential for the UV and X radiation. In theory, CRTs can be disassembled into their component parts, which comprise the faceplate (on which the image is displayed), the cone or funnel and the neck (which houses the electron gun) [1]. CRT glasses are hardly used as raw materials for new CRTs since a certain composition control is needed. The neck and funnel glass components could go to primary recycling, but the quality requirements for faceplates are very high and probably exclude the use of recycled glass in their manufacture. Lead oxide (PbO) can have a darkening effect of the screen if used for plate glass production. On the other hand, plate glass cannot be used for the funnel glass components, since it possesses higher characteristic temperatures, leading to inhomogeneous glass melts and poor mechanical properties of the obtained articles [47]. As a consequence, when a television set or a computer monitor is dismantled, the CRT almost always ends in a landfill. The amount of glass coming from CRTs today in Western Europe is about 300 kilo tonnes /year, 99% of which is land filled, where it can pollute the environment [1]. In addition, the disassembly costs are prohibitive and given that only faceplates are produced in the UK, the prospects for recycling CRT glass into primary manufacture of new CRTs are very limited.

Promising applications for CRT glass so far can be [4]:

- A feedstock for CRT manufacture
- A feedstock for Foamed Glass Manufacture
- A medium for waste encapsulation

- Glass Tile manufacture
- A feedstock for lead smelting

2.3 Legislative Forces

In 1989 one economist said "We are going to get the bill for the Industrial Age. If the projections are right it is going to be a big one: the ecological collapse of the planet"[6]. The recovery of waste and by-products fits into current legislation, which encourages research into new technologies and processes in order to exploit disposable materials into new marketable inert products [1]. In recent years new legislative and fiscal drivers have contributed to increasing the desirability of recycling glass, and these being augmented by cullet quality have greatly influenced the UK market for recycled glass.

Currently, there are main legislative pressures that are driving the increase in the use of recycled glass [4]:

1. EU Landfill Directive
2. European Community Directive on Packaging and Packaging Waste
3. The Pollution Prevention and Control (PPC) Regulations
4. Waste Electrical and Electronic Equipment (WEEE) Directive
5. End of Life Vehicles Directive (ELV)
6. Waste Framework Directive

More details about the role of legislative forces are provided in Appendix C.

A number of resources have been put forward to improve the market for recycled materials. One key issue is the development of standards to determine when recycled materials are no longer considered waste. Material is no longer seen as waste if reclassifying it would not lead to negative environmental effects and a market exists for it as a secondary material. Primary and secondary markets for glass waste are presented below.

2.4 Current Outlets of Waste Glass

Glass is an inert material with good compressive strength and hardness making it suitable for a variety of applications including: bottle manufacturing, aggregate in road

construction, insulation material, concrete aggregate, decorative aggregate, filtration material, abrasive material, art and craft products. Figure 2.5 presents graphically the primary and secondary markets for recycled glass.

Over the past few years a number of new markets for recycled glass have emerged and some of these have now achieved full commercialisation [10] and waste glass is now used in many applications [11]. As seen from Figure 2.5 the primary market that can absorb large quantities of waste glass is the bottle manufacture industry, but the capacity of it is limited especially due to the surplus of green glass as foresaid. Secondary markets exist such as the fibre-glass and construction industry, value-added products or industrial minerals.

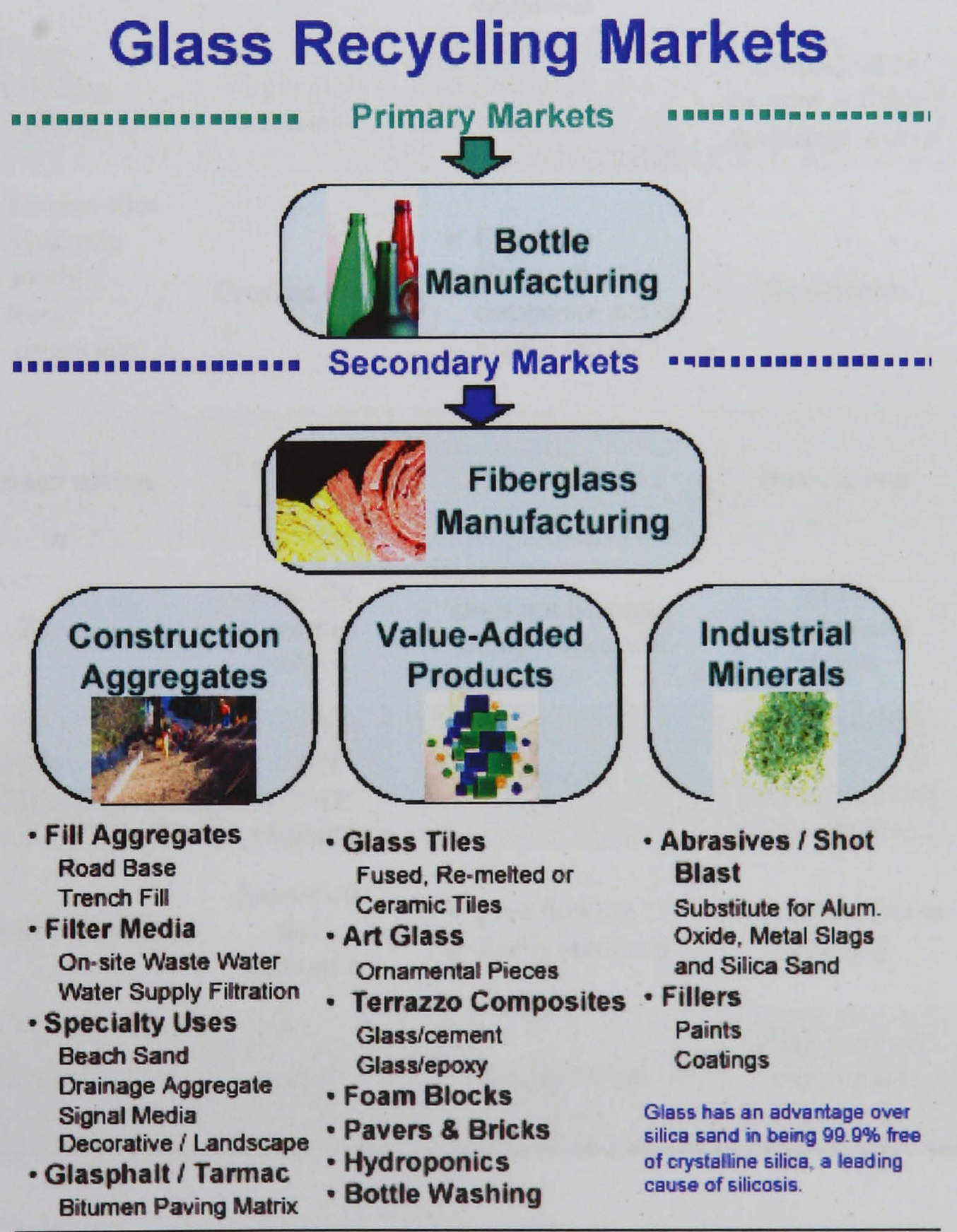

Figure 2.5 Glass Recycling Markets [12]

Table 2.4 presents a summary of the potential markets for waste glass and shows the advantages and disadvantages from each application.

Table 2.4 Summary of Potential Uses of Recycled Glass [4]

Use	Application	Products to be replaced	Advantages of recycled glass	Disadvantages of glass product	Comments
Filtration media	• Drinking water • Wastewater • Swimming • Pools • Fisheries	• Sand • Anthracite • Garnet	Resists bacterial growth	DWI approval required fro use as drinking water filtration media	• Some small scale applications • Extensive currently on-going
Abrasive	• Shot blast • Bonded • Frictionator	• Silica sand • Copper slag • Anthracite	• Glass contains no crystalline silica • Low heavy metal content • Angular particles for effective performance	Generally higher cost compared to other media	There are several suppliers in UK of recycled glass shot blast material
Flux / Binder	• Bricks • Ceramics • Pottery	• Mineral fluxes • Clay	• Reduced firing temperature & time • Reduced HF emissions	Non-known	Extensive trials currently on-going
Decorative / Art	• Tiles • Drinking glasses	Virgin glass materials	• Colourful • Low cost • recycled marketing value	Difficulties in securing reliable / consistent source	Niche market applications
Flooring	• Terrazo tiles • Synthetic marble • Resin composite	Crushed rock	• Colourful • Glass / Resin composite can be highly resistant	Non-known	A number of companies supplying this type of product
Foamed Glass Insulation	**Construction**	**Virgin glass materials**	**Low cost**	**Non-known**	**Currently no commercial applications in the UK**
Cationic Exchange	Zeolites	Naturally occurring Zeolites	Does not become "sticky" when wet	Still in development phases	No known commercial applications in the UK
Filler	• Paint • Plastic	• Titanium dioxide • Calcium carbonate	Low cost	Small particle sizes required may be difficult to achieve	No known commercial applications in the UK
Hydroponics	Rooting medium	Expanded clay aggregate	• Free flowing • Easily sterilised	Can cause cuts in handling	No known commercial applications in the UK
Packing	Water well	sand	Good drainage	High level of cleanliness required	No known commercial applications in the UK

What can be concluded from this table is that most applications are not yet exploited in the UK, but this situation will hopefully change in the future. A relatively new market for surplus of glass is its use as foamed glass insulation material, which proves to be very promising. The development of new and alternative markets for recycled glass has further contributed to the development of new technologies. Processing technologies

have needed to keep pace with the variety of specifications introduced by these new end markets. The development of these markets has significantly increased competition in the marketplace for recycled glass making it increasingly commercially attractive to recycle [1]. Based upon the estimates of these new potential markets Table 2.5 [4] projects an increase in glass recycling for all the applications that have been discussed in reference [4]. These applications will use predominantly recycled container glass and the projected growth in recycled glass will depend on continued investment in collection infrastructure. The increases in flat glass recycling are predicted to remain fairly static at the current quantity of 230,000 tonnes/year. In addition it is possible that some recycling of CRT and lighting glass may become viable given the current research activity in this area.

Table 2.5 Projected Glass Recycling By End Use Application [4]

Applications	**Year**			
	2003	**2004**	**2006**	**2008**
	Tonnes x 1000			
Containers- Green	302	250	296	300
Containers- Amber	65	100	189	200
Containers -Clear	249	350	512	560
Containers Flat	110	80	60	50
Fibre Glass (Flat)	50	70	80	90
Fibre Glass (container)	15	17	20	20
Flat Glass (Flat)	70	75	80	85
Aggregates- Concrete	**15**	**20**	**25**	**35**
Aggregates – General Fill	45	50	55	60
Aggregates – Bound Road Base Course	77	100	120	140
Aggregates – Decorative	3	3	3	3
Water Filtration – Drinking Water	0	10	30	50
Water filtration	0.2	10	20	40
Abrasives	3.5	8	15	20
Fluxing Agent for Bricks and Ceramics	0	0	20	40
Art / craft	0.02	0.05	0.1	0.3
Export	100	100	100	100
Total	**1105**	**1243**	**1625**	**1793**

Table 2.5 predicts that the quantity of recycled glass used in new applications will almost double, with the recycling rate increasing from the value of 36% at 2003 to the required 65% by 2008. As seen from Table 2.5, a sustainable outlet for recycled glass can be as aggregate in concrete. The next section briefly introduces concrete, its

constituents and outlines several comments on researches, which have examined the usage of glass as concrete aggregate or cement replacement.

2.5 Recycling For Reuse in Concrete

2.5.1 Introduction

Well compacted concrete prepared with hard and low porosity aggregates may be assumed to be a multiphase material consisting of coarse aggregates embedded in a mortar matrix [13,14]. The mortar matrix consists of fine aggregates, solid cement hydrates, un-hydrated cement, and a pore system. Therefore, selection and proportions of aggregates, cement and water are of major importance since they are prerequisites for concrete strength properties and subsequent durability.

Concrete prepared with hydraulic cement binder can be regarded as a chemically bonded ceramic. The hydration reaction of cement results in a product consisting of solids and pore system.

The density of a given concrete can be lowered by partially replacing the solid content of the mix with air voids [15]. There are three possible locations of air voids in hardened concrete:

- In the aggregate particles, the resulting aggregates being known as lightweight aggregates,
- In the hardened cement paste, the resulting concrete being known as cellular or foamed concrete,
- Between the normal coarse aggregate particles (fine aggregate being omitted), the resulting concrete being known as no fines concrete.

The production of aggregates is carried out on a vast scale in the UK; annual production is approximately 210 million tonnes, of which about one third is sand and gravel and two thirds is crushed stone (limestone, granite, sandstone etc.).

The lightweight aggregates conforming to BS 3797: 1990 can be used as aggregates in their natural form (diatomite, pumice, scoria and volcanic cinders), or man-made, manufactured from natural materials (clay, shale and slate), or from industrial by-products (manufactured from fly ash, glass, and construction waste) [14]. The most

important characteristic of the lightweight aggregates is their predominantly high porosity, which results in a lower apparent particle density. This density can have both economic and practical advantages in concrete production [15].

Since recycling of glass plays an important role in the waste management, researches have found many forms of glass waste that can be used in concrete products. Glass may be incorporated into concrete as a decorative material, fine or coarse aggregate replacement or may be finely ground and used as a pozzolanic material for the partial replacement of Portland cement. The following section will present the findings of studies with glass used in concrete production.

2.5.2 As fine aggregate in concrete

Glass has been used in many studies as fine replacement in concrete or mortars and has been examined for its effect on fresh and engineering properties [14]. Waste glass that is crushed and screened has the potential for use as a sand substitute in concrete. Glass waste was used in many studies, in size range less than 5 mm as natural sand substitute in different percentages. In many respects, glass that has been reduced to a fine aggregate size fraction (less than 2.46 mm grading) exhibited physical properties similar to that of a fine aggregate or sandy material [16].

With reference to fresh properties of concrete, many reported results show that when glass sand is used at water/cement ratios equal or greater than 0.5, up to 50% by mass replacement, increases workability while higher replacements slightly decrease the slump (increase the water demand). Workability lies within the allowed ranges due to the angular cullet particles, which may have an interlocking effect and allow less freedom of movement in the concrete mixture compared to rounded river sand, which gives greater workability. In general, cullet sand shows similar characteristics to crushed sand with sharply angular shapes and rough surfaces [16-26].

Strength result values of concrete having glass sand as fine aggregate replacement, were similar and some times higher than the control mixes (0% Glass sand). Concrete mixes reached the designed strength with faster strength development when glass sand replaced up to 50% by mass natural sand, only when Lithium compounds such as

$LiNO_3$ and LiOH or pozzolans such as Silica Fume (SF), Ground Granulated Blast Furnace Slag (GGBS) and Pulverised Fly Ash (PFA) were used [16,17,22,23,26]. Shrinkage characteristics were also reported [16,26] to be within the limits < 0.075% at 56 days, when < 2.46 mm glass was used at up to 50% natural sand replacement.

Glass sand can also be finely ground and used as glass powder. In a study it was found that if cullet sand was used at less than 300 μm size range, such as 36-50 μm, it could replace up to 70% fine sand; giving mortar strength higher than the control mix, with the lowest content of macro pores and meso pores (less than 100 μm), but with higher water demand to achieve equal workability with the control mix [18]. This behavior can be attributed to the denser microstructure of ground waste glass. In another study [19] when 30% natural sand was replaced by Glass Powder (GLP) of less than 10 μm, the strength achieved with 30% GLP replacing fine aggregate exceeded that of the mix containing Silica Fume. This is due to improvement in the particle packing as well as the pozzolanic reaction. It was shown that the more the size of glass sand is reduced the better the strength properties of concrete were.

Durability related properties of concrete such as Permeability, Carbonation and Alkali Silica Reaction are important and should be examined whenever new material especially (siliceous like glass sand) is used in concrete. Research showed that durability properties of mixes with up to 50% cullet sand were satisfactory, provided the addition of Lithium compounds or Supplementary Cementitious Materials (SCM) such as (20-30%) PFA, 40% Metakaolin (MK) or 20% (GGBS) according to published studies [16,17,22,23,26]. It is well known that the incorporation of pozzolans into cement or concrete systems provides many benefits to the properties of both fresh and hardened concrete such as improvement in workability, reduction in the heat of hydration, low permeability, high ultimate strength, and control of Alkali Silica Reaction [28].

Control of ASR when using glass in concrete is crucial since silica from glass reacts with alkali from cement and can cause gel formation. This gel expands within the matrix and weakens the concrete. However, it does not occur with fine sized glass (less than 1-2mm) [17]. Research has shown that a 'pessimum' particle size exists for which maximum expansion due to ASR is encountered. Below this particle size (around 1.2

mm) expansion declines. Thus below the pessimum, there is a gradual shift away from the ASR type of reaction towards a pozzolanic reaction [1]. Glass has high silica content, a large surface area and is amorphous, satisfying the requirements for pozzolanic behaviour as proved previously [1]. In a study [17] as expected, for 30% glass sand of particle size less than or equal to 0.6 mm –1.18 mm the expansion was less than the control mix and sometimes zero, showing a pozzolanic behaviour for green, flint and amber coloured glass. Regarding the glass size effect, 3-6 mm glass was the most reactive with 6-12 mm aggregate to follow as expected [17]. Other observations [29], with different types of cement, binders and glass as aggregate, suggest that the retardation of ASR is due to a pozzolanic reaction / ion exchange where Ca ions from the solution go into the solid phase and alkali ions from the glass go into the solution so no reaction takes place.

However, most pozzolanic materials, especially natural pozzolans when used at low water cement ratios, tend to increase the mixing water requirement for concrete and lower the rate of strength development. Therefore their application is limited to only 30% or less [28]. In a further study it was found that when glass sand is used at low w/c ratios (less than 0.5) there is slump decrease and higher water demand as the mixing ratio of waste glass aggregate increases [30]. Further, it was found that, regardless of colour, slump decreased by (20-44%) as the mixing ratios of waste glass aggregates increased by (30-70%) respectively, compared to plain concrete. This tendency is probably because:

- As the mixing ratio of waste glass aggregate increased, additional cement paste attached to the surface of the waste glass, which resulted in less available cement paste necessary for the fluidity of the concrete.
- Waste glass aggregates had sharper and more angular grain shapes and were larger than sands, which resulted in less fluidity.
- There was a tendency of compacting factor to decrease maybe because the grain shape of the waste glass aggregates were irregularly angled, which resulted in a fluidity drop parallel with an increase in the amount of the waste glass aggregate.

Results from hardened properties such as compressive, tensile and flexural strength tests were very similar regardless of the colours of glass cullet. General observation made

was that with an increase of waste green glass from (30-70%) there was a decrease in compressive, tensile and flexural strength. When 70% fine sand was used there was a reduction of 15% in the compressive strength. This tendency towards a decrease in compressive, tensile and flexural strength was attributed to the decrease in adhesive strength between the surfaces of the waste glass aggregates and the cement paste as well as the increase in Finess Modulus of the fine aggregates and the decrease in compacting factor in accordance with the increase in the mixing ratio of the waste glass. However, the compressive tensile and flexural strength increased, as the amount of a polymer Styrene Butadiene Rubber (SBR) increased from 5-10% for each mixing rate, while more than 10% of SBR caused a decrease in all mixes. Hardened properties in other studies with w/c ratio of 0.43, showed a 5% reduction in strength when 5% glass sand was used while 30% replacement decreased the strength by 30%, and total replacement decreased the strength by 50% [16].

2.5.3 As coarse aggregate substitute in concrete

Many researchers started in the last few years to examine the feasibility of using glass aggregate in place of natural coarse aggregate-gravel [31,32]. There are few published results from these studies.

In one study [21] between (0-100%) replacement of aggregates with fine waste glass (FWG), coarse waste glass (CWG) and combined fine with coarse waste glass (FCWG) were examined. Soda-Lime glass from bottles was washed and crushed to fine and coarse aggregate sizes for use in the concrete mixes. Samples were cured under 95% Relative Humidity (RH) at room temperatures of (20-22°C) for 28 days and then heated in ovens to temperatures of 20,60,150,300,500 and 700°C, allowed to cool to ambient temperatures to avoid thermal shocks and then tested for their residual compressive strength. A control mix of strength 40 MPa was designed and aggregates were used at percentages of 10, 25, 50 and 100%.

Regarding the fresh properties, the slump value seemed to increase with increasing percentages of waste glass. This was attributed to the poorer cohesion between the glass aggregates, having smooth impermeable surfaces, and the cement paste. There was a reduction in the inter-particle friction. It could also be noticed that concrete made with

FWG had lower slump values than that made with CWG and FCWG (which showed high slump).

Both initial and final setting times exhibit an increasing almost-linear relation with the percentages of replacement with fine glass and with coarse glass in concrete made with FWG and CWG. The delay could be attributed to the presence of impurities and the increase in W/C ratio due to the slow water absorption of aggregates. This effect is more pronounced with 50% of Fine and Coarse waste glass combined.

Regarding the Hardened properties, the compressive strength of concrete generally decreased with increasing temperatures. At 10% replacement of aggregates with FWG, CWG or FCWG, the compressive strength of concrete was higher than that of the control up to 700°C. Interestingly, at ambient temperatures, the control concrete possessed a slightly higher compressive strength comparing to the concrete with glass aggregates. This is due to the fact that the free water retained in the mix is dissipated at elevated temperatures much more readily in mixes containing glass than the control concrete since glass does not absorb water. Thus making concrete mixes made with waste glass more compact after the evaporation of the free water around 150°C.

As noted, with higher replacement percentages of aggregates, concrete made with FCWG exhibited lower compressive strength at elevated temperatures. This could be attributed to the weaker initial strength of concrete made with FCWG due to a combination of factors including lack of cohesion between fine and coarse aggregates on one side and cement paste on the other.

However when approaching the temperature of 700°C the compressive strength of the three types of concrete made with waste glass converge to similar values. This was attributed to the approach of the glass to its melting point (700-800°C for soda-lime glass) where the microstructure undergoes large physical and mechanical transformations, which at about 700°C causes softening of the glass introduced in the mix. The similarity in the behavior of the 3 types of mixes made with waste glass could therefore be attributed to elimination of the size effect in the softened state of the glass. However, since concrete cubes are cooled to ambient temperatures before testing, the glass then exhibits a transition from its softer and more viscous form to its solid state at

around 380°C. This explains the higher ratio of strength at elevated temperatures to that at ambient for concretes made with FWG and FCWG. The weaker strength ratio of concrete made with CWG could be due to the devitrification of coarse glass, marked by the appearance of large bubbles, above 600°C, which decreases its strength. This effect is hardly noticeable for 10% replacement percentages of CWG where the ratio of strength at elevated temperatures is higher than that of the control mix. This could be attributed to the more compact structure of the concrete where the free water to be evaporated at high temperatures is only available in the pores, not in the glass aggregate. The difference in the co-efficient of thermal expansion between glass and cement paste creates residual stresses that would cause cracks at the interface between the aggregates and the cement paste after cooling from elevated to ambient temperatures. Being less homogeneously distributed than fine glass, coarse glass is more susceptible to strength loss for concretes made with high percentages of CWG.

The concretes showed an increased propensity to ASR when particle size increased beyond 1-2 mm. The deleterious expansion when including up to 100% coarse aggregate as glass can only be controlled with the use of pozzolan such as PFA, MK and GGBS, especially when high alkali cement is used in high humidity conditions [17].

2.5.4 As cement substitute in concrete

The use of pozzolanic materials as a blended component of Portland cement production is generally associated with significant savings in energy and cost [28]. World Portland cement production is responsible for about 7% of total CO_2 emissions. A reduction in Portland cement clinker production without decreasing the amount of cement needed for the construction industry can be achieved by incorporating larger than customary proportions of pozzolanic materials into blended Portland cements [28].

Very finely ground glass less than 600 μm in size, despite its high amorphous silica content, has pozzolanic properties and therefore can serve both as partial cement replacement and filler (passing 63 μm sieve) [1,26,33]. Finely pulverized glass might be used as filler or as pozzolan together with non alkali-reactive aggregates, or in concrete containing alkali-reactive aggregates if the concrete shall be exposed to environments with low relative humidity [33]. A series of studies took place and major findings show

that the use of ground waste glass as a high volume cement replacement in concrete seems feasible, if the glass can be ground sufficiently fine.

Whilst finding alternative uses of green cullet is of most importance in the UK due to the colour imbalance, feasibility studies [1,19,20,26,33-37] examined the three most common cullet colours (white, amber and green) derived from container, flat, fluorescent lamp and cathode ray tube glasses, at Portland cement replacements of 10, 15, 20, 25, 30 and 50% by mass. The cullet at all times was washed before being ground to powder of between 10 – 600 μm in size.

Regarding the engineering properties of concrete with glass as cement replacement, results show that for up to 30% replacement of cement by glass cullet, 28-day compressive strength of mixes was the same as that of the control mix, with strength gain being satisfactory especially when fluorescent lamp glass was used, due to it's high alkali content. In general as the particle size of glass powder as cement replacement decreased from 150-38 μm, so the strength of concrete increased. Especially the use of 10 μm GLP yielded concrete with strength results similar to control and mixes with (10% SF and 20% basalt powder, non-pozzolanic material) and Fly Ash. Regarding other bulk engineering properties, drying shrinkage of the various mixtures containing up to 30% GLP replacing cement or aggregate were not excessive and they easily meet the requirements of American Standard ASTM 3600, being values less than 0.075% at 56 days [19].

Increasing the percentage of glass as cement replacement to 50% is feasible only if Fly Ash (25% by mass) is also included. Similarly in another study [37] the use of waste glass as finely ground mineral additive (FGMA) in cement was examined as a promising direction for recycling. The cements samples produced had 50% by weight of waste glass (Flat, CRT and Container) and an additional 10% of super silica. The highest 28-day compressive strength of mortars was obtained with Window Glass Cullet and Green Bottle Glass. The monitor and brown bottle glass based cement mortar prisms reached a value close to the reference mortar prism with 100% PC and 0% glass. Delay in the strength gain of glass-based cements can be explained by the fact that there is a low clinker (35%) content in these cements. The pozzolanic reaction of glass, as well as a low w/c ratio helps to offset this trend at the later stages of hardening.

Regarding the colour effect, studies [34,35] where 25% and 30% of cement was replaced by amber, flint and green glass, showed that both green and amber cullet performed better pozollanic behaviour than flint. Green and flint cullet performed better than amber glass and mixes with vitrified fly ash. The compressive strength results show that green cullet especially is undergoing a pozzolanic reaction. The green glass reacted with cement and produced Calcium-Silicate-Hydrates (C-S-H) products while amber cullet seemed inactive. Another factor showing that cullet undergoes pozzolanic reaction is the portlandite content. The content of portlandite in a mix, if a pozzolanic material is present, would be expected to be lower than that in the control mix. As time passes a drop in portlandite is observed at lower cullet replacement levels of (10-20%). All the hydration products were those, which would normally be formed in hydrating Portland cement paste, and all crystalline hydration products were present in the expected quantities. It is obvious that the pozzolanic reaction of the glass has occurred at later ages, thus the presence of glass cullet has no influence on the early hydration reactions of the Portland cement.

However it was found that at higher green glass replacements of cement greater than 30% there is a distinct increase in portlandite in the cement paste [34]. Cullet is rich in sodium and it is likely that these ions will be incorporated in the C-S-H gel formed during hydration. Since the sodium will substitute for calcium, more calcium ions will be available for the formation of portlandite - $(CaOH)_2$.

Regarding the durability related properties of mixes with glass powder as cement replacement, research has shown that glass cullet especially green glass does not exacerbate the expansion of the mortars as expected, due to its pozzolanic properties that hinder any potential for reaction. More detailed, studies of ASR with different colours of glass showed that, green glass gives much lower expansion than amber or clear glass [1,34,35] as expected. Figure 2.6 shows expansion due to alkali-aggregate reaction at 16 days for prisms containing different coloured ground cullet replacing cement by 10-40% by mass.

As shown in Figure 2.6, glass powder replacing 10-40% of cement, at the end of the 14-day test, reduces or even minimises the percentage of expansion due to ASR, as the

percentage of replacement increases. For white cullet the percentage expansion is reduced to 0.125 %, which is slightly higher than the allowable limit of 0.1% according to ASTM 1260, but for amber and green expansion is within the "safe" range at the value of 0.024% and 0.022% respectively, not causing any deleterious expansion but instead showing innocuous behaviour according to ASTM 1260. As expected better pozzolanic behaviour was shown from green cullet in agreement with similar studies.

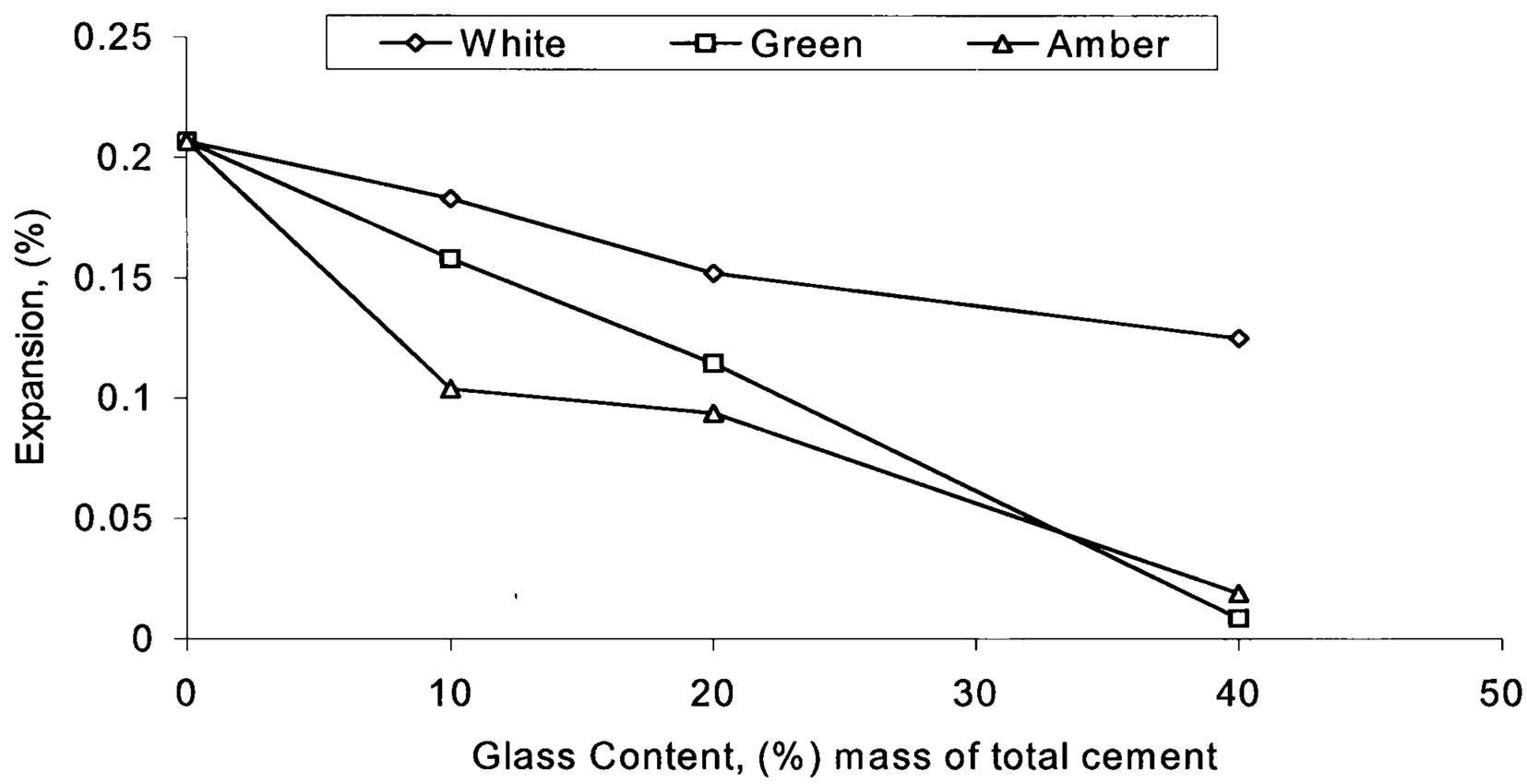

Figure 2.6 Expansion of Different Coloured Cullet [34]

Similar to this study, results of Alkali-Silica expansion tests [35] of specimens with 25% replacement of cement with (green, flint, amber) cullet, and additionally by 25% of 90 μm vitrified fly ash showed that mortar prisms performed shrinkage. Ground cullet had the effect of lessening the expansion. Similarly to another study [33], the expansion of the mortar bar with 30% cement replaced by the 75 and 150 μm glass was within the acceptable limits less than 0.1 %, while the 38 μm glass reduced to half of that in control indicative of a pozzolanic activity [33].

From other studies [19] it was also concluded that both 10% Silica Fume and greater than 30% Glass Powder (GLP) were effective in suppressing ASR expansion when used in sufficient amounts (Figure 2.7). Further, the result indicates that the releasing of alkalis from the finest pulverized glass fraction is retarded. Moreover, when the aggregate in the mix was reactive (high silica), the presence of even 30% GLP did not release sufficient amounts of alkali to trigger the reactivity of the very susceptible aggregate used. The GLP itself did not cause long-term mortar bar expansion or trigger

the expansion of reactive aggregates when present in the specimen. The alkali contained in glass powder is not available to promote ASR in the presence of reactive aggregates. Expansion values were less than 0.1% at 1 year indicative of innocuous behaviour according to ASTM 1260. For less reactive aggregates the expansion would have been completely suppressed. This confirms the beneficial effects of GLP in improving the durability properties of concrete.

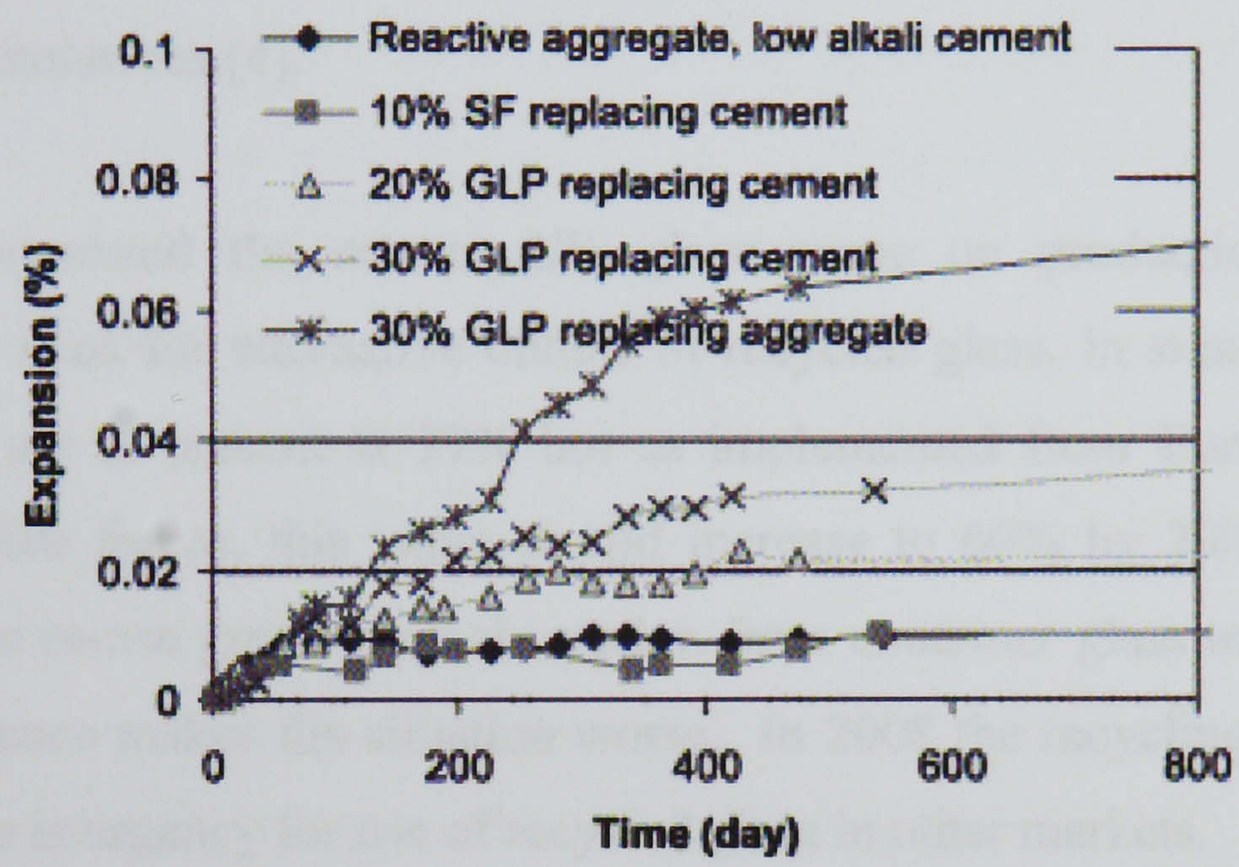

Figure 2.7 Expansion Curves for Mortar Bars Containing Low-Alkali Cement and Reactive Aggregates and 30% GLP Replacing Cement or Fine Aggregates [19].

When various proportions of GLP were also used with non-reactive aggregate in concrete but of raised alkali environment the material itself did not cause deleterious expansion the latter results also confirm that GLP would not cause harmful expansion in concrete. Even when 40% GLP was used, which had the potential to release more alkali than 30% GLP, the GLP effectively suppressed the enormous expansion of the very reactive aggregate in the concrete (80% reduction).

According to another study [37], Scanning Electron Microscopy (SEM) observations on mortar prisms containing 50% glass powder, detected a visible densification around the glass grains, due to partial hydration of glass grains and formation of additional C-S-H. According to the SEM investigation, the main difference between the glass cement pastes and the reference Portland cement is related to the decrease in the size and the amount of Calcium Hydrates (CH), caused by the consumption of CH as a result of pozzolanic reaction involving glass grains.

2.6 Concluding Remarks

A fundamental challenge of sustainable development is to deliver massive improvements in resource efficiency, if projected economic growth rates are not to cause unacceptable levels of environmental degradation. An important element in the UK government's strategy to deliver on this compensation for growth agenda, has been the policy commitments to increase levels of material recycling [38,39]. Recycling helps in the conservation of raw materials, reduces energy use and results in lowering carbon dioxide emissions [4].

This chapter presented the current UK glass scene on production and use and emphasized the need for alternative outlets of recycled glass. In summary, in the UK recycling rates are at present at 37% but as implemented from European Directives through legislative forces, this value should increase to 60% by 2008. However, the limited ability to re-use green glass absorption from container glass manufacturers due to colour imbalance makes the situation worse. In 2008 the recycling rate will almost double and there is urgency for use of recycled glass in other markets.

There are currently many primary and secondary markets, which could absorb a vast quantity of recycled glass such as container glass manufacturing, fiberglass manufacturing, value-added products and as a construction aggregate. Glass has been used a fine and coarse aggregate and as a cement replacement in concrete with some success but there are limitations on its uses unless satisfactory fresh, engineering and durability related properties of concrete are anticipated. In more detail, fine glass as a natural sand substitute is limited to 30% by mass, glass as a coarse aggregate replacement is also limited to 30% by mass, while glass powder as a cement component is limited to 40% by mass. However another form of using surplus glass is foamed glass gravel for insulation and structural applications, which has been used successfully due to its low density, low-cost and excellent thermal and sound insulation properties.

CHAPTER 3

FOAMED GLASS GRAVEL PRODUCTION

3.1 Introduction

This chapter briefly describes the process of Foam Glass Gravel (FGG) production and its potential applications in value–added outlets. The chapter has been divided into two parts; namely conventional techniques for foam gravel production and key factors influencing the characteristics of FGG. A brief overview on the foaming of waste glass, which covers the foaming process, and foamed glass products is outlined in the first part. In the second part, details of FGG as pioneered by a Hungarian company Geofil Ltd. The product they produce, Geofil foamed glass gravel (GFGG) together with the key influencing factors are described.

3.2 Foaming Waste Glass

Typically, foamed glass is produced by mixing finely ground glass (~ 100 μm) with a foaming agent such as calcium sulphate rich gypsum, limestone (calcium carbonate-$CaCO_3$), MnO_2 or Silicon Carbide (SiC) [40]. The mixture is heated to between 700°C and 900°C, and the gas generated creates a structure of cells to form a porous body, typically as shown in Figure 3.1 [41]. In general, expansion of granules starts at around 700ºC with further growth with rise in temperature to 960ºC, thereafter granules gradually collapse and melt.

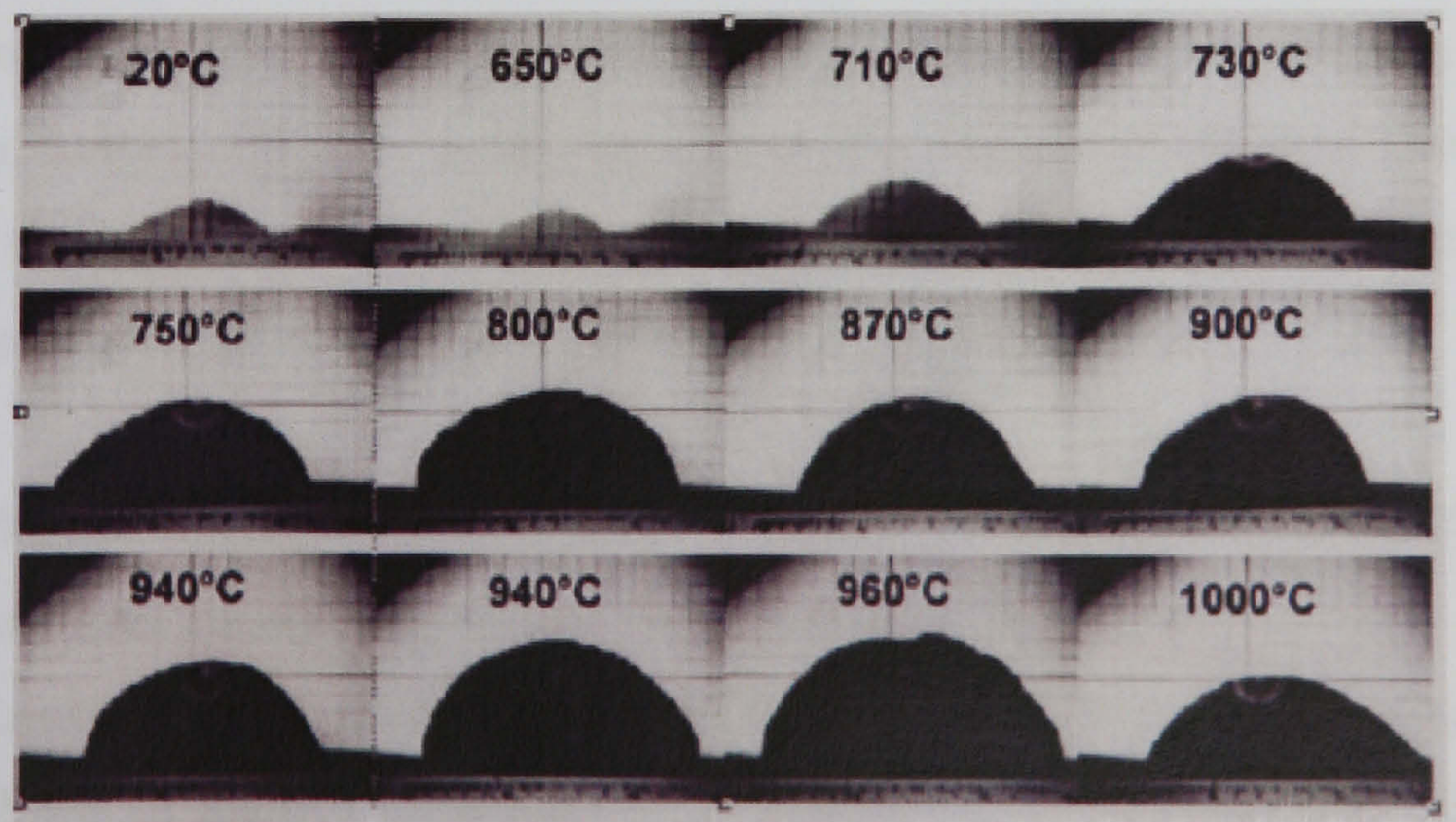

Figure 3.1 Expansion of Foamed Glass Gravel as Temperature Increases [41]

Foamed glass products have been commercially available for many years [40] outside the UK, mainly in North America and Continental Europe. Companies producing foam glass include Pittsburgh Corning based in both the USA and Europe, Misapor AG and Millcell AG in Switzerland, Hasopor in Norway and Germany, Geofil in Hungary, Cell-u-Foam in USA and GOMELSTEKLO in Belarus.

Foamed glass or cellular glass has a number of potential applications in the construction industry. These include loose foam glass aggregate for use in bricks and blocks production, and as a rigid insulation building material. In general, foamed glass products have a low density, moderate structural strength and rigidity, lower water absorption, enhanced fire resistance, and low thermal conductivity [40,42-45,47].

The current market price for such material ranges from £30-65/m^3 for loose foam glass aggregate, to £200/m^3 for pre-shaped insulation products [40]. Relatively high costs of glass foams have constituted a key disadvantage for their diffusion in the building industry [43]. In order to make this product commercially available, in recent years several innovative modifications are implemented to both the processing and raw material sourcing techniques.

Moreover, the traditional method of introducing gases directly into molten glass by blowing, now has been substituted by a sintering approach, which utilises fine glass powders, in which a pyroplastic mass is foamed by the development of gases, formed from the decomposition or oxidation of specific powder additives (the so-called "foaming or expansive agents"). At the same time, use of finely ground surplus glass powders allowed the exploiting of recycled glass as a potential substitution for pristine glass. As a direct result of this, considerable energy saving is reported in a number of cases. This is achieved by reducing temperatures below these required for blowing. Currently, there are three main types of foamed glass products listed below [40]:

- Blocks and other shapes, produced continuously in standard factory moulds, and then cut and shaped into specified dimensions.
- Loose foamed glass aggregates, derived from the continuous production of sheets of foamed glass then being broken into loose foam glass aggregate and

graded. A patented process originating in Switzerland (Misapor) is used widely in Norway under the trade name of Hasopor [46].

- Pelletisation, which is a continuous production of spherical pellets of foamed glass that are then used in the manufacture of blocks, panels and slabs (Figure 3.2). In the case of pellets, the finely ground glass and the foaming agent are formed into spheres and then fed into a rotary furnace, whereby the foaming action takes place to form spheres of foamed glass. As the spheres pass through the furnace they are annealed and cooled.

Figure 3.2 Geofil Foamed Glass Pellet (of maximum size 20 mm) [42]

Figure 3.3 shows cross-sections of granules using the pelletisation process at the pilot production plant. Generally the resulting particles are highly porous with individual pores having diameters from 0.1 to 1 mm.

Figure 3.3 Cross Section of Foamed Glass Granules [41]

The use of waste glass and potential inherent beneficial characteristics and the production of foamed glass can be considered as sustainable practices. Further economic and environmental benefits that can be gained with the use of soda-lime glass and SiC from wastes in such production are reported [43].

3.3 Foaming Process

It is widely recognised that the structure of silicate systems such as glass, when at temperature of 1200°C -1300°C lies in the field of liquids state. In a typical foaming process [47], waste glass material is first powdered in a ball mill and separated by screening into different grain size fractions from 53 to 300 μm. Thereafter, a foaming agent is added (for example, pure silicon carbide 2-5% by mass of particle size 40 μm,) followed by dry mixing prior to placing in stainless steel forms coated on their bases with alumina powder. The mixture is then lightly compacted before heating. In the final stage, by a thermal treatment at 900°C for roughly 30 minutes and 950°C for further 30 minutes (typically heating speed of 10°C per minute) foamed glasses are produced. After foaming samples are annealed at 600°C for 30 minutes and slowly cooled to room temperature.

A recent publication [37] provided a detailed analysis of the foaming process using $CaCO_3$, MnO_2 and water glass foaming agents in the production of lightweight granules from waste glass. The suitability of these foaming agents was assessed using digital analysis and hot stage microscope. For this, granules were prepared by mixing finely ground waste glass with the foaming agent and fired at different temperatures above the glass softening point. Within the temperature range, the foaming agents degas and the resulting gasses remain trapped in the glass structure (temperature range from 730°C to 900°C). Methyl cellulose and kaolin suspension was used during the granulation process to improve handling during drying and firing. Based on the laboratory experiments a pilot production plant was established. The key properties of these granules were established. These included apparent density, water absorption, compressive strength, and alkali silica reaction. Recorded apparent density was found to be between 0.18 and 0.35 Mg/m^3. Water absorption, after the samples kept under water for 30 minutes, was 8 and 11% for granules produced using $CaCO_3$ and MnO_2 respectively.

3.4 Foamed Glass Products

It is reported [47] that the foamed glass is produced using an environmentally friendly recycling technology for contaminated and toxic waste from mercury lamps, industrial slag, fly ash, PC and TV cathode ray tubes and laminated glass to batteries. The main advantage of foamed glass manufacturing from CRT glasses is that useful products can be obtained by viscous flow sintering of the glass, at relatively low temperatures, thus avoiding energy intensive processes. It is now recognised that the probable volatilisation of some noxious substances, like lead oxide (PbO) should be prevented under certain circumstances.

In Norway about 4 million mercury lamps are used every year and the aim is to recycle some 40% amounting to an annual production of some 50,000 m^3 of foamed glass. At present this product has used as a lightweight filling material on about 25 road projects in Norway. Foamed glass is based on the concept of transforming finely ground glass powder from different glass sources (flat or container glass) mixed with an activator like silica carbide into foamed glass. During the grinding process heavy metals are separated out and recycled to metal melting plants; whilst, powder is spread on a steel belt conveyor running through high temperature ovens whereby the powder expands about 4 times, producing a foamed glass material. Thereafter the material is separated into smaller units to control temperature. Normal grain size will be in the range of 10–60 mm. It is claimed that the production process is free of dust and any harmful gases and because of that, it does not need water at any stage. The final material comprises of 8% of glass and 92% gas bubbles by volume. Current research undertaken by the Norwegian Public Road Administration (NPRA) examines the possibility of using Granulated foamed glass (cellular glass) as a lightweight material for road construction applications [46]. This work concludes that such material is believed to be an 'interesting' alternative as lightweight fill material and thermal insulation for a number of civil engineering applications. Other researchers have also indicated that the waste glass can be used as a raw material for the production of lightweight aggregates with a number of inherent properties suitable for construction applications [48].

Recently, the Waste and Resources Action Programme (WRAP) funded a UK market survey into foamed glass [40] and concluded that it is suitable for a number of construction products, e.g loose fill, insulation, blocks and slabs, and has low flammability, thermal

stability, high chemical durability and contains no fibrous material. This survey also revealed that there are well-established markets that foamed glass products should be able to penetrate by between 1% to 5% without disruption to jobs and local economies. However, it is clear that to achieve a 1% penetration into existing traditional UK markets for bricks, blocks and loose aggregates could result in the production of over 2 million tonnes per year of foam glass products. It was also clear that the foamed glass process is ideally suited to consume "contaminated" glass such as lighting, CRT and glass from end of life vehicles.

3.5 Geofil –FGG (GFGG)

Geofil Foamed Glass Gravel (GFGG) was developed and pioneered by a Hungarian Company, Geofil Ltd. It is specifically designed and manufactured to meet the requirements of modern construction products. Essentially, bubbles are a pellet product made from industrial and residential glass waste. The technology utilizes waste glass (flat glass and container glass) as the main feedstock with additions of a clay mineral to assist adhesion and chemical additives to optimize viscosity and to regulate water absorbency. During GFGG production, waste materials of high glass content are finally ground to required specified particle sizes. Thereafter, homogenization is carried out with a blowing agent dosed according to the amount of impurities in the raw materials. The granulation process is carried out by adding melting point reducers and viscosity modifying agents. Granulate is then heat cured and coated to control water absorbing characteristic, followed by firing in a rotary furnace. The resulting product is a light-weight manufactured gravel with a diameter ranging from 2 to 20 mm as shown in Figure 3.4, with an inherent heat and sound insulating properties [42].

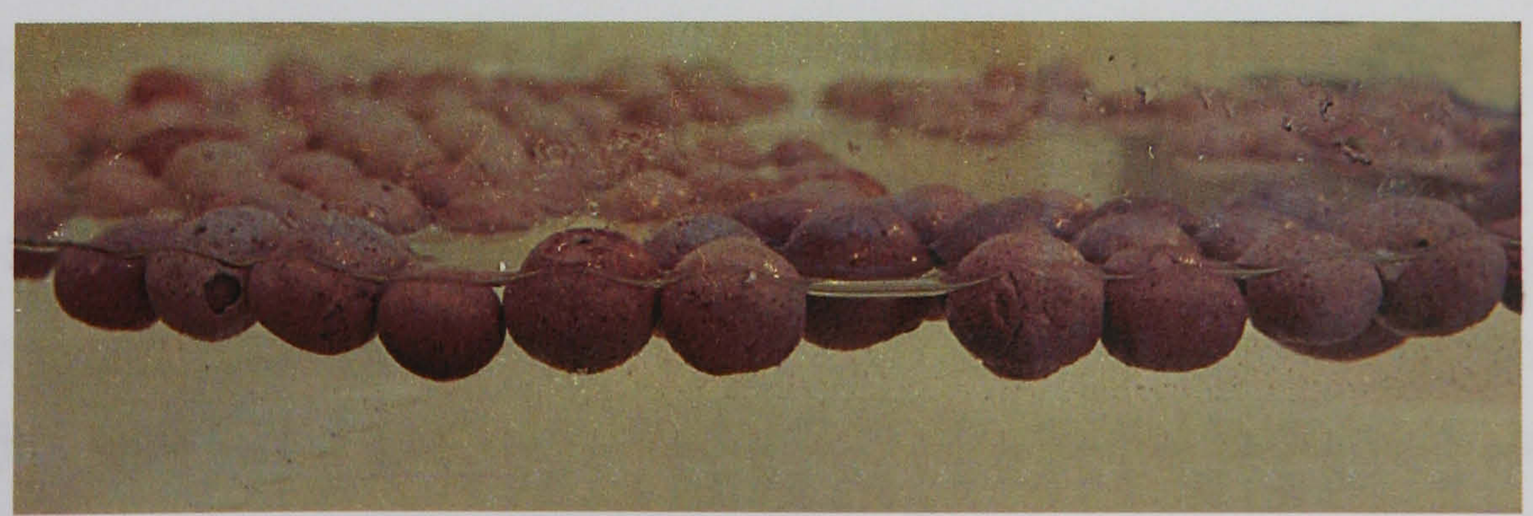

Figure 3.4 Geofil Foamed Glass Gravel -GFGG [42]

It has been reported that the GFGG has good bonding capability if embedded in gypsum, cement, or resin matrix [42]. The reported key properties of GFGG are listed below [42]:

- Particle density (Apparent) = 0.45-1.70 Mg/m^3
- Loose bulk density = 0.25-1.10 Mg/m^3
- Crushing strength (material) = 0.20-14.0 MPa
- Water absorption = 0.40-50 % by mass
- Thermal conductivity = 0.10-0.80 W/mK
- Compressive strength (mortar) = 2.50 – 58.0 MPa
- Sound insulating capacity, RW
  (thickness of element 0.12 m, density 1.100 Mg/m^3) = 42 dB

3.6 Factors Affecting the Production Process

Many studies have successfully used ground waste glass from Bottles, CRT or other silicate industrial wastes, for the production of foamed (cellular) glass [37,41,44,47,49]. In the synthesis of foamed glasses, the elaboration parameters such as reaction time, temperature, percentage mass of reducing agent, glass particle size of starting materials and firing temperature have important effects on the reaction process (i.e. on the reaction between the reducing agent and PbO and thus on density, porosity, etc) and on the physical chemical, mechanical, thermal and electrical properties of the expanded material. Pore distribution is considered to be the most important factor in determining the strength of any foamed glass products. Density, compressive strength and thermal conductivity of foamed glass can be improved by selecting appropriate optimum level of raw materials [42].

The foaming agent plays an important role in the production process. It is now widely accepted that the most important factor in choosing a suitable expansive foaming agent is the temperature range of its decomposition, which should be above the glass softening point but still within the range where the viscosity of the glass is high enough to trap the gas inside the glass [41]. It has been reported that samples with foaming agent of fine particle size distribution expanded nearly 3 times as much as samples with coarser foaming agent and that with higher quantities of additives, more porous structure is obtained. The foaming depends on decomposition or oxidation reactions [47]. The decomposition reactions are due to carbonates and sulphates, while oxidation reactions are determined by the interaction of carbon-containing species mainly within the atmosphere of the sintering

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furnace. Silicon carbide (SiC) represents an excellent foaming agent, owing to a complex oxidation process (capable of a high flexibility), which offers the possibility of accurately controlling the variety of glass foam microstructure, but its high cost generally causes the producers of glass foams to prefer inexpensive carbon. SiC causes the foaming of glass (38-300 μm) by the formation of gas bubbles, due to an oxidation reaction [47].

Generally it is accepted that when CRT waste glass containing lead (Pb) is used as a feedstock for foamed glass, SiC should not be consider as a foaming agent. As foresaid in Chapter 2, the front part of a TV is a barium and strontium-based CRT glass, while the parts hidden inside the TV set are lead-based. Moreover, the usage of glasses containing heavy metal poses difficulties in remelting (noxious PbO may evolve from glass melts). Foaming agents which cause gas evolution by oxidation (SiC and carbon, or organic substances) cannot be allowed since they may interact with the large amount of oxygen dissolved in lead silicate glasses or directly with PbO, thus inhibiting oxidative conditions and resulting in the formation of metallic lead [47]. Additionally, increases in pore diameter may lead to a large reduction in mechanical resistance. The reduction of lead oxide in these glasses increases, by the increase in metallic lead formation in the form of droplets (bubbles) on the pore surface. These drops are formed by coalescence, in a similar way to the pores and reach microscopic sizes (greater than 1 mm). However, the formation of metallic lead as a result of the reduction of lead oxide could be used to achieve the partial de-pollution of glasses containing this heavy element [49].

Another foaming agent that is commonly used during the production process of foamed glass is Calcium Carbonate ($CaCO_3$). In contrast to SiC, $CaCO_3$ was found to be suitable for the treatment of Pb-containing glasses since foaming occurred by thermal decomposition, not oxidation, without any interaction with the glass [47]. Pores of about 100μm, together with smaller one of about 10μm, could be recognized. The cell walls were very thin, with several openings. The decomposition of $CaCO_3$ can usually leave a large amount of gaseous product (CO_2), which may lead to extensive foaming and an open-cell morphology. The fine granulometry of both foaming agent and glass powders, when associated with long-standing mixing, can result in a homogeneous distribution of pores.

Regardless of the foaming agent type ($CaCO_3$, MnO_2 and Water-glass) highly porous structures can only be obtained with uniformly distributed pores having dimension less that

1 mm, with MnO_2 yielding the lowest apparent density [37]. During other research [47] foaming agents such as fly ash (FA) (1-20 μm), glass commercial carbon black powders (GC-CB) with a mean size of 18 μm and thermoplastic polymethyl methacrylate (PMMA) were also tested. The largest compressive strength was found with GC–CB, then GC-PMMA and last with GC-FA due to the presence of large pores. To obtain homogeneous size distribution of pores, the use of a foaming agent that can be dispersed in the form of a solution was recommended, as in the case of GC-PMMA foams.

Furthermore, variations (increase in the parameters- reaction time varied between 30-90 minutes, temperature between 750°C-950°C and the percentages of the reducing agents between 1% and 9% by mass) can lead to increase pore size and the heterogeneity of their distributions in the foam glasses [47,49]. It is reported that increases in the three synthesis parameters strongly affected the microstructures of the foam glasses.

The glass particle size also plays an important role during the production process of foamed glass. When the starting glass particle size is reduced, it yields a progressively lower apparent density of foamed glass. However if the size is reduced beyond 0.1 mm there is no significant difference to the final particle density (apparent) [37].

It has been shown that the homogeneity of cell size distribution increased with increasing similarity between the grain size of the glass powder and that of the foaming agent [47]. Effects of smaller cell dimensions (when decreasing glass powder size) and higher homogeneity when using fine glass powders, may be due to the fact that when glass powders, with a size considerably larger grain size than that of the foaming agent, are mixed with SiC powder, the latter can agglomerate and separate inside the mixture due to the larger voids among individual glass grains, thus resulting in an inhomogeneous distribution. The glass foams produced consist of regular spherical cells separated by struts and cell walls of various thickness, containing voids of different sizes.

According to two studies, the porosity of foamed glass also increases with increase of the firing temperature [41]. It has been also shown that if the aggregates are fired at a lower temperature than 700°C a finely porous structure occurs, whereas firing above 900°C results in a coarse porous structure. When high foaming temperatures are used in the process but keeping the amount of agent and glass powder size constant, samples

possessing an inhomogeneous distribution of the cell sizes as well a the presence of numerous strength-reducing large voids result [47]. What's more, higher density was found to be associated with larger cells and an increase in strength with decreasing cell size.

3.7 Concluding Remarks

This chapter presented the production process for foamed glass. Typically, foam glass is produced by mixing finely ground glass (~100 μm) with a foaming agent such as calcium sulphate rich gypsum, $CaCO_3$, MnO_2 or SiC [40]. The mixture is heated to between 700°C and 900°C, and the gas generated creates a structure of cells to form a porous body. Main products of foam glass are blocks and shapes, loose foam glass aggregates (Hasopor) and pellets (Geofil).

Essentially, bubbles are a pellet product made from industrial and residential glass waste. The technology utilizes waste glass (flat glass and container glass) as the main feedstock with additions of a clay mineral to assist adhesion and chemical additives to optimize viscosity and to regulate water absorbency. In the synthesis of foam glasses, the elaboration parameters such as reaction time, temperature, mass percentage of reducing agent, glass particle size of starting materials and firing temperature have important effects on the reaction process and on the physical, chemical properties and the mechanical behaviour, thermal and electrical properties of the expanded material. In general, foamed glass products have a low particle density, moderate structural strength and rigidity, lower water absorption, enhanced fire resistance, and low thermal conductivity [40,42-45].

Foamed glass or cellular glass, has a number of potential applications in the construction industry. These include loose foamed glass aggregate for use in brick and block production, as a rigid insulation building material and as an aggregate for concrete.

However, relatively high costs of glass foams have constituted a key disadvantage for their diffusion in the building industry [43]. In order to make this product commercially available, in recent years several innovative modifications are been implemented to both the processing and raw material sourcing techniques. For each mixture (glass plus foaming agent) an optical thermal treatment schedule needs to be applied, depending on the glass viscosity and the foaming agent reactions [47].

CHAPTER 4

RESEARCH PROGRAMME AND EXPERIMENTAL DETAILS

4.1 Introduction

This chapter describes the experimental programme designed to establish the suitability of FGG for use in normal strength concrete mixes. In the main, the chapter is divided into two parts; namely the overall research programme and experimental details. A brief overview of the work, comprising different phases, is outlined in the first part. In the second part, the experimental details, including test materials, mix proportions, preparation of test specimens together with the procedures used to compare FGG characteristics and to examine its influence on concrete properties are described.

4.2 Overall Research Programme

The research programme comprises four main phases, as shown in Figure 4.1, and is briefly described below. The main investigation examines the effects of glass source on FGG characteristics and compares its properties with commercially available lightweight manufactured aggregates.

4.3 Experimental Details

4.3.1 Materials

Cement

The manufacture of Cement is ecologically harmful in that the production of 1 tonne of cement results in about 1 tonne of CO_2 discharged into the atmosphere [50]. However, it is the binder between aggregates and water and gives desirable properties to concrete. The cement used for the concrete production was CEM I 42.5N PC (42.5 MPa minimum strength at the age of 28 days). Specification, composition and conformity criteria were in agreement with BS EN 197-1:1992. Storage in airtight containers ensured minimum exposure to humidity. A thin polished section of cement was prepared and through Scanning Electron Microscopy-Energy Dispersive Spectrum X-Ray technique semi-quantitative analysis was carried out as given in Table 4.1 (undertaken at Kingston University).

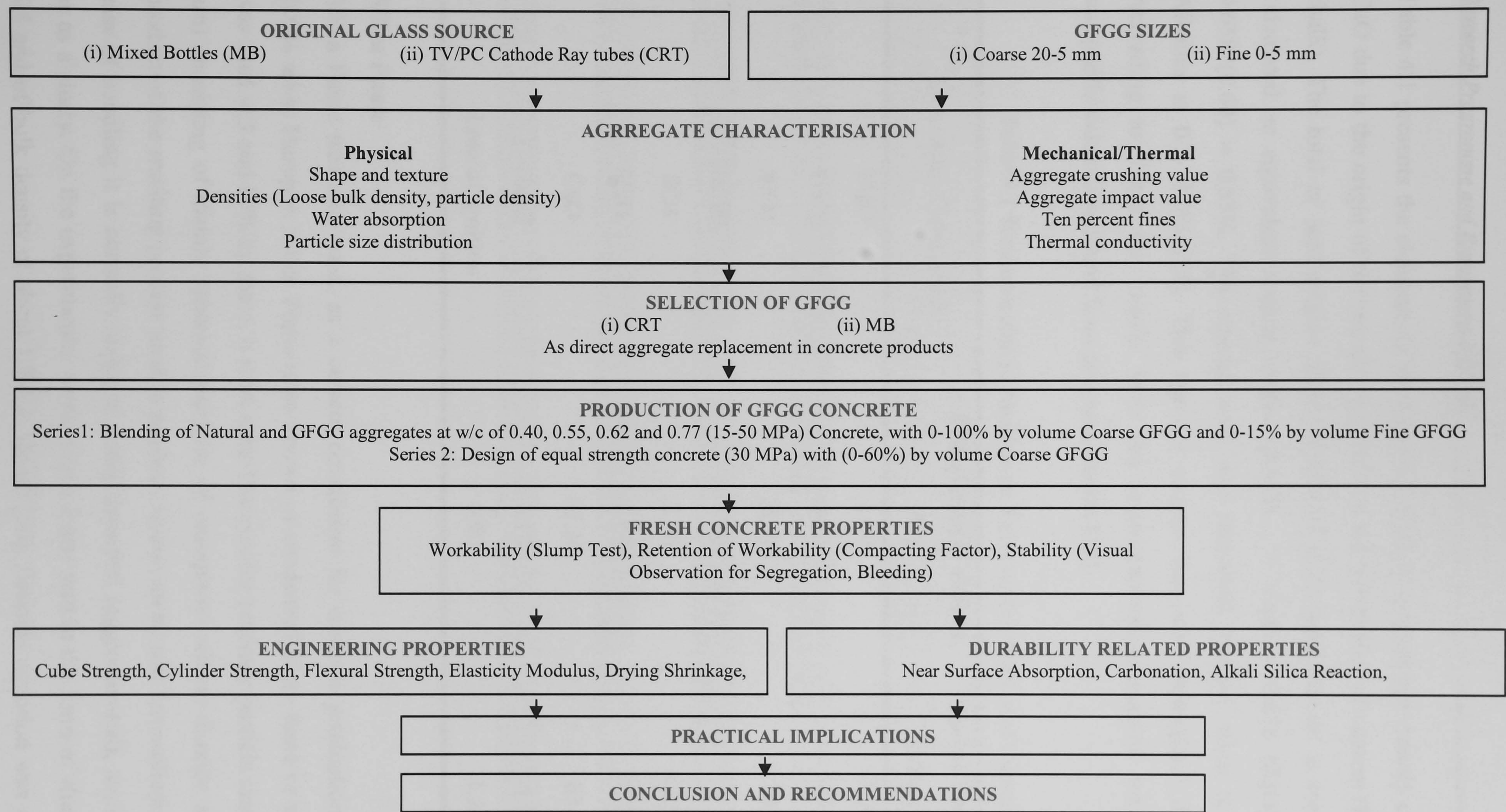


Figure 4.1 Overview of the Research Programme

Table 4.1 presents the elements in the Cement and their percentages mainly consisting of CaO due to the origin of the primary material for the production of cement (limestone or chalk). The total or acid soluble alkali content of a Portland cement is conventionally calculated as equivalent sodium oxide: $(Na_2O)_e = Na_2O + 0.658\ (K_2O) = 0.13 + 0.658*(0.64) = 0.55\%$. The cement used was low-alkali cement, since the range for Alkalies is 0.3- 1.3% [50]. This type of cement was used throughout the research. According to Table 4.1, results from the semi-quantitative analysis are within the acceptable values also found from previous studies [50].

Table 4.1 Semi-quantitative Analysis on Thin Polished Section of Cement

Elemental Compound	Experimental Values (%)	Typical Theoretical Values (%)
MgO	1.00	<5.00
Al_2O_3	4.70	6
SiO_2	21.40	20
Fe_2O_3	2.70	3
SO_3	2.90	<3.5
K_2O	0.64	1
CaO	65.20	63
Na_2O	0.13	1
Loss of ignition	0.90	1.2

Silica Fume

Silica Fume was also used, as a cement constituent for concrete production containing 100% all-in Hasopor. Silica Fume (also known as condensed silica fume or micro silica) was used at 5 and 10% by mass. It is an ultra-fine powder (average particle size less than 1 μm) consisting of mainly spherical particles of amorphous silicon dioxide and is a by-product of the smelting process used to produce silicon metal and ferro-silicon alloys. For ease of handling it is normally supplied either densified (agglomerated), micro-palletised or as a slurry. On the experimental work, Silica Fume was in the form of slurry of pH of 5.5 and of bulk density of about 1.3-1.4 Mg/m^3 [50]. Periodic agitation was necessary to maintain a uniform distribution of the silica fume in the slurry.

Aggregates

Coarse Natural aggregates used throughout the study were Thames Valley gravel (20 mm maximum size) and the fine natural aggregate was dessert sand (5 mm maximum size) conforming to BS EN 12620. The physical, mechanical and chemical characteristics are provided in Chapter 5.

Geofil Foamed Glass Gravel (GFGG) used as aggregate replacement (by volume) in the research and was imported from Hungary, in bags of 1 m^3, containing either fine (less than 5mm) or coarse aggregate (5-20 mm). Waste glass which constituted 80% of the material, was derived from glass based packaging (mixed bottles), or TV/PC cathode ray tubes (CRT). The resulting colour depended on the original glass source. The mixed (in content and colour) and contaminated (with organic and non-organic) glass waste materials were ground to produce appropriate grain measurements, which still contained paper and metal. Then they were homogenized with gas producing waste material and clay mineral assisting adhesion. Using a solution containing chemicals that lower the melting point and optimise the viscosity of the melted material granulated the mixture was gained by this way. For regulating the water absorption capacity of the granulation, an additive with a high and specific surface was applied as the last layer. After drying, the material was heat-treated in a rotating furnace controlled by its turning speed and angle of the slope then it was quickly cooled (quenched) [42].

Another lightweight manufactured FGG material from CRT glass, was used namely Hasopor, which originated from Norway and was also supplied in fine or coarse form to be used as aggregate replacement by volume. This foamed glass was produced using an environmentally friendly recycling technology for contaminated and toxic waste ranging from mercury lamps, industrial slag, fly ash, PC and TV CRTs, laminated glass to batteries. Characterisation of the material is provided in Chapter 5.

Comparison was made with Lytag, which was provided from a local company in size range between 0-12 mm. The basic raw material used in Lytag is pulverised fly ash, the by-product from the generation of electricity at coal burning power stations. The ash was pelletised and sintered at 1250°C to produce hard, spherical granules with an average 40% internal void ratio [51]. Details of the material's characteristics are provided in Chapter 5.

Water

The quality of water plays an important role for concrete. Impurities in water may interfere with the setting of cement, may adversely affect the strength of concrete or cause staining. The type of water as provided by Thames Water and supplied to the Laboratories of Kingston University used for the research procedures, was fit for drinking and conformed to BS EN 1008. Mixing water was assessed and found not to contain undesirable substances or inorganic constituents in excessive proportions.

4.3.2 Concrete Mix Proportions

Natural Aggregate (NA) concrete mixes

Natural aggregates (gravel and sand) were used as coarse and fine aggregates at 100% by volume for the production of normal weight control concrete mixes (0.05 m^3) with 28-day design strengths of 15-50 MPa, at varying water/cement ratios of 0.40-0.77. Mix proportions were calculated based on the BRE mix design method [52]. Table 4.2 presents mix proportions from NA concrete.

Table 4.2 Typical Mix Proportions for Natural Aggregate Concrete

Mix Proportions, kg/m³					
Concrete Strength (MPa)	**PC**	**Free Water**	**Aggregates**		**Water /Cement Ratio (w/c)**
			Coarse	*Fine*	
15	250	180	1220	750	0.77
25	300	180	1280	640	0.62
30	330	180	1250	545	0.55
50	450	180	1220	530	0.40

GFGG mixes

A series of normal weight concrete mixes (0.055 m^3) were prepared with Geofil-FGG aggregate (fine/coarse) in varying percentages by volume as replacement for NA and water/cement ratios, which ranged from (0.40-0.77). Coarse GFGG with size range (5-20 mm) was used as a direct Thames Valley gravel replacement at 30, 40 50 and 60% by volume. Lightweight mixes with 100% GFGG by volume were also cast at w/c of 0.55 and 0.77 for comparison reasons. Fine GFGG was also used as a direct sand replacement at 5, 10 and 15% by volume for the production of normal weight concrete. Coarse and Fine

GFGG from both sources namely TV/PC (CRT) and mixed bottles (MB) were used. Concrete mixes were proportioned following the conventional BRE mix design method [52]. Thereafter GFGG concrete mixes were developed taking into account its bulk density. Concrete mixing, placing and curing was adopted as described later.

Table 4.3 below, gives wet densities of fresh concrete mixes with natural aggregate combined with 100% by volume coarse GFGG at w/c of 0.55-0.77. Table 4.3, shows considerable lower density of concrete produced with 100% GFGG, which according to BS EN 206-1:2000 Table 9, belongs to Density Class (D2,0) since it has density between 1800-2000 kg/m^3. Density reduction of 22-29% for w/c of 0.77, 0.62 and 0.55 compared to normal weight concrete was also observed. Table 4.4 presents mix proportions for equal strength concrete (30 MPa) (Series 2). Table 4.5 presents mix proportions from GFGG concretes having equal water-cement content (Series 1).

Table 4.3 Wet Densities of NA and GFGG Concrete

Concrete Mix	Wet Density, kg/m^3
NA Concrete (w/c 0.40-0.77)	2,400-2,415
GFGG Concrete: 100% coarse GFGG + 100% Natural Sand (w/c= 0.77)	1,850-1,900
GFGG Concrete: 100% coarse GFGG + 100% Natural Sand (w/c =0.62)	1,780-1,800
GFGG Concrete: 100% coarse GFGG + 100% Natural Sand (w/c =0.55)	1,790

Table 4.4 Typical Mix Proportions of GFGG Concrete Mixes of Equal Strength (Series 2)

Mix Proportions, kg/m^3							
GFGG Content, %, by volume	**PC**	**Free Water**	**Aggregate (kg)**				**w/c**
			Natural Aggregates		**GFGG Aggregates**		
			Coarse	*Fine*	*Coarse*	*Fine*	
0	**300**	**180**	**1290**	**610**	**-**	**-**	**0.60**
30	310	180	1175	585	125	-	0.58
40	330	180	1145	560	165	-	0.55
50	375	180	1100	530	195	-	0.48
60	385	180	1075	510	230	-	0.47

Table 4.5 Typical Mix Proportions of GFGG Concrete Mixes (w/c 0.40-0.77) (Series 1)

Mix Proportions, kg/m³													
	Original Glass Source												
GFGG Content, (%), by volume	Cathode Ray Tubes (CRT)						Mixed Bottles (MB)						w/c
	PC	Free Water	Natural Aggregate		GFGG Aggregate		PC	Free Water	Natural Aggregate		GFGG Aggregate		
			Coarse	*Fine*	*Coarse*	*Fine*			*Coarse*	*Fine*	*Coarse*	*Fine*	
a) % coarse													
30	230	180	1313	520	145	0	230	180	1320	520	133	0	**0.77**
40	230	180	1265	520	190	0	230	180	1280	520	173	0	**0.77**
50	230	180	1220	520	230	0	230	180	1243	520	210	0	**0.77**
60	230	180	1190	520	267	0	230	180	1207	520	245	0	**0.77**
100	230	180	0	520	835	0	230	180	0	520	835	0	**0.77**
30	290	180	1180	600	140	0	290	180	1190	600	120	0	**0.62**
40	290	180	1140	600	180	0	290	180	1155	600	160	0	**0.62**
50	-	-	-	-	-	0	290	180	1120	600	190	0	**0.62**
30	-	-	-	-	-	0	330	180	1135	545	120	0	**0.55**
40	-	-	-	-	-	0	330	180	1100	545	160	0	**0.55**
50	-	-	-	-	-	0	330	180	1070	545	190	0	**0.55**
100	-	-	-	-	-	0	330	180	0	360	875	0	**0.55**
40	455	180	805	847	120	0	450	180	1080	530	147	0	**0.40**
50	450	180	1030	530	193	0	450	180	1050	530	172	0	**0.40**
60	450	180	1005	530	212	0	450	180	1015	530	205	0	**0.40**
b) % fine													
5	455	180	1115	525	0	7.5	450	180	1115	523	0	8.5	**0.40**
10	455	180	1115	517	0	15	450	180	1115	515	0	17.5	**0.40**
15	455	180	1115	510	0	21	450	180	1115	505	0	25	**0.40**

Hasopor mixes

This part of the study examined the feasibility of using Hasopor, as lightweight aggregate, in concrete production. Two series of lightweight Hasopor concrete mixes were cast; coarse and all-in Hasopor by volume, to establish its influence on fresh and hardened properties. Total water content (free + supplementary) of the Hasopor mixes was based on the test results of water absorption of Hasopor samples.

Series 1: Trial mixes

As a starting point, a series of 4 different trial mixes (0.01 m^3) were produced using coarse Hasopor and natural sand. Table 4.6 presents the mix proportions for these mixes.

Table 4.6 Mix Proportions of Coarse Hasopor Concrete (Trial Mixes)

Mix Proportions, kg/m³					
Mix	**PC**	**Free Water**	**Aggregate**		**w/c**
			Coarse Hasopor	*Natural Sand*	
1	275	125	900	435	0.45
2	300	165	870	415	0.55
3	325	195	865	390	0.60
4	350	325	860	373	0.92

The density of raw materials, free water content, air content and degree of compaction affects the density of concrete. Based on previous work, it was estimated that a change in free water content of 10 litre/m^3 in the mix, could alter the density by 15 kg/m^3 and an increase in 1% air content could reduce the density by approximately 25 kg/m^3. Given the potential for reduction in density by using Hasopor, the wet density of freshly compacted concrete was determined following the procedure described in the BS standard. Results obtained are tabulated in Table 4.7. In this investigation, free water and cement was kept constant for all mixes and a nominal air content of 1% achieved.

Table 4.7 Wet Densities of Fresh NA and Hasopor Concrete

Mix	Wet Density, kg/m^3
NA Concrete	**2,460**
100% coarse Hasopor + 100% Natural Sand	2,080
100% All-in Hasopor (90%PC, 10% Silica Fume)	2,120-2,130

On comparison with NA concrete, it is quite clear that the density of Hasopor concrete reduced considerably, suggesting a potential application of Hasopor in lightweight concrete. Typically the density of concrete reduced by up to 17% with the use of coarse Hasopor. The relationship between compressive cube strength and water/cement ratio for the trial mixes was established. For this reason, two 100 mm cube specimens were cast and tested at 28 days in accordance with BS 1881: Part 116, after standard 20°C water curing and results are shown in Chapter 6.

Series 2: All in Hasopor

A parallel testing programme was undertaken in Series 2; which used all in Hasopor in 20 and 30 MPa 28–day design strength concrete mixes (0.02m^3). Mix proportions are shown in Table 4.8. For this Hasopor aggregates (coarse and fine) were used as a direct replacement (by volume) to corresponding natural aggregates.

Table 4.8 Mix Proportions for All-In Hasopor Concrete

Mix Proportions, kg/m^3					
28- Day Concrete Strength (MPa)	**PC**	**Free Water**	**Aggregate**		**w/c**
			Coarse	*Fine*	
20	270	180	760	550	0.67
30	330	180	780	475	0.55

To establish the effect of all in Hasopor on the compressive strength of concrete, a series of 100 mm cube samples were cast and cured at 20ºC under water and tested up to ages of 180 days in accordance with BS 1881: Part 116. This test was carried out in two parts; in the first, the effect of Hasopor on 20 and 30 MPa concrete mixes was established; whilst in the second part, based on findings of part one, dry mixed Hasopor concrete bags were prepared for testing with a range of different water contents. Given the low-strength of Hasopor concrete, a means of extending its use as pre-bagged dry mix material for non-structural fill application was required. Using the results of the compressive strength study, mix proportions for 10 MPa strength Hasopor (all-in) concrete were established (Table 4.9). All constituents, except free water, were dry-mixed in quantities sufficient to prepare 24 bags (0.02 m^3) and divided by quartering. The bags were then mixed with a range of free water content (165, 180, 195, 210 kg/m^3) to establish compressive strength and cylinder strengths.

Table 4.9 Mix Proportions for Dry-Mixed (all-in) Hasopor Concrete Bags

Mix Proportions, kg/m^3				
		Aggregates		
Hasopor	**PC**	**Fine Hasopor**	**Coarse Hasopor**	**Free Water**
1st bag	325	425	700	165
2nd bag	325	425	700	180
3rd bag	325	425	700	195
4th bag	325	425	700	210

Finally at the request of Day Group, four mixes (0.048 m^3) with all-in Hasopor but with 5 and 10% Silica Fume as a PC constituent at w/c ratios of 0.50 and 0.55 (Table 4.10) were also produced and then tested to establish key bulk engineering and durability related properties.

Table 4.10 Mix Proportions for All-In Hasopor Concrete with Silica Fume

Mix Proportions, Kg/m³						
Silica Fume (%) by mass	**Silica Fume**	**PC**	**Free Water**	**Aggregate**		**28- Day Concrete Strength (MPa) / w/c**
				Fine	Coarse	
5%	30	310	170	475	780	30 MPa / 0.55
5%	38	345	175	450	770	35 MPa / 0.50
10%	65	290	160	475	780	30 MPa / 0.55
10%	70	325	165	450	770	35 MPa / 0.50

Lytag mixes

This part of the study examined the feasibility of using Lytag as lightweight aggregate in concrete production. A series of lightweight Lytag concrete mixes were manufactured using variable quantities of coarse Lytag to establish its influence of fresh and hardened properties. Total water content (free + water absorbed from aggregates) of the Lytag mixes was based on the 24-h water absorption tests results. Table 4.11 gives typical mix proportions of Lytag concrete. To establish the effect of 100% coarse Lytag on fresh and hardened concrete, a series of tests were carried out. Mixing of concrete and curing of specimens was followed in the same way as for Natural, GFGG and Hasopor (section 4.3.3 below).

Table 4.11 Typical Mix proportion For Concrete With 100 % Lytag

Mix Proportions, kg/m³							
28- Day Concrete Strength (MPa)	**PC**	**Free Water**	**Aggregate**				**w/c**
			Natural		Lytag		
			Coarse	*Fine*	*Coarse*	*Fine*	
15	230	180	0	520	835	0	0.77
25	290	180	0	460	840	0	0.62
30	330	180	0	375	875	0	0.55

Concrete sample testing, to examine varying w/c ratios, was carried out according to 4.3.3, to establish key bulk engineering (compressive cube strength, compressive cylinder strength, flexural strength and stiffness) and durability related properties such as Initial

Surface Absorption and will be shown in Chapter 7 and 8. Table 4.12 gives a comparison between wet densities of NA and Lytag concrete mixes.

Table 4.12 Wet Densities of Fresh NA and Lytag Concrete

Mix	Wet Density, kg/m^3
NA Concrete	**2,400-2,415**
100% coarse Lytag + 100% Natural Sand	1,520-1,900

According to Table 4.12, the wet density of concrete with 100% coarse Lytag is lower when compared to the control mixes (NA) by 22-37%. It is also observed that the higher the water/cement ratio, the lower is concrete density since less amount of cement was used.

4.3.3 Preparation of Test Specimens

Mixing and casting procedure

Before casting concrete, steel moulds were prepared according to BS EN 12390-1:2001, using lubricant oil on their surfaces so as to avoid cement paste adhering to it and for the specimen de-moulding to be easy. Depending on the type of test, different moulds were prepared prior to mixing. Table 4.13 shows the types of moulds used for individual tests. Concrete mixing took place according to BS 1881-125:1986. Materials were stored in laboratory conditions at 20°C and 65% Relative Humidity and then mixed in the Win Get Crocker type concrete mixer (50 litres capacity). After correct mixing of concrete, fresh properties were tested and then concrete casting followed. Steel moulds were filled with concrete in three equal layers being properly compacted according to BS EN 12350: 2001 Part 1 and 2 and then covered with polythene sheets for 24 hours until de-moulding.

Table 4.13 Specimens Prepared For Concrete Testing During Each Mix

Test Description	Size (mm)	Total Number of Specimens
• Compressive cube strength	(100x100x100) / (150x150x150)	14 / 4
• Compressive cylinder strength	(150 diameterx300 depth)	3
• Modulus of elasticity (E)	(150 diameterx300depth)	1
• Flexural strength	(100x100x500)	1
• Drying Shrinkage	(75x75x300)	3
• ISAT	(150x150x150)	4
• ASR	(40x40x160)	3

Curing

During the laboratory work, at the end of each mixing, specimens were cast in steel moulds and left in air at 20°C and 65% Relative Humidity for 24 hours. Concrete specimens were then de-moulded and transferred to curing regimes when one of the following methods was adopted.

1. CU1: 20°C water, 95% Relative Humidity environment (water curing) [50]. Water curing was followed for NA, GFGG, Hasopor and Lytag concrete mixes at w/c of 0.4-0.77.
2. CU2: 20°C water 65% Relative Humidity environment (air curing) [50]. For mixes with w/c of 0.77 half cubes were air cured.
3. CU3: 20°C water, 95% Relative Humidity environment (water curing) for 28 days and then under 20°C water 65% Relative Humidity environment (air curing) for 14 days.

Test procedures

Aggregates are not truly inert, and their physical, thermal and sometimes chemical properties influence the performance of concrete. Economy is not the only reason for using aggregates as possible as possible, but also to achieve volume stability and better durability than hydrated cement paste alone [50].

For physical, mechanical and chemical properties of aggregates used in the research, aggregates were taken from sources and after proper selection, representative samples were collected, prepared and tested according procedures described in BS EN 13055:Lightweight aggregates-Part 1 Lightweight aggregates for concrete, mortar and grout: 2002. Table 4.14 lists various tests undertaken and corresponding British Standards, to establish aggregate characteristics (physical and mechanical). Chemical composition enabling comparison of aggregates was determined using Scanning Electron Microscopy (SEM), with analysis of backscattered electron images (BSI) on thin polished sections of coarse and fine aggregates to provide a qualitative (elemental) analysis. Secondary electron images (SEI) on fresh fractured surfaces to examine the morphology of the material and energy dispersive spectrum (EDS) X-Ray of SEI to provide the quantitative analysis of the elements present on the material (similar to "chemical mapping" technique) were also undertaken.

Table 4.14 Physical and Mechanical Tests and the Respective Standards

Properties/ Tests	British Standards
Physical	
• Loose bulk density, percentage of voids	BS EN 1097-3:1998
• Particle density (Apparent, on saturated and surface dried basis, oven dried basis)	BS EN 1097-6:2000
• Water absorption	BS EN 1097-6:2000
• Particle size distribution	BS 933-1:1997, BS 932-1, BS 932-2
Mechanical	
• Aggregate crushing value	BS 812-110:1990
• Aggregate impact value	BS 812-112:1990
• Ten percent fines	BS 812 -111:1990

Particle shape and texture

The shape and the surface texture assessment of the aggregate were carried out by visual examination under BS 812. It was important to examine the shape and texture since they can affect the properties of concrete in both fresh and hardened state.

Loose bulk density

Bulk density was calculated for all aggregates since when aggregates are to be batched by volume it is necessary to know the mass of aggregate that would fill a container of unit volume. This value (bulk density) was used to convert quantities by mass to quantities by volume. Bulk density is affected by the particle size distribution but also greatly by the shape of the particles. If particles are of the same size will be packed to a limited extent, but if smaller are present will fill the smaller voids thus increasing the bulk density of the packed material. What's more, if the aggregate contains surface water, it will pack less densely owing to the bulking effect.

Sample preparation for this test was carried out in accordance with the BS EN 933; Part 2 and sample testing was undertaken as per BS EN 1097: Part 3. The minimum mass required for each test was determined as those specified in Table 1 of BS EN 1097: Part 3. In total, three test samples from each material were dried until constant mass was achieved, tested and the mean value of bulk density was recorded. Void space ratio among the solid

particles was also calculated to examine the packing capacity. The loose bulk density (p_b) was calculated for each test specimen according to:

$$p_b = (m_2 - m_1)/V$$

Where:

p_b = the loose bulk density, in Mg/m^3

m_2= the mass of the container filled with aggregate, in kg

m_1 = the mass of the empty container, in kg

V=the capacity of the container, in litres

The percentage of voids (v) was calculated according to:

$$v = (p_{rd} - p_b) / p_p \times 100$$

Where:

v = the percentage of voids

p_b= the loose bulk density, in Mg/m^3

p_{rd} = the particle density in oven dried basis, in Mg/m^3

Particle density and water absorption

Preparation of the test samples was undertaken in accordance with BS EN 932: Part 2. The minimum mass required for each test was determined as those specified in Table 2 of BS EN 1097: Part 6 (Figure 4.2). During these tests particle density-apparent (p_a), particle density-on an oven dried OVD-basis (p_{rd}) and particle density-on a saturated and surface dried SSD-basis (p_{ssd}) were calculated for fine and coarse materials according to:

$$p_a = M_4 / [M_4 - (M_2 - M_3)]$$

$$p_{rd} = M_4 / [M_1 - (M_2 - M_3)]$$

$$p_{ssd} = M_1 / [M_1 - (M_2 - M_3)]$$

$$\text{24 hour Water absorption } W_{24} = [(M_1 - M_4)/ M_4] \times 100$$

Where:

M_1= The saturated surface dry mass of the aggregate where no visible water is present on it's surface, in gr

M_2= The mass of the container with the saturated aggregates, in gr

M_3= The mass of the empty container, in gr

M_4= The oven dried mass of the aggregate, in gr

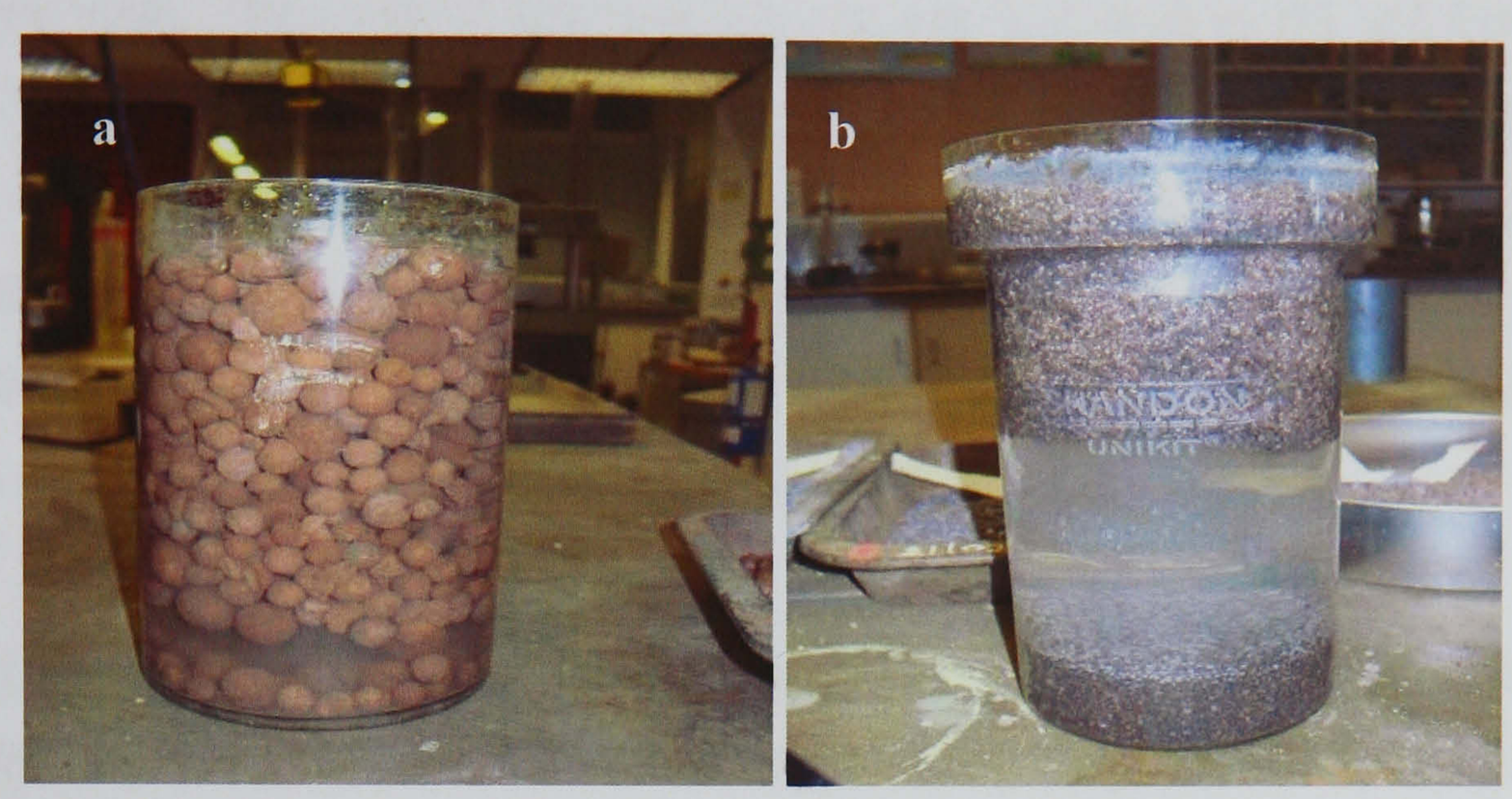


Figure 4.2 Samples for a) coarse and b) fine GFGG For Particle Density and Water Absorption Tests

Calculations with reference to concrete (during the BRE mix design stage) were generally based on the saturated and surface dry condition of the aggregate because the water contained in all the pores of the aggregate does not take part in the chemical reactions of cement and can therefore be considered as part of the aggregate.

Particle size distribution

Purpose of this test was to determine the grading of fine and coarse aggregates (NA, GFGG, Hasopor and Lytag) and based on the findings to establish their suitability for use in concrete production. Test samples were prepared using the riffle box method. Sampling of the aggregate was in accordance with BS EN 932: Part 1 and reduction was in accordance with BS EN 932: Part 2. For aggregates with particle density (apparent) less than 2.00 Mg/m^3, (as GGFG and Hasopor), an appropriate correction was applied to the test portion masses based on the density ratio. This was essentially to produce a test portion of approximately the same volume as those for aggregates of normal density. Grading was an operation of dividing a sample of aggregate into fractions, each consisting of particles of the same size. Particle size distribution was determined as described in EN 933: Part 1: 1997 by Calculation of the cumulative percentage of the original dry mass passing each sieve down to the 63μm sieve exclusive.

Aggregate Crushing Value, Aggregate Impact Value -Ten percent fines

Determination of Aggregate Crushing Value (ACV) was important since it gives a relative measure of resistance of aggregate to pulverisation (crushing under gradually applied compressive load). The method followed was the one indicated in BS 812:Part 110 from which ACV was determined. The lower the ACV was, the stronger the material. Similar procedure was followed for the determination of AIV according to BS 812:Part 112 to calculate the material's toughness. In order to find the load in kN so as to produce 10% fines (TFV) a procedure as the one indicated from BS 812:Part 111 was followed and the higher the numerical result denoted a higher strength of the aggregate.

BS 882 gives limits for AIV and TFV of aggregates of 25% and 150 kN when used in concrete for heavy floors, 30% and 100 kN for wearing surfaces and 45% and 50 kN for other concretes respectively [50]. Results are shown in Chapter 5 where characterisation is presented.

Thermal conductivity

Thermal conductivity of GFGG was found from published data [42]. Thermal testing of Hasopor aggregate was only carried out. Tests were carried out in accordance with the method described in BS EN 12664:2001. The granular product was placed loose into 305x305x67 mm wooden frames set between the hot and cold plates. One side of the frame was flexible so that on applying vertical pressure on the overfilled specimens, the gravel was able to expand laterally ensuring even contact with the measuring plates. Tests were undertaken at a mean temperature of approximately 10°C. The material was first dried in a ventilated oven at 105°C (± 5°C) and then allowed to cool. A representative sample was then prepared from the dried material for testing. The tested material was a greyish granular material ranging in diameter from approximate 1 to 30 mm. Results obtained are given in Chapter 5, where Hasopor Characterisation is presented.

Concrete properties

Regarding the Fresh properties of concrete, after thoroughly mixing the ingredients, workability of mixes was measured using the slump test, the retention of workability using the compacting factor test and stability through visual observation. Table 4.15 presents the properties tested and the corresponding standards.

Table 4.15 Fresh Property Tests on Concrete

Property	Test	British Standard	w/c
Workability	Compacting Factor and slump	BS 1881-103:1993	0.40
Consistency	Slump	BS 1881-102:1993	0.40-0.77
Stability	Tamping and visual observation	ASTM C223	0.40-0.77

Fresh properties of Natural, GFGG, Hasopor and Lytag concretes were determined immediately the mixing of concrete ended. Loss of workability using the compacting factor test measurements was determined at 30 minute intervals up to 120 minutes after mixing, following alternate mixing and standing for 5 minute periods to simulate transportation and handling conditions in practice, at 15 and 60 minutes after mixing. When mixes were dry, and the material tended to stick in one or both of the hoppers and it was eased through gently by poking with a steel rod. The number of strokes was recorded.

Workability was determined after mixing with the slump test. Additionally the any effect due to GFGG such as water demand was reported. At the end of these tests, concrete was replaced into the mixer and mixed for a further minute before casting into steel moulds. Stability of mixes was checked by visual observation of how mixes segregated while compacting/vibrating the concrete. Further, at the end of slump test, the stability and cohesiveness of the concrete was also examined through tamping the concrete slump cone to check the number of strokes before collapse. What's more, bleeding was checked after casting concrete into steel moulds to see whether any water rose to the top surface.

In order to study the engineering properties of Hardened concrete, a number of tests were carried out. Table 4.16 indicates the range of engineering tests undertaken for compressive cube and cylinder strength, Modulus of elasticity, flexural strength and drying shrinkage.

Drying shrinkage strain was measured on 75x75x300 mm prisms from mixes with a w/c of 0.55 having coarse GFGG at 30-50% replacement levels. Specimens were exposed to 20°C and a 55% relative humidity environment 24 hours after casting for 8 weeks. The shrinkage occurring under these conditions is about the same as that after a long exposure to air with a relative humidity of approximately 65%. The magnitude of shrinkage was determined using a measuring frame fitted with a dial gauge reading to 10^{-5} strain. Measurements were taken three times per week for the first 3 weeks, twice for week 3-5

and then once for weeks 6-8. The average of three prisms was recorded as the value for that day. Results are shown in Chapter 7.

Table 4.16 Concrete Engineering Properties Tested

Property	Standards	w/c	Test Age (Days)
• Cube strength	BS EN 12390-3: 2000 , BS EN 206-1:2000	0.40, 0.55, 0.62, 0.77	3,7,14,28,60,180,365
• Cylinder strength	BS EN 12390- 3: 2000, BS EN 206-1:2000	0.40, 0.55, 0.62, 0.77	28
• Modulus of elasticity (E)	BS EN: 12390-3:2000	0.40, 0.55, 0.62, 0.77	28
• Flexural strength	BS EN: 12390-5:2000	0.40, 0.55, 0.62, 0.77	28
• Drying Shrinkage	BS 1881:Part 5:1970	0.55	Up to 56

Regarding the Durability related properties of concrete tests undertaken, are presented in Table 4.17.

Table 4.17 Concrete Durability Properties Tested

Property	Standards	w/c
Initial Surface Absorption	BS: 1881-Part: 208	0.40, 0.55, 0.62, 0.77
Alkali Silica Reaction	ASTM 1260	0.40, 0.55, 0.62, 0.77
Carbonation	-	0.62, 0.77

In order to examine the absorption characteristics of the outer zone of hardened concrete, Initial Surface Absorption tests (ISAT) were carried out. Two cubes (150mm) were cast from each mix and cured for both 28 and 60 days. Prior to testing, after extraction from the curing room, cubes were dried to a constant mass and then left to room temperature for 24 hours. Drying the cement paste would increase the permeability because shrinkage could rupture some of the gel between the capillaries and thus open new passages to water. Measurements of flow through concrete were taken at 10, 30 and 60 minutes from the start of the test. For each cube, two opposite faces were examined so from 2 cubes from each mix, 4 readings were obtained. These readings were examined and the highest and the lowest were chosen for 10, 30 and 60 minutes respectively to be plotted on a graph of ISA versus Time. The slope of the graph gave the Rate of Decay or "n" value. Results for near surface absorption testing are discussed in detail in Chapter 8.

Alkali-Silica Reaction was established using the accelerated mortar bar test [53]. FGG from both sources (Mixed bottles MB and TV/PC CRT glass) replaced natural sand at 30, 50 and 100% by mass, in concrete-from which prisms were cast. Because of the nature of

the lightweight aggregates it was necessary to take into account the water absorption of FGG to ensure good workability of the cement mortar especially around the inserts but still keeping the w/c at 0.47 by slightly changing the aggregate/cement ratio from 2.0 to 2.25. Three prisms 40x40x160 mm were cast from each GFGG mix. Control specimens were cast with 100% natural sand to check if the highly silica sand was reactive, and if this worsens the situation when used in combination with GFGG.

One day (24 hours) after casting, specimens were de-moulded and the DATUM reading was taken before positioning in tap water at 80°C to achieve their reference length. Twenty-four hours later, ZERO reading was taken for each prism and then were positioned in a conventional oven in a container filled with a 1 N NAOH solution for 14-days. Solution was prepared by dissolving 40 gr of Sodium Hydroxide in 900 ml of distilled water and then adding 100 ml of tap water to reach 1 litre of solution. The total required solution was four times the volume of prisms. According to ASTM 1260 three readings were required to be taken during the 14-day period and it was decided to be taken at day 5, 9 and 14. The value for each day of measurement was the average of the three prisms and reported as mean percentage of expansion for the specific day. Results from ASR testing are given in Chapter 8.

Carbonation testing was carried out on 100 mm cubes with 30, 40, 50, 60 and 100 % GFGG by volume at water/cement ratios of 0.77 and 0.62. The specimens used were water cured under CU1 condition, later left at room temperature for two weeks and then waxed over all sides except one. Concrete was exposed to an enriched environment CU3 condition (3.5-4.0% CO_2 concentration at 20±2°C and 55% Relative Humidity (RH)). This enriched CO_2 environment was required due to the fact that exposure to a normal environment with 0.003% CO_2 concentration would not result in reasonable penetration and any effect due to GFGG would not be visible in the short term. Exposure to CO_2 was for 2, 4, 8, 12 and 20 weeks, after which the specimens were split in the middle by inducing a tensile fracture and the CO_2 depth of penetration was assessed by means of spraying the specimen with phenolphthalein indicator solution.

The carbonation depth, indicated by the colourless zone, was measured at 7 locations along the fractured face and the mean value was recorded as the depth of carbonation. Two specimens (both fractured sides) were tested for each mix. The maximum exposure period

within the chamber was 20 weeks, thought to be equivalent to a 20-year period of exposure under normal atmospheric conditions. Results from carbonation testing are shown in Chapter 8.

4.4 Concluding Remarks

This chapter described the experimental programme designed to establish the suitability of FGG for use in normal strength concrete mixes. A brief overview of the work, comprising different phases, was outlined in the first part, followed by the experimental details, including test materials, mix proportions, preparation of test specimens together with the procedures used to compare FGG characteristics and to examine its influence on concrete properties.

CHAPTER 5

FGG CHARACTERISATION

5.1 Introduction

In this chapter, physical mechanical and chemical properties of Natural, GFGG, Hasopor and Lytag aggregates are provided. A series of tests were carried out to examine various aggregate physical properties including loose bulk density, particle density, 24h water-absorption and particle size distribution. Mechanical properties were determined through aggregate crushing value, impact value and ten percent fines. Microscopy study was undertaken to establish chemical composition of materials used. In essence, it examined the elements and the microstructure of the materials.

5.2 Natural Aggregate

5.2.1 Physical and mechanical properties

Visual observation according to BS 812, showed that natural coarse aggregate –Thames Valley gravel was found to be irregular in it's shape and smooth in its texture, similar to previous experimental observations [50]. This type of aggregate is favourable since rounded aggregates tend to decrease the percentage of voids within the concrete, and subsequently its density. Natural Fine Aggregate-natural sand, was found to have round to irregular and smooth grains, favourable because it implies no demand for water in order to achieve a given workability of concrete. Table 5.2 presents physical and mechanical properties of natural aggregates. A greater detailed discussion will be made in comparison with GFGG, Hasopor and Lytag in the following sections.

5.2.2 Chemical properties

Elemental compounds (qualitative analysis) for gravel was provided from mineralogical tests (X-Ray Diffraction) [54]. Results from the XRD characterisation of natural coarse aggregate showed that gravel, had a clear predominance of Silica Oxide (SiO_2), identifying the material as chert. Through SEM-EDS-X Ray, a semi-quantitative analysis on thin polished section of sand was carried out as presented in Table 5.1. According to the results from the analysis of Table 5.1, natural sand mainly consisted of Silica Oxide (SiO_2) (95%)

and Calcium Oxide (CaO) (2.62%). Results are in agreement with the XRD characterisation of the same type of fine aggregate carried out from other researchers [54].

Table 5.1 Semi-quantitative Analysis on Thin Polished Section of Natural Sand.

Elemental Compound	Percentage (%)
MgO	0.035
Al_2O_3	0.495
SiO_2	94.440
SO_3	0.127
K_2O	0.100
CaO	2.620
TiO_2	0.055
FeO	0.542

5.3 Geofil-Foamed Glass Gravel (GFGG)

5.3.1 Physical and mechanical properties

The particle shape and surface texture of GGFG were visually examined. Shape of the aggregate affects flexural and compressive concrete strength by 31 and 22% respectively [50]. Usually undesirable aggregates are flaky and elongated since they are oriented in one plane, with bleeding water and air voids forming underneath. GFGG was found to be a lightweight aggregate and fragile and could be broken by hand. As shown from Figure 5.1, fine and coarse GGFG was found to be spherical in shape and equidimensional to Thames Valley natural gravel and sand.

Figure 5.1 (a) Fine GFGG, (b) Coarse GFGG (*GFGG glass source: Mixed Bottles and CRT*)

Surface texture depends on the hardness, grain size and pore characteristics of the material and affects flexural and compressive strength of concrete by 26 and 44% according to published results [50]. Desirable aggregates are those with rough surface since will create high adhesive forces with the cement paste and will increase concrete strength. Few pores were visible with naked eye. A rough and porous surface of GFGG will have the potential to develop high adhesive forces with the Interfacial Zone, which results in a better bond between cement paste and aggregate due to mechanical interlocking, as shown in previous researches [50]. Table 5.2 presents the results from these tests, which are similar to published data from Geofil Limited [42].

Table 5.2 Physical and Mechanical Properties of Natural Aggregates (NA) and (GFGG)

Property	**Aggregates**					
	Original Glass Source GFGG				**NA**	
	Mixed Bottles (MB)		**TV / PC CRT**			
	Fine	*Coarse*	*Fine*	*Coarse*	*Fine*	*Coarse*
Physical						
Loose bulk density (Mg/m^3)	0.45-0.65	0.45-0.50	0.45-0.50	0.55-0.60	**1.70**	**1.50**
Particle density (Apparent) (Mg/m^3)	0.90-1.00	0.95-1.00	0.95-1.05	0.98-1.10	**2.70**	**2.60**
Particle density (Saturated and surface dried) **SSD** (Mg/m^3)	0.80-1.00	0.90-1.00	0.95-1.00	0.95-1.25	**2.65**	**2.55**
Particle density (Oven dried) **OVD** (Mg/m^3)	0.90-1.10	1.00-1.05	0.95-1.05	1.00-1.30	**2.60**	**2.50**
Percentage voids, %	37.75-46.60	45.95-48.50	50.20-52.00	43.20-54.15	**37.00**	**42.30**
Water absorption (%) by mass	5.00-6.50	3.60-3.85	5.35-6.50	2.25-3.90	**0.80-1.00**	**1.00-1.40**
Mechanical						
Aggregate crushing value % (ACV)	-	71.00 -71.50	-	65.00-80.00	-	**13.00**
Aggregate impact value % (AIV)	-	64.00-66.50	-	57.00-60.00	-	**7.50**
Ten percent fines (10%) (KN)	-	23.00-23.50	-	23.00-24.00	-	**155.00**

According to Table 5.2, NA is normal weight aggregate according to BS EN 206-1:2000 since particle density (OVD) is between 0.2-0.3 Mg/m^3, while GFGG is characterised as lightweight aggregate since particle density (OVD) is less than 0.2 Mg/m^3. Its loose bulk density is lower than the bulk density of natural aggregate by 60-65%. Both coarse aggregates (NA and GFGG), have similar voids ratio around 43-48%, meaning the voids between the particles is similar. This implies that at the same volume, GFGG shows looser particle packing which is affected from aggregate grading. As a result slightly higher percentage of voids is present between fine or coarse GFGG compared to NA.

However, the lower packing capacity of GFGG (lower bulk density) may not be a barrier for lightweight concrete structures since will result in load bearing elements of smaller cross sections and corresponding reduction in the size of foundations [15]. What's more lightweight concrete can be used on soils with lower load-bearing capacity, and the total mass of concrete to be handled at site will be reduced with an increase in productivity [15]. The same trend is observed in apparent, saturated and surface dried and oven dried particle density of GFGG, which is 40-50% lower than that of natural aggregate. This reduction in density is due to the presence of pores on the surface and interior of GFGG as will be shown later.

The 24-hour water absorption, for fine and coarse GFGG aggregates is ranging between 2.5%-6.0% by mass of dry aggregate which shows good aggregate quality since for structural applications, aggregate's water absorption should be lower than 15% [5]. Water absorption of GFGG is by 3.5-5 times higher than that of natural aggregate (Thames Valley gravel and natural sand) which is in line with previous studies [37,40-42,47,50]. This feature, the ability to absorb large quantities of water is found in lightweight aggregates and is absent in normal weight aggregate. Again the inevitably higher tendency for absorbency is attributed to the higher connected-porosity of GFGG compared to natural aggregate. The 24-hour water absorption is critical when mix proportions for concrete are calculated. When aggregate is batched in dry state water added in the mix should be free water for cement hydration plus the water for aggregates. Another consequence of the absorption of water from GFGG is that when hydration of cement lowers the relative humidity in the capillary pores in the hardened cement paste, the water in the lightweight aggregate migrates outwards into these capillaries and enhances hydration [50].

Regarding the water absorption and its correlation with particle density (apparent), results are shown graphically in Figure 5.2. Figure 5.2 indicates, as expected, that an increase in apparent density causes a decrease in water absorption for fine or coarse GFGG.

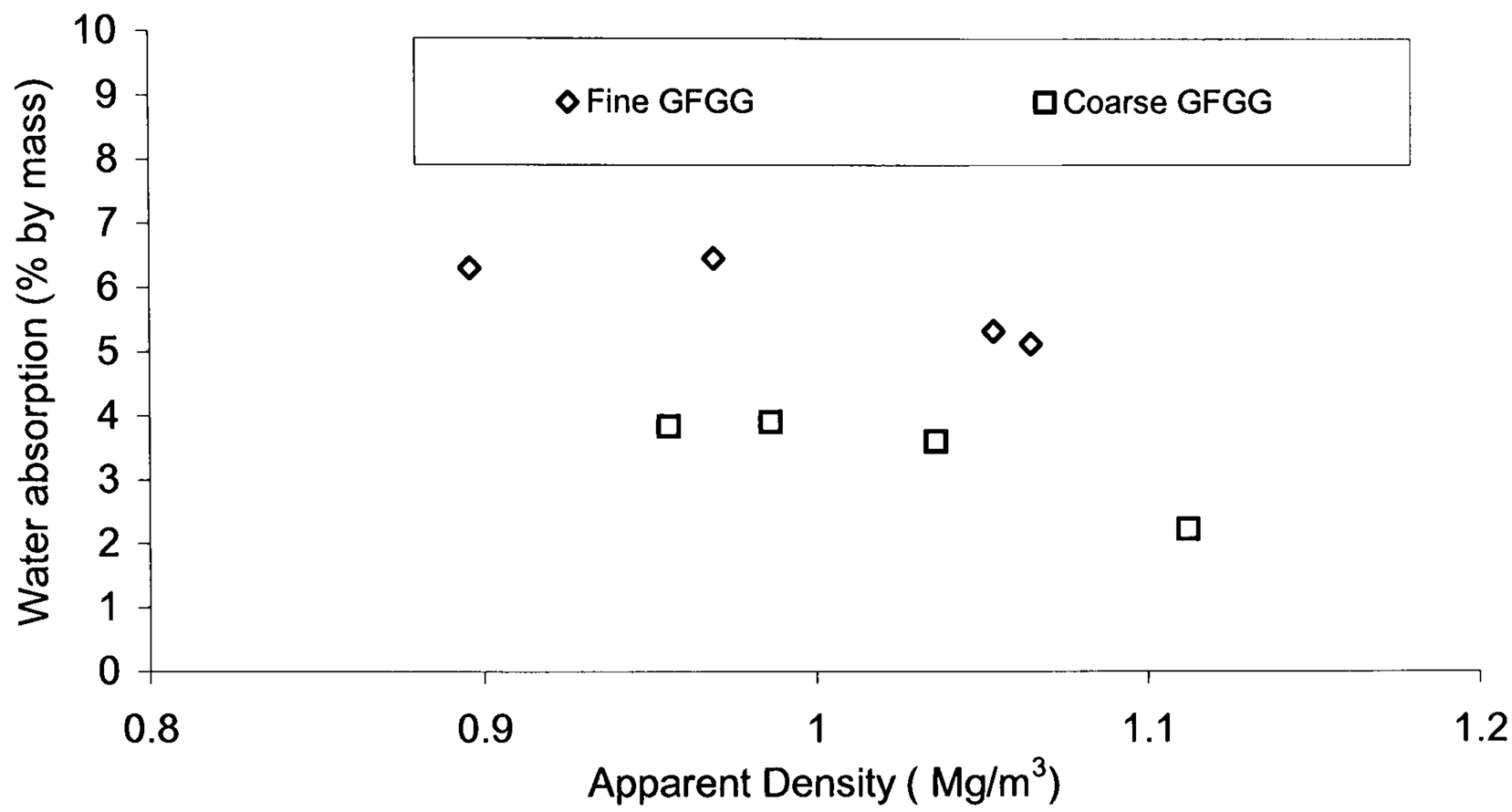


Figure 5.2 Correlation between Water-Absorption and Apparent Density for Fine and Coarse GFGG; (*GFGG glass source: Mixed Bottles and CRT*)

Comparing the strength properties of GFGG with NA it is obvious the superior performance of NA over GFGG. According to a study of lightweight aggregates in concrete [68], weaker particles require stronger mortars and thus more cement. There is a difference in the fracture path between normal weight aggregate (NWA)-Thames Valley gravel and lightweight aggregate-GFGG. In the case of LWA the fracture path travels through the aggregate, while in the case of NWA the fracture path travels around the aggregate, so the cracking load (its crushing resistance) will be higher. Aggregate crushing and impact value of GFGG was found six to eight times lower than that of NA while ten percent fines were almost one sixth of NA.

A good average value of Crushing resistance of an aggregate is around 200 MPa as stated in published study of aggregates [50] while that for GFGG was around 0.2-14 MPa according to manufacturer's results [46]. Strength resistance results are similar to those of other LWA made from expanded clay (such as Leca and Liapor), fly ash (Lytag) or natural sources (pumice), with values of 1.8-10.3 MPa [68]. Results show that NA is applicable "for heavy-duty concrete floors" since AIV is less than 25% and TFV is greater than 150 KN, while GFGG can be used "for other concrete applications" as specified according to BS 882. However, there is no simple relation between strength results and the upper limit

of concrete strength with the given aggregates according to BS EN 13055-1:1997. The results from crushing strength should be used only for internal production control [68].

The influence of aggregate on the strength of concrete is qualitatively the same whatever the mix proportions and it's possible that the influence of the aggregate on concrete strength is due not only to the mechanical strength but to a considerable degree to it's absorption and bond characteristics [50]. It is anticipated that GFGG with its rough surface will create good bond with the surrounding cement paste and will compensate for its low mechanical strength. Indeed, when crushed specimens of normal strength concrete were observed, concrete contained some aggregate particles broken right through showing good bond.

Aggregate of moderate to low strength as GFGG, can be valuable in preserving the integrity of concrete. Volume changes of concrete, arising from hygral or thermal causes, lead to a lower stress in the hydrated cement paste when aggregate is compressible. Thus compressibility of aggregate would reduce distress in concrete while a strong and rigid aggregate might lead to cracking of the surrounding cement paste [50].

Regarding the thermal conductivity of GFGG, published data from the manufacturer of GFGG shows thermal conductivity of 0.098-0.80 W/mK [42], which for lightweight aggregate is satisfactory [50].

5.3.2 Chemical properties

In order to obtain a view of the cross-section of GFGG, Scanning Electron Microscopy (SEM) was used. Through Backscattered Electron Images (BSI) on thin polished sections of coarse and fine GFGG, images as shown in Figures 5.3 and 5.4 were produced. Figures 5.3 and 5.4 show a difference in the cross sectional morphology between fine and coarse GFGG. BSI for Fine GFGG (Figure 5.3) shows that the interface is dense, compact with little-connected porosity, while BSI (Figure 5.4) for coarse GFGG shows the greater porosity, presence of "connecting windows " and its concentric circles from the core to the outer rim. Black areas are cavities, holes in the grain covered with epoxy resin during sample preparation.

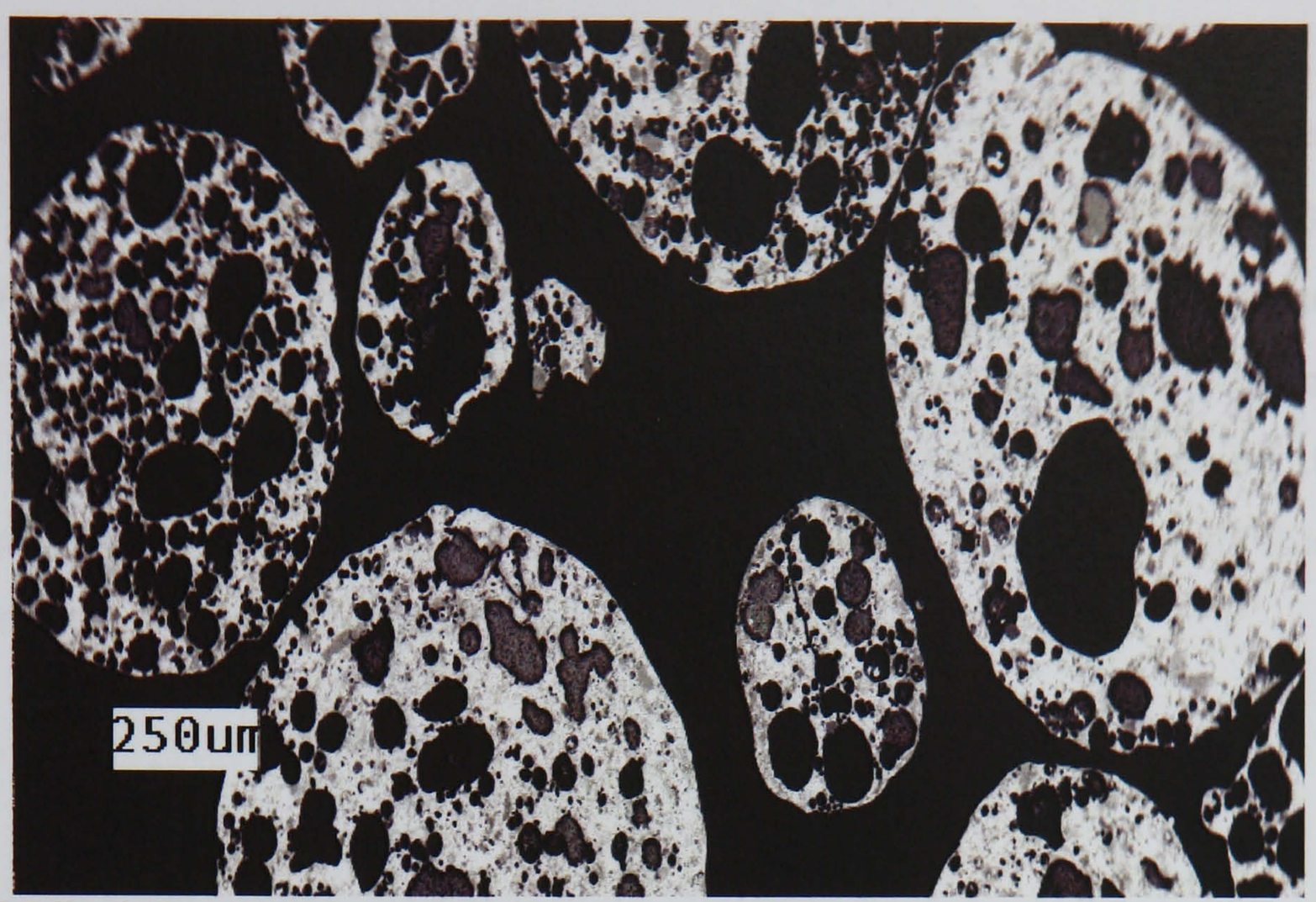


Figure 5.3 Back Scattered Images (BSI) of Fine GFGG (*GFGG glass source: Mixed Bottles*)

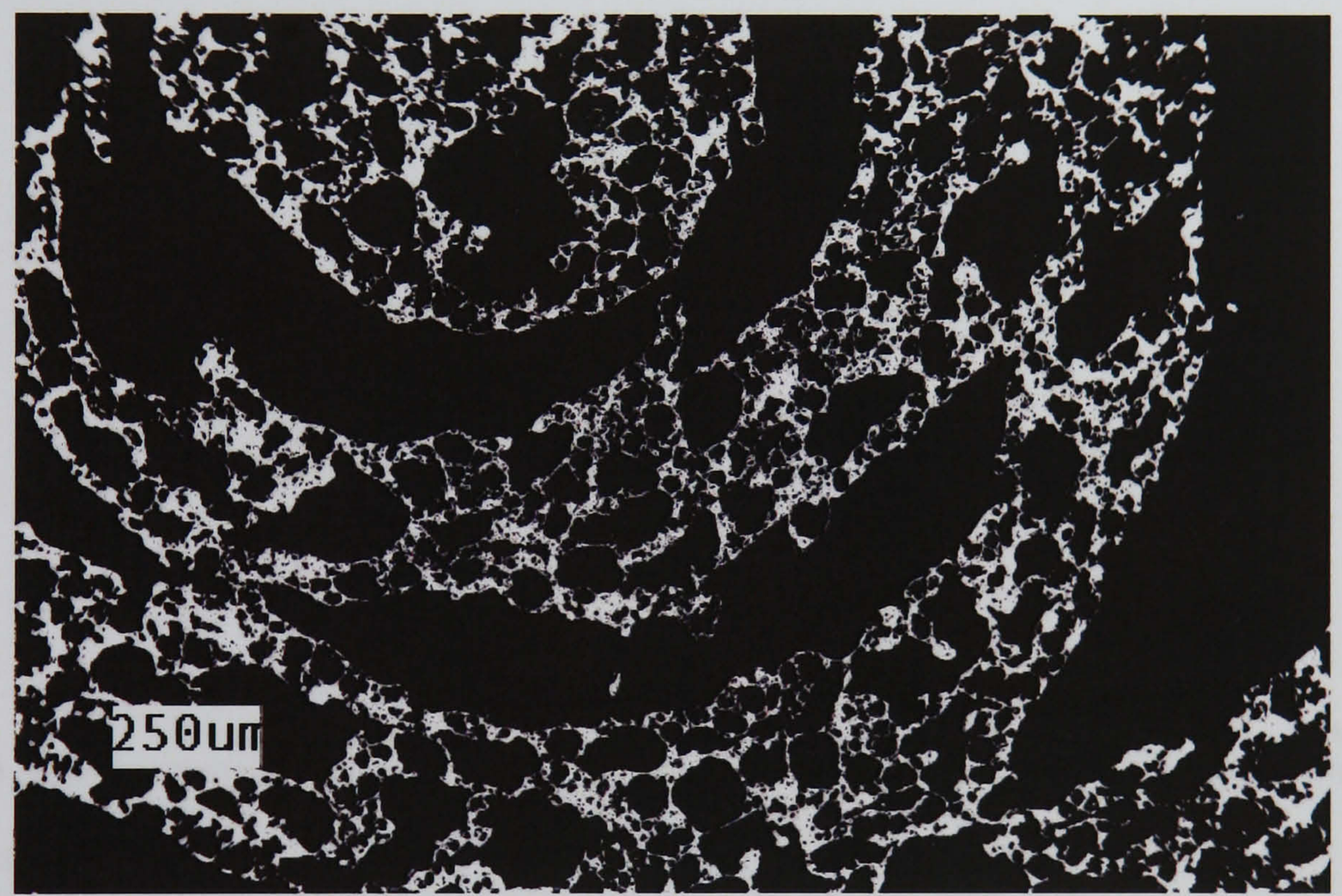


Figure 5.4 Back Scattered Images (BSI) of Coarse GFGG *(GFGG glass source: Mixed Bottles*)

Energy Dispersive Spectrum (EDS) X-Ray of Secondary Electron Image (SEI) on fresh fractured surface of GFGG provided a qualitative (Elemental) analysis as presented in Figure 5.5, while chemical mapping as shown in Figure 5.6, provided the quantitative analysis of the elements present on the material. Images show and support the experimental findings for high porosity of fine and coarse GFGG in comparison to natural aggregate.

Figure 5.5 presents the elements on the surface of a typical GFGG with the aid of EDS X-Ray spectrum on fresh fractured surface of GFGG. Analysis on the surface of several fine or coarse GFGG, showed the presence of mainly Silica (due to glass-source) and other

elements such as Na, Ca while Al, Mn and Fe at smaller percentages. Results were very similar and in agreement with chemical mapping on GFGG from mixed bottle glass (Figure 5.6). Chemical mapping provided a quantitative analysis of the elements present in the core and rim of GFGG. The values were the average for the five places in the outer rim and the average of three places in the core. According to Figure 5.6, the majority of element as expected are Silicon accounting for almost 70% with the rest being 10-12% Na, 10% Ca and 1-3% K. There is no major difference in the % of the elements from the core towards the outer rim, showing uniformity in distribution.

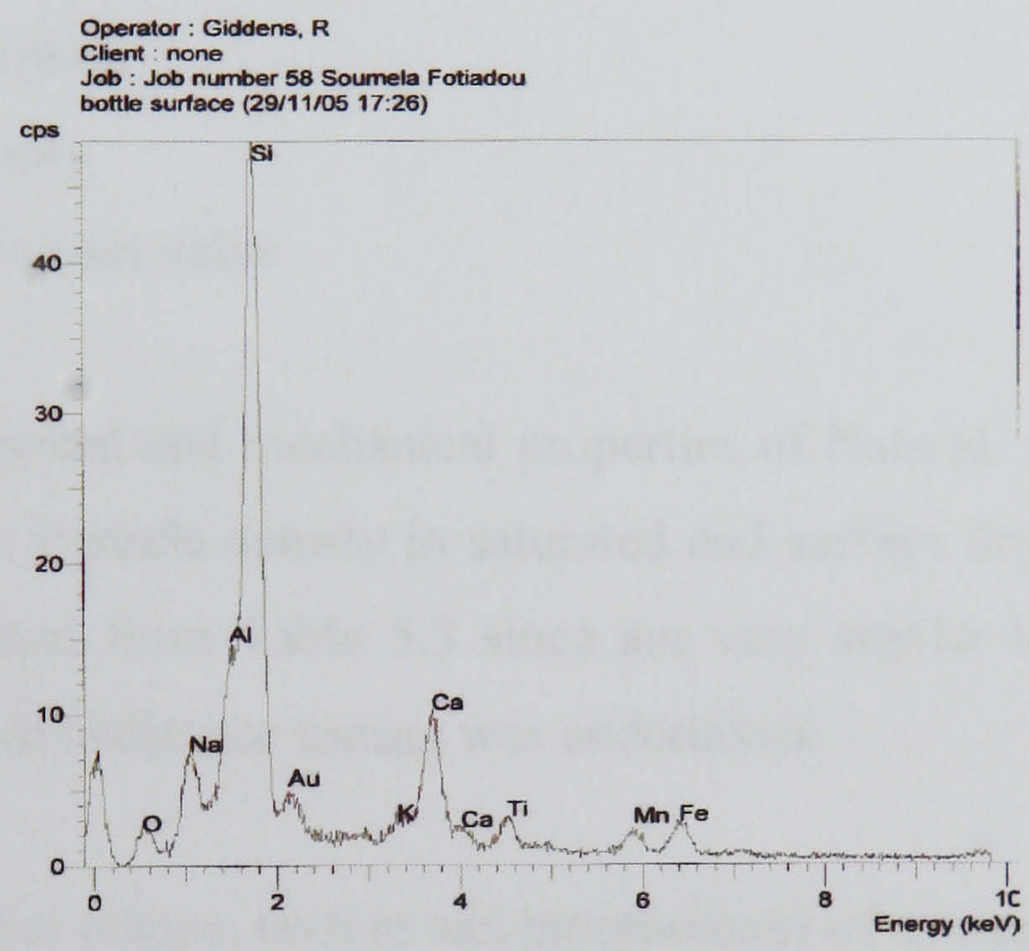


Figure 5.5 EDS Qualitative Analysis on Fresh Fractured GFGG Surface; (GFGG glass source: Mixed Bottles)

Results are similar regardless of Glass Source (TV/PC CRT or Mixed Bottles) or aggregate size (fine or coarse).

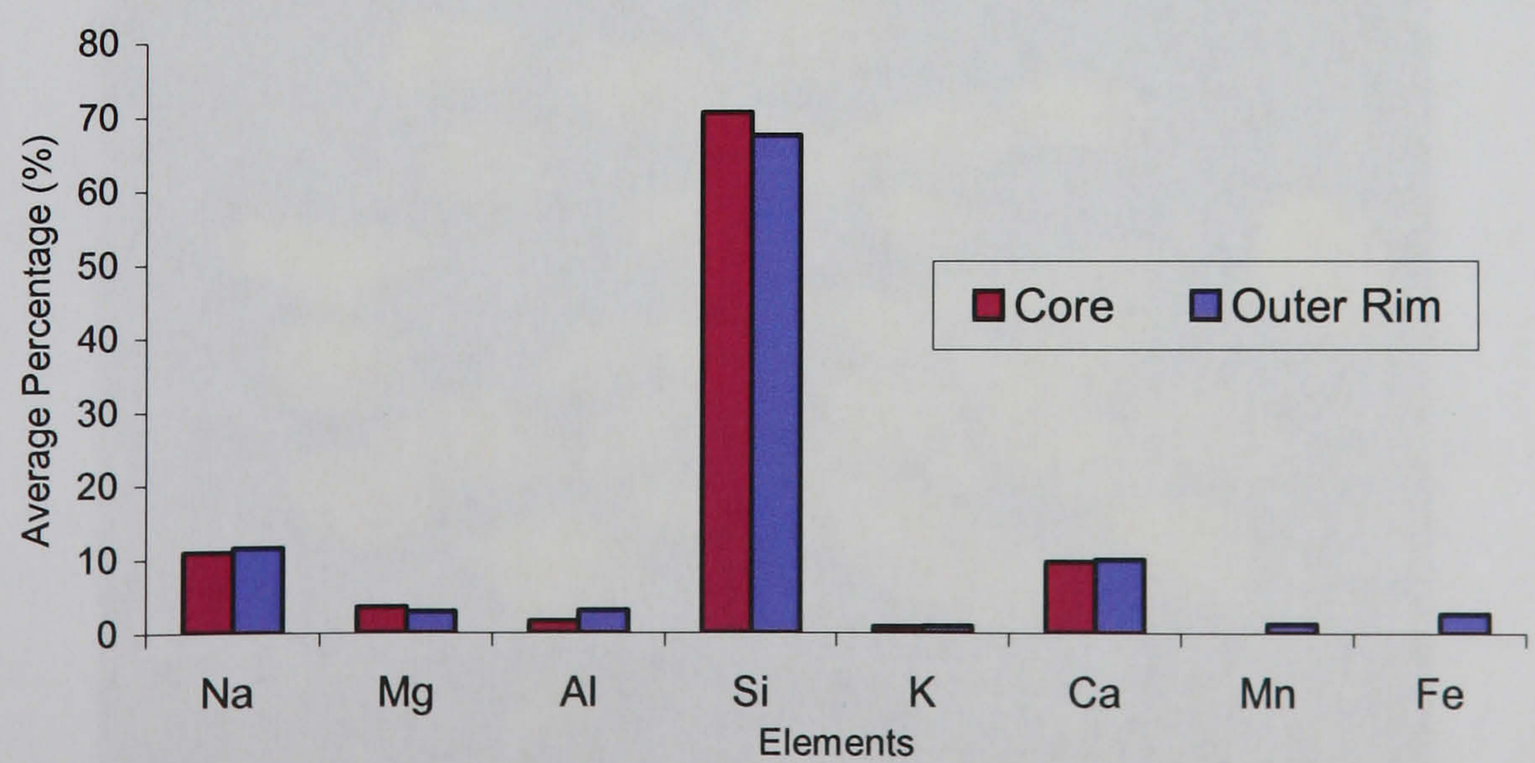


Figure 5.6 Quantitative Analysis of Elements in the Core and the Outer Rim of Foamed Glass Gravel; *(GFGG glass source: Mixed Bottles)*

5.4 Hasopor Aggregate

5.4.1 Physical and mechanical properties

A series of tests o assess key physical, mechanical and microscopy characteristics of Hasopor were undertaken. Hasopor material was characterised, for comparison purposes, as being lightweight manufactured aggregate from CRT glass. Number of tests included:

- Shape and texture
- Particle size distribution
- Loose bulk density
- Water absorption
- Particle density
- Aggregate impact value

Comparison of the physical and mechanical properties of Natural, GFGG and Hasopor is presented in Table 5.3. Particle density in saturated and surface dry basis as well as oven dried density are omitted from Table 5.3 since are very similar to apparent density. In parallel to these, thermal resistance testing was undertaken.

The visual characteristics (shape, texture and morphology) of coarse Hasopor are shown in Figure 5.7. During the visual observation of the material, it was noticed the fragile nature of it since it could be easily broken by hand. From Figure 5.7, it is clear that coarse Hasopor, similar to fine, are irregular, highly porous aggregates, with rough texture.

Figure 5.7 Coarse Hasopor in Size Fraction of (5-20) mm

Pores were visible with naked eye on its surface to a higher extent than those on GFGG. It is expected that the rough surface of Hasopor will improve the mechanical interlocking of aggregate and cement paste and will create a strong bond, increasing the concrete strength.

A series of physical and mechanical tests were carried out for Hasopor. Comparison of Physical and Mechanical properties of Natural, GFGG and Hasopor aggregate is provided in Table 5.3.

Table 5.3 Physical and Mechanical Properties of Aggregates

Properties	Aggregates		
	Natural	GFGG	Hasopor
Physical			
Loose bulk density (Mg/m³)	1.50-1.70	0.45 -0.60	**0.40**
Particle density (Apparent) (Mg/m³)	2.60-2.70	0.95 -1.10	**0.55**
Water absorption (%) by mass	0.80-1.40	2.25 - 6.50	**27.00-33.50**
Percentage Voids (%)	42.30	46.00- 47.00	**28.00**
Mechanical			
Aggregate crushing value (ACV) (%)	13.00	65.00 –79.00	**NA**
Aggregate impact value (AIV) (%)	7.50	57.00 - 66.55	**70.00**
Ten percent fines (10%) (KN)	155.00	23.00- 24.00	NA

According to Table 5.3, Hasopor has lower bulk and particle density (apparent) by 20-40% compared to GFGG, while compared to natural aggregates is lighter by 75%. This low density is attributed to the presence of pores, which constitute 92% of the material according to published results [46] and is shown later through SEM images (Figures 5.8 and 5.9). However, the percentage of voids present among the solid particles of Hasopor was found to be lower than GFGG and Natural aggregate due to the irregular shape of the material which contributes to closer packing.

Water absorption of Hasopor is more than 15% so can not be considered as good quality aggregate for structural concrete .It has higher water absorption than that of GFGG by 5-12 times and when compared to natural aggregate by 25 times. Again the higher tendency for water absorption is due to the greater connected porosity (honeycombed) that characterises Hasopor. A reason for its higher water absorption is the presence of these pores, since

surface texture, influences the water demand of the mix, especially for fine aggregates [50].

Regarding strength properties of Hasopor, according to Table 5.3, it presents slightly lower strength than GFGG. A reason for Hasopor "weakness" is the higher porosity of the material compared to GFGG. Also from published data [42], crushing resistance of GFGG was found to be between 1.20-3.00 MPa while that of Hasopor was one third of it, between 0.85-1.05 MPa [46] confirming the results of this research. In agreement with a published data [40], a comparison among foamed glass products (Geofil-FGG, Hasopor, Misapor) concluded that GFGG perform better as far as it concerns strength such as compression and flexure. GFGG also had perfect dimensional stability, was none-combustible and had no emission of fumes showing its superior performance.

Samples of Hasopor were sent to UKAS accredited facility for thermal properties testing. Results are given in Table 5.4.

Table 5.4 Thermal Conductivity of Hasopor

Mean Temperature at Test	Mean Bulk Density at Test, kg/m^3	Thermal Resistance, m^{2}K/W (thickness of element 67 mm)	Apparent Thermal Conductivity-dry, W/mK
10.1°C	318.2	0.744	**0.0913**

According to Table 5.4 thermal conductivity of Hasopor was found to be satisfactory and comparable to other lightweight aggregate's conductivity [14] and slightly lower than that of GFGG, where according to manufacturer's published data [42] GFGG Apparent Thermal conductivity was 0.098-0.80 W/mK. However, it shows it can be an efficient mean of thermal insulation.

5.4.2 Chemical properties

Secondary Electron Microscopy (SEM) was also used for the examination of the porosity within the material matrix and to examine the interfacial characteristics of Hasopor. Figures 5.8 and 5.9 show Secondary Electron Images (SEI) of fresh fractured surfaces of

Hasopor. Figures 5.8 and 5.9 show images from SEM. Figure 5.8 shows high porosity of Hasopor, characterised by concavities and depressions. The distribution of pores seems to be uniform across the material. However this pore size distribution seems different than that of GFGG. Hasopor seems more porous with less compact phases around its surface as fine GFGG. Hasopor is characterised as honeycombed structure and not as a matrix of concentric circles as coarse GFGG. Image in Figure 5.9 shows higher magnification of the sample characterised by connected holes, concavities and depressions in higher percentage as that found in GFGG. What's more, EDS X-Ray elemental analysis showed that the main elements are Si, Na, Ca and Mg, similar to GFGG with original glass source from TV/PC CRT glass.

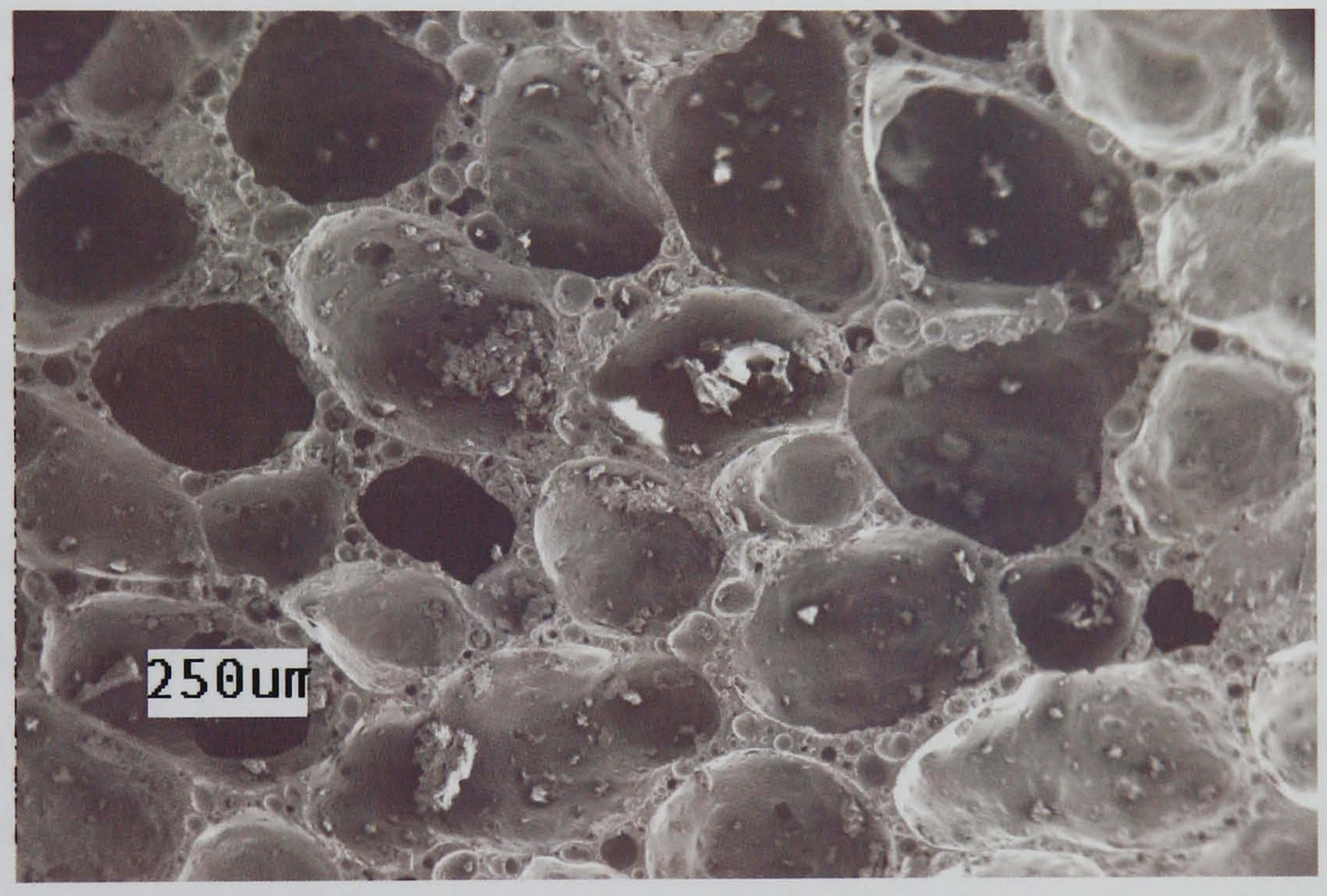


Figure 5.8 Secondary Electron Image (SEI) of Hasopor

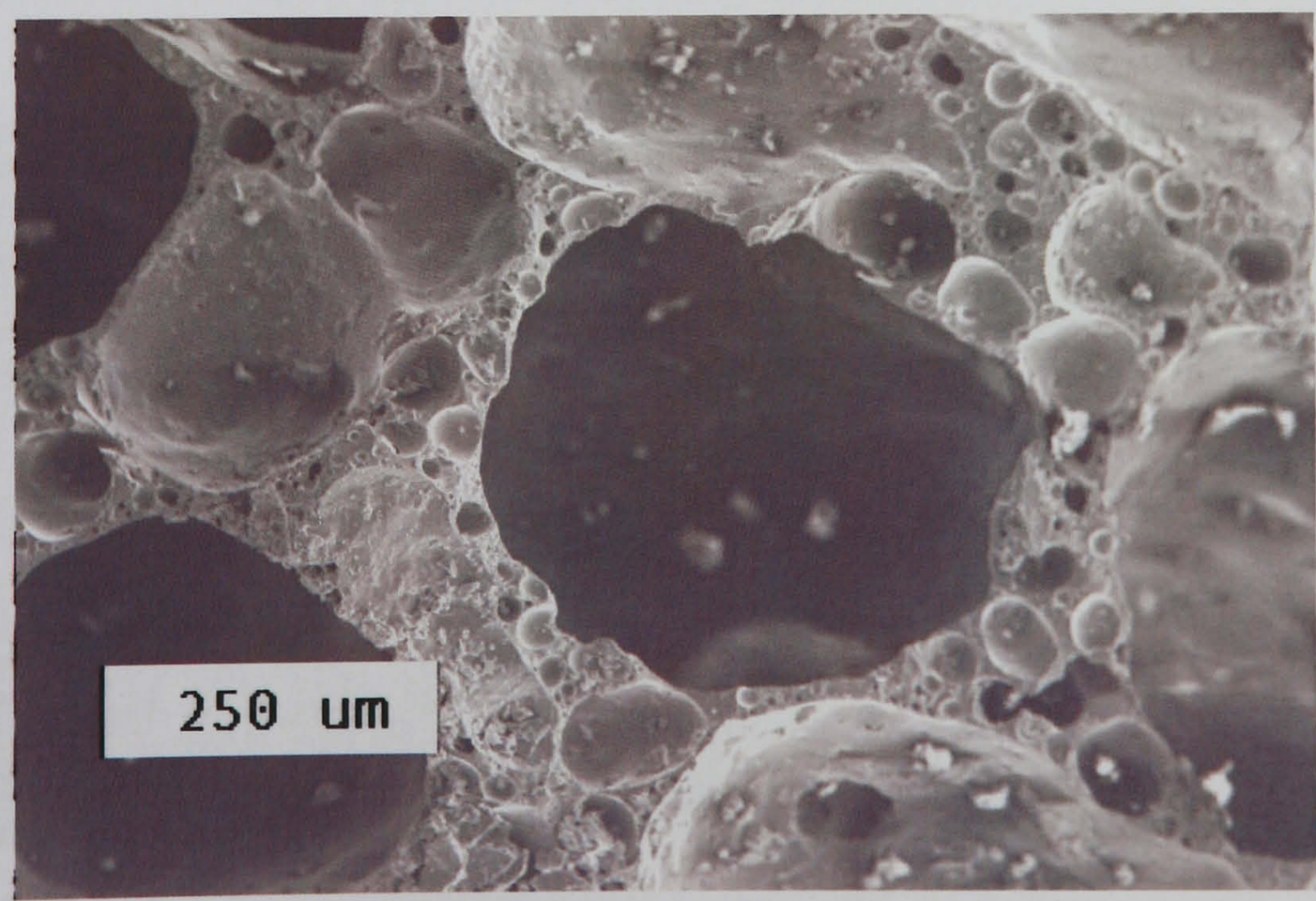


Figure 5.9 Secondary Electron Image (SEI) of Hasopor

5.5 Lytag Aggregate

5.5.1 Physical and mechanical properties

With the amount concrete used keep increasing, natural environment and resources are excessively being exploited. Lightweight aggregate produced from environmental waste as as Lytag, (0-12 mm) was also tested for its properties as a vital structural aggregate material. Lytag is a material, specifically designed and manufactured to meet all the requirements of modern construction practice requiring lightweight and thinner elements for design flexibility, ease in handling, transportation and low foundation cost.

Again, a series of physical and mechanical tests were undertaken. Summary of results and comparison with natural, GFGG and Hasopor is presented in Table 5.5. Particle density in saturated and surface dry basis as well as in oven dried basis are omitted from Table 5.5 since are very similar to apparent density. Due to the size range of Lytag (0-12 mm), mechanical tests on the material were not possible. For comparison purposes, Figure 5.12 shows the differences in densities between all aggregates used in the research.

By visual observation of Lytag it was concluded that it is a round aggregate with rough surface and few pores present. Figures 5.10 and 5.11 show Lytag and it's cross-section as used in the research. There was also observed a thick shell (probably Fly ash) at the outer surface of Lytag as shown in Figure 5.10 a). Lytag is an aggregate made from fly ash and a rich surface coating is applied at the outer layer so as to keep water absorption low and increase it's crushing strength. The material was not as fragile as GFGG or Hasopor.

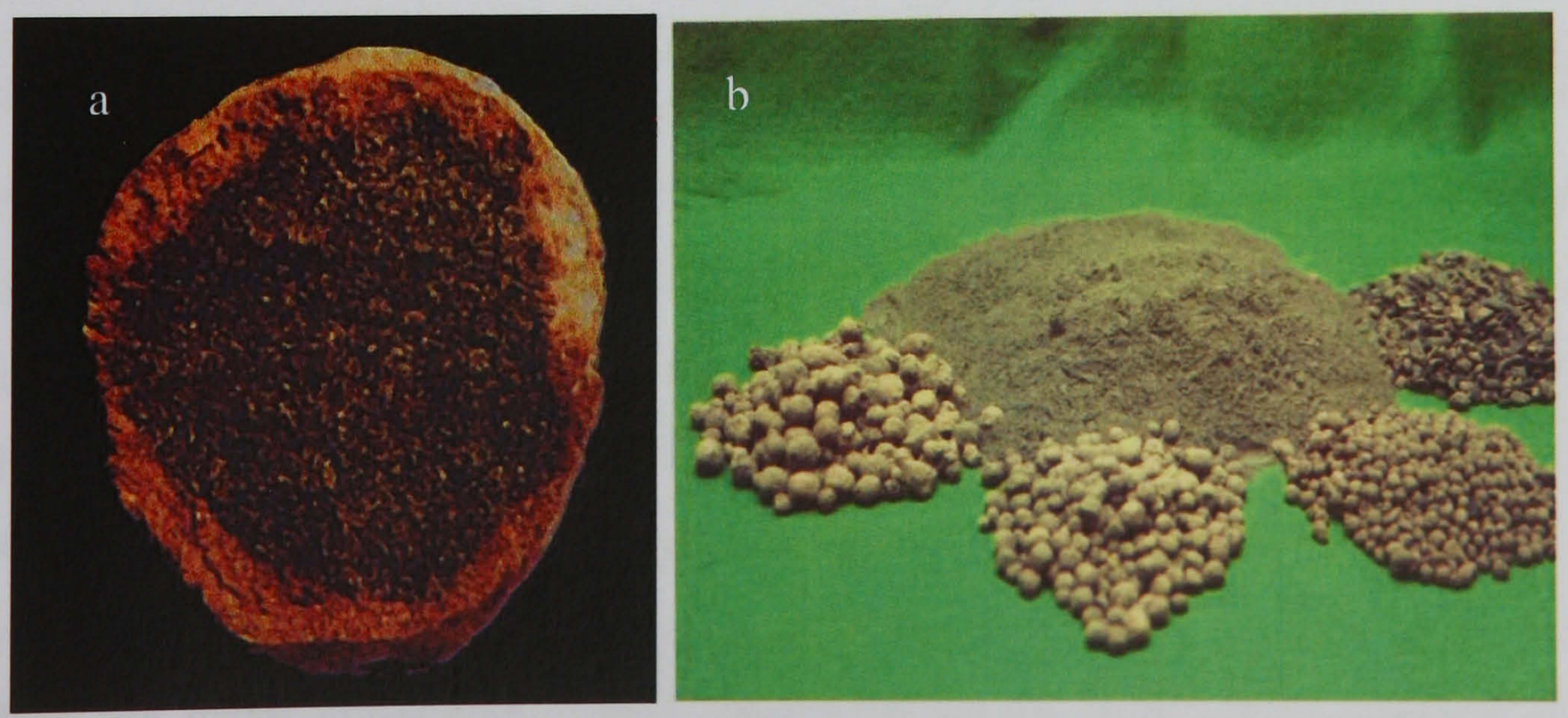


Figure 5.10 Lytag Aggregate in (a) Cross Section and (b) Fine and Coarse Form [51]

Figure 5.11 Lytag Aggregate as Used in the Research

Table 5.5 Properties of Natural, Aggregate GFGG, Hasopor and Lytag

Properties	Aggregates			
	NA	Lytag	GFGG	Hasopor
Physical				
Loose bulk density (Mg/m³)	1.50-1.70	**0.80-0.85**	0.50 – 0.65	0.40
Particle density (Apparent) (Mg/m³)	2.60-2.70	**1.40**	1.00 -1.50	0.55
Water absorption (%) by mass	0.80-1.40	**16.50**	2.25 – 6.50	30.00-35.00
Percentage Voids (%)	37.00-42.30	**40.00-45.00**	46.00-47.00	28.00
Mechanical				
Aggregate crushing value (ACV) (%)	13.00	-	65.00 –79.00	NA
Aggregate impact value (AIV) (%)	7.50	-	57.00 - 66.55	70.00
Ten percent fines (10%) (KN)	155.00	-	23.00 – 24.00	NA

According to Table 5.5 particle and bulk density, percentage voids and water absorption of Lytag is similar to published results with Lytag as LWA in concrete [55,57,58,60,68,70-71]. According to figure 5.12, Lytag has almost 50% lower bulk and particle density than natural aggregate, but still higher than GFGG by 40-50% and compared to Hasopor by 70%. According to Table 5.5, percentage of voids within the particles for Lytag was found similar to GFGG (40-47%) showing similar particle packing due to their spherical shape. Regarding the water absorption, Lytag absorb 16.5% by mass of dry aggregate and is

within the range of good quality aggregate for structural concrete. However, it tends to absorb more water than GFGG by 6 times, but half of that of Hasopor.

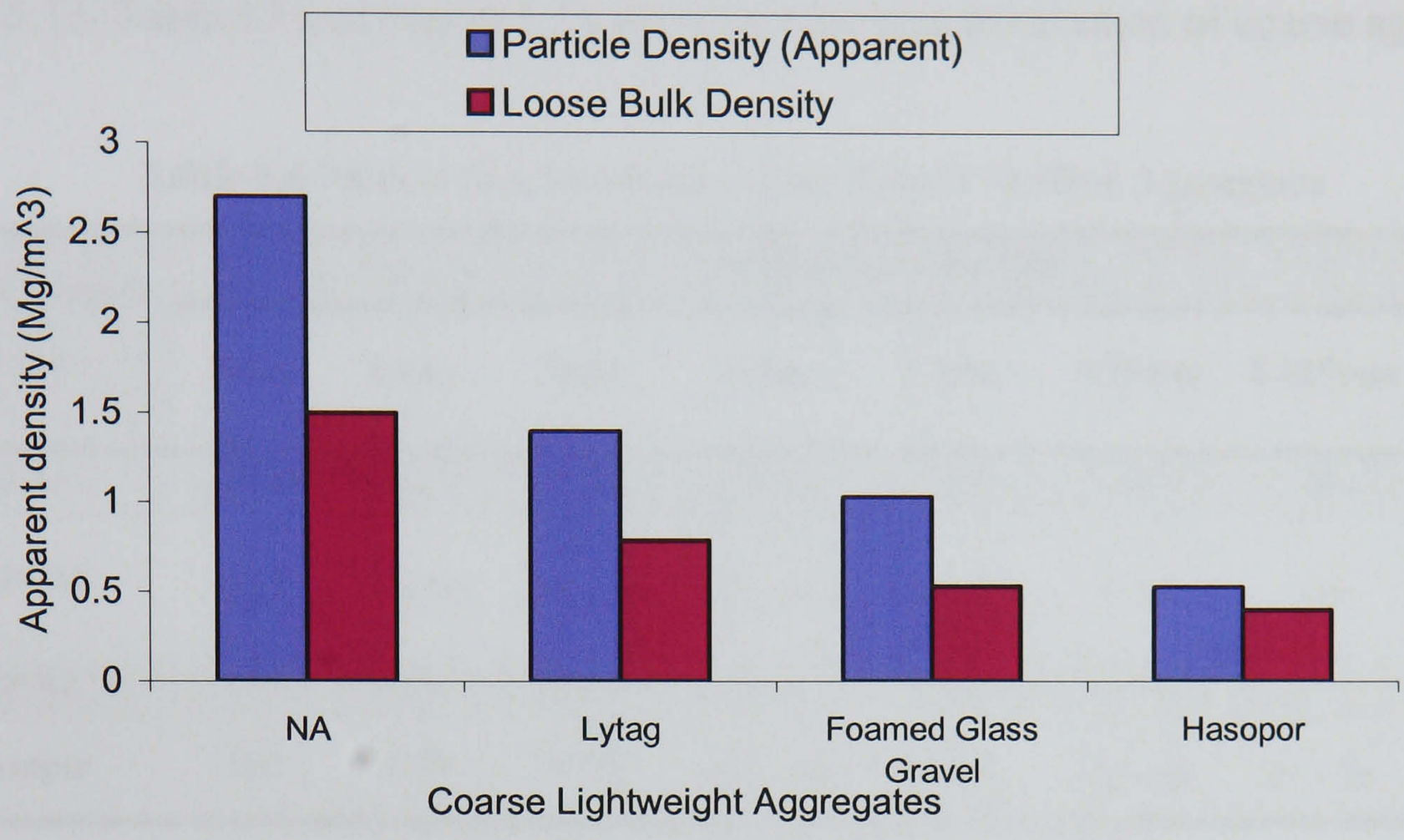


Figure 5.12 Comparison of Density of Coarse Natural Aggregates, GFGG, Hasopor and Lytag

However, according to a study [68] the high water absorption rate of lightweight aggregates as Lytag in comparison to Natural and GFGG implies semi-permeable pores, which can be beneficial, since will reduce the effective water in the concrete mix and will result in higher strength of specimens. It will act as water tank for continuous hydration of cement at later ages when the initially absorbed water will be transported to the hydrated cement paste.

What's more, according to a study of mechanical strength of Lytag, crushing strength of Lytag was found to be around 4.5-14.9 MPa [68,70], which is similar that that of GFGG (0.2-14.0) but almost 3-10 times higher than that of Hasopor. The effect of material strength in concrete will be similar for GFGG and Lytag since they show comparable strength.

5.6 Particle Size Distribution of all Tested Aggregates

Particle size distribution of Natural, GFGG, Hasopor and Lytag aggregate was also carried out during the characterisation stage. The strength of fully compacted concrete with a given water/cement ratio is independent of the grading of the aggregate, but workability is affected from grading. There is no ideal curve grading, but the main factors governing the

desired aggregate grading are; the surface area of the aggregate (water necessary to wet all solids), the relative volume occupied by the aggregate, the workability and the tendency for segregation [50]. Results for fine aggregates are shown in Table 5.6 and illustrated in Figure 5.13. Table 5.7 and Figure 5.14 show particle size distribution of coarse aggregates.

Table 5.6 Particle Size Distribution Test Results for Fine Aggregates

Fine Aggregate Type	% Passing, Sieve Size							
	8mm	**4mm**	**2mm**	**1mm**	**0.5mm**	**0.25mm**	**0.125mm**	**0.063 mm**
NA	100	98	93	90	80	14	0	0
GFGG	100	73 – 99	2.2 – 91	1.2– 65.5	0 –34.5	0-6.5	0-6	0
Lytag	100	100	76.86	6.5	4.2	4	2	2
Hasopor	100	74-79	75-78	64 - 70	55 - 61	43 - 48	21 - 26	7.5 - 11

The particle size distribution of GFGG samples was found to be of uniform nature. Majority of their grading did lie within the allowable curves- upper and lower limits set by BS 882. There is an effect of original glass source on GFGG grading since for glass source from MB grading seems coarser than that of CRT, probably due to the batched material. Lytag was found coarser for sieve fractions below 2 mm sieves while Hasopor had grading similar to Natural aggregate and GFGG from CRT glass, characterised as "medium-to fine grading" according to [50] since percentage passing the 0.5 mm sieve is between 30-100%.

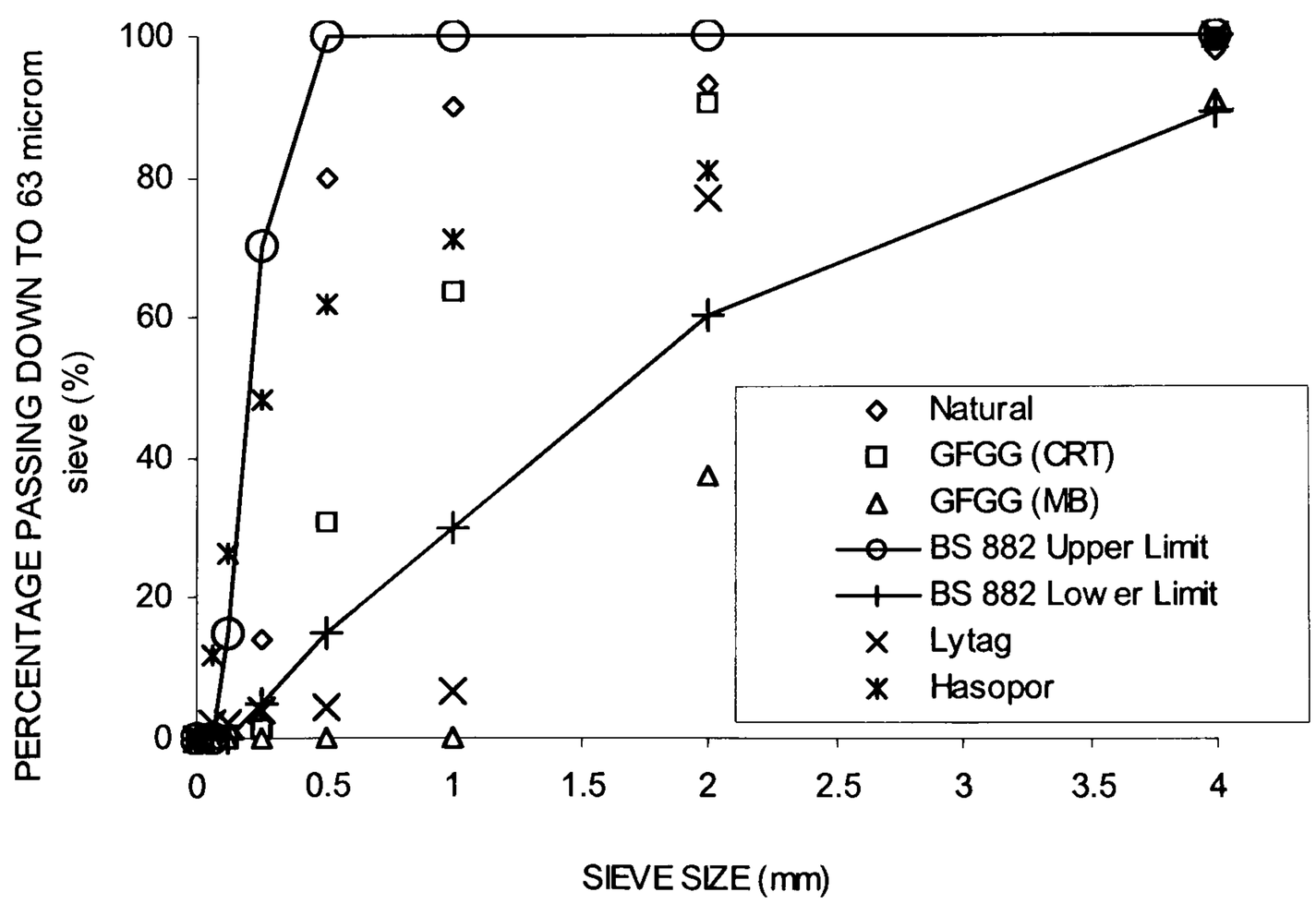


Figure 5.13 Particle Size Distribution (PSD) of Fine Aggregates

Table 5.7 Particle Size Distribution Test Results for Coarse Aggregates

Coarse Aggregate Type	% Passing, Sieve Size						
	31.5mm	**16mm**	**8mm**	**4mm**	**2mm**	**1mm**	**0.63mm**
NA	100	99	92	42	4	2	0
GFGG	57.5-100	2.0-41	0.35-2.0	0.2-0.3	0	0	0
Hasopor,	100	98 - 100	20 - 26	3.3 – 4.9	0	0	0

Similarly, according to Table 5.7 and Figure 5.14, NA grading lied within the limits set by BS 882. However, for GFGG and Hasopor materials grading appeared slightly coarser than Natural aggregate since values lie below the lower limits of BS 882. Values are acceptable for grading requirements since sharp, angular particles with rough surfaces should have a slightly finer grading in order to compensate for the high friction between the particles and to reduce the possibility of interlocking. GFGG is not angular or sharp so coarser grading is acceptable. The effect of original glass source seems negligible for GFGG grading since no difference is noticed between CRT or MB glass source grading percentages. In addition, the wide particle distribution will contribute to keep shrinkage in low values [15].

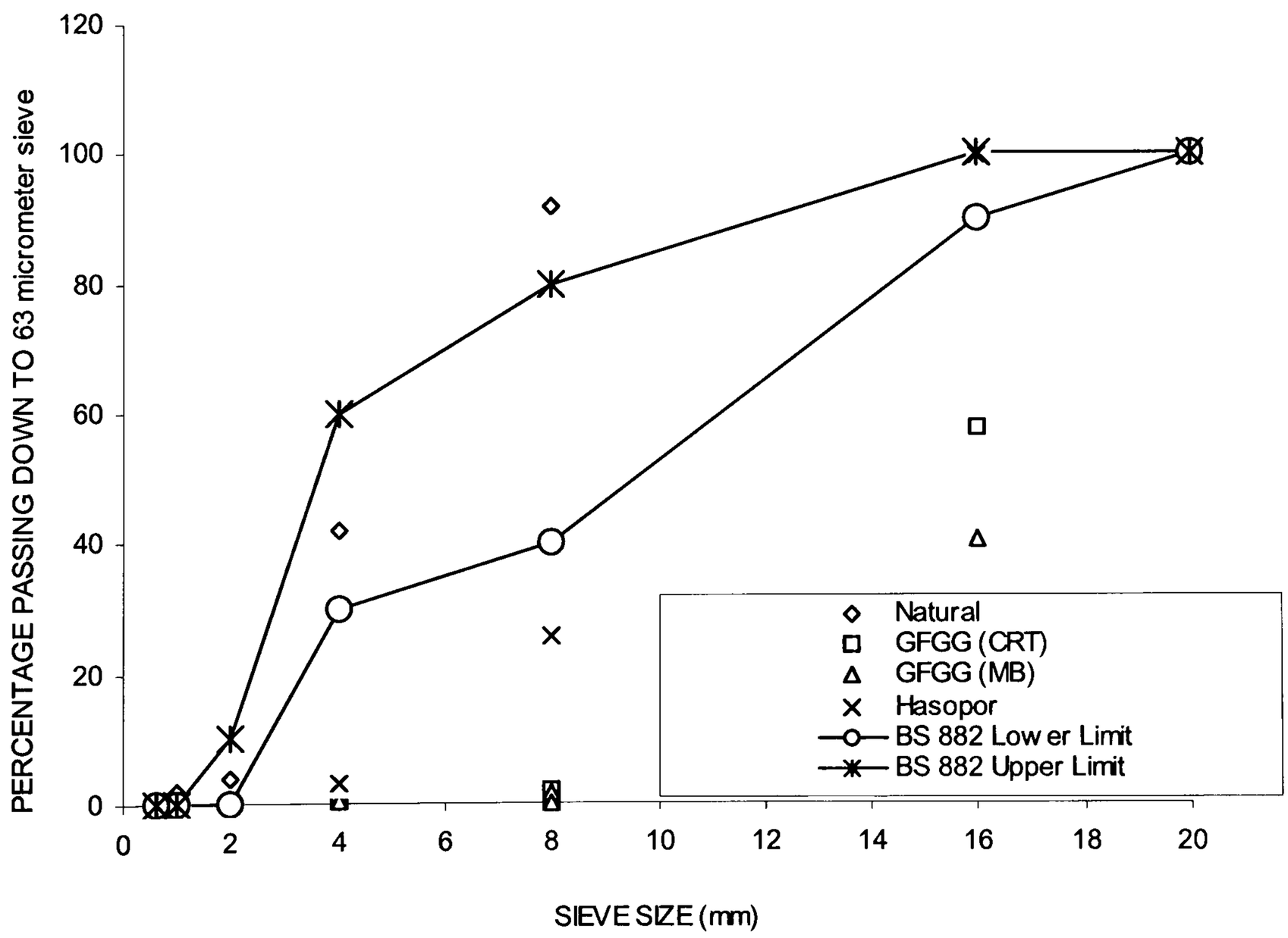


Figure 5.14 Particle Size Distribution (PSD) of Coarse Aggregates

5.7 Concluding Remarks

A series of physical mechanical and thermal testing were carried out for Natural aggregate (NA), GFGG, Hasopor and Lytag materials.

Tests indicated that GGFG was slightly rougher, somewhat porous, spherical, but equidimensional to Thames Valley natural gravel used. Fine GFGG from both glass sources, according to SEM, proved to have a more compact matrix than coarse GFGG, which indicated a structure with concentric circles with connected pores. However, an elemental analysis on both fine and coarse GFGG seemed that regardless of glass source, percentage of elements was uniform from core to rim of aggregate with the highest being Silica.

Particle density of GFGG was almost 40-50% less than NAs due to the presence of surface and inner pores. Loose bulk density of fine and coarse GGFG was also found to be reduced by 65% when compared to Natural aggregate, due to looser particle packing since the percentage of voids between particles was similar for NA and GFGG. However, the lower packing capacity of GFGG (lower bulk density) may not be a barrier for lightweight concrete structures since will result in load bearing elements of smaller cross sections and corresponding reduction in the size of foundations [15]. Due to the material's higher porosity, water absorption of GFGG was higher than NA by 3.5-5 times and increased as GFGG size fraction decreased by is recommended as good quality structural material since water absorption is less than 15%. The water absorption is expected to enhance the hydration processes within the concrete matrix, thus improving strength. In addition, its water absorption tendency is lower than that of Hasopor or Lytag, due to chemical additives during its manufacturing process improving its water repellent characteristics. Thermal conductivity of the material was found satisfactory.

Mechanical properties of GFGG were found to be inferior to NA due to fragile nature of the material, but still suitable for concrete applications. However, there is no simple relation between strength results and the upper limit of concrete strength with the given aggregates. It is anticipated that GFGG with it's rough surface will create good bond with the surrounding cement paste and will compensate for it's low mechanical strength. Aggregate of moderate to low strength as GFGG, can be valuable in preserving the integrity of concrete. Volume changes of concrete, arising from hygral or thermal causes,

lead to a lower stress in the hydrated cement paste when aggregate is compressible. Thus compressibility of aggregate would reduce distress in concrete while a strong and rigid aggregate might lead to cracking of the surrounding cement paste [50].

The particle size distribution of GFGG samples (both coarse and fine) was found to be of uniform nature but slightly coarser than Natural aggregates. However, the wide particle distribution can help minimising the drying shrinkage when used in concrete. These results are comparable to those produced by the Geofil limited. On the whole, aggregate characterisation tests suggest potential suitability of GGFG for use in a range of concrete construction applications (structural and insulating).

In general, Hasopor was found to be irregular with rough surface. Loose bulk density of Hasopor was found to be around 70% lower than NA and lower by 40% compared to GFGG. Hasopor had a honeycombed structure with higher percentage of pores compared to GFGG. As a result water absorption was increased significantly for Hasopor by 5-12 times compared to GFGG and by 25 times compared to NA. At the same time, the crushing resistance of the material was found to be lower than that of GFGG, while showing similar thermal resistance to GFGG. In general, results seem satisfactory and the material can potentially be used in concrete applications, especially as insulator or backfilling.

Lytag was found to be a spherical aggregate with PFA coating as outer shell, with rough surface and half particle density of NA. It showed particle density of 40-50% higher than GFGG due to its porosity. Water absorption was within the acceptable range of around 15%, but 5-16 times higher than NA and by 6 times higher than GFGG while its particle packing was similar to GFGG. Grading was found to be lower than the allowable limits showing coarse grading. It was also reported that its thermal conductivity is 0.8 W/mK from a published data [57], which is comparable to GFGG and that of Hasopor and shows it can perform as an effective means of thermal insulation. Its crushing strength was similar to that of GFGG but higher than that of Hasopor by 5-10 times. In general results were satisfactory and suggest the use of Lytag as aggregate in concrete.

CHAPTER 6

FRESH PROPERTIES OF FGG CONCRETE

6.1 Introduction

The largest constituent of concrete is aggregate, typically occupying some 70% of the absolute volume in normal weight natural aggregate concrete. Application of aggregate properties and their effect is fundamental to the well being of concrete. Aggregates used are generally crushed rocks or sand and gravel, but in recent years the use of lightweight aggregate, such as FGG has also been encouraged in specific applications.

So far, most research in this area has been restricted in examining the effect of FGG content on selective hardened concrete properties. However, there is limited or no data available on the fresh properties of FGG concrete, namely workability, loss of workability and stability. This, coupled with the concern that manufactured secondary aggregates, such as FGG, characteristics may compromise fresh properties have restricted acceptance of the material in wider concrete construction.

Against this background, an experimental programme was undertaken to examine the influence of GFGG sources, characteristics and content on fresh concrete properties. Geofil FGG produced from two sources of waste glass; (i) mixed bottle (MB) glass and (ii) TV/ PC Cathode Ray Tube (CRT), were used in the study. For this, a range of concrete mixes with a varying level of water/cement ratios were tested.

6.2 Experimental Programme

Essentially, the effect of GFGG content, sources and characteristics on the workability, retention of workability (slump and compacting factor) and stability (visual observation for bleeding and segregation) was determined. In these tests, GFGG concrete mixes proportional with natural and GFGG, blended by volume with up to 100% Coarse and/or 15% Fine GFGG were used. These mixes covered a range of 28-day design strength of 15 to 50 MPa.

6.3 Workability-Retention of Workability and Stability

6.3.1 Introduction

Workability can be defined as the amount of useful internal work necessary to produce full compaction [50]. According to ACI 116R-90, workability is that property of freshly mixed concrete which determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished. Whilst consistency indicates relative mobility or ability of freshly mixed concrete or mortar to flow.

Degree of compaction (compacting factor) can be expressed as a density ratio of the actual density of the given concrete to the density of the same mix when fully compacted. Variations in the workability of dry concrete are usually reflected in a large change in the compacting factor. Compaction of concrete by vibration aims at the elimination of entrapped air from the concrete providing as close a configuration as is possible for a given mix. The need for compaction becomes apparent from a study of the relation between the degree of compaction and the resulting strength. As compaction increases, voids decrease and may lead to increase in strength. Thus, as a general rule of thumb, the higher the compacting factor the higher the resulting concrete strength [50].

Stability, meaning cohesion of concrete that resists segregation [50], is very important and was also examined during concrete production. Segregation can be defined as separation of the constituents of a heterogeneous mixture, like concrete, so that their distribution is no longer uniform. It is the differences in the particle size and in the specific gravity of the mix constituents that are the primary causes of segregation. There are two forms of segregation. In the first, the coarser particles tend to separate out because they travel further along a slope or to settle more than finer mixes. The second form of segregation occurring particularly in wet mixes is manifested by the separation of grout from the mix. When mix is too dry first type of segregation occurs but when the mix is wet second type occurs [50].

Bleeding known also as water gain, is a form of segregation in which some of the water in the mix tends to rise to the surface of freshly placed concrete [50]. If the bleeding water is remixed during finishing of the top surface, a weak wearing surface, consisting of laitance, will be formed. This is caused by the inability of the solid constituents of the mix to hold

on to the mixing water when they settle downwards, water having the lowest specific gravity of all the mix constituents. In some cases, water leaves behind air pockets or lenses, and because all the voids are oriented in the same direction, the permeability of the concrete in a horizontal plane may be increased. Especially in tall element concreting such as columns or walls, as bleed water moves upwards, the water/cement ratio in the lower part of the element is reduced, but the water trapped in the upper part of the concrete results in an increased water/cement ratio there, and hence a reduced strength.

Bleeding is undesirable since some of the rising water becomes trapped on the underside of coarse aggregate particles or of reinforcement, thus creating zones of poor bond [50]. The initial bleeding proceeds at a constant rate, but subsequently the rate of bleeding decreases steadily. Bleeding continues until the cement paste has stiffened sufficiently to put an end to the process of sedimentation. If evaporation of water from the surface of the concrete is faster than the bleeding rate, another problem appears called plastic shrinkage cracking may result [50]. Less bleeding leads to plastic shrinkage cracking, while more bleeding crates a weak layer at the surface of concrete making bleeding an "enemy" of concrete. However if bleeding is undisturbed and the water evaporates, the effective water/cement ratio may be lowered with a resulting increase in strength.

6.3.2 Effect of GFGG content and original glass source

Workability

The workability test (slump) results of concrete mixes with 28-day design strength of 15 to 50 MPa and with different levels of coarse and fine GFGG are given in Table 6.1. All concrete mixes were designed for a target slump of 30-60 mm with a nominal tolerance (± 25 mm). Results also show that up to 40% coarse GFGG had no or negligible effect on slump value of concrete mixes, regardless of original glass source. However, thereafter there was a gradual reduction in workability with the increase in GFGG content, coarse or fine, regardless of the original glass source. Results indicate that smooth surface and spherical shape of GFGG act as ball bearings and provided better flow properties, with 40% coarse GFGG benchmarking level, as reported in previous research [15]. The absence of large amount of sharp particles or irregular shapes in mixes with increase GFGG leads to reduction in percentage of voids, achieving almost full compaction [50].

Table 6.1 Effect of GFGG Source and Content on the Workability of Concrete Mixes

GFGG Glass Source	28-Day Strength (w/c)	Slump, mm								
		GFGG Content , % by volume								
		Coarse						Fine		
Mixed Bottles		**0**	30	40	50	60	100	5	10	15
	15 MPa (0.77)	**60**	28	28	22	13	0	-	-	-
	25 MPa (0.62)	**35**	22	41	32	-	-	-	-	-
	30 MPa (0.55)	**40**	60	95	150	-	230	-	-	-
	50 MPa (0.40)	**42**		35	15	15		80	79	68
CRT	15 MPa (0.77)	**60**	37	35	11	3	0	-	-	-
	25 MPa (0.62)	**35**	21	60	-	-	-	-	-	-
	30 MPa (0.55)	**40**	-	-	-	-	-	-	-	-
	50 MPa (0.40)	**42**	-	38	22	20	N/A	65	43	63

Table 6.2 Description of Workability and Magnitude of Slump [50]

Description of Workability	Slump (mm)
No slump	0
Very low	5-10
Low	15-30
Medium	35-75
High	80-155
Very High	160-collapse

Table 6.3 Classification of Workability and Slump according to EN206:1992 [50]

Classification of Workability	Slump (mm)
S1	10-40
S2	50-90
S3	100-150
S4	>160

Retention of workability

Compacting factor test was also carried out to examine the loss of workability on fresh concrete with Natural and GFGG aggregates. Compacting factor was measured for mixes having coarse GFGG with original glass source Cathode Ray Tubes (CRT) or Mixed Bottles (MB) at replacement levels of 40 and 50% by volume at w/c of 0.4 (50 MPa). Control mix (0% GFGG) was also cast for comparison reasons.

The effect of GFGG on the retention of workability was assessed by measuring the compacting factor up to 120 minutes, after mixing at 30 minute intervals. Concrete mixes proportioned for 28-day design strength of 50 MPa, with 0.4 w/c ratio, were used in this test. The results are given in Table 6.4 and shown plotted in Figure 6.1. Table 6.5 presents a description of workability according to Compacting factor and slump results.

Table 6.4 Effect of Coarse GFGG on Workability (Compacting Factor) of Concrete Mixes

Coarse GFGG Content, (%) by volume	Workability (Compacting Factor)									
	Time Intervals (minutes)									
	0	30	60	90	120					
0	0.930	0.930	0.900	0.880	0.870					
	Original Glass Source									
	Mixed Bottles					*CRT*				
	0	30	60	90	120	0	30	60	90	120
40	0.894	0.874	0.854	0.834	0.816	0.810	0.800	0.760	0.730	0.700
50	0.867	0.861	0.840	0.826	0.805	0.870	0.860	0.850	0.830	0.800

Table 6.5 Description of Workability and Compacting Factor

Description of Workability	Compacting Factor	Corresponding Slump (mm)
Very low	0.78	0-25
Low	0.85	25-50
Medium	0.92	50-100
High	0.95	100-175

The results show that the relationship between workability loss and coarse GFGG content were of uniform nature, with concrete containing up to 40% GFGG exhibiting lower loss when compared to NA concrete. This trend reversed for concrete containing 50% coarse GFGG. It is likely that the surface texture and shape in 40% coarse GFGG concrete mixes lead to a greater fluidity and as a result these mixes start to be mobile for a slightly longer period. Further more, 50% GFGG concrete mixes were turned into sticky and less cohesive with time, requiring manual push after 30 minutes.

In contrary, mix with GFGG having glass source from CRT showed some increased workability compared to 40% GFGG mix from the same glass source. Visual observation showed that mix was not as dry as that with GFGG having glass source from MB. Only at 90 minutes from the start of the test manual push was necessary to enhance the flowing of concrete.

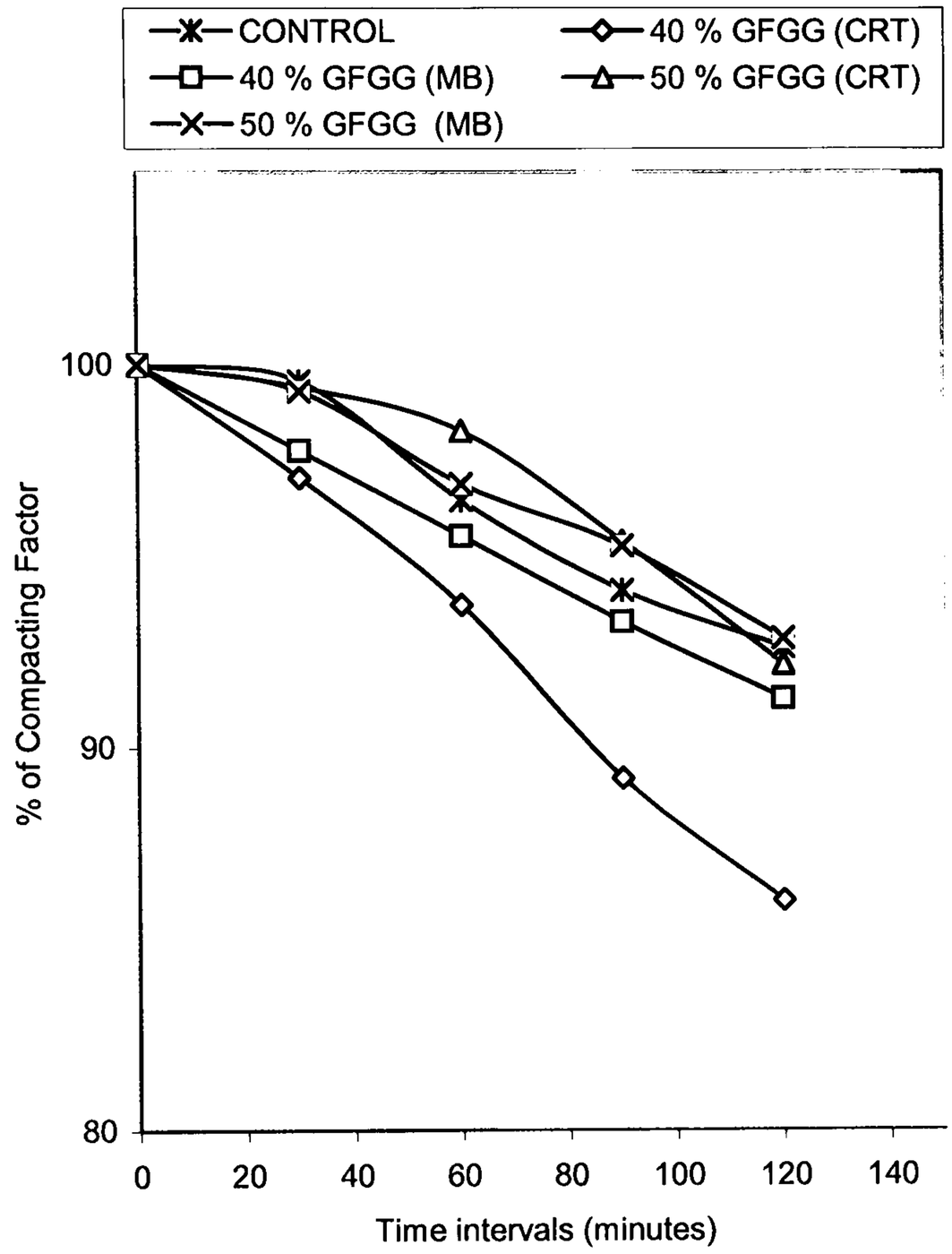


Figure 6.1 Percentage of Compacting Factor by Time

Stability

In order to assess the effect of GFGG (coarse or fine) on the stability of concrete, further tests were carried out. These included a visual observation of the mixes for segregation and bleeding phenomenon.

In general, mixes made with coarse or fine GFGG found to segregate slightly, especially at low replacement levels (0-40%) and were less cohesive than corresponding NA concrete. However, beyond 50% GFGG level segregation became more obvious, mixes were inconsistent and difficult to compact, place and finish. Figure 6.2 shows this phenomenon observed during de-moulding of concrete specimens with 100% GFGG which is the worst-case scenario (highest GFGG content).

Segregation was reduced, by avoiding prolonged vibration to avoid the formation of a laitance at the top of the concrete surface. So as to obtain smooth finish, top surface of all concrete specimens was relevelled with the use of trowel 1 hour after casting.

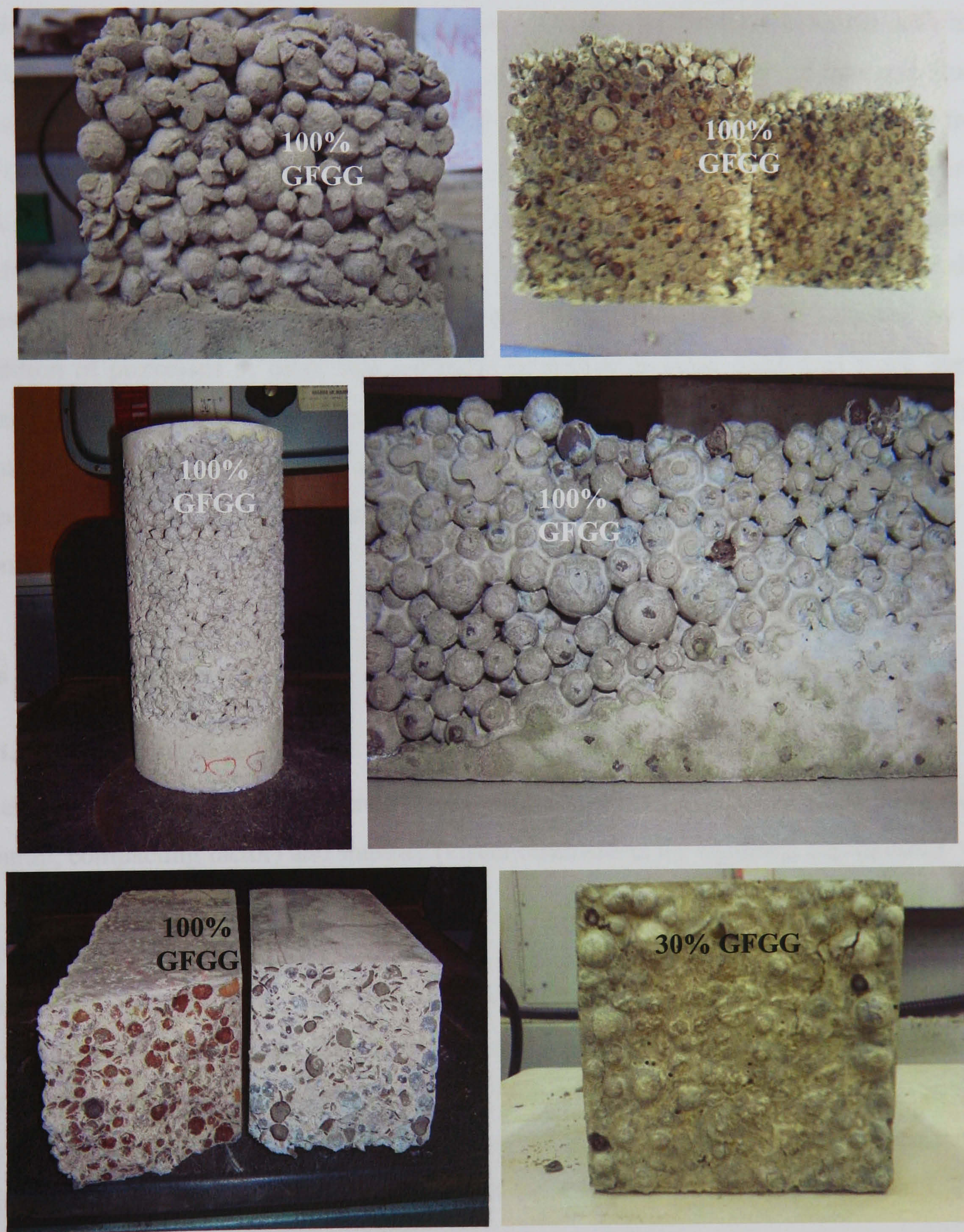


Figure 6.2 Typical Example of Segregation of Concrete Mixes Made with 100% GFGG

As seen from Figure 6.2 for 100% GFGG concrete specimens, GFGG rises to the top surface and cement paste with natural aggregates rests on the bottom. This is due to density differences in GFGG and NA. Furthermore, contributing factors can be differences in the

size of particles and bulk density of the mix constituents. Increase in segregation was evident in concrete with increased w/c ratio.

Bleeding was not observed in mixes with coarse GFGG contents up to 40% by volume or with fine GFGG mixes, while they seemed cohesive. It was observed in mixes with high GFGG contents beyond 40%, where water was visible at the bottom of concrete slump cone during visual observation. Reason for this could be that water was not absorbed from GFGG as fast as expected thus being able to escape outside the concrete matrix. Lowering w/c ratio may lead to reduction in the amount of bleeding because finer particles of cement hydrated earlier and also because their rate of sedimentation was lower as reported in previous research [59]. It is reported that reduction in bleeding may be obtained by the addition of pozzolans or other fine material. According to some published work, super-plasticizers generally decrease bleeding except at a very high slump. If they are used with a retarder, increased bleeding may occur, possibly because retardation allows more time for bleeding to occur. If air-entrainment is used, its effect in reducing bleeding may be dominant [50].

6.4 Hasopor Concrete

6.4.1 Fresh properties

Fresh properties of Hasopor concrete mixes were determined by measuring the workability (slump, compacting factor) and stability (visual observation for bleeding, segregation).

Workability

The results of slump tests on 20 and 30 MPa Concrete (all-in) Hasopor mixes were found to be of around 60 mm, and comparable to those obtained for other corresponding foamed glass gravel concrete mixes [56]. During the production of dry mixed bags the recorded slumps ranged between 50-90 mm, while for the production of all-in Hasopor concrete with 5-10% Silica Fume at 0.50 and 0.55 w/c ratio, slump results ranged between 30-40 mm.

Further tests were carried out to evaluate the effect of Hasopor on the retention of workability (compacting factor). Compacting factor was not affected by the use of 100% Hasopor since it remained between 0.93-0.95, (Table 6.6).

Stability

In order to assess the effect of Hasopor on the stability of concrete, a visual observation of the mixes and the bleeding test was carried out with similar procedure as described above. All Hasopor concrete mixes were found to be reasonably cohesive and showed no tendency of segregation or bleeding, and on the whole stability was found to be comparable to the corresponding NA concrete mixes.

Table 6.6 Effect of Coarse and Fine Hasopor on the Workability of Concrete Mixes, (Target Slump 30-60 mm)

Hasopor Content (%), by volume		**Slump, mm (Compacting Factor)**	
Coarse	***Fine***	***w/c ratio***	
		0.67	***0.55***
0	0	55 (0.92)	65 (0.95)
100	0	60 (0.94)	55 (0.93)
100	100	55 (0.95)	60 (0.95)

6.5 Lytag Concrete

6.5.1 Fresh properties

Fresh properties of Lytag concrete mixes were determined by measuring the workability (slump, compacting factor) and stability (visual observation for bleeding, segregation).

Workability

Once again the results of slump tests on Lytag mixes were found to be of around 60 mm, and comparable to those obtained for other corresponding foamed glass gravel concrete mixes. Furthermore, the slump measurements remained essentially within allowable margins (± 25 mm), Table 6.7.

According to Table 6.7 Lytag mixes at w/c of 0.77 and 0.62 perform similar to NA mixes, within the limits of 30-60 mm, showing easy to shear and workable concrete of "medium" class. At w/c of 0.55 slump increases to (215 mm-collapse), being beyond the allowable range and mix becomes highly inconsistent with "high" workability level, similar to GFGG at the same w/c ratio.

Overall fresh properties results show improvement in flow characteristics of concrete with the use of coarse Lytag, suggesting potential beneficial use of this material to produce self-leveling and self- compacting concrete mixes. Only at w/c of 0.55 workability increases at "Very High" levels, Table 6.2, consistency for Lytag mix drops dramatically, exhibiting similar behavior to GFGG with the slump being beyond the allowable range (215 mm) and belonging to S4 workability class.

Table 6.7 Effect of Coarse Lytag on the Workability of Concrete Mixes, (Target Slump 30-60 mm)

Lytag Content (%) , by volume		**Slump, mm**		
Coarse	***Fine***	***w/c ratio***		
		0.77	**0.62**	**0.55**
0	***0***	***60***	***35***	***40***
100	0	42	42	215

In contrary to GFGG mixes at w/c of 0.77, where the slump was zero at 100% replacement level and additional water was required, no water demand was observed for Lytag concrete mixes even at 100% replacement levels similar to previous studies with Lytag as aggregate where, due to "ball-bearing" effect of spherical/round shape, flow properties were improved and water demand was reduced [15,51,55,60].

Stability

In order to assess the effect of Lytag on the stability of concrete, a visual observation of the mixes and the bleeding test was also carried out. Figure 6.3 shows fresh state of Lytag concrete straight after mixing. Lytag concrete mixes were found to be reasonably cohesive and showed no tendency of segregation or bleeding, and on the whole stability was found to be comparable to the corresponding NA concrete mixes. Bleeding was observed only at w/c of 0.55, where mix was found too watery and no tamping for consolidation was needed.

From aggregate characterization results, the bulk density of Lytag was higher than that of GFGG, and its difference with normal sand/ gravel is not major, so not increasing the tendency for segregation. Top surface was re-leveled 1 hour after casting to prevent rough appearance. During concrete compaction with 100% Lytag, segregation was not observed at the same extent as in the case of 100% GFGG mixes.

Figure 6.3 Lytag Concrete Showing Little Segregation Even at high w/c (0.77) [Lytag 1 mix]

6.5 Concluding Remarks

On this chapter, the effect of GFGG content, glass sources and characteristics on the workability, retention of workability (slump and compacting factor) and stability (visual observation for bleeding and segregation) were determined. In these tests, GFGG concrete mixes proportioned with natural and GFGG, blended by volume with up to 100% Coarse and/or 15% Fine GFGG were tested. These mixes covered a range of 28-day design strength of 15 to 50 MPa. Workability results indicate that smooth surface and spherical shape of Geofil-FGG acted as ball bearings and provided better flow properties, with up to 40% coarse GFGG as benchmarking level. The absence of large amount of sharp particles or irregular shapes in mixes with increase GFGG lead to reduction in percentage of voids, achieving almost full compaction. However, use of GFGG beyond 40% by volume caused a gradual reduction in workability with the increase in GFGG content, coarse or fine, regardless of the original glass source due to higher water absorption from GFGG.

Relationship between workability loss and coarse GFGG content were of uniform nature, with concrete containing up to 40% GFGG exhibiting lower loss when compared to NA concrete. This trend reversed for concrete containing 50% coarse GFGG. It is likely that the surface texture and shape in 40% coarse GFGG concrete mixes lead to a greater fluidity and as a result these mixes start to be mobile for a slightly longer period. Furthermore, 50% GFGG concrete mixes were turned into sticky and less cohesive with time, requiring manual push after 30 minutes.

The effect of GFGG size fraction was significant since, the use of coarse aggregate (GFGG) (5-20mm) with particle density (apparent) of around 1.0 Mg/m^3 differed appreciably from that of the fine aggregate which had particle density (apparent) of 2.7 Mg/m^3, leading to increased segregation. On the other hand, segregation phenomenon was less evident in concrete produced using up to 15% fine GFGG. This may be due to only marginal differences in density of natural sand and fine GFGG. The effect of GFGG content was significant since, increased segregation was observed with coarse GFGG particles rising and floating on the top of the concrete surface especially when high replacement levels of GFGG such as 50, 60 and 100% by volume were used. Similar trends were observed, regardless of original glass source.

Overall fresh properties results show improvement in flow characteristics of concrete with the use of coarse Hasopor or all-in Hasopor. However, there was a great demand for water to achieve the required workability. Furthermore, the slump measurements remained essentially within allowable margins (± 25 mm). Workability retention and stability were satisfactory, all Hasopor concrete mixes were found to be reasonably cohesive and showed no tendency of segregation or bleeding suggesting potential beneficial use of this material to produce self- leveling and self compacting concrete mixes.

Lytag competes very well as lightweight aggregate, and concrete produced with 100% Lytag as coarse aggregate showed improved flow properties, and workability similar to NA concrete mixes. No water demand was observed for Lytag concrete mixes even at 100% replacement levels similar to previous studies with Lytag aggregate where, water demand was reduced. Lytag concrete mixes were found to be reasonably cohesive and showed no tendency for segregation or bleeding, and on the whole stability was found to be comparable to the corresponding NA concrete mixes.

CHAPTER 7

STRENGTH DEVELOPMENT AND OTHER BULK ENGINEERING PROPERTIES

7.1 Introduction

Concrete compressive strength is being used not only as basis for structural design, but also a criterion for concrete performance (BS EN 206: Part 1:2000: Specification, performance, production and conformity). At the same time, other bulk engineering properties, such as flexural strength, modulus of elasticity and drying shrinkage, are also considered to be an essential part of the design process to control the movement and deformation of the structural elements in service. As a result, limitations have been placed on many of these parameters within the appropriate standards. If GFGG is to be used as one of the constituent materials in concrete, its effect on these properties has to be established. Such information will be important in recognizing the potential of GFGG as a secondary manufactured lightweight material for concrete construction.

Against this background, a test programme was devised to establish the following;

(i) Effect of GFGG content (%) on strength development;

(ii) Influence of original glass source (MB or CRT) on compressive (cube and cylinder) strength;

(iii) Flexural strength, modulus of elasticity and drying shrinkage deformation of GFGG concrete;

(iv) Performance of GFGG compared to those concretes produced using other commercial lightweight material, such as Hasopor and Lytag.

7.2 Experimental Programme

The programme of work selected in this part of the research is shown in Figure 7.1. The study was mainly designed to establish the effect of GFGG, up to 60% by volume coarse or up to 15% fine, as aggregate replacement on normal weight concrete strength and other bulk engineering properties. Lightweight mixes with 100% GFGG by volume, were also cast for comparison reasons. These mixes were based on (i) equal water/cement ratio of 0.40-0.77 containing various proportions of GFGG and (ii) on equal strength of 30 MPa with up to 60% coarse GFGG.

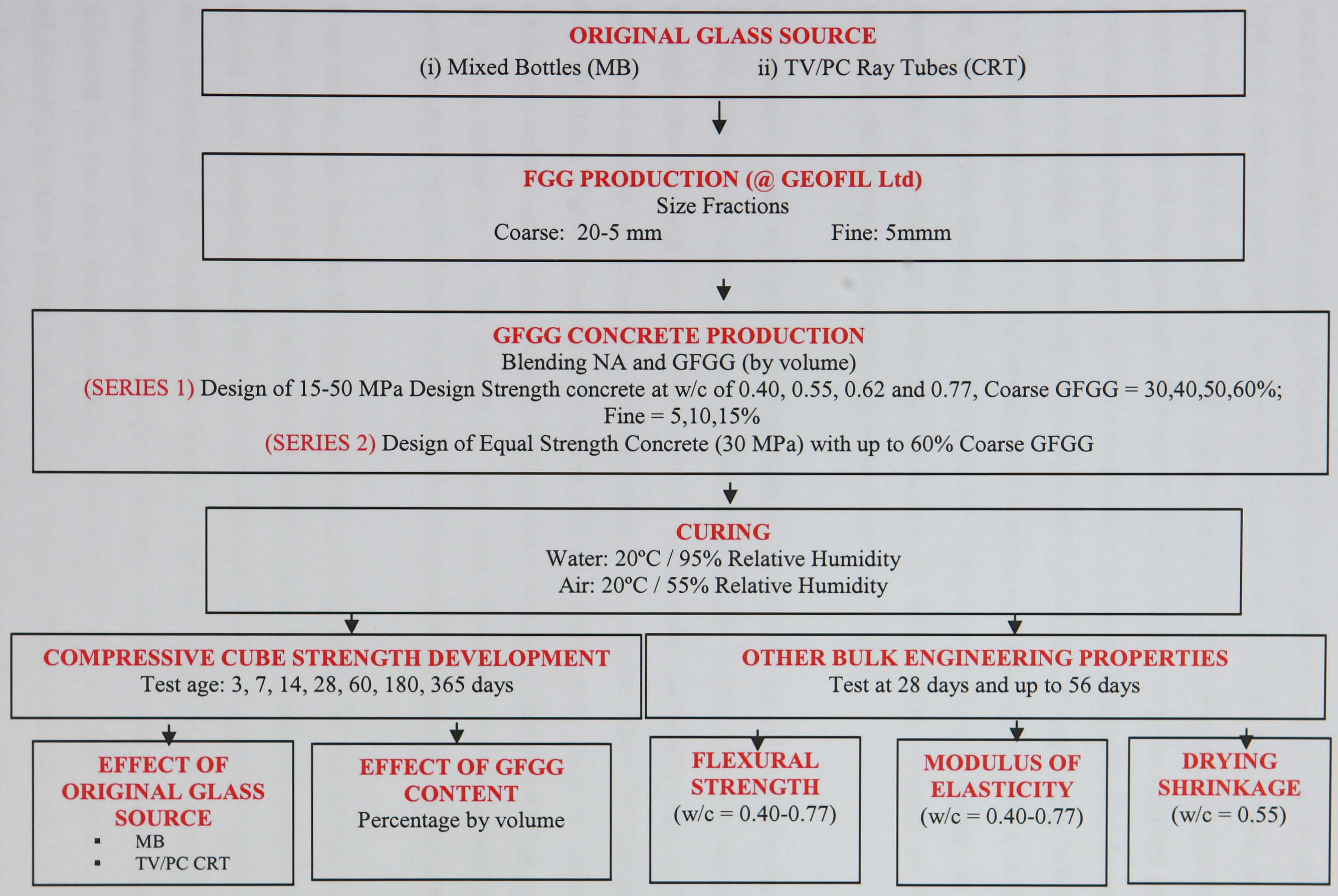


Figure 7.1 Test Programme Examining the Effect of GFGG on Strength Development and Other Bulk Engineering Properties

7.3 Strength Development

Strength of concrete is commonly considered its most valuable property. Strength gives an overall picture of the quality of concrete because is directly related to the structure of the hydrated cement paste [50]. In concrete practice, the strength of concrete is traditionally characterised by the 28-day strength value, and some other properties of concrete are often referred to the 28-day strength. The age of 28-days seems to have acquired an immutable position. Thus compliance with the specification is almost invariably laid down in terms of the 28-day strength. Knowledge of strength-time relation is of importance when a structure is to be put into use that is subjected to full loading at a later age: in such a case, the gain in the strength after the age of 28 days can be taken into account in design. In some other occasions, in precast or prestressed concrete, or when early removal of formwork is required, the strength at an early age needs to be known [50].

Compressive cube strength tests were carried out on 100mm cube specimens at 3, 7, 14, 28, 60, 180 and 365 days as specified from relevant BS 12390: Part 3 to examine the cube strength development by time. For each mix, two cube specimens were tested after the prescribed period of curing and the data value was recorded. With the implementation of BS EN 206-1:2000 compressive tests on 150 mm cubes took place for selective mixes. Only two cubes were tested instead of three, since it was not feasible a higher quantity due to space limitation in the laboratory and time limitation of the research. Cylinders conforming to BS EN 206-1 were tested for 28-day cylinder strength determination.

Four mixes, two from each original glass source (MB and/or CRT) were cast for GFGG for every replacement level, in order to examine its effect on hardened properties. Two raw results from compressive (100 mm) cube strength tests at a specific day for a particular mix proportion were recorded as in Table 7.1 for MB glass source. In order to eliminate extraneous results and to carry out the statistical analysis, a curve fitting procedure was followed in the raw data processing. This utilized the strength versus age of testing relationship by curve fitting to the raw data. A best-fitted line through the mid point of two values from each day of testing was drawn and the resulting modifications to the strength values were recorded as 'normalised' results (Table 7.1) for Coarse GFGG concrete; of w/c=0.40 with glass source from Mixed Bottles-MB.

Table 7.1 Example of Curve Fitting Method Adopted for Compressive Strength Results (*Glass source: Mixed Bottles-MB; Coarse GFGG concrete; w/c=0.40*).

GFGG Content %, by volume		Cube Strength, MPa						
		Age at test, Days						
Coarse	**Fine**	**3**	**7**	**14**	**28**	**60**	**180**	**365**
(i) Raw Data (Rd)								
0	0	26.0,31.5	34.0,35.5	33.0, 39.0	**38.0,41.0**	40.5,44.0	47.5,52.5	52.0,54.0
40	0	31.0, 33.5	32.5,34.5	38.5,39.0	**38.0,38.5**	40.0,42.5	46.0,46.5	48.0
50	0	26.5,31.5	31.0,36.5	35.0	**34.0,35.0**	39.0,41.0	43.0,44.0	46.0,48.0
60	0	23.0,25.0	27.0, 30.0	30.0,34.5	**31.5,33.0**	33.0	37.0,37.5	39.5
(ii) Raw Mean (Rm)								
0	0	29.0	35.0	37.0	**39.0**	42.0	50.0	53.0
40	0	32.5	33.5	39.0	**38.5**	41.5	46.0	48.0
50	0	29.0	34.0	35.0	**34.5**	40.0	43.5	47.0
60	0	24.0	28.5	32.0	**32.0**	33.0	37.5	39.5
(iii) Normalised Results (Rn)								
0	0	**33.0**	**39.0**	**42.0**	**45.0**	**48.0**	**50.0**	**53.0**
40	0	32.5	37.0	39.0	**40.0**	41.5	46.0	48.0
50	0	29.0	33.0	35.0	**37.0**	40.0	43.0	43.5
60	0	24.0	28.5	32.0	**33.0**	35.0	37.5	39.5
(iv) % Difference [(Rn-Rm)/Rm x100]								
0	0	12.0	11.5	13.5	**15.5**	14.5	0	0.0
40	0	0	10.5	0	**4.0**	0	0	0
50	0	0	3.0	0	**7.5**	0	1.0	17.5
60	0	0	0	0	**3.0**	6.0	0	0

As indicated from Table 7.1, differences obtained between the raw mean and 'normalised' results for 75% of results were minor (% difference less than 5%) showing the reliability and accuracy of curve fitting method. The results reported in this thesis represent those obtained following this procedure.

7.3.1 Effect of GFGG content

Table 7.2 presents and Figure 7.2 shows the typical strength development of standard 20°C water cured concrete mixes (w/c = 0.40) made with different GFGG contents (coarse or fine) for up to 28 days. The strength development results of the other concrete mixes

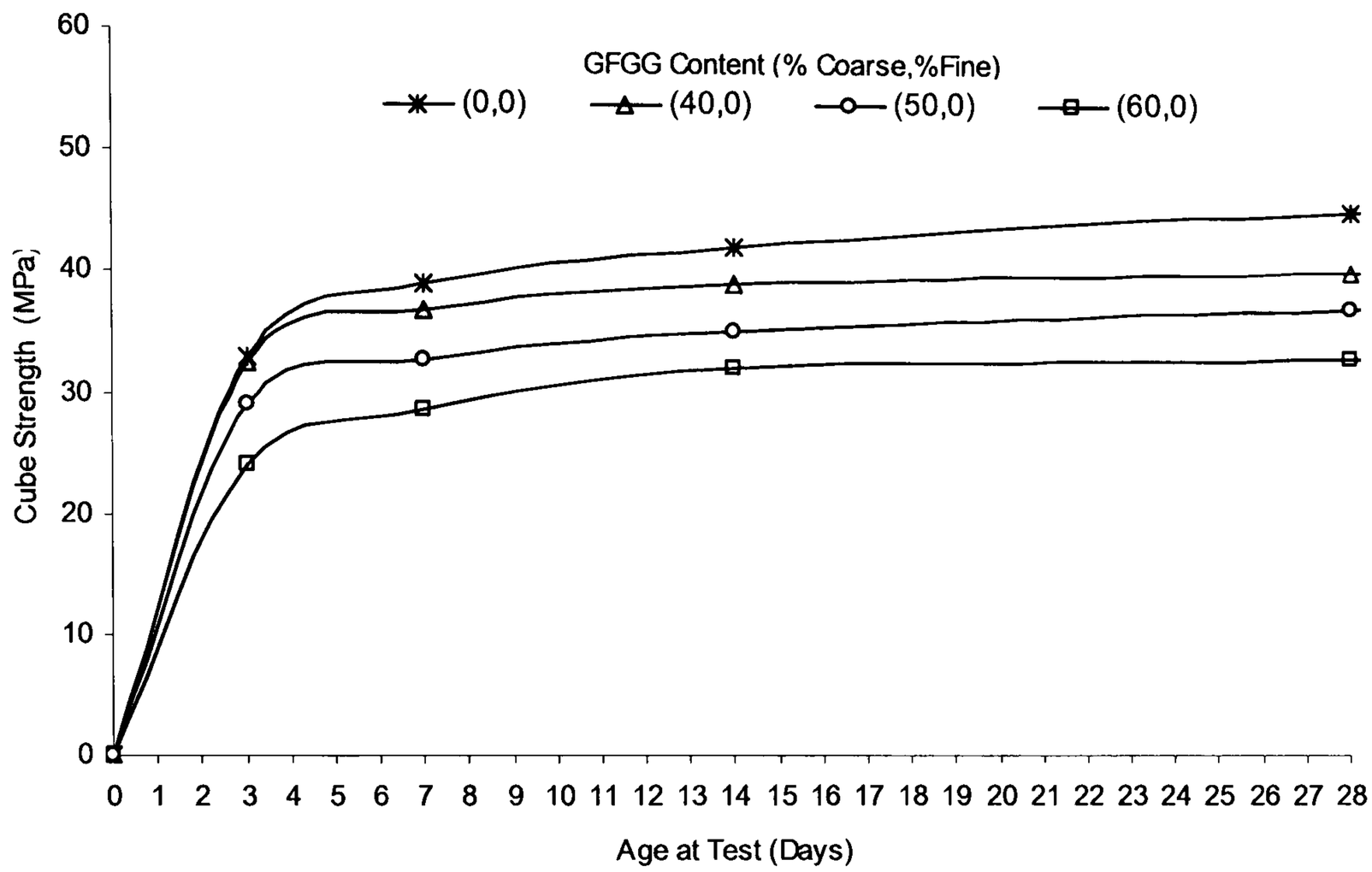
containing different levels of coarse GFGG at w/c of 0.55, 0.62 and 0.77 are also given in Table 7.2.

Table 7.2 Cube Strength of Equal Cement and Water Content Concrete Mixes; (curing: 20°C water; *GFGG Source: Mixed Bottles*)

Mix w/c ratio	GFGG Content %, by volume		Cube Strength, MPa						
			Age at test, Days						
	Coarse	*Fine*	*3*	*7*	*14*	*28*	*60*	*180*	*365*
0.40	**0**	**0**	**33.0**	**39.0**	**42.0**	**45.0**	**48.0**	**50.0**	**53.0**
	40	0	32.5	36.0	39.0	**40.0**	41.5	46.0	48.0
	50	0	29.0	34.0	35.0	**37.0**	40.0	43.0	43.5
	60	0	24.0	28.5	32.0	**33.0**	35.0	37.5	39.5
0.40	**0**	**0**	**33.0**	**39.0**	**42.0**	**45.0**	**48.0**	**50.0**	**53.0**
	0	5	30.5	34.5	37.0	**43.0**	45.5	51.5	55.0
	0	10	35.5	41.0	43.0	**45.0**	50.0	55.0	58.0
	0	15	37.0	42.0	44.0	**46.0**	51.0	56.0	59.0
0.55	**0**	**0**	**21.0**	**28.0**	**32.**	**35.0**	**40.0**	**41.0**	**-**
	30	0	21.0	27.0	30.0	**32.0**	34.0	35.0	-
	40	0	15.0	20.0	23.0	**27.5**	31.0	33.0	-
	50	0	13.0	16.5	19.0	**23.0**	25.0	26.0	-
	100	0	4.5	5.0	6.0	**7.0**	7.5	8.0	-
0.62	**0**	**0**	**23.0**	**27.0**	**30.0**	**33.0**	**36.0**	**41.0**	**44.0**
	30	0	21.0	25.0	27.0	**30.5**	35.0	40.0	41.5
	40	0	23.0	24.5	25.0	**26.5**	32.0	35.0	38.0
	50	0	15.0	18.5	20.5	**22.0**	25.0	30.0	35.0
0.77	**0**	**0**	**11.0**	**14.0**	**17.0**	**19.0**	**20.0**	**24.0**	**28.0**
	30	0	15.0	16.0	18.0	**19.0**	20.0	24.5	27.0
	40	0	11.0	14.0	15.0	**18.5**	20.0	23.0	26.5
	50	0	11.0	13.5	15.5	**18.0**	20.0	23.0	25.5
	60	0	9.0	12.0	15.0	**17.5**	20.0	22.0	24.0
	100	0	2.5	3.5	4.0	**5.0**	5.5	6.0	8.0

According to Table 7.1, Table 7.2 and Figure 7.2, the general trend of cube strength observed for w/c of 0.40, was that strength increased by time and indicated that the use of

coarse GFGG at replacement levels of 40-60% yielded concrete of 28-day strength of 33-40 MPa, while fine GFGG (5-15%) yielded higher concrete strength of 43-46 MPa.



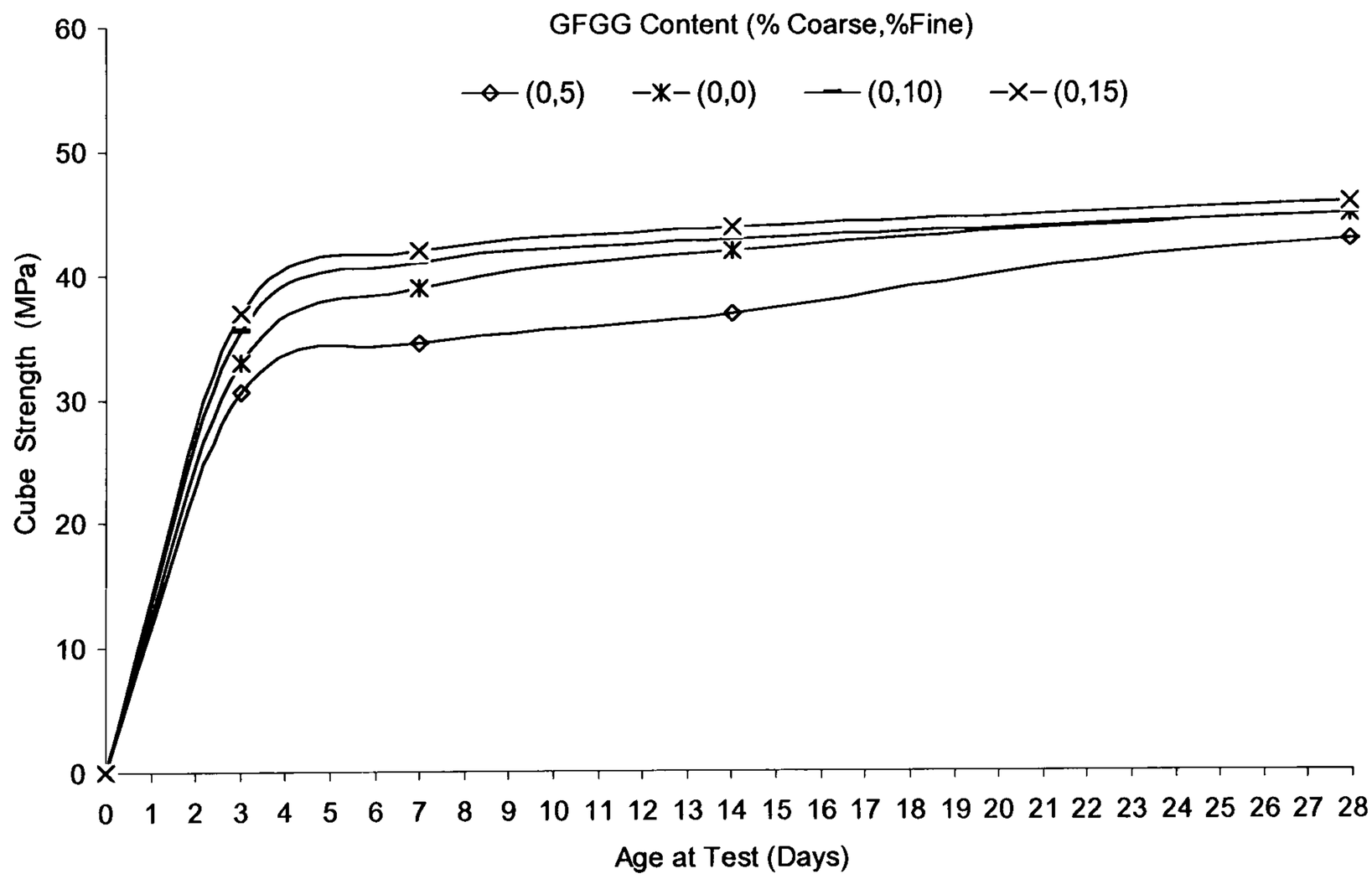


Figure 7.2 Strength Development of GFGG Concretes
(curing: 20°C water; GFGG Source: Mixed Bottles)

The phenomenon of better performance by fine GFGG can be explained by the fact that these mixes Thames Valley gravel was not replaced but only natural sand, so coarse aggregate effect was not significant. Also these mixes had better particle packing than coarse GFGG mixes. In addition, the segregation phenomenon, which was observed for

coarse GFGG mixes was not so evident for fine GFGG mixes improving compaction, reducing capillary porosity and finally strength. It was also shown that up to 30% coarse GFGG for w/c ratios (0.40-0.62) and up to 15% fine GFGG at w/c of 0.40, had no effect on strength development of normal weight concretes compared to NA concrete, but with increasing further the GFGG content, reductions in strength were apparent.

However, a slightly higher 28-day cube strength values for w/c of 0.55 and 0.62 were observed (32MPa and 30MPa respectively) for 30% coarse GFGG concrete mixes than those usually expected at these w/c ratios (30 MPa and 25 MPa respectively), due to the satisfactory performance of GFGG as aggregate replacement (strong bond of GFGG with cement paste). However, higher replacement levels from coarse GFGG beyond 30% decreased concrete strength. At high w/c of 0.77 the effect of coarse GFGG was minor no matter the percentage of replacement (30-60%) showing strength of 17.5-19.0 MPa, as usually expected at this w/c ratio.

Regarding the strength gain of GFGG mixes, the expected strength versus time behaviour was observed for normal weight concretes at w/c of 0.40 with NA and 0-60% GFGG regardless of original glass source with GFGG concrete attaining strength with faster rate than NA concrete. GFGG concretes with coarse replacement up to 60% by volume, reached around 70-85% of the 28-day strength at 3 days already, although 80% is usually achieved at 7 days in this w/c ratio [50,58,60]. Similar to this research, studies [61-67,69-71] showed that the development of initial strength of the lightweight aggregate (LWA), as in this case GFGG, was much higher than the normal weight aggregate. Satisfactory behaviour was observed regarding concrete strength gain for mixes with fine GFGG at w/c of 0.40, which at 3-days was between (77-86%) for all percentages of fine GFGG regardless of original glass source.

For concretes with coarse GFGG replacements up to 60% with w/c ratios of 0.55, 0.62 and 0.77, strength development was slower than that at w/c of 0.40, but still normal, reaching 55-65% of the 28-day strength at 3 days of testing although 40-58% is usually achieved in 3 days [50]. Mixes with low w/c ratio as at 0.40 gained strength more rapidly than mixes with higher water/cement ratios (w/c=0.55-0.77) as expected according to previous researches [50]. This is probably because at low water cement ratio, the cement grains are closer to one another and a continuous system of gel is established more rapidly. As

foresaid, during mix design of concrete mixes, water/cement ratio was gradually increased by keeping water constant but decreasing the cement content. The increased amount of cement in w/c of 0.40 increased the density and strength of hydrated cement paste and reduced the possibility of any capillary porosity, which is a key factor for reducing the concrete strength [50]. It was also stated that at w/c of 0.77, 100 mm cubes were air cured in addition to other being water cured. Results for air- cured cubes at w/c of 0.77 at 28 days show that strength values are slightly lower than that for water cured samples. Findings are consistent with similar findings [27,50] showing the positive effect of water curing due to increased cement hydration.

Strength development beyond 28 days was observed for NA and (0-60%) coarse GFGG or (0-15%) fine GFGG concretes, showing that strength continued to increase and at 365 days a strength gain of almost 10 MPa was noticed showing continuous hydration of cement paste. In addition, the maximum differences in one year of 50% coarse GFGG and NA concretes were found to be no more than 10 MPa, while 60% coarse GFGG concrete mix cube strength differed by 14 MPa from that of NA.

Lightweight concrete with GFGG replacements at 100% by volume were also cast for comparison purposes and yielded concrete strength at 3 days of 50% of that at 28 days, which is usual at w/c of 0.55 and 0.77. However, as expected, since they belong to lightweight mixes, 28-day strength values of 5 MPa and 7 MPa at w/c of 0.77 and 0.55 respectively were almost 20%-25% lower than that of NA and 30% GFGG concretes. This is primarily due to the complete absence of coarse NA content and low cement content, which could contribute to the strength properties of concrete as it happened at other GFGG replacement levels (30%-60%). The strength development of 100% GFGG concrete was comparable to other lightweight aggregate concretes of similar w/c ratios as will be shown later for Hasopor concrete in this chapter, showing it can compete well with other lightweight aggregates made from environmental by-products.

In order to show the effect of GFGG content, Figure 7.3 illustrates the 28-day strength results of concrete mixes against (0-60%) GFGG content at w/c of 0.40-0.77. Moreover, the effect of coarse and fine GFGG on strength with respect to Reference mix-(0% of GFGG) is presented in Figure 7.4.

According to Figure 7.3, it is obvious the minor reduction of strength when 30% coarse GFGG is used, while with higher percentages, strength decreases more significantly with respect to NA mixes. The effect of GFGG is more evident in high strength concrete (w/c of 0.40-0.62) than at low strength as with w/c of 0.77. Regarding fine GFGG, there is no negative effect of its use on the concrete strength; instead a slight increase is shown as fine GFGG percentage is increased.

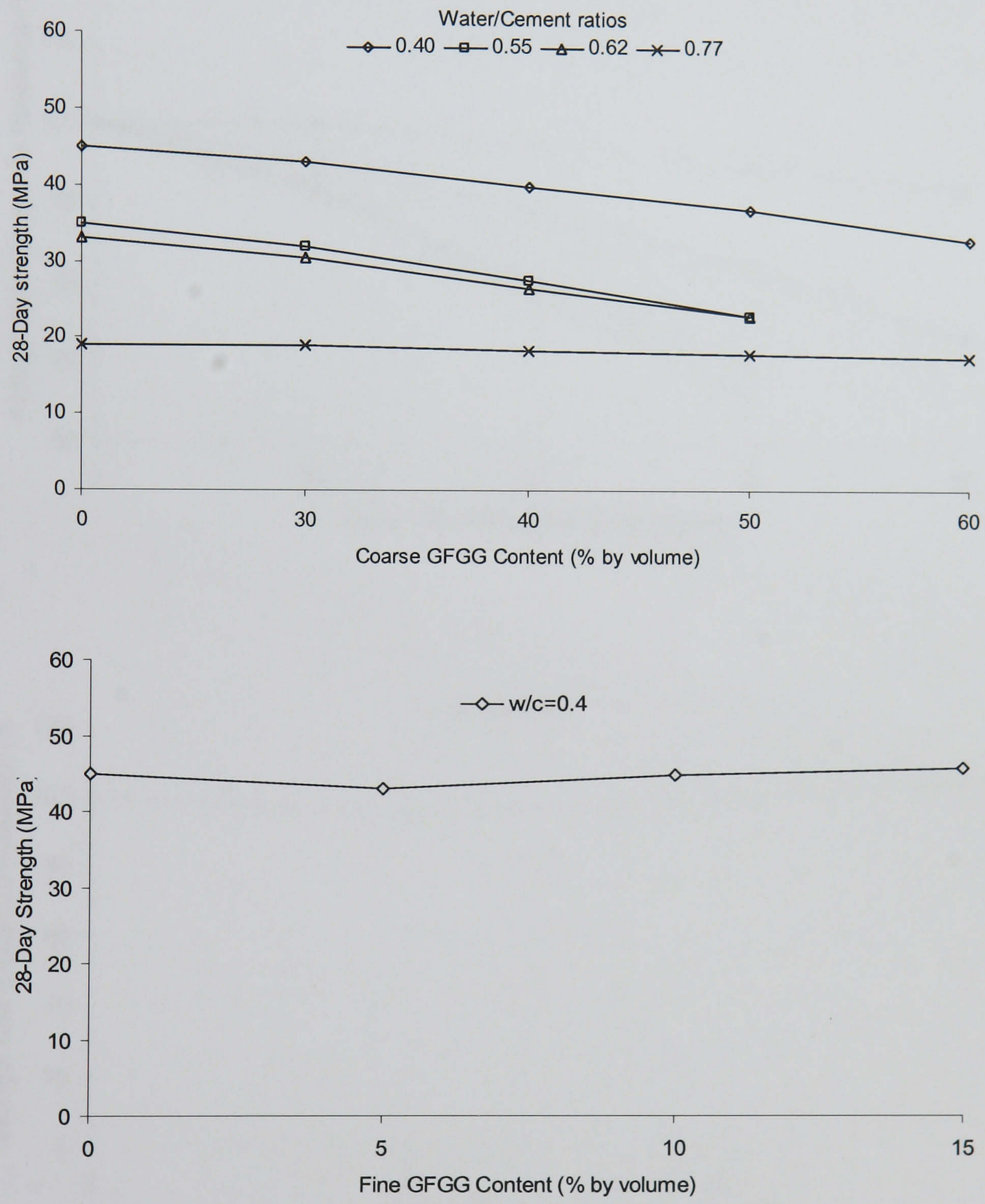
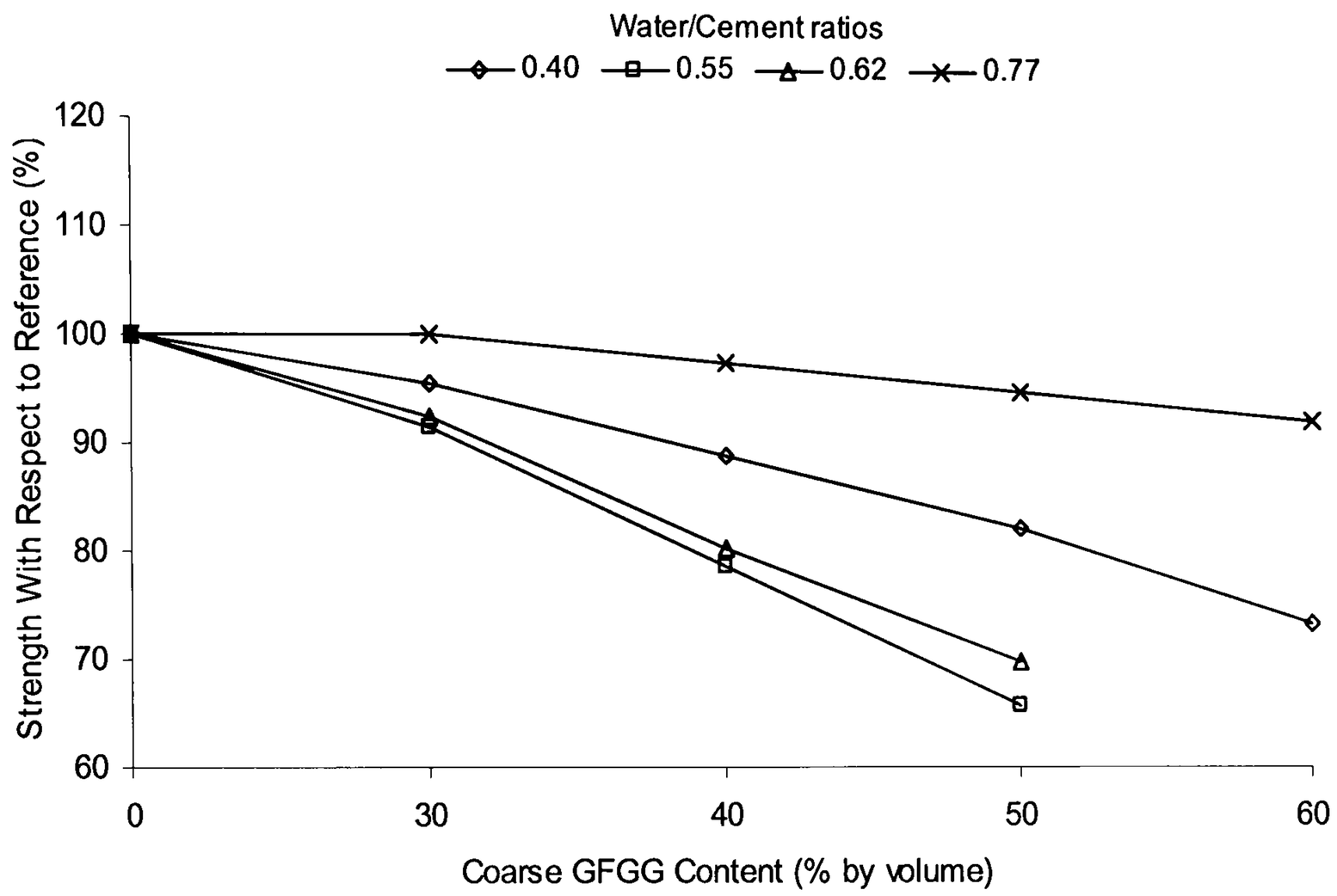


Figure 7.3 Effect of Coarse and Fine GFGG on 28-Day Cube Strength (curing: 20°C water; GFGG Source: Mixed Bottles)

Similar to the findings, a published research indicates that the influence of coarse aggregate on the strength of concrete varies in magnitude and depends on the water cement ratio. For water/cement ratio below 0.4, the use of crushed-angular aggregate results in strengths up to 38% higher than when rounded gravel is used. With an increase in the water-cement ratio beyond 0.50 the influence of aggregate falls off, presumably because

the strength of the hydrated cement paste itself becomes paramount and at w/c of 0.65 no difference in the strengths of concretes made with different aggregates had been observed [50].



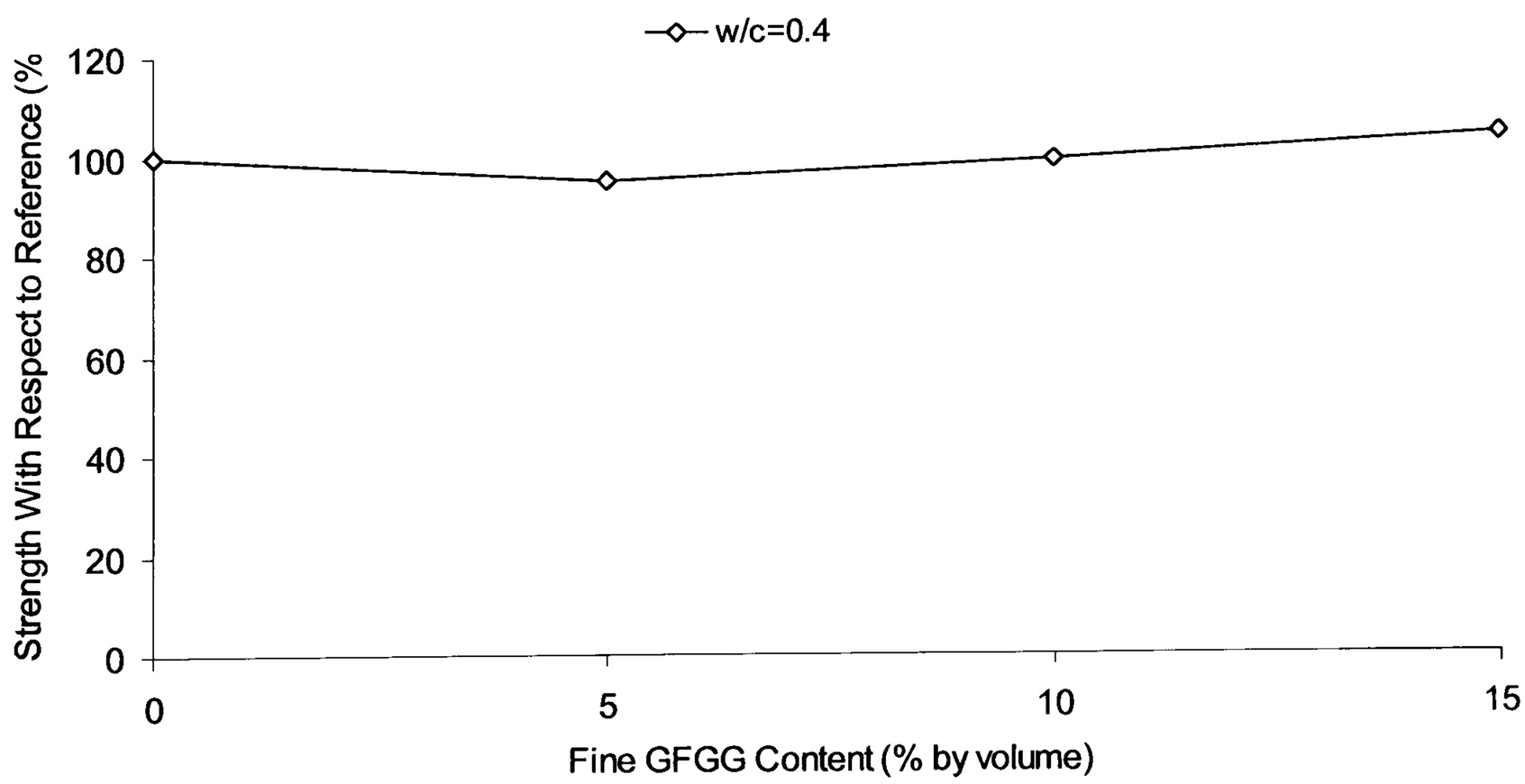


Figure 7.4 Effect of Coarse and Fine GFGG on Cube Strength With Respect to Reference Mix (curing: 20°C water; GFGG Source: Mixed Bottles)

According to Figure 7.4, the effect of coarse GFGG tended to become more noticeable in low w/c ratio (high strength) concrete mixes (0.4-0.62). The differences in strengths between NA and 60% GFGG content for 0.77 w/c ratio was 8% and that for w/c=0.4 was higher reaching 20%. On average, for w/c of 0.40-0.77, the 28-day cube strength of

concrete with more than 30% coarse GFGG was found to be 10-30% lower than that of the corresponding NA concrete.

With the use of 5% Fine GFGG, the strength was similar to that of the corresponding NA concrete, while higher replacement of Fine GFGG caused an increase in cube strength by 10-15% proving beneficial effect on concrete strength. According to ASTM C618 [62], since fine GFGG mixes show strength equal or higher than 75% of Reference mix strength, it proves behaviour of a probable pozzolan. In addition as a typical example, the influence of Coarse GFGG on the 28-day strength at 0.40-0.77 w/c ratio concrete is plotted in Figure 7.5.

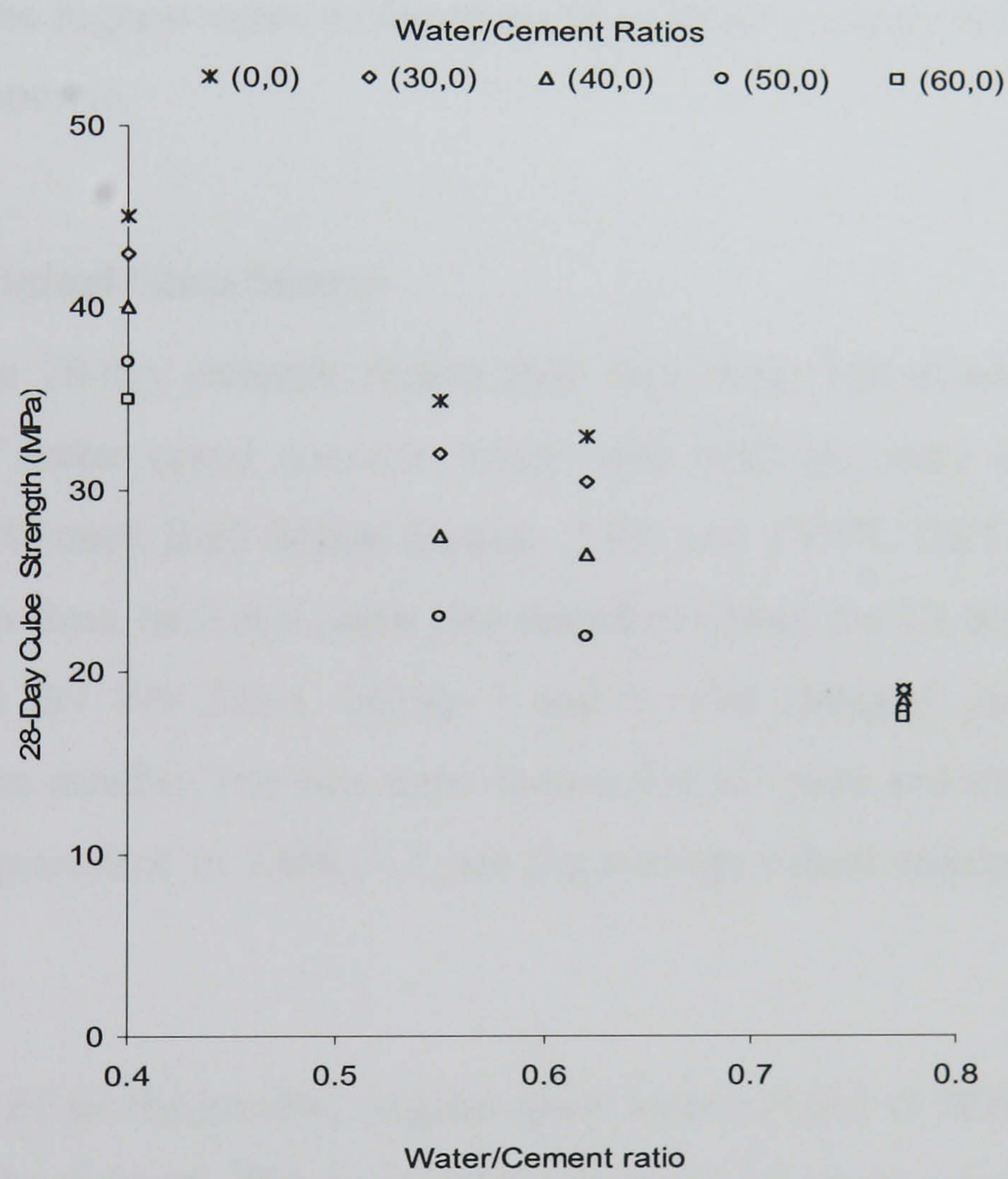


Figure 7.5 Relationship Between 28-Day Cube Strength and w/c ratio of GFGG Concrete, (curing: 20ºC water; GFGG Source: Mixed Bottles)

In engineering practice, the strength of concrete at a given age and cured in water is assumed to depend on two factors. The water-cement ratio and the degree of compaction. When concrete is fully compacted, its strength is taken to be inversely proportional to the water/cement ratio (low w/c ratio gives high concrete strength) and proportional to compaction (higher compaction higher concrete strength). The water/cement ratio determines the porosity of the hardened cement paste at any stage of hydration. Thus the w/c ratio and the degree of compaction both affect the volume of voids and consequently

the concrete strength. According to Figure 7.5, the graph of strength versus w/c ratio for coarse GFGG mixes is approximately in the shape of hyperbola as found in previous concrete studies [50]. As foresaid the slightly higher values of strength observed for w/c of 0.55 and 0.62 will affect the graph and a hyperbolic shape can not easily be shown. According to Figure 7.5, as the proportion of GFGG increased, 28-day cube strength gradually decreased. As expected, concrete strength was found to decrease with increase in water/cement ratio, regardless of age at test. However, greater differences in strength with increased GFGG content compared to NA mixes were evident at low-intermediate w/c ratios as 0.40, 0.55 and 0.62 while at high w/c ratio (0.77) concrete strength was similar no matter the percentage of GFGG. In addition the effect of percentage of GFGG in strength is also shown as the highest value is shown by 0% GFGG concrete followed by 30, 40,50 and 60%GFGG concrete.

7.3.2 Effect of Original Glass Source

For indication, the 28-day strength results (100 mm cube, 150 diameter and 300 depth cylinder) of 20°C water cured concrete mixes with 0.40 w/c ratio containing different levels of GFGG obtained from Mixed Bottles (MB) and TV/PC CRT are given in Table 7.3. Two cylinders from each mix were also tested to obtain the 28-day cylinder strength. As required from BS EN 206-1 Tables 7 and 8. The standard does not specify the minimum specimen number, but two were chosen due to space and time limitation of the research. Results presented in Table 7.3, are the average values obtained from each glass source.

From observation of all the results, original glass source (CRT or MB) did not have any major effect on cube strength. The results showed that there was no significant variation in the strength of GFGG concretes at any given GFGG content. The maximum variations in the concrete strength at a given GFGG content were found to be no more than 2 MPa, suggesting negligible effect. The effect of original glass source also seemed negligible to the majority of cylinder strength results at w/c of 0.40. No major difference in cylinder strength was noticed between two sources of glass (MB, CRT), with the maximum difference being 3.5-4.0 MPa. The same situation was noticed in other engineering and durability properties.

Table 7.3 Effect of Original Glass source on 28-Day strength of Concrete Mixes; (curing: 20ºC water; w/c = 0.40)

GFGG Content, % by volume		Cube and Cylinder Strength, MPa			
Coarse	Fine	TV/PC CRT		Mixed Bottles	
Effect of Coarse GFGG		Cube (100 mm)	Cylinder	Cube	Cylinder
0	0	45.0	33.5	45.0	33.5
40	0	42.0	30.0	40.0	31.5
50	0	41.0	29.0	37.0	25.5
60	0	34.5	27.0	33.0	25.0
Effect of Fine GFGG					
0	0	45.0	33.5	45.0	33.5
0	5	43.0	33.0	43.0	33.0
0	10	48.0	38.0	45.0	35.0
0	15	49.5	38.0	46.0	37.5

Table 7.3 also gives information about the ratio of cylinder/cube strength for mixes with (0-60%) coarse GFGG and (0-15%) fine GFGG at w/c of 0.40. Results showed that the majority of cylinder/cube ratios ranged between (0.72-0.82) which is the within the normal range of 0.75-0.80 according to BS EN 206-1:2000. Cylinder failure mode at w/c of 0.40 was characterized as "cone and split" or "cone and shear" for all the percentages of GFGG regardless of GFGG size or glass source. Similar behaviour was reported for other w/c ratios (0.55-0.77). It was also observed that increase of fine GFGG from 5%-15% increased the cylinder strength accordingly. Reason for the satisfactory cylinder strength with fine GFGG is that natural coarse aggregate was not replaced, so keeping elasticity and stiffness of concrete unchanged, low segregation of the mixes during casting and compaction, improving particle distribution and achieving maximum packing capacity.

Discussion

The mechanical behaviour of the concrete is highly affected by the aggregate (surface and texture, size) and the cement paste, as well as the interfacial zone between them. As foresaid, for concrete to possess good performance characteristics, it is essential that the interfacial zone is designed to be as dense as possible, resulting in a good bond between the aggregate and the matrix. The nature and microstructure of the IZ vary, depending on

the aggregate type, the surface structure of aggregate, pore structure of the aggregate, the porosity of the cement paste, and the bleeding of water beneath the aggregate [63]. According to a study [63], it was observed that the boundary between the cement matrix and the lightweight aggregate (LWA) shell is not distinct showing that the LWA (porous with rough texture) bonds tight and continuous with the cement matrix as shown for GFGG in Figure 7.6 b). In other words, the `Wall Effect' that appears in the normal weight concrete does not occur on the IZ of LWA. This is because the porous and rough surface of the LWA provides sites for the HCP to merge across the interfacial zone and improves the interaction mechanism between the aggregate and the matrix. The phenomenon represents the mechanical interlocking of the LWA to the cement paste. The absence of the wall effect and the lack of a distinct boundary at the Interfacial Zone improved the integrity of concrete with LWA, leading to a higher initial strength of the concrete [63]. Lightweight aggregate such as GFGG (fine and coarse) as shown in Figure 7.6 a) with a more porous outer layer, which encourages the migration of mobile ions towards it, lead to the formation of a more dense interface zone and also to improved mechanical interlocking of the aggregate particles and the hydrated cement paste [50]. There is also an increase in strength due to a chemical interaction in the form of pozzolanic reaction [63]. Also the water absorbed by the aggregate at the time of mixing becomes, with time, available for the hydration of the unhydrated cement. As most of this hydration takes place in ITZ, the bond between GFGG and the matrix becomes stronger [50]. Finally since modulus of elasticity of NA is higher than GFGG their difference will be high. But since modulus of elasticity of cement paste and that of GFGG are similar the difference will be small and the bond very strong [50]. The strong bond can lead to the absence of early development of bond micro cracking [50].These factors lead to faster strength gain as observed for GFGG compared to NA mixes.

In addition, vertical cracking in a specimen subjected to uniaxial compression starts under a load equal to 50%-75% of the ultimate load. It is shown that rough aggregate, generally leads to higher cracking load than smooth gravel, probably because mechanical bond is influenced by the surface properties and to a certain degree, by the shape of the coarse aggregate [50]. The surface properties of coarse GFGG (rough texture) up to a certain percentage (30% by volume) contributed to increased cracking load compared to a smooth aggregate, thus increasing concrete strength in compression.

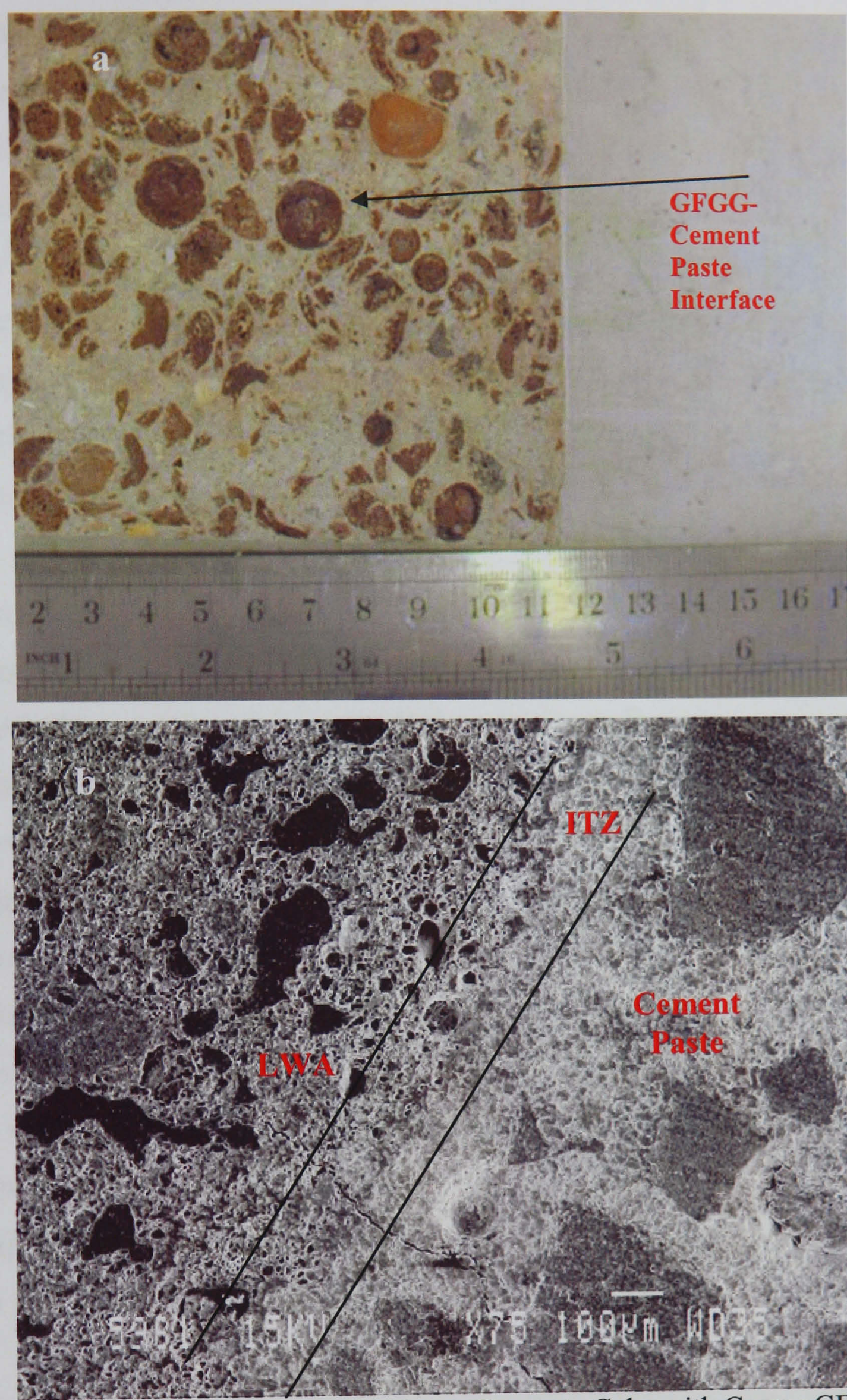


Figure 7.6 a) Cross-Section of 100 mm Concrete Cube with Coarse GFGG (*Original glass source: CRT*), b) SEM View of LWA with Cement Paste [63]

Another factor contributing to strength gain is the aggregate/cement ratio. It is reported [50] that aggregate/cement ratio of 3 or 5 give higher strength than that of 4 or 6 as observed in the research. In addition for a constant water/cement ratio a leaner mix (lower water content) leads to a higher strength. For GFGG mixes, at a constant w/c ratio, aggregate/cement ratio was not changed no matter the percentage of GFGG replacement. However, a larger amount of fine or coarse GFGG aggregate absorbed a greater quantity of free water than the natural aggregate as shown in Chapter 5 -Characterisation, the effective water being reduced. In other cases, a higher aggregate content would lead to lower

shrinkage (less available water to evaporate) and lower bleeding, and therefore to less damage to the bond between the aggregate and the cement paste. As a result, in a leaner mix, the voids formed a smaller fraction of the total volume of concrete, and it is these voids that had an adverse effect on strength. The increase of GFGG, as percentage by volume, up to a specified percentage, increased the water absorption, contributed to cement hydration through a process called "moist curing", reduced the effective water in the mix and the possibility of capillary porosity, so increased strength [50]. However, for low w/c ratios where the effective water is lower, GFGG usage beyond 30% by volume, caused a decrease in strength.

Strength of concrete is also influenced by grading, surface texture, shape, strength, and stiffness of aggregate particles. The shape of the solid particles and their modulus of elasticity also influence the stress concentration, within concrete, since aggregates act as crack arresters as cracks propagate. Maximum size of the aggregate also influences strength, showing that as maximum size decreases concrete strength increases. It was shown during GFGG characterisation that its strength/stiffness properties are lower than that of Thames Valley gravel. As the proportion of gravel is substituted from the weaker/fragile GFGG concrete strength is expected to decrease. However, it was shown previously that up to 30% by volume has no effect, while higher replacements cause a reduction. It was also shown in another study with lightweight aggregate (LWA) that the ettringite network of 0.3-1 μm in size at the ITZ of LWA as that of GFGG, is greater than that of the capillary voids but smaller than the entrained air pockets in the cement paste so it may be the 'weak link' and weaken the strength of concrete [63].

It should also be mentioned that as GFGG replaces NA, concrete density is decreased since GFGG is lighter than NA, thus causing decrease in strength. What more, during characterisation stage (Figure 5.14), grading of coarse GFGG was found to be coarser than the 'ideal' grading which gives maximum concrete strength, so it is expected that GFGG grading especially at high replacement levels will affect concrete strength since there is a absence of fine particles to fill all those voids for maximum packing. In contrary, grading of fine GFGG was found to comply with the limits for 'ideal' grading so there is no effect on concrete strength.

Moreover, the pore system in concrete plays an important role in concrete strength. Pore system consists of four types of pores: macropores due to entrained air, macropores due to inadequate compaction, capillary pores and gel pores. In addition to their volume, the shape and size of pores are also crucial [50]. This pore system governs the most important properties of concrete, notably its strength [14]. The most important characteristics of pore system are porosity and pore size distribution and is generally accepted that as porosity and pore size increase, compressive strength decreases [50]. Gel pores do not influence the strength of concrete adversely through its porosity, although these pores are directly related to creep and shrinkage. Capillary pores and other larger pores are responsible for reduction in concrete strength and elasticity modulus. Coarse GFGG, during concrete casting, was shown to cause segregation when used at high replacement levels (40%-60%) thus resulting in inadequate compaction and pores within the concrete matrix. These pores had an adverse effect on concrete strength. Segregation of concrete mixes was not observed in such extent for fine GFGG, thus no sign of reduction in strength.

7.4 Other Bulk Engineering Properties

The other bulk engineering properties, namely flexural strength, modulus of elasticity and drying shrinkage deformation of concrete made with different contents of GFGG were examined.

Like many other structural materials, concrete is to a certain degree, elastic [50]. Concrete also exhibits stiffness characteristics as measured by the modulus of elasticity (E). This value (E) is simply the ratio of stress to strain in the elastic range of the concrete material. Knowing the E-value of concrete, it is essential during the design stage of concrete structures, so a measurement of its value is crucial.

Tensile strength of concrete is usually tested under indirect tension test (flexure), direct tension or splitting. During the research flexure strength was tested under two point loading. The compressive strength of concrete is its property commonly considered in structural design but for some purposes the tensile strength is of interest; such as the design of highway and airfield slabs, dams where shear strength and resistance to cracking are important. Knowing the tensile strength enables designer to provide proper amount of

reinforcement since in general concrete is weak in tension (exceeding tensile stresses can cause cracking on the tension side of the structural element).

7.4.1 Flexural strength and Modulus of elasticity

Table 7.4 gives the results of the flexural strength and modulus of elasticity of w/c = 0.4 concretes, together with the corresponding 28-day cube strength. There is no agreement on the precise and accurate relation between compressive strength and modulus of elasticity (E-value), given that modulus of elasticity is affected by the modulus of elasticity of aggregate and by the volumetric proportion of aggregate in concrete. According to the American Concrete Institute for structural applications for normal weight concrete with strength up to 83 MPa, E-value equals:

$$E_c = 4.73 \times (f_{c,cyl}^{\ 0.5)} \text{ in GPa} \quad \text{(ACI 318-95) [50]}$$

$$E_c = 3.32 \times (f_{c,cyl}^{\ 0.5)} + 6.9 \text{ in GPa} \quad \text{(ACI 363R-62) [50]}$$

Where: E_c = Elastic Modulus in GPa and $f_{c,cyl}$ = 28-day cylinder strength in MPa

Theoretical values of E-value calculated from both formulas are similar with difference of maximum 0.5 GPa. What can be said reliably is that elastic modulus increases progressively slower than the compressive strength [50].

Table 7.4 Flexural Strength and Elastic Modulus of GFGG Concrete Mixes
(curing: 20ºC water; GFGG Source: Mixed Bottles; w/c= 0.40)

GFGG Content, % by volume		28-Day Cube Strength (MPa)	Flexural Strength (MPa)	Elastic Modulus (GPa)	
Effect of Coarse GFGG				**Experimental**	**Theoretical**
0	0	45.0	4.0	21.5	27.5
40	0	40.0	3.8	20.5	26.5
50	0	37.0	3.6	19.0	24.0
60	0	33.0	3.0	18.5	23.0
Effect of Fine GFGG					
0	0	45.0	4.0	21.5	27.5
0	5	43.0	3.9	21.5	27.0
0	10	45.0	4.1	22.0	28.0
0	15	46.0	4.2	22.5	28.0

The results from Table 7.4 indicate that there was a gradual reduction in experimental elastic modulus with increase in coarse GFGG content beyond 30%, while an increase was observed with the use of up to 15% fine GFGG by 5-10%. According to Table 7.4, experimental values for elastic modulus on concrete cylinders at 28-days, were found lower than the theoretical for all mixes by 5GPa-6GPa around 20% lower. Reason for this discrepancy can be an overestimation of E-value from the formula which is expected to be higher by 20% according to other studies examining E-value [50] and the many variables in concrete (volumetric proportion of GFGG in concrete and bond of GFGG with cement paste).

It was observed in Chapter 6 that coarse GFGG usage in concrete at w/c of 0.40 higher than 30% by volume causes increased segregation of mixes, while minor segregation was noticed for fine GFGG (5-15% by volume). Since the phenomenon of segregation was observed during cylinder casting for coarse GFGG mixes, poor particle packing took place and affected the stiffness of the concrete, showing lower values.

Lightweight aggregate as GFGG has a lower density than hydrated cement paste and influences the modulus of elasticity of concrete [50]. A higher content of natural aggregate results in a higher modulus of elasticity of concrete, since stiffness and elasticity of NA are higher than that of GFGG. So any replacement of gravel more than 30% by volume from GFGG causes a slight reduction. What more, at a constant aggregate content, the density of concrete increases with the increase in the density of aggregate. By substituting NA with lighter GFGG, density and strength of concrete decreased accordingly.

What more, the segregation during concrete compaction especially in cylinders due to high depth, caused a reduction of strength which is more obvious in cylinders than in cubes. It is expected then that cylinder properties will be more affected from segregation than cubes.

Tensile (flexural) strength of concrete is generally related to compressive strength, but there is no direct proportionality. As the compressive strength increases, the tensile strength also increases but at decreasing rate [50]. Results for GFGG mixes at w/c of 0.4 verify these observations since there was a slight increase in flexural strength when compressive strength increased. Flexural strength values at w/c of 0.40 were comparable to

published results for normal weight concrete [50] where Flexural strength for 30-45 MPa concrete strength ranged between 3.0-4.5 MPa.

Table 7.5 presents bulk engineering property values for w/c of 0.55, 0.62 and 0.77, taking into account the 28-day cube, cylinder, flexural strength and modulus of elasticity.

Theoretical values for modulus of elasticity for lightweight aggregate concrete were calculated from the following formula

$$E_c = (43 \times 10\text{-}6) \times p^{1.5} \times f_c^{0.5}$$

Where E_c= Elastic modulus in GPa, p =concrete density in kg/m^3 and f_c= cylinder strength in MPa [50]. Again research indicates an overestimation from the formula by 20% [50].

Table 7.5 Strengths and Modulus of Elasticity of GFGG Concrete Mixes (curing: 20°C water; GFGG Source: Mixed Bottles; w/c=0.55-0.77)

GFGG Content, % by volume	28-Day Cube Strength (MPa)	Cylinder Strength (MPa)	Elastic Modulus (GPa)		Flexural Strength (MPa)
			Experimental	Theoretical	
w/c = 0.55					
0	**35.0**	**28.0**	**18.5**	**25.0**	**4.0**
30	32.0	25.5	18.0	24.0	3.5
40	27.0	16.0	15.0	19.0	3.0
50	23.5	13.0	14.0	17.0	3.0
100	7.0	4.0	5.0	6.00	1.0
w/c = 0.62					
0	**33.0**	**27.0**	**18.0**	**24.5**	**3.5**
30	30.0	25.5	18.0	24.0	3.5
40	27.0	19.5	16.5	21.0	3.0
50	23.0	17.0	13.0	19.0	2.5
w/c= 0.77					
0	**19.0**	**15.0**	**15.5**	**18.5**	**2.0**
30	19.0	15.0	15.5	18.5	2.0
40	18.5	14.0	13.5	17.5	2.0
50	18.0	13.5	12.5	17.5	2.0
60	17.5	13.0	11.0	17.0	1.5
100	5.0	3.0	4.5	5.22	1.5

According to Table 7.5, cylinder strength was found to decrease as the percentage of coarse GFGG increased beyond 30%. As expected, higher cylinder strength values were observed as concrete strength increased. However, ratio of cylinder/cube strength for all w/c ranged between (0.75-0.8) for 30% GFGG concrete, as required by BS EN 206-Part 1. At higher replacement levels this ratio dropped to 0.50-0.70 due to decrease in concrete strength. For lightweight concrete mixes with 100% coarse GFGG, a sudden "shear or columnar" failure mode was observed, halving the cylinder. Cylinder values for 100% GFGG mixes were lower than those in (30-60%) GFGG mixes. This was caused from the brittle nature and low stiffness of GFGG being used as total aggregate replacement which caused an increased segregation with a resulting reduction in strength.

Experimental elastic modulus (E-value) was decreasing as the percentage of GFGG increased beyond 30%, with a reduction reaching 13%-40%. Again, experimental elastic modulus for mixes with w/c ratio of 0.55-0.77 was found lower than the theoretical values, including NA mixes, due to an overestimation of the formula and variability of the composite material. Regarding flexural strength results seem to lie within the normal range for normal weight concrete at w/c of 0.55-0.77 being between 10-20% of cube strength [50]. There was a reduction of its value as coarse GFGG replaced more than 30% NA by volume. There are many formulas relating concrete strength (cube or cylinder) with splitting or direct tensile strength [50], however, there are no formulas found for flexural strength. In addition, according to Kaplan [50] the flexural strength of concrete is lower than the flexural strength of corresponding mortar and the presence of coarse aggregate generally reduces the flexural strength.

The relationship between flexural strength, modulus of elasticity and 28-day cube strength are shown in Figures 7.7 and 7.8 for water/cement ratios of 0.4-0.77 concrete mixes with (0-60%) coarse GFGG. It should be reminded that (0-60%) GFGG mixes belong to normal weight concrete (NWC) mixes, that's why 100% GFGG concrete strength results were not included, since it belongs to lightweight concrete (LWC).

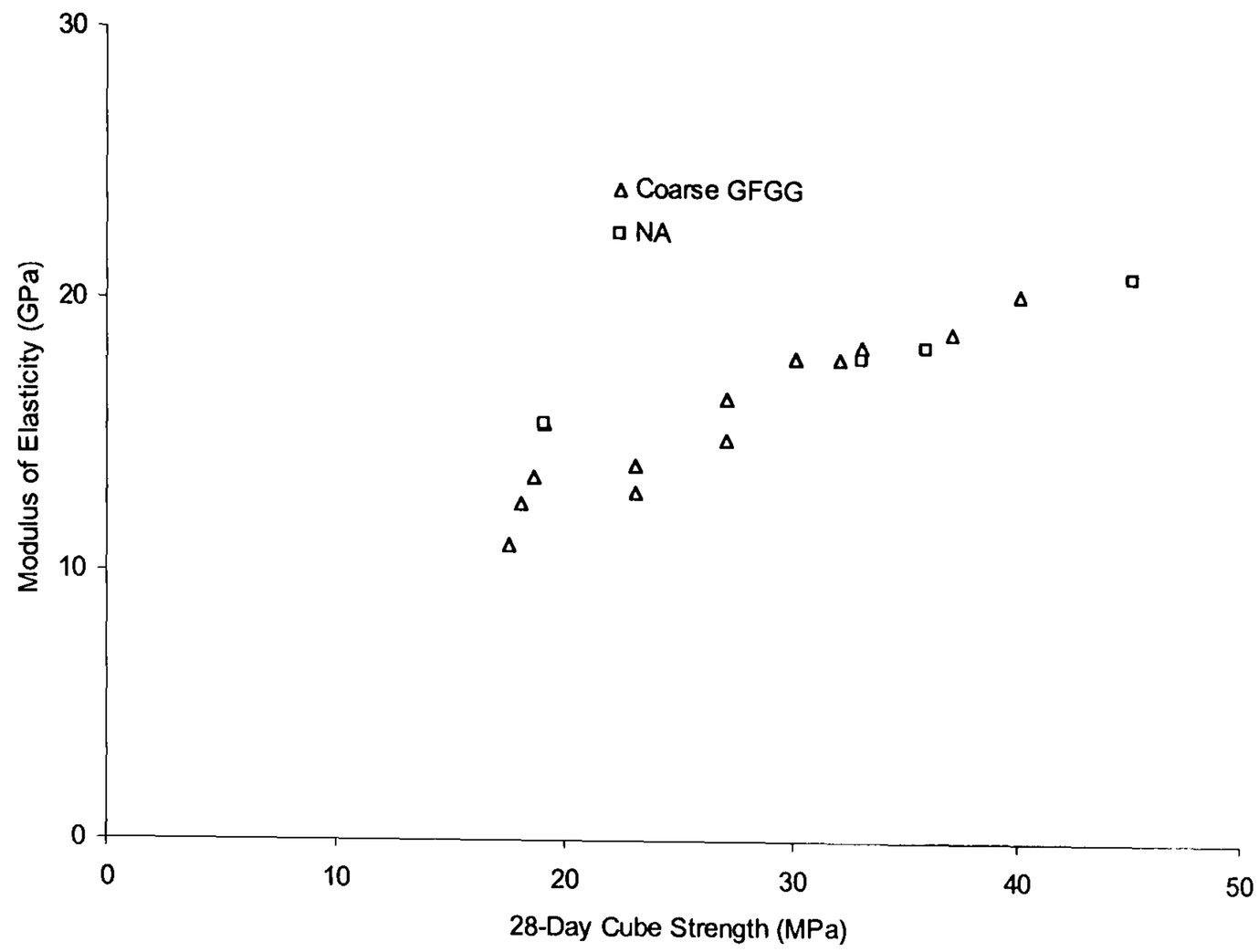


Figure 7.7 Relationship Between 28-Cube Strength and Modulus of Elasticity of GFGG Concrete Mixes (Curing: 20°C water; *GFGG Source: Mixed Bottles; w/c=0.40-0.77)*

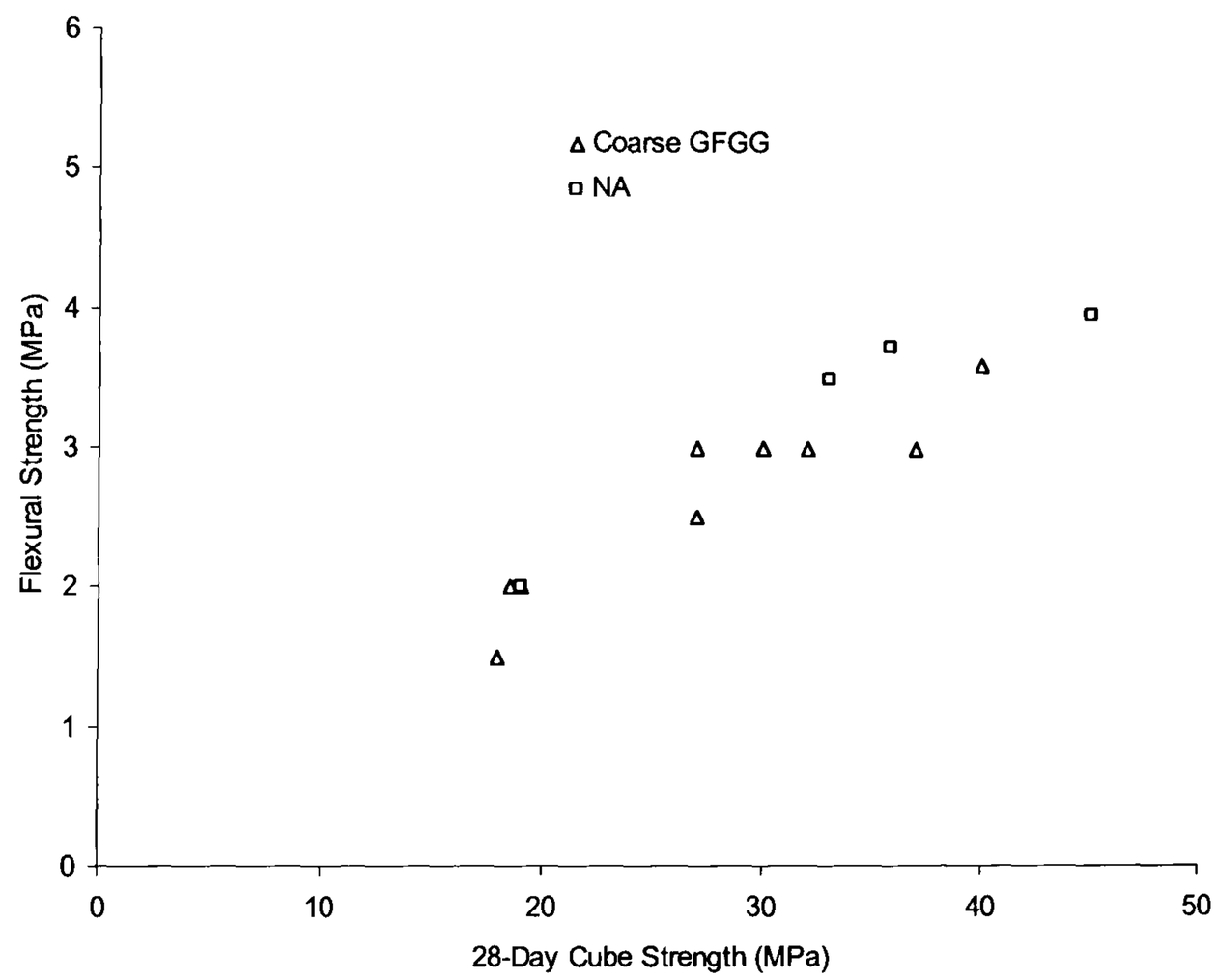


Figure 7.8 Relationship Between 28-Cube Strength and Flexural Strength of GFGG Concrete Mixes (Curing: 20°C water; *GFGG Source: Mixed Bottles; w/c=0.40-0.77)*

As expected, the flexural strength and modulus of elasticity at both NA and GFGG concretes increase with strength. In order to examine how these properties relate to compressive strength, an expression of (y=ax+c) should derive and also the co-efficient of correlation (R^2). However, due to the limited data of the present and other researches since the material is innovative and under experimental stage worldwide, such expressions can

not be calculated with confidence. Further research having higher amount of data is needed to obtain reliable relationships.

However, graphs show that Modulus of elasticity is affected from compressive strength of concrete as expected (increase in Modulus of elasticity with increase in concrete strength). A reason for the slightly reduced performance of GFGG regarding its elastic modulus can be the lower stiffness of the aggregate and the segregation phenomenon which caused uneven distribution of the solid particles (high amount of particles rose on the top surface preventing uniformity).

A close relation between flexure and compressive strength was observed from Figure 7.8 showing that as compressive strength increases, flexure increases accordingly but at slower rate, in agreement with previous studies [50]. Properties of aggregate affect the cracking load in compression and flexural strength in the same manner, so that the relation between the two quantities is independent of the type of aggregate used [50]. However, the relation between flexural and compressive strength depend on the type of coarse aggregate used because the properties of aggregate, especially its shape and surface texture, affect the ultimate strength in compression very much less than the strength in tension. Factors influencing this relation are, type of coarse aggregates (crushed-angular aggregates in concrete present higher flexural strength than irregular or rounded aggregates), properties of fine aggregate, grading of aggregate, age (beyond a month of curing flexural strength increases more slowly than compressive strength), inadequate curing (lower tensile strength), air entrainment and inadequate compaction (affects lower the compressive strength more than the tensile strength) [50]. It is expected that the lower mechanical properties of GFGG combined insufficient grading and inadequate compaction will affect flexural strength as shown for GFGG contents higher than 30% by volume.

As expected, the flexural strength and modulus of elasticity at both NA and GFGG concretes for water/cement ratios of 0.4 concrete mixes with (0-15%) fine GFGG increase with strength. However, in order to derive scientifically correct formulas relating the properties to compressive strength, more research is needed examining the effect of fine GFGG at varying w/c ratios at different replacement levels.

The use of 100% GFGG as lightweight aggregate reduced dramatically the cylinder, flexural strength and modulus of elasticity by 50-70% when compared to other GFGG concrete mixes.

The elastic properties of lightweight aggregate have a greater influence on the modulus of elasticity of concrete than in the case of normal weight concrete [50]. Values of elastic modulus are within the typical range of 4-8 GPa for lightweight mixes [50] as stated from other studies. It is usually expected that E-value of lightweight mixes is by 12GPa lower than that of normal weight mixes, as shown in Table 7.5 [50]. Reason for this is that lightweight mixes had lower cement content compared to normal weight mixes with lower percentage of GFGG, in combination to the low mechanical strength and elasticity of GFGG. Since larger proportion of GFGG was present in the mix, larger was the water to voids demand (higher water absorption of GFGG), in combination with segregation caused a reduced cement hydration and a consequent reduction in strength [15]. However, theoretical values of E-value were very comparable with experimental as expected since concrete strength is quite low.

Flexural strength values also lie within the range for lightweight mixes being between is expected to increase with relation to concrete strength as proved from Table 7.5 however; the increase is expected to be lower than that in cube compressive strength [50]. Only an indication of how 100% GFGG concrete performs compared to 100% Lytag or Hasopor can be given later in this section.

7.4.2 Drying Shrinkage

This section provides experimental data and analysis of the drying shrinkage of concrete consisting of natural and GFGG aggregates at w/c of 0.55. When concrete is examined under a microscope, gaps are observed between the paste and the aggregate particles [67]. The presence of a gap is intuitive evidence that the volume of paste has changed since set. Surprisingly, it is not obvious whether gaps are caused by expansion or shrinkage of the paste. Moisture and temperature changes, sulphate exposure, freezing and other exposure conditions can cause the paste to change dimensionally, and these changes have important effects on concrete performance, particularly deterioration.

In a two phase system consisting of solid and pores, uniform expansion of the solid phase will clearly lead to enlargement of the pores. If the same two-phase system is completely restrained so that the external dimensions cannot change, expansion of the solid phase must cause the pore volume to decrease which is favourable for concrete strength. Concrete consists of solid phases that can shrink or expand/swell (notably C-S-H), inert solid phases such as aggregate and CH, and pores. Additionally, phases such as ettringite and gypsum can precipitate in the smallest pores, causing swelling. While the total volume of concrete can and does change, the presence of inert solid phase ensures that there is some degree of restraint.

Drying shrinkage of concrete is the shrinkage caused by evaporation of internal water in hardened concrete during the drying process [73-75]. Chemical Shrinkage is the consequence of withdrawal of water from the capillary pores by the hydration of the unhydrated cement, a process also known as self-desiccation and the shrinkage called autogeneous shrinkage, meaning shrinkage from within the original mass of concrete. Water can also be lost while concrete is in the plastic state–called plastic shrinkage. It is therefore essential immediately after casting of concrete to prevent water evaporation so bleeding water equals the rate of loss / unit area and to avoid plastic shrinkage cracking on the surface of concrete [50]. Concrete made with shrinking aggregate, and which therefore exhibits high shrinkage, may lead to serviceability problems in structures where restraints are provided from reinforcement or adjacent members, leading to higher tensile stresses than the tensile capacity of concrete, with a result the initiation of cracking [50]. Restraint to shrinkage causes time-dependent cracking and gradually reduces the beneficial effects of tension stiffening. It results in a gradual widening of existing cracks and, in flexural members, a significant increase in deflections with time [74,75]. It was therefore critical to examine the drying shrinkage values of concrete mixes with 0-50% GFGG to check whether there is a possibility of excessive contraction within the concrete mass. The drying shrinkage of concrete with w/c ratio of 0.55 containing (0-50%) GFGG by volume was measured. Results from the 56-day testing regarding the strain are presented in Figure 7.9.

Requirements of AS 3600 suggest shrinkage limit, as a percentage, to be less than 650-750 $\mu\varepsilon$ (micro strain) at 8 weeks (56 days). Figure 7.9 indicates that prisms from Control mix showed an increase in the percentage of shrinkage at the first 1-2 weeks and was stabilised until the end of 56 days.

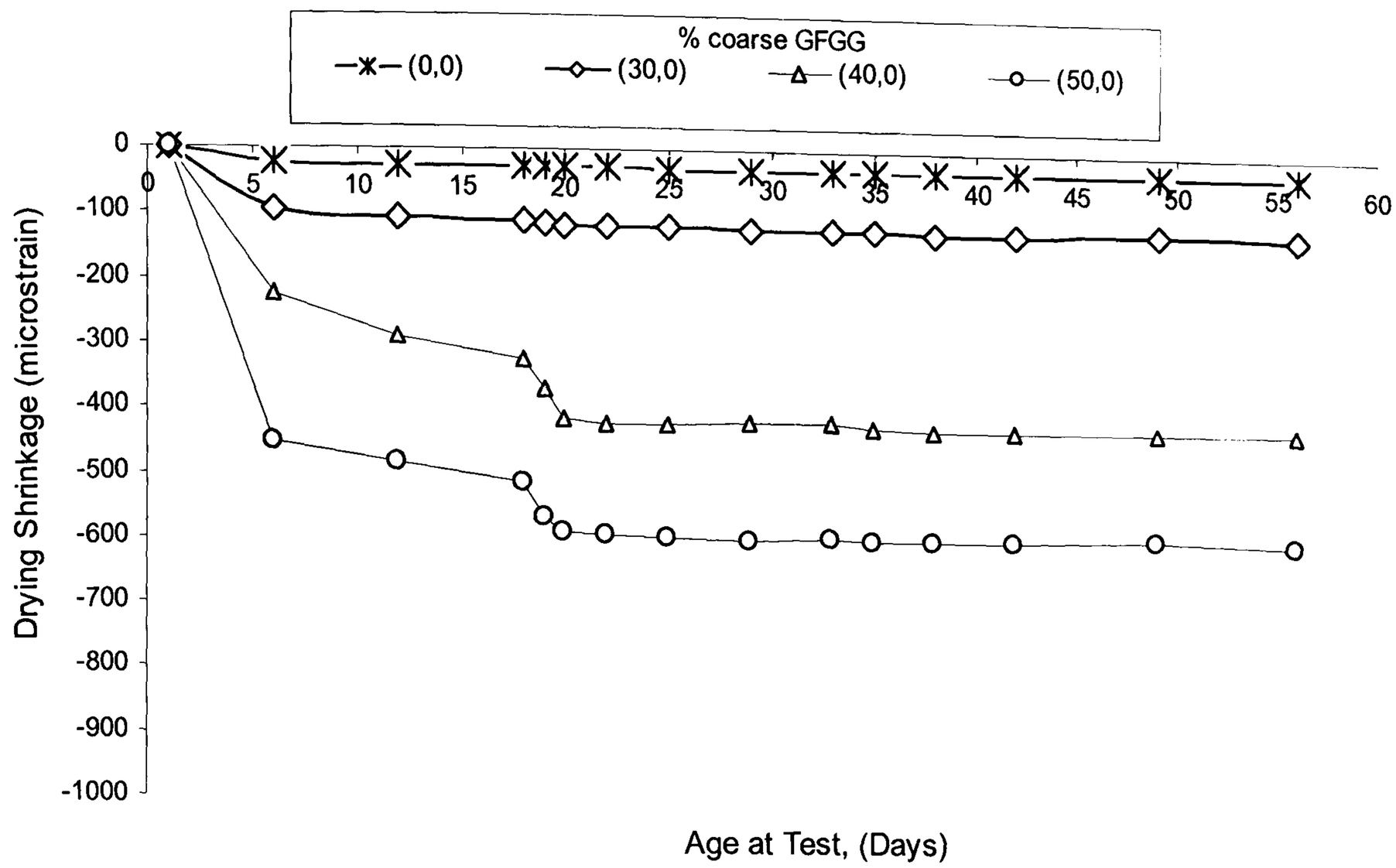


Figure 7.9 Drying Shrinkage of Coarse GFGG Concrete Mixes

(Curing: air 20°C / 55% RH; GFGG Source: Mixed Bottles; Coarse GFGG 0-50%)

However, as expected, the value of NA mix shrinkage at 56 days was 30 με showing in not normally subject to shrinkage, being comparable to the value of researches with the same w/c and aggregate/cement ratio [50] being between 20-50 με . Prisms from mix with 30% GFGG increased the shrinkage to the value of 120 με and the final value was stabilised after 3 weeks. Prisms with 40% and 50% GFGG showed a further increase in shrinkage which became stable after 3 weeks with values of 420 με and 600 με respectively at 56 days. According to Figure 7.9, drying shrinkage of 30-50% GFGG concrete mixes did not exceed the allowable limit. However, there was an increase in the value of shrinkage by almost 16% when GFGG increased from 30%-50% in concrete mix. In higher GFGG replacements, shrinkage is expected to increase more because of the rough surface of GFGG and poor compaction [58]. Reason for the increased value of shrinkage due to high replacement levels from GFGG is that in concretes with lightweight aggregate the moisture movement is higher than in the case with normal weight aggregate concrete so the drying shrinkage of lightweight aggregate concrete can be higher by 5%-40% [50]. Also shrinkage is larger the higher the water content because the latter determines the amount of evaporable water in the cement paste and the rate at which water moves towards the surface of the specimen [50]. Usually an increase in water content of NA mixes by 50

kg/m^3 increases shrinkage from 250 με to 450 με [50]. The mass of water loss and shrinkage is proportional if no capillary water (water in pores) is present and only absorbed water is removed. So the higher the water absorbed from aggregates the higher is the water loss during drying and the higher the percentage of shrinkage. GFGG proved to have higher water absorption than natural aggregates, so an increased proportion of GFGG leads to higher % of shrinkage. However, shrinkage did not exceed the specified values no matter the GFGG content.

According to published literature, the most important influence in drying shrinkage is exerted by the aggregate, which restrains the amount of shrinkage that can be realized. Size, grading and total volume of aggregate was kept constant throughout the mixes, so these factors can not affect shrinkage values. Cement content was the same for all mixes, so no volume changes were caused from increased or decreased hydrated cement paste [50]. What can be seen from Figure 7.9 is that GFGG being lightweight aggregate, leads to higher shrinkage, largely because having a lower modulus of elasticity than Natural Aggregate, offers less restraint to the potential shrinkage of the cement paste. The elastic properties of aggregate determine the degree of restraint offered. A researcher [50] found a correlation between shrinkage and the modulus of elasticity of concrete, which depends on the compressibility of the aggregate used. Control aggregate has lower compressibility (higher Aggregate Crushing and Impact Value than GFGG) as shown in aggregate characterisation (Chapter 5) having as a result its lower shrinkage ability. As proportion of GFGG aggregate increases from 0-50%, by volume, shrinkage dramatically increases since volume of Natural Aggregate decreases, offering less restraint to volume changes [50]. . It is also expected that lightweight concrete mixes with 100% GFGG will show increased shrinkage of value 600 με -1000 με according to a research [50] with lightweight aggregates.

7.5 Hasopor Concrete Strength Development and Other Engineering Properties

7.5.1 100% Coarse Hasopor / 100% All-in Hasopor Mixes

Strength development

From the strength development test results (Tables 7.6) is quite clear that Hasopor has a significant effect on compressive cube strength of the concrete.

Table 7.6 Cube Strength of NA and Hasopor (HAS) concrete, (curing; 20ºC water)

Concrete Type	Cube Strength, MPa						
	Age of Test, Days						
	3	*7*	*14*	*28*	*60*	*90*	*180*
w/c =0.67							
NA Concrete	**11.5**	**15.5**	**18.0**	**20.0**	**22.5**	**24.0**	**25.5**
100% Coarse HASOPOR	2.0	3.5	4.5	**6.0**	7.0	8.5	10.0
All-in (100% Coarse & Fine HASOPOR	1.0	2.0	2.5	**3.0**	4.5	5.5	6.5
w/c = 0.55							
NA Concrete	**21.5**	**25.5**	**28.0**	**30.0**	**33.5**	**35.0**	**36.5**
100% Coarse HASOPOR	4.5	6.0	7.0	**8.5**	9.0	10.0	11.5
100% GFGG	**4.5**	**5.0**	**6.0**	**7.0**	**7.5**	**8.0**	**-**
All-in (100% Coarse & Fine HASOPOR	2.0	2.5	3.0	**4.0**	5.5	7.5	9.5

At 28-days of testing, strength values for normal weight (100% coarse Hasopor) mix and lightweight (100% all-in Hasopor) mix were 30 and 15% respectively of the NA concrete strength. The reduction is major showing that such material can not be used as 100% coarse replacement or as total replacement.

However, comparing GFGG and Hasopor at w/c of 0.55, results seem quite similar. When Hasopor was used as total aggregate replacement in concretes, strength was lower compared to those with only coarse Hasopor. This implies that Hasopor can not be used as total aggregate replacement.

In addition, slow strength development was noticed at both w/c ratios, since after 3 days these Hasopor concrete mixes at w/c of 0.55 and 0.67 achieved around 35-50% of 28-day compressive strength which is lower than the normal range of 40-58% at this w/c ratios [50]. It should be noted that as expected, mixes with lower w/c ratio gained strength faster than that with higher w/c ratio. The maximum strength for Hasopor concrete mixes at 180 days of testing, differed by 4MPa-6MPa from that at 28 days showing slow cement hydration. On the whole, none of the Hasopor concretes reached the design strength set for NA concrete.

Other Bulk Engineering Properties

The compressive cube, cylinder, flexural strength and modulus of elasticity (stiffness) were tested for Hasopor concrete mixes according to relevant British Standards as with NA and GFGG concrete mixes. Specimens were water cured at 20ºC and 95% RH-before the day of the test. Table 7.7 gives comparison between the flexural strength, modulus of elasticity, cylinder strength as well as the 28-day cube strength of NA and Hasopor concrete mixes at w/c of 0.55. Once again, results show considerable reduction in flexural strength and modulus of elasticity for concrete produced with 100% coarse Hasopor. However, these differences can be accounted for by the change in compressive cube strength of corresponding concrete mix. There is a further reduction when 100% all-in Hasopor is used. Concrete produced with all-in Hasopor was found to be too weak for these tests, indicating unsuitability of this aggregate for use in structural concrete. Compressive cylinder strength of Hasopor concrete was found to be around 65% of cube strength of corresponding concrete, compared to 80% for NA concrete. Flexural strength and elastic modulus decreased by almost 60% when compared to NA, due to decreased concrete strength. Comparing 100% coarse Hasopor with 100% GFGG, results seem that Hasopor performed similar to GFGG at w/c of 0.55.

Table 7.7 Comparison of Key Bulk Engineering Properties of NA and Hasopor Mixes (curing; 20ºC water; w/c = 0.55)

Concrete Type	Compressive Strength, MPa		Flexural Strength, MPa	Modulus of Elasticity, GPa
	Cube	*Cylinder*		
NA Concrete	**30.0**	**23.5**	**5.0**	**25.5**
100% Coarse HASOPOR	8.5	6.5	2.0	6.5
100% GFGG	7.0	4.0	1.0	5.0
All-in (100% Coarse & Fine HASOPOR	4.0	3.0	Failure	Failure

7.5.2 Dry mixed Bags of Hasopor Concrete

Given the low strength of Hasopor concrete, a means of extending its use as pre-bagged dry mix material for the non-structural fill application was required. Using the results of the compressive strength, mix proportions for 10 MPa (all-in) Hasopor concrete were established as foresaid in Chapter 4. All constituents, except free water, of this mix were

dry-mixed in quantity sufficient to prepare 24 bags (0.02 m^3) - following quarter/quarter separation method.

These bags were then mixed with a range of free water content (165,180,195 and 210 kg/m^3) to establish compressive cube and cylinder strengths. In total, 4 dry-mixed bags were used with each water contents for concrete production. Mean compressive cube and cylinder strength results are given in Table 7.8.

On the whole, compressive strength of dry-mixed Hasopor concrete was found to be comparable to those reported for commercially available bags for paving and general concrete applications for similar water contents. Compressive cylinder strength was found to be around 70% of corresponding cube strength, which is normal as stated in BS EN 206-1.

Table 7.8 Compressive Strength Results of Dry-Mixed all-in Hasopor Concrete Bags

Free Water (Kg/m^3)	**Compressive Strength, MPa**						
	Age, Days						
	3	*7*	*14*	*28*	*60*	*90*	*180*
165							
Cube Strength	4.0	5.5	7.0	**9.5**	11.5	13.0	14.0
Cylinder Strength				**6.5**			
180							
Cube Strength	3.5	4.5	6.0	**8.5**	9.5	11.0	12.0
Cylinder Strength				**6.0**			
195							
Cube Strength	3.0	4.0	5.5	**7.0**	8.5	10.0	11.5
Cylinder Strength				**5.0**			
210							
Cube Strength	2.5	3.5	4.5	**5.5**	7.0	8.0	9.0
Cylinder Strength				**4.0**			

7.5.4 Hasopor Silica Fume Concrete

Strength development

On request from Day Group, a new series of testing was undertaken to examine the effect of 5% and 10% silica fume (when used as PC constituent) on key engineering and near surface properties of Hasopor concrete. Concrete mixes with w/c of 0.55 and 0.50 were tested in these series. In order to assess influence of silica fume on compressive strength development, results of 100 mm cube specimens tested up to 180 days are given in Table 7.9. General trend observed indicate, as expected, considerable reduction in Hasopor

concrete strength at all-ages-suggesting effect on compressive strength of concrete. It is also clear that the use of silica fume had a significantly positive influence on cube strength of Hasopor concrete. It was also apparent that after 3 days silica fume Hasopor concrete mixes recorded more than double cube strength. Furthermore, this was maintained throughout the test period, suggesting considerable enhancement in the strength performance through silica fume use. Similar trends were observed in the compressive cylinder strength results.

Table 7.9 Cube Strength Actual Results of NA and all-in Hasopor concrete with Silica Fume (curing; 20ºC water)

Concrete Type	Cube Strength, MPa						
	Age of Test, Days						
	3	*7*	*14*	*28*	*60*	*90*	*180*
w/c = 0.55							
NA Concrete	**21.5**	**25.5**	**28.0**	**30.0**	**33.5**	**35.0**	**36.5**
All-in (100% Coarse & Fine HASOPOR)							
% Silica Fume							
0	1.5	2.5	3.0	**4.0**	5.0	6.0	7.5
5	2.5	4.0	5.5	**8.0**	9.5	211.0	12.5
10	4.0	5.0	6.0	**9.5**	10.5	12.5	13.0
w/c = 0.50							
NA Concrete	**29.0**	**34.5**	**38.0**	**40.0**	**42.5**	**44.0**	**45.5**
All-in (100% Coarse & Fine HASOPOR)							
% Silica Fume							
0	2.0	3.0	3.5	**5.5**	6.0	7.0	8.0
5	4.0	6.5	7.5	**10.5**	12.0	13.0	14.5
10	5.5	7.5	9.0	**12.0**	13.5	14.5	16.0

Other Bulk Engineering Properties

The flexural strength and modulus of elasticity (stiffness) of 20ºC water-cured prism specimens were also determined for Hasopor concrete with Silica Fume. Table 7.10 gives comparison between the flexural strength, modulus of elasticity and cylinder strength together with 28-day cube strength of NA and Hasopor concrete mixes. Once again,

improved performance was apparent for silica fume Hasopor concrete, but still strength values were by far lower than the reference mix strength at w/c of 0.55 and 0.50. However, improvements can be accounted for by the change in strength of corresponding concrete mix. The cylinder /cube strength ratio ranged between 0.75-0.8, being within the allowable range. The failure mode was found to be sudden-shear for cylinders with all-in Hasopor at w/c 0.50 and 0.55.

Table 7.10 Comparison of Key Bulk Engineering Properties of NA and Hasopor Mixes with Silica Fume (curing; 20°C water)

Concrete Type	Compressive Strength, MPa		Flexural Strength, MPa	Modulus Of Elasticity, GPa
	Cube	*Cylinder*		
w/c = 0.55				
NA Concrete	30.0	23.5	5.0	18.5
All-in (100% Coarse & Fine HASOPOR)				
% Silica Fume				
0	4.0	3.0	Failure	Failure
5	8.0	5.5	2.0	2.9
10	9.5	7.0	2.5	3.12
w/c = 0.50				
NA Concrete	40.0	32.0	5.0	20.5
All-in (100% Coarse & Fine HASOPOR)				
% Silica Fume				
0	5.5	3.5	1.5	-
5	10.5	7.5	2.5	3.6
10	12.0	9.0	3.0	3.8

7.6 Lytag Concrete Strength Development and Other Engineering Properties

7.6.1 Strength development

Strength development of lightweight concrete Lytag mixes was also examined through a series of mixes containing 100% by volume Coarse Lytag and 100% Fine Natural Sand at w/c of 0.55-0.77 so as to give a comparison with the lightweight mixes using GFGG. Table 7.11 presents the normalised strength values of NA and Lytag concrete mixes (using the curve fitting method).

Table 7.11 Strength Development of Lytag Concretes; (curing; 20°C water; Lytag: 100% coarse)

Concrete Type	Cube Strength, MPa						
	Age at test, Days						
	3	*7*	*14*	*28*	*60*	*180*	*365*
w/c =0.55							
NA	21.0	28.0	32.0	**35.0**	40.0	41.0	-
100% Coarse Lytag	15.0	20.0	26.0	**30.0**	35.5	37.0	-
100% GFGG	4.5.0	5.0	6.0	**7.0**	7.5	8.0	
w/c =0.62							
NA	23.0	27.0	30.0	**33.0**	36.0	41.0	44.0
100% Coarse Lytag	17.0	25.0	29.0	**32.0**	37.0	44.0	45.0
w/c =0.77							
NA	11.0	14.0	17.0	**19.0**	20.0	24.0	25.0
100% Coarse Lytag	13.5	17.0	20.0	**26.0**	29.0	34.5	39.0
100% GFGG	2.5	3.5	4.0	**5.0**	5.5	6.0	8.0

Results show that with the use of 100% Lytag, at w/c ratios of 0.55,0.62 and 0.77 concrete cube strength was equal and higher than the design strength as in previous studies of Lytag as total coarse aggregate replacement for the design of lightweight concrete [57,60,71]. At w/c of 0.55-0.62 Lytag concrete showed slightly lower strength than NA mixes. However, it had positive influence on cube strength on concrete mixes with w/c of 0.77 exceeding the NA concrete cube strength at all times by 20-30%. It is also observed that as w/c ratio decreases, strength of Lytag concrete increases accordingly, as expected. Comparing Lytag with GFGG, Lytag performs better due to the higher absorption characteristic of the material. According to a research with Lytag aggregate in lightweight mixes [70], Lytag performed better than other LWA of similar material strength, due to two processes. Firstly, a physical process during which the aggregate of higher absorption, in this case Lytag, provides higher strength due to its denser interfacial transition zone compared to GFGG which has lower water absorption by 6 times. Secondly, a chemical process at later age, pozzolanic reaction between aggregate and the cement paste which penetrates into it and Calcium Hydrates deposit in the pores of the aggregate provide beneficial effects to concrete strength when aggregate has higher water absorption.

7.6.2 Other bulk engineering properties

Table 7.12 presents values of Cylinder, Flexural strength and Modulus of Elasticity together with the 28 -day cube strength of concrete mixes with NA and 100% Coarse Lytag. According to Table 7.12, cube/cylinder strength ratio was found to be between 0.7-0.86, which is within that the expected values of 0.75-0.8 set by BS EN 206-Part 1. What more, the mode of failure for cylinders with Lytag aggregate was found to be sudden, brittle (shear) and resulted in halving the cylinder. Dramatic reduction of stiffness of Lytag concrete mixes with respect to reference mix, was also reported reaching a reduction of almost 60%. Reason for this is the segregation during casting and the low stiffness of the aggregate (Lytag) which replaced NA. As expected elastic modulus decreased as concrete strength decreased (increase in w/c ratio). Flexural strength decreased as concrete strength decreased. It is expected that flexural strength and modulus of elasticity will be lower for lightweight concretes compared to normal weight concretes as proved in other studies [71]. Comparing GFGG and Lytag concrete with 100% coarse aggregate replacement, Lytag performs better since concrete strength is higher than that of GFGG.

Table 7.12 Key Bulk Engineering Properties of NA and Lytag Concretes; (curing; 20ºC water)

Concrete Type	Compressive Strength, MPa		Modulus of Elasticity, GPa	Flexural Strength, MPa
	Cube	*Cylinder*		
w/c =0.55				
NA	35.0	28.0	18.5	5.0
100% Coarse Lytag	30.0	25.0	8.0	4.5
100% GFGG	7.0	4.0	5.0	1.0
w/c =0.62				
NA	33.0	27.0	18.0	4.0
100% Coarse Lytag	32.0	26.5	7.0	4.0
w/c =0.77				
NA	19.0	17.0	15.0	3.0
100% Coarse Lytag	26.0	19.8	Failure	2.5
100% GFGG	5.0	3.0	4.5	1.5

7.7 Equal Strength Concrete

7.7.1 Strength development

A series of hardened engineering tests were carried out for GFGG mixes with adjusted w/c ratio to reach a designed strength of 30 MPa. During the experimental procedure, cubes (100mm) and (150 mm) were tested for compressive strength for up to 60 days of curing.

Similarly, beams and cylinders were also tested for flexural strength, cylinder strength and elastic modulus. Figure 7.10 shows the (100mm) cube strength development of GFGG concrete for up to 60 days of testing, while Table 7.13 presents the 28-day engineering properties results.

According to Figure 7.10, at 28 days of testing cube strength results showed that Control (0% GFGG) and 60% GFGG mix had equal strength of almost 28 MPa, followed by 50, 40 and 30% GFGG mixes reaching 25.0, 23.0 and 17.5 MPa respectively. Results show that as proportion of GFGG increases from 30-60% by volume, strength increases accordingly. This behaviour is expected since correction in cement amount took place (increase by 28% by mass compared to Control) when increasing GFGG content from 30-60% by volume.

Table 7.13 Cube and Cylinder Strength and Other Bulk Engineering Properties of Concrete Containing (0-60%) Coarse GFGG, (curing: 20ºC water; *GFGG Source: Mixed Bottles)*

Coarse GFGG Content, % by volume	Compressive Strength, MPa			Modulus of Elasticity, GPa	Flexural Strength, MPa
	Cube		*Cylinder*		
	100mm	*150 mm*		Experimental	
0-Control	**28.0**	**26.0**	**22.0**	**17.0**	**4.5**
30	17.5	18.0	11.5	9.5	1.0
40	22.5	22.0	16.0	13.0	2.0
50	25.0	22.5	16.0	12.5	2.5
60	28.0	26.0	17.0	20.5	4.5

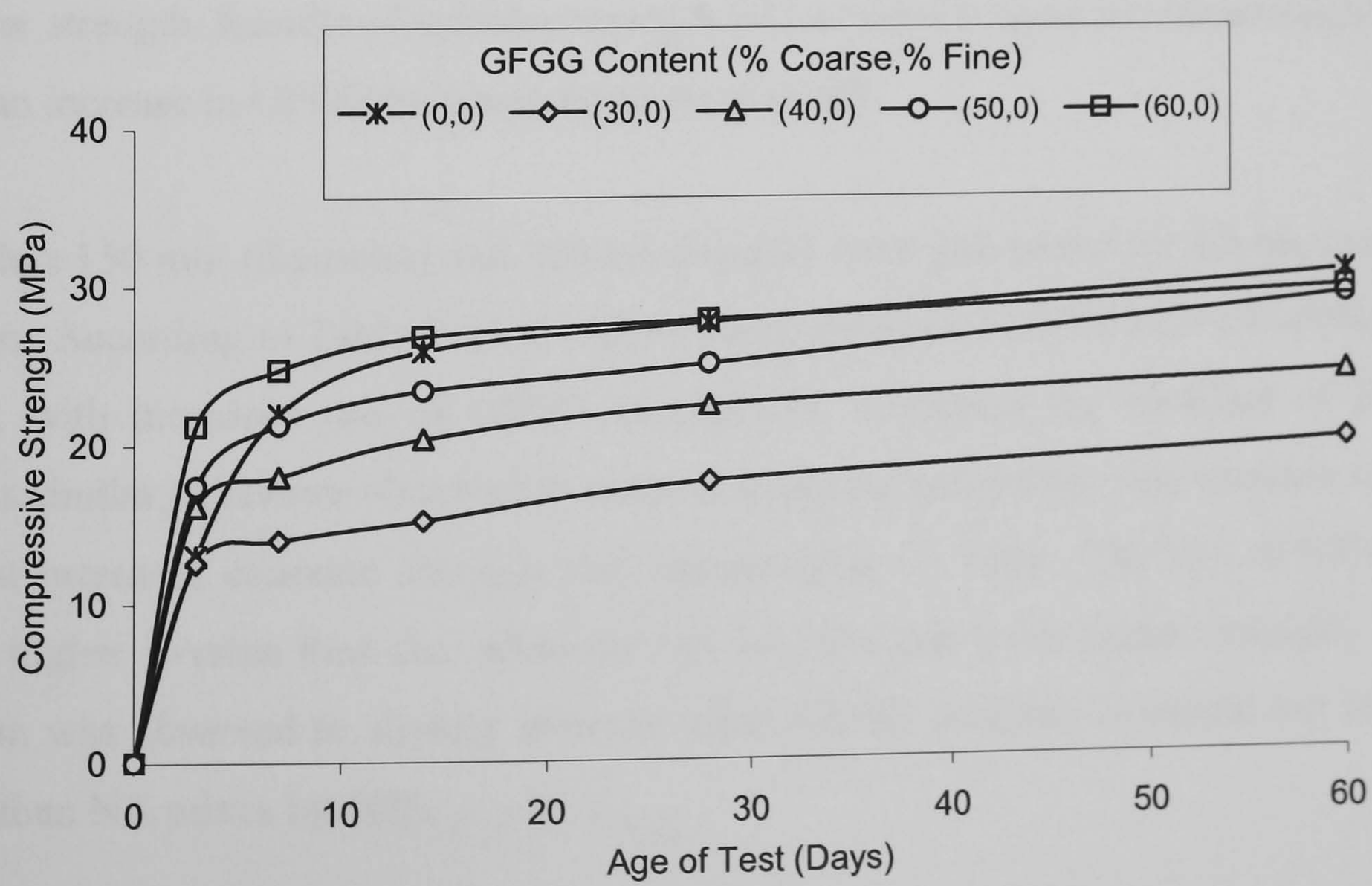


Figure 7.10 Strength Development of GFGG Concretes Containing; %Coarse GFGG; (28-Day Strength-MPa) (curing: 20ºC water, *GFGG Source: Mixed Bottles*)

At 3 days of testing, mixes with 30-60% coarse GFGG, showed equal or more than 60% of the 28-day strength, while Control mix showed only around 45%. At 7 days. percentages of 28-day strength increase for all mixes with the highest being that of the 60% GFGG mix being (90%), followed by, 50, 40 and 30% GFGG and control mixes around (80-85%). At 28 days, mixes with 30-60% GFGG reached more than 75% of control mix strength (60-90%). As GFGG increased by volume, mixes tended to reach strength equal to the reference-control.

Cubes of (150mm) were also tested at 28 and 60 days of curing as shown above in Table 7.13. At 60 days, cube strength was higher than the 28-day strength by a ratio of almost 2.35 as expected since additional curing increases concrete strength. It was also shown that as the percentage of GFGG increases from 30-60% cube strength increases and becomes equal to control mix. What more, strength values were observed to be smaller than the corresponding of 100 mm cubes by a ratio of 0.97-0.99, similar to another research were 150 mm cube strength was found to be around 0.9801 of the 100 mm cube strength [68].

7.7.2 Other bulk engineering properties

Regarding cylinder strength of equal strength concrete, according to Table 7.13 above, mix with 30% GFGG reaches an average of 50% of control mix cylinder while increasing the GFGG content to 40-60% increase cylinder strength to an average of 70% of control cylinder strength. Results of cylinder strength follow similar trend to cube strength results, since an increase in GFGG increases concrete strength.

Cylinders 150 mm (diameter) and 300mm (height) were also tested for Elastic modulus at 28 days. According to Table 7.13, E-values range between 9-20 GPa for (30-60%) GFGG mixes, with increased use of GFGG in concrete increasing the modulus of Elasticity Results similar behaviour observed to other engineering properties were increase of GFGG content increases concrete strength and subsequently E- value. The use of 60% GFGG yields higher E-value than the reference mix by 20% due to its higher strength. Flexural strength was observed to slightly increase when GFGG contents increased but still being lower than NA mixes by 10%.

7.8 Concluding Remarks

In Series 1, normal weight mixes at w/c of 0.40-0.77 having as Thames Valley gravel replacement 30%-60% coarse GFGG by volume or as natural sand replacement fine GFGG (5%-15%) by volume, were cast and cube strength development, cylinder strength, modulus of elasticity and flexural strength were examined (Series1).In series 2, 30 MPa normal weight concrete was designed and coarse GFGG was used at 30-60% replacement levels by adjusting the cement content. Lightweight mixes having 100% coarse GFGG as coarse aggregate were also cast at w/c of 0.55 and 0.77 and its engineering properties were compared to those of 100% coarse Lytag and 100% Hasopor lightweight mixes.

Regarding the strength development of mixes with fine and coarse GFGG for Series 1, following the curve fitting method, results showed that is feasible to obtain 15MPa-45MPa concrete strength at 28-days using GFGG in both forms. The general trend observed at high strength concrete (w/c=0.40) was that up to 30% coarse or 15% fine GFGG could be used and had no effect on strength development, but thereafter reductions in strength were apparent. For w/c ratios higher than 0.40, as 0.55-0.62 again 30% GFGG did not cause any reduction but higher GFGG contents caused a descending behaviour in concrete strength. On average, for w/c of 0.4-0.62, the 28-day cube strength of concrete with 60% Coarse GFGG was found to be 20-30% lower than that of the corresponding NA concrete. The effect of coarse GFGG tended to become more noticeable in lower w/c ratio (high strength) concrete mixes. On low strength concrete with w/c of 0.77, no effect from the use of GFGG was observed. However, all mixes regardless of GFGG content and size, showed normal strength gain at all the w/c ratios. This was explained by the dense Interfacial Transition Zone, enhanced cement hydration and the mechanical interlocking of rough surface of GFGG with the surrounding cement paste. High strength mixes gained strength faster than low strength mixes as expected.

Original glass source (CRT or MB) did not have any major effect on cube, cylinder, flexural strength or elastic modulus. The results showed that there was no significant variation in the strength of GFGG concretes at any given GFGG content.

Other bulk engineering properties from Series 1, showed that there was a gradual reduction in Modulus of elasticity with the increased use of coarse GFGG in normal weight mixes. Reduction by 13-40% in E-value was observed with increase in coarse GFGG content

beyond 30% by volume, while theoretical values were found slightly higher than the experimental. Reason for the reduction in modulus of elasticity is the low mechanical properties and low density of GFGG compared to Thames Valley gravel, which lowers the density and stiffness of concrete, in combination with the segregation during casting which lead to poor particle packing, reduction in concrete strength and thereafter reduction in modulus of elasticity. No reduction in E-value was observed for fine GFGG concretes since NA was not replaced so stiffness and density were not changed, segregation phenomenon was not more evident as with coarse GFGG mixes and the fact that fine GFGG has better particle packing than natural sand.

Flexural strength was within the expected range for normal weight concrete being 10-20% of cube strength for 30-60% GFGG contents. As expected, the flexural strength increased with strength but with slower rate than the compressive strength. In order to derive reliable equation for the relationship between flexural strength and cube strength as well as modulus of elasticity and cube strength further testing will be required examining additional concrete strength ranges.

Drying shrinkage of 30-50% GFGG concrete mixes did not exceed the allowable limit. However, there was an increase in the value of shrinkage by almost 16% with GFGG increase due to the higher compressibility of the material compared to NA and higher tendency of the matrix for water movement. Regardless of GFGG content (30-50%), drying shrinkage values remained less than 650 $\mu\varepsilon$ at 8 weeks (56 days) conforming to relevant standards.

Results from Series 2, where cement adjustment took place to compensate for the effect of coarse GFGG as shown from Series 1, show that as proportion of GFGG increases from 30-60% by volume, strength increases accordingly. This behaviour is expected since correction in cement amount took place (increase by 28% by mass compared to Control) when increasing GFGG content from 30-60% by volume. Mix with 60% GFGG reached the NA concrete mix. Similar results were observed for other bulk engineering properties. With proper cement adjustment to compensate for the inferior performance of GFGG, concretes of normal strength can be designed.

Lightweight mixes showed decreased cube, cylinder, flexural strength and elastic modulus compared to normal weight mixes as expected, since the mechanical properties and cement content in these mixes highly affected the concrete performance. However strength results were comparable to other lightweight mixes at similar water/cement ratios.

On the whole, none of the Hasopor concretes reached the design strength set for NA concrete. Results show considerable reduction in flexural strength and modulus of elasticity for concrete produced with 100% coarse Hasopor. There is a further reduction when 100% all-in Hasopor is used. Concrete produced with all-in Hasopor was found to be too weak for these tests, indicating unsuitability of this aggregate for use in structural concrete. Compressive strength of dry-mixed Hasopor concrete was found to be comparable to those reported for commercially available bags for paving and general concrete applications. It is also clear that the use of silica fume had a significantly positive influence on cube strength of Hasopor concrete. Similar trends were observed in the compressive cylinder strength results, and other bulk engineering properties. Comparing GFGG lightweight mixes with Hasopor it was observed that GFGG performed better due to its inferior physical and mechanical properties.

Results show that the use of 100% Lytag, by volume, causes no major decrease in strength development in concretes with w/c of 0.55-0.62. At higher w/c ratios (0.77) Lytag concrete cube strength was higher than that of NA concrete by 20-30%. It is also observed that as w/c ratio decreases, strength of Lytag concrete increases accordingly. A dramatic reduction (50%) of Modulus of elasticity was observed compared to NA mixes due to lower mechanical properties of Lytag compared to NA and lower density than NA which cause reduction in strength and elastic modulus. Similar reduction was observed for cylinder and flexural strength. Lytag concretes showed higher strengths than the corresponding GFGG lightweight mixes, owing to their reduced segregation during compaction and casting of concrete.

CHAPTER 8

DURABILITY PERFORMANCE OF FGG CONCRETE

8.1 Introduction

Concrete durability has been defined by the American Concrete Institute as its resistance to weathering action, chemical attack, abrasion and other degradation processes [74]. Durable concrete is assumed to remain intact throughout its intended life. Durability depends on the ease with which fluids, both liquids and gases, can enter into, and move through, the concrete; this is commonly referred to as a permeability of concrete [50]. The movement of gases, liquids and ions through concrete is important because of their interactions with concrete constituents and the pore water which can alter the integrity of concrete directly and indirectly, leading to the deterioration of structures (corrosion of reinforcement and cracking due to excessive carbonation and Alkali-Silica Reaction gel.

The durability of any concrete against environmental attack is dependent upon the permeability of that concrete, which determines how fast aggressive soluble chemicals enter the concrete. There are many factors affecting permeability and these are: hardened cement paste (hcp), Interfacial Transition Zone (ITZ), porosity of concrete, w/c ratio and aggregate morphology. Most of the important properties of hardened concrete are related to the quantity and characteristics of various types of pores in the cement paste and aggregate components of the concrete. The total volume of pores, not their size or continuity affects the strength and elasticity of concrete, whereas concrete permeability is influenced by pore volume, size and continuity. It is believed that capillary voids larger than 50 μm, referred to as macro pores, are detrimental to strength, whereas voids less than 50 μm, referred to as micro pores, are more related to durability properties (drying shrinkage and creep) [76]. If the porosity (proportion of the total volume of concrete occupied by pores) is high (high water content) and the pores interconnected, they contribute to transport of fluids through concrete so that its permeability is also high [35]. The pores relevant to permeability are those with a diameter greater than 120 nm and have to be continuous. Pores, which are ineffective with respect to flow, are that is to permeability, in addition to discontinuous pores, those, which contain absorbed water, which have a narrow entrance, even if the pores themselves are large [50].

During previous several decades, the problem of how to make a durable concrete for use in its environment has been discussed by many concrete researchers and practitioners. At the same time, standards and building codes (BS EN 206-1; BS 8500) have placed limitations on the quality and quantity of constituent materials used in concrete, as well as specifying the proper processing of concrete, i.e mixing, transportation, placing, compaction and curing, in order to prolong a service life of concrete. Such requirement criteria are essentially based on long-term experience with materials, particularly natural aggregates that have been used under certain exposure conditions. However, this may not be transferable to a new material such as FGG. Since physical and mechanical characteristics of FGG quite differ from that of NA investigation is required to assess FGG concrete performance in physical and chemical environments.

To date, very limited data are available on the durability performance of FGG concrete designed to have water and cement content equivalent to corresponding NA concrete, and even for equal strength FGG and NA concrete.

The main aim of this chapter was to determine the effect especially of Geofil-FGG content and sources on aspects of concrete durability. Tests for the permeation property (near surface absorption) and determination under exposure to the main chemical processes of attack were considered (carbonation resistance and ASR).

8.2 Experimental Programme

This part of research has a specific aim to examine the effect of coarse and fine GFGG content on the selective durability related properties of concrete, and compare it with the corresponding NA concrete. Three main aspects of durability relevant to lightweight GFGG concrete mixes were considered. These included surface absorption, carbonation resistance and ASR.

8.3 Near Surface Absorption

Almost all process of physical and chemical attacks that may cause deterioration to the concrete structure involve permeation of water, gases and other aggressive substances into concrete. Such permeability is considered to represent a material parameter, which could serve as a performance criterion for concrete durability. Of the permeation tests available,

the initial surface absorption test (ISAT) was selected in this study, mainly because of simplicity, ease of performance and producing repeatable results. Also, test results of ISAT can be used to estimate the results of other permeation test satisfactorily. The near surface absorption characteristics of GFGG and NA concretes described by measurement taken at 10 minutes (ISA-10) after initiation of the tests and rate of decay (n-value). This is because both ISA-10 and n-value are indicative of concrete quality surface, in particular at low to medium strength, which is often vulnerable to deterioration.

8.3.1 Effect of coarse GFGG content

The ISA test results obtained for a range of w/c ratio concrete mixes cured under 20°C water are shown plotted in Figures 8.1-8.4. Figures 8.1-8.4 show that for the 28 day-ISA-10 minute value, up to 30% GFGG did not have a major effect, when compared to Control mix. As the proportion of GFGG increased from 30-60% 10-minute water absorption increased for both 28 and 60 days of testing. At 100% GFGG replacement level, the 10-minute value was significantly higher than the Control at all times. From Figure 8.1-8.4 it is also evident that at 60 days of testing, ISA-10 values of water absorption are lower when compared to 28 days.

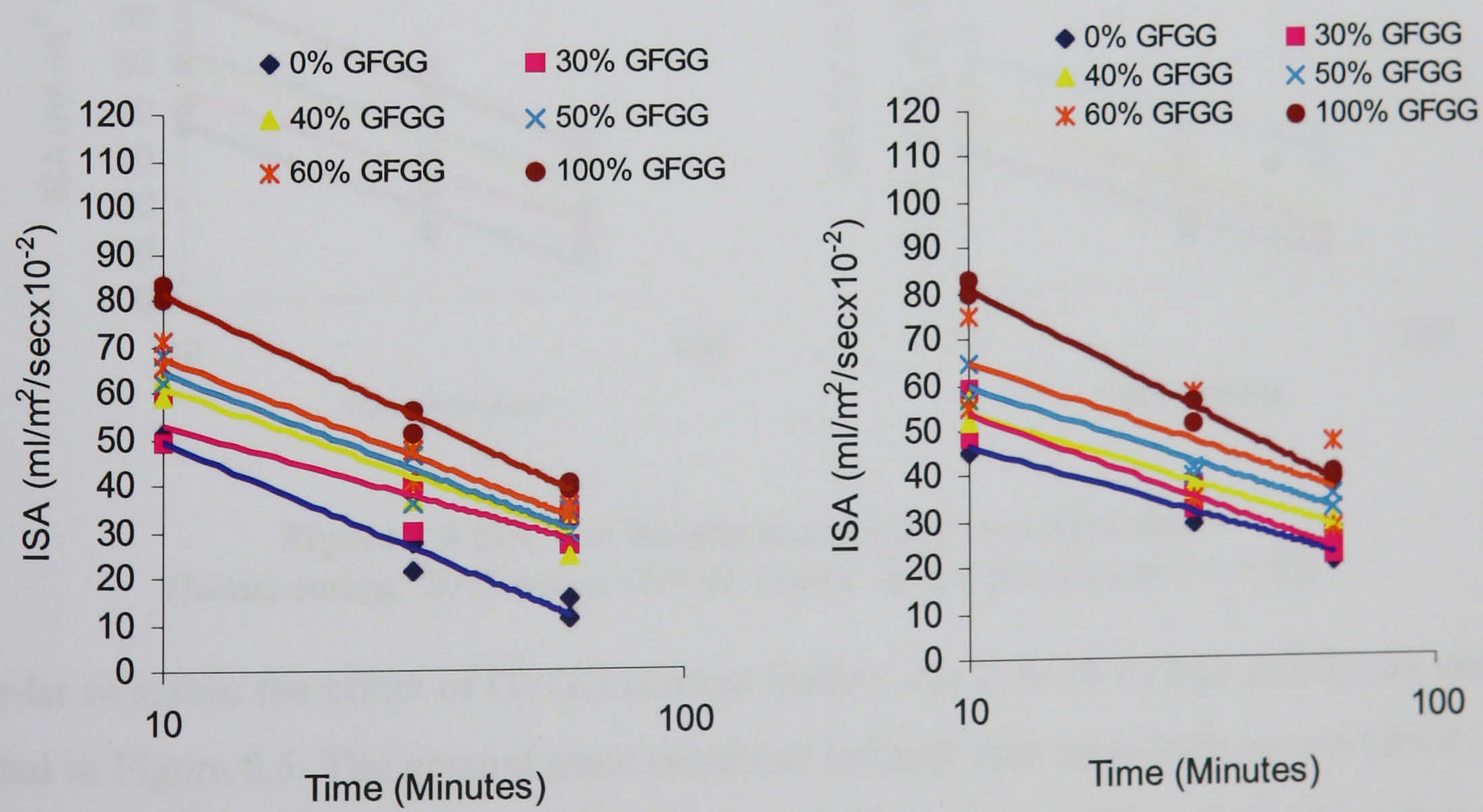


Figure 8.1 ISA Test Results at a) 28-days and b) 60 days
(Initial curing; 20ºC water; *GFGG source: Mixed Bottles*) (w/c= 0.77)

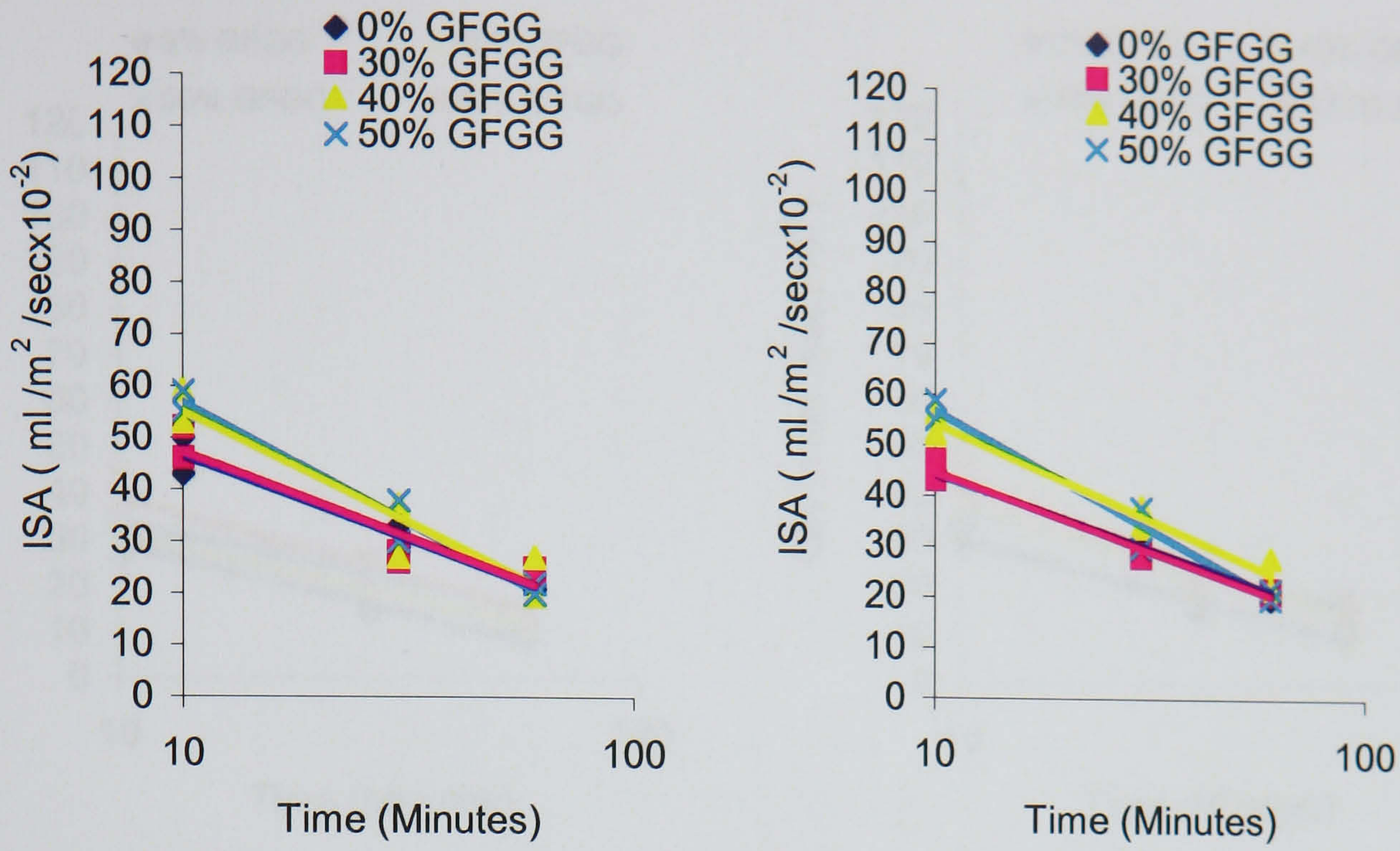


Figure 8.2 ISA Test Results at a) 28-days and b) 60 days
(Initial curing; 20ºC water; *GFGG source: Mixed Bottles*) (w/c = 0.62)

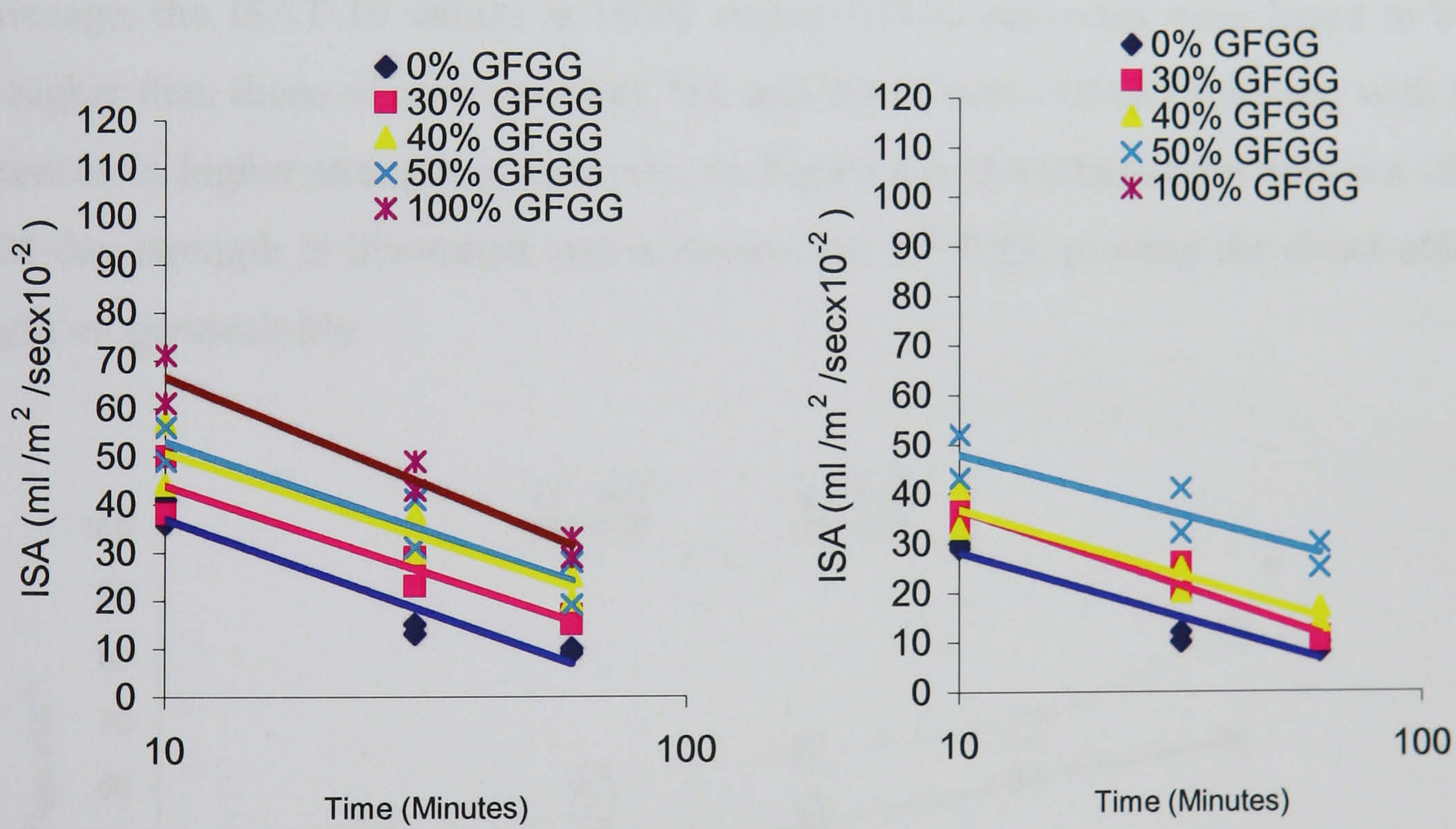


Figure 8.3 ISA Test Results at a) 28-days and b) 60 days
(Initial curing; 20ºC water; *GFGG source: Mixed Bottles*) (w/c = 0.55)

In order to assess the effect of GFGG content further, the ISA-10 minute results are shown plotted in Figure 8.5. The general trend observed indicate that up to 30% coarse GFGG has beneficial influence on the ISAT-10 results; with improved ISA values than those of corresponding NA concrete. However, thereafter ISA-10 was found to increase with GFGG content. Such increase in surface absorption of concrete with high level of GFGG is though to be directly related to reduction in compressive strength (increase of w/c ratio) as shown in Figures 8.5.

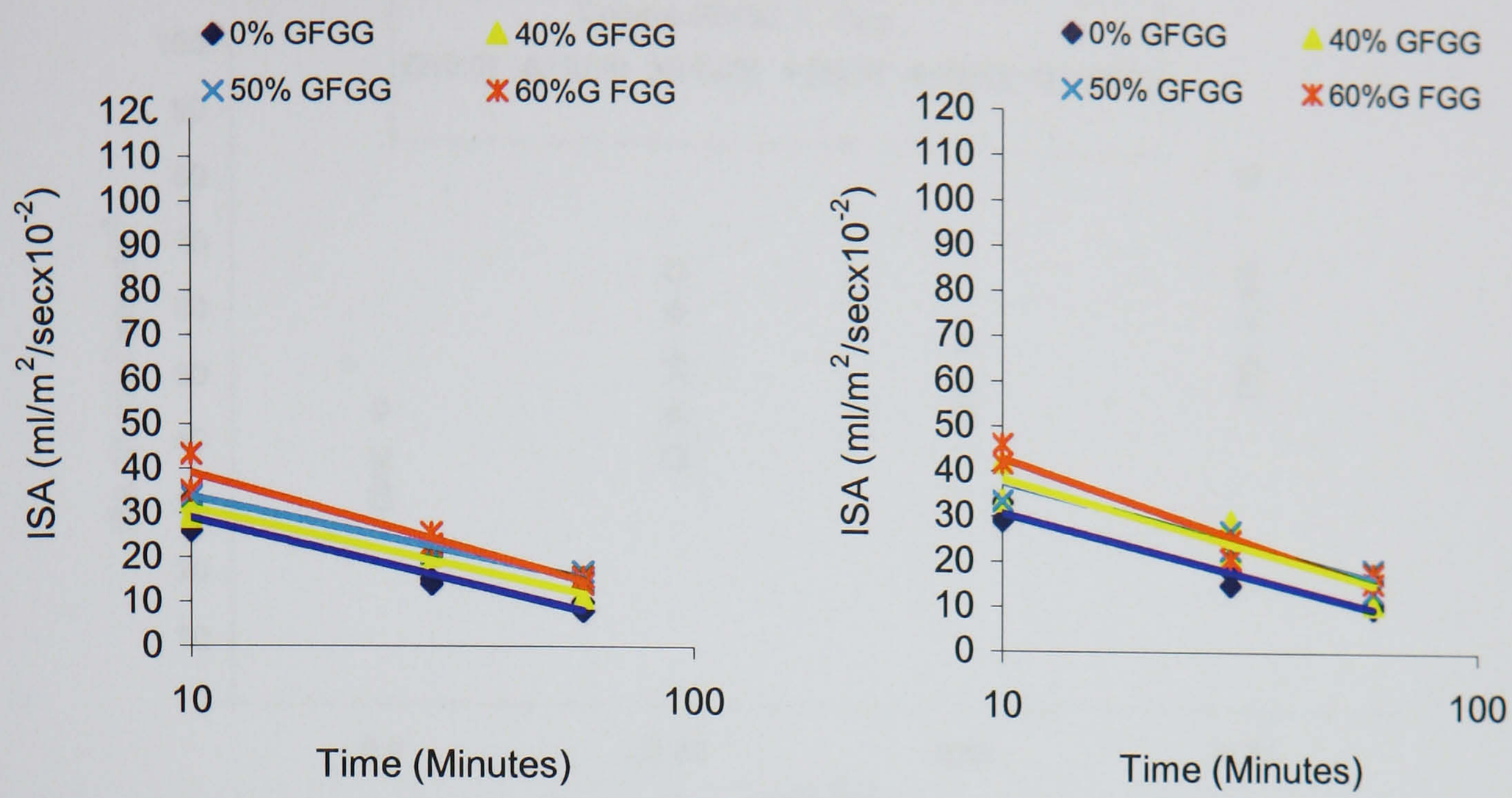
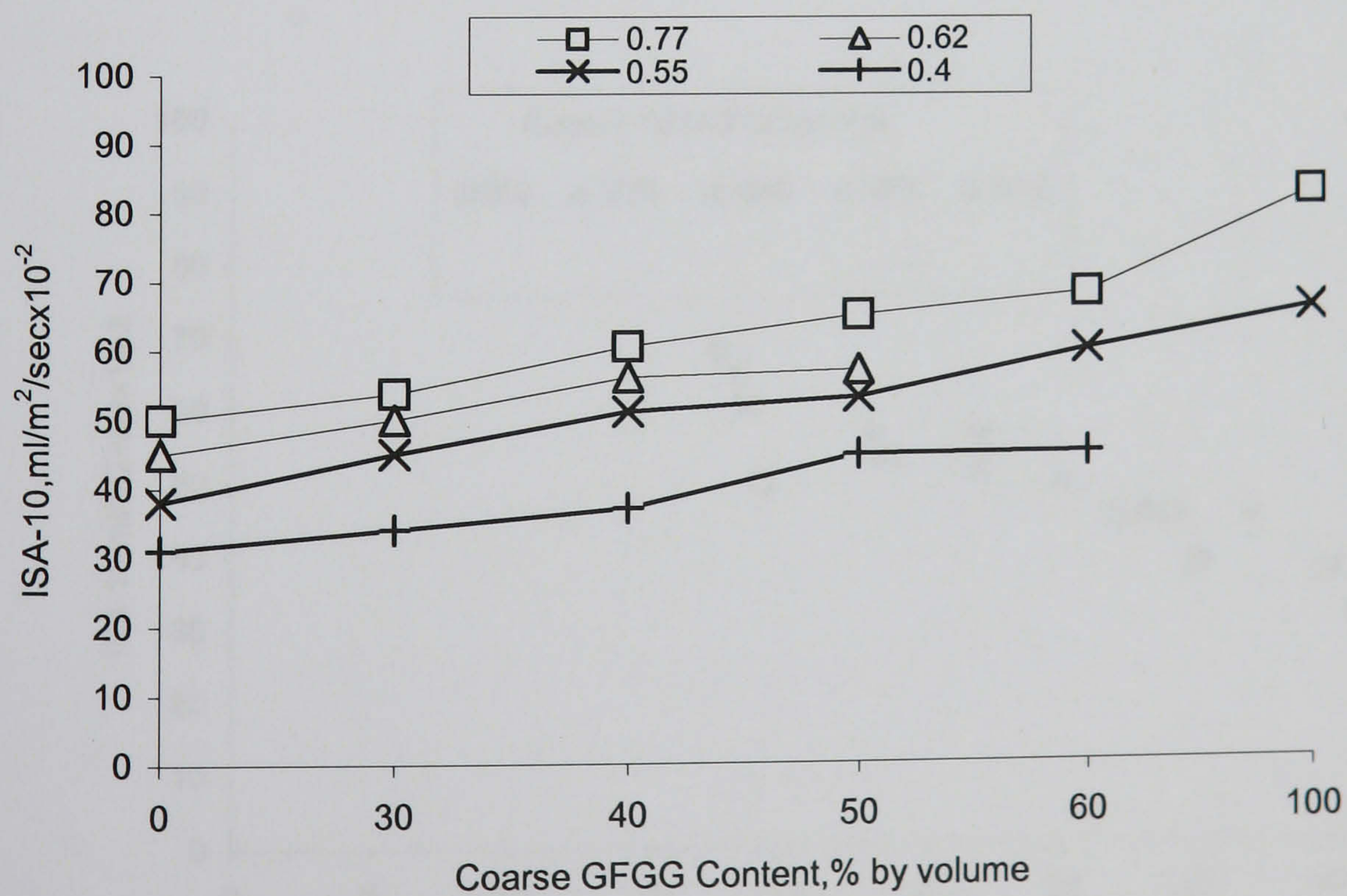


Figure 8.4 ISA Test Results at a) 28-days and b) 60 days
(Initial curing; 20ºC water; *GFGG source: Mixed Bottles*) (w/c= 0.40)

On average, the ISAT-10 values at 100% coarse GFGG concretes were found to be 35-70% higher than those of corresponding NA and 30% Coarse GFGG concrete, with lower differences in higher strength of concrete. In Figure 8.6, the relationship between ISA-10 and 28-day strength is illustrated and is shown that R^2=0.93, proving the direct effect of strength on permeability.



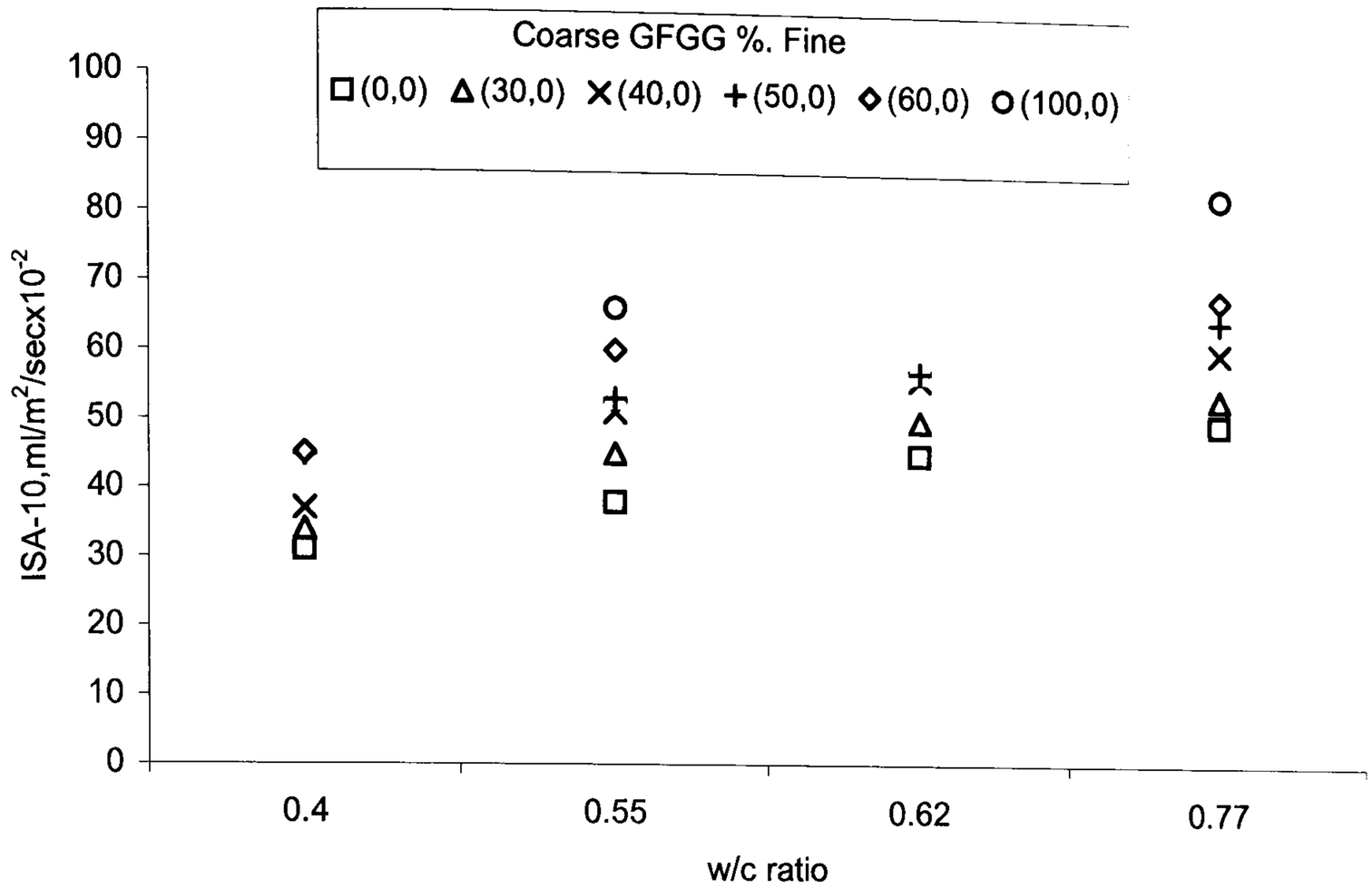


Figure 8.5 Effect of Coarse (0-100%) GFGG Content at ISA-10 for Concrete Mixes at w/c 0.4-0.77 (Initial curing; 20°C water; *GFGG source: Mixed Bottles*)

Further analysis of ISAT results were carried out to determine n-value, which reflects the delay in the absorption rate with time. The relationship between n-value and w/c ratio, considering the effect of coarse GFGG are shown in Figure 8.7. As expected, for both Na and GFGG concrete, the near surface absorption characteristics were improved as w/c ratio and GFGG content decreased. This is due to the combined effects of slower moisture evaporation rate and faster hydration rate with an increase in cement content.

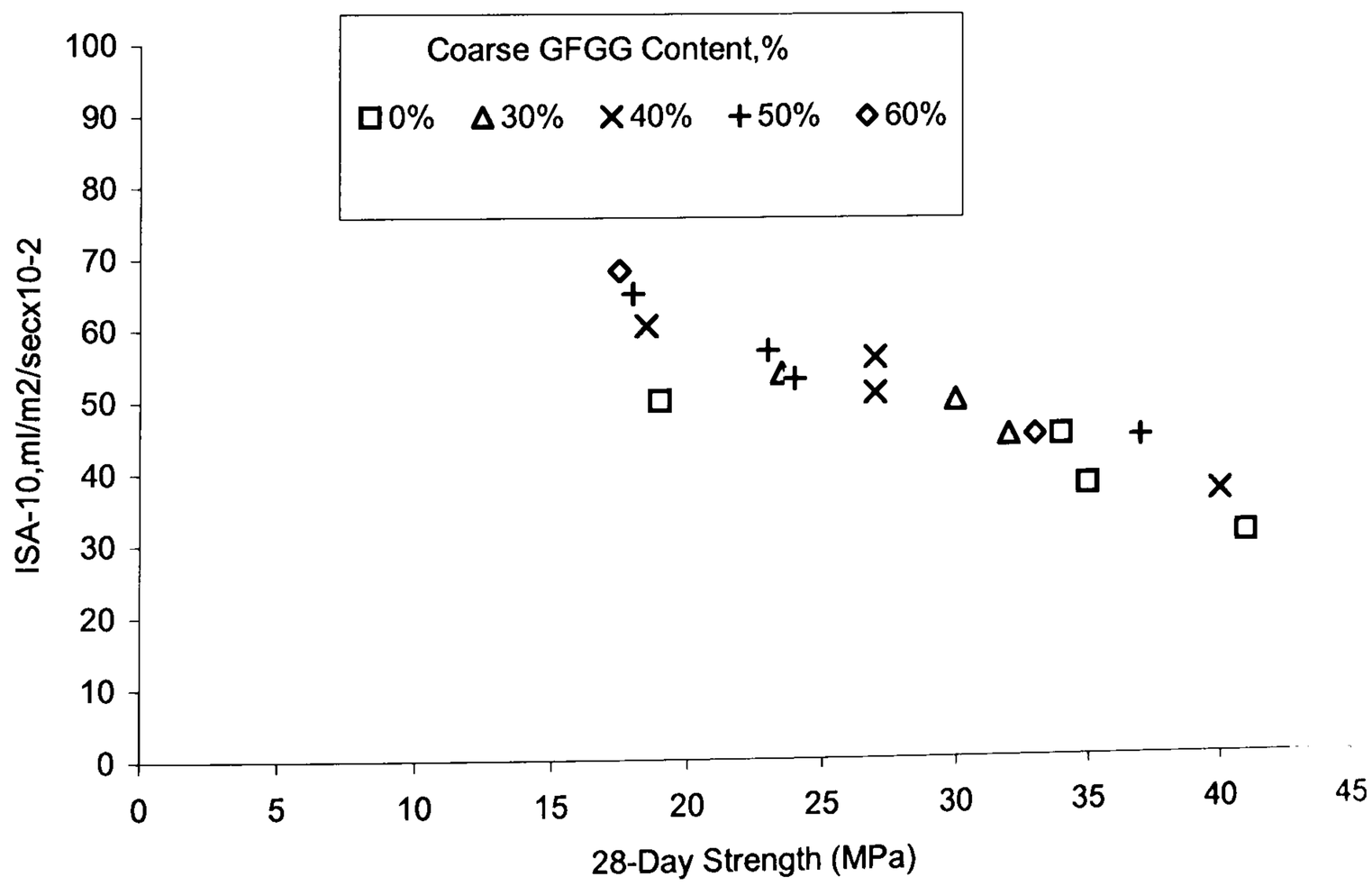


Figure 8.6 Relationship between ISAT-10 and 28-Day Strength for Concrete Mixes with Coarse GFGG (0-60%), (Initial curing; 20°C water; *GFGG source: Mixed Bottles*)

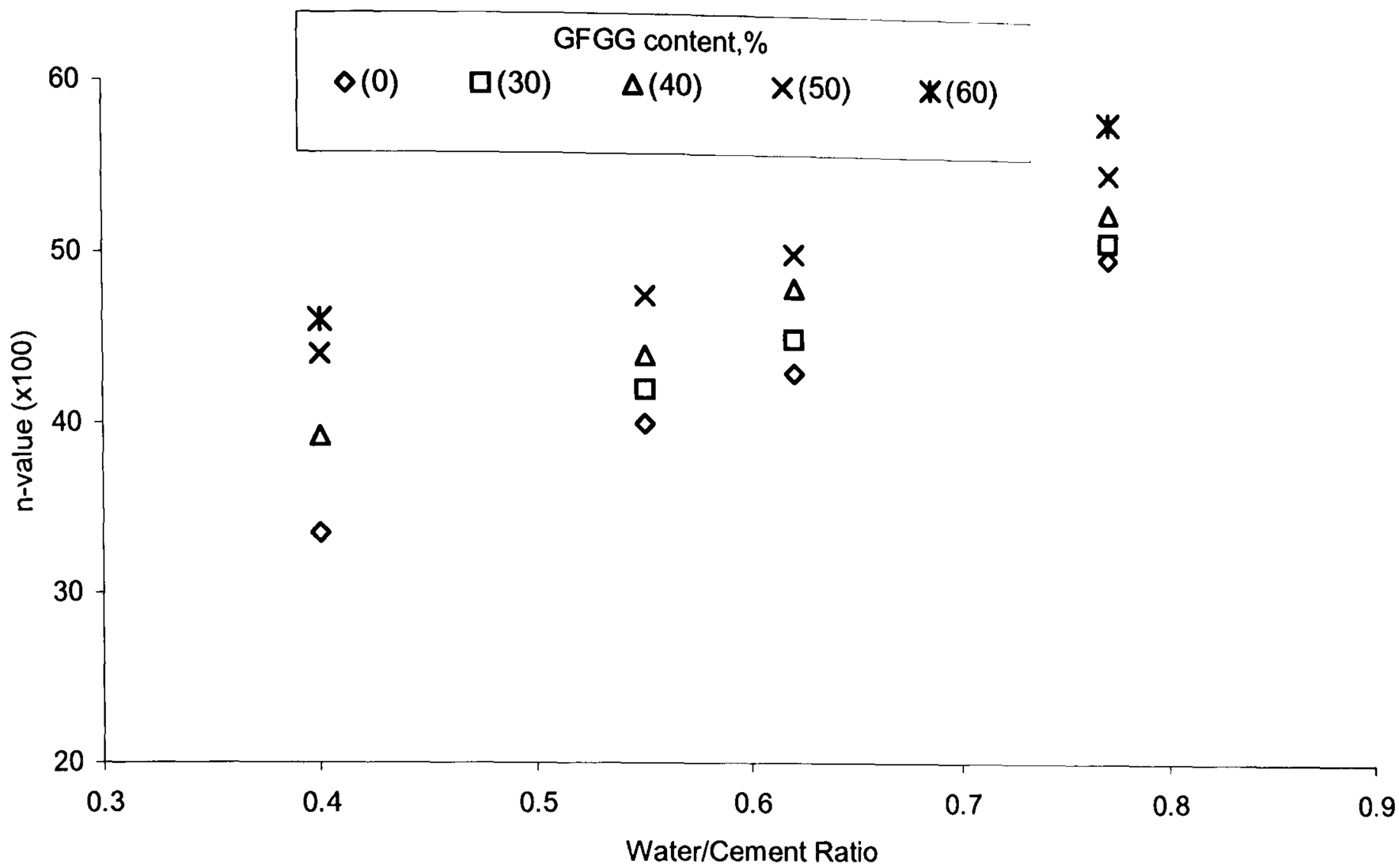
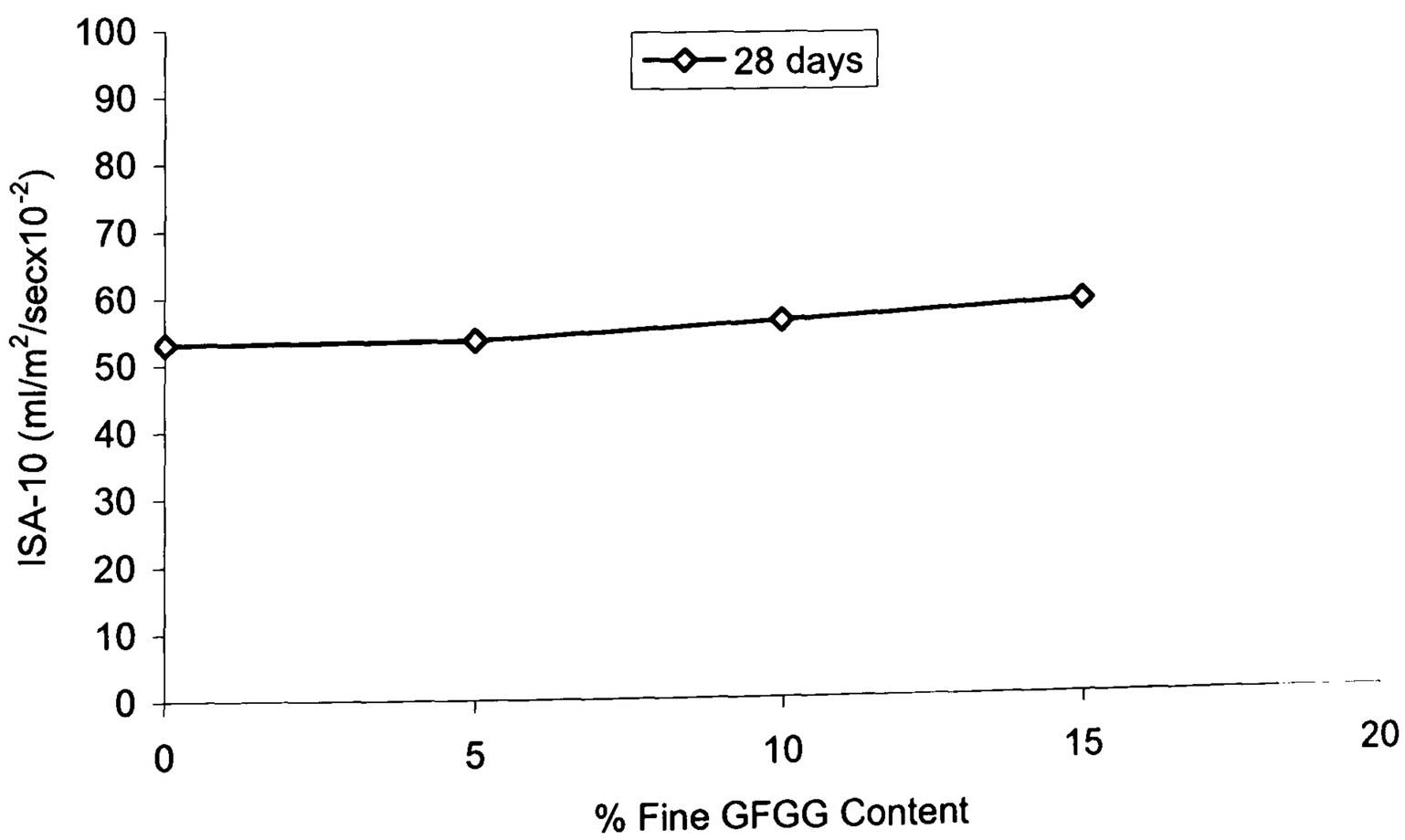


Figure 8.7 Relationship between n-value versus w/c Ratio of Concrete Made of NA and (0-100%) Coarse GFGG, (Initial curing; 20°C water; GFGG source: Mixed Bottles)

8.3.2 Effect of Fine GFGG

The ISA-10 and n-value obtained for equal strength cement and water content NA and fine GFGG concrete mixes cured under standard 20 °C water are shown in Figures 8.8 and 8.9 respectively.



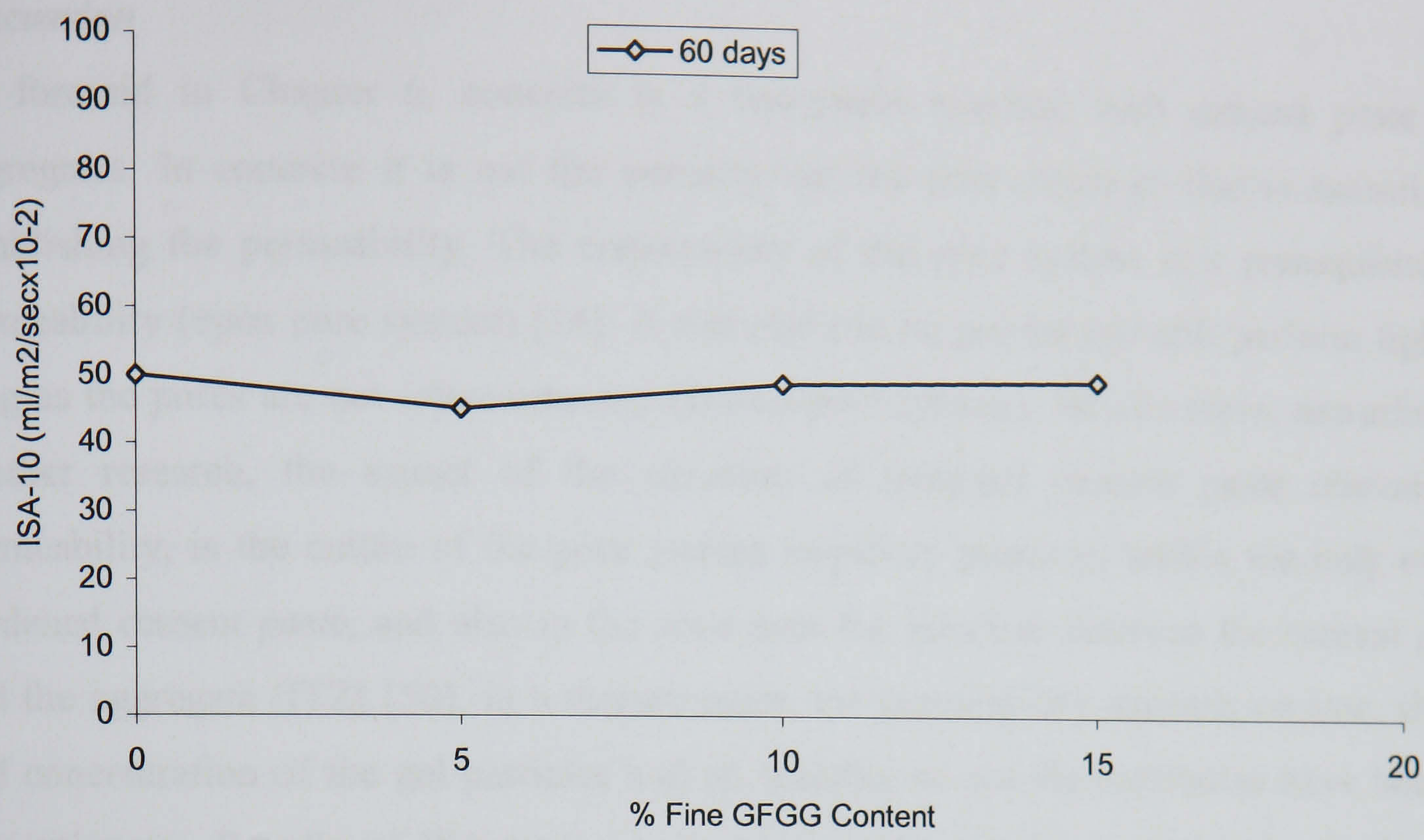


Figure 8.8 Effect of Fine GFGG Content on a) 28-Day and b) 60-day ISA-10 (Initial curing; 20ºC water; *GFGG source: Mixed Bottles*)

The general trend observed indicate reduction in ISA-10 values with increase in fine GFGG content from 5-15% by volume, exhibiting improved performance. This is maybe due to filler effect of fine GFGG. On the other hand, n-values for NA and fine GFGG concrete mixes remain within a narrow band. On the whole, according to Figure 8.9, n-value seems to decrease considerably with increase in fine GFGG content. As expected, similar trends were observed in 60-day results.

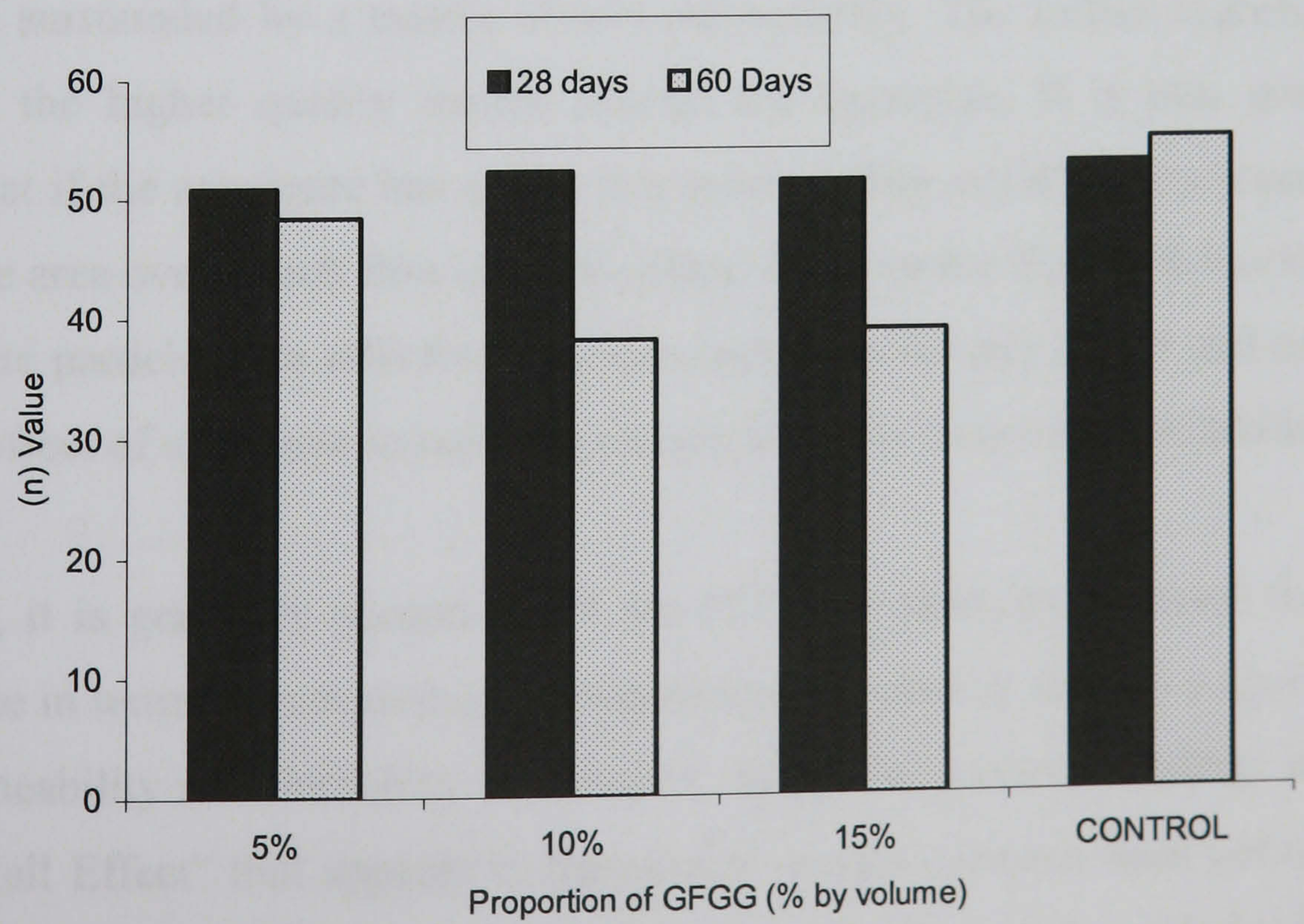


Figure 8.9 Rate of Decay (n) For Mixes with w/c 0.4 at 28 and 60 Days (Fine GFGG) (Initial curing; 20ºC water; *GFGG source: Mixed Bottles*)

Discussion

As foresaid in Chapter 6, concrete is a two-phase material with cement paste and aggregates. In concrete it is not the porosity but the pore structure that is essential in establishing the permeability. The connectivity of the pore system is a prerequisite for permeability (open pore system) [14]. A material can be porous and still perform tight as long as the pores are not interconnected (closed pore system). What's more, according to another research, the aspect of the structure of hydrated cement paste relevant to permeability, is the nature of the pore system (capillary porosity) within the bulk of the hardened cement paste, and also in the zone near the interface between the cement paste and the aggregate (ITZ) [50]. In a mature paste, the permeability depends on size, shape, and concentration of the gel particles and on whether or not the capillaries have become discontinuous. Results of ISA tests are in agreement with these observations, since as concrete strength increased (higher percentage of gel particles, little connected porosity), permeability decreased (lower ISA-10 and n-values).

GFGG, especially fine, according to SEM images (Chapter 5) was shown that has closed, little connected pore system and water absorption slightly higher than NA but a lot lower than other lightweight aggregates (Hasopor, Lytag). A result was that its use (30 and 15% for coarse and fine GFGG respectively) did not cause a major increase in water ingress and cement paste performed satisfactorily in terms of permeability. In addition, the water absorption of GFGG may contribute to reduce the free water/ cement ratio in ITZ zone so GFGG was surrounded by a matrix of low permeability. The further ingress of water is resisted by the higher quality matrix around the aggregate. It is also proved from a research, that if the aggregate has a very low permeability as GFGG, its presence reduces the effective area over which flow can take place. Because the flow path has to circumvent the aggregate particles, the effective path becomes considerably longer and more tortuous so that the effect of aggregate in reducing the permeability may be considerable [50].

In addition, it is generally accepted that the ITZ is profoundly different from the bulk cement paste in terms of morphology, composition and density and has a significant effect on the permeability and durability of concrete. Based on previous findings it was shown that the "Wall Effect" that appears in the normal weight concrete does not occur at such extent on the ITZ of GFGG concrete. This is because the porous and rough surface of GFGG provides sites for the HCP to merge across the interfacial zone and improves the

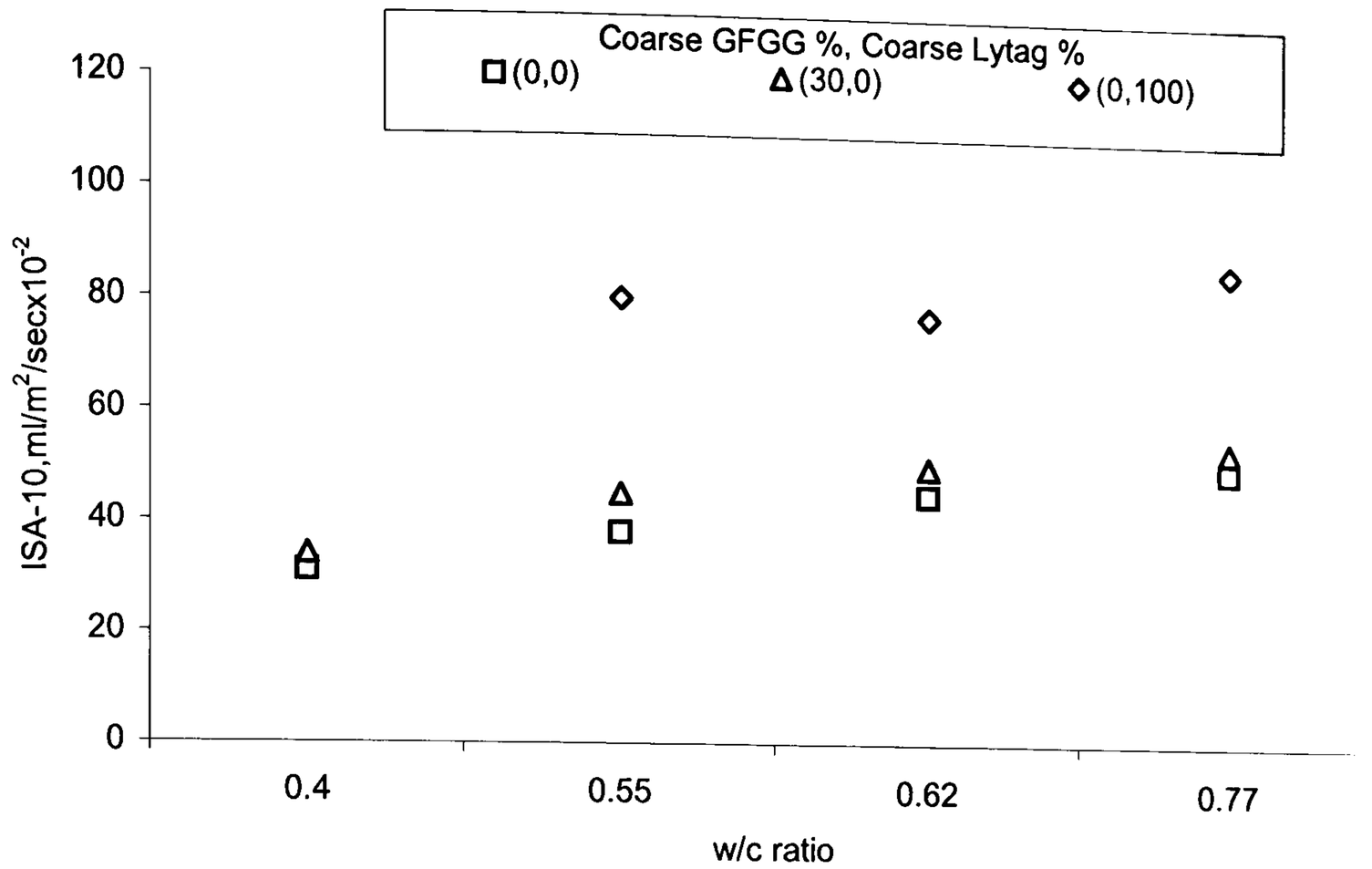
interaction mechanism between the aggregate and the matrix, the phenomenon representing the mechanical interlocking of the GFGG to the cement paste. Results are in agreement with another study examining permeability of lightweight aggregate concrete (LAC), where it was shown that the water ingress of LAC was lower than that of normal aggregate concrete (NWC) due to more unified and improved ITZ [77].

However, a higher use of GFGG would cause a significant increase in permeability as shown before for 50-100% coarse GFGG concrete, due to honeycombed structure presenting high porosity and lack of cement paste. This phenomenon is firstly due to the presence of capillary pores and secondly due to the absence of cement gel especially at high w/c ratios; the capillaries become segmented so that there is a substantial difference in permeability between mature cement pastes with a water/cement ratio below 0.4 and those with higher water/ cement ratio [50]; water can flow easier through the capillary pores than through the cement gel. In general, durability results are in agreement with engineering results, where concrete with 100% GFGG concrete was found to have very low strength at w/c of 0.55 and 0.775.

8.3.3 Lytag near surface absorption

A comparison of ISA-10 results of concrete mixes with NA, 30% coarse GFGG and 100% coarse Lytag aggregate, versus w/c ratio is provided in Figure 8.10 a), while in Figure 8.10 b) a comparison is given between n-values of GFGG concrete mixes with that of Lytag mixes.

According to Figure 8.10, regarding the ISA-10 results from Lytag mixes, is evident the higher water absorption of the aggregate compared to NA and 30% GFGG. Reason for this can be the higher water absorption ability of the Lytag, which was reported during characterisation tests, resulting in a porous ITZ and cement paste. Results of n-value show an increase in value when Lytag is used in concrete, as expected, followed by 30% coarse GFGG and NA. However, permeability properties are improved as concrete strength increases.



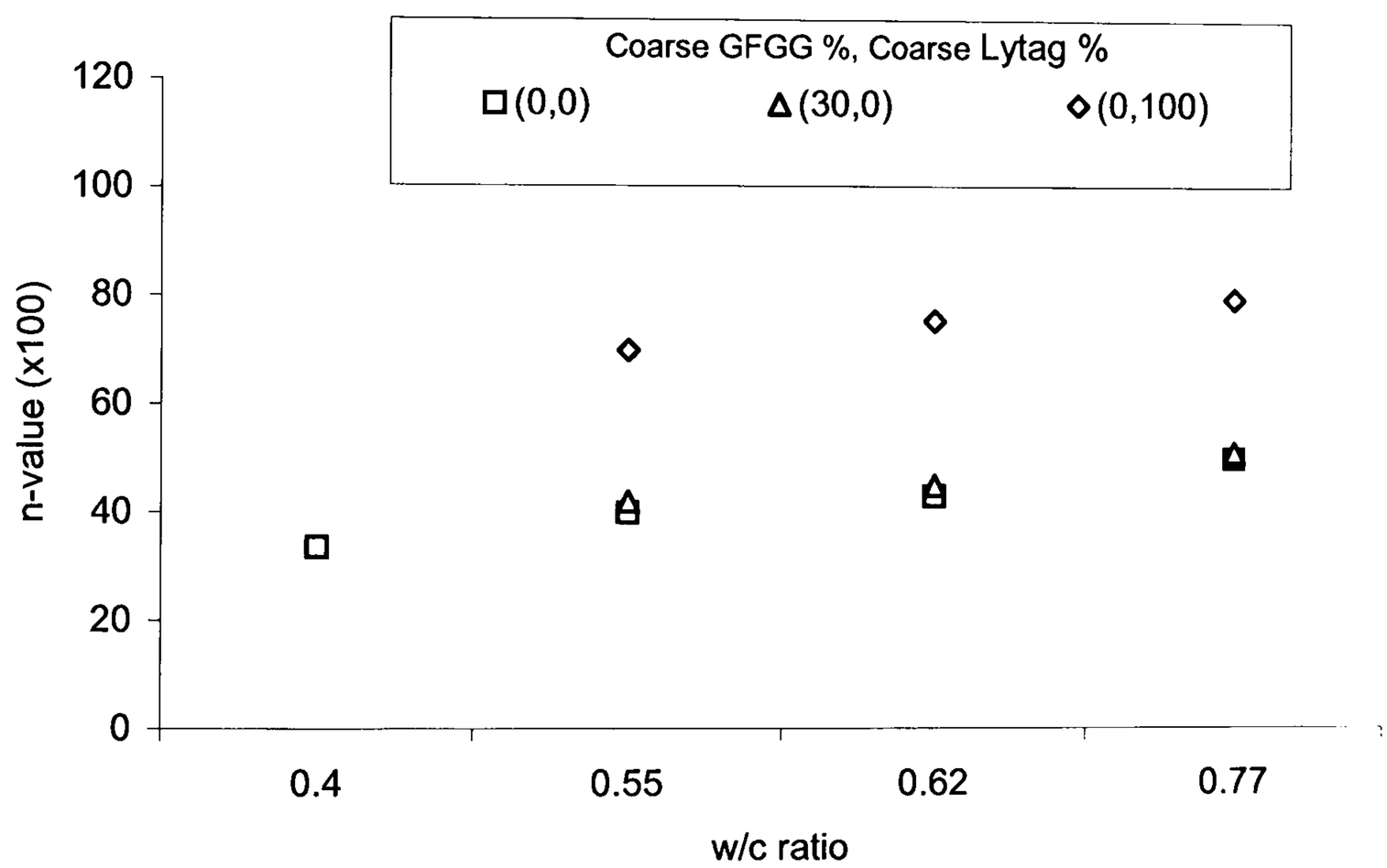


Figure 8.10 Relationship Between ISAT-10, n-value and water/cement ratio of NA, 30% Coarse GFGG and 100% Coarse Lytag Concrete (Initial curing; 20°C water; *GFGG source: Mixed Bottles*)

8.3.4 Comparison with Equal strength concrete

As mentioned earlier (section 4.3.2 Chapter 4), using 28-day cube strength results of all concrete mixes, the adjustment necessary to w/c ratio of GFGG concrete to achieve strength equivalent to corresponding NA concrete was determined. In order to assess its influence on surface absorption, ISAT data were further analysed and ISAT-10 and n-value results are given in Table 8.1 together with 28-day cube strength results.

Table 8.1 ISAT-10 Results of 30 MPA Concrete at Equal Design Strength
(Initial curing; 20°C water; *GFGG source: Mixed Bottles*)

Concrete Type	28-Day Cube Strength (MPa)	ISAT-10 ($ml/m^2/sec x 10^{-2}$)	n-value ($x 10^{-2}$)
NA	*28.0*	*47.0*	*43.0*
Coarse GFGG, % by volume			
30%	17.5	57.0	44.0
40%	22.5	54.5	48.0
50%	25.0	46.0	47.5
60%	28.0	38.0	41.0

The results showed that ISAT-10 values of GFGG concrete, designed to have strength equivalent to the corresponding NA concrete via increasing cement content, were found to be remaining almost the same as NA concrete. However, ISAT-10 values were found to be reduced by 20% in 60% coarse GFGG concrete compared to their corresponding NA concretes, similar to strength result's trend. In general, satisfactory ISAT-10 and n-values within the allowable limits can be obtained.

8.4 Carbonation Rate

8.4.1 Introduction

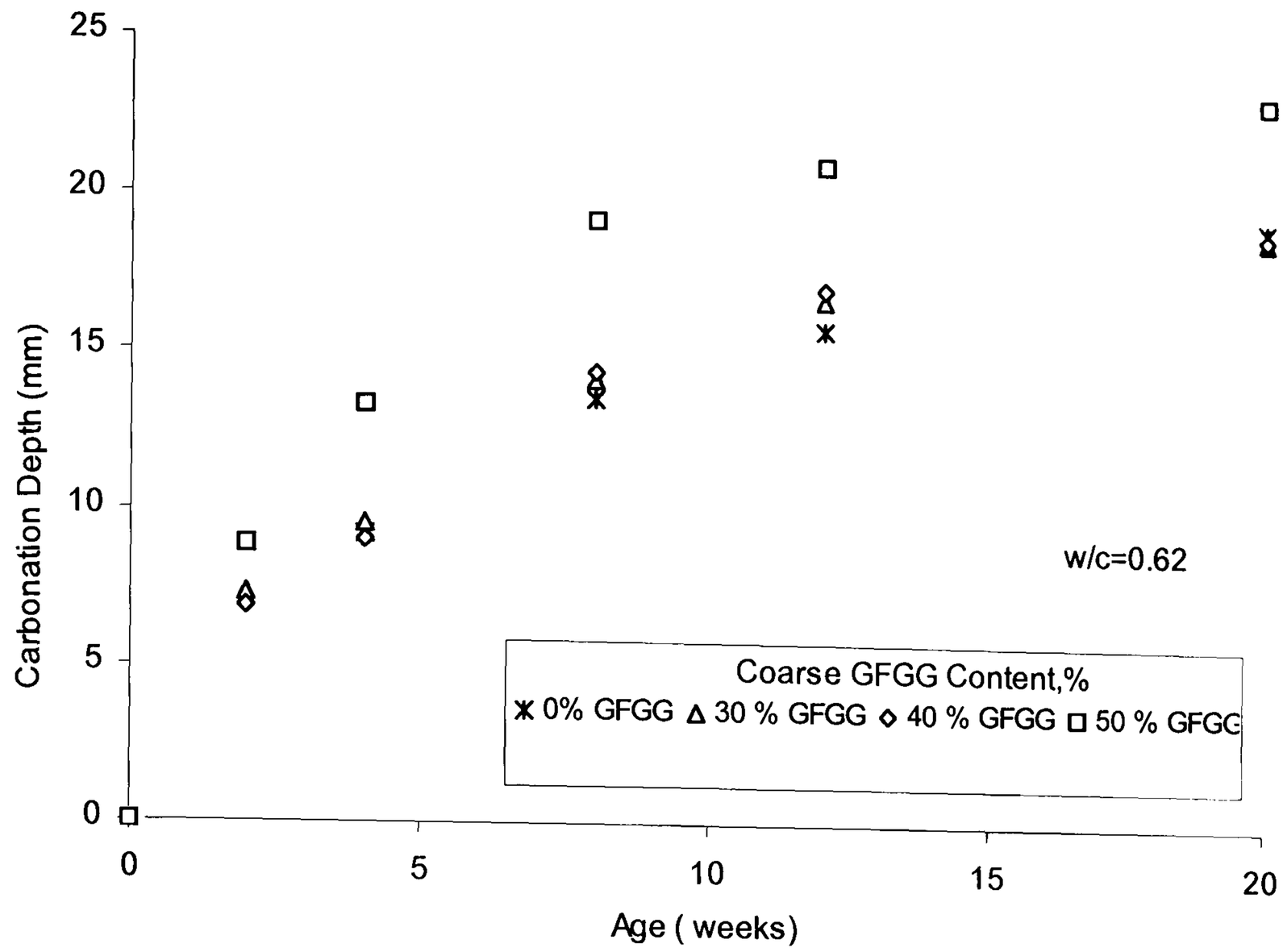
Carbonation occurs in concrete because the calcium bearing phases ($Ca(OH)_2$) present within the matrix are attacked by carbon dioxide (CO_2) from the air and converted to calcium carbonate ($CaCO_3$). The concrete will carbonate if CO_2 from air or from water enters the concrete: $Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$ [78,79].

On the other hand, when $Ca(OH)_2$ is removed from the paste, hydrated calcium silicate hydrate (CSH) will liberate calcium oxide (CaO) which will also carbonate. The rate of carbonation depends on porosity and moisture content of the concrete. Generally high w/c ratio leads to higher carbonation rate. The carbonation process requires the presence of water because CO_2 dissolves in water forming H_2CO_3. If the concrete is too dry (RH less than 40%) CO_2 cannot dissolve and carbonation may not occur. If on the other hand, if concrete is too wet (RH greater than 90%) CO_2 cannot enter the concrete and it will not carbonate. Optimal conditions for carbonation to occur are at around 50% RH (range 40-90%) [78,79].

Carbonation is a particularly important form of deterioration. Strangely enough carbonation may give the immediate positive effects of increased compressive strength, modulus of elasticity, surface hardness, and resistance to frost and sulphate attack [79]. However, more importantly, it reduces the alkalinity of the concrete, which leads to the corrosion of the reinforcing steel. Normal carbonation results in a decrease of the porosity making the carbonated paste stronger. Because $CaCO_3$ occupies a greater volume than Ca $(OH)_2$ which it replaces, the porosity of carbonated concrete is reduced. Also, water released by Ca $(OH)_2$ on carbonation may aid the hydration of hitherto un-hydrated cement. These result in increased surface hardness, increased strength and decreased permeability, reduced moisture movement and increased resistance to those forms of attack which are controlled by permeability [50]. Carbonation is therefore an advantage in non-reinforced concrete. However, it is a disadvantage in reinforced concrete, as pH of carbonated concrete drops to about 7; a value below the passivation threshold of steel.

8.4.2 Carbonation testing

The most important factor controlling carbonation is the diffusivity of the hardened cement paste. During this study, in order to examine diffusivity of up to 100% GFGG concrete, different mixes were produced with 0.62 and 0.77 w/c ratios, with enriched 4% CO_2 environment (at 20°C and 53% RH) and finally tested. GFGG samples produced from mixed bottle glass were used to examine the effect of GFGG content on carbonation rate. The depth results of carbonation measured at testing ages of 2, 4, 8, 12 and 20 weeks for w/c ratio of 0.62 and 0.77 concrete are shown plotted in Figure 8.11.



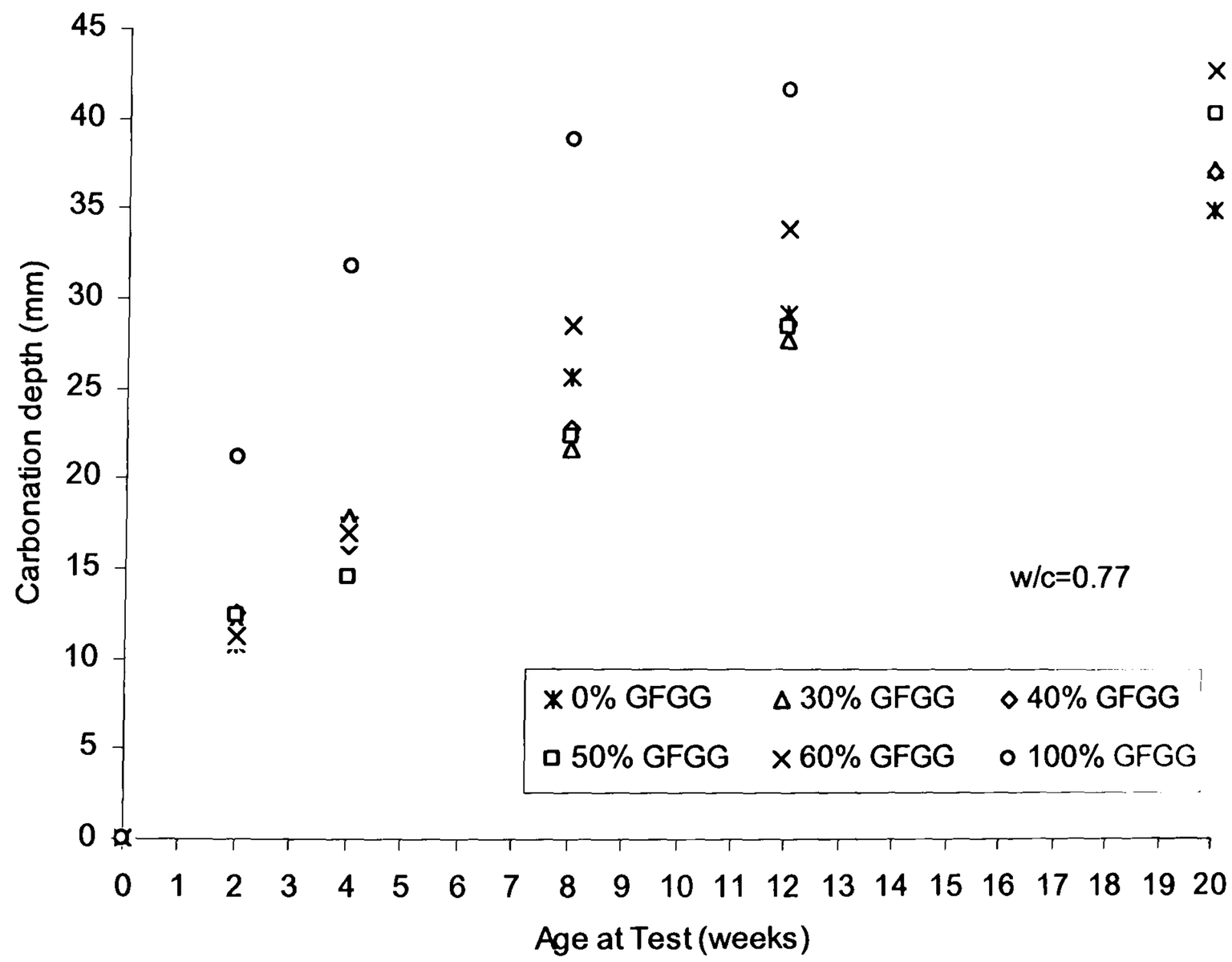


Figure 8.11 Depth of Concrete Carbonation with Time, for Concrete Containing up to 100% GFGG at w/c 0.62 and 0.77 (Initial curing; 20°C, 53% RH; *GFGG source: Mixed Bottles*)

The diffusivity is a function of the pore system of the hardened cement paste during the period when the diffusion of CO_2 takes place. The results showed that up to 60% coarse GFGG had negligible influence on carbonation rates, but there after a slight increase in carbonation depth was observed. After 20 weeks of exposure in the laboratory, indicating

20-years in service in real life, the maximum differences observed between 50% coarse GFGG and NA concretes were 4 and 5 mm for 0. 62 and 0.77 w/c ratio concretes respectively, while for 60% GFGG concrete mixes difference increased slightly to 9 mm for w/c of 0.77. Further replacements of 100%, increased the difference significantly to 18 mm at w/c of 0.77. These results are in line with those reported by other researchers [50,77-82]. It was also observed that carbonation was increased at high w/c ratio by twice (from 20 mm to 40 mm) which is in line with other research [50]. Figure 8.12 shows a cube with 30% GFGG at 2 weeks after exposure to CO_2. Colourless zone indicated the carbonation depth.

It is worth mentioning here that there was a slight difference in results depending on the original glass source (Figure 8.12). However, the highest values were presented previously; from Mixed Bottles. The difference was between 4.5-7.8% for 30-40% GFGG mixes and increased to 34 and 43 % for 50 and 60% GFGG concrete mixes respectively compared to NA concretes.

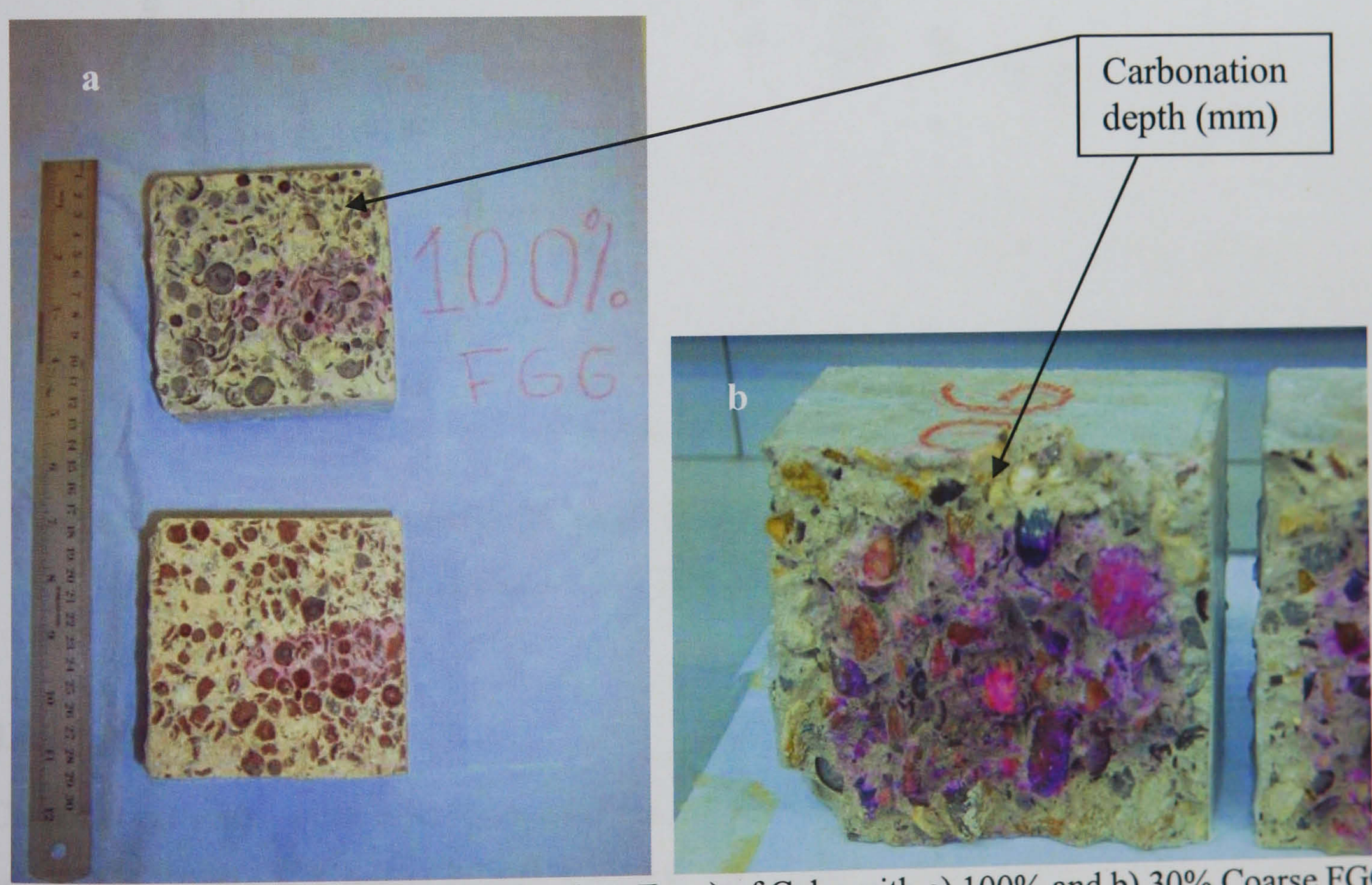


Figure 8.12 Carbonation Depth (Colourless Zone) of Cube with a) 100% and b) 30% Coarse FGG at 2 Weeks Testing (Initial curing; 20ºC 53% RH; *GFGG source: Both*)

Relationship between carbonation rates and concrete strength

According to several published research reports, the carbonation of concrete containing natural aggregates was found to correlate well with the corresponding compressive

strength (increase in strength reduced carbonation depth). This shows the good quality of cement-aggregate interface, hindering of water and air movement and keeping carbonation rate at similar values as the Control mix. Thereafter, carbonation test results were further assessed and the reliability between 20-week carbonation depth results of concretes containing various levels of coarse GFGG and corresponding 28-day strength was established as shown in Figure 8.13.

According to Figure 8.13, as expected there is a close relation between the carbonation of concrete containing NA and GFGG aggregates and the corresponding 28-day compressive strength for w/c of 0.77. Due to limited data for w/c of 0.62, presentation was not possible.

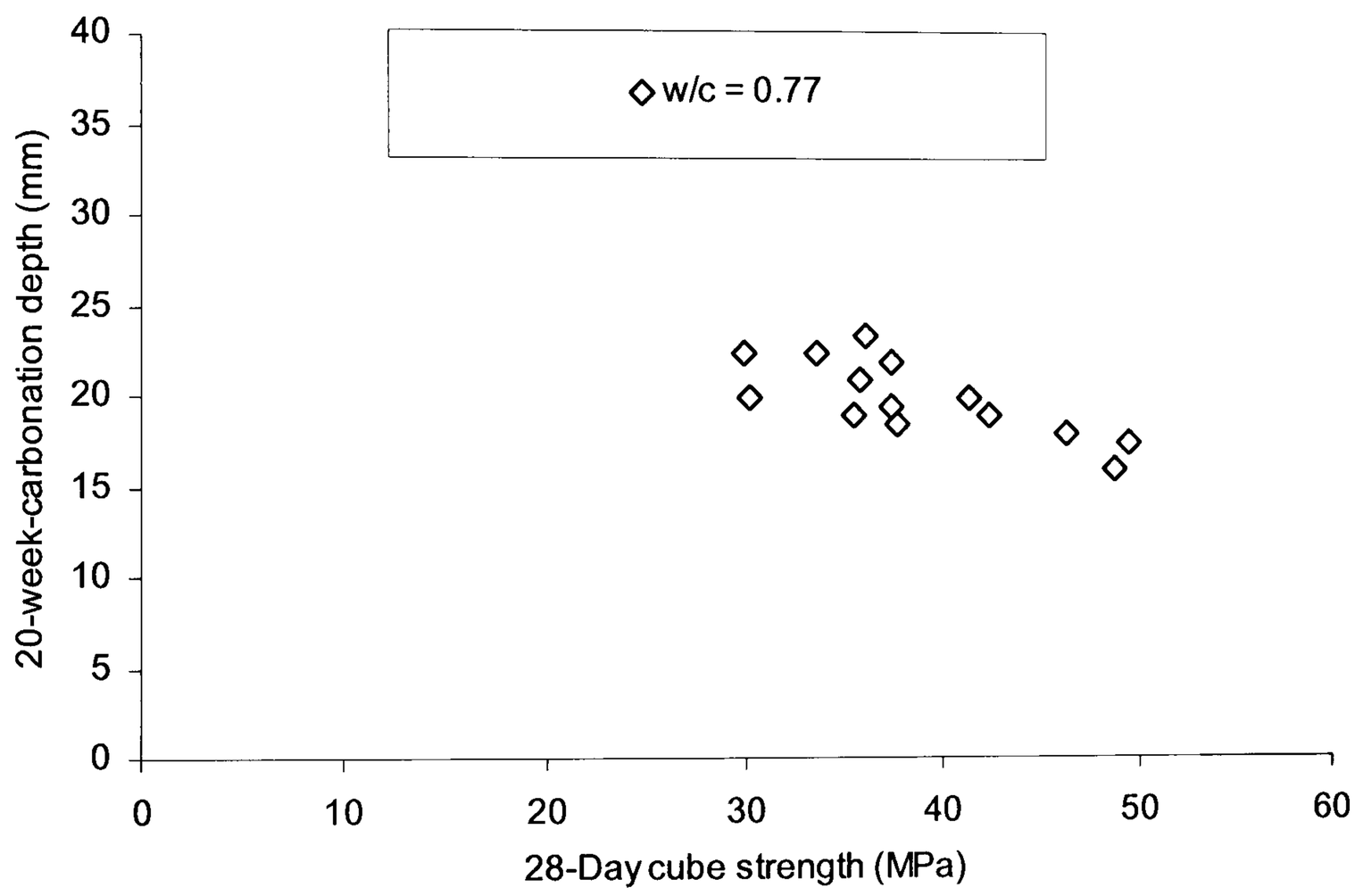


Figure 8.13 Relationship Between 20-Week Carbonation and 28-Day Strength of Concrete with NA and Coarse GFGG (Initial curing; 20°C 53% RH; *GFGG source: Mixed Bottles*)

8.4.3 Lytag Mixes

Carbonation rates were also measured for mixes with 100% coarse Lytag at w/c of 0.62 and 0.775. Table 8.2 presents the 20-week carbonation depth value, since it is the most critical. A comparison is made with rates of NA and GFGG mixes at corresponding w/c ratios.

Table 8.2 Carbonation Rates for Mixes with NA, 30% Coarse GFGG and 100% coarse Lytag. (Initial curing; 20ºC 53% RH; *GFGG source: Mixed Bottles*)

Concrete Mix	Age at Test (Weeks)					
	0	*2*	*4*	*8*	*12*	*20*
w/c=0.77	Measurements (mm)					
Natural	0	11.0	17.5	25.75	24.5	**35.5**
30% GFGG	0	12.0	19.5	22.0	28.0	**39.0**
100% Coarse Lytag	0	10.0	22.0	27.5	27.0	**41.0**
w/c=0.62						
Natural	0	9.0	9.5	13.5	14.0	**20.0**
30% GFGG	0	7.5	9.5	14.0	17.0	**19.0**
100% Coarse Lytag	0	12.5	15.0	22.0	24.0	-

Analysis of results from Table 8.2 gives information about the carbonation resistance of Lytag concrete, which seems to have slightly higher carbonation rates when compared to both NA and GFGG concrete mixes. Carbonation values were very comparable for GFGG and Lytag mixes at low concrete strength (w/c 0.77) while it differed significantly at higher concrete strength. As expected, resistance of Lytag to diffusion of CO_2 is lower (higher depth), the lower the strength is (Figure 8.14). These findings are in agreement with published research since the rate of carbonation depends on porosity and moisture content of the concrete and generally high w/c ratio leads to higher carbonation rate [78].

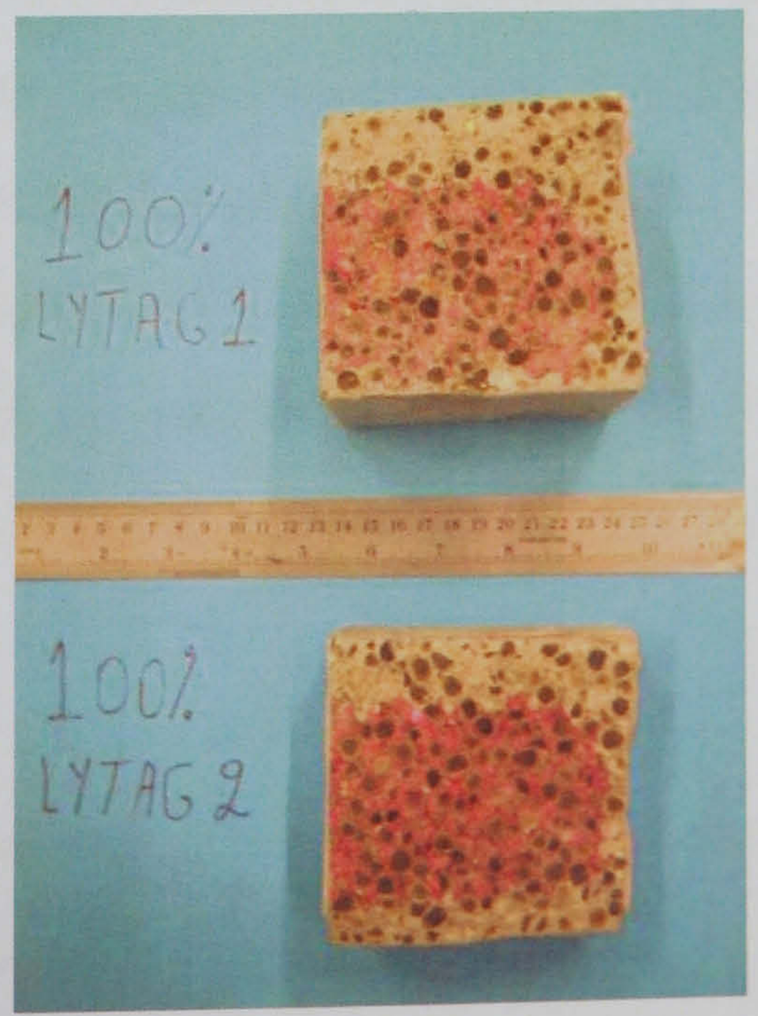


Figure 8.14 Carbonation Depth (Colourless Zone) of Lytag Concrete at w/c 0.77 (Lytag 1) and 0.62 (Lytag 2); (Initial curing; 20 ºC 53% RH;)

Results are in agreement with other Durability properties such as ISA, where Lytag was found to have slightly increased water ingress at 10-minutes and increased hcp porosity when compared to GFGG and Control mixes. Regarding the results at w/c of 0.62, results are in agreement with ISA tests at the same w/c ratio, where Lytag concrete showed increased capillary action and permeability compared to GFGG mixes.

8.5 Alkali-Silica Reaction Test

8.5.1 Introduction

Alkali-Silica Reactivity, also termed ASR, is the expansive deterioration of concrete due to a chemical reaction involving components in aggregates and the cement paste. At the natural pH of concrete (approximately 12.4) and in the presence of calcium hydroxide and water (compounds normally present in concrete), many siliceous minerals in aggregates eventually will decompose into silica gel. This may take anywhere from a relatively short to an extremely long time -- from months to centuries -- depending upon the reactivity of the aggregate particles, the internal humidity of the concrete and the presence or absence of other compounds in the concrete [25].

As mentioned before, ASTM C1260 accelerated mortar bar test has been established for evaluating the ASR risk from aggregates destined for use in concrete, by testing specially made prisms with embedded gauge studs (DEMEC pins) used for accurate measurement of any change in the test prism length. This test can also be used to evaluate combinations of aggregate and cement where the mortar or concrete may be liable to expansion through ASR. The basis of the test is to immerse test prisms in sodium hydroxide (NaOH) solution at 80°C for a period of 14 days (as described in Chapter 4). The length of these mortar bars is measured accurately to accuracy of 0.001 mm to determine length changes indicative of ASR. With allowance for set up and measurement, ASTM 1260 has scope to permit detection within 16 days from casting, of the potential for alkali silica reaction of aggregate in mortar bars.

Against this background, at the start of this project it was decided and agreed to undertake ASR studies in accordance to ASTM C1260. In the event of a risk of ASR, storage in sodium hydroxide solution for 14 days at 80°C is said to lead to significant expansion. Furthermore, ASR is normally accompanied by other tangible signs of attack, for instance,

visible cracking, and degradation of the test pieces. The appendix to the ASTM standard [53] gives expansion limits for prisms with embedded gauge (Table 8.3). Table 8.4 gives mix proportions for ASR testing while Table 8.5 gives the dimensional changes that were recorded for 0-100% GFGG mortar prisms.

Table 8.3 Summary of Limits Suggested in the Appendix to the ASTM 1260 Standard

Expansion (14 Days)	Comments
• Less than 0.10 %	Indicative of innocuous behaviour in most cases[1]
• 0.10 % to 0.20 %	Indicative of potentially deleterious expansion[2]
• Greater than 0.20 %	Indicative of deleterious expansion[3]

[1] Some granite gneisses and metabasalts have been found to be deleteriously expansive in the field even though expansion in this test was less than 0.10% after testing. With such aggregates the ASTM recommends prior field performance be taken into account.

[2] In such case it is advised to seek supplementary data to show that aggregate is innocuous and/or continue testing to 28 days.

[3] When excessive expansions are developed, it is recommended that supplementary information be developed to confirm that expansion is actually due to ASR, e.g microscopic evaluation to see if products of ASR are present.

8.5.2 Sample preparation and Experimental Method

Given the satisfactory engineering and near surface absorption performance of concrete containing up to 15% fine GFGG, it was decided to undertake ASR testing using up to 100% fine GFGG bubbles. Over 80 mortar mixes were cast containing up to 100% fine GFGG with both original glass sources; mixed bottles and CRT, to assess its influence on alkali silica reaction phenomenon. It is important to note that this test method permits detection within 16 days of the potential for deleterious alkali silica reaction of aggregate in mortar bar.

Figure 8.15 shows photo of mixer and specially designed and purchased container used in this test. Container consists of an insulated water bath constructed to hold within it, a sodium hydroxide solution for 14 days and test specimens. The test bath was maintained throughout to 80°C ± 2°C. The test bath had a lid preventing escape of moisture to the atmosphere and its water level was checked daily to ensure that it did not change.

During testing there was very little change on the levels and only a small amount of de-ionised water was needed to maintain the levels. The whole system was also well insulated to minimize temperature variations within the tank and this was confirmed by measurements of temperature across the test tank showing that the temperature was the same throughout.

The solution was prepared by dissolving 40 grams of sodium hydroxide in 900ml of de-ionised water and made up to 1 litre by the addition of further de-ionised water. Fresh solution was prepared for each batch of tests.

Figure 8.15 Sample Preparation and Hot Water Bath Used for ASR Test

Over 100 prisms (40x40x160mm) were prepared using GFGG at varying percentages as shown in Table 8.4 with 42.5 CEM I Portland Cement. For each batch and combination of GFGG proportions, minimum of three test specimens were cast. Table 8.4 gives the mix proportions used to cast test prism specimens with up to 100% fine GFGG.

Table 8.4 Mix Proportions of GFGG Mortars for ASR Test

Sieve size (mm)	% Retained in sieves	Mix Contents							
		Fine GFGG %, by mass							
		0%		*30%*		*50%*		*100%*	
		NA (g)	*GFGG (g)*	*NA (g)*	*GFGG (g)*	*NA (g)*	*GFGG (g)*	*NA (g)*	*GFGG (g)*
2.36	10	99.0	-	69.0	30.0	49.5	49.5	-	99
1.18	25	248.0	-	173.5	74.5	124.0	124.0	-	248.0
0.6	25	248.0	-	173.5	74.5	124.0	124.0	-	248.0
0.3	25	248.0	-	173.5	74.5	124.0	124.0	-	248.0
0.15	15	148.0	-	103.5	44.5	74	74	-	148.0
				762.5	227.0	495.0	495.0		
Total	100	990		990		990		990	

In general, the following sample casting and preparation procedure was followed:

- Addition of fine aggregate (natural and/or GFGG) in mix bowel and mixing for 1 minute.
- Addition of graded PC (440g) and mixing for 1 minute.
- Addition of required water (using water/cement ratio = 0.47 by mass) and mix further for 1 minute (volume of solution = 4 x volume of specimens).
- Casting of prism specimens and measurement of initial length reading "datum" (to the nearest 0.001 mm) using standard strain frame.
- Specimen storage in a sealed container with sufficient tap water, and then placement in 80°C tap water for 24 hours.
- Removal of one by one test specimens and record " zero" readings and then transfer in to a container with sufficient 1 N NaOH at 80°C.
- Subsequent readings of the prisms were taken periodically (with at least three intermediate readings) at the same time of the day, for 14 days after the "zero" reading. At each test age the samples were removed and surface dried and within 30 seconds from their removal from water bath, readings were taken and any observations were reported. Weight measurements were also taken, although not being compulsory from ASTM, but only to give an extra indication of concrete "health", firstly in terms of initial quality and subsequent changes related to weight gain.

8.5.3 Results

Percentage of expansion

Table 8.5 presents the expansion percentages of prisms with 0-100% GFGG at the duration of ASR testing.

Table 8.5 ASR Length Change and Expansion of Mortar Made with Natural Sand and up to 100% GFGG in 1 N NAOH (at 80ºC) for 14 Days; (*original glass source: mixed bottles*)

Mortar Type	Test Age, Days	Total Length Change, mm	Expansion, %
0% GFGG (Control)	5	0.030	0.020
	9	0.060	0.0400
	14	0.070	**0.046**
30% GFGG	5	0.030	0.020
	9	0.065	0.045
	14	0.075	**0.055**
50% GFGG	5	0.045	0.030
	9	0.080	0.055
	14	0.095	**0.065**
100% GFGG	5	0.120	0.080
	9	0.140	0.093
	14	0.150	**0.100**

Despite the difficulties and complexity of such measurements, final results indicated that regardless of GFGG glass source, very little dimensional change took place at 30-50% replacement level from GFGG, indicating according to Table 8.3 (ASTM Limits), that the aggregate is well below the range that would lead to potentially deleterious swelling due to ASR. Looking at the results more closely it might be noted that at the end of testing, percentage of expansion observed for 30%, 50% and 100% GFGG mortar prisms being 0.055%, 0.065% and 0.100% respectively, is higher than the expansion of the control mix (0.046%). However, at 100% GFGG prism results are within the range listed by the ASTM standard as "indicative of potentially deleterious expansion". In general, prisms actually kept expansion levels within the limits as shown in previous researches with ASR studies with glass as aggregate [19,22,27,29,33,34,41,83,85]. Generally, results obtained indicate that none of tested samples with GFGG expanded significantly beyond the recommended limits and during the tests damaging deleterious expansion due to ASR has not occurred. Although the particle size of fine GFGG ranged between 0-5 mm, it did not promote ASR as expected especially when the size of 1.2-1.5 mm size was used [1,16,22] at 25% proportion. As expected, as proportion of glass increased in the mortar from 30-100%, so did the expansion (ε), where expansion was found according to Bazant [22] to be proportional to Va, glass volume/unit of concrete volume and inversely proportional to D, glass cullet diameter. As Va increased expansion increased and as glass particles decreased below 1.18 mm, expansion is usually decreased. A_1 and A_2 are constants.

$$\varepsilon = A_2Va - A_1/D^{1/2}$$

Nevertheless, the somewhat higher expansion for GFGG prisms specimens suggests (as recommended by the ASTM standard) further investigation to confirm that the mix design and/or other material used is not liable to ASR expansion. Further microscopical analysis of samples and chemical composition of recovered solutions after the end of the ASR test were carried out to supplement the ASR expansion result analysis. Figure 8.16 shows the increase in mass during the ASR test for prisms with 0-100% GFGG. There was an increase in the mass of GFGG prisms as shown in Figure 8.16, increasing as GFGG proportion increased, as expected. An increase in mass was observed which was higher in prisms with GFGG due to the higher porosity of interface and higher absorption of GFGG when compared with natural aggregates. The increase in weight was 5 % for 30% GFGG, 6% for 50% GFGG and 14% for 100% GFGG mortar prisms. Figure 8.17 shows images of Control, 30, 50 and 100% GFGG prisms after the 14-day test.

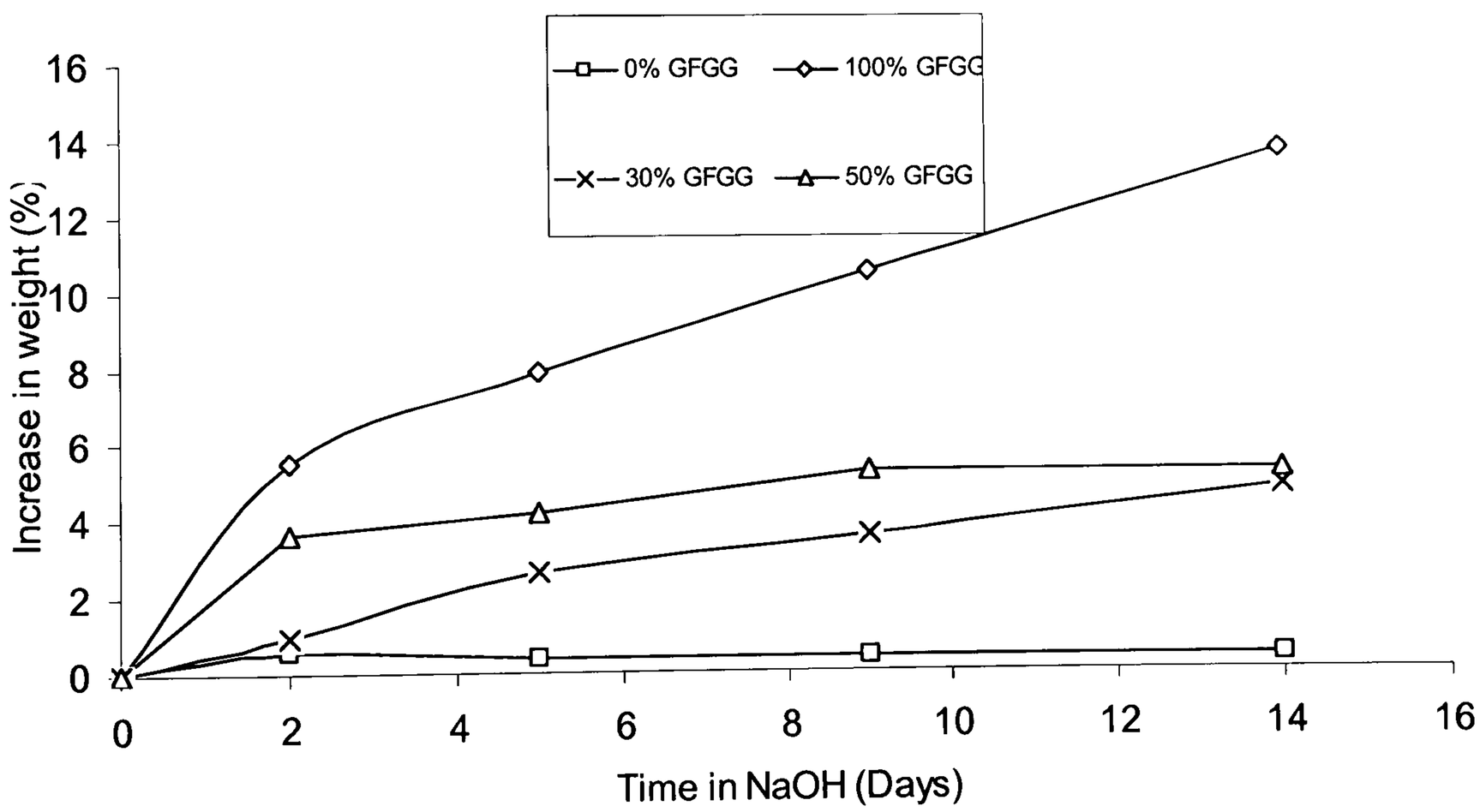


Figure 8.16 Increase in Mass for Mortar Prisms Containing 0-100% GFGG Stored in 1 N NaOH (at 80 °C) for 14 Days; (*Original glass source: mixed bottles*)

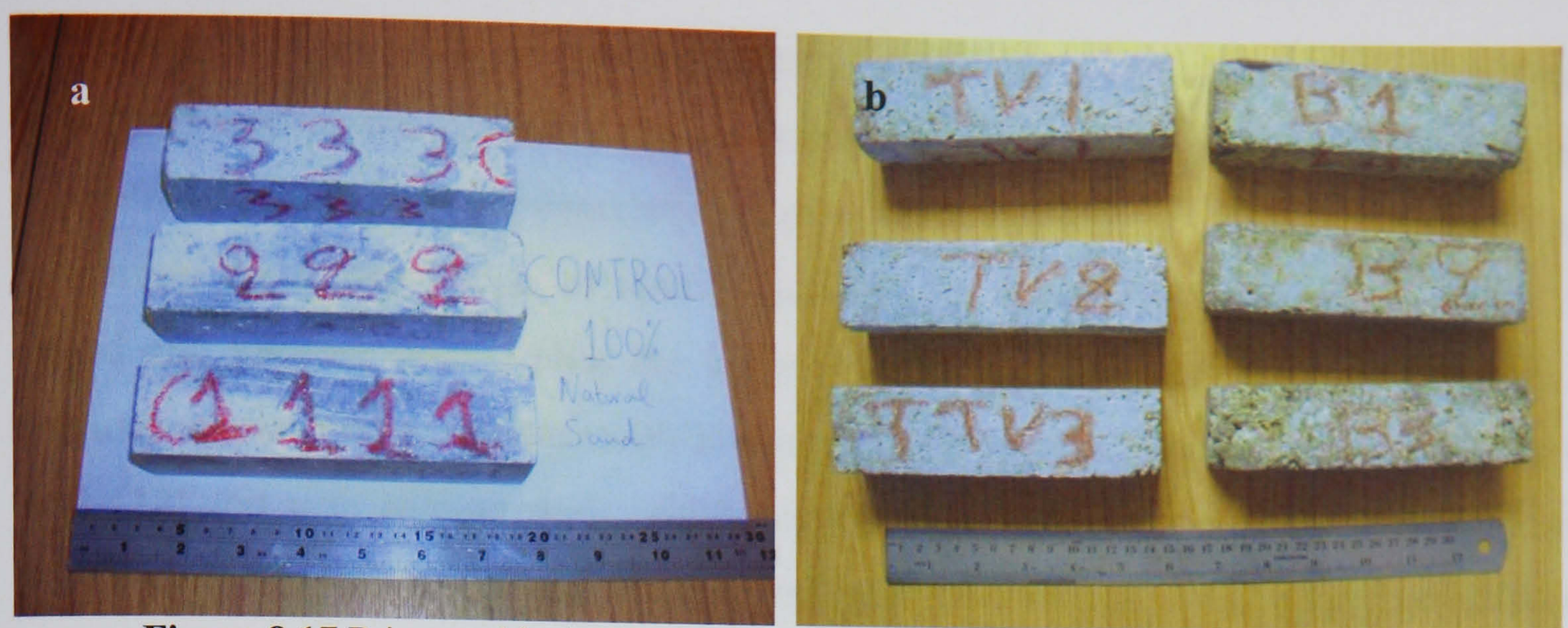


Figure 8.17 Prisms with a) 0% GFGG and b) 100% GFGG from both glass sources

According to Figure 8.17 a) white colouring in some places of all prisms was observed due to carbonation. White colour was observed on the surface of the prisms due to the presence of $CaCO_3$, from reaction between Ca $(OH)_2$ and CO_2. However, sign of decay of the 100% GFGG prism surface in contact with NaOH solution was observed [Figure 8.17 b)]. In the majority, after the 14-day period no major ASR cracks, gel spots or wet patches were observed on the surface of the samples, in agreement with other studies [19,33,41] showing no deleterious expansion of prisms with glass in fine form as with GFGG.

GFGG was assumed to be susceptible due to high amount of silica and being an additional source of alkalies. According to ASR studies reactivity of any aggregate is affected by its particle size and porosity, which influence to the area over which the reaction can take place [14,15,61,63,86]. According to SEM images of fine GFGG surface texture and morphology was characterised as smooth and the interface as compact and dense (Chapter 5) having in its interface few discontinuous pores and concavities. These discontinuous pores could have satisfactorily contributed to accommodate any reaction products during the ASR. Any expansion products could be incorporated within these pores without stretching the matrix. However an increased used of GFGG beyond 50% inevitably caused a significant increase in expansion.

It is generally accepted that the progress of alkali-aggregate reaction depends on the permeability of the hydrated cement paste because this controls the movement of water and of the various ions, as well as of the silica gel [50]. As reported previously in Chapters 5-7, the interfacial transition zone of lightweight aggregate as GFGG is denser than that of natural aggregate. This is because the porous and rough surface of the GFGG provides sites for the HCP to merge across the interfacial zone and improves the interaction

mechanism between the aggregate and the matrix [14,15,61,63,64]. Since there is no "wall effect", as well as the lack of a distinct boundary between cement paste and aggregate, improves matrix quality and decreases the permeability of ITZ of GFGG and mortar thus preventing the transportation of ions (alkalis) in the material since the pore system is closed and keeping ASR within the limits. This behavior comes in agreement with a previous research where prisms with low transport properties showed great resistance to ASR [32] and with another study which suggests that ASR is suppressed by refined and densified micro/pore structure leading to reduced ionic mobility and water permeability probably due to the additional C-S-H formation [19,37,87].

Chemical Analysis of Solutions and SEM

The composition of the solutions with 0 and 30% GFGG samples were examined for the containing ions before and after the 14-day period test using J Y Ultima 2 C inductively coupled plasma atomic emission spectrometry (ICP-AES). With this technique multi-element analysis of metals and non-metals in a solution was carried out giving quantitative analysis. It was essential to check release of alkalies or silica from samples into solutions, increasing in this way their concentration with respect to the reference solution at day 0 (1 M NaOH). As a reference sample, 40 g of NAOH was diluted in distilled water. The solution was further diluted 100 times for use in the analysis. Solutions from containers with recovered prisms with 30% GFGG were also diluted after the test 100 times with distilled water for comparison reasons with the reference sample. Concentration of ions from recovered solutions is provided in Table 8.6.

Table 8.6 Concentration of Ions in the NAOH Solution at Day Zero and Day Fourteen of the Test.

Mixture	Concentration of Ions					
	Parts Per Million (ppm) or mg/l					
	Element					
	Al	*Ca*	*K*	*Li*	*Na*	*Si*
Day 0						
Reference	14.0	**58.0**	34.0	2.0	**19335.0**	**89.0**
Day 14						
0% GFGG	25.0	**2.0**	223.0	1.0	**17105.0**	**3942.0**
30% GFGG	199.0	**43.0**	1270.0	4.0	**206156.0**	**17554.0**

During ASR an intense pressure is generated by the ingress of materials, Ca, Na, OH and water from outside the particle, into the reactive grains. Dissolution and diffusion of silica opposes the pressure generation [88]. The pressure generation could be avoided either (i) by decreasing the ingress of materials from outside by decreasing of ionic strength (ii) by increasing the dissolution and diffusion of silica by increasing OH ion concentration or (iii) by removing Ca ion from the reaction environment by using high volume of a reactive pozzolan which react with Ca $(OH)_2$ and decrease Ca concentration in the pore solution [63]. The calcium concentration in the pore solution surrounding the grain controls the rate of diffusion of silica away from the reactive site, and at high levels of calcium the migration of silica is prevented leading to an expansion. Ca acts as a "buffer" to maintain a high OH concentration in the pore solution and exchanges for alkali in the ASR gel, leading to alkali release and further production of swelling alkali silicate gel [89,90]. It is expected that in the operating conditions such that of ASR, of high temperature (80° C) and high OH high pH, at reaction sites, the concentration of Ca is depressed; while the liberation and diffusion of silica from prisms are increased [87].

As expected, the solution of 0% GFGG (control) prisms after the test (day 14) showed an increase in the concentration of silica (diffused) x 45 times, depression of Ca and slight reduction of Na (alkalies) with respect to the reference solution at the start of the test (day 0). There seemed to be a transport of Ca and alkalies (K) from solution to the prisms during the test. This indicated that cement paste was not impermeable and allowed the mobility of ions causing slight ASR, but still with expansion within the limits.

For the recovered solution of 30% GFGG test prisms, the concentration of Calcium (Ca) was not remarkably decreased, indicating low transport properties from the solution to the prisms due to refined pore structure of GFGG mortar. The concentration of Silica (Si) was increased by 200 times when compared to reference solution at day 0. This was attributed to the release of Si from prisms with GFGG (Si from glass powder) during the 14-day period. It should be noted that the diffusion is almost 3 times higher than that observed for 0% GFGG mortars at the end of the test. So although GFGG aggregate being an additional source of Silica, it migrated out of the prism into the solution and did not take part in the expansion within the mass of the prism similar to other studies [27, 42, 84]. The diffusion and dissolution was high so that chemical reaction took place in the solution outside the prisms instead of expansion within. Whatsmore, when portlandite- Ca $(OH)_2$ was present

in a pore solution, the diffusion of silica from reactive aggregates was high. ASR possibly started forming in GFGG mortars only after all available Ca $(OH)_2$ had been consumed to form C-S-H and probably cause grain aggregation, which is in agreement with previous ASR research [88].

In concrete and mortar a reactive transport barrier around aggregate grains is needed to produce ASR gel. These barriers may consist of Si-rich polymerised C-S-H. These barriers should provide a mechanism to prevent Si from migrating too rapidly out from the site of dissolution and Ca from migrating too rapidly in according to a study [88]. In the case of GFGG silica migrated out of the site of dissolution and prevented the Ca to migrate too rapidly in due to the dense ITZ of GFGG.

There was also an increase in the concentration of ions such as pottasium (K) and sodium (Na) when compared to the reference sample almost by 10 times for Na and by 100 times for K, due to the release of alkalies from cement hydration. When aggregate with silica embeds in a cement paste an alkaline pore liquid surrounds the aggregate particles. The composition of the pore liquid affects the rate and extent of alkali-silica reaction. Alkalies of the pore solution could not enter the GFGG due to its dense interfacial zone, having as a result the reduction of the ionic strength of the surrounding solution, which led to minimising ASR [88]. The ingress of Na and K was obstructed by the impermeable and dense interfacial zone of GFGG, thus hindering any pressure generation.

GFGG having innocuous behaviour inhibit the deleterious expansion of prisms even when highly silica sand was used. This beneficial (pozzolanic) behaviour can be attributed to refined and densified microstructure, the highly dissolution of silica and alkalies from GFGG grains and mortar on the solution during the test, preventing the migration of Ca and dissipating the net pressure generation on the grains as foresaid in other researches [1,19,88-91]. The same trend is expected to be followed for 50 and 100% GFGG prisms but with higher ASR expansion due to higher percentages of silica (glass). It has been proven that ASR can be totally eliminated with the incorporation of pozzolan such as silica fume or metakaolin or GGBS as cement replacement as other previous researches [1,16,31-34,50,89,92] or with the use of lithium compounds [93,94].

Secondary Electron Microscopy of Prisms

Secondary Electron Microscopy (SEM) was performed using JEOL 6310 SEM software for imaging in backscattered secondary electron mode (BSE) (on thin polished sections) and secondary electron mode (SEI) on fresh fractured surfaces of 30% GFGG prisms. Oxford analytical ISIS system was used for carrying out energy dispersive x-ray analysis (EDS) (for both the qualitative and quantitative elemental analysis). The accelerating voltage was always 15KV. Images are shown in Figures 8.18-8.31. Figure 8.18 shows a backscattered image of thin polished section of a prism with 30% GFGG. SEM on fractured surface of prism with 30% GFGG with original glass source from CRT and mixed bottles took place after 3 months of drying the prisms in normal temperature so as to get rid of any moisture within the interface.

It is quite evident from Figure 8.18 the lack of a distinct boundary between aggregate, very good bond and cement paste, and the discontinuity of pores within the aggregate (fine structure). No "band" distribution in interfacial transition zone was observed as with that found in normal aggregate matrix [92].

From Figure 8.18, it is also clear that the foamed glass granule is not cracked, and that there are no cracks along the boundary between the cement mortar and the granule. Contact between the granule and the cement matrix has not been lost as with the case of expanded glass and cement paste in a previous ASR test [41].

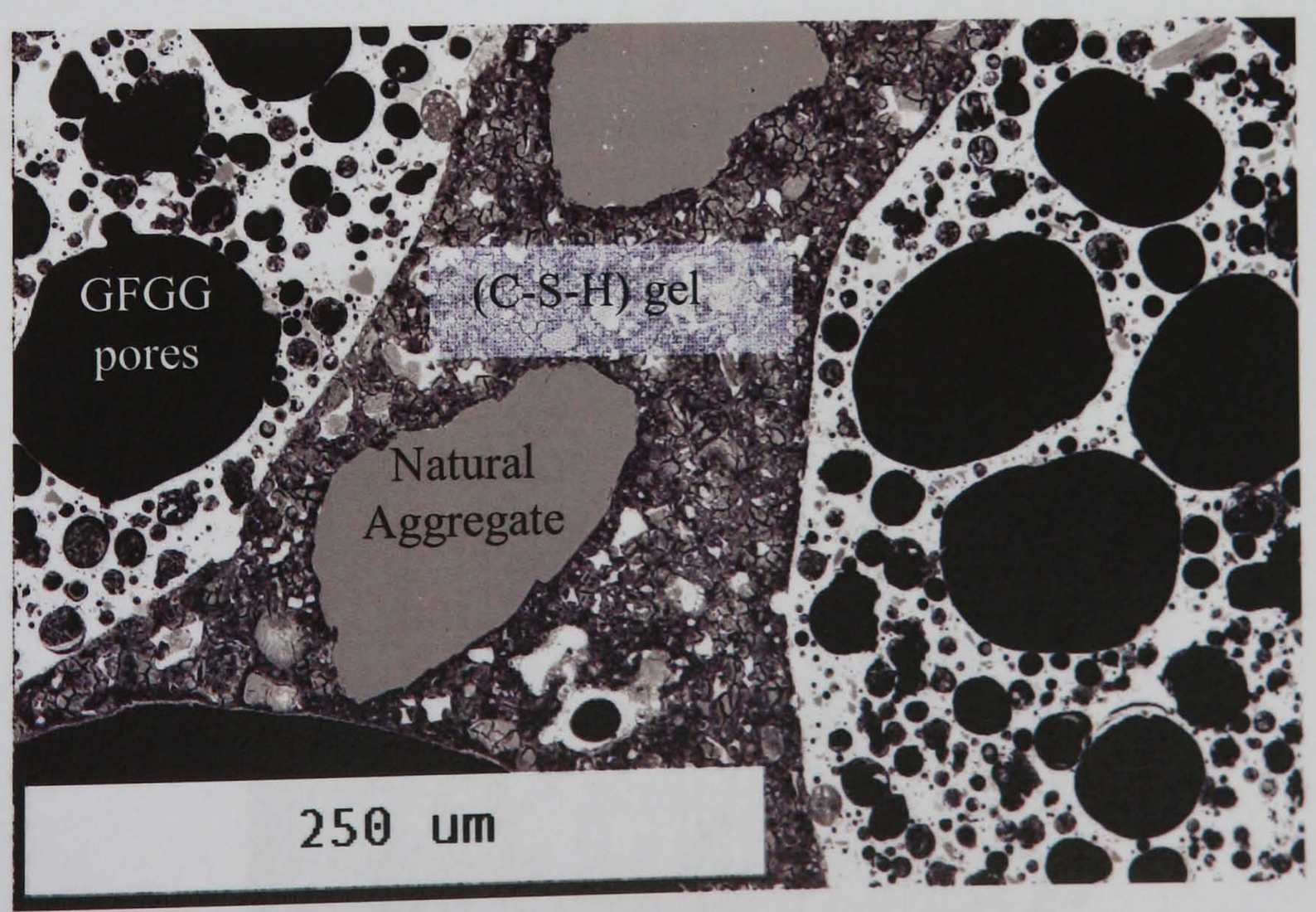


Figure 8.18 Back Scattered Image of Thin Polished Section of 30% GFGG Mortar Prism

SEM-SEI in Figure 8.19, showed, regardless of GFGG glass source, a compact-dense microstructure, with a good dispersion of GFGG in cement paste as in previous researches with glass powder as cement replacement [12,33]. Prisms showed minor reaction products from ASR, only found within the GFGG cavities. The presence of calcium-silica-hydrate (C-S-H) was also confirmed, which are hydration products of mortar [1,89-91]. What more, according to Figure 8.18(a) GFGG prisms interface presents concavities and porosities (discontinuous) but still being compact and dense. An amorphous area is shown in 8.18(b) showing cracked grain (due to drying shrinkage from sample preparation for SEM-not from ASR gel) and a more dense area next to it.

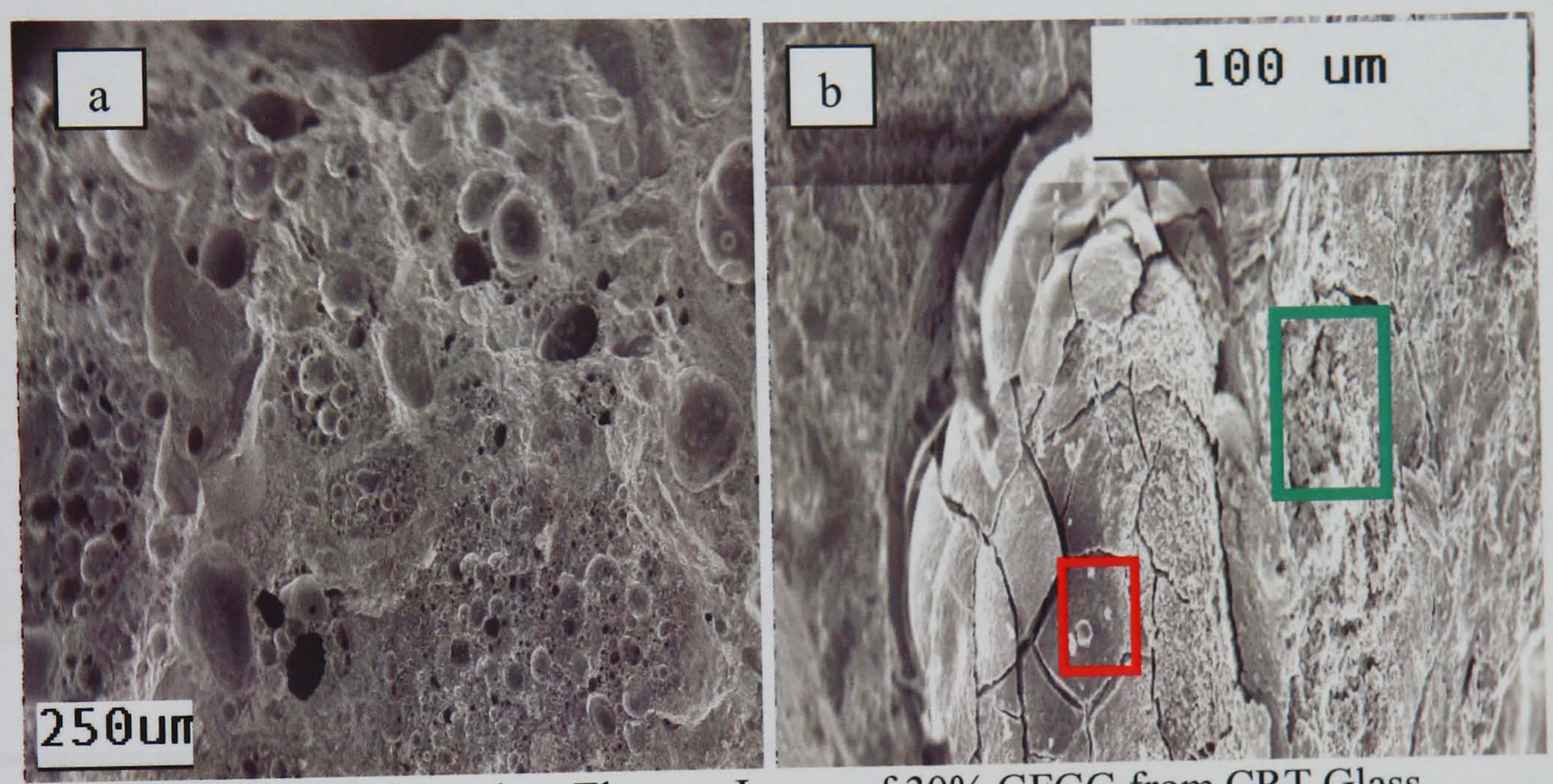


Figure 8.19 Secondary Electron Image of 30% GFGG from CRT Glass.

Both areas were examined and are shown later. Higher magnification on the area around red square of Figure 8.19 (b) showed gel agglomerates of etched form as in previous studies [91,92,95,96] show in Figures 8.20 and 8.21.

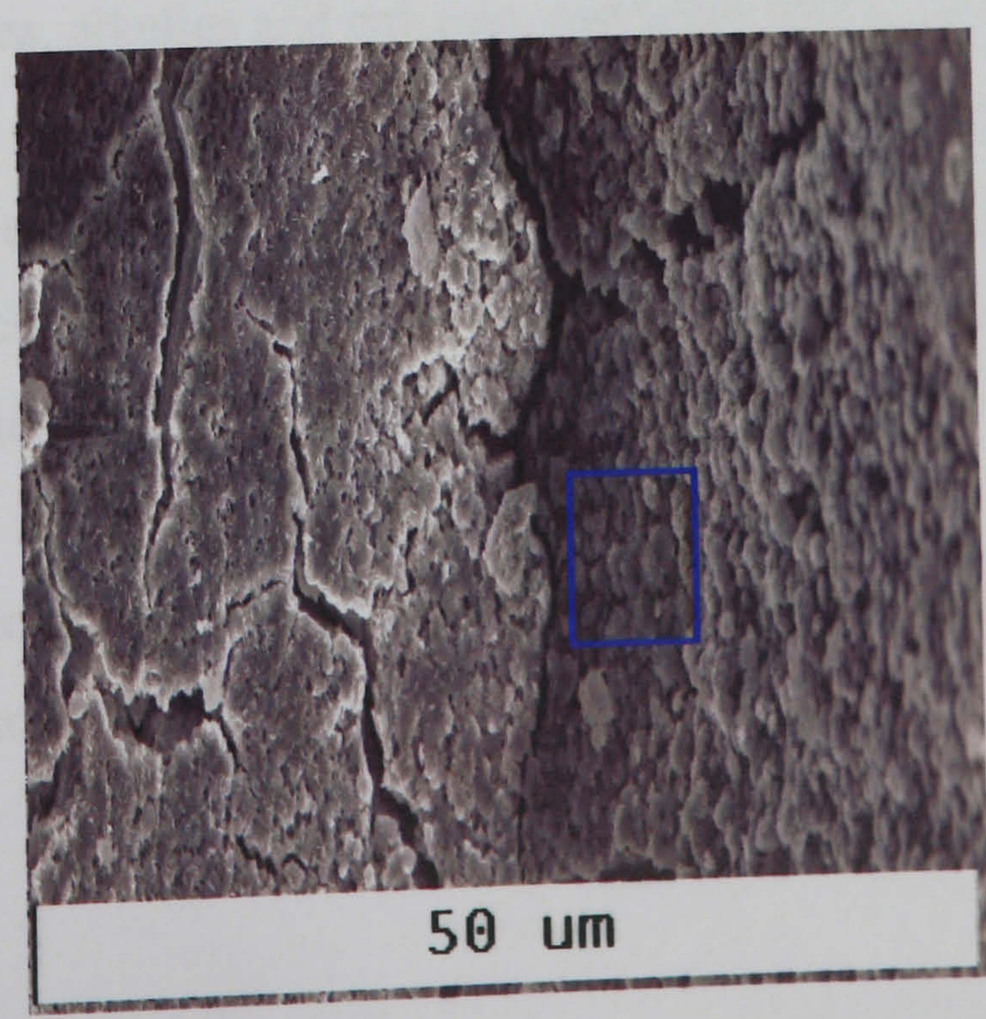


Figure 8.20 Secondary Electron Image of 30% GFGG Prism Showing Etched Areas.

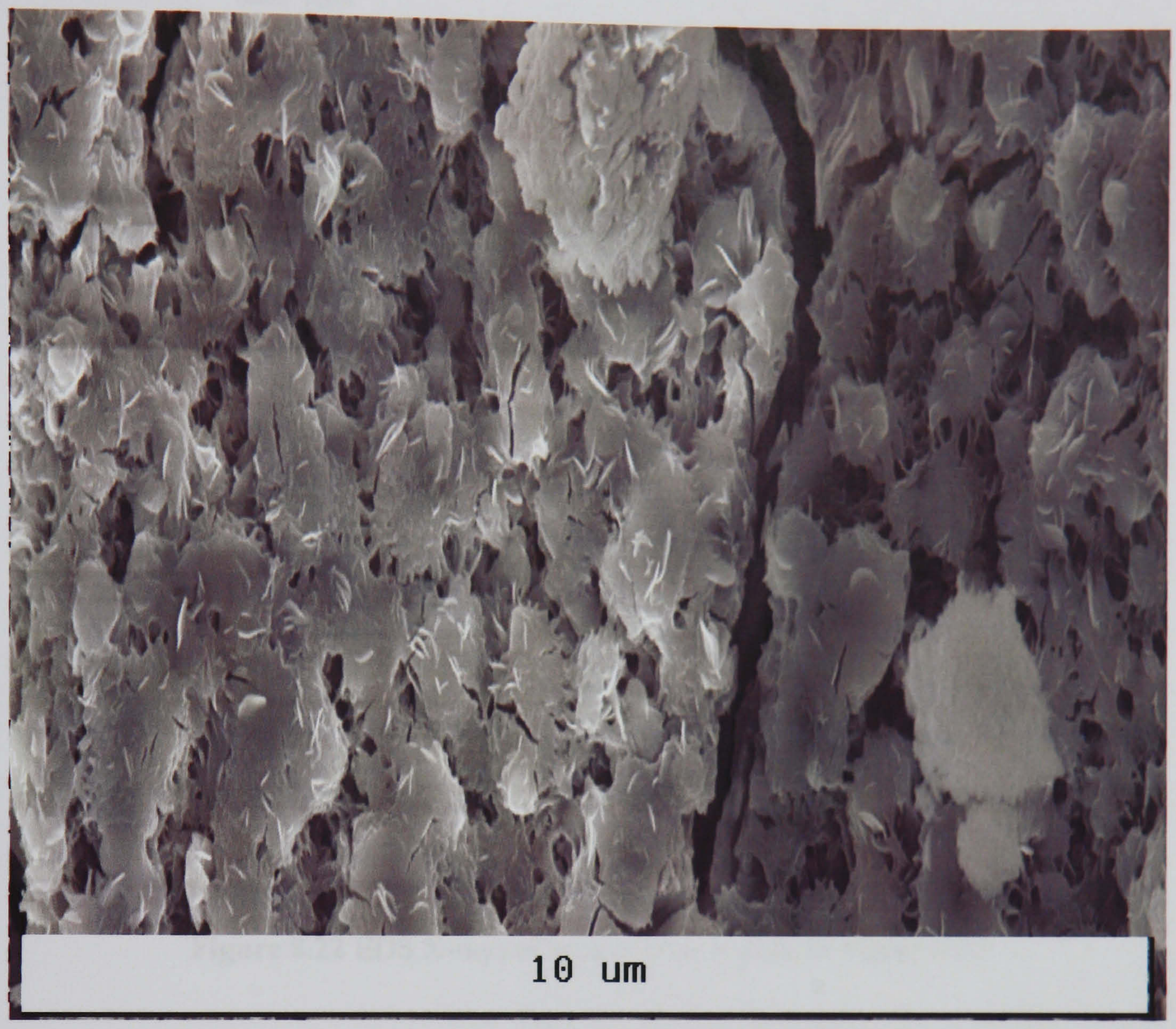


Figure 8.21 Secondary Electron Image of 30% GFGG Prism Showing Etched Areas in Higher Magnification.

A greater magnification of the area is shown in Figure 8.21. It shows rough surface texture that appears to be caused by a preferred etching along specific planes as found in previous researches [89,92,95]. EDS-X-Rays on the area as shown in Figure 8.22 confirmed the presence of mainly Silica, alkalies and calcium, probable ASR.

Examining along the fresh fractured surface of 30% GFGG prisms, in very few occasions, on the GFGG interfacial zones the following phenomenon of "banding" occurred as observed in other studies [87]. Figure 8.23 presents the phenomenon. Figure 8.23 shows the presence of a rim probably gel from ASR as suggested by [92]. Pores within the aggregate are also obvious. EDS-X-Rays around red circle of Figure 8.23 shown in Figure 8.24, proved the presence of a probable ASR gel.

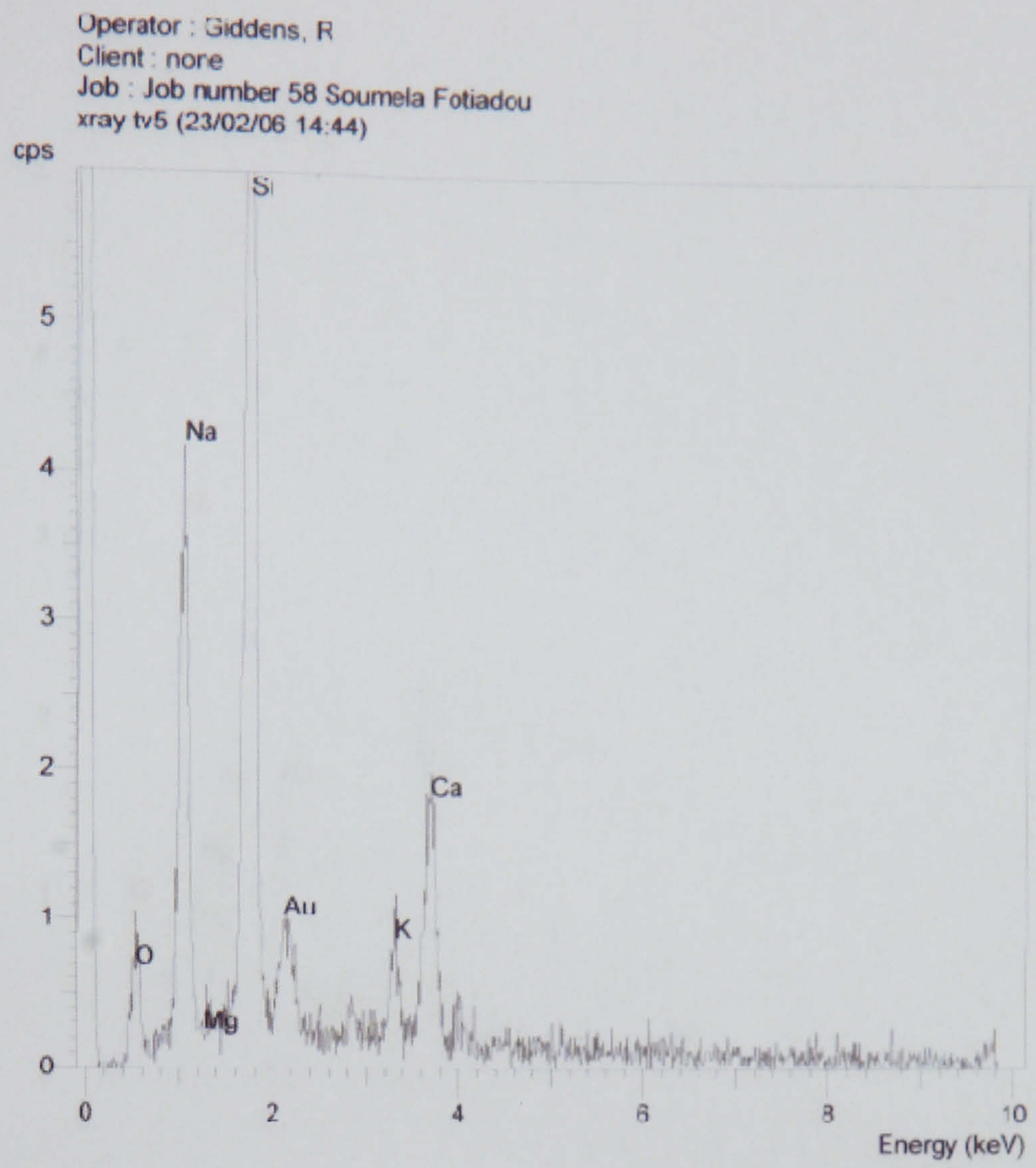


Figure 8.22 EDS X-rays of area in Blue Square of Figure 8.20

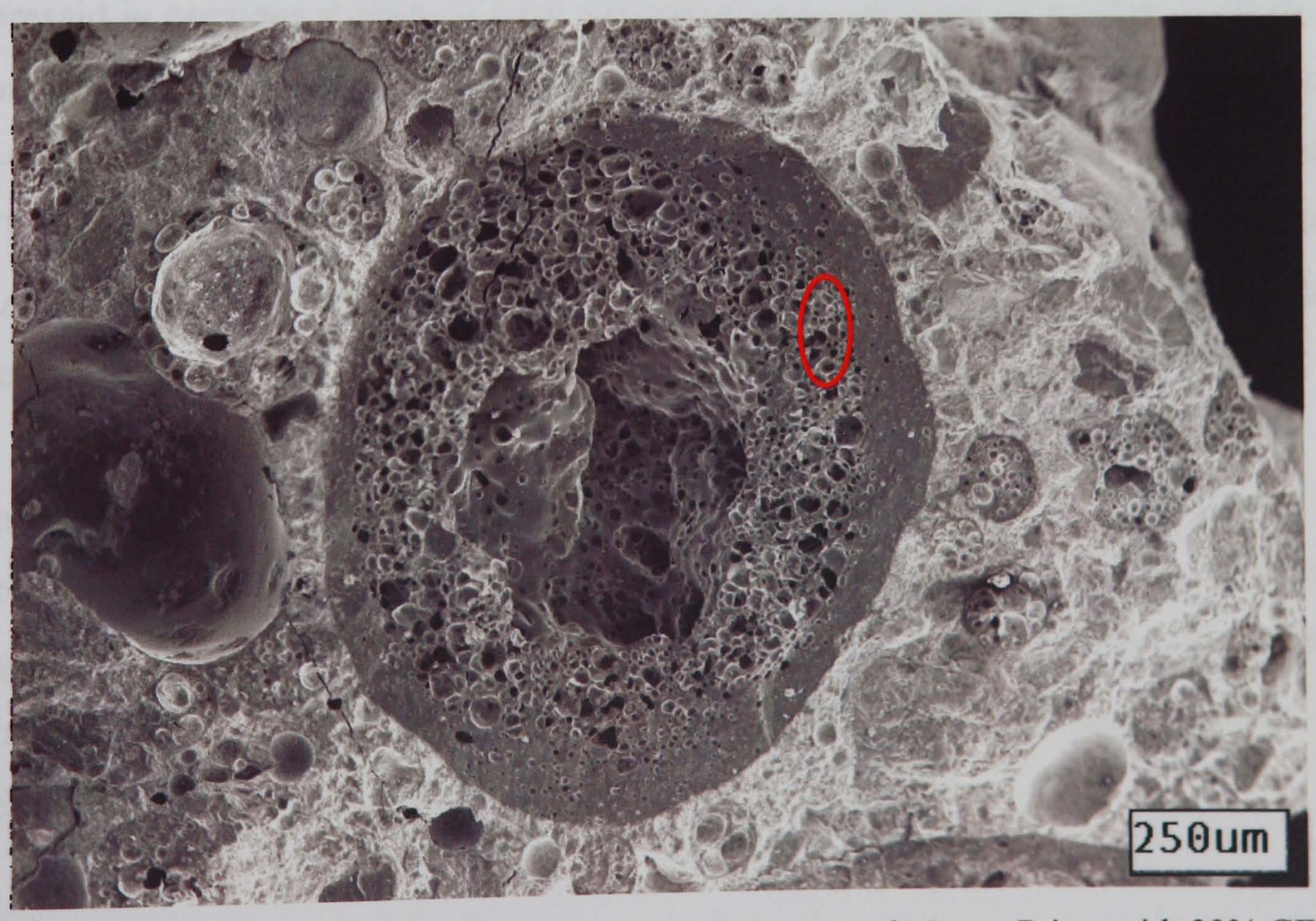


Figure 8.23 Secondary Electron Image on Fractured Surface of Mortar Prism with 30% GFGG.

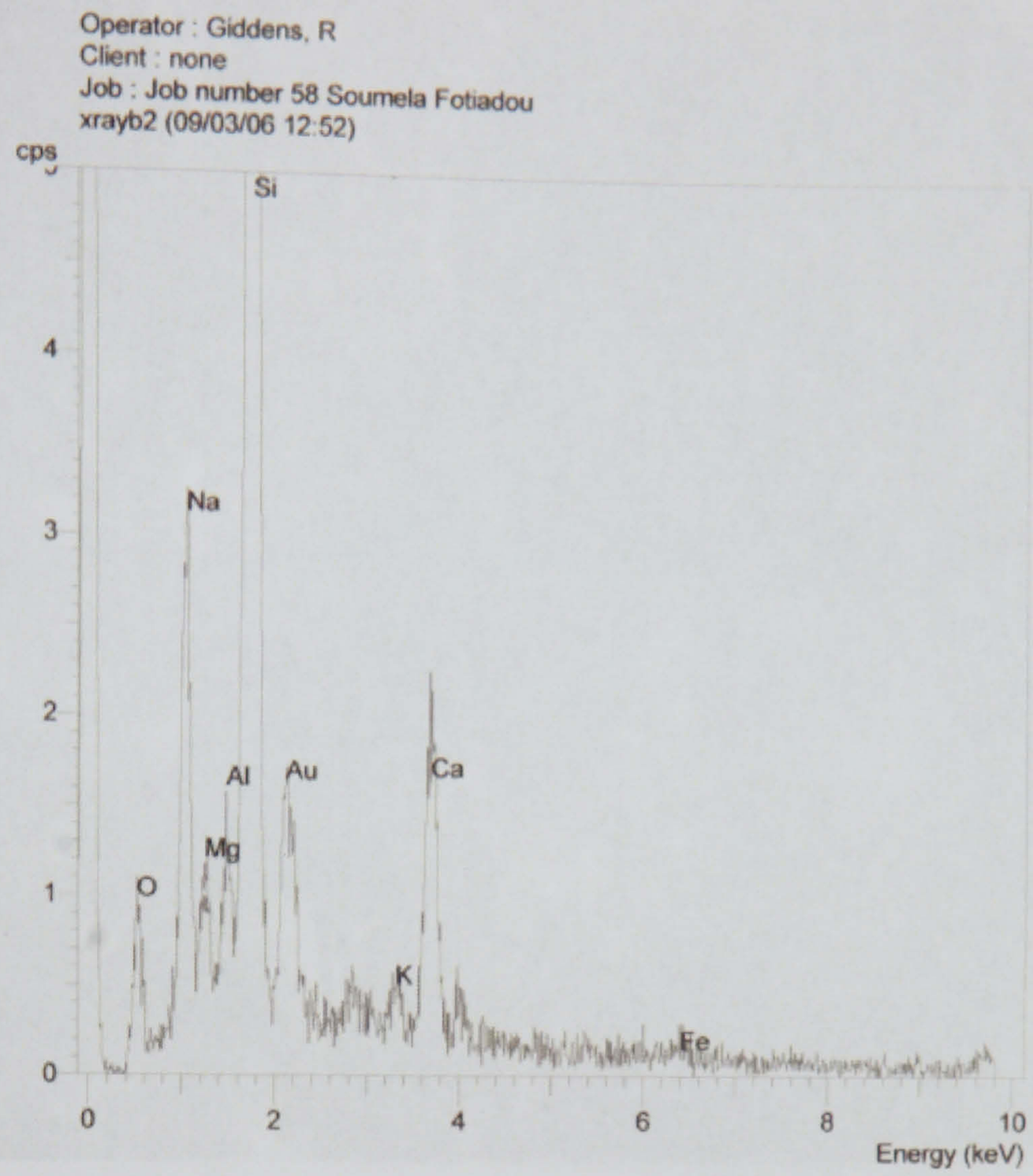


Figure 8.24 EDS X-Ray analysis of Red Circle of Figure 8.23

As foresaid in previous studies of ASR, [87] there is a formation of a calcium-alkali-silica rim on the aggregate-cement paste interface, producing expansive forces itself, or acts as a semi-permeable membrane preventing diffusion of alkali-silicate solution from the reaction site. This rim of Ca-A-S is scarcely observed in the GFGG ITZ, so pressure is dissipated and ASR is highly obstructed. With the higher percentages of GFGG this "band" is expected to appear more often leading to higher percentages of ASR

Examination of the dense-compact area within the fresh fractured surface, area in green square in Figure 8.19, showed low porosity with no ASR products or cracks, as presented in Figure 8.25. EDS-X-Rays on the area is also shown in Figure 8.26. From Figure 8.25 is obvious the needle like structure which is different from the crystalline products found earlier in other places of GFGG prisms (Figures 8.20 and 8.21).

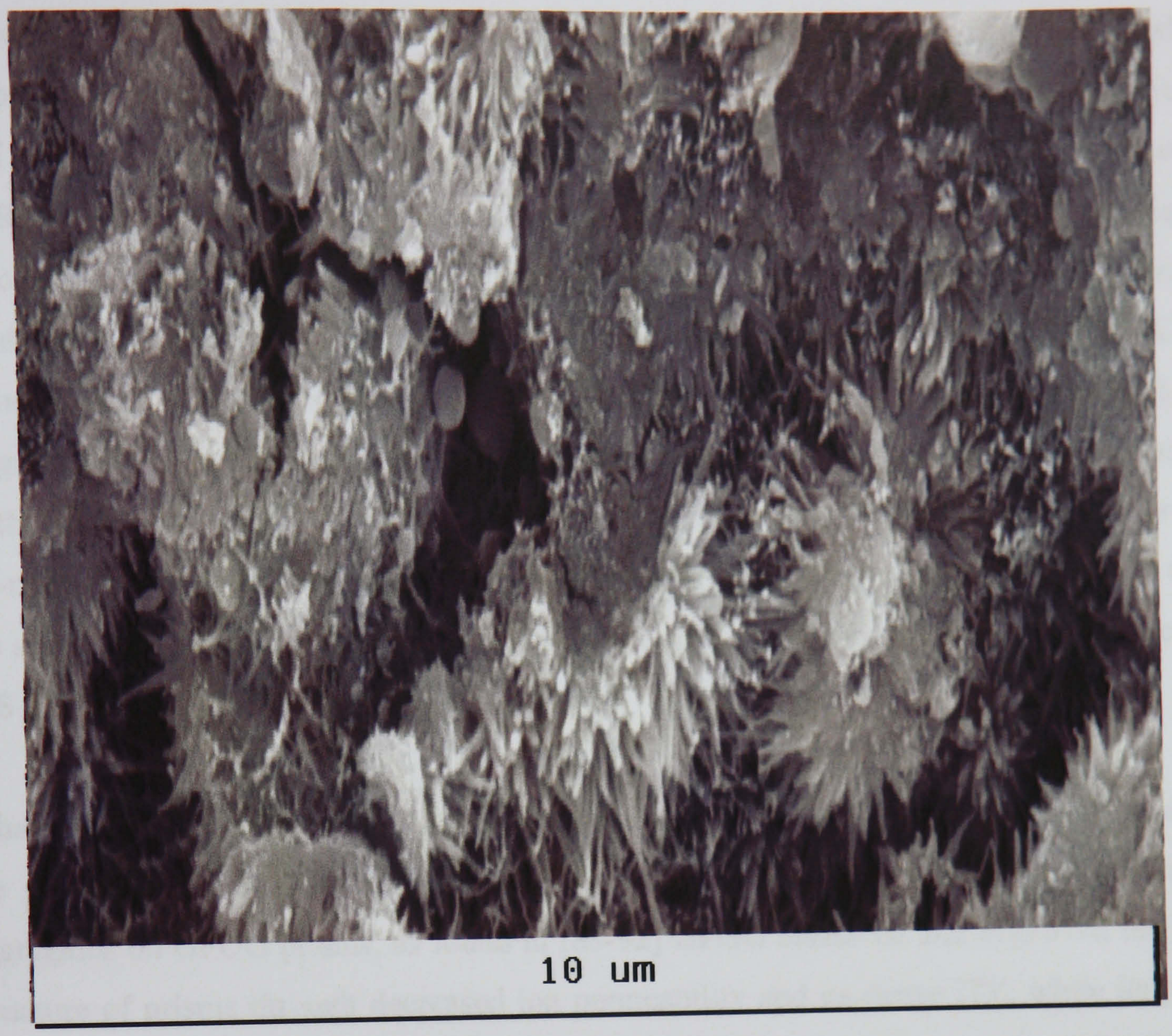


Figure 8.25 Secondary Electron Image of 30% GFGG Prism on a Dense Area (Green Square of Figure 8.19)

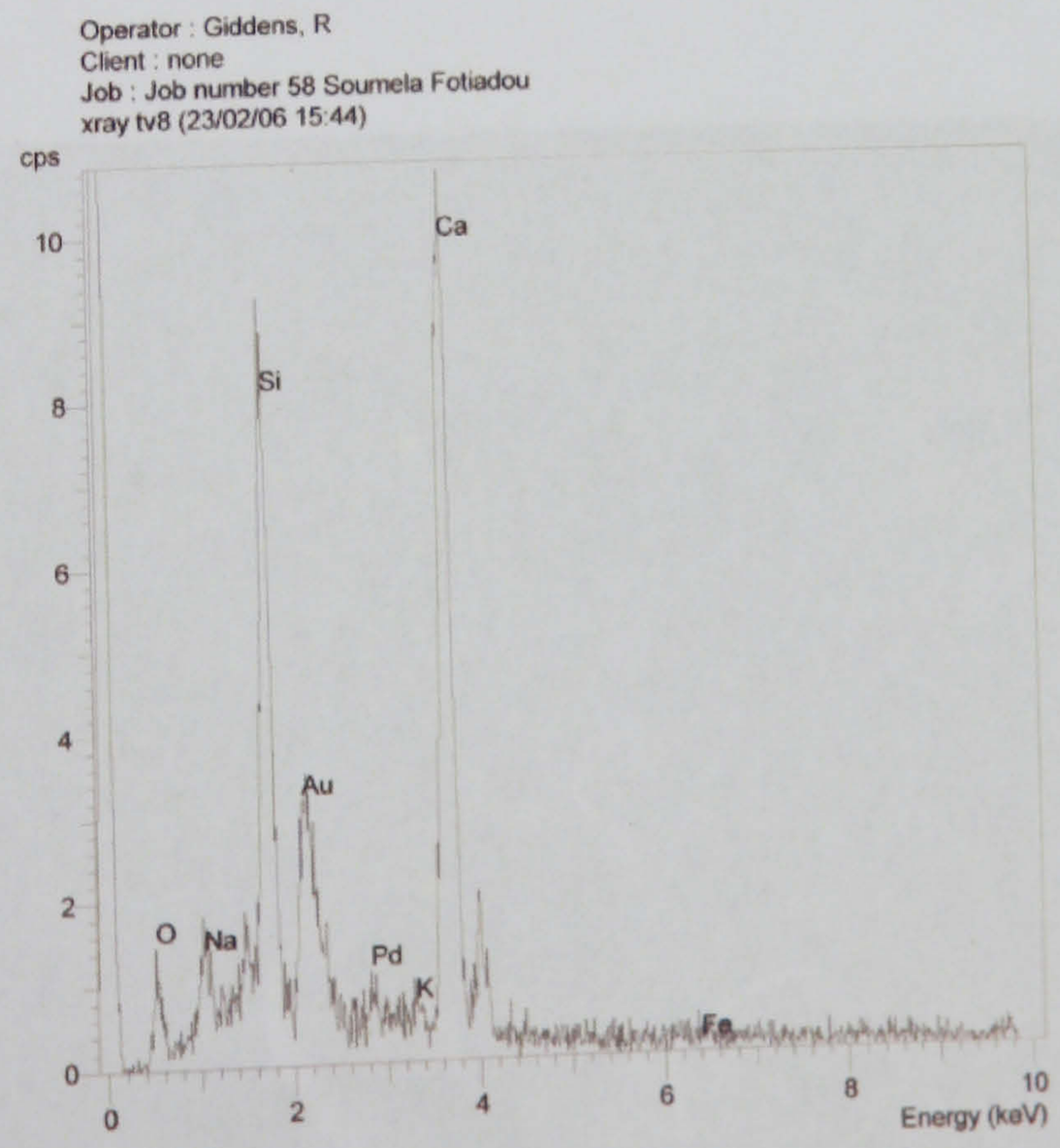


Figure 8.26 EDS-X Rays of Compact Area Showing Mainly Silica and Ca, Very Small Amount of Na, and Au -Due to Sample Preparation.

According to Figure 8.26, the compact area mainly consists of Silica and Calcium, while no presence of alkalies was observed as with previous analyses. Presence of pozzolanic C-S-H gel is suspected due to cement hydration, which is favourable. The difference between ASR and Pozzolanic reaction is that the resulting gel from pozzolanic reaction has higher ratio of calcium /alkali [Ca/(K+Na)] and whether a beneficial or detrimental effect is produced depends on the timescale (rapid for pozzolanic, slower for ASR) [1]. EDS-X ray shows that the ratio of Ca/Na is higher than that found previously in a probable ASR gel (Figure 8.24). According to a research [88] alkali-silicate-hydrate gel (A-S-H) comparable to that formed by the alkali-silica reaction (ASR) does not form when Portlandite or the Ca-rich, Si poor C-S-H of ordinary Portland cement (PC) paste is available to react with the silica, so reason for no reaction products within the dense area can be the presence of C-S-H. gel.

What can be concluded is that there is a co-existence of C-S-H gel in the compact areas of the prisms and small amount of swelling A-S-H on the pores-concavities or rim of aggregates on GFGG prisms, as found in [88-92] GFGG enhanced and improved the pore structure of prisms through decreased ion permeability and its dense ITZ, while its pores became areas of ASR product accommodation and pressure dissipation; and a minor expansion as shown in similar researches [41,95-100]. Figure 8.27 presents this phenomenon.

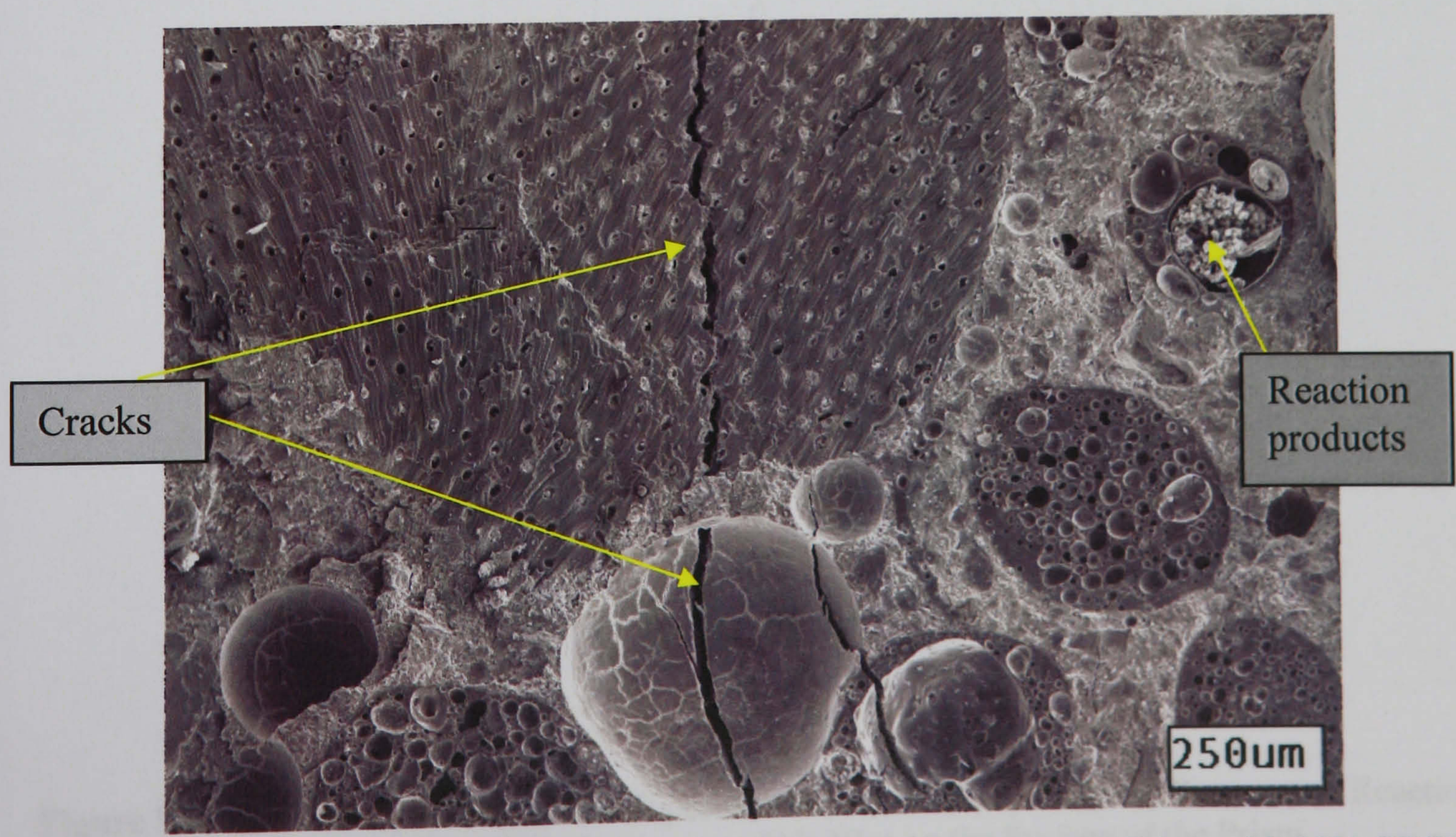


Figure 8.27 Secondary Electron Image at Magnification (x 30) of Mortar Prism with 30% GFGG.

Figure 8.27 shows some products of ASR (agglomerates) in the cavities of GFGG. Broken grains are also present, probably due to drying shrinkage during specimen preparation; and testing; but not caused from ASR since a gel should have been traced. Figure 8.28 shows image at the end of ASR test of reacted surface of prisms with 30% GFGG in contact with NaOH.

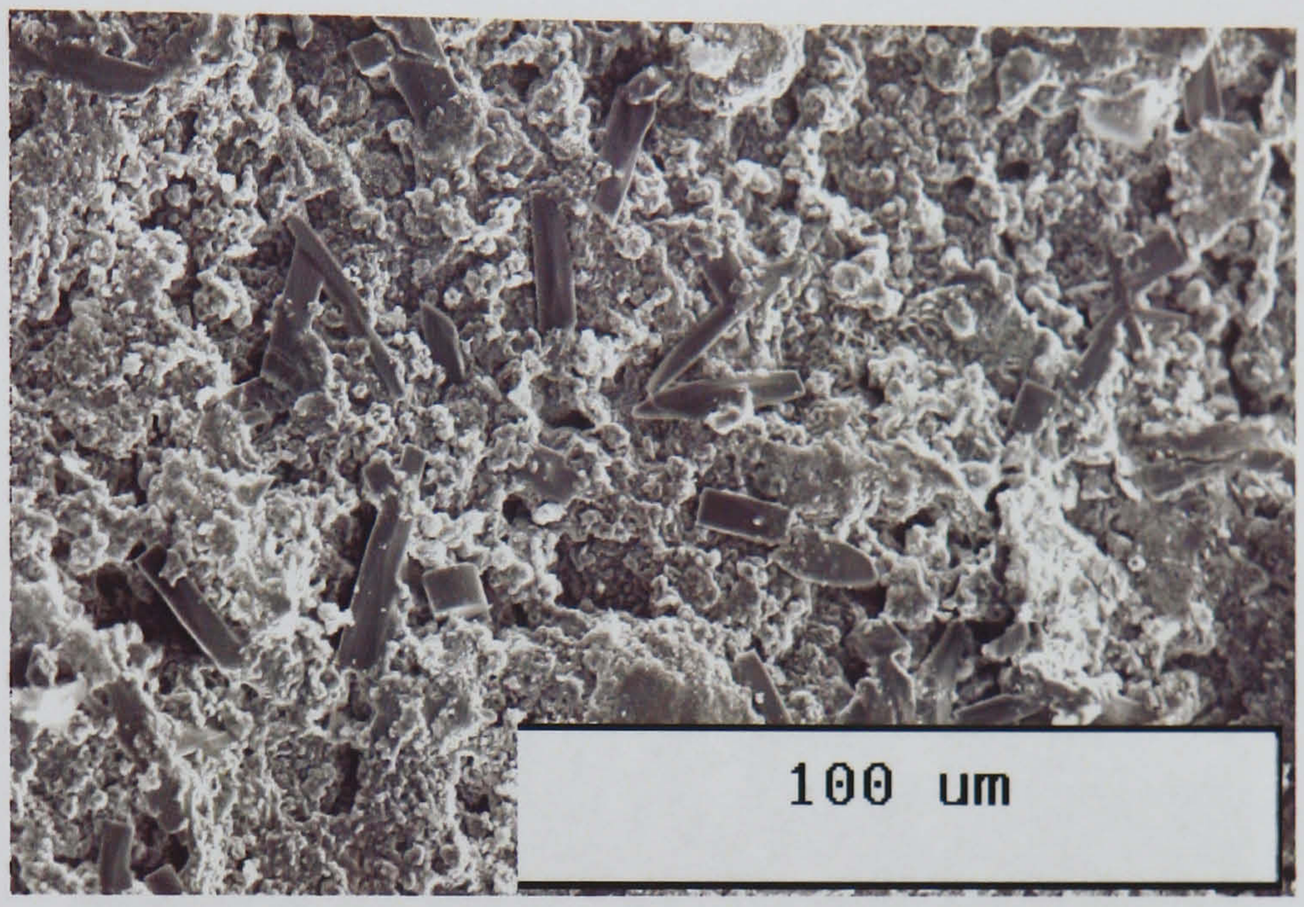


Figure 8.28 SEI of the Fresh Fractured Surface of 30% GFGG Prisms after Exposure to 1 N NaOH for 14 Days.

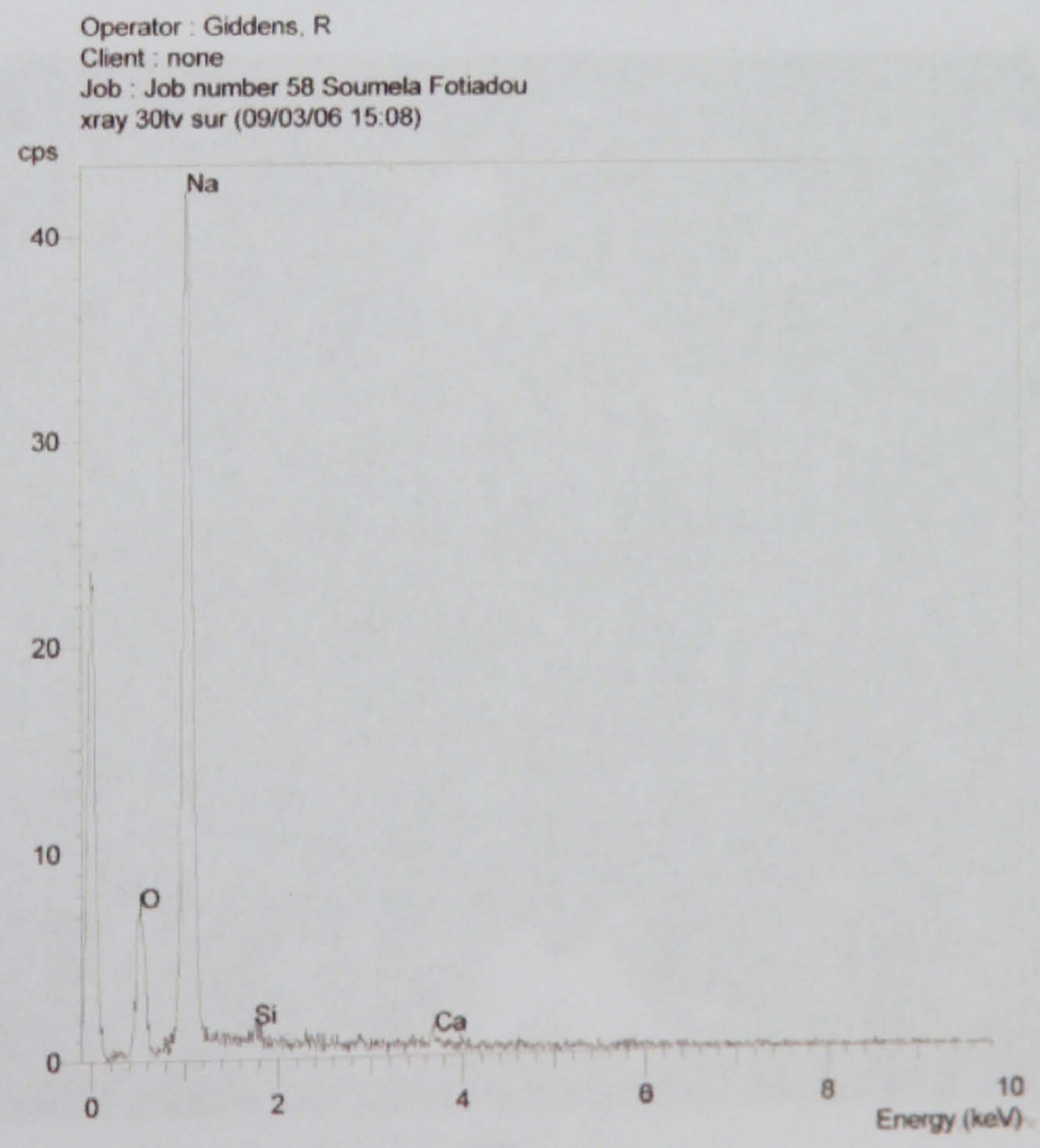


Figure 8.29 EDS X-Ray Showing the Superior Amount of Na, Proving the Presence of Reaction Products. Although High Amount of Na Was on the Surface of the Prism.

Crystalline Products and Agglomerates (rosettes) were observed which were probable precipitates of the solution. EDS X-Ray proves the Presence of Alkalies from NAOH solution (Figure 8.29). Examination of control prisms under SEM showed that reaction products were on the surface of sand grains and in weakness zones. Since the porosity of these grains is minor, matrix was stretched and slight expansion also occurred. Destruction of the bond between the aggregate and the surrounding hydrated cement paste was observed as noted in previous researches [1,95]. Figures 8.30 and 8.31 show images from probable ASR sites in control prisms.

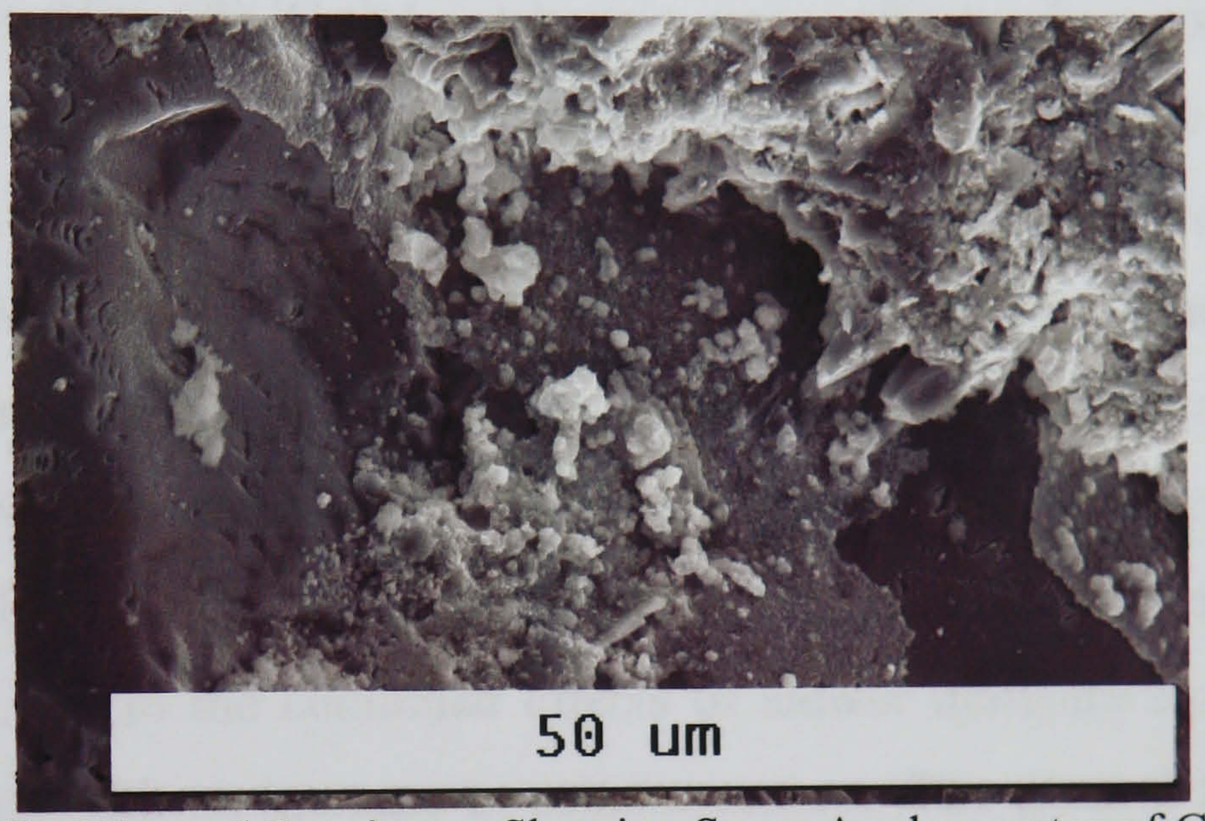


Figure 8.30 SEI of Control Specimens Showing Some Agglomerates of Gel with Rosette Morphology and Etched Exposed Areas.

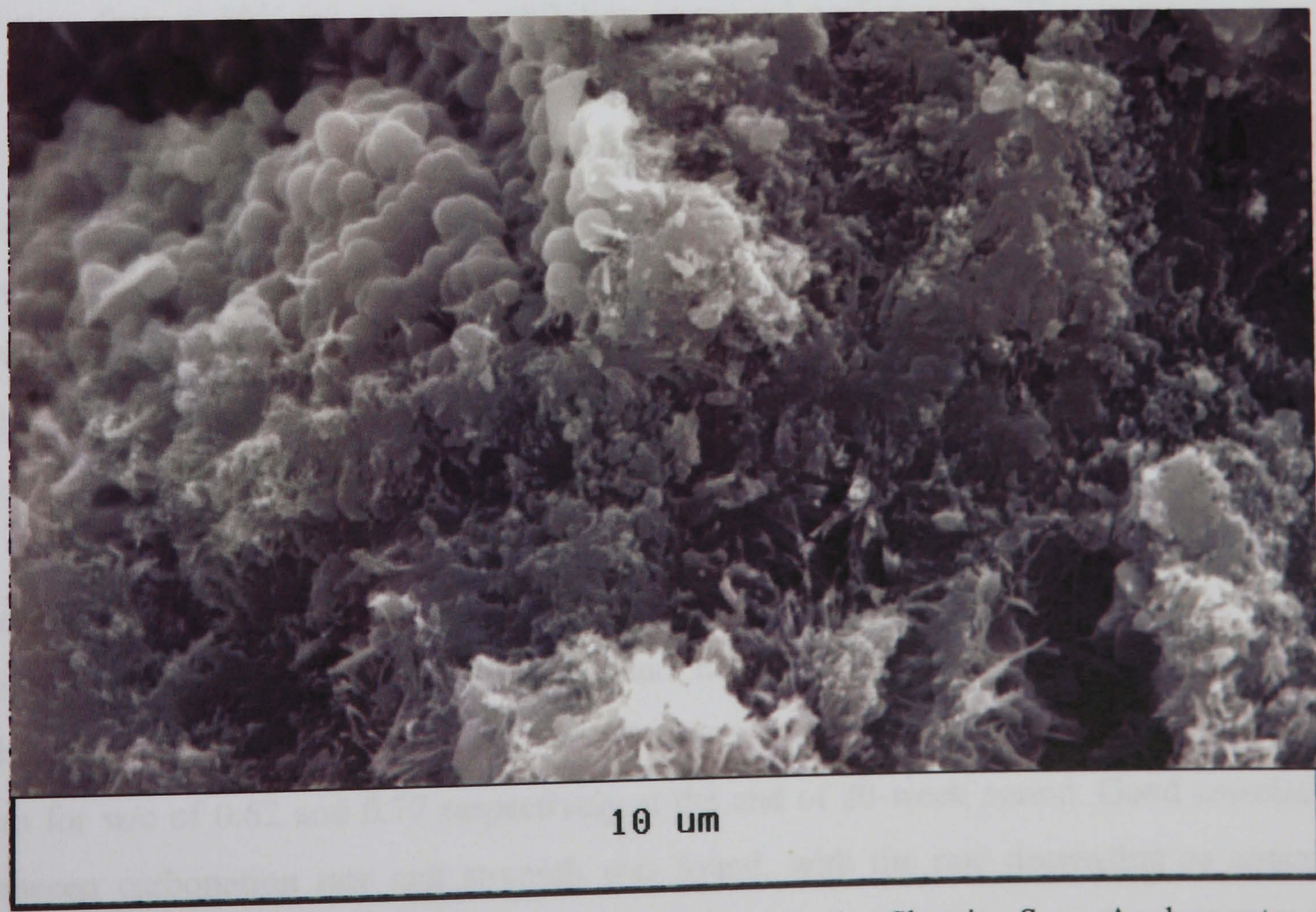


Figure 8.31 SEI of Control Specimens In higher Magnification Showing Some Agglomerates of Gel with Rosette Morphology and Etched Exposed Areas.

Various crystalline products were generated on the original material, and also partly replaced it, bringing about the rupture or decay of the texture of the aggregate particles similar to other study [19]. EDS X-rays analysis of rosettes showed that it mainly consisted of Na, K indication of ASR reaction products.

8.6 Concluding Remarks

In this chapter durability related properties of NA, GFGG and Lytag concrete were examined. Results from near surface absorption tests show that for the 28 day-ISA-10 minute value, up to 30% GFGG did not have a major effect, when compared to control mix. As the proportion of GFGG increased from 30-60% 10-minute water absorption increased for both 28 and 60 days of testing due to higher water absorbency of GFGG compared to NA. At 100% GFGG replacement level, the 10-minute value was significantly higher than the control at all times. Such increase in surface absorption of concrete with high level of GFGG is thought to be directly related to reduction in compressive strength. The near surface absorption characteristics were improved as w/c ratio and GFGG content decreased. This is due to the combined effects of slower moisture evaporation rate and faster hydration rate with an increase in cement content. The general trend observed for fine GFGG mixes indicates reduction in ISA-10 values with increase in Fine GFGG content from 5-15% by volume, exhibiting improved performance. This is maybe due to filler effect of fine GFGG. On the other hand, n-values for NA and fine GFGG concrete mixes remain within a narrow band. On the whole, n-value seems to decrease considerably with increase in fine GFGG content. For Series 2 mixes, ISAT-10 values were found to be reduced by 20% in 60% coarse GFGG concrete compared to their corresponding NA concretes, similar to strength result's trend. In general, satisfactory ISAT-10 and n-values within the allowable limits can be obtained. Lytag concrete mixes showed higher ISA-10 and n-values compared to GFGG and NA mixes, due to Lytag higher water absorbency.

Regarding the carbonation rate of GFGG mixes with coarse GFGG (30-60%), results showed that up to 60% coarse GFGG had negligible influence on carbonation rates. Maximum difference between 50% GFGG concrete and NA concrete mixes was 4 and 5 mm for w/c of 0.62 and 0.77 respectively at the end of 20-week period. Good correlation between carbonation rate and strength was found, with the rate decreasing as concrete strength increased. Lytag concrete, had slightly higher carbonation rates when compared to

both NA and GFGG concrete mixes. Carbonation values were very comparable for GFGG and Lytag mixes at low concrete strength (w/c 0.77) while it differed significantly at higher concrete strength. It is obvious that resistance of Lytag to diffusion of CO_2 is lower (higher depth), the lower the strength is.

ASR test results on prisms with 30-100% fine GFGG from both glass sources showed that the use of 30-50% GFGG yielded similar expansion values as the control mix, while as the percentage of GFGG increased between 50-100% there was a significant influence to ASR tendency but still within the ASTM limits. Generally, results obtained indicate that none of tested samples with GFGG expanded significantly beyond the recommended limits and during the tests damaging deleterious expansion due to ASR has not occurred during testing. However, at 100% GFGG prism results are within the range listed by the ASTM standard as "indicate potentially deleterious expansion". The effect of glass source (mixed bottles or CRT glass) was found to be negligible. SEM showed some minor ASR products within the cavities of GFGG, and rarely in the interfacial transition zone of GFGG. The air voids present in GFGG could accumulate any ASR gel and not cause expansion. GFGG by having big sized bubbles could behave as pumice and accommodate any reaction products as shown in other studies.

ICP-AES test on recovered solutions showed a huge diffusion of silica from GFGG prisms into solution. Silica migrated from aggregates and did not take part in the reaction. The very susceptible aggregate as believed, did release sufficient amounts of silica but these were transported to solution outside the prisms and did not trigger the reactivity. Alkalies were transported from pore solution and did not ingress into the GFGG matrix. Calcium did not ingress on the GFGG due to excellent interfacial transition zone. The impermeable hydrated cement paste of GFGG prisms inhibited the movement and migration of ions such as alkalies, hydroxides and calcium within the mass of mortar preventing expansion.

SEM images support the ASR test results not showing any major ASR products for 30% GFGG prisms, only in few places such as GFGG pores and rim. There also seems to be a co-existence of C-S-H and A-S-H gels. However no band distribution was found around the GFGG zone similar to other studies of finely ground glass. Some products were also found in Control prisms in planes of weaknesses.

CHAPTER 9

WASHED GLASS SAND CONCRETE

9.1 Introduction

This stage of the research consisted of a product development programme designed to address the use of washed glass sand as partial (10,15,20 and 50% by mass) replacement of natural sand in concrete productions. For this, samples of washed glass sand (WGS) were obtained from Day Group. This type of material is quite new to construction industry and very limited data of its properties is available. Method of production of WGS included, taking mixed glass bottles and wash them until all impurities as sugar, paper and other contaminants were removed. Then this glass was crushed at less than 5 mm size so as to be used as sand replacement. It was decided to examine WGS since it had similar glass source with GFGG and would be an additional comparison with the properties of GFGG. WGS was not crushed to powder form as GFGG and was not mixed with chemical additives to control water absorption. Also its surface texture and shape was not the same as GFGG (pellet), but was similar in shape to normal sand, so its properties in concrete would be expected to differ from that of GFGG. An important aspect of this short research was to examine if ASR occurred in prisms with WGS. Time and resources available allowed its examination and by agreement with the technical staff a short research programme started.

WGS key physical characteristics were established to compare them with GFGG and NA. Next, the bulk engineering properties (compressive cube and cylinder strength, flexural strength and modulus of elasticity) and selective durability related performance of glass aggregate concrete were assessed, with particular emphasis on alkali-silica reaction (ASR); since this considered to be a key issue when using glass in concrete. Finally, the practical implications for use of washed glass sand in concrete products are listed. It is anticipated that the application and practical issues associated with the washed glass sand concrete products development will be resolved fully during this stage. These cover washed-glass sand introduction, handling, placing, finishing, health and safety etc.

The principal objective of this short research study was to examine properties of washed glass sand concrete and potential for use in value-added concrete products, creating the

opportunities to absorb vast quantity of surplus material. The main objectives of the study were to:

1. Investigate and compare key characteristics of washed glass sand and assess its suitability for use in concrete production.
2. Assess the influence of washed glass sand, when used as fine aggregate replacement, on the fresh properties of concrete.
3. Establish the bulk engineering properties (compressive strengths, flexural strength, modulus of elasticity- stiffness and stress/ strain relationship) of washed glass sand concrete.
4. Assess the influence of washed glass sand on the durability related performance (near surface absorption and alkali-silica reaction) concrete.

9.2 Waste Glass as Aggregate

Full details on the recycled glass alternative markets were summarised in the literature review Chapter 2. This section concentrates on the use of glass, as aggregate in concrete construction.

The use of waste glass as aggregate for concrete production has been attempted decades ago. Those early efforts were thwarted by the problems of alkali-silica reaction (ASR), which was not well understood then. Cullet is a hard material that in its broken form is a granular in nature. This makes it an obvious contender for use as an aggregate in construction and related applications. This approach to cullet use is in many ways highly favourable from a commercial perspective, since very little processing is required to obtain a serviceable product. On the other hand the value realised by using the material in this way is relatively low.

The simplest route to recycling cullet as an aggregate, albeit commanding the least resource value, is as an unbound road-base material [101]. Research carried out using this material has demonstrated that it displays much greater stability compared to natural aggregates. Further value can be added by using such aggregate in asphalt or concrete [102,103]. Whilst use as a concrete aggregate presents an attractive concept (given that concrete is used globally in volumes only exceeded by water) the issue of alkali-silica reaction (ASR) is one, which must be addressed with great care during the product

development stage. ASR occurs when solubilized alkali ions react with chemically active forms of silica to create a gel-like product. The gel has a high propensity for imbibing water, which leads to swelling. This swelling leads to expansion of concrete structural elements and eventually leads to cracking and spalling. It is well known that glass is capable of undergoing ASR and, indeed, the ASTM for assessing ASR suppressing additives utilises glass (albeit pyrex) as the active aggregate component [102].

Most of the ASR studies with glass concrete utilised the ASTM C1260 test. This is the most popular accelerated test, because it lasts just a little over two weeks. It has been developed primarily to assess the potential reactivity of aggregate. It calls for the preparation of 25x25x280mm mortar bars containing the aggregates to be investigated, which are immersed in 80°C sodium-hydroxide solutions for two weeks. Their expansions are interpreted as being indicative of the material's potential reactivity. Although a positive result is not a guarantee that the material is innocuous, the ASTM C1260 test is of great value for comparative purposes.

However, research into ASR of cullet aggregate in concrete has uncovered a number of interesting phenomena that can be exploited to minimise the influence of this reaction. ASR testing of concrete products containing cullet over a series of discrete particle size fractions has identified a 'pessimum' particle size at which ASR expansion is maximum, and either side of which expansion declines [1]. This pessimum point varies depending on the type of glass and possibly on the nature of the concrete in which it is present, but the research identifies it as being around 1200μm for clear soda-lime glass. Furthermore, glass colour also has a significant effect on ASR expansion, with concrete containing green glass showing no more expansion than control materials. Thus, by selecting suitable size fractions ASR can be avoided. Furthermore, larger particles can be incorporated if a suitable ASR suppressing additive is also employed [102-105]. The results of work undertaken [29] has shown that glass releases alkali when it is exposed in lime solutions respectively, in humid alkaline environments like cement paste, and the amount of releasable alkalis increases with increasing surface area. It was concluded that finely pulverized glass should be avoided in humid exposed concrete.

Concrete products produced using recycled glass can be categorised as commodity products and value-added products. For simple commodity products, the primary objective

is to utilise as much waste glass as technically, economically and practically possible/ feasible. Whether the glass can be seen is a secondary issue. For value-added products, on the other hand, the aesthetic potential of the glass is utilised, because glass can be very attractive and aesthetically pleasing. Several research and development works. both scientific and applied researches, have been under taken to exploit the use of recycled glass in a range of concrete product [1]. These include concrete masonry blocks, paving stone, floor tiles, kerbs and paviers, precast wall panels, flooring concrete etc.

In the following section, characterization of WGS takes place, followed by fresh and hardened properties of WGS concrete.

9.3 Characterisation of WGS

Given that the acceptance of washed glass sand as a constituent material in new concrete production will highly depend on its properties, key physical characteristics of this were established. Samples supplied by Day Group were used throughout the study (Figure 9.1). During this testing, current and recently adopted British and/or European standards were used, where applicable. A series of tests to assess key physical characteristics of WGS were undertaken. These included:

- Shape and surface texture
- Loose bulk density
- Apparent density
- Water absorption
- Particle size distribution

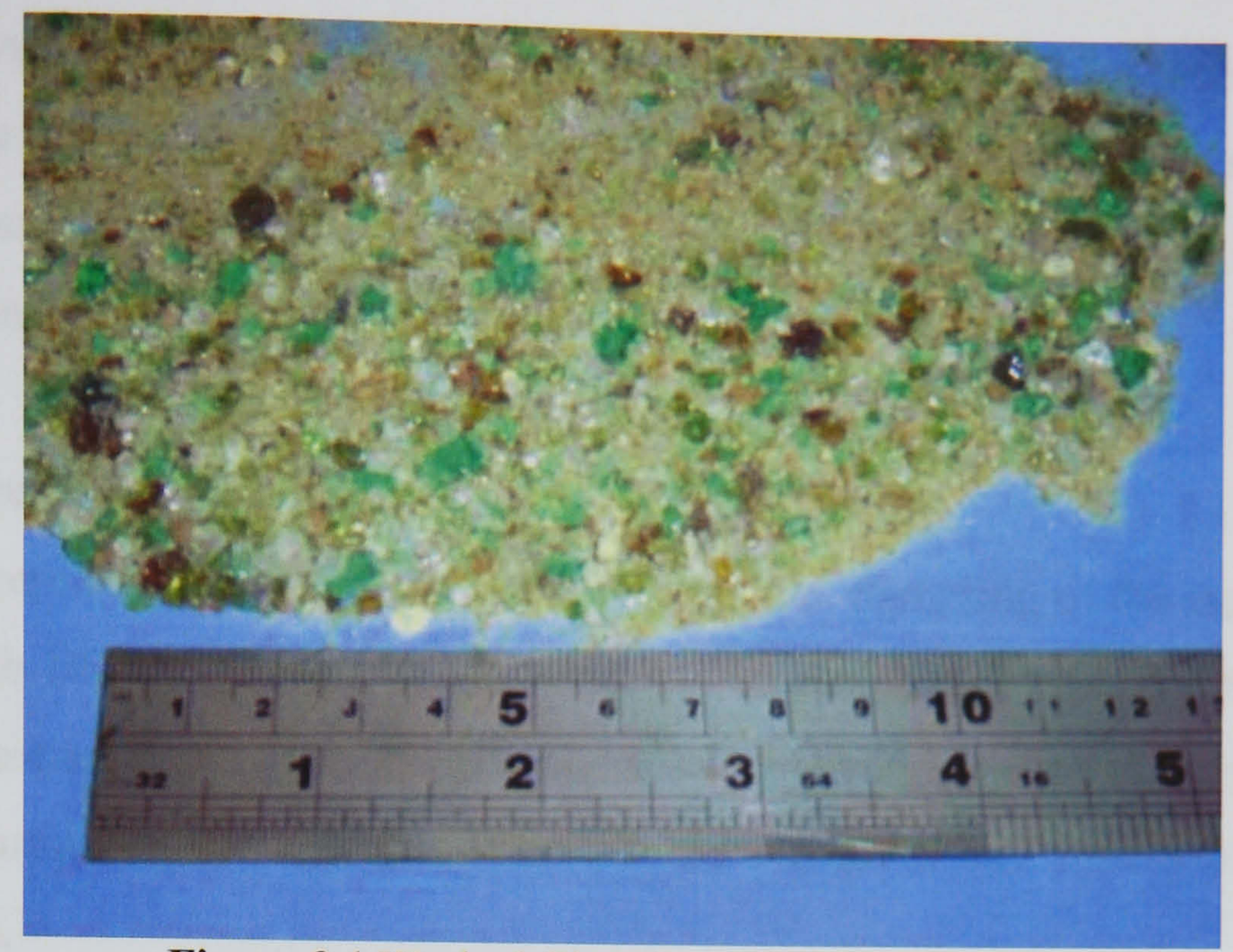


Figure 9.1 Washed Glass Sand (less than 5 mm)

As seen from Figure 9.1, WGS has similar morphological characteristics with normal sand, meaning similar irregular-rounded particle shape with the exception of having small sizes of crushed glass of green and clear colour due to its source. Visual examination on WGS indicated that the material was very similar to normal sand in the texture with the only difference the presence of sharp edges due to crushed glass. However, handling of the material was not dangerous from health and safety point of view.

In parallel to these, Scanning Electron Microscopy (SEM) to identify surface charcateristics and key chemical components of glass particles were also undertaken (Figure 9.2). According to Figure 9.2, there is no morphological difference between green or clear glass and is similar to common soda-lime glasses. Energy Dispersive Spectrum -X-Ray analysis on clear and green glass of WGS took place to examine the elements present. Figure 9.3 presents the elemental analysis for green and clear glass.

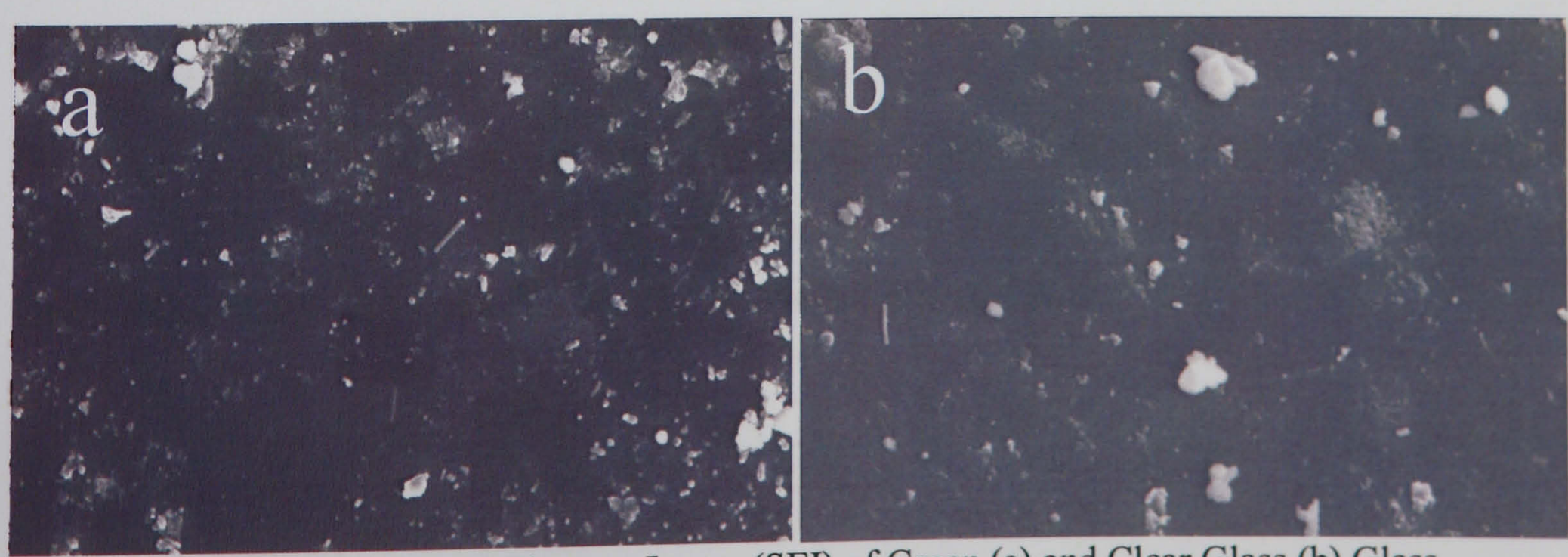


Figure 9.2 Secondary Electron Image (SEI) of Green (a) and Clear Glass (b) Glass

Chemical analysis on the surface of green and clear glass from WGS, proved to be similar and showed the presence of Silica (due to glass-source) and other elements such as Na, Ca while Al, Mn and Fe at smaller percentages, similar to Natural Sand and Foamed Glass Gravel elemental analysis.

Particle size distribution

Test samples were prepared using the riffle box method. Sampling of the aggregate was in accordance with BS EN 932-1 and reduction was in accordance with BS EN 932-2. The mass for the washed glass aggregate sample was calculated according to Table 1 of BS EN 933-1. Test portion of 0.5 kg was used. Table 9.1 gives test results and Figure 9.4 illustrates them.

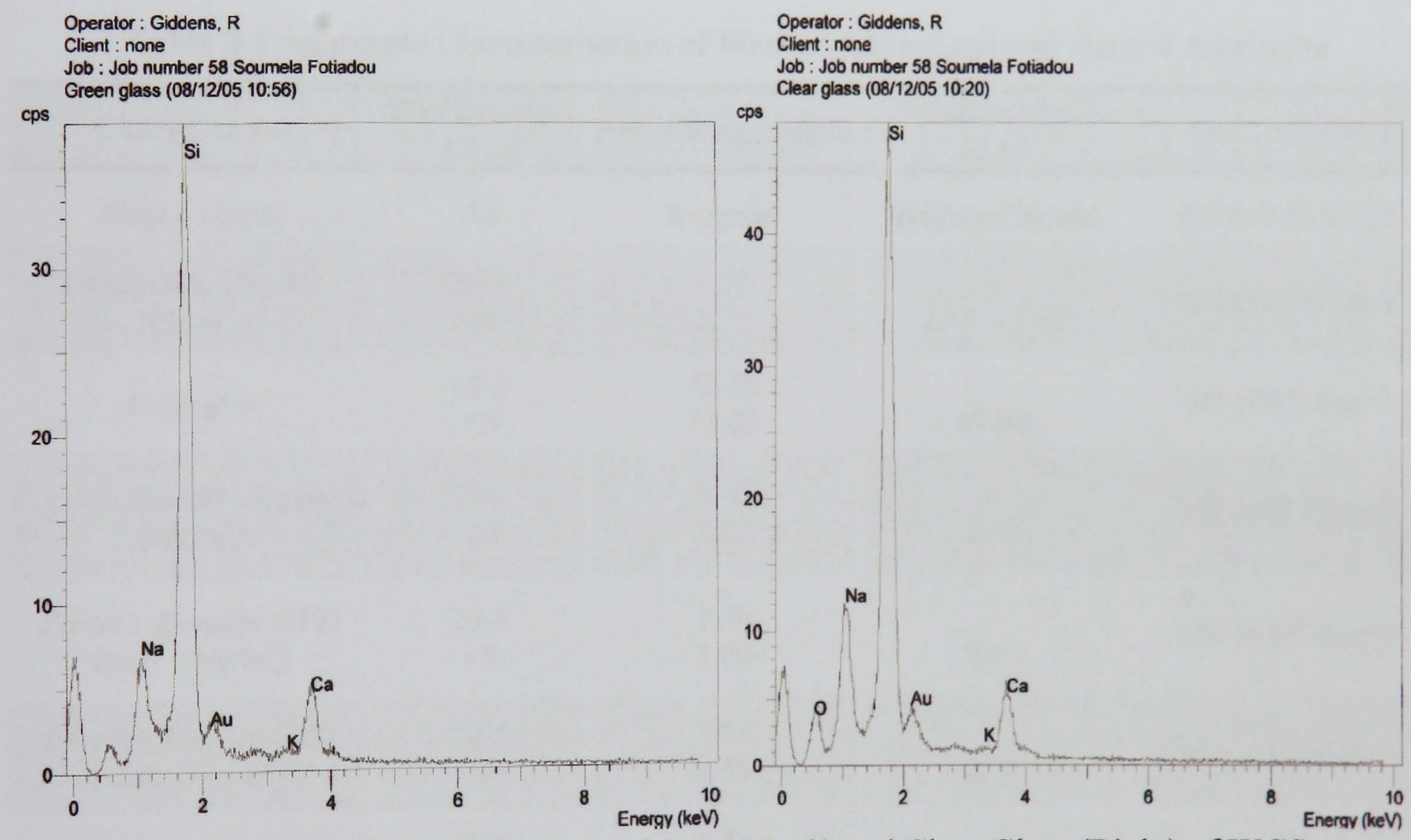


Figure 9.3 EDS-X-Ray Analysis of Green (Left) and Clear Glass (Right) of WGS

Loose bulk density

Sample preparation for these tests were carried out in accordance with the BS EN 933; Part 2 and sample testing was undertaken as per BS EN 1097; Part 3. In total, six samples of washed glass sand were tested and the mean value was recorded.

Particle density and water absorption

Preparation of the test samples was done in accordance to EN 932; Part 2. The minimum mass required for the test portion was worked out as per those specified in Table 2 of EN 1097; Part 6. Again, apparent, saturated and surface dry and oven dry particle density was calculated. Results of main physical characteristics of washed glass (WG) and natural sand are given in Table 9.2. According to Table 9.1, as expected, Bulk density, Particle density and water absorption of WGS was very similar to Natural sand. Only the percentage of voids between WGS particles was found to be lightly higher than the natural sand. The higher percentage of voids can be due to the presence of gaps due to the angular particles of glass, which was present in WGS as shown in Figure 9.1. There was poor particle packing due to lack of round/spherical particles as in the case of natural sand, resulting in the presence of higher amount of voids.

Table 9.1 Aggregate Characterisation of Washed Glass Sand and Natural Aggregate

Characteristics	Size Fraction (mm)	Natural Aggregate	Washed Glass Sand	Test Procedure
Shape, Visual	All	Irregular	Irregular/ Round	BS 812-Part 105
Loose Bulk Density (Mg/m^3)	20-5 <5	1.50 1.70	- 1.45 – 1.50	EN 1097- Part 3
Voids (%)	20-5 <5	42.30 37.00	- 67.50	EN 1097- Part 3
Particle Density, Apparent (Mg/m^3)	20-5 <5	2.60 2.70	- 2.50	EN 1097- Part 6
Particle Density, OVD basis (Mg/m^3)	20-5 <5	2.50 2.60	- 2.15	EN 1097- Part 6
Particle Density, SSD basis (Mg/m^3)	20-5 <5	2.55 2.65	- 2.25	EN 1097- Part 6
Water Absorption (%)	20-5 <5	1.25 0.80	- 1.40	EN 1097- Part 6

Regarding the grading of WGS, Table 9.2 and Figure 9.4 show that WGS grading values are very similar regardless of the % of WGS. There is a reduction in the percentage passing as sieve sizes decrease. However, all grading range within the allowable curves (upper and lower limit) set by BS 12620. It is also observed that as the percentage of natural sand (NS) decreased (increase in the percentage of WGS); the mix became slightly finer (slight increase in the percentage passing the 63 μm sieve from 37%-57%). This is due to the crushing of mixed bottle glass during production process. At 100% replacement level of natural sand by WGS, mix was finer than other mixes. In comparison with grading values

of NS mix (0% WGS), results were very similar and grading curves of WGS samples were very comparable with that of NS (0% WGS).

Table 9.2 Particle Size Distribution Test Results.

Aggregate Sample	Percentage Passing Down to 0.063 mm Sieve Size							
	8mm	4mm	2mm	1mm	0.5mm	0.25mm	0.125mm	0.063mm
100% WGS	100	100	100	97.47	82.01	65.59	59.49	57.49
50% WGS / 50% NS	100	100	100	99.89	87.79	66.77	46.49	44.38
15% WGS / 85% NS	100	100	100	99.9	90.34	66.07	38.33	37.48

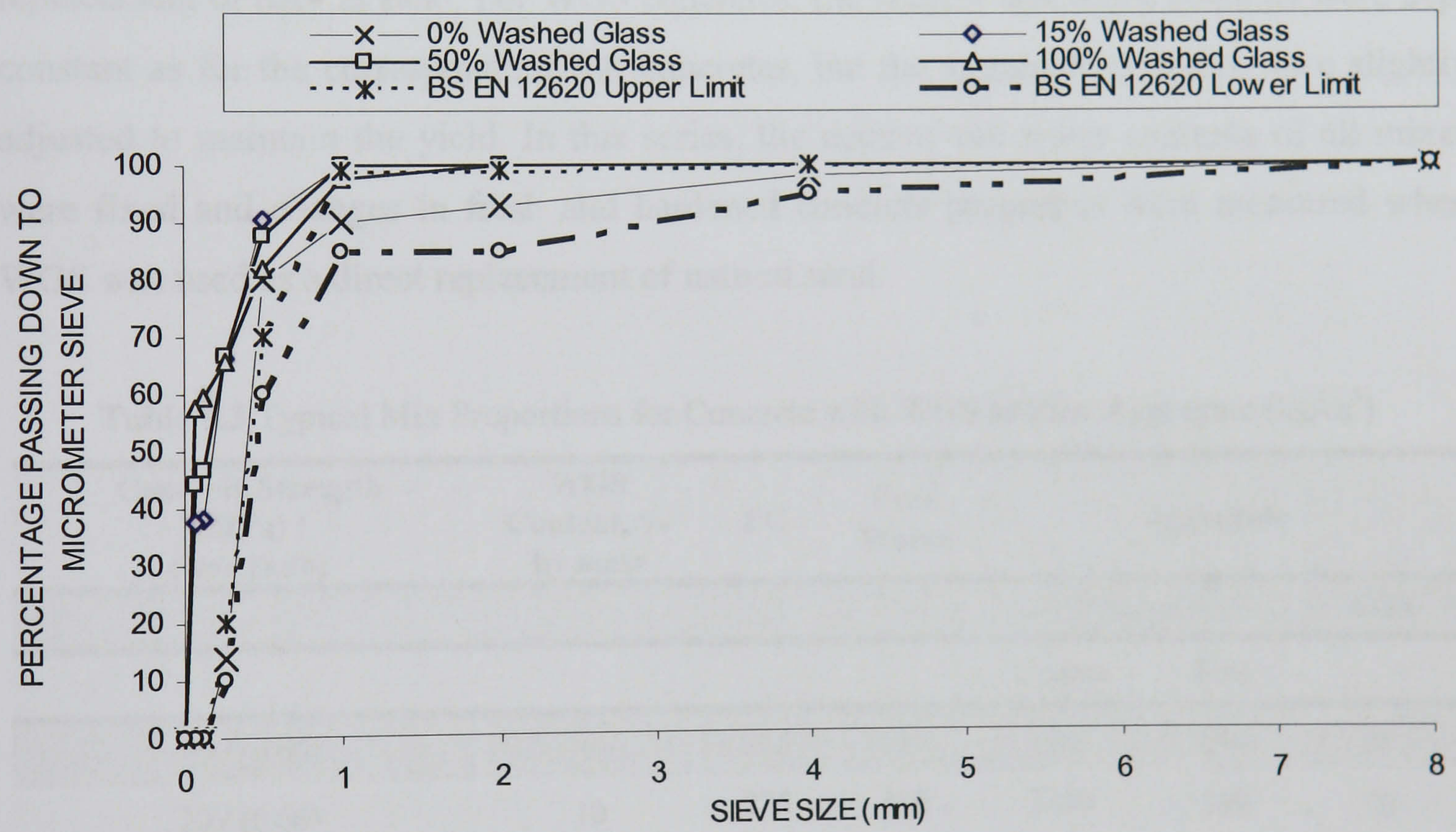


Figure 9.4 Particle Size Distribution of NA and WGS.

In general, characteristics of WGS were similar to natural sand, as far as it concerns, densities, water absorption and visual observation. However, WGS showed looser particle packing due to angular glass particles present and slightly finer grading than NS, implying the presence of fine particles from the crushing of mixed bottle glass.

9.4 Fresh Properties of WGS Concrete

A series of concrete mixes were cast to assess the effect of washed glass sand (WGS) on fresh and properties of concrete. The conventional mix design method for normal concrete [52] was used for Thames Valley Gravel and natural sand concrete mix proportioning with design strength of 20MPa and 30MPa. In this, proportions of fine aggregates were established based on the percentage passing a 600μm BS sieve and the average relative density of aggregates. Both Thames Valley gravel, natural and WGS were laboratory dried, prior to their use in the production of concrete. A Portland cement of Grade 42.5N conforming to BS EN 197-1, was used throughout the study for concrete production. All mixes were designed to be of average workability (75mm nominal slump) (Table 9.3). Washed glass sand concrete mixes (0.058 m^3) were proportioned using Thames Valley gravel, natural and washed glass sand blends, with 10,15,20 and 50% WGS used as direct replacement of natural sand. For WGS concretes, the cement and water contents were kept constant as for the corresponding NA concretes, but the aggregate contents were slightly adjusted to maintain the yield. In this series, the cement and water contents of all mixes were fixed and changes in fresh and hardened concrete properties were measured when WGS was used as a direct replacement of natural sand.

Table 9.3 Typical Mix Proportions for Concrete with WGS as Fine Aggregate (kg/m^3)

Concrete Strength (MPa) / (w/c ratio)	WGS Content, % by mass	PC	Free Water	Aggregate		
				Natural		WGS
				Coarse	Fine	
20 / (0.66)	0	275	180	1295	640	0
20 / (0.66)	10	275	180	1295	580	70
20 / (0.66)	15	275	180	1295	550	95
20 / (0.66)	20	275	180	1295	520	130
20 / (0.66)	50	275	180	1295	320	320
30 / (0.55)	0	330	180	1300	570	0
30 / (0.55)	10	330	180	1300	510	60
30 / (0.55)	15	330	180	1300	480	90
30 / (0.55)	20	330	180	1300	455	110
30 / (0.55)	50	330	180	1300	285	285

Workability and Stability

The fresh properties of WGS concrete mixes were determined by measuring the workability (slump, compacting factor) and stability (visual observation for bleeding, segregation). The results obtained then compared with the corresponding NA concrete mixes. In addition, in order to assess the effect of WGS on the maintenance of the workability and entrained air content with time, further tests were carried out up to 150 and 60 minutes respectively.

The workability results in terms of slump and compacting factor found to be within specified tolerances (EN 206-1, ±20 mm). However, the stability of mixes with 50% WGS was found to be slightly reduced (Tables 9.4).

Table 9.4 Effect of Washed Glass Sand on Workability of Concrete Mixes, (*Design for nominal slump of 75mm (± 20mm)*).

Washed Glass Sand Content, % by volume	Workability Measurements Slump, mm (Compacting factor)	
	Design Strength	
	20 MPa	30 MPa
0	**90 (0.99)**	**75 (0.97)**
10	90 (0.98)	75 (0.97)
15	85 (0.98)	75 (0.96)
20	85 (0.98)	70 (0.97)
50	80 (0.96)	65 (0.95)

Reason for satisfactory fluidity in 10-15% WGS concrete mixes is the decreased water demand from WGS. Glass particles are not able to absorb water fast, so there is more free water to enhance the fluidity. It was shown that when glass sand is used at water/cement equal or greater than 0.5, up to 50% by mass replacement, increases workability while higher replacements slightly decrease the slump – increase the water demand. In general, cullet sand shows nearly similar characteristics as crushed sand with sharply angular shapes and rough surfaces, similar to previous studies with crushed glass [16-31]. Further increase of WGS to 20-50% decreases slump. This decrease can be due to the angular cullet particles, which may have an interlocking effect and less freedom of movement in the concrete mixture compared to rounded river sand, which gives greater workability. As the mixing ratio of waste glass aggregate increased, additional cement paste attached to the surface of the waste glass, which resulted in less available cement paste necessary for the

fluidity of the concrete as shown in another researches [30]. Waste glass aggregates had sharper and more angular grain shapes and were larger than sands, which resulted in less fluidity.

Loss of Workability

The workability loss, in terms of compacting factor, of both washed glass sand and natural aggregate concrete mixes was measured up to 150 minutes after casting, at 30 minutes intervals. Results show uniform nature of workability loss, with negligible influence on WGS on this property- indicating equivalent performance (Table 9.4).

Stability

In order to assess the effect of WGS on the stability of concrete, a visual observation of the mixes and the bleeding test in accordance with ASTM C232: Method A: Sample consolidated by tamping was carried out. All WGS concrete mixes were found to be cohesive and showed no tendency of segregation or bleeding, and on the whole stability was found to be equal to the corresponding NA concrete mixes.

After correct compaction, steel moulds filled with concrete in three equal layers and then were covered with polythene sheets for 24 hours until de-moulding. Specimens were then placed in CU1 curing Conditions (20°C ± 2 and 95% RH) until the time of the test. Section 9.5 presents the results from Engineering Tests on Hardened Concrete.

9.5 Influence of WGS on Bulk Engineering Properties

9.5.1 Cube Compressive strength

This section discusses the effect of WGS up to 50% fine fraction on the compressive cube and cylinder strength of concrete mixes. In addition to compressive strengths, tests were carried out to study the effect of WGS (when used as direct replacement of natural sand) on the 28-day flexural strength and elastic modulus of concrete. Compressive strength tests were performed on two 100 mm cube specimens, tested at 3, 7, 14, 28 and 60 days in accordance with BS1881, Part 116. At 28 and 60 days, two 150 mm cubes were also tested for compressive strength according to BS EN 206-1. All test specimens were cured under the standard 20°C water. In order to eliminate extraneous results and to assist in the analysis, a curve fitting procedure was followed in the data processing similar to the one

described in Chapter 7 for GFGG, Hasopr and Lytag. This considered strength against water/cement ratio relationship. Curves were fitted to the raw data and resulting modifications checked with strength - time plots. Strength development test results are given in Table 9.5. These are the normalised results obtained from curve fitting method.

The general trends observed negligible influence of up to 20%WGS on compressive cube strength of the concrete compared to NA concrete mix. It is also apparent that the effect of WGS on strength variation compared to NA concrete mix became more significant for levels greater than 20%. However, all mixes including the 50% WGS reached and exceeded the designed value of 20MPa and 30 Mpa at 28 days and continued to gain strength after 28 days and at 180 days the increase was between 5MPa-8 MPa.

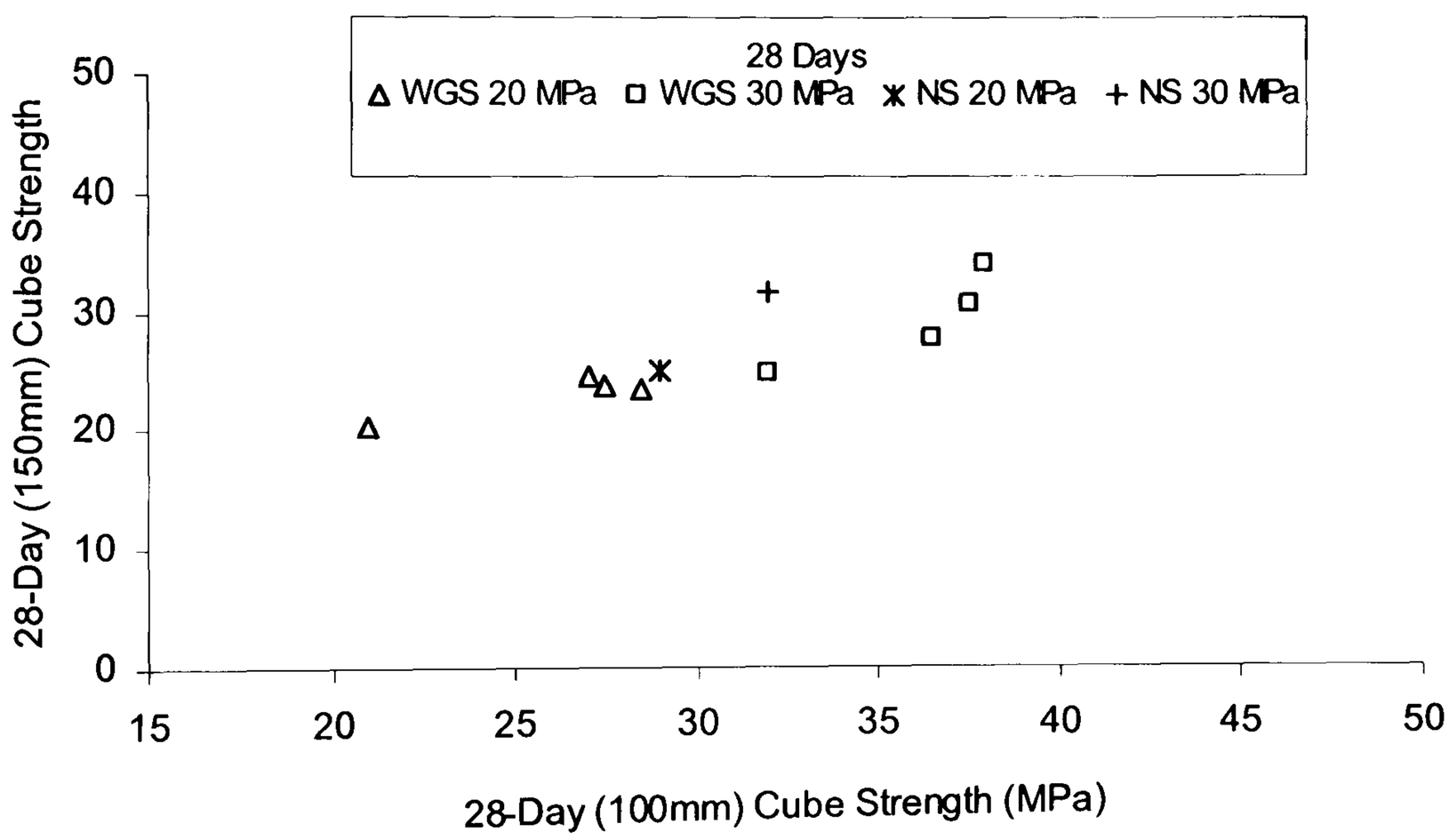
Table 9.5 Cube Strength Development of NA and WGS concrete; curing: water at 20°C

Concrete Type	Cube Strength, MPa						
	Age of test, days						
	3	7	14	28	60	90	180
Design Strength = 20 MPa							
NA Concrete	**18.0**	**21.5**	**24.0**	**29.0**	**32.0**	**34.5**	**36.0**
WGS Concrete							
10% WGS	17.0	20.5	23.0	**28.5**	31.5	34.5	36.0
15% WGS	16.0	21.0	23.5	**27.5**	31.0	34.0	35.5
20% WGS	16.5	20.5	23.5	**27.0**	29.5	32.5	34.0
50% WGS	11.5	15.0	17.0	**21.0**	22.0	23.5	26.0
Design Strength = 30 MPa							
NA Concrete	**26.0**	**29.0**	**34.0**	**40.5**	**42.5**	**44.5**	**48.5**
WGS Concrete							
10% WGS	25.5	29.0	34.0	**38.0**	41.0	43.5	47.0
15% WGS	25.5	28.5	33.0	**37.5**	40.5	43.5	46.0
20% WGS	24.5	27.5	32.5	**36.5**	38.5	42.5	44.5
50% WGS	20.5	23.0	28.0	**32.0**	36.0	39.0	41.0

According to Table 9.5, strength development was normal for all mixes. In more detail, mixes with 10-50% WGS, reached the design strength of 20 MPa and 30 MPa strength showing values of 21-28MPa and 32-38 MPa respectively. However, replacements from

WGS higher than 20% by mass caused a significant reduction when compared to nA mixes. Regarding strength gain, development at 3-days around 60-70% of the 28-day value, implying a normal-rapid strength development. The usual strength gain is expected to be between 50-60% at 3 days.

Cubes of 150 mm were also tested with similar procedures to 100 mm cubes at 28 and 60 days. Similar trend was observed as with the 100 mm cubes, with cube strength being similar to control mix for 10-20% WGS replacement levels while decreasing as percentage of WGS increased from 20-50%. Relationship between 150 mm cube strength and 100 mm cube strength for 20 and 30 MPa are shown in Figure 9.5 (a) and (b) respectively for 28-day and 60 day of testing.



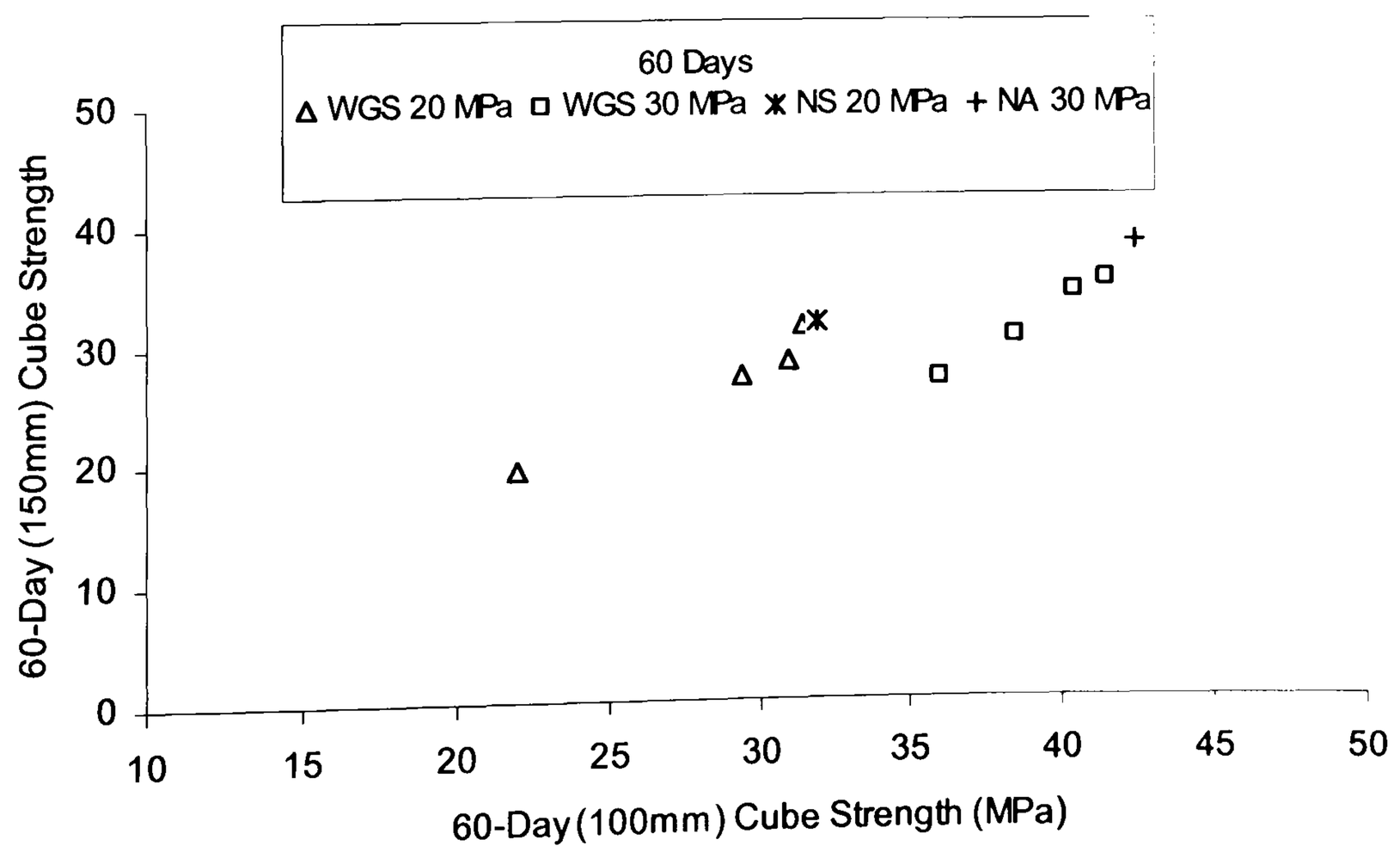


Figure 9.5 Relationship Between 150 mm and 100 mm Cube Strength for 20 and 30 MPa Concrete, at (a) 28 days and (b) 60 days; Curing: water at 20°C

According to Figure 9.5 (a), there is a close relationship between 150 and 100 mm cubes, increasing as concrete strength increases. Similar trend was observed for Figure 9.5 (b) for 60 days of testing. However, further testing is required for a variety of concrete strengths to obtain sufficient data and a reliable relation of y=ax+c between the two properties (150 m cube and 100 mm cube strength) to be derived.

9.5.2 Other bulk engineering properties

The flexural strength and modulus of elasticity (stiffness) of 20ºC water-cured prisms and cylinder specimens were determined in accordance with BS 1881: Parts 118 and 121, respectively. Table 9.6 gives comparison between the flexural strength, modulus of elasticity and 28-day compressive cube strength, as well as cylinder strength of NA and WGS concrete mixes.

Table 9.6 Comparison of Key Bulk Engineering Properties of NA and WGS Concrete (at 28-day) (*Concrete Strength: 20 MPa*); curing: water at 20ºC

Concrete Type	28-day Compressive Strength, MPa		28-day Flexural Strength, MPa	28-day Elastic Modulus, GPa	
	Cube	Cylinder		Experimental	Theoretical
NA	29.0	25.0	3.0	17.0	24.0
% of WGS, by mass					
10% WGS	28.5	24.5	3.0	17.0	23.5
15% WGS	27.5	24.0	2.5	17.0	23.0
20% WGS	27.0	21.0	2.5	16.0	21.5
50% WGS	21.0	15.5	2.0	15.0	19

Once again, results show comparable performance for concrete produced with up to 20% WGS, while further replacements yielded concrete with slightly lower cylinder strength. However, cylinder /cube ratio ranged between 0.85-0.9 for all WGS mixes, which is within the allowable range according to BS EN 206-1, showing an increase as concrete strength increased. Similar trend was observed for flexural strength and modulus of elasticity values of concretes with replacement levels of up to 20% WGS, which were similar to NA concrete mixes. Higher replacement levels decreased both Modulus of elasticity and

flexural strength. Theoretical values for Elastic modulus were calculated from the following formula.

$$E_c = 4.73x\ (f_{c,cyl}^{0.5})\ \text{in GPa}$$

Where: E_c = Modulus of elasticity in (GPa), $f_{c,cyl}$ = Compressive cylinder strength in (MPa).

According to Table 9.6, theoretical values were higher than the experimental by 20-25%. Reason for this discrepancy is probably an overestimation from the formula combined with the lower strength of glass particles when they replace normal sand. Figures 9.6 and 9.7 show the relationship between flexural and modulus of elasticity versus 28-day cube strength for 20 MPa concretes. According to Figures 9.6 and 9.7, there seems to be an increase in Modulus of elasticity and flexural strength with increase in concrete strength. However, due to limited data and the innovative material no published data is available, so further testing is needed for different water/cement ratios so as to obtain a confident relation between these properties.

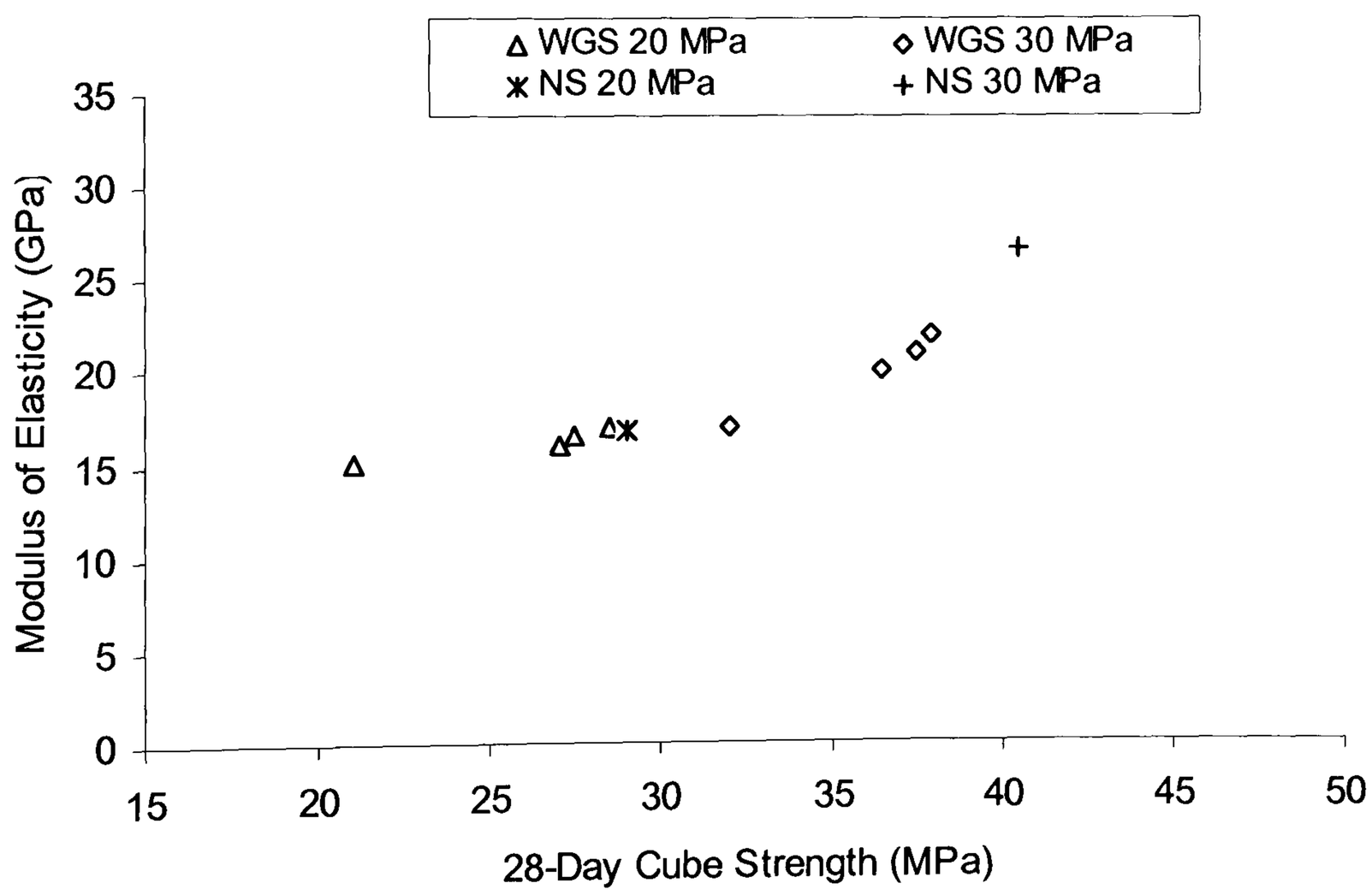


Figure 9.6 Relationship Between Modulus of Elasticity and 28- Day Cube Strength For 20 and 30 MPa WGS Concrete; Curing: water at 20°C

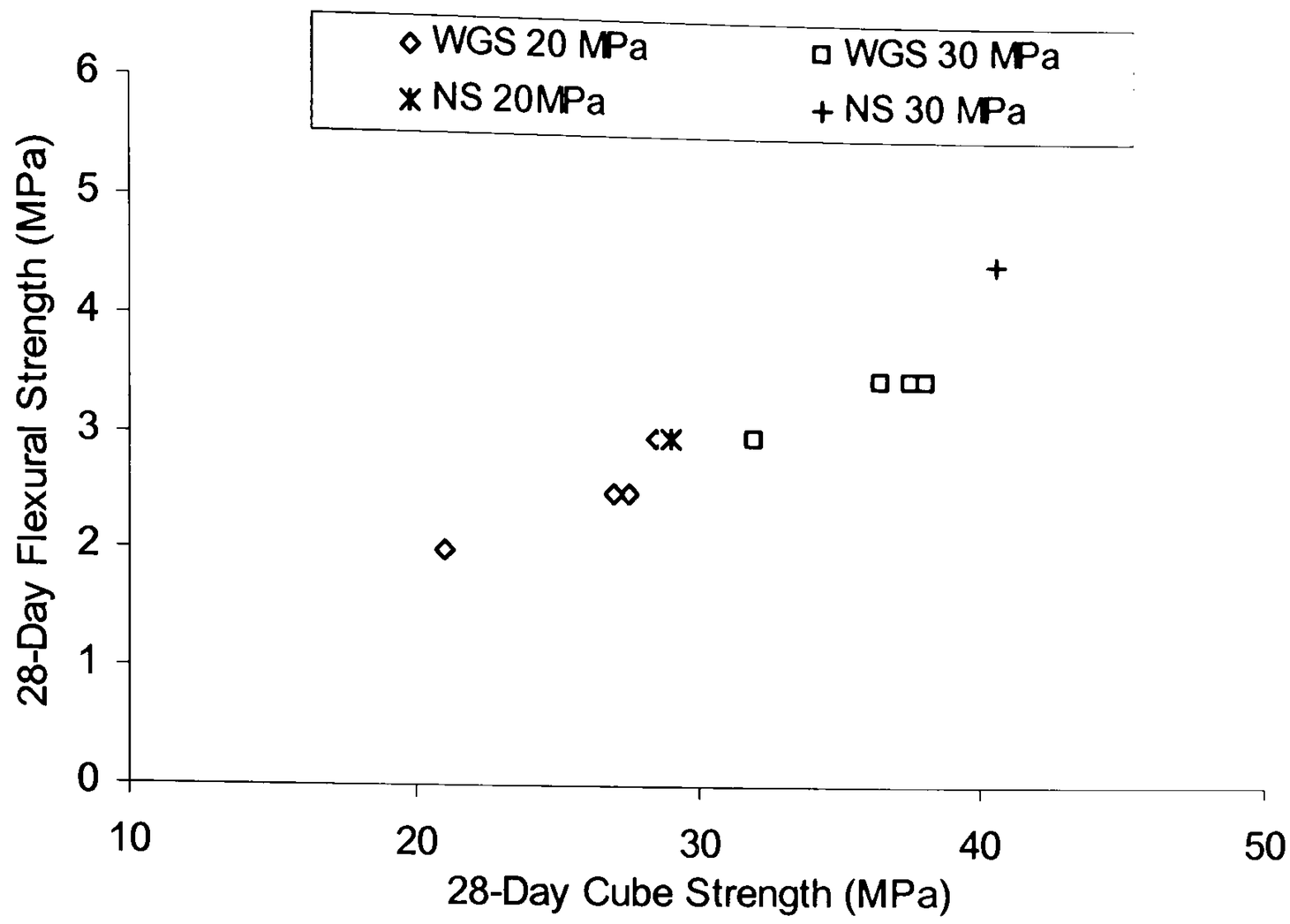


Figure 9.7 Relationship Between Flexural Strength and 28- Day Cube Strength For 20 and 30 MPa WGS Concrete; Curing: water at 20°C

9.6 Durability Related Performance of WGS

9.6.1 Initial Surface Absorption (ISA)

In this, Initial surface absorption tests (ISAT) were performed on 150mm cube specimens, essentially following the method described in BS 1881: Part 5. In each case, two replicates were tested. After the prescribed period of curing, the test specimens were oven-dried at 105°C to constant weight, defined as a weight change not exceeding 0.1% over a 24 hour period. On completion of drying, the test specimens were cooled to ambient laboratory temperature (17°C - 20°C) in a desiccator for a period of 24 hours. ISA measurements were taken at 10, 30, 60 and 120 minutes after the initiation of the test. The measurements are referred to as ISA-10 at 10 minutes, and so on. The ISA data taken from 10 to 120 minutes were then plotted on (ISA) versus Log (time) graph. The decay of the absorption rate, N-value, may be obtained from the slope of this graph and results have shown that the surface property of concrete can be more meaningfully determined by using the initial surface absorption measurement at 10 minutes (ISA-10) and the slope of the linear regression (n-value). This approach has been used in this study and test specimens were tested after 28 and 60 days.

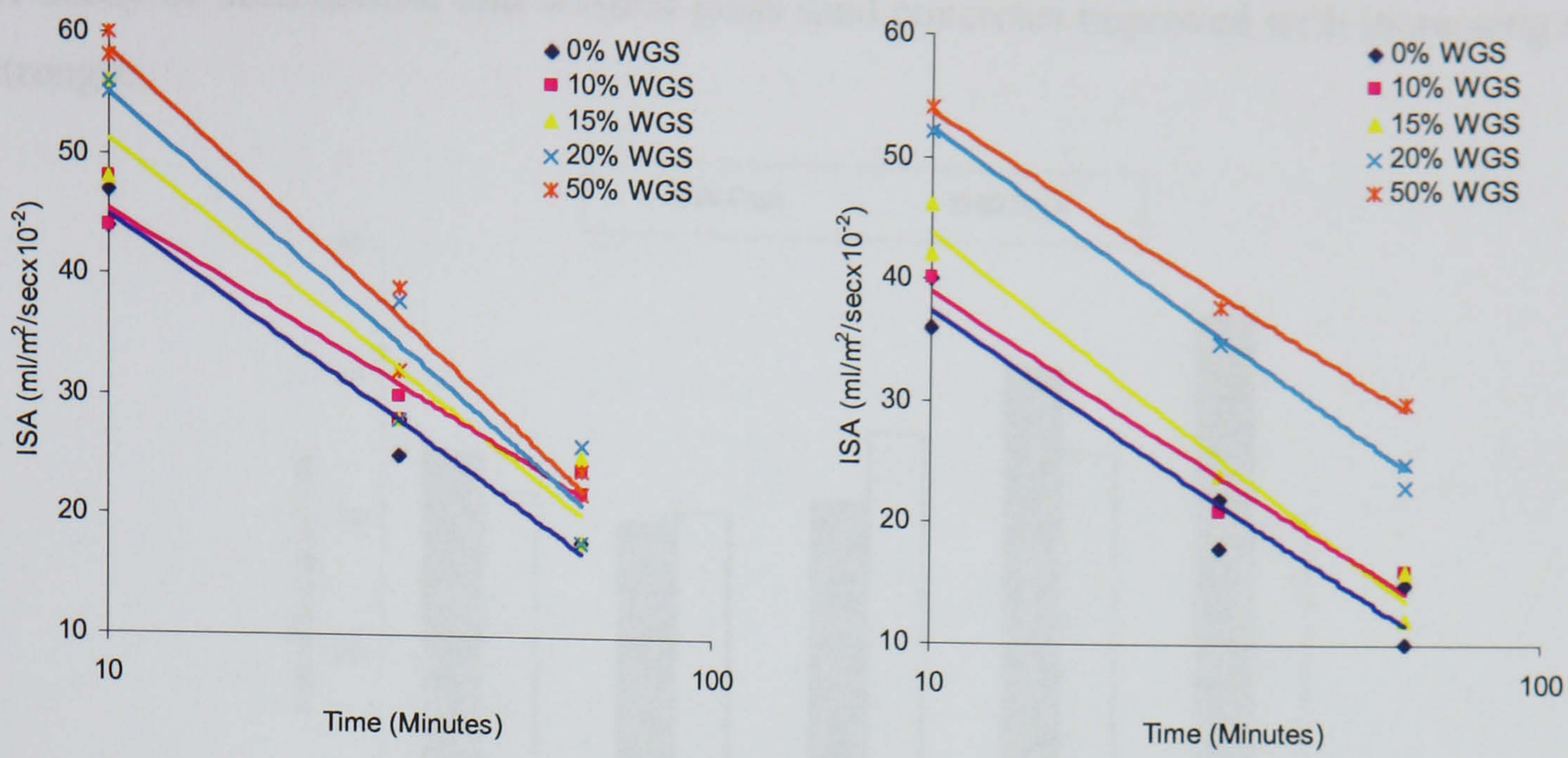


Figure 9.8 28 and 60 Day values of ISA for NA and WGS Concrete; (*Concrete Strength: 20 MPa*); Initial Curing: water at 20ºC

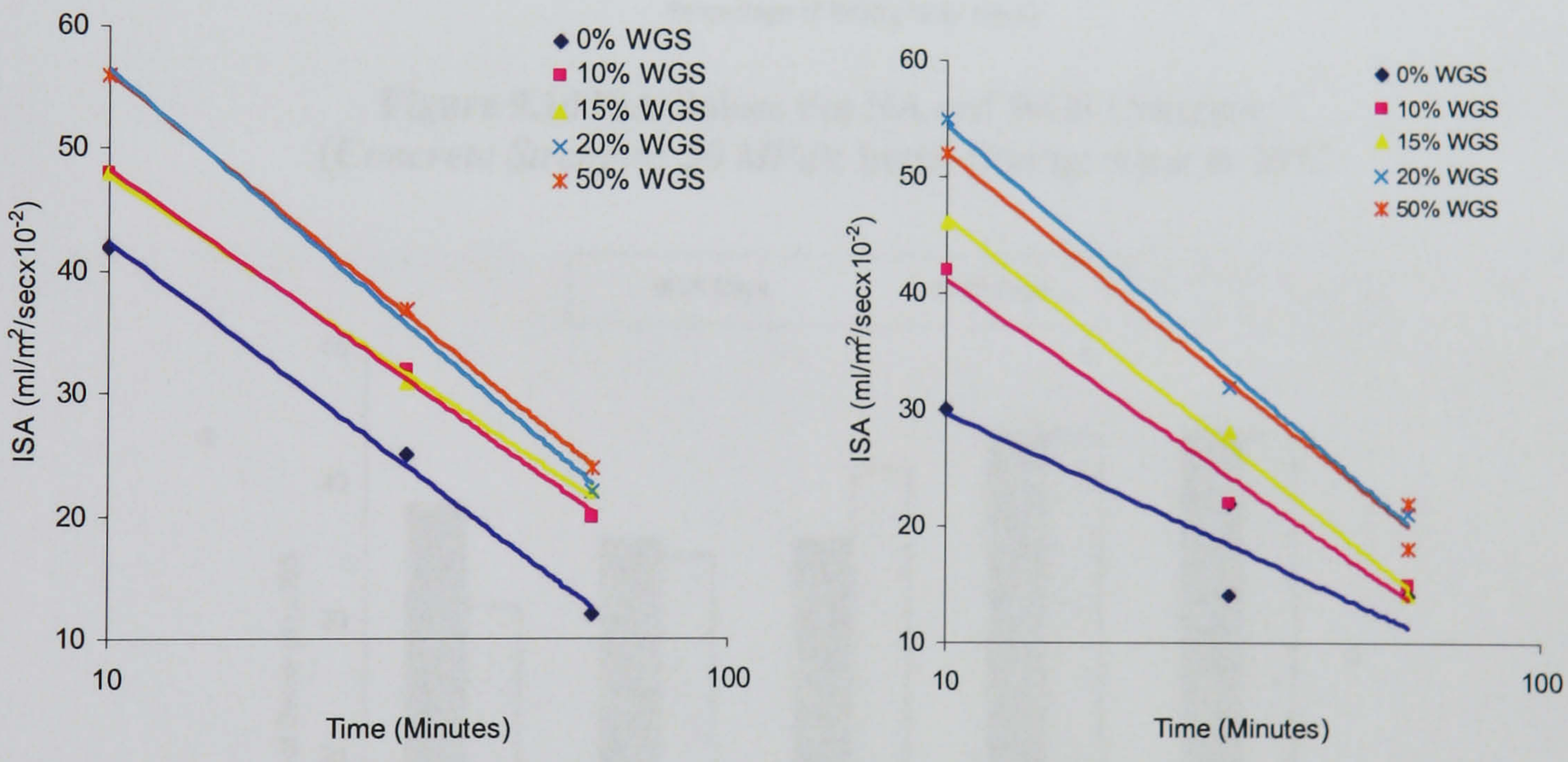


Figure 9.9 28 and 60 Day values of ISA for NA and WGS Concrete; (*Concrete Strength: 30 MPa*); Initial Curing: water at 20ºC

The results showed that for both w/c ratios (0.66 and 0.55) up to 15% WGS content had no influence on the initial surface absorption measured at 10 minutes (ISA-10) and thereafter ISA-10 very slightly increased with WGS content, as shown in Figures 9.8 and 9.9 for 20MPa and 30 MPa concrete mixes. However, further analyses of the ISAT results show that the n value, which reflects the decay in the absorption rate with time, remained unchanged with increase in WGS content in the mix, indicating equivalent comparable performance (Figures 9.10 and 9.11 for 20MPa and 30 MPa concrete mixes). As expected, comparing absorption properties of 20MPa and 30 MPa concretes, ISA-10 value and rate

of decay of both natural and washed glass sand concretes improved with increasing design strength.

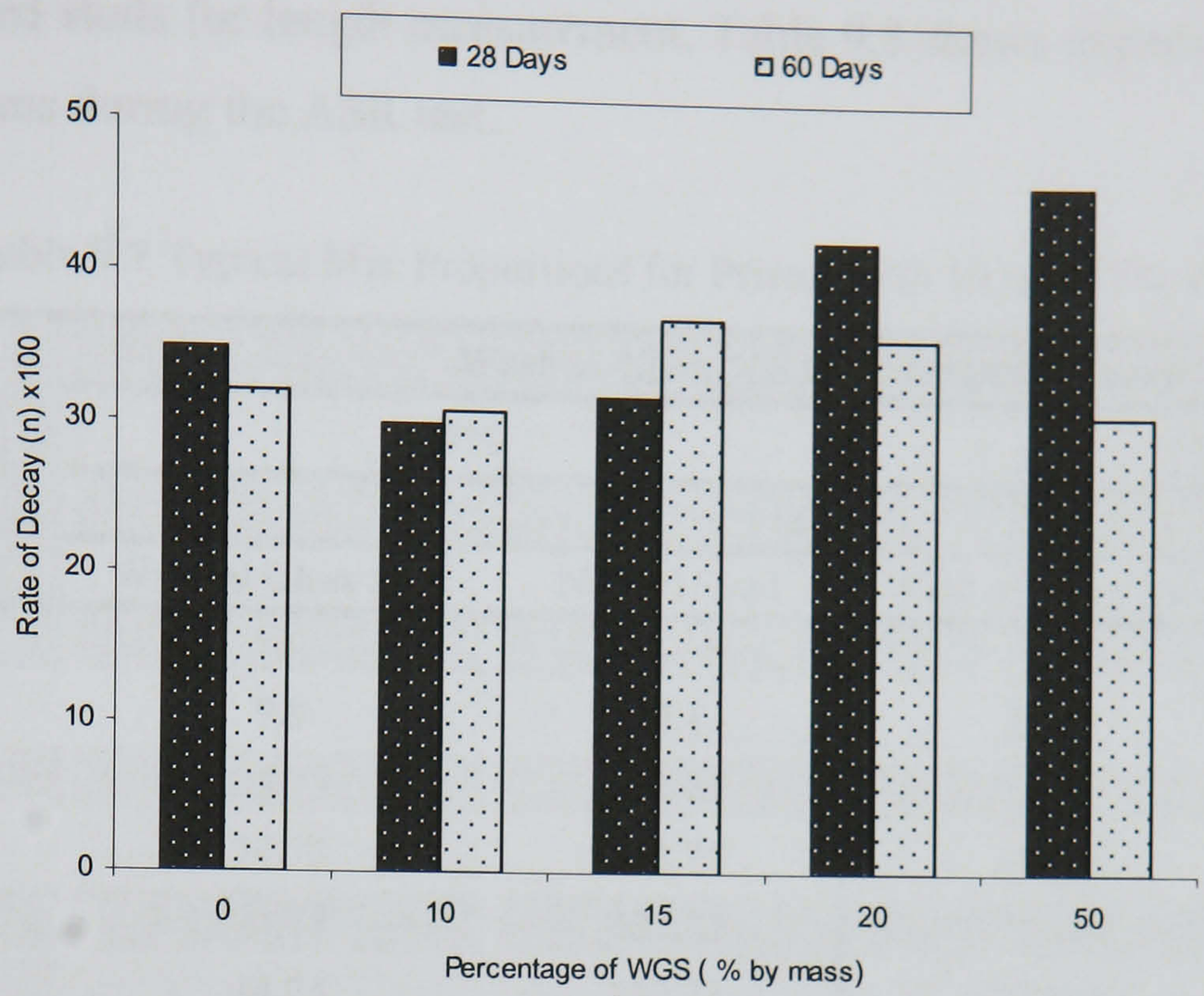


Figure 9.10 ISA Values For NA and WGS Concrete; (*Concrete Strength: 20 MPa*); Initial Curing: water at 20°C

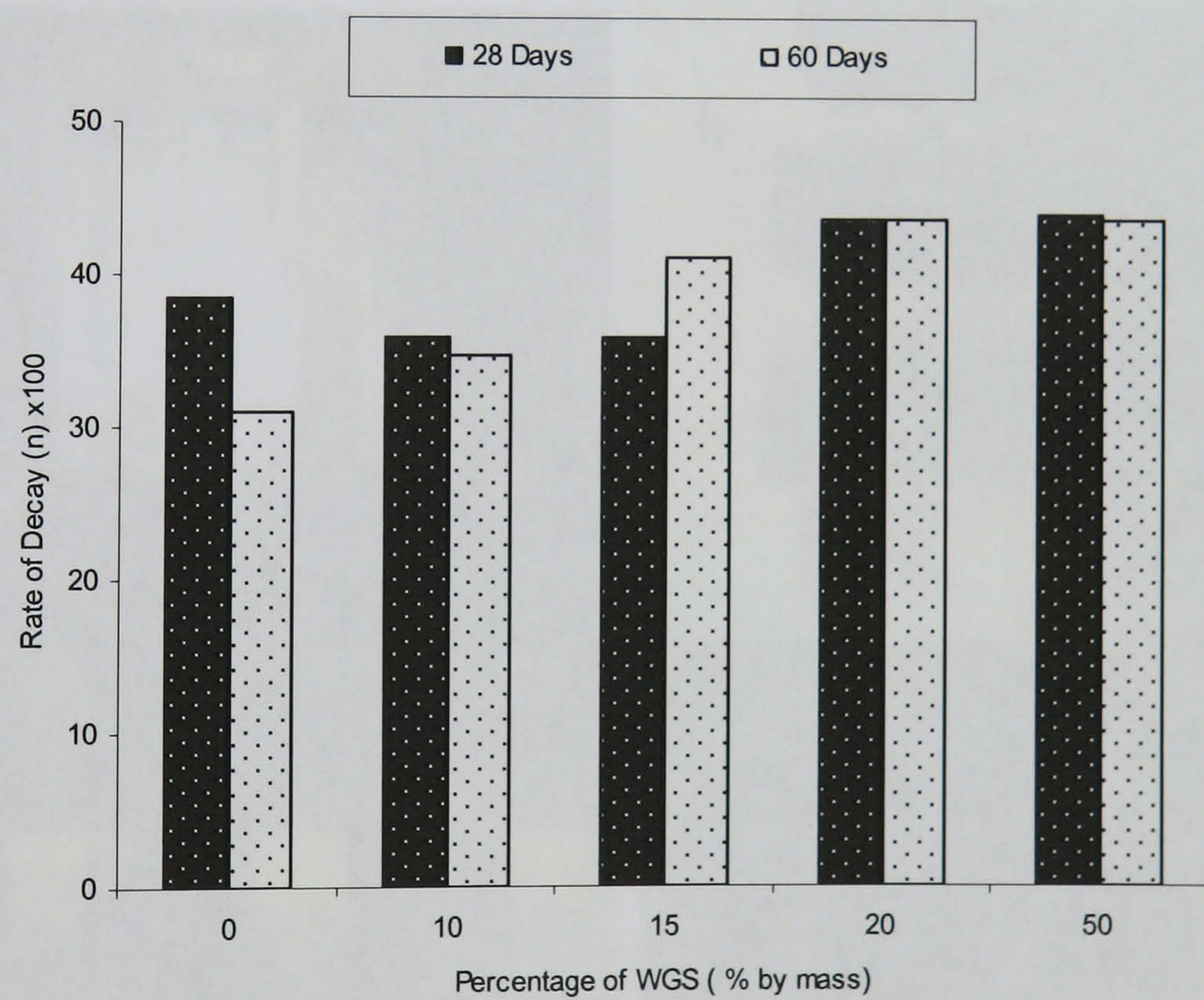


Figure 9.11 ISA Values For NA and WGS Concrete; (*Concrete Strength: 20 MPa*); Initial Curing: water at 20°C

9.6.2 Alkali Silica Reaction (ASR)

Given the satisfactory engineering and near surface absorption performance of concrete containing 15-20% WGS, it was decided to undertake ASR similar to the one described in Chapter 8. Mortar mixes were cast containing up to 15% WGS to assess its influence on

alkali silica reaction phenomenon according to ASTM 1260. Table 9.7 presents the mix proportions for Prisms with 10 and 15% WGS by mass. Figure 9.12 shows WGS prisms and their inserted studs for length measurement. Table 9.8 shows expansion values of NA and GFGG prisms during the ASR test.

Table 9.7 Typical Mix Proportions for Prisms with 10 and 15% WGS

Sieve size (mm)	Washed Glass Sand Content, % by mass			
	10%		15%	
	Mass,(g)			
	Washed Glass Sand	Natural Sand	Washed Glass Sand	Natural Sand
5.00	-	-	-	-
2.36	9.9	89.1	14.85	84.15
1.18	24.75	222.75	37.125	210.375
0.6	24.75	222.75	37.125	210.375
0.3	24.75	222.75	37.125	210.375
0.15	14.75	132.75	22.125	125.375
TOTAL	99	891	148.35	841.5

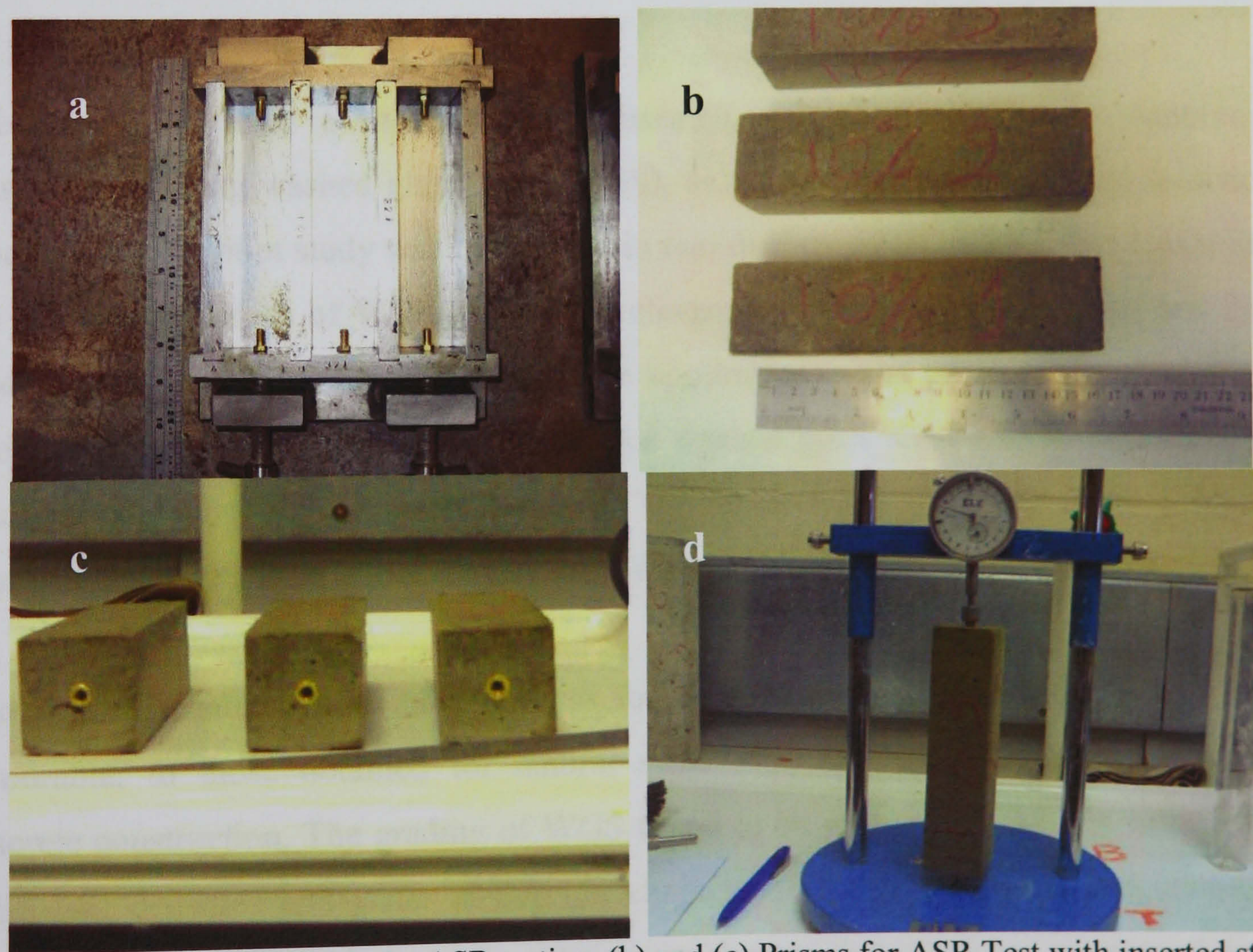


Figure 9.12 (a) Steel moulds for ASR testing, (b) and (c) Prisms for ASR Test with inserted studs and (d) Prisms During Measurement of Change in Length Using Gauge Apparatus.

According to Table 9.8, ASR expansion values for NA and 10-15% WGS prisms were within the range of "indicative of innocuous behaviour" according to ASTM limits.

Expansion percentages were below 0.1% at the end of the test, regardless of percentage of WGS. However, there was a slight increase of expansion with WGS increase. Further SEM investigation and ICP solution analysis reflected similar results.

Table 9.8 Expansion Values for NA and WGS Prisms for the 14-Day Duration of ASR Testing. *(1N NaOH Solution (at 80°C)*

Mortar Type	Test Age, Days	Total Length Change, mm	Expansion, %
0% WGS (Control)	5	0.03	0.02
	9	0.035	0.025
	14	0.05	**0.03**
10% WGS	5	0.03	0.02
	9	0.05	0.03
	14	0.07	**0.04**
15% WGS	5	0.04	0.03
	9	0.06	0.04
	14	0.07	**0.05**

9.7 Concluding Remarks

This report described a short intensive research project carried out to examine the feasibility of using washed glass sand (WGS), as a fine aggregate substitute in concrete production. This pilot study was carried out in two distinct parts; namely Part 1 examining the key characteristics of WGS (following relevant BS and BS EN standards) and Part 2 assessing its suitability for use in concrete applications. The programme of work was designed to establish benchmarking level for washed glass sand and to provide simple practical guidelines for its use in concrete. The research has identified some of the key practical and application issues for utilising WGS in concrete.

The physical characteristics of WGS was found to be comparable, in some cases much favourable, to those obtained for natural sand/ fine aggregates traditionally used in concrete construction. The grading of WGS found to be within the limits of natural sand. WGS had densities and water absorption characteristics comparable and equivalent to natural sand. Overall, characterisation test results showed that WGS has a potential for use as quality fine aggregates in concrete production. However, it was noted that the precautions may be necessary to take account of chemical composition and reactivity characteristics to guarantee suitable fresh and hardened concrete performance.

In order to determine the practical upper limit of WGS content for a range of applications and to assess the performance of WGS concrete, over 150 mixes were proportioned using NA and WGS blends with up to 50% washed glass sand- by mass. The general trends observed indicate comparable workability with inclusion of WGS in concrete mixes and slump loss with time was not adversely affected. Results of compressive strength testing showed that up to 20% WGS had negligible effect on the cube and cylinder strength of concrete. However, results show gradual reduction in strength with an increase in WGS content beyond 20% in the mix. Indeed, such reduction in strength with high WGS proportions can be compensated by adjusting the water/cement ratio easily. The results also showed that up to 20% WGS had a negligible effect on other key bulk engineering properties of resulting concrete.

The subject of WGS concrete durability study included initial surface absorption and alkali-silica reaction testing. So far, WGS concrete mixes were found to posses near surface absorption properties similar to the corresponding NA concrete mixes, providing WGS content restricted to 15%. Results of limited accelerated ASR testing indicate that none of tested samples with 10-15% WGS, expanded significantly during the test and that damaging deleterious expansion due to ASR has not occurred during testing. Microscopy investigation together, with long-term durability testing will provide well sought technical information.

Since there are no fundamental technical objections to the use of washed glass sand, potential extent to which they can be used in concrete production has been identified. Following completion of recommended work, detailed practical implications on the use of WGS in concrete production and related applications can be provided with confident.

CHAPTER 10

PRACTICAL IMPLICATIONS AND FUTURE RECOMMENDATIONS FOR THE USAGE OF FOAMED GLASS GRAVEL

10.1 Summary of Main Findings

The summary of main findings drawn from the results of various experiments has been given at the end of relevant Chapters. The main aim of this Chapter is to draw the various aspects of the research together, to identify the major concluding remarks and inline with these review practical implications, and provide recommendations for further study.

10.2 Desk Study/ Information Gathering

Throughout the course of the study the state of waste glass supply chain, recycling and its reuse have been reviewed, and the requirements for adopting sustainable practices aimed at maximum value-added recovery is quite clear. Glass waste recycling and its reuse have remained relatively static and conservative. Moreover, it was recognised that there are still a number of technical and economical barriers to increasing rate of glass recycling in the UK. These include the colour imbalance of glass packaging. This arises because the UK glass container manufacturers primarily serve the need of the UK food and beverage industry and their production is in clear glass.

Due to concern with potential variability and deleterious chemical reaction, the use of finely-ground glass cullet in concrete products has been largely restricted. It has been stated and now widely accepted that the simplest route to waste glass recycling as an aggregate, albeit commending the least value, is as an unbound road-base material [101,102]. On the other hand, concrete products produced using recycled glass can be categorised as commodity products and has potential for being value-added products. Several research and development work, both scientific and applied researches, have been undertaken to demonstrate the use of recycled glass in concrete blocks, paving stone, floor tiles, floor construction etc.. However, given the labour intensive sorting and processing this may provide an economical barrier for use in such applications, and therefore this should be judged on a case-by-case basis. An alternative recycling outlet via foaming waste glass, such as Geofil FGG bubbles, may be more appropriate. The need and demand

to consider the transfer and optimisation of current foam glass technology from rest of Europe for manufacture of GFGG in UK was identified.

Foam glass, such as GFGG, found to have required properties and suitability for use in a number of construction products e.g. loose fill, insulation, blocks, slabs etc. Moreover, foam glass gravel has characteristics of low flammability, thermal stability, high chemical durability and contains no fibrous material. It has been reported that there are well established markets in which foam glass products should be able to penetrate by 1 to 5% without disruption to jobs and local economies [40]. It was also recognised that the foam glass process is ideally suited to consume 'contaminated' glass such as lighting, CRT and glass from end of life vehicles- showing a great potential.

10.3 Characterisation of Coarse and Fine GFGG

The study has clearly shown that good quality glass foam gravel can be produced using technique pioneered by Geofil Ltd, Hungary. In the main, Geofil Ltd utilises waste glass, regardless of its original source, as the main feedstock with additions of a clay mineral to assist adhesion and chemical additives to optimise viscosity and to regulate water absorbency. Geofil foam glass gravel (GFGG) product has been tested and promoted in Hungary for a number of applications including post insulation for buildings, heat and sound insulation, frost insulation for motorways, a roof product of less density for unsupported spans and fire resistant systems for buildings. Clearly, this information could encourage waste management organisations and local authorities to direct waste glass cullet for novel production of foam gravel with a potential use in a variety of applications, whilst reducing disposal to landfill.

The properties and characteristics of two size fractions, namely coarse (20-5mm) and fine (< 5mm), GFGG produced from mixed colour bottles and television tubes were established, following appropriate British and newly implemented European standards. Key physical properties of these bubbles were found to be comparable to corresponding commercially available lightweight manufactured aggregates. For all GFGG bubble samples tested, the bulk density was found to be 40% lower than corresponding manufactured lightweight aggregate, thereby suggesting potential suitability of GGFG

bubbles for use in a range of concrete construction applications. Thus, providing further value-added outlet for surplus waste glass.

10.4 GFGG Concrete: Experimental Programme

Since there are no fundamental technical objections to the use of GFGG in concrete, the extent to which they can be used has been identified. This study has clearly demonstrated the suitability of coarse and fine GFGG for use in concrete production. Indeed, the results have shown that up to 30% coarse GFGG or 15% fine GFGG can be used in a range of concrete applications, without risk to fresh, engineering and key durability properties of concrete. In addition, the retention of workability and stability of fresh concrete was unaffected by the inclusion of GFGG in the mix. This is of great importance for both ready-mixed and in-situ concrete producers.

The study has made significant achievements in establishing methods for taking account of inherent GFGG characteristics in the production of concrete mixes that are stable in the fresh state and able to develop properties comparable to the natural aggregate concrete in the hardened state. Also, the results of current limited work demonstrate that the 30% coarse or 15% fine GFGG can be used in the range of concrete products without risk to structural strength or key bulk engineering performance. The test results also indicate that for GFGG samples produced from two different sources, there was no significant variation in strength of concrete at a given GFGG content. This suggests that the original source of GFGG has no significant effect on ultimate strength development, if adequate provisions for foam glass gravel characteristics are made.

The results of durability related properties, including near surface absorption, carbonation rate and alkali-silica reaction, show satisfactory performance irrespective of GFGG original source is achievable, providing the concrete mixes are of similar design strength. Also, results of this work suggest that the use of GFGG can be extended to a broader range of applications with further research.

The practical benefits resulting from the current work are not only on environmental and economical fronts, but they could also provide the construction industry with technical information on a marketable product, which is presently underutilised and has a large

potential. For example, the responsibility for choice of aggregates in certain concrete products lies with the concrete producers and/or product manufacturer and with this information and further research technical data the specifiers may feel able to consider using GFGG in various concrete products. This will mean that GFGG can potentially be used in non-structural concrete, which represent some 50% of the total UK concrete market, and its use can progress step-by-step towards general mild/ moderate exposed construction. However, it is important to recognise that there is a need to undertake further detailed research and development work for foam glass gravel before its widespread use in concrete construction.

10.5 Recommendations for Future Research

Current work has shown that GFGG has a significant part to play in the implementation of sustainable glass recycling and concrete construction but, for this to be effective, the following actions should be considered;

- Levels of chemical impurities have to be closely controlled when GFGG is to be used in concrete production. This is necessary to ensure that the finished concrete has consistent strength and durability. Most of the British and European standards limit the chloride content of any aggregate to be used in concrete. It is apparent that testing procedures and acceptance criteria are not readily available. Hence, further research in this field is recommended.
- Segregation of GFGG mixes should be adequately controlled in the future concrete mixes and a method for designing optimum particle packing with the aid of software as "Europack" in other studies should be found to avoid adverse effects on workability and concrete strength.
- Additional concrete casting and testing of GFGG as coarse and fine replacement of 0-100% by volume in a wider range of concrete strengths except the 15-50 MPa.
- Technical information is required on the full range of durability properties (including freeze-thaw, chloride and abrasion resistance- related to possible future applications) of concrete containing GFGG to assist in the preparation of a realistic specification requirement. This together with leaching assessment is

require to enable the setting up of quality systems for GFGG to make it suitable for use in non-structural/ structural concrete construction.

- A reliable long-term test data on potential alkali-silica reactivity of GGFG needs to be obtained for effective practical guidance document.
- Demonstration projects, together with the development of GFGG specifications, can also be useful to create greater awareness on the use of GFGG. As a result, there will be a reduction in consumption of natural resources (natural aggregates) and in the volume of waste glass going to landfill.

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APPENDICES

Appendix A. Thermal Conductivity, Sound and Fire Resistance Testing of GFGG Panels

Introduction

The main driver for foam glass use has been the requirement of high-energy efficiency standards for building construction, both domestic and commercial. The use of foamed glass in the construction of housing and buildings could greatly reduce the energy consumption and hence the carbon dioxide emission of newly built housing and buildings. In addition to the potential energy saving from the use of foam glass, there are other less obvious advantages of the material due to the lightweight nature of the material. As shown from tests results, GFGG had around 60% lower bulk density compared to normal aggregates). This lightweightness of GFGG, when used in structural concrete, means design flexibility, construction productivity, reduced manual handling, lower transport costs, and lower foundation costs. Also GFGG is rodent resistant, fire resistant, an effective sound absorber and non-toxic [40]. The water absorbency is higher than normal aggregates (3.5-5 times) due to the high presence of pores on the surface and interior of the material.

Foam glass gravel also has inherent strength properties. The desirable properties of foam glass are low density. Generally these properties are achieved by having a large number of small, evenly sized bubbles, with thin walls in between. As the product is made of glass it is naturally inert in most environments with respect to biological, thermal, chemical and environmental degradation [40].

Foam glass, or cellular glass, has a number of applications in the construction industry. Foamed glass is best suited as a rigid insulation material [40]. Due to its excellent structural properties, it is suitable for use as insulation in roofs, walls and traffic areas such as flat roofs or floors, where other insulation products may be compressed resulting in an uneven surface and the loss of insulating properties. Foam glass has excellent fire resistant properties and its very low water absorption and water vapour transmission means that, unlike many other types of insulation, it tends to retain its insulating properties even when wet. It is also used as industrial insulation for a number of minor uses such as sandwich

panels or is used as a product in extreme environmental conditions [40]. Glass foams represent a highly valuable solution for thermal and acoustic insulation, since they possess a generally higher mechanical, chemical and thermal stability than the polymeric foams currently employed due to their inorganic nature [43].

Because of successful outcome of the research [106] in establishing the bubble characteristics and its influence on concrete performance and expressed needs to assess fire resistance and acoustics of partition wall panels made using Geofil bubbles as infill, this supplement work was carried out. In this, further testing programme was developed to establish (i) thermal resistance of loose GFGG, (ii) fire resistance of load bearing walls and (iii) acoustic testing on wall panels prepared with GFGG bubbles.

Objectives

The prime objective of this work was to extend the use of GGFG in building construction with a view to exploit inherent beneficial characteristics. In particular;

1. Establish an apparent thermal conductivity of GFGG;
2. Assess the effects of the sound transmission performance of separating wall panel constructed using GFGG infill.
3. Carry out a fire resistance test to BS 476; Part 21 on a load-bearing partition wall with GFGG infill;

Approach and methodology

Given the nature of work, the project was divided into the following three distinct parts. The first part was concentrating in testing GGFG to establish an apparent thermal conductivity of the material. Whilst, second and third parts dealt with testing of acoustic testing (sound insulation) and fire resistance of load-bearing partition wall panel in accordance with BS 476- Part 21, respectively. *Given the nature of the work, subcontractors were appointed to undertake these testing.*

Testing and results

Thermal Resistance

Thermal conductivity is the rate at which heat is transmitted through a material, measured in watts per square metre of surface area for a temperature gradient of one Kelvin per metre thickness, simplified to W/mK. Whilst, thermal mass is the mass in a structure,

which is used to absorb solar heat during the day and then release the heat in the evening. *A* measure of the thermal resistance of a particular thickness of material is known as Thermal Resistance. It is measured in m^2K/W and is equal to the thickness of the material (in metres) divided by the conductivity of that material. In general, thermal resistance is proportional to the thickness of a layer of the construction and inversely proportional to its conductivity. Surfaces and cavities also provide thermal resistance and there are standard figures for these resistances that must be taken into account when calculating U-values. The resistances of each material within an element are added together to determine the overall resistance of the element. The reciprocal of the overall resistance is the U-value.

The heat flow through building construction/elements depends on the temperature difference across it, the conductivity of the materials used and the thickness of the materials. Given this, a sample of coarse GGFG were prepared (from the bulk jumbo bag supplied by Geofil Ltd.) and delivered to testing organisation. Thermal resistance tests were carried out in accordance with the method described in BS EN 12664: 2001. The GGFG bubbles were loose filled into a 305 x 305 x 67.9 mm wooden framed container set between the hot and cold plates. One side of the frame was flexible so that on applying vertical pressure on the overfilled specimens the gravel was able to expand laterally ensuring even contact with the measuring plates.

The tests were undertaken at a mean temperature of approximately 10°C and 20°C. Table A.1 gives result of thermal resistance for mean thickness of 67.9mm. Whilst, an "Apparent Thermal Conductivity" expressed from the results obtained are given in Table A.2.

Table A.1 Thermal Resistance for Mean Thickness of 67.9mm.

Thermal Resistance, M^2k/W	Mean Temperature (At Test)	Mean Bulk Density (At Test), kg/m^3
0.623	19.4°C	473.5
0.625	10.3°C	473.5

Thermal resistance of GFGG was found to be around 0.623-0.625 M^2k/W.

Table A.2 An Apparent Thermal Conductivity *(based on Table A.1)*

Apparent Thermal Conductivity, W/mK (element thickness = 67.9 mm)	Mean Temperature (At Test)	Mean Bulk Density (At Test), kg/m^3
0.109	19.4°C	473.5
0.104	10.3°C	473.5

According to Table A.2 apparent thermal conductivity of 0.109 W/mK ranges within the values given form the GFGG manufacturer being between 0.09-0.8 W/mK [42] and proves it's a good thermal insulator.

Sound Testing

Sound testing of GFGG wall panels was also tested to examine the sound insulation of the material given the fact that is lightweight and that can be a disadvantage in sound insulation. A 2400 (H) x 3600 (W) x 90 mm (Thick) galvanised steel frame prepared and supplied by DMS Composites Ltd. was used to construct a test panel. Testing panel was assembled by laying them on the floor horizontally; first by screwing 9mm thick Magnelite board on one side of frame- (Figure A.1). Thereafter, all in GGFG bubbles mixed with a highly diluted cement slurry (water/ cement ratio of 0.67) was poured and levelled into the frame- (Figure A.2). At this stage, coarse and fine GGFG were first mixed in pan mixer, followed by addition of cement and water, prior to pouring into the test frame -(Figure A.3). Upon sufficient hardening of slurry GGFG other side of frame was fixed using 9mm thick Magnelite board. All joints were visually examined and where necessary taped and filled.

Given the practical difficulties and other circumstances beyond our control- sound insulation testing was not carried out within the initial agreed timescale. Full details on how to improve sound insulation in homes is given in a BRE Guide [107].

Typically sound insulation prevents two kinds of sound transmission: airborne sound and impact sound. The conventional rule for reducing sound transmission is the mass law. According to this- the heavier the structure, the less sound it will transmit.

However, other factors, such as discontinuous construction and stiffness, mean it is possible to achieve good sound insulation levels with lightweight construction, making the most of the drywall advantage. One of the most important features of sound insulating structures is that they should be imperforate or without any opening. Even the smallest of cracks, say only 0.4mm wide, have a significant area along the length of a wall, and could halve the effectiveness of a 50dB partition.

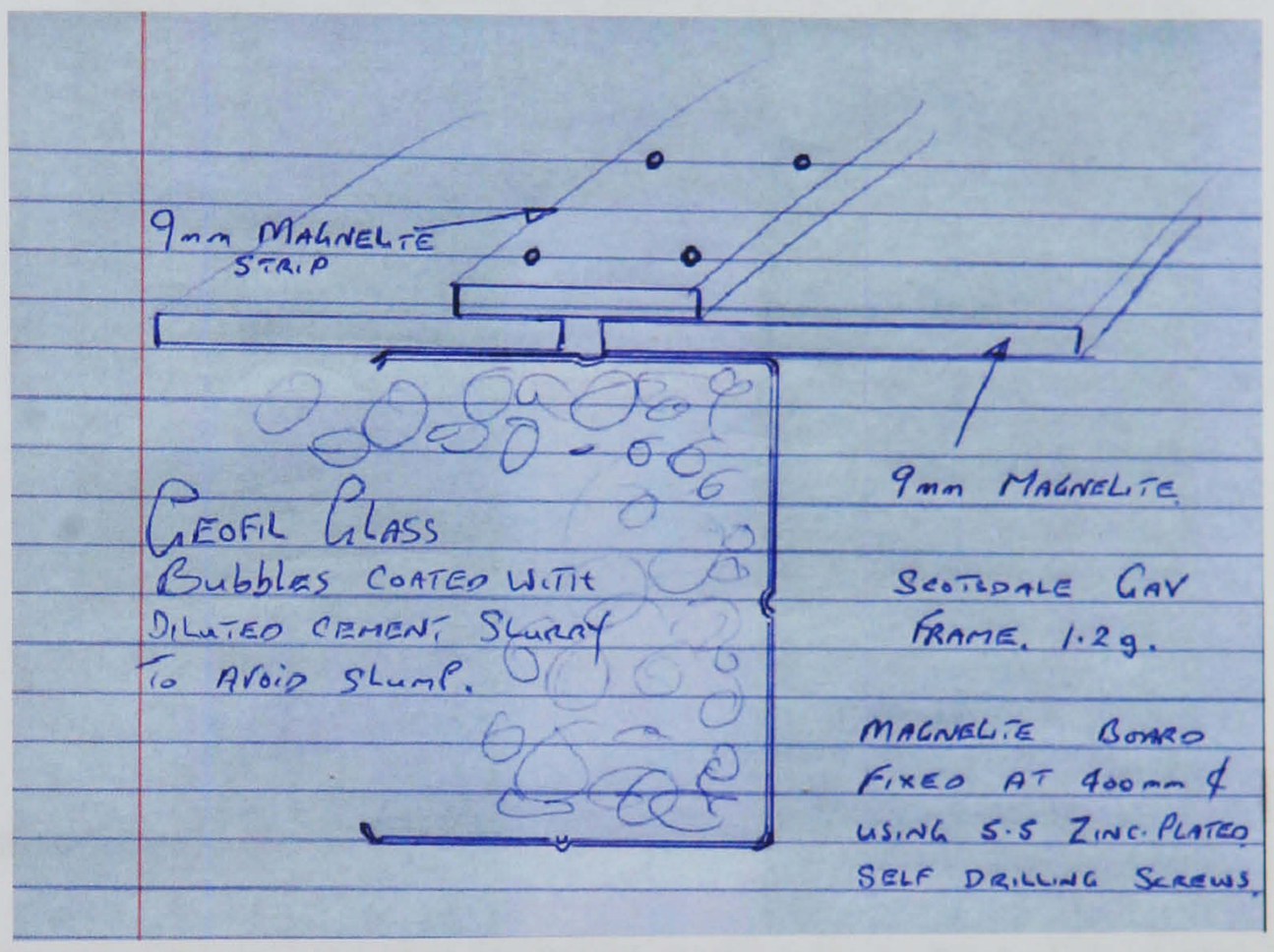

Figure A.1 Setup and Internal Connection of the Test Panel

Airborne sound is measured in RwdB, which is the difference in sound levels either side of, for example, a partition wall in this work. In general, structures have variable sound insulation values depending on the frequency of the sound.

Figure A.2 Galvanised steel frame with 9mm magnelite board on one side- ready for GGFG filling.

Figure A.3 GGFG bubble pouring and levelling.

In general, the airborne sound insulation of a wall is determined by;

- generating a loud steady noise in a room on one side of the wall (the source room),
- measure the average sound pressure level produced in the source room,
- measure the average sound pressure level in a room on the other side of the wall being tested (the receiver room),
- measure the average sound pressure level in the receiver room with the noise in the source room switched off,
- measure the reverberation time of the receiver room (this is achieved by measuring the time is takes for the sound to die away after a noise source in the receiver room is switched off), and then
- calculate the sound insulation value for comparison with the standards set out in Tables 1a and 1b of Approved Document E [108].

The measurements are all made in third octave bands between 100 and 3150 Hz. The parameter to be calculated is a single figure, the airborne sound insulation DnT, W + Ctr. The results of this process produce a set of figures, which can be expressed as a graph of standardised level difference (DnT) against frequency. This graph is then compared to a

family of reference curves, which are given for 1dB intervals, to determine the single DnTw figure for the construction. The standardised level difference curves for airborne sound insulation for the test undertaken are shown in Figure A.4. Average value of sound insulating capacity (RW) of test panel prepared using GGFG gravel was 45dB, in line with manufacturers published figures, which was found to be 42dB [42]. It is important to recognise that to ensure the highest acoustic performance standards, partitions must be installed strictly in accordance with the material supplier's recommendations including the use of specialist seals around perimeters, and acoustic brackets/ joints.

Frequency f Hz	DnT 1/3 Octave dB
50	0.0
63	0.0
80	28.6
100	25.0
125	30.7
160	33.0
200	34.3
250	38.1
315	41.2
400	44.1
500	44.2
630	49.4
800	54.6
1000	56.2
1250	58.9
1600	61.8
2000	64.1
2500	62.6
3150	59.5
4000	60.4
5000	65.4

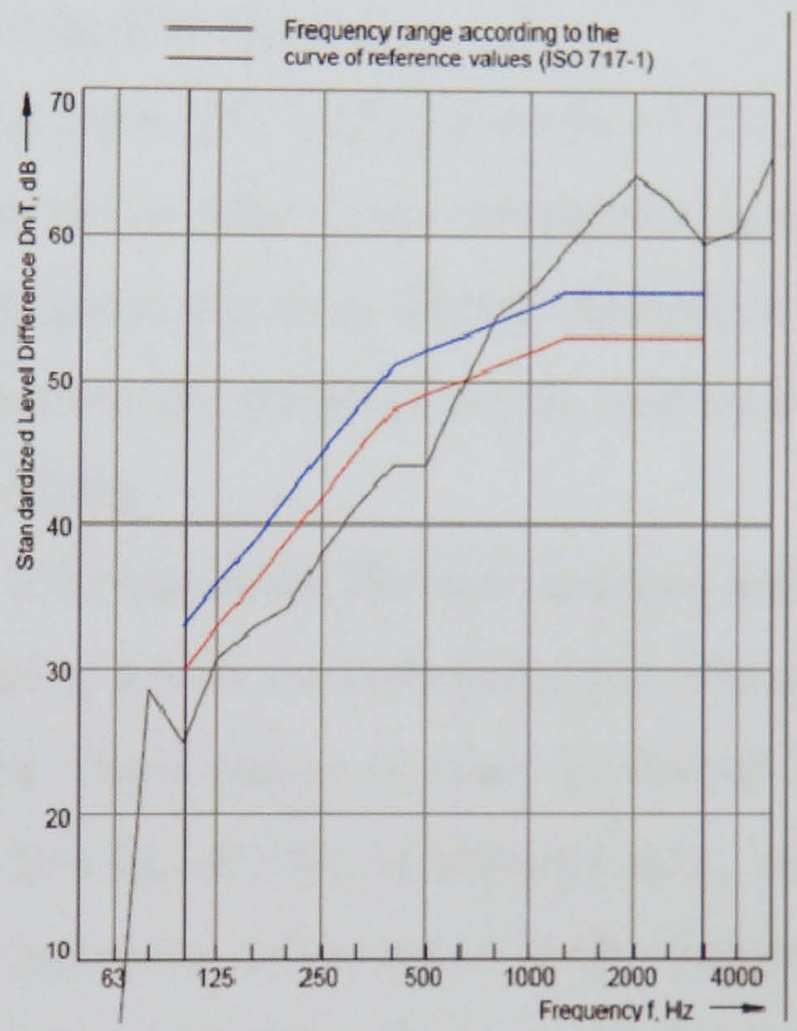

Figure A.4 Comparison of Test Results with the Standard Curve

Fire Resistance

An indicative fire resistance test was carried out for duration of 92 minutes on a 3000mm (wide) x 3000mm (high) galvanised steel stud wall panel with imposed load of 70 kN. For this test, panel sample was prepared following procedure described above. During testing, the furnace hearing regime, appropriate procedures and criteria stated in BS 476: Part 21: 1987 for load-bearing wall panels were utilised. Prefabricated/ pre-assembled standard wall panel was delivered to testing organisation. Once again fire resistance of GFGG panel was proven satisfactory but can not be presented here for reasons of confidentiality.

Appendix B. Literature Review- Glass Recycling Benefits

More reasons for glass recycling are provided below:

1. Glass is an ideal material for recycling and in some cases can be used repeatedly without any deterioration in its physical properties. Glass is a material having properties that provide attributes for many commercial products. As some of these products reach the end of their useful life and are discarded, that there is often the opportunity to have the glass recycled into other useful products. This alternative is preferred over the glass entering a municipal waste stream for landfill disposal.
2. It is said that UK recycling saves 10-15 million tonnes of CO_2 equivalent green house gases per year compared to other waste management options, and a major contribution is made from glass recycling. This is equivalent to about 10% of the annual CO_2 emissions from the transport sector, and equates to taking 3.5 million cars off UK roads [109].
3. There are also additional CO_2 reductions through avoiding the use of soda ash, limestone and dolomite, all of which are carbonates and release CO_2 during the glass-making process. For every tonne of glass produced from virgin raw materials approximately 200 kg of CO_2 is released from the breakdown of carbonate raw materials. Increased cullet use will also reduce particulate and nitrogen oxide emissions from the glass furnace [1]. Every tonne of cullet (crushed glass) that is used in any glass manufacturing process potentially saves 1.1 tonnes of virgin raw material (soda, soda ash, limestone) and 140 litres of oil.
4. Glass cullet, by melting at a lower temperature than glass-forming raw materials, allows for a reduction of energy input to melting furnaces. This prolongs furnace life. Longer furnace life – since by increasing the proportion of cullet to raw materials, the furnace can operate at slightly lower temperatures thus prolonging its life and reducing maintenance and replacement cost. Saving varies approximately linearly from zero to 17% as the proportion of recycled glass varies from zero to 100%. In addition, the amount of energy that is required to make glass form totally recycled material can be up to 35 % less.

5. Substituting cullet for raw materials can also reduce emissions into atmosphere (air and water). Reduces solid wastes by 75 %, air pollutant emissions by 14-20 % and water pollutant production by 50% [1].
6. Advantages of recycling the glass include a reduction in the requirement for landfill sites. Glass will not biodegrade so landfill is not a sustainable disposal option. Reduced demand for raw materials is accomplished and energy savings associated with glass production. From a non-manufacturing prospective, using cullet conserves landfill space for disposal of non-recyclable materials.
7. Aggregates are cheap materials typically costing between £5-10/tonnes [4]. However, the Aggregates Tax, which was introduced in April 2002, added £1.60/tonne. This tax applies to quarried materials, but recycled products are exempt. This is a strong incentive for the use of recycled materials.

Appendix C. Literature Review- Legislative Forces

1. EU Landfill Directive

Despite landfill being the final step within the waste hierarchy, it continues to be the dominant method of waste disposal in the UK with 85% of the 30 million tonnes of municipal household waste being land filled each year [4].

The EU adopted the Landfill Directive in April 1999, and the deadline for transposition into UK legislation was July 2001. The Directive is transposed into English and Welsh legislation though the Landfill (England and Wales) Regulations 2002, and is still to be introduced in Scotland and Northern Ireland. The overall aim of the Directive is to deal with the full social, environmental and economic impacts of landfill as a disposal option whilst generally improving waste management practices. The Directive also aims to reduce greenhouse gas emissions from landfill sites.

One of the main provisions of the Directive is the gradual reduction in biodegradable municipal solid waste going to landfill. The Directive promotes alternatives to landfill in order to manage the diverted waste and encourages initiatives to minimize the amount of biodegradable municipal waste being produced.

Challenging targets and timescales have been established for the progressive diversion of biodegradable waste disposed of to landfill. The UK and other countries with high dependence on landfill have been granted a 4-year extension period to meet the targets imposed by the Directive. The amount of biodegradable municipal waste disposed of to landfill will need to be reduced to 75% by weight of 1995 levels by 2010 and eventually to 35% by 2020.

For local authorities, the targets set in Waste Strategy 2000 will increase the need to establish collection and recycling systems for all recyclables, including glass and the need to use alternative waste management options for certain wastes. Increased costs will provide an incentive to recycle waste streams.

The Landfill Tax, introduced in October 1996, was the UK's first "green tax". For Local Authorities, if effective recycling schemes are implemented and the amount of waste going

to landfill is reduced, this tax burden is lower and considerable savings can be realised. At 2003 the landfill tax stands at £35 per tonne, and will be increased to £3 per tonne each year.

2. European Community Directive on Packaging and Packaging Waste

The Producer Responsibility Obligations (Packaging Waste) Regulations, which came into force in 1997, implement the European Community Directive on Packaging and Packaging Waste Directive [4].

The objectives of the Directive are to reduce packaging waste and to encourage the re-use, recycle and recovery of packaging waste. The targets under the Directive are to achieve certain targets for the recovery and recycling of 60% of packaging waste by 2006.

The Packaging Recovery Note (PRN) system was established in an effort to meet the requirements of the European Community Directive. The PRN system is a major incentive for container glass recycling since container glass falls within the scope of the packaging regulations. This means that when a re-processor recycles a tonne of glass they are entitled to issue a PRN that has a commercial value.

3. The Integrated Pollution Prevention and Control Directive (IPPC)

The Integrated Pollution Prevention and Control (IPPC) Directive, introduced in 2004, will set out targets within permit conditions to reduce pollution and emissions which glass companies will be required to meet [2]. For aspects of an installation not regulated, permit conditions will be required to use Best Available Technologies (BAT) to prevent and reduce emissions.

Use of cullet in glass making will reduce CO_2 emissions from two sources. First, the reductions in energy requirements associated with increase use of glass cullet in furnaces will produce similar reductions in gaseous emissions such as CO_2 from the burning of fossil fuels. Second, melting cullet glass instead of using virgin raw materials will avoid CO_2 produced from the thermal degradation of raw materials containing carbonates such as soda ash, limestone and dolomite. It has been estimated that for every tonne of glass produced from virgin raw materials approximately 200 kg of CO_2 is released from the

breakdown of carbonate raw materials. Increased cullet use will also reduce particulate and nitrogen oxide emissions from the glass furnace.

The March 2005 Carbon Trust Report "Energy Use in the Glass Container Industry" highlighted the fact that energy consumption per tonne of glass had halved over the last 20 years. In the container sector making bottles lighter had meant more bottles per tonne giving a 60-70% energy reduction per unit.

4. Waste Electrical and Electronic Equipment (WEEE) Directive

The European Waste Electrical and Electronic Equipment Directive came into force in Europe in 2005 [4,6]. The Directive sets targets for collection, recycling and recovery for all types of electrical products (CRT, fluorescent lamps), ranging from small electronic toys to large electrical household appliances. EU Member States were obliged to implement the Directive by August 2004. The UK had to introduce September 2005 take-back schemes, collection and treatment facilities. The first collection and treatment targets are to be attained by December 2006. Different recovery and recycling / re-use targets have been set for each category of WEEE, ranging from 60-80% recovery and 50-80% recycling. However, a compulsory collection target of 4 kg per household per year by the end of 2006 has been set. For the UK, this amounts to around 236,000 tonnes of WEEE per year. A new target will be established for the end of 2008. The glass content of WEEE obviously varies with the type of equipment. However, overall the glass content of WEEE is around 6%, mainly in the form of cathode ray tubes (CRT) in monitors and televisions and the directive is likely to be a significant driver to recycling CRTs in the future.

With regard to WEEE Directive, British Glass has expressed its concerns and kept up a watching brief [5]. Developments in this area were slow for 2005, although the Energy Minister has instigated an immediate review of proposals for implementing the WEEE Directive.

5. End of Life Vehicles (ELV) Directive

The EU adopted the End of Life Vehicle Directive in October 2000 [4][6]. However, to date, the Directive has still yet to be transposed into a national law. The sectors affected by the ELV Directive are motor vehicle manufacturers and importers, Vehicle component manufacturers, dismantlers, shredders and re- processors. The recycling rates for 2004

were 85% by weight of all ELV by 2006, with an aid to increase the rate of re-use and recovery to 85% in 2006 and 95% by 2015.

The ELV Directive has seen little action throughout 2005 according to British Glass statistics [5].

6. Waste Framework Directive

Under the proposals released by the Commission on 21 December 2005, European countries would have to submit national waste prevention plans, which would update the EU's overarching legislation on waste- the Waste Framework Directive [110]. The Waste Policy overhaul is part of the European Commission's Thematic Strategy on the Prevention and Recycling of Waste, and was released in conjunction with the Thematic Strategy on the Sustainable Use of Natural Resources. All EU member states would have to produce prevention plans three years after the legislation is agreed upon by European policy makers. Measures suggested in the Commission document include the use of economic instruments to influence availability and price of primary resources as well as the consumer level measures. The Strategy will move to a material-based approach rather than focusing legislation on individual products groups and waste streams as packaging. New approach of the Commission is to prioritise action on waste where it can have the biggest environmental impact at the greatest cost efficiency, looking at the whole life cycle of a product. The Commission said that its proposals were the first specific political measures to decouple waste generation from economic growth.