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USE OF COARSE RECYCLED AGGREGATES IN DESIGNATED CONCRETE MIXES

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Dedicated to my parents
Αικατϵρίνη and Γ*ϵώργιος*.

The interactions of "cause" and "effect" are orderly, and if we understand their relationships we are prepared to control them, or at least to adapt ourselves to them.

William Vogt - Road to Survival, 1948.

PAPERS PUBLISHED

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ABSTRACT

This thesis is a detailed investigation on the suitability of secondary aggregates for use in concrete production. The aggregates under investigation, originated from construction and demolition sites of the Greater London area and were mainly from reinforced concrete structures dating back to the 60's-70's.

The study investigated three sources of recycled concrete aggregate (RCA I, RCA II and RCA III). The first step in the investigation involved the characterisation of the aggregates through an extensive testing regime including physical, mechanical and chemical-mineralogical assessments. Aggregates where then classified based on the requirements of BS 8500 and BSEN 12620 which provide the main guidance for aggregates for concrete. All sources conformed to the relevant standard requirements and RCA I was selected for the next step of this investigation.

Following the establishment of conformity of these aggregates for concrete production a further in depth investigation involved the production of designated concrete mixes conforming to BS 8500 and BSEN 206 using coarse RCA I at various proportions up to 100%, totally replacing coarse natural aggregate. The investigation included assessment of equivalent strength concrete in the fresh (workability, stability, air entrainement etc.) and hardened states (engineering properties and durability performance). Concrete performed satisfactorily in most of its performance aspects.

In order to demonstrate the performance of RCA concrete and compare with conventional concrete containing natural aggregates, a full scale demonstration programme was devised. It involved the construction of industrial pavements in real construction sites, using conventional concrete and concrete containing up to 100% coarse RCA. Site visits and site inspections at 3 and 6 months into service revealed concrete performing satisfactorily regardless of the RCA content. These findings were in line with those of the scientific investigation carried out in the laboratory.

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List of Abbreviations

A	
AEA	Air Entraining Agent
ARV	Abrasion Resistance Value
ACV	Aggregate Crushing Value
AIV	Aggregate Impact Value
AR1, AR2, AR3	Abrasion Resistance Classes
ASR	Alkali Silica Reaction
B	
BS	British Standard
BRE	Building Research Establishment
C	
CEN	Comitè Europèen de Normalisation (European Committee for Standardisation)
CF	Compacting Factor
C&D	Construction and demolition
CSD	Commission on Sustainable Development
D	
DF	Directly Finished concrete pavement surface
E	
EN	European Normative
EU	European Union
G	
ggbfs	Ground granulated blast furnace slag
I	
ICP-MS	Inductive coupled plasma - mass spectrometer
ICP-AES	Inductively coupled plasma - atomic emission spectrometer
IDRC	International Development Research Centre

IIED	International Institute for Environment & Development
IUCN	International Union for Conservation of Nature and Natural Resources
I.S.A.T.	Initial Surface Absorption Test
IISD	International Institute for Sustainable Development
L	
LA	Los Angeles Abrasion Value
M	
MR	Modulus of Rupture
N	
NA	Natural Aggregate
O	
OECD	Organisation for economic co-operation and development
OPC	Ordinary Portland Cement
P	
PC	Portland Cement
ppp	Parts per million
ppb	Parts per billion
prEN	European Normative under development
R	
RA	Recycled Aggregate
RC	Reinforced Concrete
RCA	Recycled Concrete Aggregate
RCAC	Recycled Coarse Aggregate for Concrete
RMC	Ready Mixed Concrete
S	
SSD	Saturated Surface Dry
T	
TFV	Ten percent Fines Value
U	
UNCED	United Nations Conference on Environment & Development
UNEP	United Nations Environment Programme

UNI	Ente Nazionale di Unificazione Italiano (Equivalent to BS and EN)
W	
WA	Water Absorption
WCED	World commission on environment and development
WRAP	Waste Resources Action Programme
X	
XRD	X-ray diffraction
XRF	X-ray fluorescence

List of Symbols

$C_i^{Solid}\ wt\%$	concentration in the solid, expressed as percentage by weight (eq.4.6)
C_i^{Soln}	concentration in the solution, expressed in $\frac{\mu g}{ml}$ (eq.4.6)
E-Value	Young's Modulus of Elasticity
E_c	Static Modulus of Elasticity
E_d	Dynamic Modulus of Eleasticity
f_{flex}	Flexural Strength
$f_{ck,cyl}$	Characteristic compressive strength of concrete determined by testing cylinders
$f_{c,cyl}$	Compressive strength of concrete determined by testing cylinders
$f_{ck,cube}$	Characteristic compressive strength of concrete determined by testing cubes
$f_{c,cube}$	Compressive strength of concrete determined by testing cubes
L	Length of specimen measured immediately after de-moulding (eq. 7.5)
m	Weight of the solid expressed in g (eq.4.6)
n	Number of framework planes ”piani retticolari” eq.4.5
S1 to S5	Slump consistence classes
WA_{24}	Aggregate 24 hour water absorption
w/c	Free water over cement ratio of concrete mix
X0	Exposure class for no risk of corrosion or attack
XC	Exposure classes for risk of corrosion induced by carbonation
XD	Exposure classes for risk of corrosion induced by other than sea water chlorides
XS	Exposure classes for risk of corrosion induced by sea water chlorides
XF	Exposure classes for freeze-thaw attack
$\Delta\ l$	Change in length of shrinkage/swelling specimen (eq. 7.5)
ρ_b	Aggregate Loose Bulk Density

ρ_{ssd}	Aggregate Particle density on a saturated and surface-dried basis
ρ_{rd}	Aggregate Particle density on an oven-dried basis
ρ_a	Aggregate Apparent Particle Density
ρ_c	Fresh Density of Concrete
$\mu\epsilon$	micro strain
σ	Stress
ε	Strain
V	Volume of the solution, expressed in ml (eq.4.6)

CHAPTER 1

INTRODUCTION

This chapter aims to provide an introduction to this thesis. Initially a brief background will be given to set out the research context of this study followed by identification of the specific research objectives. Finally, an overview of the thesis structure will be given to assist the reader.

1.1 Background.

One of the main streams of waste generation in the EU is the construction industry, with rapid development and economic growth increasing new construction. An estimate of construction and demolition (C&D) waste for the EU gives the figure of 180 billion tonnes per year. In addition the continuous wholesale extraction and use of massive quantities of natural aggregates has raised questions at national, and international levels.

Over the last two decades, governments on all continents have begun to realise that consumption of natural resources at the current rates is unsustainable and that future generations may be deprived. This situation prompted discussions at government levels to address the issue and develop future policies and sustainability targets, at national and international levels. A milestone was established at the Rio Earth Summit in 1992 where a plan of action and recommendations were agreed by leaders, that countries should develop national strategies promoting sustainable development.

Following this summit, EU governments have reacted by forming policies supporting sustainable practices. In the case of the construction industry and the waste produced by it, economic incentives such as the aggregate and landfill tax were introduced in a move to promote re-use and recycling and reduce the price margin between natural and recycled aggregates. Reluctancy to use recycled construction materials such as aggregates for concrete was evident and considered due to the lack of scientific information regarding their suitability and performance.

1.2 Research Objectives.

In the light of these developments this research project was devised with the main aims of reviewing existing research on the use of recycled aggregates in concrete and to further investigate the use of commercially produced recycled aggregates for use in concrete applications conforming to BS 8500 and BSEN 206 requirements.

The objectives of this research programme can be listed as follows:

i) To review existing research and established scientific knowledge.

ii) To investigate the conformity of commercially produced recycled aggregates from various sources using existing and developing British Standards and European Normatives.

iii) To produce concrete using coarse RCA as a replacement for natural aggregates and assess a wide range of properties in the fresh and hardened states and establish concrete performance.

iv) To demonstrate through full scale construction/demonstrations that quality recycled aggregates can be produced at commercial level and be suitable for use in a range of concrete applications.

1.3 Report Structure.

This thesis comprises 11 chapters generally following the order of the objectives identified above.

Chapter 2 provides a more in detailed background to the concept of sustainability including key post war events and publications outlining the world wide approach towards sustainability. European and UK developments are discussed, general policies introduced and statistics regarding waste production and natural resources are presented.

Chapter 3 reviews established findings related to the use and characteristics of aggregates for concrete as well as published research findings dating back to the late seventies.

Chapter 4 provides a concise breakdown and explanation of the project broken into phases: from production of aggregates to production of concrete and full scale constructions. The chapter also provides details and methods used for the characterisation of constituent materials and investigations of concrete performance in the fresh and hardened states.

Chapter 5 covers details on the production of recycled aggregates and presents the results and discussion on the material's characterisation.

Chapter 6 covers results, discussion and conclusions on the investigations into the fresh properties of concrete.

Chapter 7 presents the findings, discussions and conclusions related to the engineering properties of concrete.

Chapter 8 includes a discussion of results and conclusions on the durability performance of concrete.

Chapter 9 describes the full scale demonstrations and key findings and observations associated with them.

Chapter 10 summarises the key conclusions and recommends future research especially in areas where the author feels time restrictions prevented more in depth investigation.

1.4 Use of the Terms Waste and Debris.

The term construction and demolition waste has been used extensively in the literature. From chapter 4 onwards, however, the term 'waste' will be replaced by 'debris' in line with recent thinking. 'Waste' is considered a material which needs to be disposed of and has no use at all whereas 'debris' is simply material which still may have a use.

CHAPTER 2

BACKGROUND ON SUSTAINABILITY

The construction industry world-wide is using natural resources and disposing of construction and demolition debris to landfill in very large quantities. Both these practices are damaging to the environment and are no longer considered sustainable at their current levels. Many governments throughout the world are therefore actively promoting policies aiming at reducing the use of primary resources and increasing reuse and recycling.

2.1 Sustainable Development

Sustainability means different things to different people, but the most frequently encountered definition comes from the report "Our Common Future" [12] which states:

> *"Sustainable is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs."*

The idea of sustainability is to improve the quality of life for current and future generations without extending the use of natural resources beyond the capacity of the natural environment to supply them indefinitely. This means a change in policy and practice at all levels, from the individual to the international. Although the idea of sustainability is simple, its achievement involves meeting four, often contradictory objectives [13] at the same time:

- *social progress recognising the needs for everyone*

- *effective protection of the environment*
- *prudent use of natural resources*
- *maintenance of high and stable levels of economic growth*

Although the concept of sustainability became popular during the last two decades, it is not a new idea. Throughout human history cultures have recognised the need for harmony between the environment which surrounds them and their society and economy. *"New is the articulation of these ideas in the context of a global industrial and information society".*

In this research program, two of the objectives of sustainable development are directly promoted. These are the *effective protection of the environment* and the *prudent use of natural resources.* However, the maintenance of high and stable levels of economic growth will also be enabled.

2.2 World Wide Approach

During the last two decades particularly, governments around the world have begun to realise that the wholesale consumption of natural resources is unsustainable and indeed promotes the risk that future generations may be deprived. As a result, the rapid implementation of many concepts of "sustainable development" have occurred since the 1980's.

However, although progress in sustainable development occurred during the last two decades, modern understanding of it dates from the 1960's or before.

Prior to the Earth Summit in 1992 [14] the following important events occurred, extracted from the SD Timeline publication of the IISD [15]:

- **1962** - Silent Spring by Rachel Carson brought together research on toxicology, ecology and epidemiology to suggest that agricultural pesticides were building to catastrophic levels. This was linked to damage to animal species and to human health. The book was read widely by the general public.
- **1969** - Partners in Development 1970 - International Development Research Centre (IDRC)- The report of the Commission on International Development.

chaired by the former Prime Minister of Canada, Lester B. Pearson was produced. This event was the first of the international commissions to consider a new approach to development, focused on research and knowledge. It led to the formation of the IDRC.

- **1971** - International Institute for Environment & Development (IIED) established in Britain with a mandate to seek ways to make economic progress without destroying the environmental resource base.
- **1972** - UN Conference on the Human Environment Sponsored by the United Nations Environment Program (UNEP) held in Stockholm [16] under the leadership of Maurice Strong. The conference focused on regional pollution and acid rain problems of northern Europe, and lead to the establishment of many national environmental protection agencies and the United Nations Environment Programme (UNEP).
- **1977** - UN Conference on Desertification
- **1980** - World Conservation Strategy released by the International Union for Conservation of Nature and Natural Resources (IUCN). The section "Towards Sustainable Development" identifies the main agents of habitat destruction as poverty, population pressure, social inequity and the terms of trade. It calls for a new international development strategy with the aims of redressing inequities, achieving a more dynamic and stable world economy, stimulating economic growth and countering the worst impacts of poverty.
- **1982** - World Resources Institute established in the U.S. Began publishing annual assessments of World Resources in 1986.
- **1984** - International Conference on Environment and Economics sponsored by the Organisation for economic co-operation and development(OECD). Concludes that the environment and economics should be mutually reinforcing. Helped to shape "Our Common Future [12]."
- **1987** - Our Common Future [12] the Brundtland Report. Report of the World Commission on Environment and Development (WCED) weaves together so-

cial, economic, cultural and environmental issues and global solutions. Chaired by Norwegian Prime Minister Gro Harlem Brundtland. Popularises the term Sustainable Development.

- **1992** - The Rio de Janeiro Earth Summit [14]. Based upon the framework of the Brundtland Report [12] published in 1980, leaders at the Rio de Janeiro Earth Summit formed agreements and conventions on critical issues such as climate change, desertification and deforestation.

  The Summit agreed a plan of action (Agenda 21) and a recommendation that all countries should produce national sustainable development strategies. Agenda 21 is a wide-ranging assessment of the social and economic sectors with goals for improving the environmental and developmental impact of each. The Rio Declaration also summarises other principles of sustainable development that were agreed unanimously by the summit leaders. Generally the Rio de Janeiro summit gave a call for national sustainable development strategies to be in place by 2002.

  In order to monitor and report on the progress of how those countries which took part in the earth summit were implementing the agreements, the Commission on Sustainable Development (CSD) was formed. It was agreed that a five year review of Earth Summit progress would be made in 1997 by the United Nations General Assembly meeting in a special session which would report on how well countries, international organisations and sectors of civil society had responded to the challenge of the Earth Summit. Unfortunately five years after the 1992 Earth Summit, at the so called Earth Summit +5 it was demonstrated that implementation of sustainable development plans was very slow.

- **2002**-World Summit on Sustainable Development held in Johannesburg South Africa [17]. World governments, concerned citizens, UN agencies, multilateral financial institutions, and other major groups participated and assessed global change since the United Nations Conference on Environment and Development (UNCED) in 1992. Some of the key outcomes of the summit are:

- A reaffirmation that sustainable development is a central element of the international agenda hence giving new impetus for world wide action to fight poverty and protect the environment.
- The understanding of sustainable development was broadened and strengthened as a result of the Summit, particularly the important linkages between poverty, the environment and the use of natural resources.
- Governments agreed to and reaffirmed a wide range of concrete commitments and targets for action to achieve more effective implementation of sustainable development objectives.
- A policy to encourage and promote the development of a 10-year framework of programmes to accelerate the shift towards sustainable consumption and production.

During this World Summit, its secretary General Nitin Dessay stressed the centrality of the role of technology in the policies promoting sustainable development. Talking at the *Forum on Science, Technology and Innovation* [18], he emphasised that it is essential to bring the world of science and the world of policy together. He personally suggested that such an event should take place during the summit, on the grounds that unless focused attention is provided to the scientific and technological side of sustainable development, *"it would get lost in a jungle of discussion and other things"*

Summarising, thirty years ago, in Stockholm, leaders agreed on the urgent need to respond to the problem of environmental deterioration [16]. Twelve years ago, at the United Nations Conference on Environment and Development, held in Rio de Janeiro, [14] leaders agreed that the protection of the environment and social and economic development are fundamental to sustainable development. To achieve such development, the global programme entitled Agenda 21 [19] and the Rio Declaration on Environment and Development [14], to which participating countries reaffirmed their commitment were agreed. The Rio Conference was a significant milestone that set a new agenda for sustainable development.

2.3 European and UK Developments

European and UK governments have responded to international pressure on sustainability. As this particular programme of work focuses on the construction industry, aspects of sustainability relevant to that industry are the focus.

In a move towards a more sustainable use of natural resources and consequent reduction of environmental impact, successive governments have introduced measures in order to convince the construction industry to reduce the use of primary aggregates and where possible to reuse and recycle aggregates. These measures were usually in response to European Union (EU) directives.

The 2000 edition of Environmental Signals [20] reported that the EU generates around 1.3 billion tonnes of waste every year. The data also show that waste generation is directly connected to economic growth, making it impossible to achieve economic growth without generating increasingly serious waste management problems. There is a particularly close link between economic growth and waste from the construction industry, which is responsible for around a fifth of all waste. Within the industry the largest producers of waste are the manufacturing and mining/quarrying sectors.

In the UK, the construction industry is one of the largest consumers of natural resources. About 260 million tones of minerals are extracted annually, mainly for use as aggregates along with other construction materials [21] such as plastic, cement, wood, iron and steel. Figure *2.1* shows the main resources absorbed by the construction industry as well as the products generated and their value [1].

Construction and Demolition (C&D)waste is generated by the construction and demolition of buildings and civil engineering works and in the EU is estimated at 180 million tonnes per year [22]. Great potential for recycling this waste as aggregates in new concrete, filling material, road sub-base, brickwork, block-work etc exists. Currently, approximately 104 million tones of C&D waste are produced per year in the UK [21] and this amount is expected to increase considerably in the future with rapid growth in infrastructures development. Of this, about 30% is being recycled in low-value applications, such as filling holes, drainage applications, sub-base filling material etc. Therefore, 70% (about 73 million tones) of C&D waste is still dumped at landfill sites throughout the UK. Most of this is avoidable and reduces the profits of construction companies, by up to 25% [1]. The implications on the environment and the economy of these practices are unsustainable.

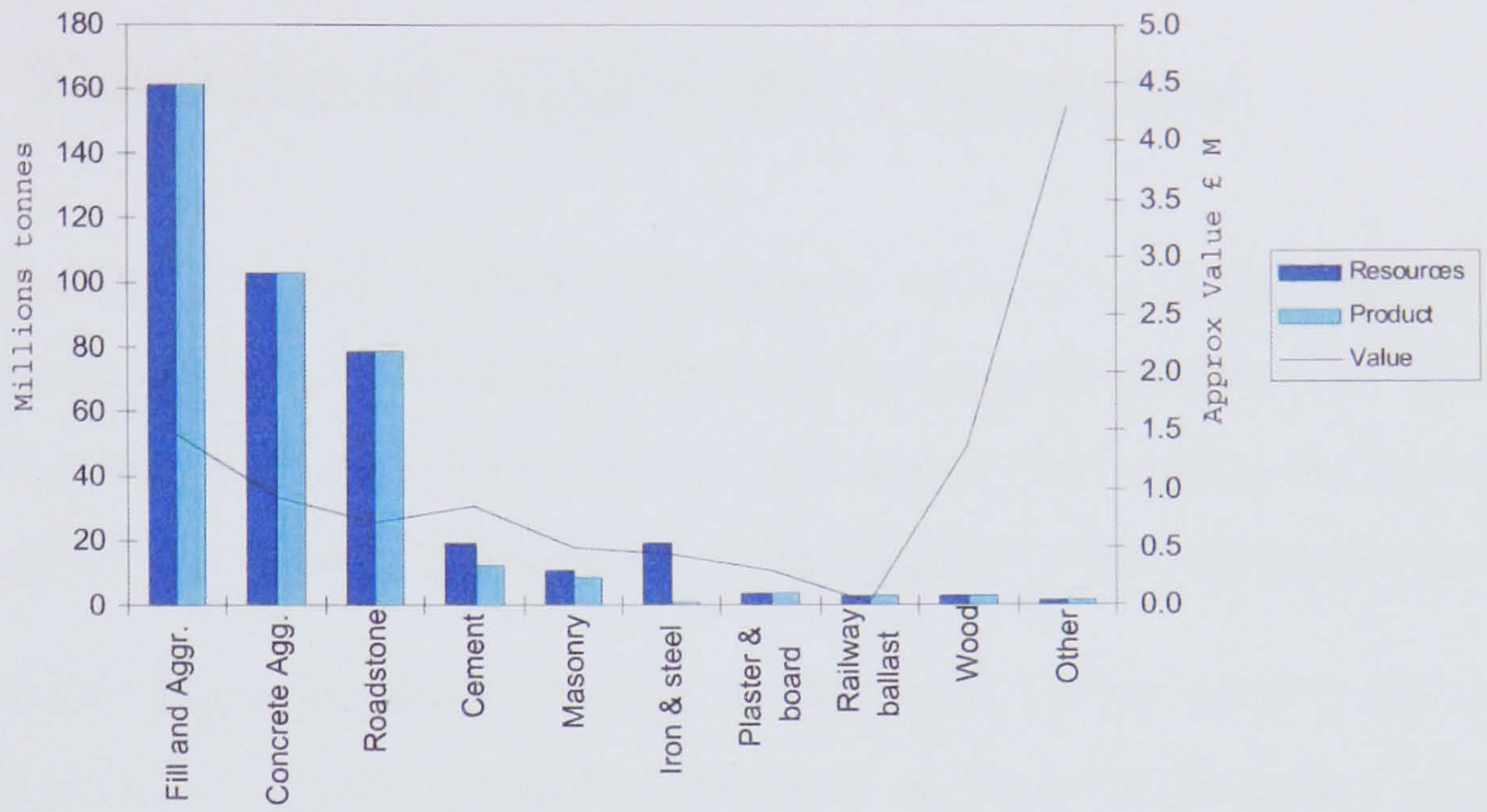

Figure 2.1: Main Construction Resources, Products and their value [1]

Table 2.1 shows the waste generated and recycled in some European countries. The UK is ranked second after Germany in production of total and C&D waste and last in the recycling of C&D waste. Only 20% is recycled in the UK while countries such as Denmark and Belgium recycle up to 80% of their annual C&D waste production.

Table 2.1: Production of C&D waste and its recycling in Europe

Country	Waste (m ton/year)	C&D waste (mt/year)	Current C&D waste recycling (%)	Target for C&D waste recycling (%)
Germany	338.602^b	131.645^b	50	90(by 2005)
Netherlands	44.072^b	13.650^b	-	-
UK	434^a	104^c	30	80(by 2006)
Denmark	11.609^b	3.427^b	80	-
Belgium	28.864^b	7.718^b	45	85(by 2005)
(Brussels)			75	95(by 2005)

[a] Source: DEFRA Statistics [23]
[b] Source: European Environment Agency Statistics [24]
[c] Source: DEFRA Statistics [25]

CHAPTER 3

LITERATURE REVIEW

3.1 Established Aggregate Properties

Concrete consists mainly of three components, water, cement and aggregate. Aggregates usually occupy up to about 80% of the concrete volume. Due to this considerable proportion aggregate properties are of great importance as they can affect fresh properties, strength development, durability and structural performance.

Previously aggregate was considered an inert material in concrete and was often included only for economic reasons. However, its thermal, chemical and physical properties can affect the performance of concrete considerably. Now it is appreciated that aggregate inclusion in concrete gives it the advantage of higher volume stability, better durability and higher strength than pure cement paste [11]. It can also be used to improve thermal and sound insulating properties of the composite.

There are usually two sizes of aggregate used in concrete, and according to BS 882 [26] these are *fine aggregate* also referred to as *sand* with maximum particle size of 5 mm and *coarse aggregate* with maximum size of 20 mm. However, the new European standard EN 12620 [9] which is replacing BS 882, classifies fines as having a maximum particle size of 4 mm and coarse aggregates with a maximum of 16 mm.

Aggregates derive from rock, being either naturally formed or artificially crushed. The properties of the resulting material, such as its chemical and mineral composition, specific gravity, water absorption, strength, physical and chemical stability and pore structure depend entirely on the original material of which it was part. There are some other important aggregate properties that may not have been possessed by the original rock, such as particle shape, size and surface texture which are of significance for concrete in the fresh and hardened state.

When all the properties of aggregate are satisfactory, it will always produce good quality concrete but the converse is not necessarily true. For example, aggregate with some unsatisfactory properties may still produce excellent concrete [11]. On the other hand aggregate which is unsatisfactory in more than one respect may negatively affect the properties of concrete.

Hence aggregate testing greatly assists in assessing its suitability for use in concrete but only testing the concrete itself will confirm the suitability of the aggregate.

3.1.1 Physical Properties

3.1.1.1 Particle shape and texture

The shape of aggregate is significant as it affects the properties of the concrete mix. In order to achieve a given workability the more angular the particles the more water is required [11]. With coarse aggregates, there are two types of particles that are of interest: these are *elongated* and *flaky particles.* The elongation of aggregate particles (referred to as the *shape index*) is assessed according to the European Standard EN 933-4 [27], their flakiness according to EN 933-3 [28]. Elongated particles have a ratio where the larger dimension over the smaller dimension is greater than 3. These particles are classified as non-cubical(elongated). Non-cubical particles should not exceed 10 to 15% of the volume of the coarse aggregate although formal limits do not exist. The limit in BS 882 for flaky aggregate particles is 50% for natural gravel and 40% for crushed or partially crushed coarse aggregate.

The *surface texture* of the particle affects the bond between the cement paste and the aggregate and also the water demand of the concrete mix. Bond between the aggregate particle surface and the hydrated cement paste is mainly due to mechanical interlock, the rougher the particle surface the better the bond. Surface texture assessment is carried out by visual inspection and guidance on the classification of the aggregate is given in BS 882 [26]. The shape and texture of aggregate particles affects the compressive strength of concrete. However, according to Kaplan [29], these factors affect the flexural more than the compressive strength. Further, the influence of shape and surface texture are more evident in high strength concrete.

3.1.1.2 Particle density and water absorption

From the practical point of view the water absorption of the aggregates is one of the most important properties. In order to maintain the free water content of the concrete mix, and therefore the desired w/c ratio, it is necessary to know how much water can be absorbed by the aggregate and adjust the free water accordingly. Maintenance of the w/c ratio to that specified in the mix design will ensure that the required workability is achieved as well as the required strength for a given application. Although particle density is loosely related to strength, excessively low densities may be problematic. Particle densities at a saturated surface dry state are around $2.5Mg/m^3$ for natural aggregates while for recycled will depend on the constituent materials and the processing methods employed during production. Generally RCA has very similar densities to NA whilst RA due to its high content in masonry presents densities $2.5Mg/m^3$.

3.1.1.3 Bulk density

Another important physical property of aggregates used in concrete is the *bulk density* which in short defines the packing capacity of the material. Knowing the absolute density of the particles is not of use since it is not possible to pack the particles without leaving any voids. For the mix proportioning of concrete by volume it is necessary to know the mass of aggregate that can fill a unit volume. This mass per known volume is known as the bulk density of the aggregate. A higher bulk density means more material can be compacted in a predefined container. Bulk density is affected by the particle size distribution but also greatly by the shape of the particles which define how closely they are packed. Therefore, the higher the bulk density the lower is the percentage of voids between the particles and this is of great importance for concrete production.

3.1.2 Mechanical Properties

3.1.2.1 Aggregate crushing value (ACV)

The compressive strength of concrete is limited to some extent by the compressive strength of the aggregate contained therein. For example, when testing concrete for compressive strength, if numerous aggregate particles are fractured, this indicates that the compressive strength of the aggregate is lower than the nominal strength of the concrete specimen. A method to determine the Aggregate Crushing Value (ACV) which gives a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load, is described in BS 812-110 [30].

3.1.2.2 10% fines value (TFV)

The crushing value test determines the amount of fines produced due to a 400kN compressive load. However, when aggregate is weak the amount of fines produced at loads below 400 kN is compacted in the test moulds and prevents further crushing during later stages of the test. In these cases another test is used according to BS 812-111 [31] which describes the method of establishing the 10% fines value (TFV). This test determines the load required to produce 10% fines in a similar manner to the ACV. To simplify the computations a formula is given in BS 812-111. According to BS 882 [26] the minimum TFV for aggregates used in heavy duty concrete floors (PAV designated concrete mixes) is 150 kN, 100 kN for wearing surfaces and 50 kN for other concretes.

3.1.2.3 Aggregate impact value (AIV)

When aggregate is used for pavement construction the *toughness* of the aggregate needs to be assessed. Toughness is the capacity of the aggregate to resist failure by impact. For this purpose a test is described in BS 812-112 [32]. As in the ACV the lower the aggregate impact value the tougher the aggregate. Guidance is given in BS 882 [26] for the AIV for aggregates used in heavy duty concrete floors

(PAV designated concrete mixes) as 25, 30% for wearing surfaces and 45% for other concretes.

3.2 Existing Findings

3.2.1 Aggregate Properties

3.2.1.1 Physical properties

According to Frondistou [33] and Buck [34] crushed uncontaminated concrete debris produces aggregates of good particle size distribution. Buck [34] asserts that recycled aggregate does not contain a high content of flaky and elongated particles. Malhotra [35] reported that the aggregate used in his study was rounder and with smoother surface texture than crushed limestone and natural sand.

In the majority of studies to date on recycled aggregates, they are reported to have very similar particle size distribution curves (within the limits set by various international specifications), relatively higher water absorption values and lower specific gravities when compared to natural aggregates [35, 36].

The coarse RCA deriving from laboratory concrete studied by Hansen and Narud [37], was found to have a lower relative density at about 2.5 as opposed to 2.6 Mg/m^3 for NA and higher water absorption ranging from 3.7%-4.0%, this being around four times that of coarse NA. They also found that RCA produced from concrete rubble had reasonably good grading compared to the NA used in the study and similar to that of many other natural aggregates.

Aggregates deriving from pavement concrete used by Forster [38] presented higher water absorption values of between 3.9%-4.3%, this being about two to four times higher than that of the chert gravel and crushed limestone used in the reference concrete. The grading of the RCA as assessed by visual inspection indicated good particle shape but did not meet the normal grading requirements although when used for concrete produced good results.

Kikuchi [39] in 1994 reported that coarse recycled aggregates deriving from concrete demolished structures had a dry specific gravity ranging from 2.32-2.35 Mg/m^3 whereas fine aggregates ranged from 2.01-2.08 Mg/m^3. These values were about 10% lower than natural coarse and fine aggregates. In the same study water absorption of recycled coarse aggregate was found to be 4 to 5 times higher than natural coarse aggregate ranging from 4.5%-5.1%. In the case of recycled fines the water absorption was ten times that of natural sand ranging from 10.5%-12.5%.

Forster et al, [40] in agreement with Kikuchi's results, reported recycled concrete aggregate with lower specific gravity than natural aggregates. Absorption of recycled aggregate was found to be higher than natural aggregates due to the attached cement paste.

In a study by Prakash [4] in 1996 RCA was produced from laboratory cast specimens and found to have comparable characteristics to NA. Some of the results are shown in *Table* 3.1, the biggest difference being the higher water absorption as found by all previous studies reviewed.

In a study carried out by Morel [41], recycled aggregates deriving from demolished structures containing concrete, ceramic, stone and brick were found to have high water absorptions ranging from 5.5%-7%. This was attributed to the highly porous surface of the recycled aggregate particles due to attached cement paste.

Rashwan and AbouRizk [42] tested aggregates produced from concretes of different ages. He found that RCA had considerably higher water absorption than NA ranging from 4%-7%. Further he reports that older parent concrete produces RCA with higher absorptions. This is explained by the fact that longer hardening periods result in loss of moisture due to the ongoing hydration process. The capacity to maintain moisture content during storage was also assessed and indicated that RCA can maintain higher moisture contents than NA during storage periods.

Table 3.1: Physical properties of RCA [4]

Property	**NA**	**RCA**
Surface texture	Polished & smooth	Dull & rough
Bulk density (Mg/m^3)	0.90	1.40
Flakiness index (%)	8.35	9.55
Elongation index (%)	38.68	43.40
Water absorption (%m/m)	1.96	3.25

In a recent study [43] recycled aggregates containing mainly concrete (88-95%) were used and their total water absorptions ranged from 4% to 14%. In this study it was assumed that the amount of water absorbed by the aggregate during the first 10 minutes represents that amount that lowers the water content during mixing and therefore affects the w/c ratio. It is possible then to calculate the effective w/c ratio by knowing the water absorption of the aggregates used. Observations indicated that on average 10 minutes absorption amounts to 65% of the total absorption but with a large scatter. Therefore, it is very important that an accurate determination of the 10 minute absorption be found if the effective w/c ratio is to be calculated.

Corinaldesi et al. [44] carried out a study using coarse RCA derived from concrete rubble. Water absorption was found to be 8%, four times higher than the coarse NA used. Despite the higher water absorption the RCA concrete had a similar performance to NA concrete.

Gallias [45] in 1998 carried out work using recycled concrete aggregates and found they had water absorptions around 5.5% by wt, about 5 times that of the coarse natural aggregates used. The density was assessed in the dry and wet states and found to be 2.230 and 2.360 Mg/m^3 respectively and the percentage of fines ($<80\mu m$) 1.3% by wt.

Dessy et al. [46] reported water absorption of coarse recycled aggregates to be 4.7% while tests for dry and saturated surface dry densities were found to be 2.335 and 2.453 Mg/m^3 respectively.

Salem and Burdette [47] in a study involving the crushing of old laboratory specimens in the production of coarse RCA found that it had identical dry density (2.7 Mg/m^3) and similar SSD density (RCA:2.55 Mg/m^3 and NA:2.67 Mg/m^3) when compared to natural limestone aggregates. However, the water absorption after 24-hrs was found to be 4.7% for RCA, considerably higher than natural aggregates but in agreement with most of the studies so far reviewed.

Yamasaki [48] assessed the characteristics of coarse recycled aggregates originating from a 38 year old RC frame. The aggregate was produced using jaw and impact crushers followed by screening to the required particle sizes. He found the water absorption to be about 2.7%, almost three times that of coarse NA but the SSD density was 2.6 Mg/m^3 showing the high quality of recycled aggregate produced.

Limbachiya et al. [5] in 2000, carried out a study which included the characterisation of RCA and found its water absorption to be 4.9 to 5.2% which was over two times the absorption of the coarse NA used. The high water absorption was a reflection of the somewhat lower densities of the RCA found at 2.4 Mg/m^3 for the SSD state compared to 2.6 Mg/m^3 for NA. RCA loose bulk density was also lower ranging between 1.17 to 1.21 Mg/m^3 compared to 1.36 Mg/m^3 for the coarse NA showing reduced packing capacity of RCA by about 12%.

3.2.1.2 Chemical-mineralogical characteristics

Morel [41] in a study in 1994 found that recycled aggregates originating from a concrete structure were found to contain sulphates (SO_3) at contents ranging from 0.35-0.70% by mass of concrete. One percent of organic matter, mainly due to the presence of bitumen, was found. The chloride ion content was negligible.

Gallias [45] assessing the sulphate content (SO_3) of recycled aggregates found it to be between 0.8 - 1.2% which was always higher when compared to natural aggregates. Using X-ray diffraction, he also established that about half of the SO_3 in recycled aggregates was due to presence of gypsum as plasters and partition walls in the C&D debris.

3.2.1.3 Mechanical properties

A study by Bairagi et al. [49] reported that RCA had significantly lower resistance to mechanical action such as crushing and impact.

In an other study [50] it was reported that RCA concrete had lower crushing resistance compared to NA. The ACV for NA was found to be 19.8% while for RCA it was 35.8%. Furthermore it was reported that the impact resistance of RCA was half that of NA when assessed using the AIV test. Results reported by Kohler et al [51] revealed AIV for RCA that ranged from 26 to 36%, higher than natural aggregate values confirming the previous result.

Kikuchi in 1994 [39] carried out aggregate crushing value tests on RCA and found that the ACV was between 33-83% higher than for natural aggregate. The ACV's for RCA ranged between 18.4-25.2% compared to 13.8% for natural coarse aggregate.

In a study by Prakash [4] in 1996 RCA was produced from laboratory cast specimens and found to have comparable characteristics to NA. Some of the results are shown in *Table* 3.2 which indicate the differences are well within the limits for aggregates for concrete.

Table 3.2: Mechanical properties of RCA [4]

Property	**NA**	**RCA**
Aggregate Impact Value (%)	11.93	19.78
Aggregate Crushing Value (%)	28.23	32.08
LA abrasion value (%)	8.35	9.55

In 2000 Limbachiya et al. [5] reported on aggregate characteristics which included mechanical properties of coarse RCA. These results here given in ***table 3.3*** found the RCA crushing resistance was lower compared to coarse NA but compared to the NA used by Prakash [4] it was considerably higher. Resistance to impact was also lower but not excessively and the 10% fines value indicated RCA was considerably weaker in crushing but still meeting requirements [26] for use in high wear pavements.

Table 3.3: Mechanical properties of RCA [5]

Property	NA	RCA
Aggregate Impact Value (%)	19.7	23.7
Aggregate Crushing Value (%)	14.0	20.0
10% Fines Value (%)	289	160

3.2.2 Concrete Fresh Properties

Four studies [33, 34, 49, 52] reported similar consistency results by means of slump and/or compacting factor for RCA and NA concrete mixes of different w/c ratios. However, results from Rasheeduzzafar [53] do not agree, as RCA concrete in this study assessed by Compacting Factor (CF) and VE-BE was found to have higher workability when compared to NA concrete.

Hansen and Narud [37] reported that RCA concrete in general required about 5% more free water in order to achieve an identical slump to NA concrete due to the angularity and rough surface of the RCA particles as opposed to the smooth and rounder NA particles.

RCA concrete mixes were more cohesive than NA mixes due to the fine particles produced during mixing deriving from the attached cement paste. Therefore, the lower the strength of the parent concrete the more fines are produced and increased cohesiveness results [37].

Although the initial workability of RCA and NA concrete of the same composition was the same, the loss of workability with time is accelerated for RCA concrete because dry RCA particles continue to absorb water after mixing [37].

Forster [38] reported that the inclusion of coarse RCA did not have any detrimental effects on workability and mix proportions of pavement concrete, when compared to NA concrete. However, when fine RCA was also used as a replacement for fine NA the mix became less workable and more water and therefore more cement was required to maintain the w/c ratio. The inclusion of up to 30% of fine RCA improved the consistency of the mix.

In research carried out by Ravindrarajah et al [54] in assessing the fresh properties of RCA concrete it was found that the workability was not affected significantly by the inclusion of either coarse and/or fine RCA. In agreement with Hansen [37] it was found that RCA concrete showed marginally accelerated loss of workability when compared to NA concrete. Overall the setting times of RCA and NA concrete show very little difference.

In a study by Ray [50], workability results in agreement with the majority of research carried out before were found. In addition Ray found that the higher the w/c ratio the closer the workability between RCA and NA concrete.

De Vries [55] reported that due to the angularity of RCA/RA, the total water demand of concrete mixes was higher when compared to NA concrete. A suggestion was made to pre-wet the recycled aggregates while in storage but finally it was proposed to add the extra requirement of water when mixing as opposed to pre-wetting in order to ensure homogenous mixes. With a replacement of no more than 20% of NA with RCA/RA no effects on workability were observed.

Prakash [4] in 1996 found that RCA concrete made with aggregates from laboratory crushed specimens, had very similar workability when compared to NA concrete. With the addition of superplasticiser the mixes become very workable with collapse slumps and high compacting factors (CF) as a result. Some of the results are presented in *Table* 3.4.

Table 3.4: Workability of RCA concrete [4]

Concrete mix	w/c	Slump	CF
NA concrete	0.45	0	0.87
	0.50	0	0.89
	0.60	10	0.90
	0.70	15	0.92
	0.80	20	0.94
	0.90	collapse	0.97
RCA concrete	0.45	0	0.84
	0.50	0	0.84
	0.60	0	0.86
	0.70	12	0.90
	0.80	18	0.92
	0.90	collapse	0.95
RCA concrete with Superplasticiser	0.45	0	0.89
	0.50	0	0.91
	0.60	8	0.93
	0.70	14	0.94
	0.80	collapse	0.96
	0.90	collapse	0.98

Another study by Rashwan and AbouRizk [42], reported that mixes containing RCA were harsher than NA mixes. It was suggested that this was due to higher water absorption as well as the texture and shape of the recycled aggregates. RCA as a crushed aggregate is more angular than NA with a higher surface/volume ratio and rougher texture resulting in friction between particles and therefore requires more cement paste in order to improve workability. As a conclusion the author reported that RCA concrete workability is not mainly dependent on the water content but on the aggregate surface and texture.

Sagoe et al [56] in his study reported that concrete mixes containing RCA had comparable workability to NA concrete as determined by the slump and setting characteristics.

3.2.3 Concrete Engineering Properties

3.2.3.1 Compressive Strength

Several studies [33, 52] have concentrated on the type of aggregate used in the original concrete as well as the strength of the original concrete. A report by Gluzhge [57] states that concrete produced with RCA was not better than the concrete the RCA was derived from. However, this was contradicted by further research [34, 58] when concrete manufactured using weak original concrete was found to be of higher strength. A more recent study [33] reported that "concrete is as strong as its weakest link". The weakest link for concrete is the bond between cement paste and aggregate. The fracture of concrete usually follows a path between the aggregate-cement paste interface and in this way the full strength of the aggregate is not utilised. Therefore, if an aggregate is replaced with a weaker aggregate, there may be no difference in the resulting concrete strength. According to Frodistou-Yannass [33] when the recycled aggregate consists mainly of aggregate from old concrete, then the cement paste - aggregate bond, is as strong as the bond of cement paste with NA. However, when the aggregate consists of aggregate with attached cement paste, then the interface between this aggregate and the new cement paste constitutes the "weakest link" in the concrete and may result in reduced strength. Other studies [34, 58] have shown that concrete containing RCA can give higher strength than the strength of the parent concrete.

Frondistou-Yannas [33, 52] assessed the effect of RCA in new concrete for different water/cement (w/c) ratios compared to NA concrete. The results were in agreement with Buck [34, 58] and Malhotra [35] and showed that the compressive strength of the RCA concrete ranged between 64 and 100% of the strength of NA concrete. However, the compressive strength of RCA concrete can be controlled producing concretes for a considerable range of applications. Equivalent strength to NA concrete can be reached by simple adjustments such as increased cement content [33, 35]. It was also shown that the relative performance when coarse RCA and NA are used in concrete is not affected by the different w/c ratios or age but with the inclusion of fine RCA there is a greater demand for water and therefore additional cement is needed in order to obtain the required w/c ratio. In another study [49] it was found that in order for RCA concrete to reach an equivalent strength to NA concrete an adjustment to the cement content ranging from 8 to 13% is required, the higher the strength the higher the adjustment.

In a study by Hansen and Narud [37] it was found that the strength of RCA concrete is dominated by the w/c ratio of the original concrete. In other words RCA obtained from original concrete of low w/c ratio can produce RCA concrete with the same or even higher strength as the original concrete. In addition it was found that RCA concrete can be produced with a strength comparable to the reference NA concrete but this requires an increase in the cement content.

Rasheeduzzafar and Tam [53] reported that for concrete with w/c ratios lower than 0.40 there is a decrease of compressive strength for RCA concrete when compared to NA concrete. Typically for a 0.35 w/c ratio the strength of RCA concrete was 30% lower than that of NA concrete. With increasing w/c ratios the difference in strength between RCA and NA concrete decreased up to a w/c ratio of 0.45 after which the strength was equivalent.

Compressive strengths achieved by Forster [38] with concrete for pavements containing coarse and fine RCA were 2.0 to 9.0 N/mm^2 lower than NA concrete strengths. Using low strength RCA did not have detrimental effects on strength and the use of water reducing agents improved the strength of RCA concretes.

Ravindraradjah and Tam [54] found the compressive strength of RCA concrete to be about 10% lower than NA concrete and that coarse RCA affects strength more than fine RCA.

Ong and Ravindrarajah [59] reported that the strength of the parent concrete from which RCA concrete was made only has a marginal effect on the strength of the RCA concrete. However, the use of RCA produced from high strength concrete is beneficial in producing high strength RCA concrete. The use of fine RCA proved to reduce the strength of RCA concrete especially in the case of low strength original concrete when the reduction in strength was serious. This finding disagrees with

Ravindrarajah and Tam [54] who reported that fine RCA had less effect on strength than coarse RCA. It is also important to note that RCA from low strength concrete can be used to produce concrete with higher strength. The strength development of RCA and NA concrete was found to be comparable irrespective of the strength of the original concrete.

In another study [55] it was reported that up to a 20% replacement of NA with RCA or RA had no effect on concrete strength and C45 concrete was easily achievable. Replacing up to 100% of the NA resulted in strength reductions of between 10 and 20%, but C25 concrete was still achievable.

In a study by Forster [40] it was reported that although the compressive strength of recycled concrete aggregate concrete was lower when compared to natural aggregate concrete, required minimum strengths can be easily achieved. In addition some of the compressive strength results were found to be higher for recycled aggregate concrete and well above required levels.

Wainwright in 1994 [60] reported that concrete made with coarse and fine recycled concrete aggregates had the same strength development as the reference concrete. However, the strength of the concrete with recycled aggregates was lower than that of concrete with natural aggregate. The strength of concrete made with coarse recycled aggregate and natural fines was reduced by 11% and 20% for low and high strength original concrete respectively. One of the concretes made with coarse RCA deriving from low strength concrete had slightly higher strength when compared to concrete with recycled aggregates from high strength concrete. A possible explanation of this reported by the author in a previous study in 1992 is that the aggregates deriving from low strength concrete have less cement paste attached to them. In general concrete made with recycled aggregate (coarse and fine) originating from strong concrete had strengths approximately 5 N/mm^2 higher than concrete manufactured with recycled aggregates from low strength concrete. Overall it can be concluded that a relationship between the strength of the original concrete and the concrete containing the coarse recycled aggregates cannot be established. The opposite though can be said for concrete containing recycled fines.

Ajdukiewicz in 1996 [61] in disagreement with Wainwright's results [60], observed that concrete made with coarse recycled aggregate deriving from high strength concrete (C50) showed strength values 15-20% higher than NA concrete. Recycled aggregate concrete containing aggregate from mid-strength original concrete gave strength results which were about 10% higher than NA concrete.

In 1996 Prakash [4] found that RCA concrete made with aggregates from laboratory crushed specimens, had compressive strengths lower by 13% when compared to NA concrete. However, with the inclusion of superplasticiser the RCA concrete improved in strength by approximately 24% compared to NA.

Di Niro et al [62] carried out experiments on concrete containing up to 100% RCA as replacement to NA. The mixing involved pre wetting the coarse RCA for 10 minutes with the additional water required due to water absorption . The results showed reductions in strength for concretes containing RCA. However, it was found that RCA concrete with up to a maximum of 30% RCA reached the characteristic strength.

In 1997 Rashwan [42] carried out a study which examined the effect of crushed concrete as RCA. It was found that concrete containing RCA from 24 hour old parent concrete produced 25% higher strengths than NA concrete. However, RCA that remained in storage for seven days and was then used, produced concrete 7% lower in strength than NA concrete. It was suggested that using RCA from early crushed concrete may improve the strength.

In 1998 Sagoe et al found that RCA concrete had lower strength at all ages when compared to NA concrete. This was found when both or either fine and coarse NA was replaced with RCA. However, the strength development was similar for all RCA and NA concrete mixes.

Limbachiya et al. [5] carried out a study assessing the effect of RCA on strength of RCA concrete. He reported that the maximum strength of concrete containing RCA in excess of 30%, was found to be lower, around 72 N/mm^2 when compared to NA concrete which reached over 80 N/mm^2. The reduction in high strength gradually increased, with decrease of the w/c ratio below 0.28 and this point was referred to as the start of ceiling strength. However, he also reported that by applying adjustments to reduce the w/c ratio of RCA concrete, equivalent compressive strength performance was achieved.

3.2.3.2 E-Modulus of elasticity

Frondistou [52, 33] reported that RCA concrete has a static modulus of elasticity that ranges between 60 and 100% of that of NA concrete. This is consistent with the fact that RCA has a lower modulus of elasticity than NA.

In a study by Hansen and Boegh [63] the static and dynamic modulus of elasticity of RCA concrete was found to be 15 - 30% lower than the corresponding moduli of the original concretes from which the RCA was derived. It was also found that RCA concrete made with poor RCA deriving from very low strength concrete had moduli of up to 50% lower, this being in agreement with Frondistou [33].

According to Ravindraradjah and Tam [54] the static modulus of elasticity of RCA concrete when compared to NA concrete was found to be 14% lower when only coarse aggregate was replaced and about 30% lower when both fine and coarse aggregates were substituted.

Ong and Ravindrarajah [59] in agreement with Frondistou [52] reported that the static modulus of elasticity for RCA concrete was found to be up to 60% lower than that of NA concrete when both fine and coarse RCA was used. Another study [64] reported a decrease in modulus of elasticity of between 15 - 24% when fine and coarse RCA was included.

Ajdukiewicz [61] in 1996 found that coarse and fine recycled aggregate produced concrete with similar E-values when compared to NA concrete. It was also noted that in the case of higher strength (C50) parent concrete there was an improvement in E-value while with lower strength parent concrete (C30) a decrease was observed.

Limbachiya et al. [5] reported very similar elastic modulus of elasticity for high strength RCA and NA concretes in contradiction to the results reported by several previous studies reviewed [52, 33, 63, 59]

3.2.3.3 Flexural Strength

Malhotra [35] reported that RCA concrete was found to have a flexural strength of 80-100% that of NA concrete. However, Gluzhge [57] found RCA concrete had higher flexural strength than the reference NA concrete.

The flexural strength of RCA pavement concrete studied by Forster [38] was slightly lower than NA concrete but always above the requirements set by the Michigan Department of Transportation minimum specifications for pavement concrete.

In an investigation by Ong et al [59] the flexural strength of high strength RCA concrete was found to be marginally lower than NA concrete but for low strength RCA concrete it was higher.

The flexural strength of recycled and natural aggregate concrete was assessed by Forster [40] who found that some recycled aggregate concrete mixes produced higher flexural strengths when compared to natural aggregate concrete.

Ajdukiewicz [61] in 1996 reported that all the recycled concrete mixes he tested (coarse or coarse and fines replaced) produced lower tensile splitting strengths than NA concrete by 10% and 5% for high and low strength original concrete.

In 1996 Prakash [4] found that RCA concrete made with aggregates from laboratory crushed specimens, had lower flexural strength by about 7% when compared to NA concrete. However, with the inclusion of a superplasticiser the RCA concrete improved by approximately 23% when compared to NA .

The flexural strength of high strength RCA and NA concretes assessed by Limbachiya et al. [5] was found to be very similar and sometimes improved for RCA concrete and this was compatible with findings from previous studies reviewed [57, 59, 40, 4].

3.2.3.4 The Concept of equivalent strength concrete

Previous research carried out by Limbachiya et al [2] involved the adjustment of the w/c ratio in order to produce RCA concrete with equivalent 28-day strength when compared to NA concrete. The study established that the reduction of strength increases with increase of the RCA content in a consistent manner. Therefore, if the w/c ratio of RCA content is slightly reduced then this will compensate for the strength loss. To assess how much the w/c ratio needs to be reduced the following procedure was recommended.

Concretes containing RCA contents up to 100% were produced and the 28-day compressive cube strength was established. A family of strength vs w/c ratio curves was plotted and the required correction factors for the w/c ratio were established as shown in *figure 3.1*. Using this graph it was possible to establish the reduced w/c ratio for any RCA content concrete based on the conventional concrete curve and hence to obtain a set of adjustment factors (*table 3.5*) to be used in order to adequately reduce the w/c ratio for a given RCA content and so achieve equivalent strength to that of the conventional concrete.

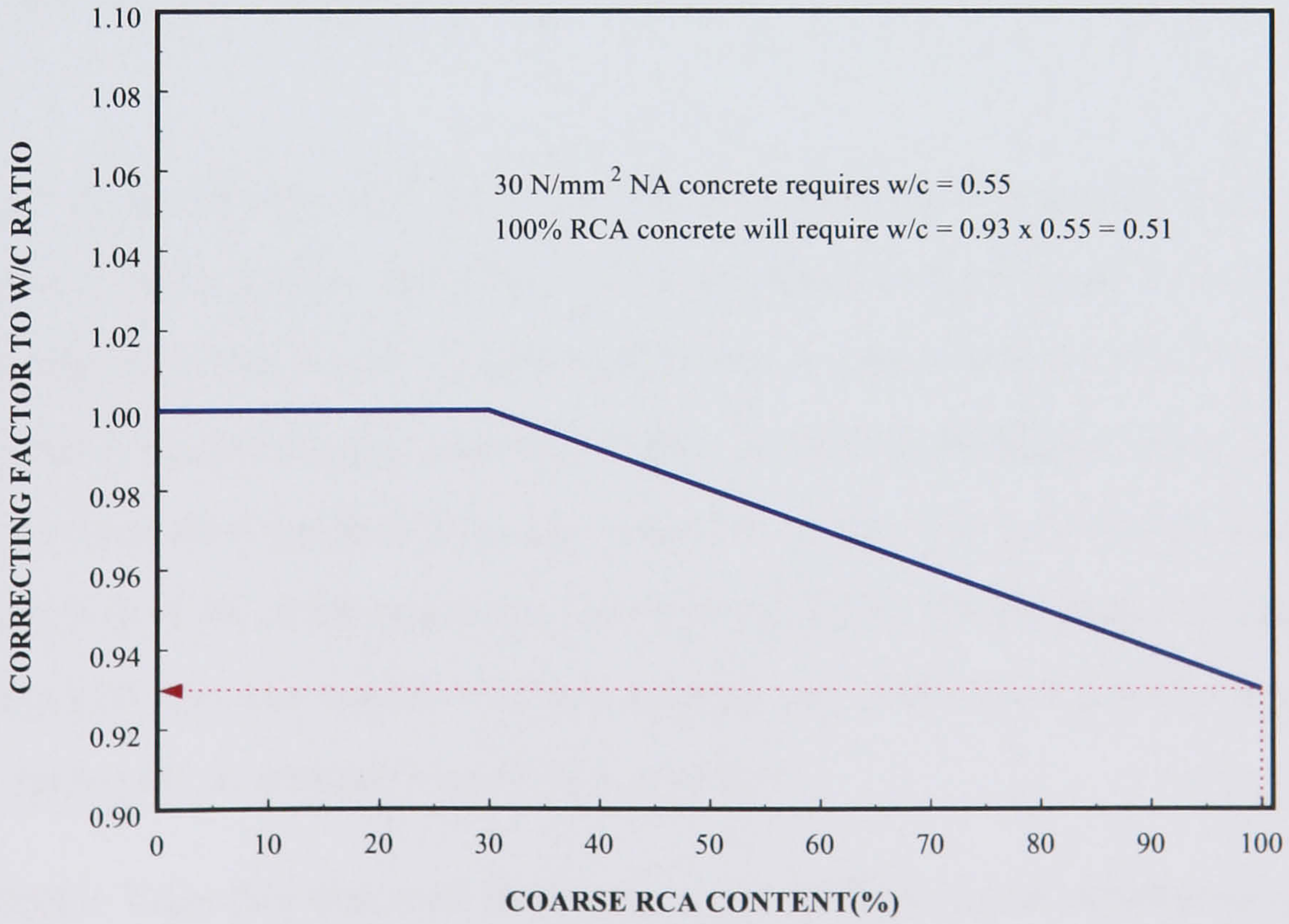

Figure 3.1: Correcting factors required for the achievement of equivalent strength RCA concrete established by Limbachiya et al. [2].

Table 3.5: Adjustment factors required for the reduction of w/c ratio and achievement of equivalent strength concrete [2].

RCA (%) CONTENT (%)	W/C RATIO ADJUSTMENT FACTOR
0	1
30	1
50	0.975
75	0.95
100	0.93

3.2.3.5 Drying shrinkage and swelling deformations

The behavior of both RCA and NA concrete specimens was studied by Buck [34] who found that under controlled moisture conditions the linear dimensional changes were similar with either constant or variable temperature. In a study by Hansen et al [37] it was found that the amount of attached cement paste on coarse graded RCA can be about 40% by volume and the author suggested that such an amount is considerable and can negatively affect elasticity, creep and drying shrinkage of this concrete.

Hansen et al [63] reported that concretes containing coarse RCA have a drying shrinkage 40 - 60% higher than that of conventional concrete and in the case where fine RCA replaces fine NA the percentage increases even further. The use of very low strength RCA can result in shrinkage values several times higher than NA concrete and attention should be drawn to the selection of the concrete rubble processed for the production of RCA for concrete. The susceptibility to cracking was also assessed by Hansen [63] and the results did not suggest any particular risks to cracking due to RCA inclusion in comparison to NA concrete.

In 1993 De Vries [55] reported that with up to 20% inclusion of coarse crushed concrete or mixed aggregate, the effects on shrinkage and creep are negligible. However, at a 100% inclusion of the same materials it was found that a 10% extra thickness of elements was required to ensure adequate stiffness of structural members.

Ravindraradjah [54] reported that coarse RCA concrete developed 55% higher drying shrinkage than NA concrete over a period of 90 days. With both fine and coarse RCA the shrinkage was almost double that of NA concrete and it was established that including fine RCA accounts for 40% of the increase. It is suggested that the lower modulus of elasticity of aggregates and the original attached cement paste are possible causes.

According to Wainwright [64] the drying shrinkage of RCA concrete containing fine and coarse RCA was found to be around 37% higher than that of NA concrete at 56 days. This is somewhat lower than what is reported by Hansen [36] who when reviewing others notes increases in shrinkage of up to 80% for RCA concrete containing both fine and coarse RCA.

Merlet [65] in 1994 studied the effect of recycled concrete aggregates on the shrinkage of concrete. When comparing coarse natural aggregate concrete with coarse recycled aggregate concrete both with fine natural sand he found that the shrinkage pattern up to 90 days was similar. However, the shrinkage for concrete containing both coarse and fine recycled aggregates ($672\mu\epsilon$) was much higher than NA concrete ($500\mu\epsilon$). The incorporation of recycled fines had a major effect increasing shrinkage by approximately $100\mu\epsilon$. Mixes incorporating superplasticisers shown shrinkage values comparable to NA concrete. Finally, Merlet reported that the process of pre-moistening recycled aggregates had no influence on the shrinkage of the concrete.

Ajdukiewicz [61] in 1996 reported that no significant differences were found in the shrinkage values of recycled concrete when compared to NA concrete.

In a study by Tavakoli [66] it was found that higher contents of attached cement paste on the recycled concrete aggregate, result in higher drying shrinkage. A good indication of the amount of attached cement paste is the water absorption of the recycled aggregate. In some of the mixes tested it was noted that initial dry mixing of the recycled concrete aggregates reduced the adhered cement paste and shrinkage decreased.

The swelling of concrete was studied by Gallias [45] who reported that concrete specimens containing coarse and/or fine recycled aggregates showed higher expansions but with maximum strains recorded being 90 $\mu\varepsilon$ still much lower than the 200 $\mu\varepsilon$ considered critical for cracking.

Limbachiya et al. [5] in 2000 investigated the effects of coarse RCA on the drying shrinkage of equivalent strength concrete and found that shrinkage increases with increase in RCA content whih was probably due to the w/c ratio adjustment resulting in additional cement in the mix.

3.2.4 Concrete Durability Performance

3.2.4.1 Porosity and permeability

In a study by Wainwright [60] in 1994 it was found that concrete made with coarse recycled concrete aggregates as a replacement for natural aggregates presented higher porosity and permeability. In the case where natural fines were also replaced by recycled fines the effect was even greater. Although the required strength of these concretes was achieved, the increased permeability and porosity will compromise significantly the durability of this concrete.

The near surface absorption of concrete incorporating RCA was assessed by Limbachiya [5] using the I.S.A.T. method and results showed that RCA up to 30% content had no effect on absorption but further increases up to 100% resulted in higher absorption values. The decay of the water absorption was also increased with increase in RCA content and this was probably due to the cement paste attached on the RCA particles

3.2.4.2 Freeze-thaw

The resistance of RCA concrete to freezing and thawing was assessed by Buck [34] and Malhotra [35] and found to be comparable to NA concrete . In these studies the amount of air entrained agent used was the same for RCA and NA concrete except in the case when fine RCA was used as a replacement for fine NA when the amount of the agent was doubled [57].

In another study by Merlet [65] it was also reported that recycled aggregate concrete had good freeze-thaw resistance with sample mass reduction not exceeding 1%.

Forster[38] in 1985 reported that pavement concrete made with coarse RCA susceptible to freeze-thaw attack performed much better than the original concrete. On the other hand concrete made with coarse RCA originating from frost resistant NA performed only slightly worse than NA concrete.

In 1998 Salem and Burdette [47] reported on the freeze-thaw resistance of concrete made with recycled aggregates. They found that the high water absorption and subsequent the saturation of recycled aggregates during testing, resulted in concrete with reduced freeze-thaw resistance. Having said that they also reported that the use of air entrainment is the most effective way to produce freeze-thaw resistant recycled aggregate concrete.

Yamasaki [48] assessing the freeze-thaw resistance of concrete containing coarse recycled aggregate, found that if the appropriate air content is introduced in conjunction with a reduction in w/c ratio then improved freeze-thaw resistance can be achieved. He reported that the water absorption played a significant role in the reduced freeze-thaw resistance.

Springenschmid [67] studied the freeze-thaw resistance using de-icing salts and reported that concrete containing fine recycled aggregates ($< 4mm$) has lower freeze-thaw resistance but when coarse ($> 4mm$) recycled aggregates are used it performed adequately. He also reported that recycled aggregates with particle sizes $> 4mm$ were used in a section of the A93 Autobahn and the pavements showed no deterioration after severe winter conditions.

Resistance to freeze-thaw cycling was investigated in 2000 by Limbachiya et al. by measuring the dynamic modulus of elasticity of concrete specimens exposed to up to 300 freeze-thaw cycles. It was reported that heavy duty paving concrete required no adjustment in the air-entrainment dosage due to RCA content and that the resistance to freeze-thaw was satisfactory even for 100% RCA content, with results sometimes better than for NA concrete.

3.2.4.3 Resistance to carbonation

Carbonation refers to a number of natural processes causing the neutralisation of concrete. The most significant process occurs when carbon dioxide in the atmosphere reacts with calcium hydroxide ($Ca(OH)_2$) in the cement in the presence of moisture resulting in the formation of calcium carbonate ($CaCO_3$). This results in a reduction of the pH (to about 9 from 13) of the concrete and increases the potential for corrosion of steel reinforcement.

Concrete will carbonate if CO_2 from air or dissolved in water enters the concrete according to:

$$Ca(OH)_2 + CO_2 \quad -> \quad CaCO_3 + H_2O$$

When $Ca(OH)_2$ is removed from the paste, hydrated calcium silicate hydrate (CSH) will liberate CaO which will also carbonate. The rate of carbonation depends on the porosity and moisture content of the concrete.

The carbonation process requires the presence of water because CO_2 dissolves in water forming H_2CO_3. If the concrete is too dry ($RH < 40\%$) CO_2 cannot dissolve and no carbonation occurs. If on the other hand it is too wet ($RH \geq 90\%$) CO_2 cannot enter the concrete and again the concrete will not carbonate. Optimal conditions for carbonation occur at a RH of 50% (range 40-90%).

Normal carbonation results in a decrease of porosity making the carbonated paste stronger. Carbonation is therefore an advantage in non-reinforced concrete. However, it is a disadvantage in reinforced concrete, as the pH of carbonated concrete drops to about 7; a value below the passivation threshold of steel.

In a paper by De Vries [55] in 1993 it was reported that when RCA/RA and NA concretes of the same w/c ratio and equivalent strength were subjected to carbonation, the rate of carbonation was not affected by the inclusion of the RCA/RA.

3.2.4.4 Sulphate attack.

Limbachiya et al. [2] investigated the resistance to sulphate attack of concrete containing RCA up to 100%, exposing concrete to a mild sulphate environment (0.3 g/l Na_2SO_4) and measuring expansions up to 180-days. It was found that up to 50% RCA had insignificant effects to the strains ($47 - 56\mu\varepsilon$) of 10N and 20N concretes and only RCA in high contents caused some increase (but still not more than $63\mu\varepsilon$ being around 20% higher than NA concrete).

3.2.4.5 Chloride ingress.

The resistance to chloride ingress was studied by Limbachiya et al. [5] on high strength concretes containing combinations of RCA and NA coarse aggregates and found that there was no effect at all on the diffusion of chlorides into concrete due to RCA content and that 100% RCA concrete performed as NA concrete.

3.2.4.6 Abrasion resistance.

In 2000 Limbachiya et al. [5] reported on the abrasion performance of high strength coarse RCA and NA concretes and found that all performed similarly with minor effects due to RCA content. The differences recorded between NA and 100% RCA concrete were 0.03 and 0.04 mm for 50 and 60 N/mm^2 concretes respectively.

3.3 Practical implications of RCA/RA Use in Concrete

A study by Hansen and Narud [37]in 1983 states that the considerably higher water absorption of coarse RCA, compared to coarse NA, can cause practical difficulties in maintaining uniformity in the quality of concrete and more importantly it will be difficult to control quality when RCA water capacity and absorption change during the production of concrete.

Although the aggregate producer will be responsible for any changes to and adaptations of his plant in order to be able to process C&D waste this does not mean that the concrete producer can use the recycled product as usual. In order to integrate the use of RCA in daily production, the producer needs to adjust the quality control procedures. In the case of natural aggregates, contaminants are not a problem while with recycled aggregates thorough inspection is required in order to detect and discard any contaminants. In addition, due to the varying properties of recycled aggregates, the use of technology to control these properties and adjust mixing parameters will incur extra costs. The main additional requirements [68] will include:

- Inspection of recycled aggregates in order to exclude contaminants
- Storage requirements for recycled aggregates
- Additional concrete mix designs with optional use of recycled aggregates

In order for recycled aggregates to be widely used by the construction industry, their price must match that of natural aggregates. Considering that the cost of a recycling plant is considerably higher than a conventional plant, the price of recycled aggregate will be higher. However, if the producer applies a fee for the disposal of C&D waste on the production site then the price can be balanced. Therefore, the most suitable areas for the production of recycled aggregates will be areas without any natural aggregate and with high landfill costs [68].

Practical implications for the use of coarse RCA were identified by Limbachiya et al. in 2000 in a study of high strength RCA concrete. The required adjustments (w/c ratio reductions) proposed for the production of equivalent strength concrete can be easily integrated in current design and production methods. The durability performance of RCA concrete examined through chloride ingress, abrasion, freeze-thaw, absorption rates and chloride induced corrosion was found to be satisfactory which should encourage its use. However, it was identified that when specifying RCA additional consideration should be given concrete, with respect to shrinkage and creep deformations of concrete intended for structural components prone to these deformations.

3.4 Specifications, Recommendations and Guidance

Since the early 1990's recognised associations and research establishments have published guidance documents recommending the use of RCA originating from C&D waste as aggregate in new concrete.

One of the first documents was published by "The Danish Concrete Association" entitled "Recommendations for the Use of Recycled Aggregates for Concrete in Passive Environmental Class" [69].

In the Netherlands regulations [55] for the use of RCA date back to 1984. These regulations are entitled CUR-VB Recommendation 4 for crushed concrete aggregate and CUR-VB Recommendation 5 for crushed masonry aggregate. According to the regulations RCA must contain at least 95% concrete. The amount of secondary materials such as clay, building bricks, lightweight concrete, ceramic materials etc. is restricted to 5% while gypsum and any gypsum containing materials are not permitted. Finally, a restriction to 1% is recommended for all non stone-like materials such as paper, wood, plastic etc. According to the regulations for crushed masonry aggregates the principal constituent, crushed masonry, must form at least 65% of the total while other constituent materials are restricted as follows:

- 20% lightweight concrete
- 10% foamed concrete

- 20% ceramic materials
- 25% masonry mortars
- Total exclusion of gypsum or products containing gypsum

There are other limitations on such aspects as grading, fines content, organic material, chlorides and very importantly sulphates since these later are responsible for swelling leading to the destruction of concrete.

A very significant amendment to the Dutch regulations, made in 1993 was the recommendation that up to 20% coarse recycled aggregate could replace NA. The recycled aggregates used must comply with the relevant CUR-VB recommendations.

In 1994, Task Force 1 of RILEM TC 121-DRG produced a RILEM Recommendation [70] for the use of coarse recycled aggregates for concrete. The specification classifies the aggregates in different categories and indicates the suitable concrete application for which these aggregates can be used. The suitability of coarse recycled aggregate for a particular application is indicated in the context of environmental exposure classes and strength classes in line with EUROCODE 2 [71] requirements.

According to the RILEM Recomendation coarse recycled aggregates are classified as Type I, mainly consisting of masonry rubble, Type II, mainly originating from concrete demolished structures and Type III aggregates consisting of a blend between recycled and natural aggregates providing there is a minimum of 80% natural aggregate in the blend.

The specification sets some mandatory requirements for recycled aggregates for concrete, the most important being presented in *Table* 3.6

Table 3.6: Classification of recycled coarse aggregates for concrete (RCAC)

Mandatory requirements	RCAC		
	(Type I)	(Type II)	(Type III)
Min. Dry particle density (kg/m^3)	1500	2000	2400
Max. Water absorption (%m/m)	20	10	3
Max. Content of foreign materials (metal,glass,bitumen etc.)(% m/m)	5	1	1
Max. Content of sulphate (% m/m)	1	1	1

The specification also requires that some recycled aggregate properties which include grading, form index, abrasion value, chloride content, and frost resistance be determined in accordance to national or implemented European standards.

In addition, the specification [70] allows that the aggregates complying with the above requirements can be used in plain and reinforced concrete, provided that the requirements of table 3 of the specification are met.

The use of fine recycled aggregates is restricted by the RILEM specification mainly due to a combination of lack of research as well as of suitable methods to assess the strength and the alkali reactivity of the fines. In addition recycled fines often contain excessive amounts of contamination.

3.5 Case studies

During the 1980's a ready mix concrete producer [72] regularly returned unused concrete to his site in an effort to operate an environmentally friendly plant. As a result the equipment used for the disposal of this unused concrete regularly needed maintenance and cleaning, resulting in extra costs and lost time. Decision by the president of this company to then install a special recycling plant to re-process unused concrete into RCA, resulted in considerable cost savings as well as a more environmentally friendly operation and an improved image.

In 1993 a project was undertaken with the support of the Danish Ministry of Environment, called The Recycled House in Odense [73], in which a two wing, two and a half storey house was built by using only recycled materials which included repaired doors, old slates for the roof, old timber for the roof trusses, crushed concrete as the drainage layer and crushed concrete and bricks as aggregate for the basement concrete. Recycled materials were obtained from the site and other neighboring sites and contributed to a reduction of waste and energy consumption of new materials. The benefits achieved from this project show that it is possible for recycled materials to be used in construction in a country which at the time, had very limited recycling facilities or experience. From the practical point of view, experience was collected on the handling of recycled materials in construction. The project raised the question as to whether RCA is more beneficial when used in road construction than in structural concrete.

In 1996 Collins [6] reported on a full scale demonstration carried out by the BRE involving the construction of an energy efficient and environmentally friendly model of an office building. The building was constructed on the BRE Garston site. Existing buildings on site were demolished and using a mobile plant crushed and reused as hardcore for the new building. All wood and metal were collected for recycling. Fittings such as sockets, alarms, filing cabinets, office blinds etc were recovered. For the purposes of the structural concrete part of the new building it was necessary to locate sources of recycled aggregates. A 12 storey block was demolished at the time in central London and the demolition waste was processed and used as coarse aggregate for over 1500 m^3 of concrete which was used for foundations, floor slabs, structural columns and waffle floors.

The project involved, for the first time in the UK, the use of recycled aggregates in ready mixed concrete (RMC). There were two mixes used; a C25 with 75 mm slump and a w/c ratio of 0.5, was specified for the foundations and for the slabs a C35 concrete with 75 mm slump was specified. Following trial mixes it was decided to use concrete containing water reducing admixtures and ground granulated blast furnace slag (ggbfs) as a cement replacement, as shown in *Table* 3.7.

Table 3.7: Mixes used in the project [6]

Description	OPC+ggbfs	OPC/ggbfs	28 day cube strength
C25 Class 2	375 kg/m^3	30/70	36.0 N/mm^2
C35	385kg/m^3	50/50	46.0 N/mm^2

The high proportion of ggbfs used in the C25 concrete was required in order to provide maximum chemical resistance whereas only 50% ggbfs was included in the C35 concrete to improve resistance to CO_2 penetration.

A site laboratory was used to test frequently aggregates and concrete. The aggregate results show a mean water absorption of 5%. The drying shrinkage of concrete remained within the requirements of the job specification.

Overall it was concluded that the problems identified during this project were not technical but logistical, the main problem being to find sufficient quantities of recycled aggregate at convenient locations. Finally, the study concluded that there is a clear need for market development before the use of recycled concrete aggregate can be considered as a widely used material in concrete construction.

3.6 British and European Provisions for Recycled Aggregates

In the European Union the move towards the normalisation of standards and specifications between European member states commenced in the 1980's. At the same time research backing up the use of recycled aggregates as suitable for use in concrete started becoming even more convincing and as a result provisions in national standards was made. The first of the member states to introduce these provisions were Denmark and the Netherlands as discussed in earlier sections.

The normalisation mainly took place using existing established standards rather than introducing new aspects such as provision of recycled aggregates. Two of the most important concrete related standards now common in the EU are BSEN 206 [10] providing guidance on specification. production and conformity of concrete and BSEN 12620 [9] covering guidance on aggregates for concrete. Having said that, neither directly provides guidance for recycled aggregates for concrete. *Figure 3.2* illustrates the current standing of recycled aggregates in the EU.

According to BSEN 206 Part 1 cl. 5.1.1 and note 1, use of recycled aggregates in concrete, not originating from natural resources but from C&D debris material previously used in construction, is permitted according to provisions of established national standards. In the UK the newly introduced BS 8500 covers provisions for recycled aggregates from sources other than natural. The standard classifies recycled aggregates as "recycled concrete aggregate" (RCA) and "recycled aggregate" (RA) based on strict limitations of the content of the constituent materials.

RCA will mainly consist of recycled concrete at a minimum of 82.5% while other materials such as masonry, fines and asphalt can be present but limited to 5%. Lightweight material[1] should be limited to 0.5% and the acid soluble sulphate content (SO_3) limited to 1%. Other materials are limited to 1% collectively and can include wood, glass, metal etc.

RA can include up to 100% masonry, up to 3% fines, and a maximum of 10% asphalt while other foreign and lightweight materials as well as acid soluble sulphate contents are limited to 1%. The presence of natural aggregate and crushed concrete is obviously not limited. Having stated these requirements, the guidance also allows the use of material obtained by crushing hardened concrete of known composition and which was not contaminated during its service life. In this case the only requirements are those for grading and maximum fines content.

Once the class of the recycled aggregate (RCA or RA) has been established, further limitations exist on their uses in concrete production. These include restrictions in strength class as well as exposure conditions and their severity. Coarse RCA ($D \not> 20mm$) can be included into concrete with maximum characteristic strength of C40/50 ($f_{ck,cyl}/f_{ck,cube}$) such as concretes from the RC and PAV series of designated

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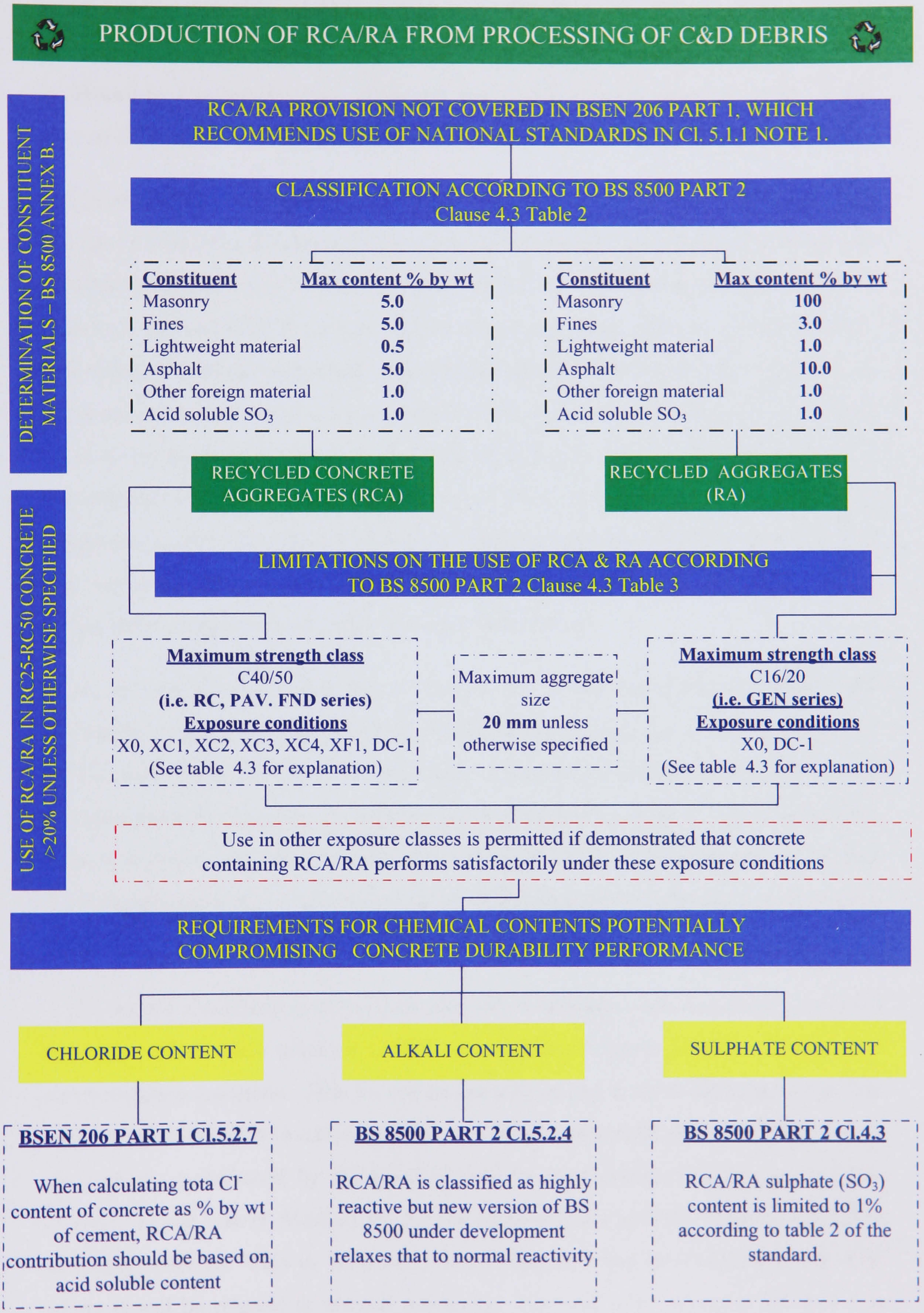
[1] Material with a density less than 1.000 kg/m^3



Constituent	**Max content % by wt**
Masonry	**5.0**
Fines	**5.0**
Lightweight material	**0.5**
Asphalt	**5.0**
Other foreign material	**1.0**
Acid soluble SO_3	**1.0**

Constituent	**Max content % by wt**
Masonry	**100**
Fines	**3.0**
Lightweight material	**1.0**
Asphalt	**10.0**
Other foreign material	**1.0**
Acid soluble SO_3	**1.0**

Maximum strength class
C40/50
(i.e. RC, PAV. FND series)
Exposure conditions
X0, XC1, XC2, XC3, XC4, XF1, DC-1
(See table 4.3 for explanation)

Maximum aggregate size
20 mm unless otherwise specified

Maximum strength class
C16/20
(i.e. GEN series)
Exposure conditions
X0, DC-1
(See table 4.3 for explanation)

Use in other exposure classes is permitted if demonstrated that concrete containing RCA/RA performs satisfactorily under these exposure conditions

BSEN 206 PART 1 Cl.5.2.7

When calculating tota Cl^- content of concrete as % by wt of cement, RCA/RA contribution should be based on acid soluble content

BS 8500 PART 2 Cl.5.2.4

RCA/RA is classified as highly reactive but new version of BS 8500 under development relaxes that to normal reactivity

BS 8500 PART 2 Cl.4.3

RCA/RA sulphate (SO_3) content is limited to 1% according to table 2 of the standard.

Figure 3.2: RCA/RA provisions in UK and the EU.

mixes used in this study. Although the use is allowed, currently a maximum of 20% of natural coarse aggregate can be replaced by RCA in RC25 and RC50 unless more is allowed by the specification. Although restrictions to strength class apply, in the case of RCA derived from uncontaminated crushed concrete, no restrictions apply.

Restrictions to the exposure conditions (see table 4.3 for class descriptions) limit the use of concrete containing RCA to environments where there is no risk for reinforcement corrosion and to all exposures related to carbonation induced corrosion. However, the use of RCA concrete is not permitted where there is any risk of chloride induced corrosion including both sea and non-sea water. Use where freeze-thaw exposure is possible is not recommended by the code except for the mildest of conditions where no de-icing salts are used and moderate water saturation occurs. RCA concrete can also be used in designed concrete but only in the lower class DC-1. A relaxation to the rule exists if it can be demonstrated that RCA concrete is suitable for other exposure conditions, i.e. if concrete performs satisfactorily under a freeze-thaw exposure class higher than the XF1 limit.

In the case of coarse RA ($D \not> 20mm$) use of this aggregate is allowed only in concrete with maximum strength of C16/20 ($f_{ck,cyl}/f_{ck,cube}$). This includes the GEN series of concrete used in this study. Concrete containing coarse RA is only recommended for applications exposed to environments posing no risk to reinforcement corrosion (X0) and in design concrete class DC-1. If it is demonstrated that RA concrete performs satisfactorily under other exposure conditions then it may be used.

To ensure durability performance and avoid damage such as chloride induced corrosion, alkali silica reaction (ASR) and sulphate related damage the standard provides some guidance. This is, not necessarily in the form of limiting values but rather as a set of rules to follow in order to minimise potential damage. The chloride ion content contributed by RCA/RA should be that detected in the acid soluble content. In the case of Alkalis (Na, K) the requirements currently classify RCA/RA as highly reactive. This is, however, due to change in the new version of BS 8500 where it will be relaxed to normal reactivity. The sulphate content of RCA/RA is limited to 1% as mentioned earlier based on the SO_3 acid soluble content. If SO_4 is require its content can be obtained by multiplying SO_3 value by 1.2.

CHAPTER 4

RESEARCH PROGRAMME

4.1 INTRODUCTION

In order to achieve the objectives of this study, an extensive research and development program was devised. This chapter outlines the experimental programme undertaken to assess the suitability of coarse RCA for use in a range of BS 8500 designated mixes.

The chapter is divided into two main sections briefly outlined below, namely, research programme and detailed experimental programme. In the first section, work carried out during the different phases of the project is briefly described , whilst the second section details experimental procedures covering materials used, concrete mix proportions, development of the standards , assessment of key fresh and hardened properties of concrete finally, leading to the identification of practical issues due to the use of RCA in new concrete production.

4.2 SECTION 1: RESEARCH PROGRAMME

The research program devised is shown schematically in *Figures* 4.1 and 4.2. It consists of five main phases as described below. Information on tests carried out under the different phases and the number of specimens tested are included in the appendices.

4.2.1 Phase 1: Production and Characterisation

During phase 1, demolition debris from a number of construction sites within the Greater London area was obtained and transferred to the DAY Aggregates recycling plant at Greenwich in London to produce recycled aggregate (RCA, RA). The main stages of debris processing at the plant are shown in *figure 4.3.* This newly designed plant had been commissioned specifically to produce quality recycled aggregate and, throughout this study, graded coarse RCA 20-5 mm was produced which met the requirements of relevant standards such as BS 882 [26], and EN 12620 [9]. Debris mainly originated from reinforced concrete frame structures but included bricks, plaster, reinforcement etc.

Initially tests to determine a range of physical and mechanical characteristics were undertaken as well as a complete chemical-mineralogical analysis to assess recycled aggregate conformity for use as aggregate in new concrete mixes. Testing was undertaken following methods described in the appropriate British standards and European normatives where possible.

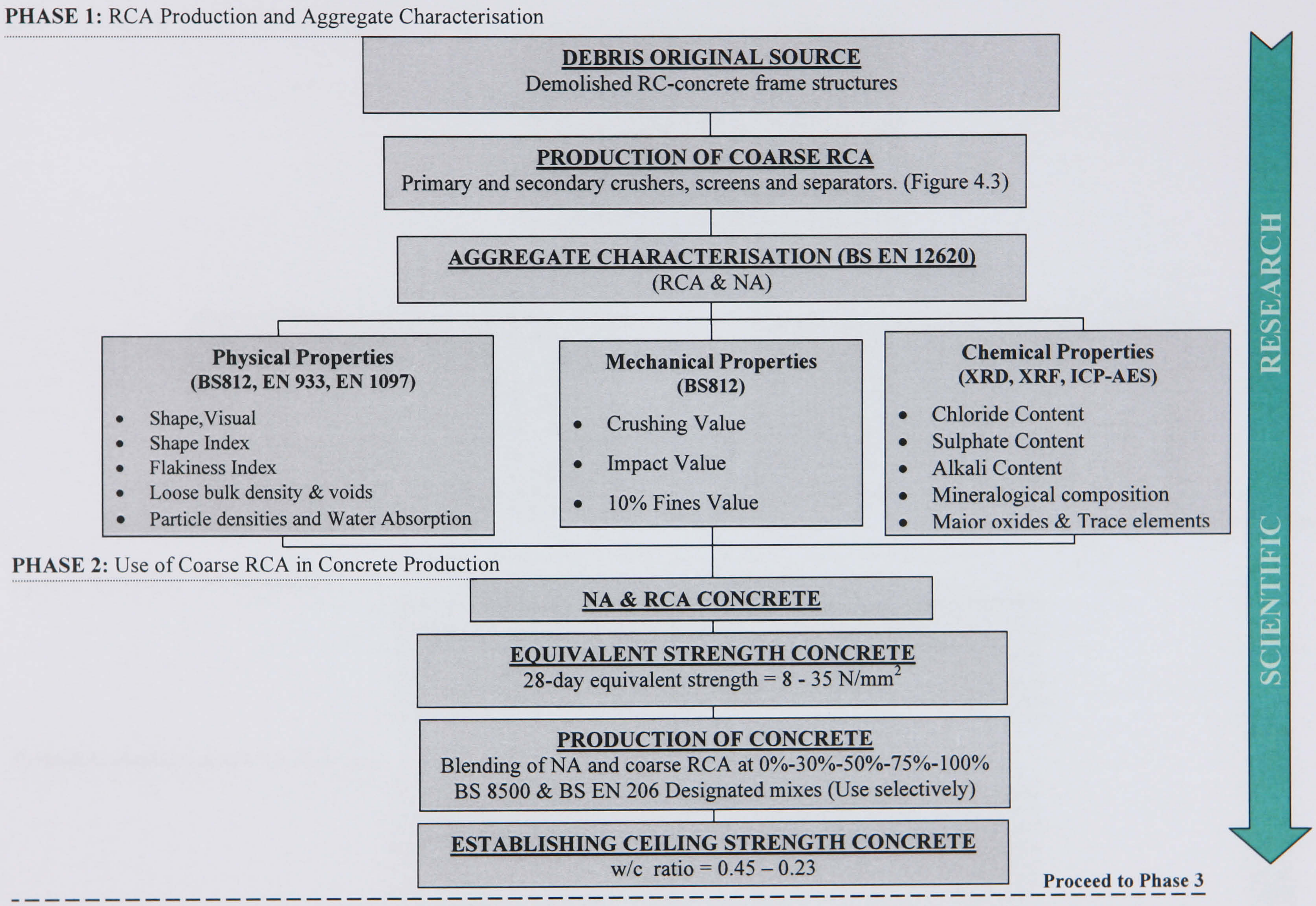


Figure 4.1: Research programme overview: Phases 1 to 2

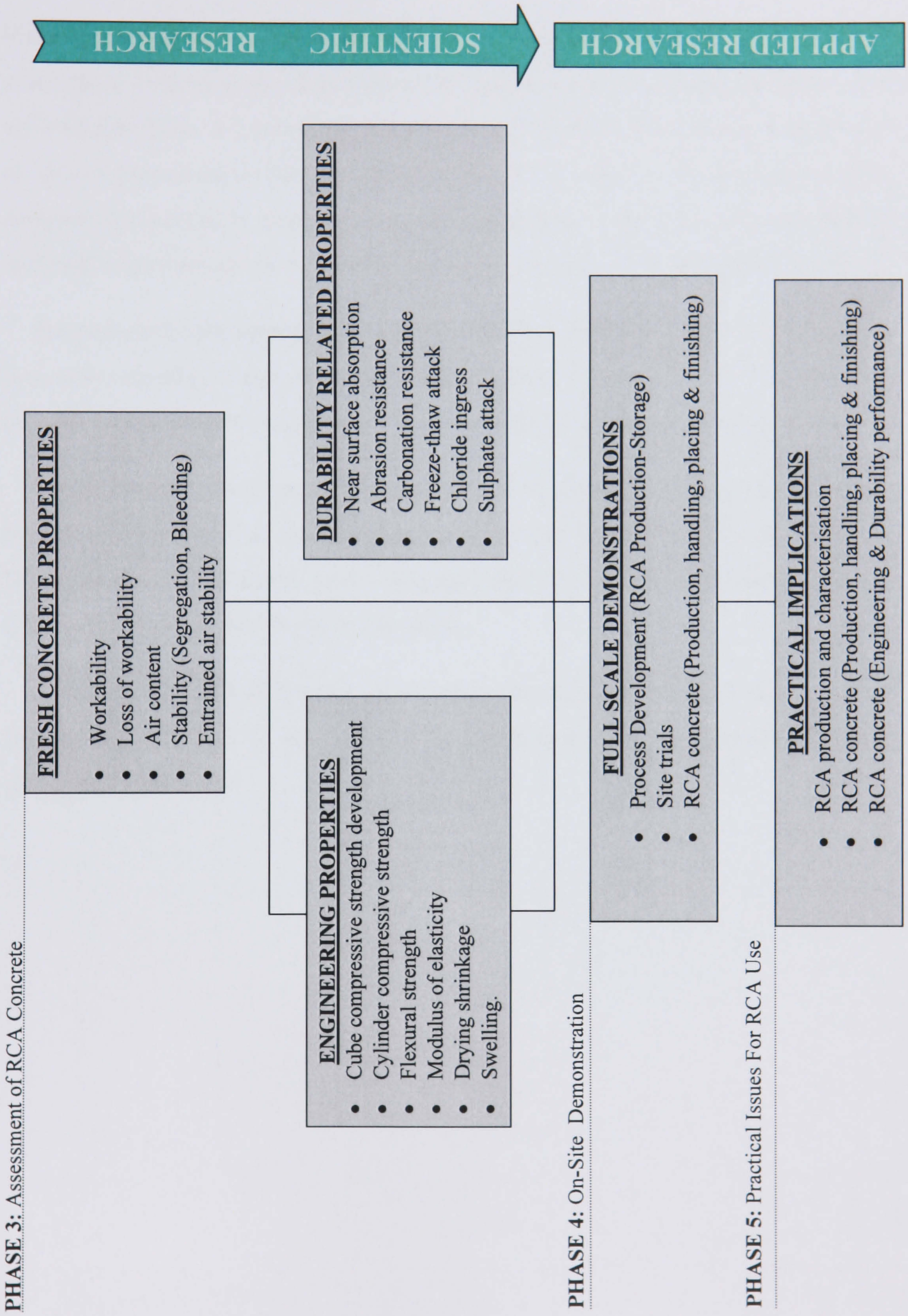


Figure 4.2: Research programme overview: Phases 3 to 5

4.2.2 Phase 2: Use of Coarse RCA in Concrete Production

Phase 2 was designed to assess the suitability of coarse RCA for use in new concrete production. Following the characterisation, aggregates were classified as RCA or RA according to *figure 3.2 paragraph 3.6*. As a first step, RCA was selected and blended at various proportions with NA (0% to 100%). Then based on results from previous research [2] reviewed in *paragraph 3.2.3.4*, adjustments to the w/c ratio were applied and trial mixes produced in order to verify the validity of the adjustment method.

Once the w/c ratio adjustment was validated, the RCA/NA blend was introduced into new concrete, designed for equivalent 28-day strength, in order to assess its influence on fresh and engineering properties and durability performance

Phase 2 was concluded with the assessment of the influence of coarse RCA content on ceiling (optimum w/c ratio) strength of concrete. The study involved producing RCA/NA concrete with w/c ratios ranging from 0.40 – 0.26 in addition to the range 0.55 – 1.03 covered elsewhere in this study.

A range of BS 8500 designated mixes were selected for testing in this investigation summarised in *Table* 4.1 which also gives applications and characteristic strengths of the selected mixes.

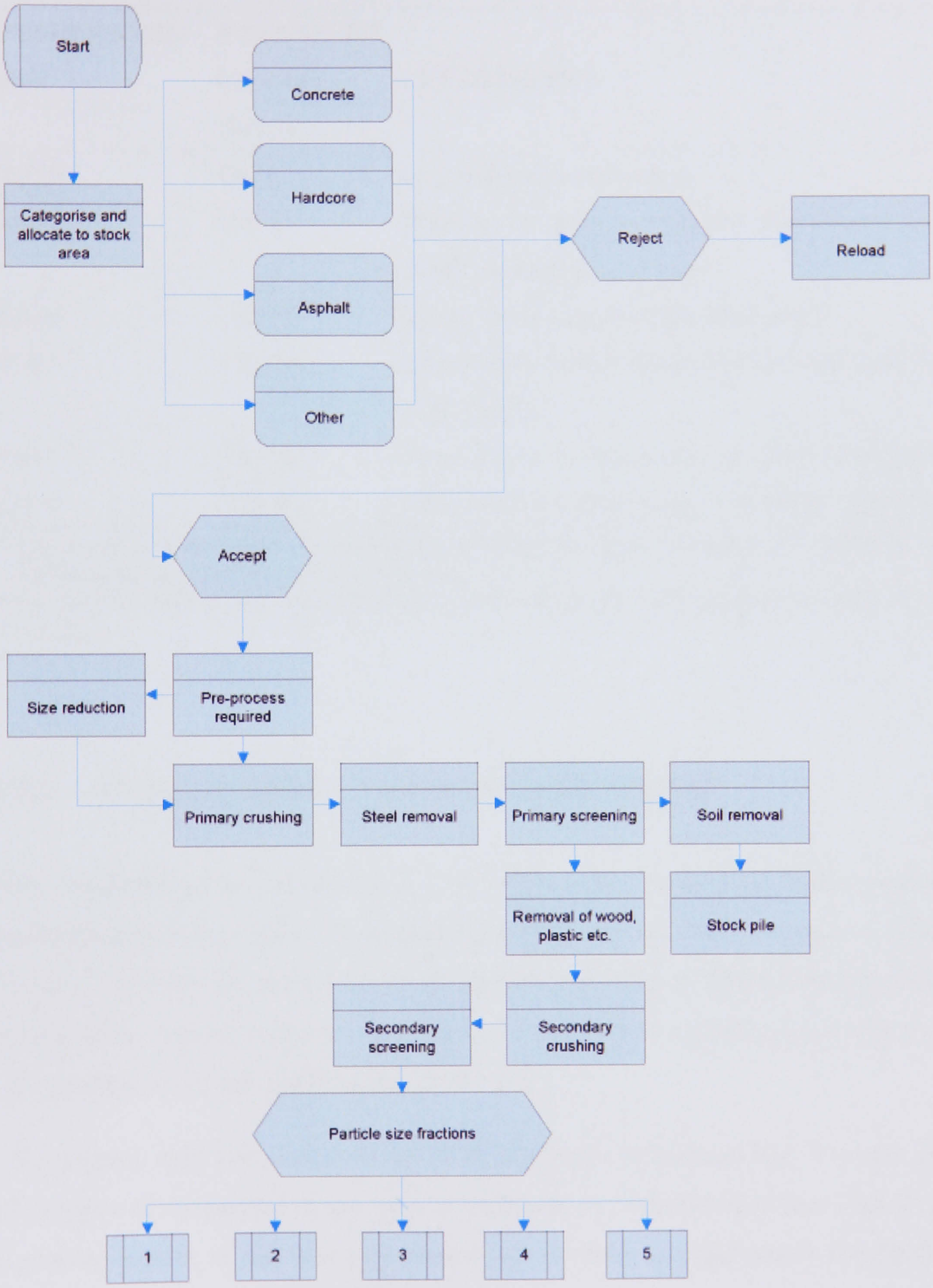


Figure 4.3: Recycling Plant processing flow chart at DAY Group Ltd.

Table 4.1: BS 8500 designated mixes and relevant applications [7]

DESIGNATED MIX	STRENGTH CLASS[♮] N/mm^2	APPLICATION
GEN0	C6/8	Kerb bedding and backing
GEN1	C8/10	Blinding and mass concrete fill, mass concrete & trench foundations, drainage.
GEN3	C16/20	Garage floors with no embedded metal
RC30	C25/30	Fully buried reinforced foundations, light foot & trolley traffic
PAV1 [†]	C25/30	House drives, domestic parking and external paving
PAV2 [†]	C28/30	Heavy-duty external paving with rubber tyre vehicles [‡]

[†] The concrete shall contain an air-entraining admixture to give a minimum air-content by volume of 3.5% according to Table A.14 of BS 8500 [8].

[‡] For extreme applications, e.g.foundry floors and busy public roads, specialist advice is required.

[♮] f_{cyl}/f_{cube}

4.2.3 Phase 3: RCA Concrete Performance

After establishing the required w/c ratio adjustment, equivalent 28-day strength concrete mixes were produced to establish the fresh and hardened properties of RCA concrete. All concrete mixes were proportioned according to BS 8500 requirements, for minimum cement contents, maximum w/c ratio and suitable exposures (*table 4.3*) appropriate to the application (*Table* 4.2).

To achieve this, the conventional BRE/DOE mix design method [74] was used and a series of designated mixes were established. An additional adjustment to the free water content of the mix was carried out in order to compensate the 24 hour water absorption, WA_{24} of the RCA.

The performance of equivalent strength concrete was assessed in terms of its fresh, engineering and durability related performance. Designated mixes were selected for testing according to their functional requirement, application and relevance to the assessed properties. Fresh properties included: (i) workability, (ii) loss of workability over time, (iii) Air content, (iv) stability ie. segregation, bleeding and,(v) entrained air-stability. Engineering properties included: (i) cube/cylinder compressive strength, (ii) flexural strength, (iii) static modulus of elasticity and, (iv) drying shrinkage and swelling. From the point of view of durability related performance the properties assessed included: (i) near surface absorption, (ii) abrasion resistance, (iii) resistance to carbonation, (iv) chloride ingress, (v) sulphate attack and (vi) freeze-thaw resistance. Full details of testing are given in *section* 4.3.

Table 4.2: BS 8500 Designated mixes selected and requirements for exposure conditions

DESIGNATED MIX	**SUITABLE EXPOSURE** (*see Table 4.3*)		**MINIMUM CEMENT CONTENT** (kg)	**MAXIMUM W/C RATIO**
	Un-reinforced	Reinforced[‡]		
GEN0	-	-	120	-
GEN1	-	-	180	-
GEN3	-	-	220	-
RC30	X0	XC2, XD2, XF3	320	0.55
PAV1 [†]	X0,XF1-XF3	XC2, XD2, XF3	320	0.55
PAV2 [†]	X0,XF1-XF4	XC3&4, XD3, XF4	340	0.50

[†] The concrete shall contain an air-entraining admixture to give a minimum air-content by volume of 3.5%

[‡] Reinforcement cover to comply with requirements of Tables A.11, A12 and A.14 of BS8500-1 [8].

Table 4.3: BS 8500 exposure classes and descriptions

No risk of corrosion	
X0	Concrete without reinforcement or embedded metal: all exposures except where there is freeze/thaw, abrasion or chemical attack. Concrete with reinforcement or embedded metal: very dry
Corrosion induced by chlorides other than from sea water[†]	
XD1	Moderate humidity
XD2	Wet, rarely dry
XD3	Cyclic wet and dry
Corrosion induced by chlorides from sea water[†]	
XS1	Exposed to airborne salt but not in direct contact with sea water
XS2	Permanently submerged
XS3	Tidal, splash and spray zones
Corrosion induced by carbonation[†]	
XC1	Dry or permanently wet
XC2	Wet, rarely dry
XC3-XC4	Moderate humidity or cyclic wet and dry
Freeze-/thaw attack	
XF1	Moderate water saturation without de-icing agent
XF2	Moderate water saturation with de-icing agent
XF3	High water saturation without de-icing agent
XF4	High water saturation with de-icing agent or sea water[‡]
Chemical attack (Design Sulphate class)	
DS1	Groundwater $SO_4 < 0.4g/l$

[†] The moisture condition relates to that in the concrete cover to reinforcement or other embedded metal but, in many cases, conditions in the concrete cover can be taken as being that of the surrounding environment. This might not be the case if there is a barrier between the concrete and its environment.

[‡] It is not normally necessary to classify in the XF4 exposure class those parts of structures located in the United Kingdom which are in frequent contact with the sea.

4.2.4 Phase 4: On-site Demonstrations

Having established the performance of RCA concrete in the fresh and hardened state through laboratory investigations (Phases 1-3), phase 4 examined the suitability of using RCA concrete commercially through the application of research findings. Verification of research findings was achieved through site demonstrations in real conditions at a DAY aggregates LTD production plant where quality RCA was produced using C&D debris delivered, to the company.

Following the production of recycled aggregates, site trials took place in the form of pavement construction. For these trials predefined strips of pavement were constructed using concrete containing 100% coarse RCA. However, the location chosen for the initial trials was not regularly used by heavy duty traffic although during the trial the performance of concrete was assessed both on site and in the laboratory by testing specimens taken on site. Visits at regular intervals for the assessment of performance took place during the year after construction.

Having established positive outcomes from the initial site trials it was decided to carry out a full scale demonstration involving the construction of heavy duty pavements, this time located at the heart of activity of the DAY aggregates Greenwich production plant, so subjecting the product to heavy duty traffic and equipment.

Through these demonstrations, the production of RCA concrete, its handling, placing and finishing were assessed. Post construction assessments involving site visits and sample laboratory testing took place for a year after construction in order to establish performance.

4.2.5 Phase 5: Practical Implications

The purpose of this final phase of the research program was to emphasize the practical implications resulting from the findings of the previous phases of the study and to introduce simple guidance on the use of RCA as coarse aggregate in construction.

4.3 SECTION 2: EXPERIMENTAL DETAILS

4.3.1 Introduction

This section briefly describes the materials used and test procedures employed for the purposes of the research programme. Procedures employed follow current and/or developing standards, mainly British Standards(BS) and European Normatives(EN).

4.3.2 Materials

4.3.2.1 Portland cement (PC)

The cement used was **Portland cement EN 197-1 - CEM I 42,5 N**, conforming to the requirements of BSEN 197 [75]. Storage in air-tight containers ensured minimum exposure to humidity, and it was purchased in the quantities required, avoiding long storage times and minimising strength loss. The details of chemical and physical properties including particle size distribution of the PC are shown in *Table 4.4*.

Table 4.4: Chemical and Physical Properties of PC used in the study

CHEMICAL COMPOSITION	THIS STUDY (%)	TYPICAL VALUES [a](%)	USUAL LIMITS (%)
SiO_2	20.60	20	17-25
Al_2O_3	5.47	6	3-8
Fe_2O_3	3.31	3	0.5-6
CaO	62.50	63	60-67
MgO	2.26	< 5.0	0.5-4.0
SO_3	2.40	< 3.5	2.5-3.5
K_2O	1.71	1	
Na_2O	0.65	1	0.3-1.2
Na_2O_{eq} .	0.6 declared		0.4-0.75
C_3S	49.49	54.1	45.0-60.0
C_2S	21.73	16.6	15.0-25.0
C_3A	8.89	10.8	7.0-12.0
C_4AF	10.07	9.1	6.0-10.0
Physical properties			
Specific surface (m^2/kg)	-	-	290-420
Initial setting time (min)	-	-	80-200
Mortar prism compressive strength test results (BSEN 196 Part 1) (N/mm^2)			
2-day = (22-24) 7-day = (36-41) 28 day= (54-57)			

[a] Neville A. M. Properties of concrete. Page 11 Table 1.3 [11]

Typical particle size distribution														
μm	87	54	38	28	22	17	13	10	8	6	5	4	3	2
% passing	90	80	66	54	43	34	27	21	17	12	8	5	3	2

4.3.2.2 Aggregates

Graded natural sand with a maximum particle size of 5 mm was used throughout this study as fine aggregate in concrete production. The coarse aggregates used were un-crushed Thames valley, and 20 – 5 mm graded recycled aggregates.

Recycled aggregates were produced using construction and demolition debris obtained from various sites within Greater London. In essence C&D debris derived from RC-structures built some 30 years ago. The composition and properties of the original concrete were not known but it can be assumed that 28-day strength ranged between 10 and 50 N/mm^2. This lack of knowledge represents a real life situation, in which it is not possible to identify the composition of debris delivered to recycling plants from various sites.

RCA was produced using a custom made recycling plant located at the DAY Aggregates Greenwich production plant. The recycling plant consisted of a primary jaw and secondary cone crushers, electromagnets for removal of reinforcement and other metals, blowers for air-separation of lightweight materials and a series of screens to achieve the required particle size distribution. Detailed production stages and key sequences of this recycling plant are shown schematically in *Figure* 4.3.

4.3.2.3 Water

In concrete production standard tap water, was used. For the purposes of tests such as the initial surface absorption, freeze thaw resistance, soluble chloride content and calibration of apparatus, de-ionised water was used.

4.3.2.4 Admixtures

Air-entrainment. Darex AE3, air entraining agent based on the salt of an ether sulphate was used. It has a pale yellow color and is supplied in liquid form. According to the manufacturers data, Darex AE3 conforms to the requirements of BS 5075 [76] replaced by BSEN 934 Parts 2 and 6 [77] and BSEN 480 [78]. A copy of the data sheet is included in Appendix G.

Superplasticiser. Darex SP1, superplasticiser based on the soluble salt of a polymeric naphthalene sulphonate was used. It has a brown color and is supplied in liquid form. Darex SP1 conforms to the requirements of BS 5075 [76] replaced by BS EN 934 Parts 2 and 6 [77] and BSEN 480 [78]. A copy of the data sheet is included in Appendix G.

4.3.3 Mix Proportions

4.3.3.1 Concrete Mix Design

As mentioned earlier, initially NA concrete mix proportions were established following steps described in the conventional BRE/DOE method for concrete mix design [74]. Using RCA concrete, proportions were established by using a blend of natural sand, Thames Valley gravel and up to 100% coarse RCA. The mixes were developed to replicate BS 8500 GEN, RC,and PAV series of designated mixes for various applications with characteristic strengths ranging between 8 and 35 N/mm^2. In RCA concrete production, 30%, 50%, 75% and 100% of coarse RCA was used as a direct replacement for coarse NA.

For NA concrete, proportions of the constituents were established based on the cumulative percentage of fine aggregate passing the 600 μm sieve obtained from the particle size distribution test and the density of the aggregates. NA concrete mix proportions together with slump class and admixtures, are given in *Table* 4.5. In the case of RCA concrete, Thames Valley gravel was replaced by coarse RCA and proportions calculated taking its properties and characteristics into account, (*Table 4.6*).

Concrete mixes were proportioned to meet the requirements of BS 8500 designated mixes as stated in *Table 4.2*, for maximum w/c ratio and minimum cement content. All mixes were designed for either slump class S1(10-40mm) or S2 (50-90mm) relevant to the designated applications.

The PAV series of mixes were produced using an air entraining admixture, following standard requirement for PAV series mixes. According to BS 8500 the PAV series of mixes are required to have a minimum air content of 3.5% at delivery. Through trial mixes the required amount of air entraining admixture was established.

Throughout this study and based on the densities of coarse and fine aggregates the proportions were adjusted slightly to maintain the yield. Figures *4.4 b) and c)* graphically represent the fine tuning required in aggregate quantities. In the case of air-entrained concrete (PAV mixes), entrainment was considered to be part of the fine aggregates and adjustments were made only in aggregate content.

4.3.3.2 Equivalent strength concrete

Initially, a series of trial mixes were produced following the methods described by Limbachiya et al. [2]. A series of correction factors to w/c ratio were established in order to compensate for any compressive strength loss in RCA concrete. These adjusted mixes were then verified through further trial mixes during Phase 2 of the research programme. In order to achieve equivalent strength concrete, the w/c ratio was adjusted only for mixes containing coarse RCA in excess of 30% (Figure 4.4 a). The adjustment factors used to achieve equivalent 28-day strength RCA concrete are given in *Table 4.6*. These are in line to those recorded previously by Limbachiya et al. [2].

Following laboratory testing it was concluded that the adjustment can be applied either by increasing the cement content or by reducing the water content of the mix. It is important to note that in the latter case superplasticiser admixture is required in order to maintain the workability of the mix. In this study the w/c ratio was always adjusted by increasing the cement content but coarse and fine aggregate contents were slightly adjusted to maintain the yield. Total water content was decided by taking into account the aggregate water absorption characteristics at 1 hour and therefore adding the water absorption to the calculated free water content.

Table 4.5: Mix proportions for NA reference concrete [8].

DESIGNATED MIX	MIX PROPORTIONS (kg/m^3)				w/c	AEA ml/100kg of cement	Slump class (mm)
	PC	Water	Aggregates				
			Coarse	Fine			
GEN0	180	185	1140	835	1.03	-	S3(120)
GEN1	195	185	1160	800	0.95	-	S2(75)
GEN3	270	180	1250	650	0.67	-	S2(75)
RC30	335	185	1205	615	0.55	-	S2(75)
PAV1†	345	165	1285	475	0.55	360	S2(55)
PAV2†	385	165	1250	480	0.50	360	S2(60)

† The concrete shall contain an air-entraining admixture to give a minimum air-content by volume of 3.5% according to Table A.14 of BS 8500 [8].

Table 4.6: Mix proportions for equivalent strength RCA concrete used for the study.

Coarse RCA content (%)	**w/c correction factor**	**AGGREGATE PROPORTIONS (kg/m^3)**								
		Designated mixes								
		GEN0			**GEN1**			**GEN3**		
		Coarse		**Fine**	**Coarse**		**Fine**	**Coarse**		**Fine**
		RCA	**NA**	**NA**	**RCA**	**NA**	**NA**	**RCA**	**NA**	**NA**
30	1	340	780	835	350	810	800	375	875	650
50	0.975	573	572	815	583	582	790	625	625	640
75	0.95	865	290	810	880	290	775	940	310	635
100	0.93	1160	0	800	1175	0	770	1250	0	630

Coarse RCA content (%)	**w/c correction factor**	**AGGREGATE PROPORTIONS (kg/m^3)**								
		Designated mixes								
		RC30			**PAV1**†			**PAV2**†		
		Coarse		**Fine**	**Coarse**		**Fine**	**Coarse**		**Fine**
		RCA	**NA**	**NA**	**RCA**	**NA**	**NA**	**RCA**	**NA**	**NA**
30	1	360	845	615	385	900	505	375	875	480
50	0.975	605	605	610	635	635	495	625	630	475
75	0.95	900	300	595	950	315	490	930	310	470
100	0.93	1200	0	585	1260	0	485	1235	0	465

† Air-entrained mixes have a min of 3.5% air content.

4.3.3.3 Ceiling strength (optimum w/c ratio) of RCA concrete mixes

Following the successful use of RCA in normal strength concrete mixes an additional study was undertaken to assess the use of coarse RCA in high strength concrete. For this purpose a series of concrete mixes with w/c ratios ranging from 0.40 to 0.26 were prepared and standard 100 mm cube specimens were cast to establish the effect of coarse RCA on the optimum w/c ratio of concrete. Concrete mixes were designed with a maximum w/c ratio of 0.4 followed by increases in cement content by 40 kg/m^3 steps until the w/c ratio reached 0.26. The water content was maintained

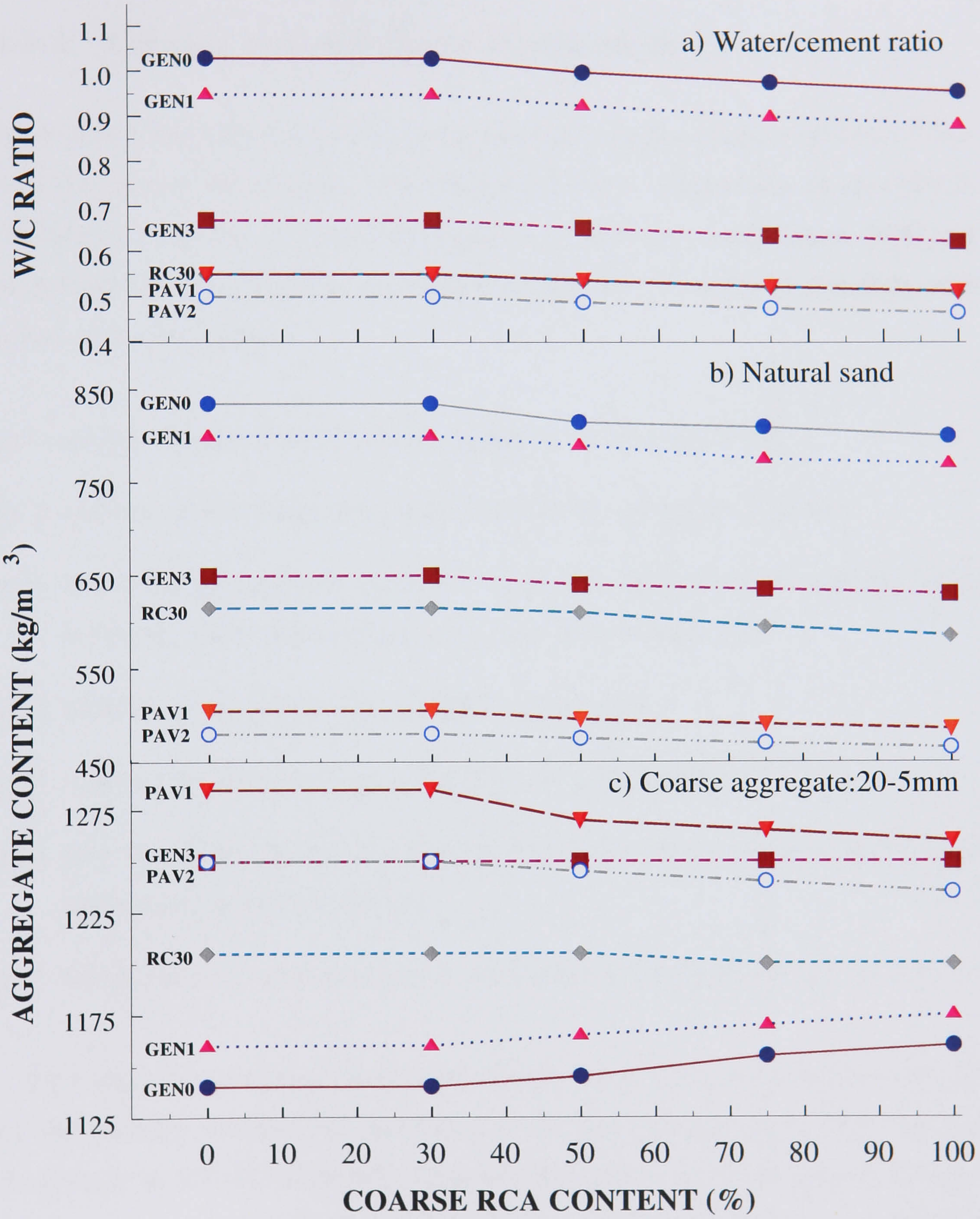


Figure 4.4: Mix proportions plotted for NA and RCA mixes used in the study

at 185 kg/m^3 throughout the study. The use of superplasticiser was necessary to maintain the required workability for mixes with w/c ratios below 0.33.

4.3.4 Casting and Specimen Preparation

A horizontal WinGET Crocker type concrete mixer, with a capacity of 0.05 m^3 was used throughout the research. The mixing procedure adopted was as specified in BS 1881 Part 125 [79]. Aggregates were stored in laboratory conditions at $20°C$ and 35-55% RH prior to their use in concrete production. Constituent materials were mixed as outlined below:

Stage 1: mixing of batch coarse and fine aggregate for 30 seconds

Stage 2: addition of half of the total water and further mixing for 1 minute

Stage 3: mix left standing for 8 minutes to allow aggregate water absorption during which the mixer was kept covered to minimise evaporation.

Stage 4: addition of the cement and mixing for 30 seconds

Stage 5: cleaning of adhered cement paste from the paddles from

Stage 6: addition of the remaining half of the water with admixtures if applicable and further mixing for 2.5 minutes

Stage 7: finally concrete hand mixed to ensure uniformity, before casting of specimens.

On completion of mixing, fresh concrete mixes were tested to establish workability and stability followed by the casting of the test specimens using steel moulds conforming to BS EN 12390 [80]. Concrete was placed in to the moulds in three equal layers and each layer was compacted using a vibrating table until sufficient compaction was achieved. Care was taken to avoid over-compaction and consequent segregation of the constituents. Specimens were then covered using wet hessian and polythene sheets for 24 hours and then de-moulded, coded and transferred to the appropriate curing regimes.

4.3.4.1 Curing regimes selected

Different curing regimes were adopted according to BSEN 12390 Part 2 [81] depending on the test method and simulated environment required by the method. The curing regime included standard 20 ± 2^oC water or the equivalent environmentaly controlled room at 20 ± 2^oC and 95% RH. All different curing regimes used are described and given against the appropriate test in *Table 4.7*.

Table 4.7: Pre-curing and curing regimes applied in engineering and durability tests.

CODE	CURING METHOD	TEST
CU1	under water 20^oC ($\pm 2^oC$)	Compressive strength, flexural strength, modulus of elasticity, swelling, near surface absorption, chloride diffusion, carbonation.
CU2	Air 20^oC ($\pm 2^oC$),55%RH	Drying shrinkage
CU3	28-days CU1, then 14-days CU2	Carbonation penetration
CU4	25 days CU1, then 2 days CU2	Sulphate attack
CU5	Chamber:20^oC ($\pm 2^oC$),65 ±5%RH	Freeze-thaw
CU6	7-days CU1, then 14-days in CU5	Freeze-thaw
CU7	Chamber:20^oC ($\pm 2^oC$),95±5%RH	Abrasion
CU8	28-days CU7, then 21-days CU2	Abrasion

4.3.5 Aggregate Characterisation Procedures

To assess the suitability of aggregate used in the research a range of physical, mechanical and chemical properties of NA and RCA were tested using current as well as newly developed standards published by the BS and CEN authorities. However, in some specific tests, established methods designed and developed at Kingston University, were also employed as an alternative aiming to produce more accurate results or fill gaps in case of lack of existing guidance. These included accelerated carbonation, X-ray diffraction, ICP-AES analysis etc.

4.3.5.1 Physical Characteristics of Aggregates

All aggregate samples were prepared using the riffle box and the quartering methods as described in EN 932 Part 1 [82] followed by separation to representative portions as required.

Particle Size Distribution - The purpose of this test was to determine the grading of coarse and fine aggregates and based on findings establish their suitability for use in concrete production.

Grading was determined using a set of sieves assembled in a column format as shown in *Figure 4.5.* Test sieves used during the study conformed to the requirements as specified in EN 933-2 [83] (replacing BS882 [26]), and comply to ISO 3310-2 and ISO 3310-1. Particle size distribution (grading) was determined as the cumulative percentage passing by weight through the sieves as described in EN 933 Part 1 [3]. Limits for these percentages are given in EN 12620 [9] and presented in *Table 5.2.*

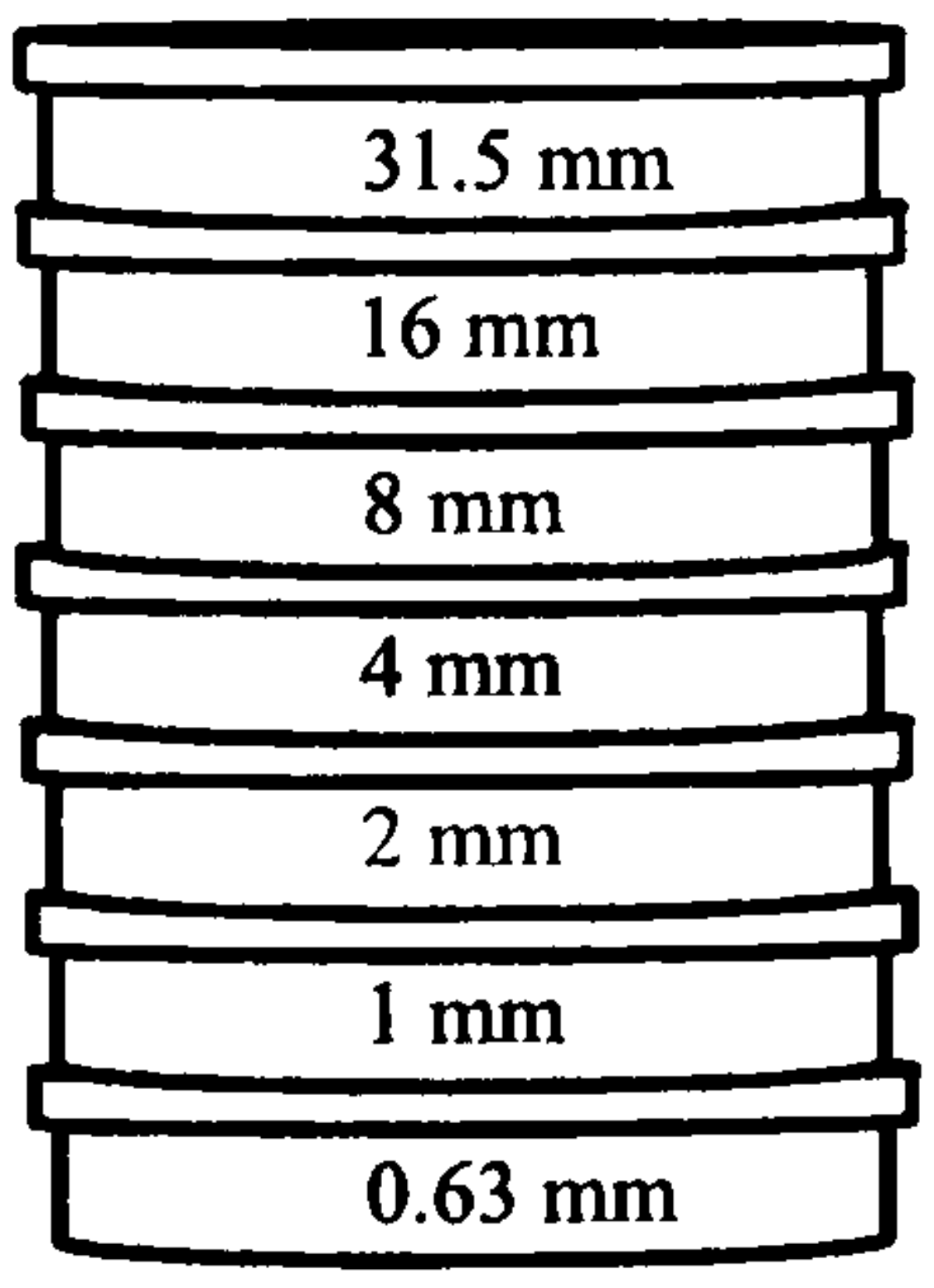


Figure 4.5: EN 933 size sieves assembled in column format

A typical example of coarse aggregate conforming to the requirements is shown in *Figure 4.6.* A detailed discussion on these findings and their practical implications is given in the chapter 5.

Particle density and water absorption - Following the method described in EN 1097-6 [84], particle densities and water absorptions of both natural and recycled aggregate were determined. Testing involved assessment of three samples each soaked in 20°C water for 24 hours then surface dried and finally oven dried. The masses of the samples at each state were measured and the apparent ρ_a, oven

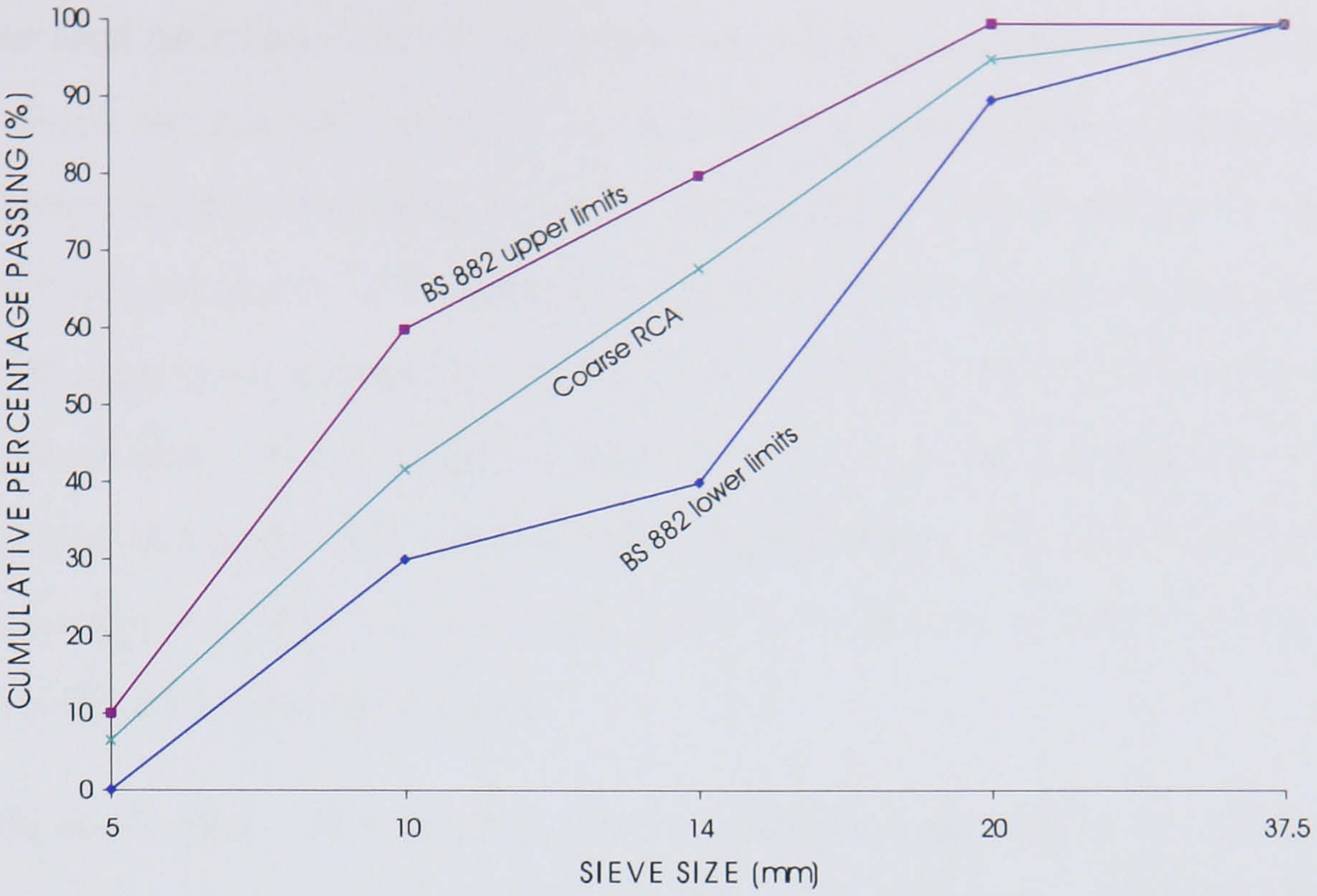


Figure 4.6: Typical results for particle size distribution of coarse aggregate.

dried ρ_{rd}, and surface saturated dry ρ_{ssd} particle densities, as well as 24 hour water absorption WA_{24} were calculated using standard *Equations 4.1 to 4.4*. This method was suitable for coarse aggregate with particles between 4 mm – 31.5 mm and fine aggregate with particles between 0.063 mm – 4 mm.

$$Apparent\ density: \quad \rho_a = \frac{M_4}{M_4-(M_2-M_3)} \tag{4.1}$$

$$Oven-dried\ density: \quad \rho_{rd} = \frac{M_4}{M_1-(M_2-M_3)} \tag{4.2}$$

$$Saturated\ surface-dry\ density: \quad \rho_{ssd} = \frac{M_1}{M_1-(M_2-M_3)} \tag{4.3}$$

$$24hrWater\ absorption: \quad WA_{24} = \frac{100(M_1-M_4)}{M_4} \tag{4.4}$$

Where:

- M_1 is the mass of the saturated and surface dried aggregate in the air, in grams;
- M_2 is the mass of the basket containing the sample of saturated aggregate, in grams;
- M_3 is the mass of the empty container, in grams;
- M_4 is the mass of the oven-dried test portion in air, in grams.

Shape and texture - By visual inspection, aggregates were classified according to their shape as rounded, irregular, elongated or flaky and elongated particles and their texture as smooth, glassy, granular and rough. The classification was based on BS 812 [85] guidance. It is important to assess these characteristics (shape and texture) of aggregates as they can affect the properties of concrete in both the fresh and hardened state. For example, a high proportion of angular particles will affect the water demand of the mix and therefore workability, on the other hand the surface texture (rough, smooth) will affect the bond between the particle and the cement paste as well as the water demand.

Flakiness index - The method used to determine the flakiness index of coarse aggregates was that described in EN 933 Part 3 [28] (replacing BS 812 [85]) and it applies to aggregates of natural or artificial origin, including lightweight aggregates.

According to BSEN 12620:2002 [9] the flakiness of coarse aggregate, can be classified into the different categories given in *Table 4.8.* The standard provides the basic classification method, but offers no further guidance. However, during the development of BSEN 12620 (prEN12620:1996) guidance was given in the form of general note for each category as briefly outlined in *Table 4.8.* The limit in BS 882 for flaky aggregate particles was 50% for natural gravel and 40% for crushed or partially crushed coarse aggregate.

Table 4.8: Categories for maximum values of flakiness index according to EN12620 [9].

FLAKINESS INDEX	CATEGORY	APPLICATION(prEN12620)
≤ 15	FI_{15}	-
≤ 20	FI_{20}	not generally applicable to concrete
≤ 35	FI_{35}	generally applies to crushed rock, crushed gravel, slag and artificial aggregates
≤ 50	FI_{50}	generally applies to uncrushed aggregates
≥ 50	$FI_{Declared}$	used if it can be demonstrated that satisfactory concrete can be produced
No requirement	FI_{NR}	-

Shape index - The method used for the determination of shape index for coarse aggregates was as described in EN 933-4 [27] (replacing BS 812-105.1 [86] and can be applied to aggregates of natural or artificial origin, including lightweight aggregates.

According to EN 12620 [9] the shape of coarse aggregate can be classified into different categories as given in *Table 4.9*. It is generally accepted that the shape index should not exceed 10 to 15% of the volume of the coarse aggregate although formal limits do not exist [11].

Table 4.9: Categories for maximum values of shape index according to EN 12620[9].

SHAPE INDEX	CATEGORY
≤ 15	SI_{15}
≤ 20	SI_{20}
≤ 40	SI_{40}
≤ 55	SI_{55}
≥ 55	$SI_{Declared}$
No requirement	SI_{NR}

Loose bulk density and voids - The method used to determine loose bulk density and associated calculation of voids was that described in EN 1097-3 [87]. Loose bulk density ρ_d was calculated as the ratio of the un-compacted sample mass to the volume of the container used. This test method is applicable to natural and artificial aggregates up to a maximum size of 63 mm.

Determination of RCA Composition - The method described in BS 8500 [7] (Part 2 Annex B) was adopted to identify and quantify the constituent materials present in RCA samples. The limitations implied by the standard are given in *figure 3.2* of the previous chapter.

4.3.5.2 Mechanical Characteristics

The methods briefly described in this section to assess mechanical characteristics are those currently specified in the relevant British standards. However, it is important to note that these are partially replaced by BS EN1097 Part 2 [88] providing two further methods for the determination of resistance to fragmentation of coarse aggregates. In this study only the current BS methods were used, since the European Normatives had not been introduced in the U.K. at the time of testing.

Aggregate crushing value (ACV) - Determination of the Aggregate Crushing Value (ACV) gives a relative measure of the resistance of aggregate to crushing under a gradually applied compressive load. The method followed is described in BS 812 Part 110 [30] from which the ACV of aggregates was determined. Specimens consisting of the particle size fraction 10-14 mm of the sampled coarse aggregate were prepared using suitable sieve sizes and each specimen was compacted into a cylinder with a plunger placed on top. A 400 kN load was applied at constant rate over a period of 10 minutes. Then the sample was removed and sieved through a 2.36 mm sieve. The percentage of the material passing the sieve represented the crushing value so the smaller the ACV the stronger the aggregate.

Aggregate impact value (AIV) - The method described in BS 812-112 [32] was used to determine the aggregate impact value. Specimens were prepared in the same way as those for the ACV test. In this method, instead of a plunger compressing specimens into a cylinder as in ACV test, a hammer falls 15 times onto the aggregate from a height of 600 mm. The sample was then sieved through a 2.36 mm sieve (as in the ACV test) and the percentage of material passing represented the aggregate impact value (AIV). According to BS 882 [26], AIV values below 25% indicate aggregate suitable for use in heavy duty concrete floors (PAV designated concrete mixes), values between 25-30% for wearing surfaces and between 30-45% for other concrete applications. Recently BS 812-112 was replaced by EN 1097 Part 2 [88]. The normative covers the Los Angeles method as the reference method and the Impact value (similar concept to the BS) as an alternative method.

Ten percent fines value (TFV) - BS 812-111 [31] describes the method of establishing the 10% fines value (TFV) of aggregates. In this test the sample was prepared as in the ACV test and a load was applied at constant rate over 10 minutes in order to cause a penetration of the plunger into the cylinder of about 15 mm, for rounded aggregate. With this penetration the percentage of fines produced (material passing a 2.36 mm sieve) should be between 7.5 and 12.5 percent. According to BS 882 [26] the minimum TFV for aggregates used in heavy duty concrete floors (PAV designated concrete mixes) is 150 kN and 50 kN for wearing surfaces and other concretes.

4.3.5.3 Chemical-Mineralogical Characteristics

Chemical-mineralogical characteristics of aggregates may adversely influence the results of concrete performance. For example the presence of silica in the aggregate may initiate a reaction with the alkalis of the cement leading to decreased durability. Typically, this results in alkali-silica reaction (ASR) producing a gel with expanding tendencies, culminating in the weakening of the cement paste-aggregate bond and causing serious damage to concrete. Another aspect of concern is the chloride content of the aggregates. Standards such as BS 882 [26], EN 12620 [9] and BS 8500 [7] set certain limitations to the soluble chloride content of aggregates. Although methods for the determination of contents of alkalis, chlorides and sulphates are covered by European normative BSEN 1744 [89], these methods are for preliminary determination only. For this reason a more rigorous scientific approach was chosen including chemical-mineralogical analysis methods which enable better understanding of the behavior of the constituent materials as well as their contribution to the contents of various substances in concrete. Techniques included the standard practices presented below:

4.3.5.3.1 X-ray diffraction (XRD) characterisation XRD provides a qualitative bulk analysis of a powdered sample, providing e good indication of the predominant minerals present. It is widely used to determine the phase composition of rocks and ores, to enable the determination of the nature and concentration of impurities in the raw material.

Basic principle: X-ray diffraction analysis uses the property of crystal lattices to diffract monochromatic X-ray light. This involves the occurrence of interferences of the waves scattered at the successive planes, and is described by Bragg's equation

4.5:

$$Bragg's\ equation:\ n\lambda = 2d\ sin\theta\ (n = 1, 2, 3, ...) \qquad (4.5)$$

where λ is the wavelength, d is the lattice plane distance, n the number of lattice planes and θ is half the diffraction angle. This relationship is used to analyse the structure of crystals.

In diffractograms of powders not free from phase shifts, several diffraction patterns of different crystalline fractions can be superimposed. The detector is a position-sensitive proportional counter for high-speed recording or a scintillation counter for better angular resolution. Instruments that work on this principle are called diffractometers.

XRD analysis was performed using a Phillips PW1860/00 diffractometer, with graphite-filtered CuK radiation (1.54$\AA$).

4.3.5.3.2 X-ray fluoresence (XRF) characterisation

XRF spectroscopy is widely used for the qualitative and quantitative elemental analysis of environmental, geological, biological, industrial and other samples. Compared to other competitive techniques, it has the advantage of being non-destructive, multi-elemental, fast and cost-effective.

The X-ray fluorescence principle is depicted in *Figure* 4.7. An inner shell electron is excited by an incident photon in the X-ray region. During the de-excitation process, an electron will move from a higher energy level to fill the vacancy. The energy difference between the two shells appears as an X-ray, emitted by the atom. The X-ray spectrum acquired during the above process reveals a number of characteristic peaks. The energy of the peaks leads to identification of the elements present in the sample (qualitative analysis), while the peak intensity provides the relevant or absolute elemental concentration (semi-quantitative or quantitative analysis).

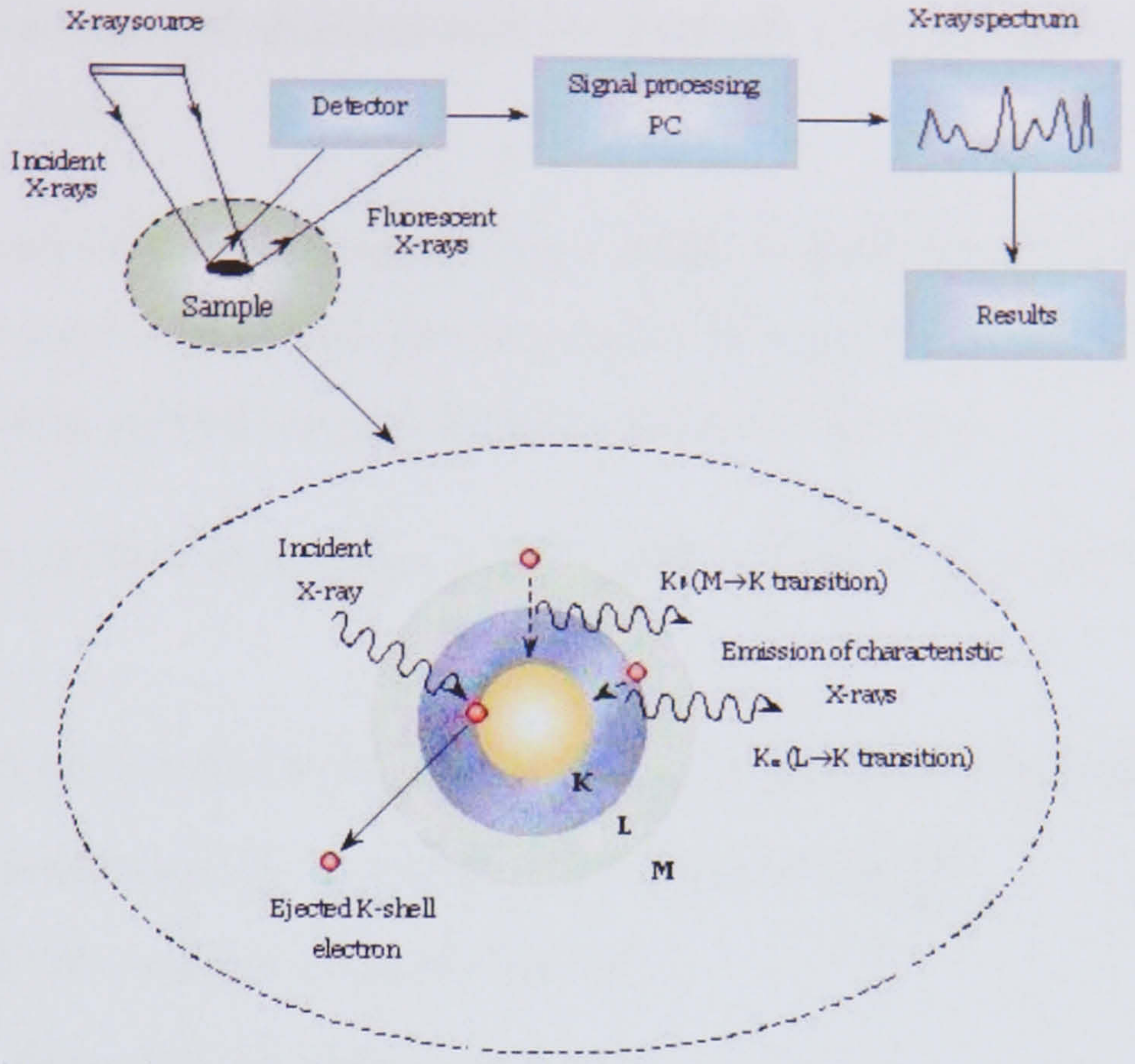


Figure 4.7: Principle of XRF analysis

The method used is described in detail in BSEN ISO 12677 [90] but with a variation in the preparation of samples. Instead of a fused sample, a powder pellet type of sample was used.

XRF analysis of major elements as well as some trace elements (Pb, Zn, Ni, Co, Cr, V, Th.) was carried out using an ARL.ADAVNT.XP spectrometer.

4.3.5.3.3 Inductively Coupled Plasma - Atomic Emission Spectrometer (ICP-AES) analysis This method is useful in detecting and precisely quantifying (ppm) the presence of the majority of the elements in the periodic table. Samples required for this type of analysis were prepared following the UNI 11087 [91] procedure briefly described below.

Weigh 2 g of powdered sample to an accuracy of 0.1 mg and dilute in 100 ml of distilled water. Place the solution in a 250 ml beaker and seal with parafilm to avoid evaporation, followed by slow agitation for 1 hour. Leave the solution to rest for 24 hours and then filter using medium paper filter before the ICP analysis. Produce a second set of solutions but prepare using hydrochloric acid to detect the content of acid soluble content of elements such as chlorides ($NaCl$), sulphates (SO_3) and alkalis (Na_2O, K_2O).

ICP-AES analysis was performed using a Jobih-Yvoh Horiba Ultima 2c ICP spectrometer. The results produced were expressed in ppm and conversions from ppm to % wt have been carried out according to Equation 4.6 [92].

$$ppm\ to\ \%wt\ conversion\quad C_i^{Solid}\ wt\% = C_i^{Soln} \times \frac{V}{m} \times 10^{-4} \tag{4.6}$$

Where:

$C_i^{Solid}\ wt\%$ - is the concentration in the solid, expressed as percentage by weight.

C_i^{Soln} - is the concentration in the solution, expressed in $\frac{\mu g}{ml}$

V - Volume of the solution, expressed in ml

m - Weight of the solid expressed in g

4.3.6 Concrete Assessment

4.3.6.1 Fresh properties

The properties of concrete in the fresh state were assessed through a series of tests carried out on NA and RCA concrete mixes. The effect of coarse RCA content on workability was established. In addition, for the PAV series of mixes the effect of RCA content was also established in relation to the air-entraining admixture content required. The assessment was carried out immediately after the mixing process using the slump, compacting factor and air content measuring tests. Observations were also made for bleeding, stability and segregation. Tests used in this study are briefly described below.

Slump Test - Slump test was carried out in accordance to EN 12350-2 [93] (replacing BS 1881-102 [94]). The aim of this exercise was to determine the consistency of fresh concrete and identify its classification as given in table 3 of EN 206 [10] given here in *Table* 4.10.

Table 4.10: Slump classes according to EN 12620 [9].

CLASS	SLUMP(mm)	APPLICATIONS†
S1	10 to 40	Kerb bedding and backing
S2	50 to 90	House drives, domestic parking and external parking, heavy-duty external paving with rubber tyre vehicles
S3	100 to 150	Blinding and mass concrete fill, Strip footings, mass concrete foundations, in-situ RC-concrete
S4	160 to 210	Trench fill foundations
S5	≥ 220	Trench fill, in-situ piling (self compacted)

† Table A.19 Suitable consistences for different uses BS 8500 Part 1 [8].

Compacting factor - Compacting factor tests were carried out, following the procedure described in BS 1881-103 [95], the prime aim of the test being to assess the compactability of concrete for use in different applications. However, after the completion of this study the compacting factor test was withdrawn and replaced by EN 12350-4 [96] entitled Degree of Compactability. The classes of compactability set by EN 206 [10] are given in *Table 4.11*.

Table 4.11: Compaction classes according to EN 206 [10].

CLASS	DEGREE OF COMPACTABILITY
C0	≥ 1.46
C1	1.45 to 1.26
C2	1.25 to 1.11
C3	1.10 to 1.04

In the case of compacting factor there was no classification but *Table* 4.12 below describes workability and corresponding slump and compacting factor values.

Table 4.12: Description of workability and compacting factor [11]

DESCRIPTION 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

Loss of workability - It is of great importance that the workability of a mix is maintained to allow for transportation time. The effect of coarse RCA content on the loss of workability up to 150 minutes from mixing completion was established using the compacting factor test. Compacting factor was measured at 30 minute intervals up to 150 minutes after mixing completion. During the waiting time the mixer was operated at 5 minute intervals for 30 seconds in order to simulate transportation conditions.

Stability - The stability of fresh concrete mixes and the effect of the RCA content were established through visual inspections of fresh concrete. Visual observations were carried out for cohesiveness, handling and finishing properties of the concrete mixes. The cohesiveness of fresh concrete was carried out on the resulting cone from the slump test. A 16 mm diameter steel rod was used and the cone was disturbed by tamping up to five times on one side. The behavior of the concrete was observed and classified according to *Table* 4.13. Finishing of the concrete surfaces was manually applied 1 hour after placing the concrete into the form and any effect due to RCA inclusion was observed.

Table 4.13: Stability classification.

CLASS[†]	COHESION PROPERTY	
	Description	**Observation**[‡]
1	Over cohesive	Little further slump
2a	Very cohesive	Gradually slumps further, no shearing
2b	Cohesive	Gradually slumps further, some shearing
2c	Little cohesion	Gradually slumps further, then partial collapse
3	No cohesion	Slumped concrete shears

[†] Intermediate classifications can also be determined.
[‡] Gently tap five times the concrete after the slump test is carried out using a 16 mm steel rod.

Air content - The air content of fresh concrete was measured using the pressure gauge method as described in EN 12350 [97] which recently replaced BS 1881-106 [98]. The equipment used was a type B pressure air meter.

Entrained air stability - In order to simulate transportation time, air content was measured at 15 and 60 minutes after mixing. During this time, alternative mixing and standing at five minute intervals simulated the delivery time and handling conditions in practice. The effect of coarse RCA on retention of air content was established by comparing the results with those of the reference concrete.

4.3.6.2 Hardened properties

Compressive strength development - Compressive strength of concrete was determined using 100 mm concrete cubes and standard cylinders (h=300 mm, D=150 mm) with specimens loaded at a rate of $0.4N/mm^2$ until failure, following the method described in EN 12390 Part 3 [99] (replacing BS 1881-116 [100]). Specimens were cured in CU1 conditions (*table 4.7*) up to the day of testing. Compressive strength testing was carried out at 3, 7, 14 , 28, 56, 90, 180 and 360-days after casting. Two cube specimens of each mix were tested for compressive strength using an Avery Denison 2500 kN machine. In the case of more than 10% difference in the two results a third specimen was also tested. Some guide values for compressive strength at ages up to 1-year that can be used for comparison are given by BS 8110 Part 2 [101] and extracted in *table 4.14* to assist with comparisons later on.

Table 4.14: Compressive strength of concrete for use in structural design according to BS 8110-2.

$f_{ck.cube}$	CUBE STRENGTH (N/mm^2)				
	AGE				
	7-days	2-months	3-months	6-months	1-year
20.0	13.5	22.0	23.0	24.0	25.0
25.0	16.5	27.5	29.0	30.0	31.0
30.0	30.0	33.0	35.0	36.0	37.0
40.0	38.0	44.0	45.5	47.5	50.0
50.0	36.0	54.0	55.5	57.5	60.0

Flexural strength - Flexural strength of concrete was assessed using the method described in EN 12390 Part 5 [102] (replacing BS 1881-118 [103]). The method requires testing of (100 x 100 x 500mm) concrete beam specimens, subjected to two point loading. Flexural strength was calculated using simple bending theory. Two specimens were tested after being cured in CU1 for 28-days.

Static modulus of elasticity - Static modulus of elasticity of NA and RCA concrete specimens was established following the procedure described in BS 1881 Part 121 [104]. The test involved step loading of standard cylinders (D=150 mm, h=300 mm) up to a maximum of one third of the failure load. Length change of the test specimen, at each load step, was recorded and converted to strain (ϵ) and load at each step converted to stress (σ) enabling the (σ) - (ϵ) relationship to be established, the slope of which gives the static modulus of elasticity expressed in kN/mm^2. Two specimens were cured in CU1 until tested at 28-days. A computer driven RUBICON-MAYES testing machine was used in order to apply the loading cycles at precise rates and achieve maximum consistency throughout testing. A typical equipment and specimen setup during testing is shown in *figure 4.8*

Figure 4.8: A typical arrangement for the measurement of static modulus of elasticity.

Some guide values for the static modulus of elasticity at 28-days that can be used for comparison are given by BS 8110 Part 2 and extracted in *table 4.15* [101] to assist with comparisons later on.

Table 4.15: Typical range for static modulus of elasticity at 28-days according to BS 8110-2.

$\mathbf{f}_{c.cube}$	$\mathbf{E}_c{}^{\dagger}(kN/mm^2)$	
	Mean value	**Typical range**
20	24	18 - 30
25	25	19 - 31
30	26	20 - 32
40	28	22 - 34
50	30	24 - 36
60	32	26 - 38

† Static modulus of elasticity.

Drying shrinkage and swelling - The effect of coarse RCA on the long term deformation (shrinkage and swelling) of concrete was assessed by testing 75 x 75 x 300 mm long prism specimens. Metallic stud inserts with a conical rebate were fixed at both ends in order to fit the specimen in the measuring frame. Following de-moulding the length of the specimen was measured to an accuracy of 0.002 mm using a measuring frame apparatus as shown in *Figure 4.9* to establish the reference $\mu\epsilon$. Specimens tested for shrinkage were left in the laboratory environment under CU2 conditions while specimens tested for swelling (expansion) were left under CU1 conditions up to 90-days. The length of each specimen was measured every day for the first two weeks, every second day for the two weeks following and once a week thereafter up to 90-days. Measurements were then converted into microstrain ($\mu\epsilon$) and a plot was produced for $\mu\epsilon$ vs time.

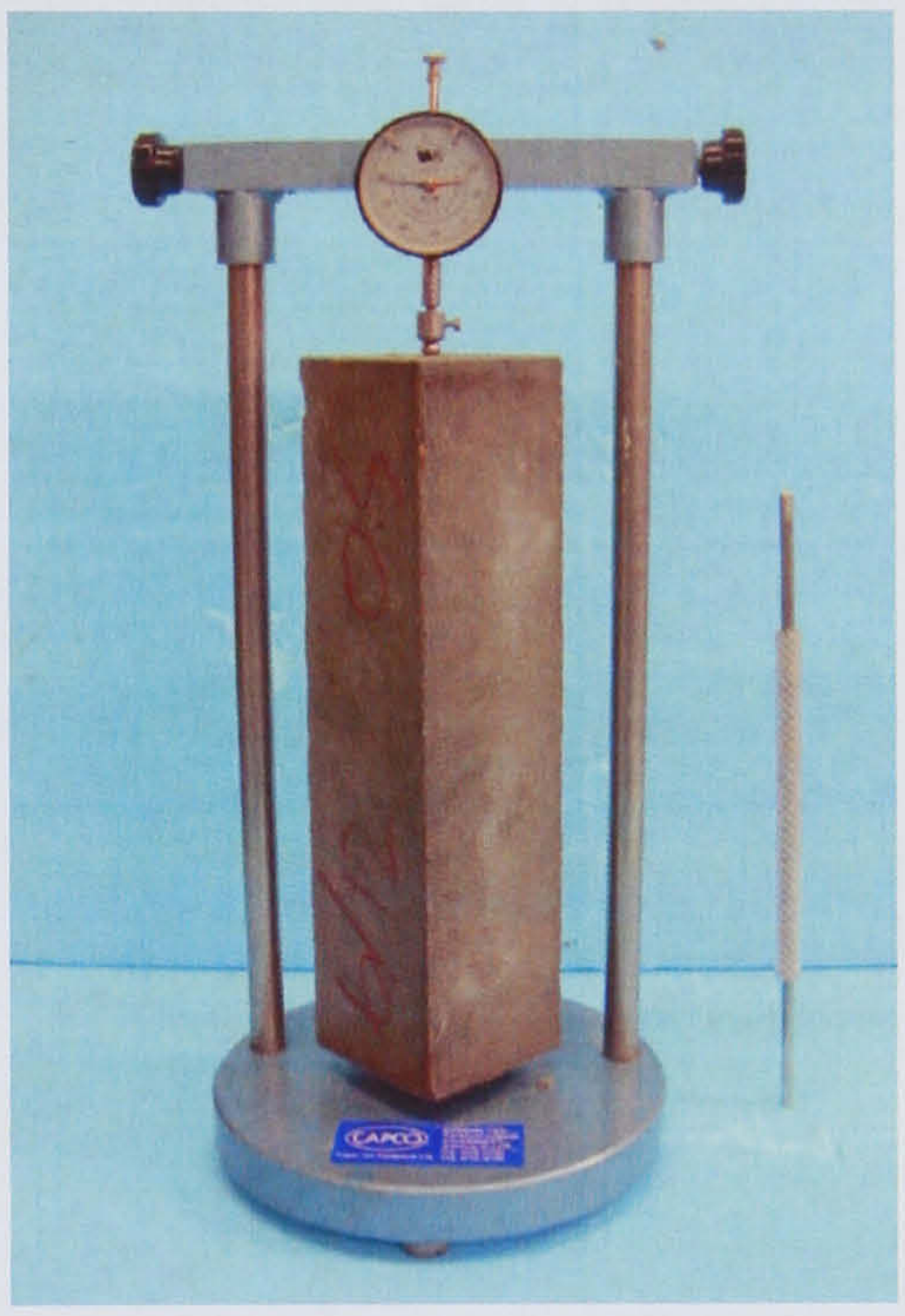


Figure 4.9: Frame used for deformation measurement.

Initial surface absorption - Near surface absorption of concrete was measured using the initial surface absorption test (I.S.A.T.), as described in BS 1881-208 [105]. The method involved 150 mm concrete cubes cured under CU1 for 28-days, after which the specimens were oven dried to constant mass at 105°C. The I.S.A.T. was carried out on NA and RCA concrete specimens at 10, 30 and 60 minutes and the surface absorption was recorded in $ml/m^2/second$. Determining the rate of water penetration into concrete constitutes a good indication of its durability performance. *Figure 4.10* shows the I.S.A.T. apparatus used.

Carbonation penetration - The effect of coarse RCA on CO_2 penetration into concrete was assessed using 100 mm cubes exposed to an enriched environment of 3.5

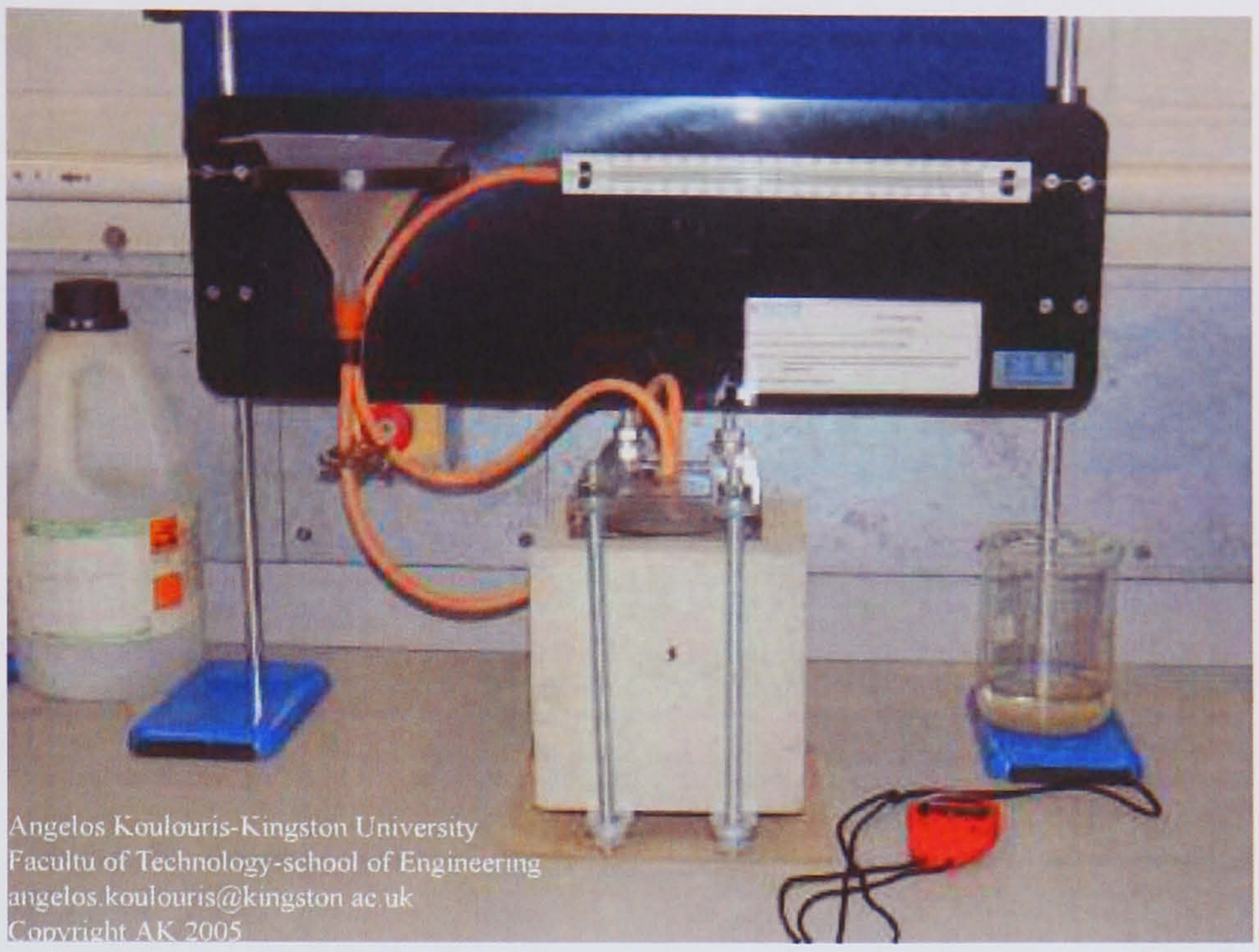


Figure 4.10: I.S.A.T. apparatus used.

to 4.0% CO_2 concentration at 20 ± 2°C and 55% RH. An enriched CO_2 environment is required due to the fact that exposure in a normal environment with 0.03% CO_2 concentration will not result in reasonable penetration and any effect due to RCA will not be visible over a three year programme. Specimens used were cured under CU3 followed by waxing over all sides except one, then exposed to CO_2 for 2, 4, 8, 12 and 20 weeks. Testing involved splitting the cubes in the middle by inducing a tensile fracture and CO_2 depth of penetration was assessed by means of spraying the specimen with phenolphthalein indicator solution (1 g phenolphthalein in 50 ml of 95% ethanol and diluted in 100 ml of distilled water). The carbonation depth, indicated by the colourless zone of concrete was measured at 7 locations along the fractured face and the mean value was recorded as the depth of carbonation. Both sides of two specimens were tested for each mix.

The total exposure period within the chamber was 20 weeks, simulating a 20 year exposure period under normal atmospheric conditions [106].

Freeze-thaw resistance - Resistance of the PAV series concrete to continuous freeze-thaw cycling was assessed according to EN 12390 [107]. The method used was the reference method described in clause 6 of the standard using demineralised water as a medium. Two specimens cured under a combination of CU5 and CU6 curing regimes were tested for both NA and RCA mixes from the PAV series. The surface scaled material was collected, oven dried to constant mass and weighed. Results were expressed in kg/m^2 of scaled material.

Resistance to sulphate attack - In order to assess the effect of coarse RCA on the resistance of concrete to sulphate attack, prismatic specimens of size 75 x 75 x 300 mm long were cast, and metallic stud inserts with a conical rebate were fixed at both ends in order to monitor deformation of the specimen during exposure to the sulphate environment. The samples were cured under CU4, then their lengths measured to establish a reference and they were transferred into a tank containing a solution of 0.3 g/l sodium sulphate (Na_2SO_4) at 20 ± 2°C according to exposure conditions set in table A.2 of BSEN 8500 Part 1. Simulated exposure was for class DS1 groundwater conditions. Care was taken by using a circulating pump to allow free flow of the solution around the specimens while the level of the solution was always kept constant in order to avoid differential pressure effects. The specimens were exposed to the solution for 60-days and measurement of their length was taken twice a week up to 60 days. The solution was refreshed every 30-days. Two specimens were tested for each mix.

Chloride ingress - The method involved casting of 150 mm concrete cubes with a rebate formed on the bottom face of the specimen. This was achieved using a 148 x 148 x 10 mm thick pvc insert placed in the mould as shown in *Figure 4.11* . The cubes were cured for 7-days under CU1 and then removed from the water and left in the laboratory for two weeks to dry when they were sealed by applying three layers of bitumen on all sides except the side containing the rebate.

Figure 4.11: PVC insert for 150 mm special cubes [3]

After sealing, the rebate was filled with a 1 mol. sodium chloride solution (1 mol=58.4g NaCl/l of distilled water) and kept full for three months at the end of which the specimens were left to dry in the laboratory for three weeks. Then each specimen was cleared of salt deposits on the surface using a stiff bristle brush and dust samples collected at depths of 5 mm, 10 mm, 15 mm, and 20 mm by drilling from three locations on the surface. Drilled material from each depth was collected and solutions were then prepared and tested according to the method described in *paragraph 4.3.5.3.3.*

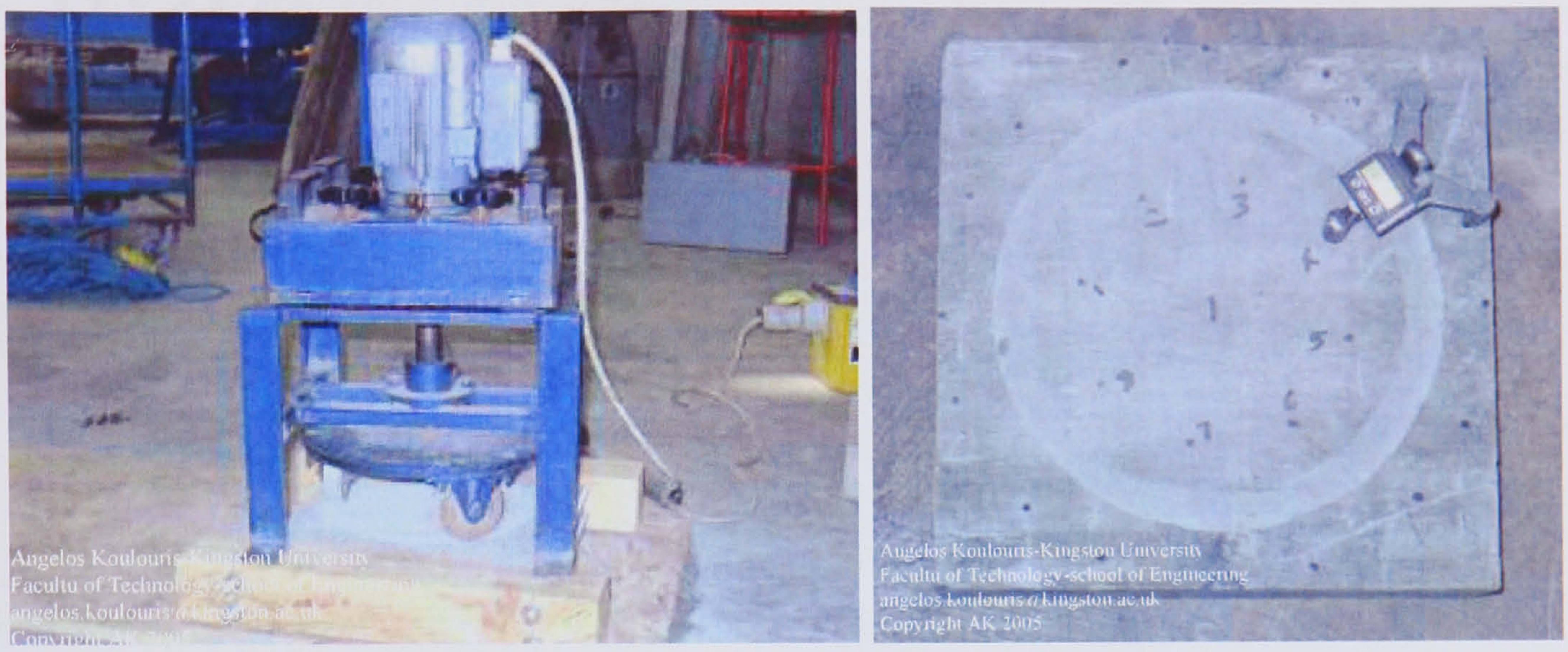
Abrasion resistance value (ARV) - Resistance to abrasion for concrete mixes used for pavement applications was assessed using the Chaplin abrasion method as described in BS 8204-2 [108]. In this method three hardened steel wheels rotate over a ring shaped area for a specified time period, at a set number of revolutions/minute and under a standard load. The depth of wear within the ring pattern was measured at various locations and the average depth was obtained in order to assign an abrasion resistance value using the classification given in *Table 4.16.* Details of the specimen and apparatus are shown in *Figure 4.12.*

Table 4.16: Abrasion resistance classification and limiting depths of wear for concrete bases, directly finished (DF) only as wearing surfaces.

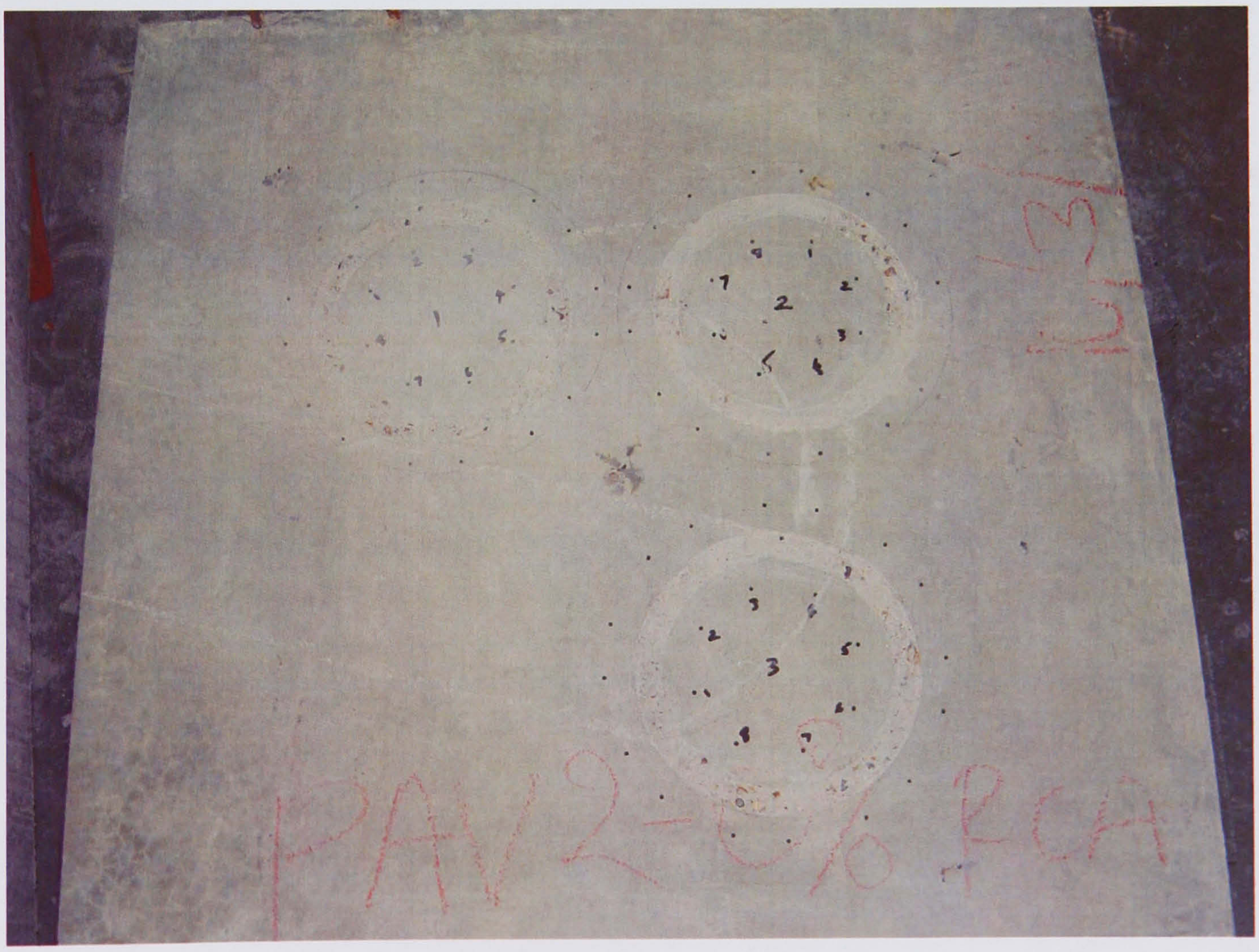
ABRASION RESISTANCE CLASSIFICATION (BS 8204 Part 2)

Class	**Service conditions**	**Application**	**Max test wear depth (mm)**
Special/DF[†]	Severe abrasion and impact from steel or hard plastics wheeled traffic or scoring by dragged metal objects	Very heavy duty engineering workshops and very intensively used warehouses, etc.	0.05
AR1/DF	Very high abrasion; steel or hard plastics wheeled traffic and impact	Heavy duty industrial workshops, intensively used warehouses, etc.	0.10
AR2/DF	High abrasion; steel or hard plastics wheeled traffic	Medium duty industrial and commercial	0.20
AR3/DF	Moderate abrasion; rubber-tyre traffic	Light duty industrial and commercial	0.40

[†] Directly finished concrete bases as wearing surfaces - table 4 of BS8204-2 [108].



(a) Chaplin apparatus (b) Wear measurement



(c) Wear measurement

Figure 4.12: The Chaplin abrasion apparatus and specimen detail.

CHAPTER 5

PRODUCTION OF RCA AND CHARACTERISATION OF ALL AGGREGATES

5.1 INTRODUCTION

The method used to process C&D debris for the production of recycled aggregates, has a direct influence on the characteristics of the produced aggregates. Both mechanical and physical properties are influenced by the type of crushers used, the methods for removing unwanted material and the screening and sorting techniques. It is also widely accepted that the characteristics of recycled aggregates are different to those of natural aggregates and as a result some of the characteristics may not conform to current standard requirements for concrete aggregates.

Given this background the characteristics of coarse RCA and NA, and natural sand used in this study have been investigated and checked for conformity to the relevant standards.

5.2 RCA PRODUCTION

RCA used in this project was produced using a C&D debris process plant mainly comprising of a primary jaw and secondary cone crushers, electromagnetic separation for reinforcement and other metals, air separation for lightweight materials using blowers, manual removal of pieces of wood, plastic etc. missed in previous stages of the process and finally screening for the achievement of the required grading. *Figure*

4.3 illustrates the process of recycling used in this study. Debris processed for this study was delivered from demolished concrete structures around London.

Initially the concrete rubble was reduced to a maximum size of 0.4 m using hydraulic shears as shown in *figure 5.1*. Further reduction down to 75 mm was achieved using a primary jaw crusher shown in *figure 5.2* after which an electromagnet separated out the reinforcement as shown in *figure 5.3*. The following activity involved primary screening, separating soil and directing it to a stockpile while diverting the soil-free material to the next stage involving removal of plastic, wood etc. Secondary crushing using a cone crusher followed, reducing the particle size to 20 mm maximum. At this stage the material was further inspected visually on a conveyor belt and other foreign material was manually removed. The final stage involved screening the aggregate into various particle size fractions; in this case $20-10$ mm, $10-5$ mm and $<$ 5 mm. Combining the 20-10 mm and 10-5 mm fractions produced quality RCA with the required grading. *Figure 5.4* shows (b) the product after primary crushing and (c) following the final screening and blending of 20-10 mm and 10-5 mm size fractions.

Figure 5.1: C&D debris reduced to a maximum of 0.4 m using hydraulic shears.

Figure 5.2: Primary jaw crusher loaded with concrete following the process using shears.

Figure 5.3: Electromagnet located after the primary jaw crusher used for removal of reinforcement.

(a) C&D $\leq$ 0.4 m after process by hydraulic shear.

(b) C&D $\leq$ 75 mm following process by primary jaw crusher

(c) Quality RCA as the final product

Figure 5.4: From debris to quality RCA.

5.3 AGGREGATE CHARACTERISATION

5.3.1 Composition of RCA

The method described in Annex B of BS 8500 Part 2 [7] was followed to identify and quantify the constituent materials of coarse RCA. *Table 5.1* gives the percentages of the constituents of three RCAs and the requirements as set by BS 8500. Since all limits are satisfied the recycled aggregates from all three sources conformed to the requirements for use in concrete. Having said that, the asphalt content for RCA I, was found to be very close to the limit at 4.9% and the masonry content for RCA III at 5% was on the limit. The same was observed for foreign materials content for RCA II and RCA III, being only marginally below the limit. Although a small increase over the limits may still produce good quality concrete it is obviously wise to stay well within them.

Table 5.1: Constituent materials of coarse RCA from three sources used in the study.

PROPORTIONS (% wt)				
Constituents present[a]	**Test sample 20-5mm**			
	RCA I	**RCA II**	**RCA III**	**Limit[7]**
Concrete[b]	92.7	92.1	90.96	-
Masonry	1.9	2.6	5.0	5.0
Asphalt	4.9	2.4	3.3	5.0
Lightweight material[c]	0.0	0.0	0.0	0.5
Foreign materials				
plastic	0.16	0.29	0.22	-
wood	0.08	0.14	0.11	-
metal	0.30	0.47	0.51	-
	0.54	0.90	0.84	1.0

[a] Where the material to be used is obtained by crushing hardened concrete of known composition that has not been contaminated by use, the only requirements are those for grading and maximum fines.

[b] minimum of 83.5% content concrete, m/m.

[c] Material with a density less than 1.000 kg/m^3.

5.3.2 Physical Characteristics

The physical properties of coarse RCA (obtained from 3 different sources), NA and natural sand were examined following the procedures indicated by BSEN 12620 [9]. Properties investigated included particle size distribution (grading), particle density and water absorption, shape and texture, and bulk density and voids. Results were then compared to the somewhat conservative requirements for natural aggregates for concrete as per BSEN 12620.

5.3.2.1 Particle size distribution

Grading of aggregates used in this study is graphically represented in *figure 5.5* and also given in *table 5.2*. Both coarse RCA and coarse NA conformed to BSEN 12620 [9] grading requirements. At the beginning of the study the assessment was carried out following the now withdrawn BS 882 method and compliance to the BS requirements was also achieved as is shown in *figure 5.6* and *table 5.2*. Although both aggregates conformed to the code requirements it was observed from the grading curves according to both EN and BS analysis, that RCA tends to be closer to the upper limits while NA closer to the lower limits set in the codes indicating that the NA was somewhat coarser than the RCA.

The limitations on the amount passing each sieve by mass are defined according to Clause 4.3.2 and table 2 of BSEN 12620 [9]. Additional requirements exist for graded aggregate limiting the percentage of material passing the mid-size sieve (D/2 = 10 mm), to between 20-75% according to table 3 of the same clause.

Table 5.2: Particle size distribution for coarse RCA, NA and sand used in the study. BSEN 12620 and BS 882 requirements.

AGGREGATE TYPE	**PERCENTAGE PASSING**, (by mass)						
	EN Sieve size (mm)						
	40.0	28.0	20.0	10.0	5.0	2.5	-
EN 12620 Limits: 20-5 mm	100	98-100	90-99	25-75	0-15	0-5	-
RCA	100	99	97	59	13	3	-
NA	100	99	92	42	4	2	-
	EN Sieve size (mm)						
	8.0	5.6	4.0	2.0	1.0	0.3	0.15
EN 12620 Limits: < 5 mm	100	95-100	85-99	-	-	-	-
NA	100	98	93	90	80	14	-
	BS Sieve size (mm)						
	37.5	20.0	14.0	10.0	5.0	2.36	-
BS 882 Limits: 20-5 mm	100	90-100	40-80	30-60	0-10	-	
RCA	100	98	65	21	4	-	-
NA	100	93	57	12	3	-	-
	BS Sieve size (mm)						
	10.0	5.0	2.36	1.18	0.6	0.3	0.15
BS 882 Limits: < 5 mm	100	89-100	60-100	30-100	15-100	5-70	0-15
NA	100	99	89	82	68	14	1.5

Grading for natural sand (< 5 mm) used in the study was assessed following both EN and BS procedures. *Figures 5.7* and *5.8* show results for EN and BS analysis respectively. The upper and lower limits are defined in a similar way to coarse aggregates according to Clause 4.3.2 and table 2 of BSEN 12620 [9]. The grading curve lies within the limits set by EN 12620 as well as meeting the tolerances required for the producer's declared values for particle sizes below 4 mm. Fineness or coarseness of the sand can be classified, according to table B.1 of EN 12620 [9] given here in *table 5.3*, as medium grading ***MP*** since the percentage passing the 0.5 mm sieve (35%) falls within the range of 30 to 70%.

BS 882 limits are as defined in table 4 of the standard. Analysis of the results showed a curve located within required upper and lower limits. Fineness or coarse-

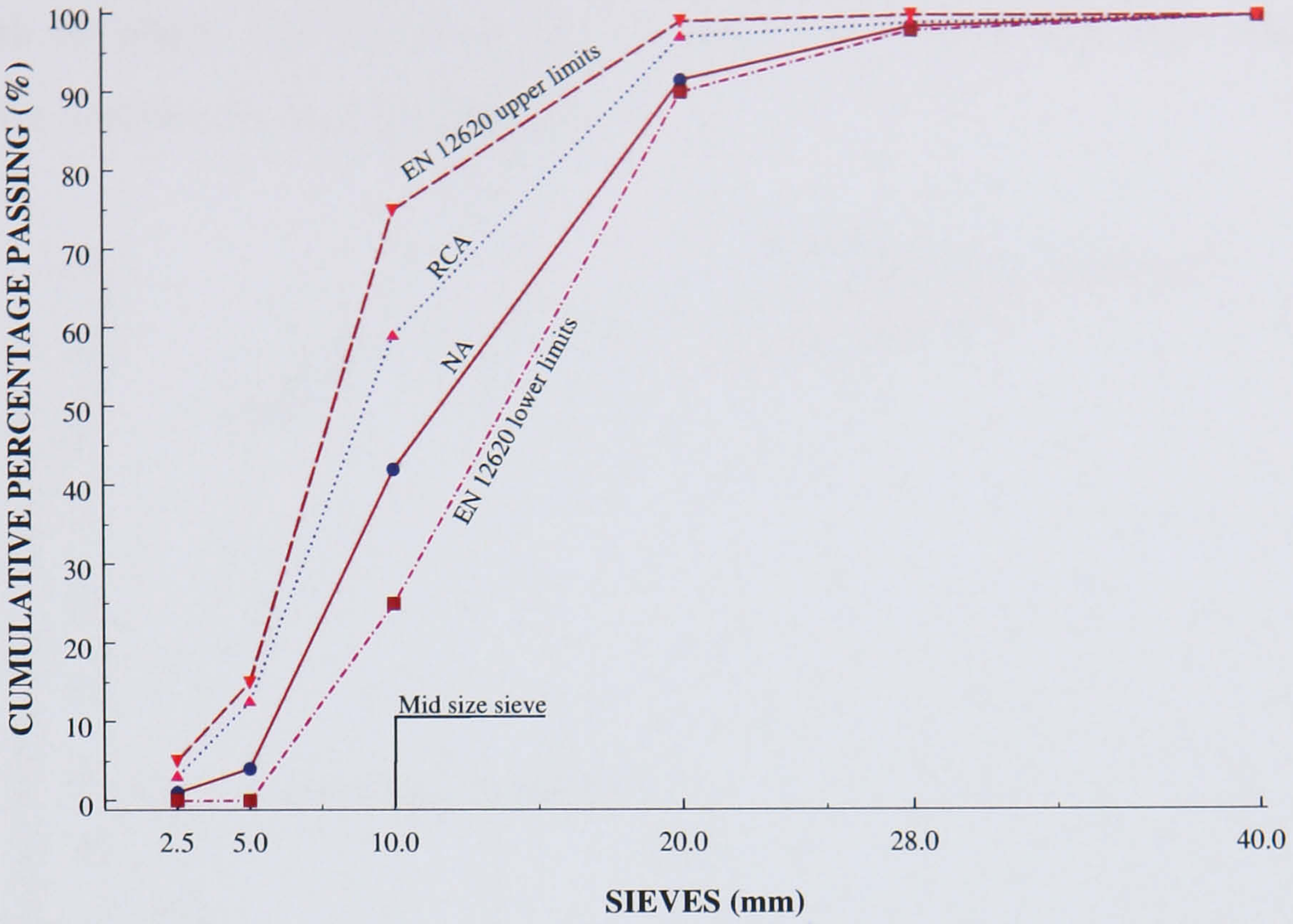


Figure 5.5: Particle size distribution for coarse RCA and NA used in the study. BSEN 12620 requirements.

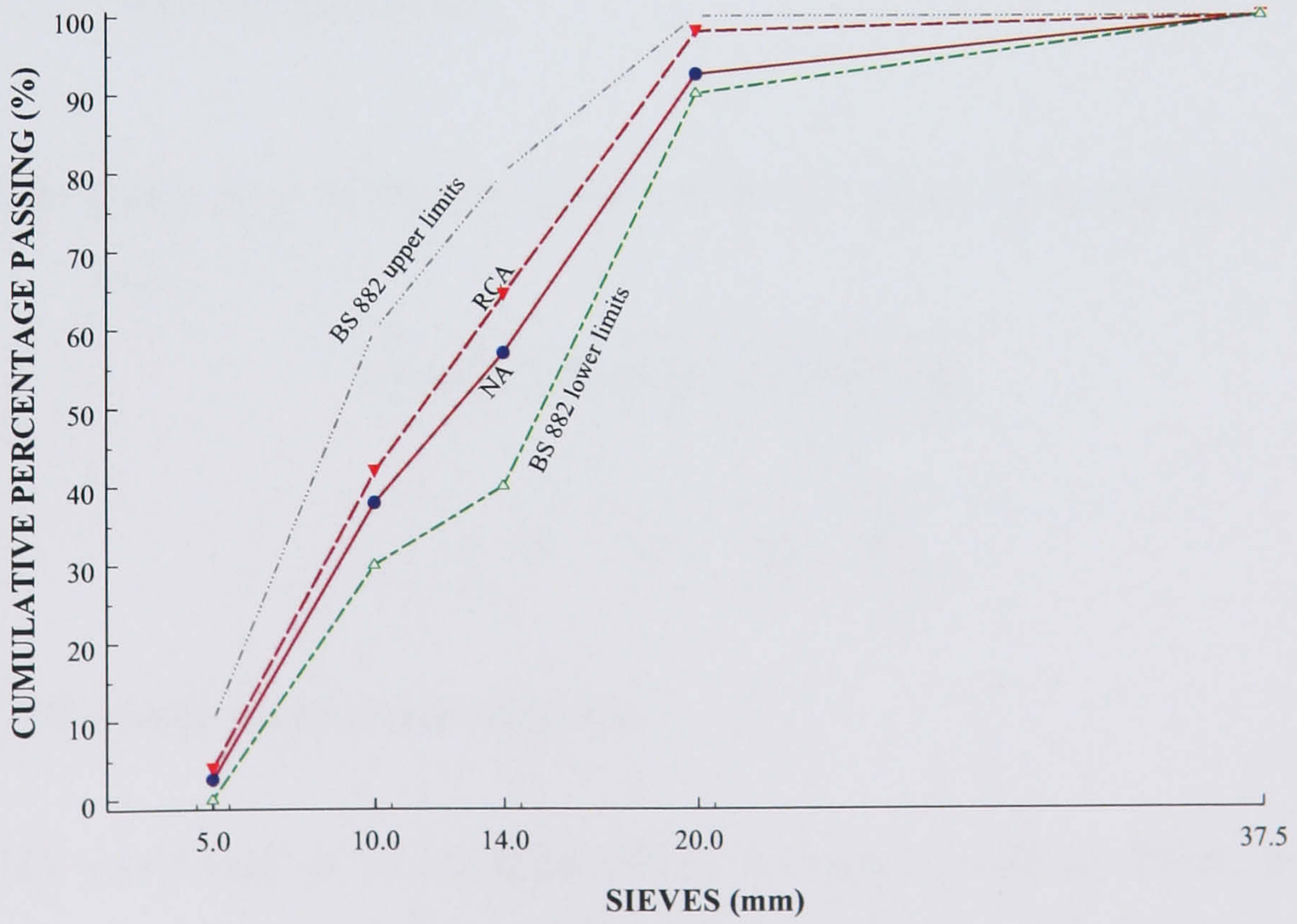


Figure 5.6: Particle size distribution for coarse RCA and NA used in the study. BS 882 requirements.

ness of the sand can be assessed using the additional classifications represented on the graph as zones. In this case size fractions 2.36 to 0.3 mm were found to be within the medium to fine grading zone.

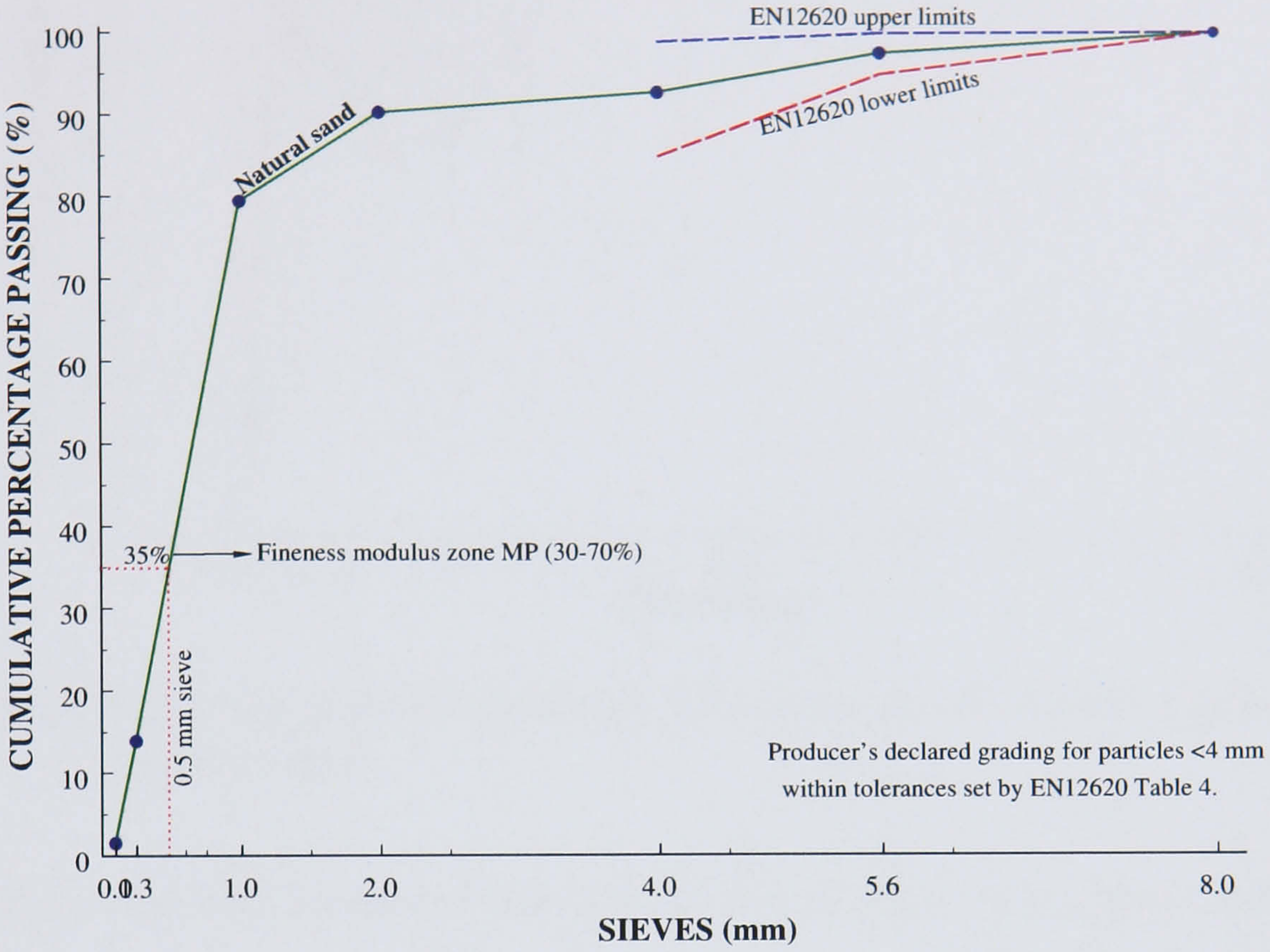


Figure 5.7: Particle size distribution for natural sand used in the study. BSEN 12620 requirements.

Table 5.3: Coarseness or fineness based on the percentage passing the 0.5 mm sieve.

PERCENTAGE PASSING		
CP	MP	FP
5 – 45	30 – 70	55 – 100

5.3.2.2 Particle shape and texture

Coarse NA was found to be irregular when compared to coarse RCA. It is to be expected that a high proportion of angular particles will result in increased water demand in the concrete mix in order to achieve a given workability [11]. However, in this study the angularity of the NA did not result in an additional water demand requirement. A visual inspection indicated NA had a *smooth* surface while RCA was

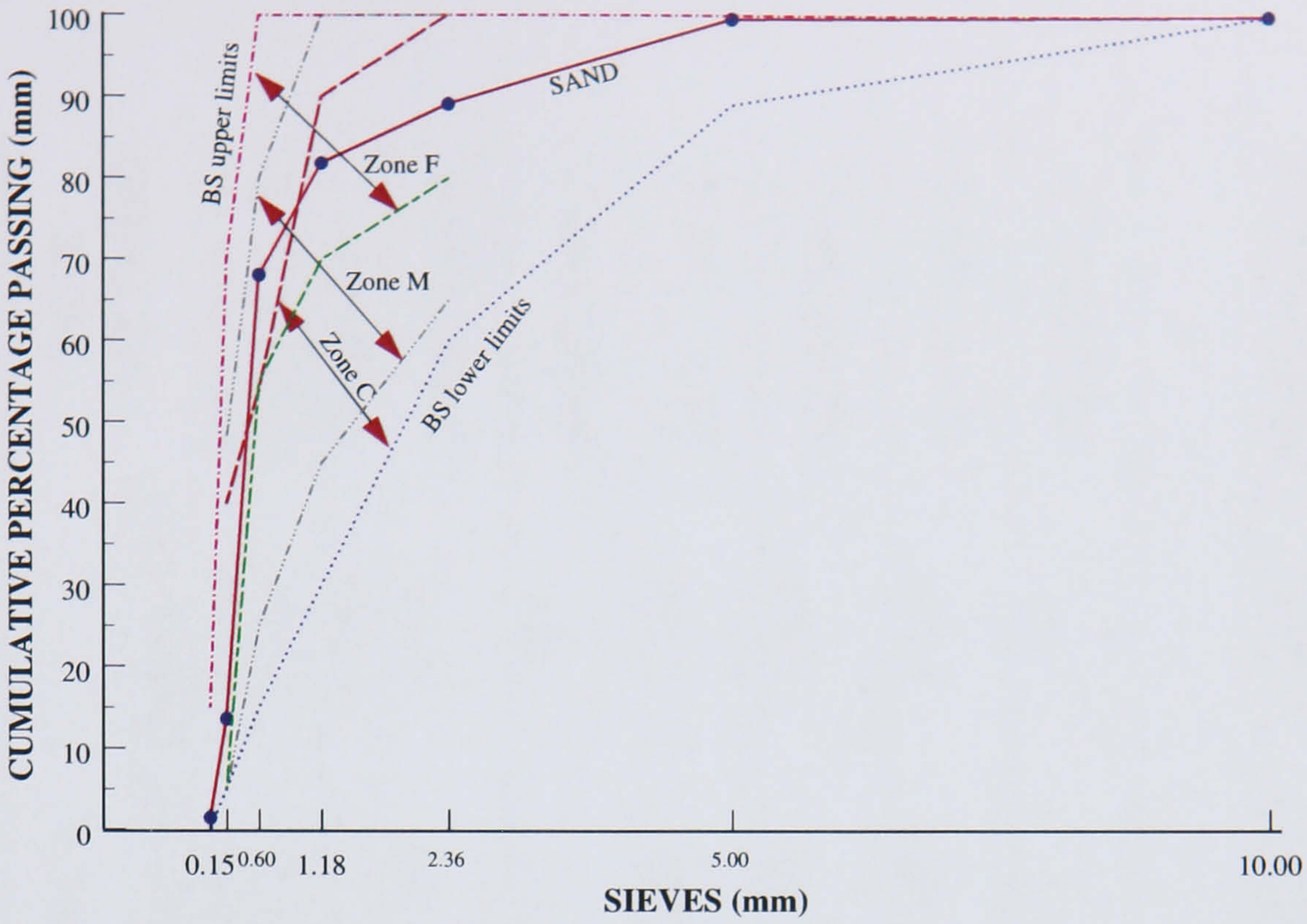


Figure 5.8: Particle size distribution for natural sand used in the study. BS882 requirements.

rough and *porous* due to some of the original cement paste remaining attached to it after the recycling process or in fact, due to particles consisting only of cement paste. This may improve the bond between the cement paste and RCA when used for the production of new concrete. Bond is partly affected by the mechanical interlock between the aggregate particle and the cement paste therefore, a rougher surface such as the RCA's will be expected to improve the bond more and this will be more evident in flexural strength than any other strength property of concrete [11].

Table 5.4: Aggregate characterisation for recycled and natural aggregates.

PHYSICAL PROPERTIES	SIZE FRACTION (mm)	NA	RCA			TEST METHOD
			Source I†	Source II†	Source III†	
Shape, visual	All	Irregular	Round	Round	Round	BS812:Part 105
Flakiness index (%wt)	28-6.3	13-16	9-10	8.25-9.2	5.8-6.2	EN933:Part 3
Shape index (%wt)	28-6.3	20-22	18-19	14.7-15.5	5.5-6.0	EN933:Part 4
Loose bulk density (Mg/m^3)	20-5	1.483	1.271	1.360	1.251	EN933:Part 3
	< 5	1.667	-	-	-	
Voids (%)	20-5	40.9	43.7	39.9	45.4	EN933:Part 3
	< 5	36.9	-	-	-	
Apparent particle density (Mg/m^3)	20-5	2.603	2.567	2.585	2.548	EN933:Part 6
	< 5	2.701	-	-	-	
Oven dried particle density (Mg/m^3)	20-5	2.511	2.260	2.263	2.291	EN933:Part 6
	< 5	2.644	-	-	-	
Saturated surface dry density (Mg/m^3)	20-5	2.546	2.377	2.387	2.392	EN933:Part 6
	< 5	2.665	-	-	-	
Water absorption (%wt)	20-5	1.0-1.4	5.2	5.5	4.8	EN933:Part 6
	< 5	0.8-1.0	-	-	-	
MECHANICAL PROPERTIES						
Aggregate crushing value (%)	14-10	12.4	22	17.5	23.9	BS812:Part 110
Aggregate impact value (%)	14-10	6.7-7.3	13.0-15.4	11.8-12.2	7.2-9.6	BS812:Part 112
10% fines value (kN)	14-10	155	170	190	193	BS812:Part 111

† Demolished concrete structure, recycled concrete aggregate RCA.

5.3.2.3 Shape and flakiness indexes

The *shape index* of coarse NA and RCA was examined and is expressed as the percentage of particles with ratio of their longest dimension over their shortest, greater than 3. Particles with this ratio greater than 3, were classified as *non-cubical* (BS equivalent: *elongated*) . In the case of various deliveries of NA, the shape index was found to range between 20 and 22 classifying them as SI_{40} according to *table 4.9*. The presence of non-cubical particles in excess of 10 to 15% by mass is generally undesirable but no further guidelines are available [11]. For the various RCA's the range was found to be 5.5 to 19 giving classifications for these aggregates of SI_{20} for Source I, and SI_{15} for Source II and Source III. With respect to shape index in this testing program the RCA improved with every new delivery while NA was found to be consistently well within the classification for maximum content of non cubical particles but always exceeded the desirable range of 10-15% as recommended by Neville [11]. In this case RCA was found to meet this recommendation and therefore be more suitable.

Flakiness index (BS equivalent: *flakiness*) was examined and found for NA to range between 13 and 16, just classifying it as FI_{15} according to *table 4.8*. In the case of RCAs the results were once again more positive with values ranging between 5.8 and 10 classifying them comfortably as FI_{15}. The results for shape and flakiness index are given in *table 5.4*.

With both, shape and flakiness indexes, the improvement in RCA when compared to NA results reflects the use of a secondary cone crusher as opposed to a jaw crusher. The action of a cone crusher by its nature produces rounder particles resulting not only in the reduction of shape index but also the reduction of the flakiness index.

5.3.2.4 Loose bulk density

Loose bulk density (ρ_b) was assessed to establish the packing capacity of the aggregates. Results given in *table 5.4* show NA to have a higher packing capacity with values ranging between 1.425 and 1.483 Mg/m^3, compared to RCA which was found to vary from 1.251 to 1.360 Mg/m^3. This reduction in bulk density of the RCA is a direct consequence of the attached cement paste and increased porosity of the particles. However, as described in *paragraph* 5.3.2.1 RCA was found to be finer than NA resulting in fewer voids when packed therefore increasing the bulk density and partially compensating for the lower bulk density due to the porous attached cement paste, and so reduced the difference of this characteristic in comparison to NA.

5.3.2.5 Water absorption (WA_{24})

One of the most important characteristics of aggregates from the practical point of view, is their *water absorption.* NAs tested in this study were found to have consistent water absorptions varying between 1.0-1.4%. These results were expected for natural gravel. On the other hand the RCA absorptions ranged from 4.8-5.5%. This was about 4 times the water absorption of NA but is in agreement with the majority of previous studies [37, 39, 41, 42]. Different values are as a result of the various amounts of cement paste attached to the particles and to particles consisting of cement paste. This quantity changes with the source of C&D debris as well as the crushing process. In the case of high strength original concrete it is expected that the amount of cement paste after the recycling process will be higher when compared to low strength original concrete. This is because during the various stages of the recycling process, cement paste from high strength concrete is more difficult to detach from the NA particles than the weak concrete's cement paste.

Rates of water absorption for coarse RCA and NA are given in *table 5.5.* It can be seen that during the first half hour 70 to 90% of the 24 hour water absorption (WA_{24}) was already achieved. Then the rate reduced until total water absorption was achieved at the end of 2 hours of soaking. No further change was observed during the rest of the soaking period (2-24 hours). This behavior was of great importance as it played a major role in the mix design process where the water content had to be increased to compensate for the water absorption of the aggregates.

Table 5.5: Rate of water absorption of coarse NA and RCA.

AGGREGATE TYPE	PARTICLE SIZE (mm)	RATE OF ABSORPTION[†](% m/m)			
		30 min	60 min	120 min	24 hrs
NA	20 - 5	1.0	1.4	1.4	1.4
	< 5	0.7	0.8	0.8	0.8
RCA Source I	20 - 5	4.8	5.2	5.2	5.2
RCA Source II	20 - 5	3.9	4.9	5.5	5.5
RCA Source III	20 - 5	4.2	4.6	4.8	4.8

[†] Mean values of three results reported.

Examining the data, a high coefficient of correlation was identified between oven dry particle density and water absorption as shown in *figure 5.9*. Correlation with oven dry density was chosen because the particles were tested at a completely dry state (dried to constant mass) and therefore the aggregates have their full potential for water absorption. This shows that lower particle density is directly related to the porosity of the RCA which in turn results in high water absorption.

5.3.2.6 Particle densities

Particle densities of the aggregates were also examined and overall the results showed RCA had lower values when compared to NA. Despite this, results are still well within the classification range for normal weight aggregates (oven-dried density $\rho_{rd} \geq 2.000 Mg/m^3$). *Apparent particle density* (ρ_a) of RCA was found to range between 2.548 and 2.585 Mg/m^3 compared to 2.603 Mg/m^3 for NA, a decrease of about 0.7 to 2%. *Oven dried density* ρ_{rd} of RCA was found to range between 2.260 and 2.291 Mg/m^3 a reduction of about 8.8-10% when compared to the 2.511 Mg/m^3 of the NA. The noticeable decrease in density due to the oven drying process reflects the higher water content capacity of RCA when compared to NA. *Saturated surface dry density* (ρ_{ssd}) was also examined and RCA had densities ranging between 2.377 to 2.392 Mg/m^3, a reduction of 6% when compared to the density of 2.546 Mg/m^3 for NA. It is worth noting that although the differences for the apparent and oven

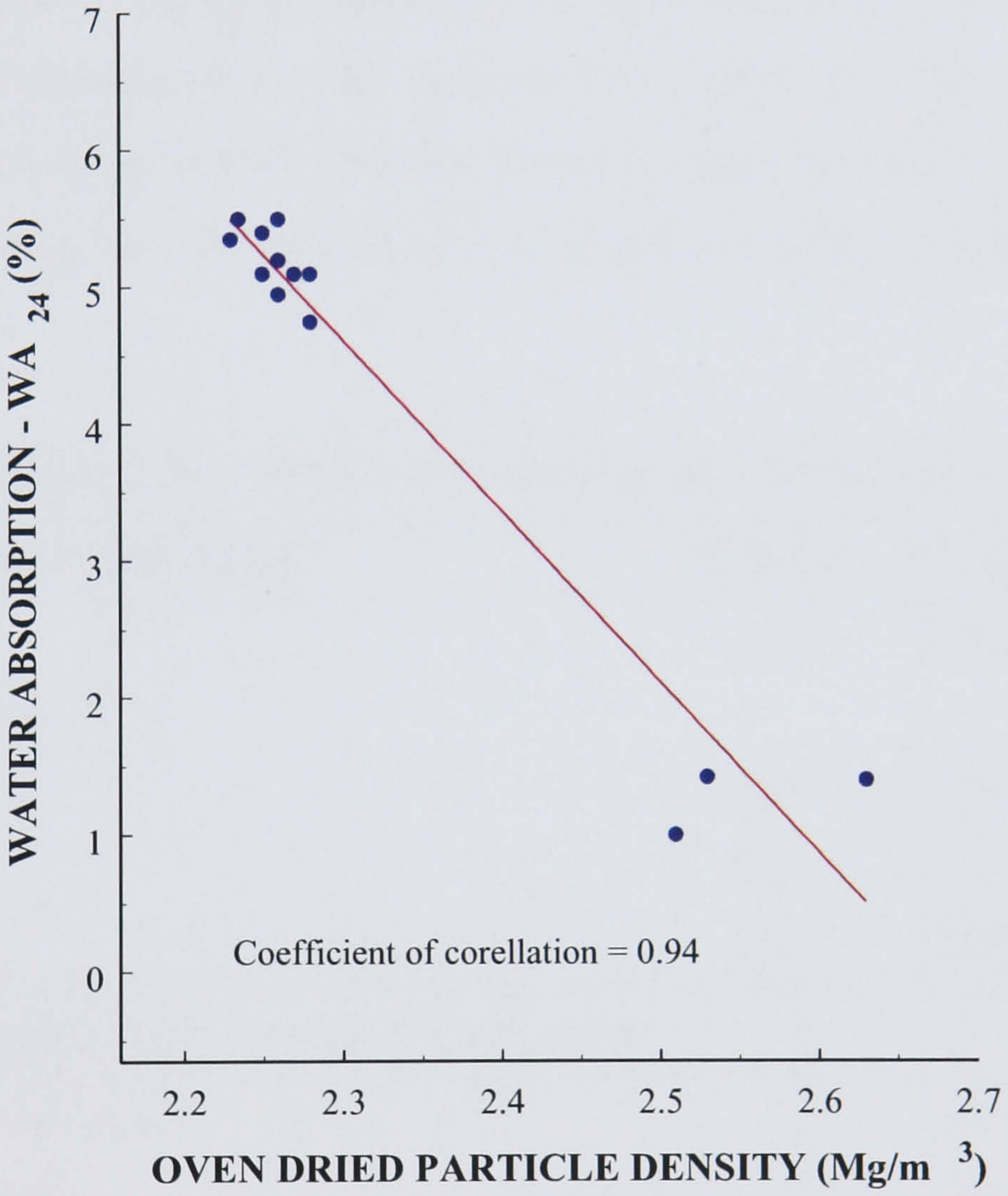


Figure 5.9: Relationship between water absorption and oven dried particle density (ρ_{rd}).

dried densities were low and high respectively, the density of most interest is the SSD density considered in the mix process.

5.3.3 Mechanical Characteristics

Mechanical properties of all coarse aggregates used in the study were assessed to establish the Aggregate Crushing (ACV), Aggregate Impact (AIV) and Ten percent Fines Values (TFV). Although testing was carried out following BS 812 procedures as described in *Section* 4.3.5.2, the standard is now partially replaced by BSEN 1097 Part 2 [88]. According to EN 12620 the determination of resistance to fragmentation can be assessed by the AIV and/or the Los Angeles coefficient (LA) as described in EN 1097.

Table 5.6: Mechanical characteristics of RCA and NA.

AGGREGATE SOURCE	**ACV(%)**	**AIV(%)**	**TFV(kN)**
NA	12.4	6.3-7.3	155
RCA sources			
Source I	22.0	13.0-15.4	170
Source II	17.5	11.8-12.2	190
Source III	23.9	7.2-9.6	193
BS 882 requirements for a range of applications			
Heavy duty pavements	-	25	150
Wearing surfaces	-	30	100
Other concretes	-	45	50

Results are given in *table 5.4* and in *table 5.6* against limitations for various concrete applications. The ACVs for RCAs ranged between 17.5-23.9% almost double the value of NA at 12.4%. The ACV value reflects the resistance of the aggregate under gradually increased load expressed as the percentage of crushed material at the end of the test and therefore the higher the value the lower the aggregate strength.

Results for the AIV test revealed a similar trend, with RCA ranging from 7.2-15.4%. This was double the values of 6.3-7.3 for NA but only for the first two sources of RCA. There was a considerable improvement in the AIV for source III RCA although the average decrease in aggregate impact resistance was still about 20% when compared to NA results.

Another test used to establish the resistance to fragmentation was carried out. namely the TFV. Results for RCA were found to be considerably higher than NA. In detail RCA Source I, had a TFV of 170 kN, Source II, 190kN and Source III, 193 kN. These values compared to NA TFV of 155 kN and despite their differences indicate that according to *paragraph* 4.3.5.2 both NA and RCA used met the requirements for any type of concrete.

Concluding, higher ACV and AIV values from RCA samples reflect the higher quantities of crushed material resulting from the attached cement paste around the RCA particles. It is therefore expected that with improved processing techniques the attached cement paste will be reduced and hence the aggregate crushing and impact values will be more comparable to NA values.

With the TFV test, the higher values for RCA may be due to the fact that the required 15 mm penetration of the plunger, caused the particles to compact, detaching attached cement paste in fragments mainly $>$ 2.36 mm. It is believed that this compaction was enough to allow the 15 mm movement before the original aggregate particles were crushed by the penetration of the plunger and particles $<$ 2.36 mm were produced.

5.3.4 Chemical-Mineralogical Characterisation

Aggregates for concrete including recycled and natural are subject to limits on their content of alkalis, chlorides and sulphates. In this study the chemical-mineralogical characteristics of coarse NA, RCA and natural sand have been analysed using XRF, XRD and ICP-AES techniques. Although in this study the main interest was concentrated on chloride, sulphate and alkali contents, the techniques provided much more detailed compositional results. The discussion of these additional results will be brief. Complete results will be included in Appendix C.

5.3.4.1 X-ray diffraction (XRD) characterisation

Results from X-ray diffraction provide information on the mineralogical composition of the samples. It would be expected that coarse RCA has a different composition from coarse NA due to the presence of attached cement paste as well as other materials and/or contaminants associated with the C&D debris. *Table 5.1* as discussed earlier gives the proportions of the RCA constituents and it is helpful to refer to this while discussing RCA from a mineralogical point of view. Coarse NA and natural sand compositions are much more predictable due to the lack of impurities that characterise recycled materials.

The main aim of this analysis is the comparison between the RCAs from various sources. This will give an indication as to how the source can affect their composition. Also it is important to assess how clear is the relationship between the XRD results and the quantities of constituent materials given in *table 5.1.*

Results are analysed and presented in the form of diffractograms produced by data included in Appendix C.2.

Figure 5.10 shows the diffractograms for coarse NA and natural sand. Coarse NA shows a clear predominance in SiO_2 identifying the material as chert. With sand again there is a predominance of SiO_2 but with another but low peak at 29^o 2θ, that indicates the presence of calcite $CaCO_3$. Although XRD gives a qualitative analysis it can be inferred that the very low peak indicates relatively low contents of this mineral.

However, it is much more interesting and challenging to interpret the XRD analysis, of the coarse RCA from the three sources. This is due to the increased number of peaks indicating a larger collection of minerals. For this reason each RCA will be dealt with separately and a summary diffractogram of all the RCAs investigated will be discussed at the end.

The diffractogram for RCA I is shown in *figure 5.11*. As with the NA discussed earlier, SiO_2 is the predominant mineral indicated by the high peak at 26.6^o 2θ. The only important difference when compared to coarse NA is the presence of a calcite

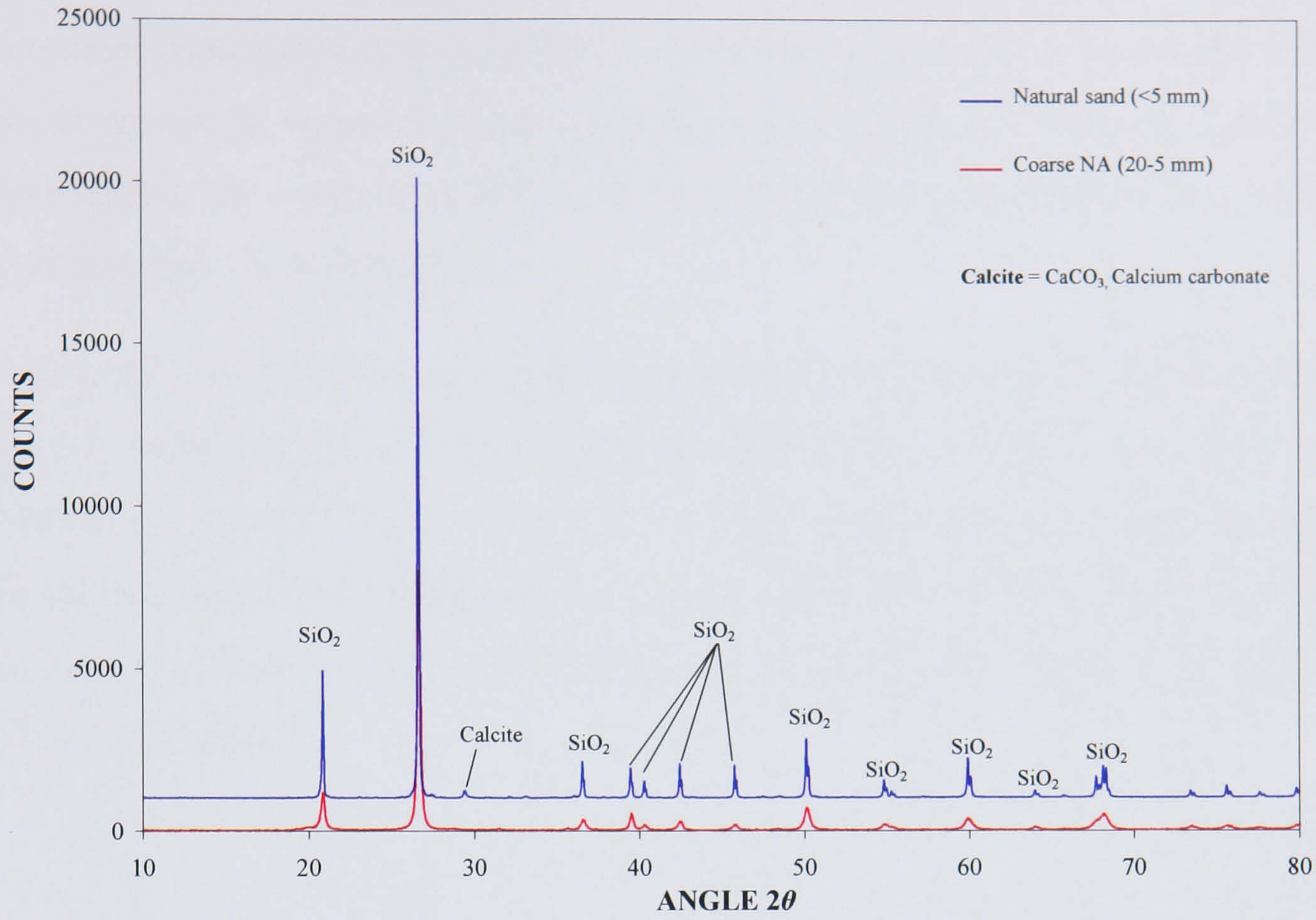


Figure 5.10: XRD analysis for coarse NA and natural sand used in the study.

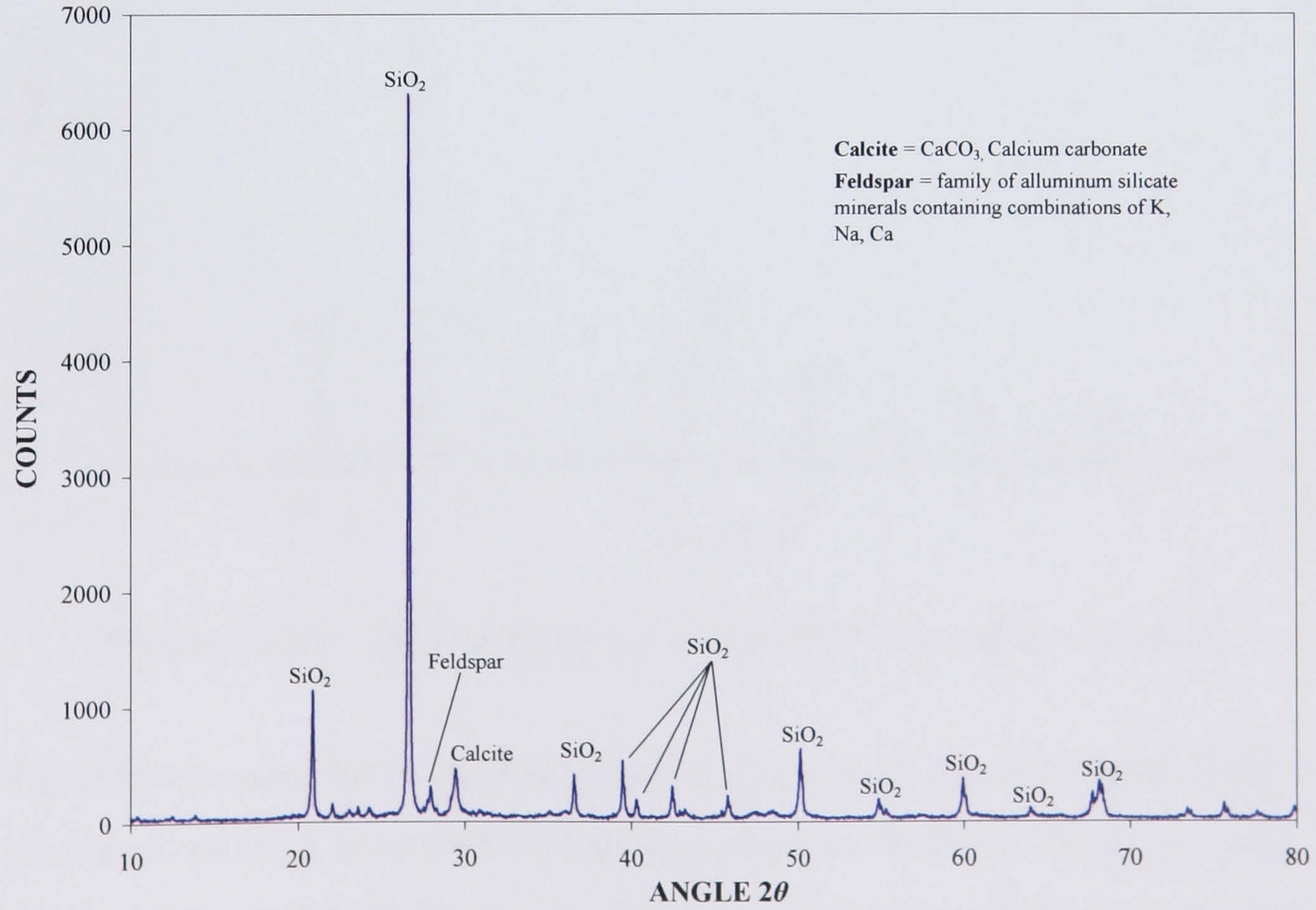


Figure 5.11: XRD analysis for coarse RCA I used in the study.

$(CaCo_3)$ peak shown at 29.5^o 2θ which could be present in the natural aggregates and cement paste of the original concrete, the sand contained in the attached cement paste or caused by exposure of the original concrete to the environment. The latter would involve the reaction between CaO present in the cement and CO_2 resulting in calcium carbonate $(CaCO_3)$.

Since recycled concrete aggregates are covered in cement paste from the original concrete, detection of the mineralogical phases corresponding to the products of hydration ie. C-S-H [1,2] etc. would be expected. However, due to their very small content compared to the predominant phases (i.e. SiO_2), the peaks representing these phases are very small and therefore subsumed in the background and very difficult to interpret.

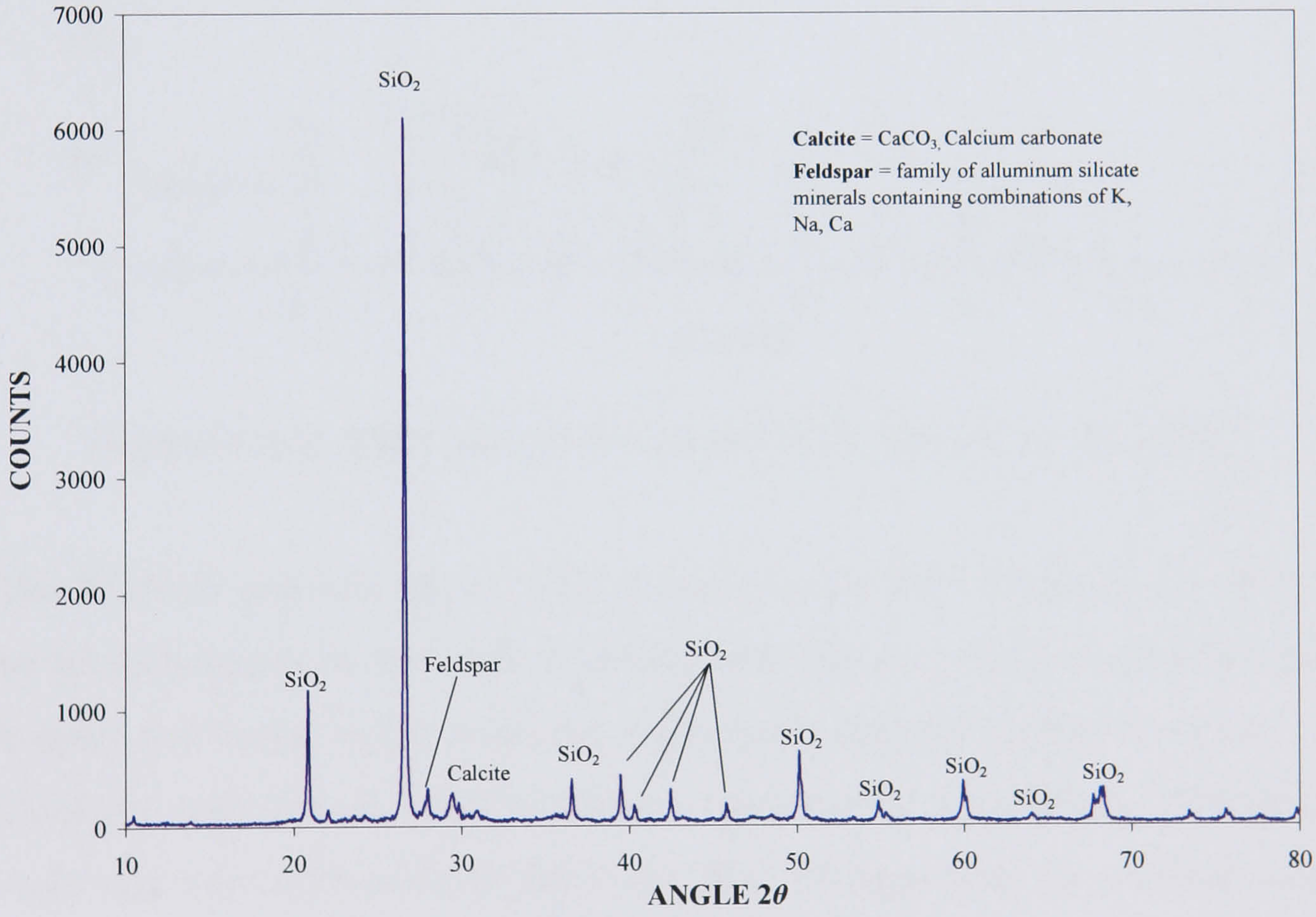


Figure 5.12: XRD analysis for coarse RCA II used in the study.

The diffractogram for RCA II is shown in *figure 5.12* and once again SiO_2 is the predominant mineral identified by the high peak at 26.6^o 2θ. A calcite peak also appears, shown at 29^o 2θ due to the presence of calcium carbonate in the original

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[1] Tricalcium silicate (C_3S) reacts with H_2O producing calcium silicate hydrate $C-S-H$

[2] Dicalcium (C_2S) reacts with H_2O producing calcium silicate hydrate $C-S-H$

aggregates as discussed for RCA I. Also detected was feldspar as shown by the peak at 28^o 2θ suggesting the presence of sodium aluminium silicate ($NaAlSi_3O_8$). Hydrated cement products were not visible for the same reasons as explained in RCA I.

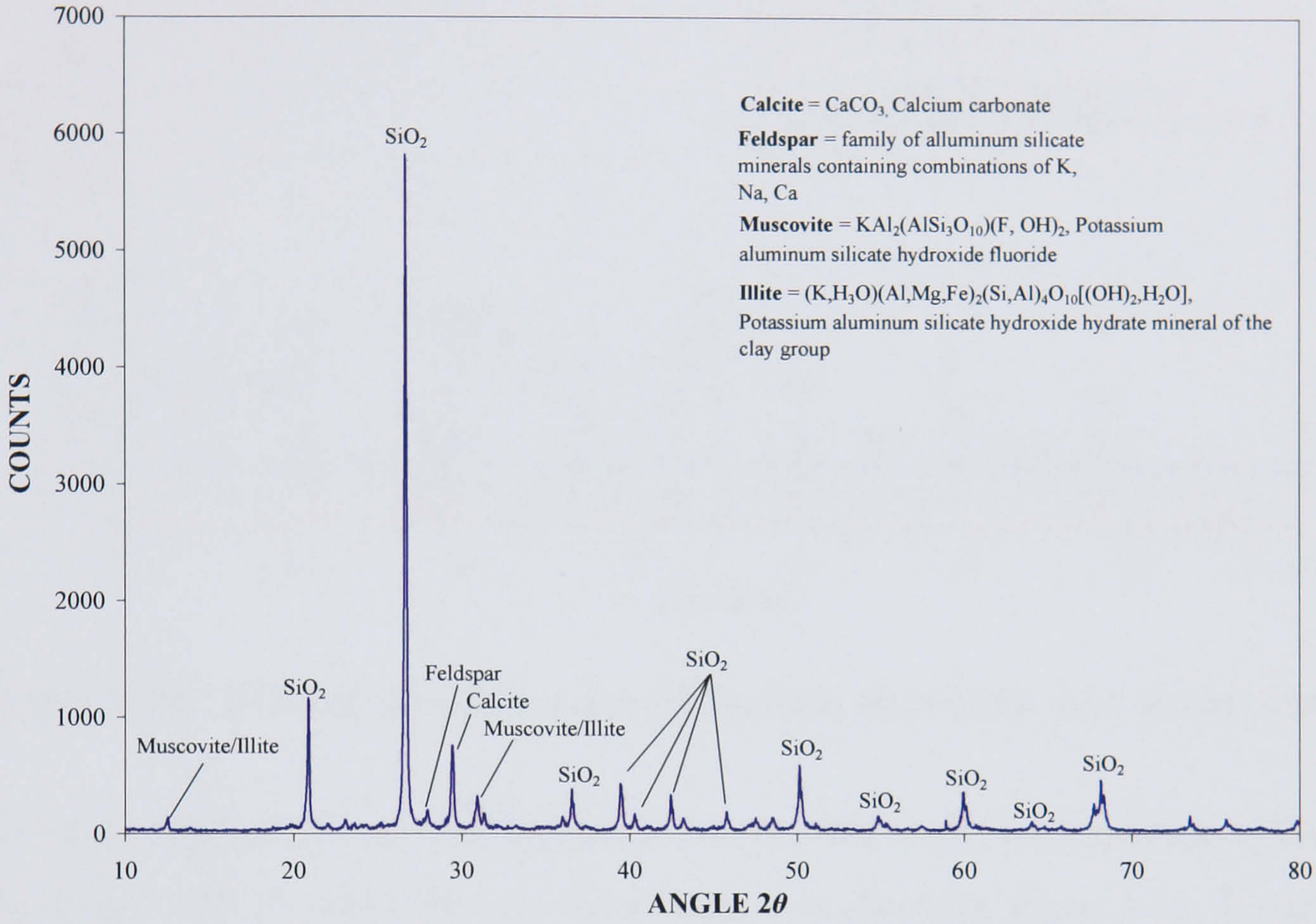

Figure 5.13: XRD analysis for coarse RCA III used in the study.

The RCA III analysis (*figure 5.13*) revealed as for RCA I and II, the predominance of SiO_2 shown at 26.6^o 2θ. A calcite peak was also present revealing calcium carbonate, and based on the relatively higher peak suggests increased content. The low feldspar peak reveals a lower content of this family of minerals. RCA III was the only aggregate with peaks at 12.6^o and 29.5^o 2θ suggesting the presence of muscovite [3] or illite minerals [4]. Due to the very similar structural arrangement of the two minerals, it was difficult to identify which one was present. These minerals are commonly present in masonry (bricks, mortar et.) and indicate the presence of masonry in the sample. Hydrated cement products were not visible for the reasons explained in RCA I.

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[3] Potassium aluminum silicate hydroxide fluoride - $[KAl_2(AlSi_3O_{10})(F,OH)_2]$

[4] potassium aluminum silicate hydroxide hydrate - $[(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$

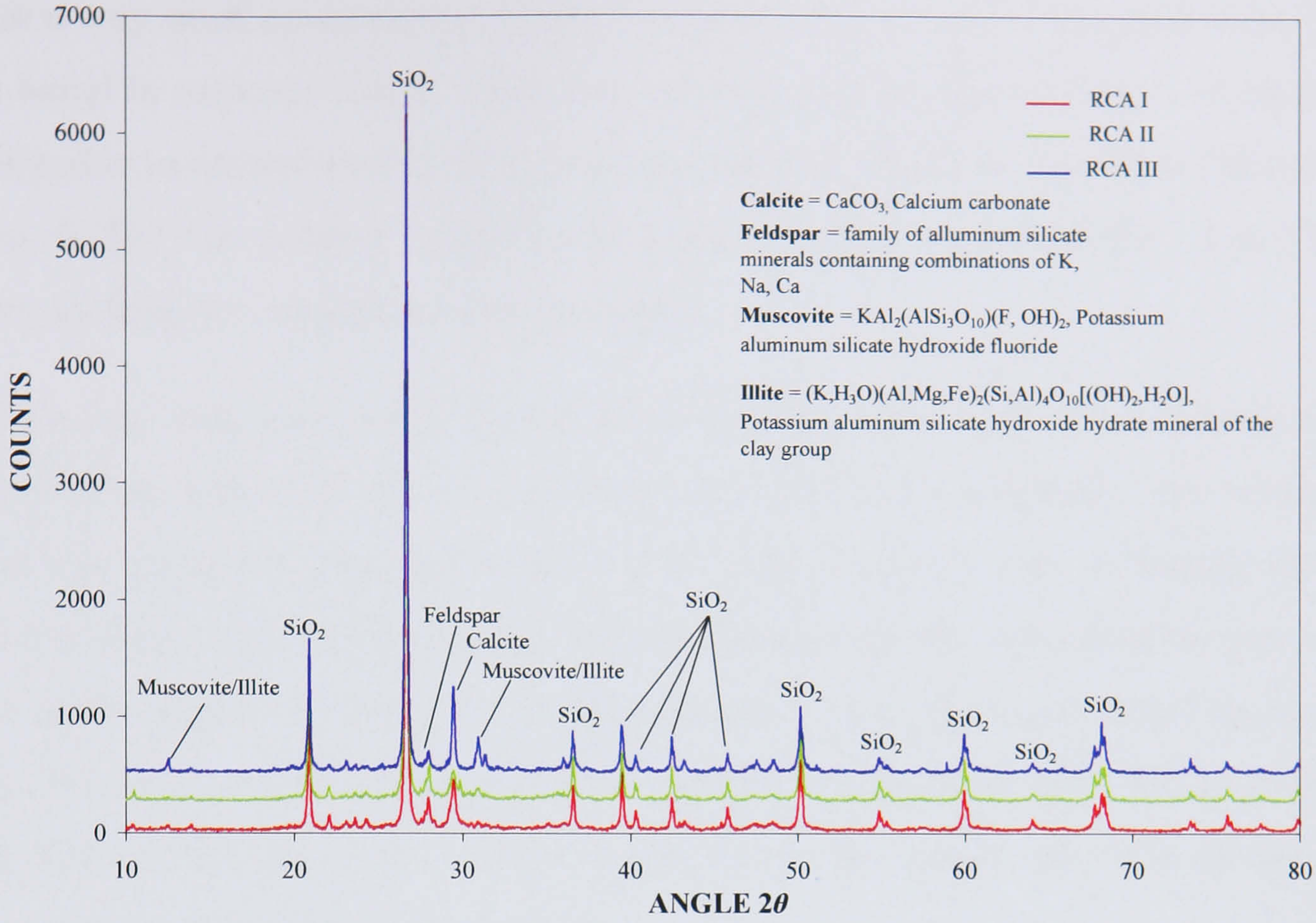

Figure 5.14: XRD analysis for coarse RCAs from all sources used in the study.

Summarising for the recycled aggregates used in this study, a comparison of X-ray diffraction results for RCA from all three sources is shown in *figure 5.14*. From the mineralogical point of view there is very little difference between the composition of the three recycled aggregates. All RCAs show a predominance in SiO_2 characterising them as mainly chert.

Calcite in the form of calcium carbonate was present as suggested by the peaks in all RCA diffractograms. The peak of calcite in RCA III was higher compared to RCA I which in turn was higher than in RCA II. It may be that since calcium carbonate is also present in bricks, the brick content may be related to the calcite. In fact according to the RCA constituents given in *table 5.1* the brick content shows the same trend as the calcite suggesting a relation between the XRD and RCA constituents' results.

A feldspar peak was also present in all RCAs showing the presence of minerals from the feldspar family. Finally, muscovite and/or illite minerals were present in RCA III and if carefully examined *figure 5.14* shows RCA II and possibly RCA I, also show a very small peak suggesting very low contents. As calcite and muscovite/illite are found in masonry (brick, block and mortar) used in construction it is therefore reasonable to assume that masonry content may be related to muscovite/illite presence. In fact the masonry content of RCA III is much higher that RCA I and II as given in *table 5.1* reinforcing this agreement.

From the comparison between the mineralogical composition of the three recycled concrete aggregates, it can be concluded that very small differences were detected from the qualitative analysis results of the XRD investigation. Although various other minerals were detected apart from silicon dioxide, all were minerals very common in the earths crust and at low proportions do not present potential hazards to concrete. However, the calcite and muscovite/illite phases detected which probably reflect the brick content of the RCA would need to be kept at low levels as table 5.1 suggests, as they could be deleterious.

Overall it can be concluded that RCA of very similar quality can be produced regardless the source subject to consistent production procedures and techniques.

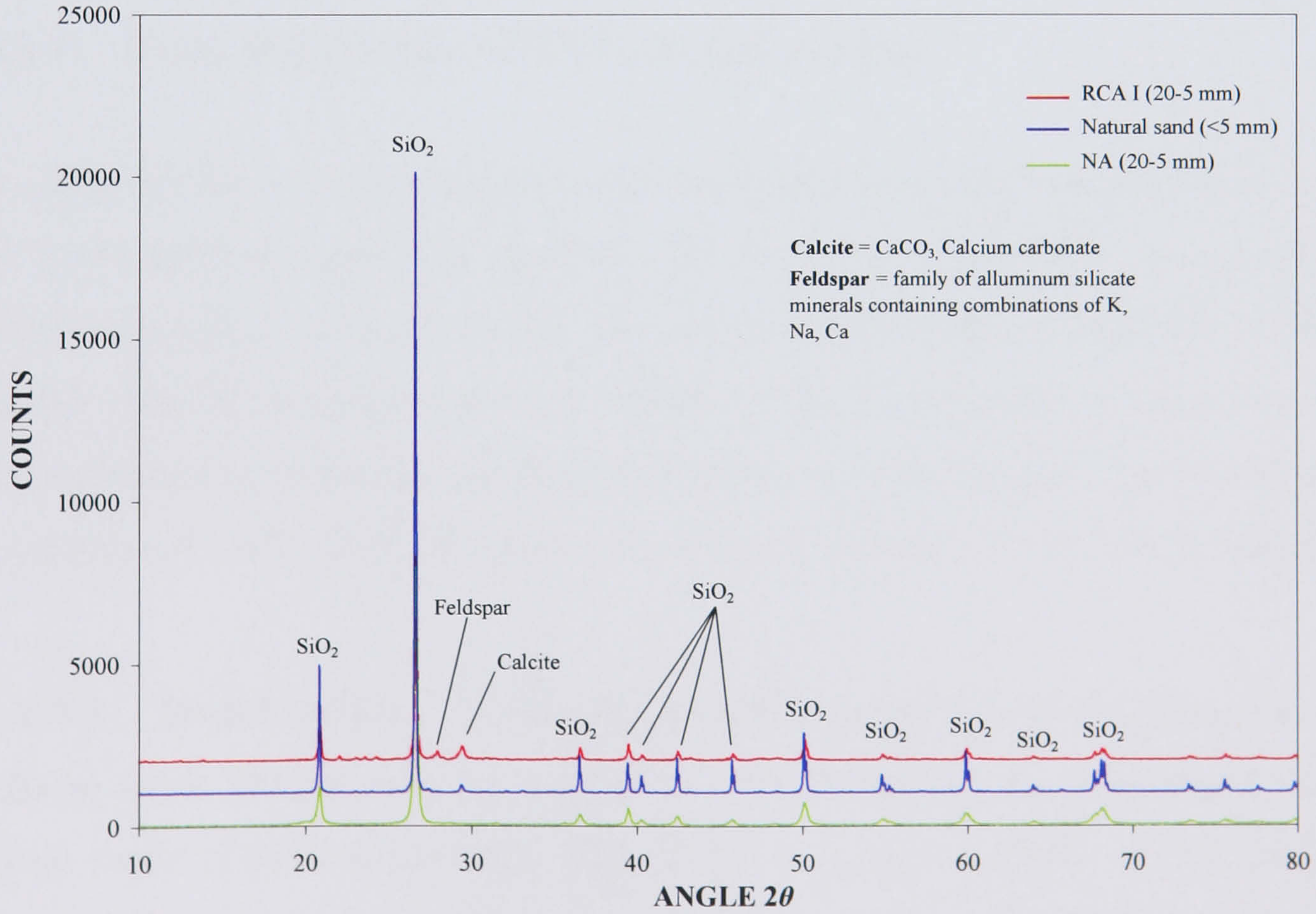

Figure 5.15: XRD analysis for coarse and fine aggregates used in the study.

Having analysed mineralogically both natural and recycled aggregates used in the study, it was considered worth while looking at and comparing the composition of recycled and the natural aggregates used for concrete production in this study. Therefore, results for RCA I, coarse NA and sand are superimposed in *figure 5.15*. The similarity between all three aggregates is evident, the main difference being the calcite peak present in RCA I and the natural sand but not in coarse NA. The suggestion in earlier paragraphs, that calcite presence in RCA partly originates from the sand forming part of the attached cement paste, is supported by the fact that both RCA and sand have the commonality of the calcite peak lacking from coarse NA.

Summarising, both the recycled and natural aggregates used in this study, presented very similar if not identical mineralogical phases. Having said that XRD analysis being a qualitative analysis technique needs to be coupled with XRF investigations which provide quantitative analysis of the aggregates' compositions. The following section will deal with this aspect of the study.

5.3.4.2 X-ray fluoresence (XRF) characterisation

The major oxides present in the recycled and natural aggregates used in this study, have been detected using XRF analysis and are given in *table 5.7*. As mentioned earlier the elements of most interest to concrete technologists are alkalis (K, Na), chlorides $(NaCl)$ and sulphates (SO_3). XRF provided the contents of potasium and sodium oxides needed for the calculation of the total alkali content. The variation in the contents of CaO, Al_2O_3, SiO_2 and other minor elements will be briefly discused.

5.3.4.2.1 Major oxides. Looking at the results given in *table 5.7*, the reduction in silicon oxide (SiO_2) and the increase in all other elements, most importantly calcium oxide (CaO), Aluminium oxide (Al_2O_3), potasium oxide (K_2O), sodium oxide (Na_2O) and iron oxide (Fe_2O_3) is striking when comparing RCA and NA. This is mainly due to the presence of the attached cement paste on the RCA particles and the inclusion of masonry (bricks, blocks, mortar) as part of the recycled aggregate.

As identified in XRD analysis with all aggregates there was a predominance of SiO_2 followed mainly by calcite, feldspar and muscovite/illite minerals. XRF revealed the exact content of silicon oxide for coarse NA at 97.03% and natural sand at 88.54% as was expected from the XRD investigation. Natural sand showed a small decrease in SiO_2 when compared to coarse aggregate due to this material being crushed and potentially mixed with similar material from different locations as well as containing $CaCO_3$ from natural deposits. This also explains the increase mainly in CaO and Al_2O_3 as well as small increases in most other oxides.

The most important observations concern RCA compositions. It was clearly identified that the presence of cement paste and other constituents resulted in decreased SiO_2 content. This was based on the fact that calcium, aluminium and iron oxides are mainly constituents of firstly cement paste and secondly masonry materials although the other oxides may also derive from those sources. The contents of the oxides are balanced in a very consistent way as shown in *figure 5.16*. Mainly, calcium and aluminium oxides are taking the place of the silicon dioxide of the original aggregate reducing its content from 97% to as little as 63.6%. To a lesser extent, all other oxides and particularly sodium, iron, potassium and magnesium oxides behave in the same way. This inversely proportional behavior of the major oxides may be

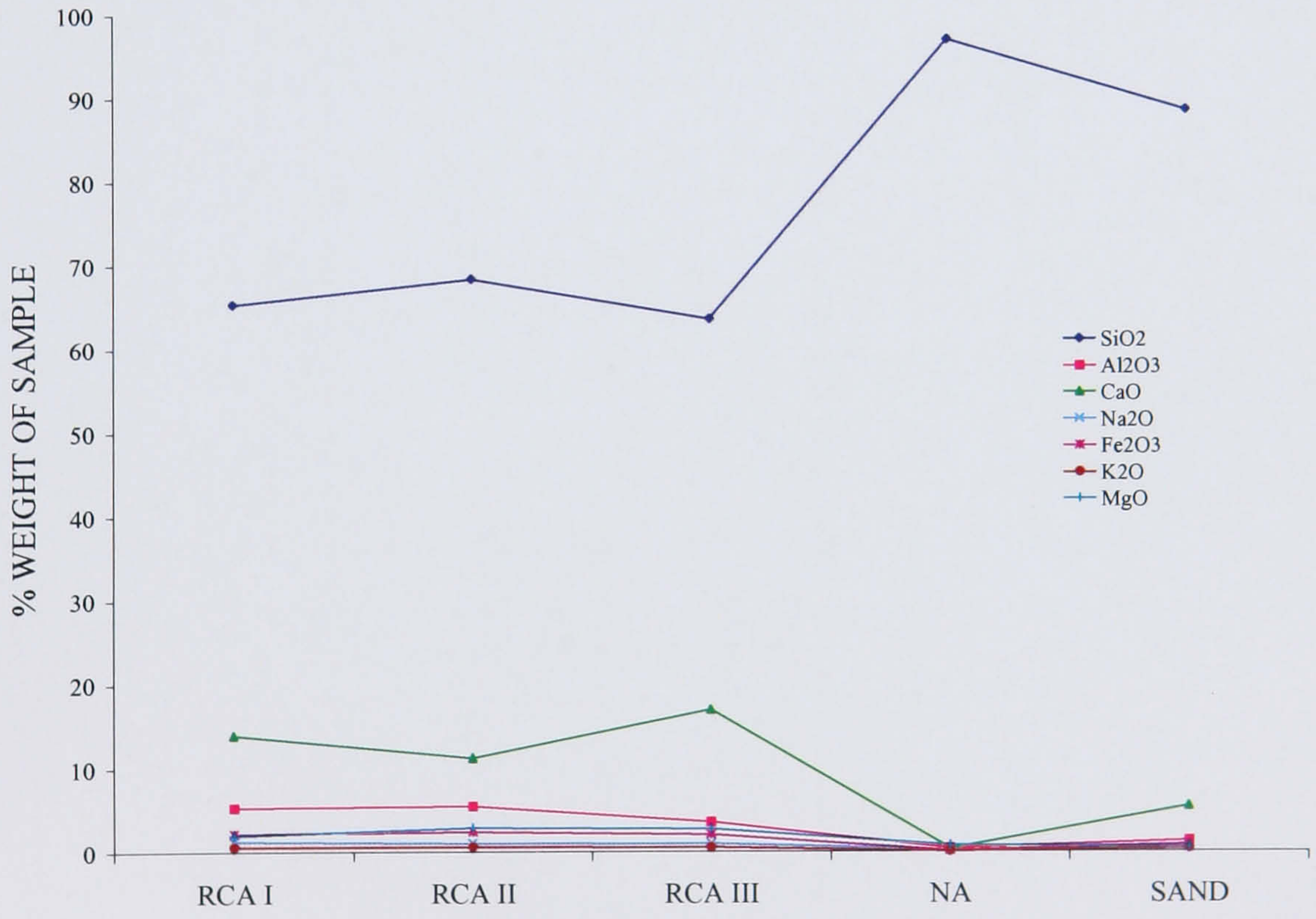

Figure 5.16: XRF analysis results showing the balance of oxide contents.

used as a way of measuring the amount of cement paste attached and in general the level of impurities present in the recycled aggregate produced.

More importantly in the context of this study was the observation made by looking at the RCA oxide contents alone. Calcium oxide (CaO) ranged between 11.19 and 16.86% which is a very narrow range considering this material derived from demolition debris. The same observation can be made for the aluminium and most importantly silicon oxide where results ranged from 3.57-5.49% and 63.61-68.43% respectively. In a similar though less dramatic way the contents of all other oxides showed narrow ranges also.

Therefore, in agreement with XRD results (qualitative), XRF quantification of the major oxides showed how similar the three recycled concrete aggregates are despite their origins being completely different.

Table 5.7: Major oxides of coarse NA, RCA and sand used in the study obtained by XRF analysis.

AGGREGATE TYPE	SIZE FRACTION (mm)	CHEMICAL COMPOSITION (% wt)									
		CaO	Al_2O_3	SiO_2	K_2O	Na_2O	Fe_2O_3	MnO	MgO	P_2O_5	TiO_2
NA	20 – 5	0.26	0.34	97.03	0.01	0.16	0.10	0.00	0.65	0.02	0.01
NA	< 5	5.33	1.21	88.54	0.31	0.33	0.76	0.02	0.42	0.08	0.05
RCA source	20 – 5										
Source I		13.93	5.33	65.37	0.61	1.19	2.16	0.05	1.91	0.11	0.22
Source II		11.19	5.49	68.43	0.62	0.98	2.40	0.05	2.84	0.10	0.39
Source III		16.86	3.57	63.61	0.51	0.87	2.03	0.06	2.62	0.49	0.17

Table 5.8: Chloride and sulphate contents of NA, RCA and sand used in the study obtained by ICP-AES analysis.

AGGREGATE TYPE	**SIZE FRACTION** (mm)	**a) CHLORIDE CONTENT**(% wt Cl^-)		**b)SULPHATE CONTENT**(% wt SO_3)	
		Water Soluble	Acid Soluble	Water Soluble	Acid Soluble
NA	20-5	0.00361	0.01212	0.00002	0.00003
NA	< 5	0.01043	0.05153	0.00005	0.00014
RCA sources	20-5				
Source I		0.01261	0.07902	0.00028	0.00046
Source II		0.00768	0.06257	0.00019	0.00033
Source III		0.01249	0.08954	0.00036	0.00057

5.3.4.3 Inductively Coupled Plasma - Atomic Emission Spectrometer (ICP-AES) analysis

5.3.4.3.1 Chloride content. Results for water soluble and acid soluble chloride contents were obtained for the three coarse RCAs, NA and natural sand and are given in *sections (a)and (b) of table 5.8.* The water soluble chlorides present in RCAs were found to be 2 to 3.5 times greater than in coarse NA but very similar (0.7 to 1.2) to that of natural sand. Both RCA I and III were found to have identical water soluble chloride contents whilst RCA II showed a content about 0.6 that of the other RCAs and also much less than that of natural sand. This latter finding indicating RCA having lower chloride content than natural sand shows how low are the contents of the aggregates used in general.

Assessing the acid soluble chloride contents, the RCAs were found to have 5 to 7 times more chlorides when compared to coarse NA, and 1.2 to 1.7 times that of natural sand. Referring back to the very low water soluble chloride content of RCA II, the same cannot be said for its acid soluble content which was very similar to the other recycled aggregates, suggesting that the chlorides present can be best revealed by acid attack. This also justifies the fact that BS 8500 Part 2 [7] requires the use of RCA's acid soluble content, for the determination of the concrete chloride content contributed by all constituents, while water soluble for natural aggregates is sufficient.

Limitations to the chloride content set by BS 882 are expressed as water soluble chloride content by weight of combined aggregate and to enable comparisons this value was deterrmined. A typical calculation is given in *table 5.9.*

Table 5.9: Typical calculation of water soluble chloride content as % by mass of combined aggregate.

RC30 mix containing 100% coarse RCA I

Coarse RCA content=1200 kg/m^3, Sand content=595 kg/m^3 (from *table 4.6*)

Water soluble chloride content (% wt):

Coarse RCA=0.0126%, sand= 0.0104% (*from Table 5.8*)

Therefore, :

Total water soluble chloride content = (1200 × 0.0126%) + (595 × 0.0104%)

$= 0.21 kg/m^3$ of concrete

0.21 × 100/2340 = **0.0091** % by weight of combined aggregate.

Table 5.10: Percentage of water soluble chloride content by weight of combined aggregate for all concrete mixes using ICP-AES analysis.

MIX DESIGNATION	CHLORIDE CONTENT(% wt)				
	RCA CONTENT (%)				
	0	**30**	**50**	**75**	**100**
GEN0	0.0055	0.0068	0.0076	0.0087	0.0098
GEN1	0.0054	0.0067	0.0076	0.0086	0.0098
GEN3	0.0048	0.0063	0.0072	0.0084	0.0095
RC30	0.0046	0.0060	0.0069	0.0080	**0.0091**
PAV1	0.0043	0.0059	0.0068	0.0080	0.0092
PAV2	0.0042	0.0057	0.0066	0.0078	0.0090
BS 882 requirements [11]	**% wt combined aggregate**				
Prestressed concrete	0.01				
RC with sulphate resisting cement	0.02				
Other reinforced concrete	0.05				

Results of water soluble chloride content, by weight of combined aggregate of the concrete mixes used in this study, are given in *table 5.10*. The calculated chloride contents for all aggregate combinations used in the designated mixes investigated, are well within the requirements for reinforced concrete and concrete containing sulphate resisting cement according to BS 882 [26] requirements. It can also be said that the requirement for prestressed concrete (applicable to RC and PAV series) was also met. However, the aggregate combinations containing RCA in excess of 50% are just below the 0.01 limit with values ranging from 0.0078 to 0.0091.

Table 5.11: Typical calculation of concrete total chloride content for RC30 100% calculated as the sum of the contributions from all constituent materials.

RC30 mix containing 30% coarse RCA I

Coarse NA content=845 kg/m^3, Coarse RCA content=360 kg/m^3, Sand content=615 kg/m^3 (from *table 4.6*), Cement content=335 kg/m^3 (from *table 4.5*)

Water soluble chloride content (% wt):

Coarse NA=0.0036%, Coarse RCA*=0.0790 %, sand=0.0104% from *table 5.8*), Cement=0.0781% (*from App. C*)

Therefore, :

Total chloride content = (845 × 0.0036%) + (615 × 0.0104%) + (360 × 0.0790%) + (335 × 0.0781%) =0.64 kg/m^3 of concrete

0.64 × 100/335 = **0.19** % by cement mass. aggregate.

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[*] For RCA and RA use of acid soluble content is required according to BS 8500 table 2 [7].

The total chloride content of concrete from all constituents, is subject to limitations set by the newly introduced BSEN 206 Part 1 [10]. Requirements are expressed as maximum chloride content by mass of cement. Chloride contents used in these calculations involve water soluble contents for natural aggregates and cement while acid soluble content is used for RCA according to table 2 of BS 8500 Part 2 [7]. A typical calculation according to BSEN 206 [10] is given in *table 5.11.*

Table 5.12: Chloride content of concrete mixes calculated as the sum of the contributions from all constituent materials according to BSEN 206.

MIX DESIGNATION	**CHLORIDE CONTENT**(% wt cement)				
	RCA CONTENT (%)				
	0	**30**	**50**	**75**	**100**
GEN0	0.15	0.29	0.38	0.49	0.59
GEN1	0.14	0.28	0.36	0.46	0.56
GEN3	0.12	0.22	0.29	0.37	0.44
RC30	0.11	**0.19**	0.24	0.30	0.35
PAV1	0.11	0.20	0.25	0.31	0.37
PAV2	0.11	0.18	0.23	0.28	0.34

EN206:1 requirements[10]	**Chloride class**	**Max Cl^- by mass of cement**
Not containing steel reinforcement or other embedded metal i.e GEN series concrete	Cl 1.0	1.0%
Steel reinforcement or other embedded metal i.e RC30 concrete	Cl 0.2 Cl 0.4	0.2% 0.4%
Containing prestressing steel reinforcement	Cl 0.1 Cl 0.2	0.1% 0.2%

Concrete chloride contents in accordance with BSEN 206 are given in *table 5.12*. The results show that all designated mixes investigated, meet the requirements for chloride class 1.0 applicable to concrete not containing reinforcement or any other metal. This class is most applicable to the GEN series of mixes which all fall well within the 1% requirement regardless of the content of coarse RCA. However, in the case of GEN 3 used in domestic floors requiring embedded steel, a chloride content < 0.4 needs to be met. In this case a maximum of 50% RCA content will be recommended.

With the RC and PAV series, which in most cases include reinforcement or some kind of embedded metal (pavement joints), they all met the requirements for class

0.4 although with a 100% RCA the concrete chloride content is close to this limit. Suitable mixes for the more restrictive class (< 0.2) are those with a maximum RCA content up to 30% and for < 0.4 up to 100%. Finally, the most severe limit applicable to prestressed concrete (not applicable to RC and PAV series) of class 0.1, was not met by any of the mixes investigated in this study.

As a final observation it is worth noting that the ICP-AES technique used in this study detects exact concentrations and therefore provides higher values compared to the recommended EN 1744 [89] method which is less capable in detecting accurately exact concentrations of chlorides. Nevertheless the results were very satisfactory.

5.3.4.3.2 Alkali content Calculation of the total alkali content from all concrete mix constituents was carried out and a typical calculation for the RC30 mix containing 30% coarse RCA from source I is given in *table 5.13.* Using the equivalent sodium oxide (Na_2O_{eq}) as recommended by BS 8500 Part 2 [7], alkali contribution by each of the constituent materials was calculated using equation 5.1 as given in BSEN 206 Annex C except in the case of cement where the mean declared value was used, at 0.575% by wt as allowed by the same standard.

$$BS\ 8500\ Part\ 2 - Annex\ c.2 \quad Na_2O_{eq} = 0.76 \times \%Cl^- \tag{5.1}$$

Where:

- Na_2O_{eq} is the equivalent alkali content expressed in kg/m^3
- $\%Cl^-$ is the chloride ion content expressed in % wt given in table 5.8

In the case of alkali content there are no set limits by current standards. In order to minimize the occurrence of damaging alkali silica reaction (ASR) in concrete, it is necessary to conform with a set of conditions as required by BS 8500 Part 2. Clause 5.2.4 of this standard, covers RCA as high reactivity aggregate and therefore concrete containing such aggregate is potentially prone to ASR. A recent report by the Waste Resources Action Programme (WRAP) [109], covers the 2005 amendment of BS 8500 where the reactivity classification for RCA is relaxed to normal reactivity.

Table 5.13: Sample calculation for alkali content contributed by constituents of RC30 mix containing 30% RCA.

	DATA	CALCULATION
ALKALI CONTENT CONTRIBUTED BY PC		
Cement content	$= 335kg/m_3$ (Table 4.5)	
$\%Na_2O_{eq}$	$= 0.575$ mean declared value (Table 4.4)	$335 \times 0.575 \div 100 = 1.9263kg/m^3$
ALKALI CONTENT CONTRIBUTED BY NA SAND		
Sand content	$= 615kg/m_3$ (Table 4.6)	$Na_2O_{eq} = 0.76 \times \%Cl =$
$\%Cl^-$	$= 0.05153$ (Table 5.8)	$= 615 \times (0.76 \times 0.05153) \div 100 =$
		$0.2409\ kg/m^3$
ALKALI CONTENT CONTRIBUTED BY 70% NA		
20 - 5 mm content	$= 900kg/m_3$ (Table 4.6)	$Na_2O_{eq} = 0.76 \times \%Cl =$
$\%Cl^-$	$= 0.01212$ (Table 5.8)	$= 845 \times (0.76 \times 0.01212) \div 100 =$
		$0.0778\ kg/m^3$
ALKALI CONTENT CONTRIBUTED BY 30% RCA		
20 - 5 mm content	$= 386kg/m_3$ (Table 4.6)	$Na_2O_{eq} = 0.76 \times \%Cl =$
$\%Cl^-$	$= 0.07902$ (Table 5.8)	$= 360 \times (0.76 \times 0.07902) \div 100 =$
		$0.2133\ kg/m^3$
	TOTAL ALKALIS CONTRIBUTED BY ALL CONSTITUENTS:	**2.46** kg/m^3

The total alkali contents (Na_2O_{eq}) for all designated mixes used in this study, are given in *table 5.14*. From the results, it can be observed that the contributions of alkali content from all constituent materials of the mixes used in this study, ranged between 1.47 and 3.29 kg/m^3. Such contents are highly unlikely to result in ASR affecting concrete durability. As shown in the sample calculation given in *table 5.13* cement is the main contributor accounting for 78% of the alkali content of concrete. The contribution from RCA ranged from 7% to 20% varying according to mix proportions and being very similar to the natural sand contributions at 6% to 15%. Coarse NA alkali contribution was limited to a maximum of 5% of the total content.

Table 5.14: Equivalent alkali content contributed by all constituents in all concrete mixes used containing various RCA contents.

MIX DESIGNATION	EQUIVALENT ALKALI CONTENT (kg/m^3)				
	RCA content (%)				
	0	**30**	**50**	**75**	**100**
GEN0	1.47	1.64	1.90	1.96	2.13
GEN1	1.54	1.72	1.86	2.05	2.22
GEN3	1.92	2.11	2.28	2.46	2.67
RC30	2.28	**2.46**	2.64	2.86	3.09
PAV1	2.30	2.50	2.67	2.87	3.07
PAV2	2.52	2.71	2.87	3.08	3.29

Summarising, the total alkali content of all designated concrete mixes used in the study was calculated based on the $\%Na_2O_{eq}$ content of each constituent. This was calculated for both the natural and recycled aggregates used, whilst the mean declared manufacturer's value was used for cement. Results have shown small contributions by all aggregates including RCA with the major contributor being the cement. Therefore, to control the total alkali content in the concrete mix, adjustments and/or cement replacements need to be used to lower the alkali content. In this study the alkali content of concrete was very low and therefore damaging from ASR is unlikely.

5.3.4.3.3 Sulphate content. The rules for permissible sulphate contents are clearer. According to BSEN 12620 [9] aggregates are classified according to their sulphate content in classes which limit the content to $\leq 0.2\%$, $\leq 0.8\%$, and $> 0.8\%$ as given in table 20 of EN 12620. This European normative is not currently covering RCA requirements but a new version with RCA/RA provisions is under development. Currently, use of RCA, including sulphate requirements, is covered in BS 8500, which sets a clear limit to acid soluble sulphates (SO_3) at 1% by mass of RCA. This limit is high when compared to natural aggregates and this recognises that although RCA may contain increased amounts of sulphates, they are not necessarily in soluble form [110].

The detected sulphate contents for all aggregates used in this study are given in *table 5.8.* The results although higher for RCA when compared to NA, are still extremely low, easily meeting requirements as set by the relevant standards.

5.3.5 Practical Implications

Work carried out during this phase of the study has clearly shown that quality recycled aggregate can be produced which conforms to the requirements for natural aggregates for concrete as per BSEN 12620 and BS 8500. However, more efficient methods of sorting the debris produced during construction and/or demolition on sites have to be developed. In this manner, further recycling, including reinforcement, glass, paper, wood etc. could be achieved at the same time as delivering better quality C&D debris to recycling plants, accelerating the process, and improving the quality of the final product. The aggregate and landfill taxes already on construction and demolition contractors have provided incentives resulting in the development and implementation of proper methods for sorting foreign materials which have enhanced the recycling of C&D debris for reuse in concrete instead of diverting it to landfills.

However, due to the higher water absorption of RCA (up to 4 times that of NA) care needs to be taken in designing the concrete mix. i.e. additional water is required to compensate for the RCA's higher water absorption in order to maintain the required workability. The mechanical properties of RCA produced similar if not better results when compared to NA. Indeed ten percent fines value indicated RCA was stronger when compared to NA although the crushing and impact values indicated that RCA is weaker under steadily increased and impact loads. Although there are differences in the results, all meet the requirements for any type of concrete application as given in *table 5.6.*

5.3.6 Conclusions

- Construction and demolition debris from RC frame structures of unknown concrete composition was assessed and it was proven that quality coarse RCA can be produced regardless of the source.
- Coarse RCA was found to be rounder less angular and less flaky than NA comfortably conforming to the requirements of EN 12620 and sometimes being better than NA.
- As a result of the original cement paste attached to the surface of RCA, the SSD particle density (ρ_{ssd})was found to be about 6% lower than that of NA and the water absorption (WA_{24}) up to 4 times that of NA. This reflects the production methods used and the development of new and improved methods of recycling over the years.
- RCA produced TFV results which showed a higher resistance to fragmentation than NA. However, the ACV and AIV for RCA were much lower (up to 100%) when compared to NA values. Despite the differences in mechanical properties, both RCA and NA are well within the limits for use in concrete for heavy-duty pavements.
- Chloride contents of RCA were found to be higher when compared to NA especially in the case of acid soluble contents. However, results met the requirements set by the standards for combined aggregate chloride content relevant to concrete applications.

- Alkali contents were found to be very low with RCA contribution not significantly greater that that of natural aggregates used in the concrete mixes. As a result all designated mixes, regardless of their RCA content, showed low alkali contents thereby minimising ASR potential.

- Sulphate contents of recycled as well as natural aggregates were found to be very low, conforming to all requirements set by British standards and European Normatives.

- In addition RCA was found to conform with all requirements of BS 8500 for RCA as given in *figure 3.2* and clause 4.3 of the standard.

- RCA of very similar quality can be produced regardless of the source subject to there being consistent production procedures and techniques.

- In general RCA contained lower proportions of SiO_2 to NA and higher proportions of Aluminium, Calcium, Sodium, Iron, Potassium and Magnesium oxides.

- If alkali contents need to be controlled in a concrete mix containing RCA, it is recommended that the adjustments to the cements or cement replacements be employed.

CHAPTER 6

FRESH PROPERTIES OF RCA CONCRETE

6.1 INTRODUCTION

Of all the constituent materials of concrete, aggregate accounts for up to 80% of the volume of normal weight concrete. Consequently it is important to understand the influence of the various properties of aggregates on concrete. In the case of fresh properties aggregate plays a key role. For example, water demand of the mix is affected by characteristics such as shape, texture, density, porosity and water absorption of the aggregate used.

Previous studies have mainly concentrated on the effect of various contents of RCA on the fresh properties of concrete. Few studies investigated other aspects of workability such as loss of workability over time, retention of air entrainment, stability and cohesiveness.

Against this background an extensive experimental programme was devised to investigate the effect of coarse RCA content on the fresh properties of concrete. The program was divided into two studies as shown in *figure 6.1*. **Study 1** dealt with workability in terms of slump, compacting factor, and stability, by assessing cohesiveness, handling, bleeding and segregation. **Study 2** dealt with loss of workability by means of compacting factor and retention of air entrainment.

The investigation included equivalent strength RCA concrete mixes containing up to 100% coarse RCA. Mixes suitable for applications such as blinding, mass filling, foundations, (GEN1, GEN3), paving (PAV1, PAV2) and reinforced concrete (RC30) were used. The mixes reflected characteristic strengths ranging from 10-35 N/mm^2

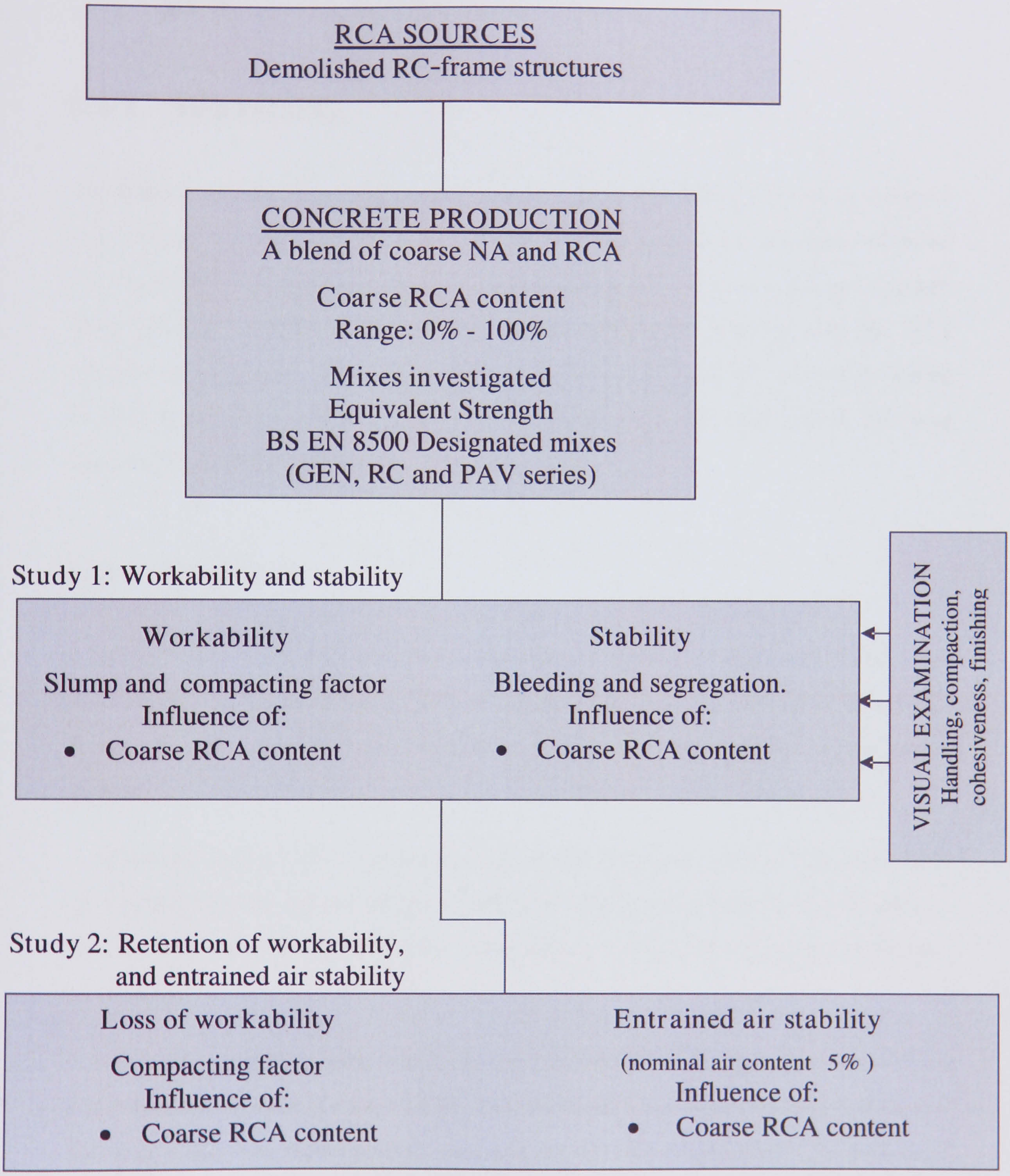


Figure 6.1: Experimental programme examining the influence of coarse RCA on fresh properties of concrete

6.2 STUDY 1:WORKABILITY AND STABILITY

6.2.1 Workability

Workability and stability results are given in *Table 6.1* for the designated mixes used in the study. Generally it was observed that the inclusion of RCA had no effect on the workability of concrete measured by the slump test. The variations in slump between RCA concretes of the same designation had no correlation with the RCA content, and although 100% RCA concretes for the GEN and RC series were found to have lower slump values, these remained well within the tolerance of ±20 mm required by EN 206 Part 1 [10].

6.2.2 Stability

Stability observations reflected the slump results. All mixes were found to be cohesive and the inclusion of RCA did not indicate the need for additional mix water further to that added for water absorption since all slump results met the target values.

Observations showed RCA concrete mixes did not bleed while at the same time produced workable concrete with no deleterious effect on finishing when compared to NA concrete. Stability was classified according to *Table 4.13* and results are shown in *Table 6.1*.

Observations during compaction showed no indication of segregation tendencies regardless the content of coarse RCA. Also as noted above there was no evidence of bleeding which was most carefully assessed on the PAV series where the surface of 1 m^2 specimens were left to dry for an hour before being carefully finished.

Handling involved concrete being transferred from the mixer using scoops into moulds and compacted. No special care was necessary for RCA concrete mixes and similar durations of compaction times between specimens were maintained. No difficulties were encountered due to RCA content.

Table 6.1: Workability results and stability classification.

DESIGNATED MIX AND (% RCA)	SLUMP (mm)	TARGET SLUMP (mm)	CLASS[a]	STABILITY PERFORMANCE
GEN1 (0)	125	120 (S3)[b]	2c	Normal
GEN1 (30)	130		2c	Normal
GEN1 (50)	135		2c	Normal
GEN1 (100)	120		2c	Normal
GEN3 (0)	60	45 (S2)[b]	3	Normal
GEN3 (30)	55		2b	Normal
GEN3 (50)	50		2b	Normal
GEN3 (100)	45		2b	Normal
RC30 (0)	80	75 (S2)[b]	2a	Normal
RC30 (30)	75		2b	Normal
RC30 (50)	70		2a	Normal
RC30 (100)	65		2a	Normal
PAV1 (0)	55	55 (S2)[b]	2a	Normal
PAV1 (30)	60		2a	Normal
PAV1 (50)	65		2a	Normal
PAV1 (100)	45		2b	Some shear
PAV2 (0)	55	60 (S2)[b]	2a	Normal
PAV2 (30)	60		2a	Normal
PAV2 (50)	55		2a	Normal
PAV2 (100)	70		1	Normal

[a] Stability classification according to *table* 4.13.

[b] Slump class according to *table* 4.10.

6.3 STUDY 2: LOSS OF WORKABILITY AND ENTRAINED AIR STABILITY

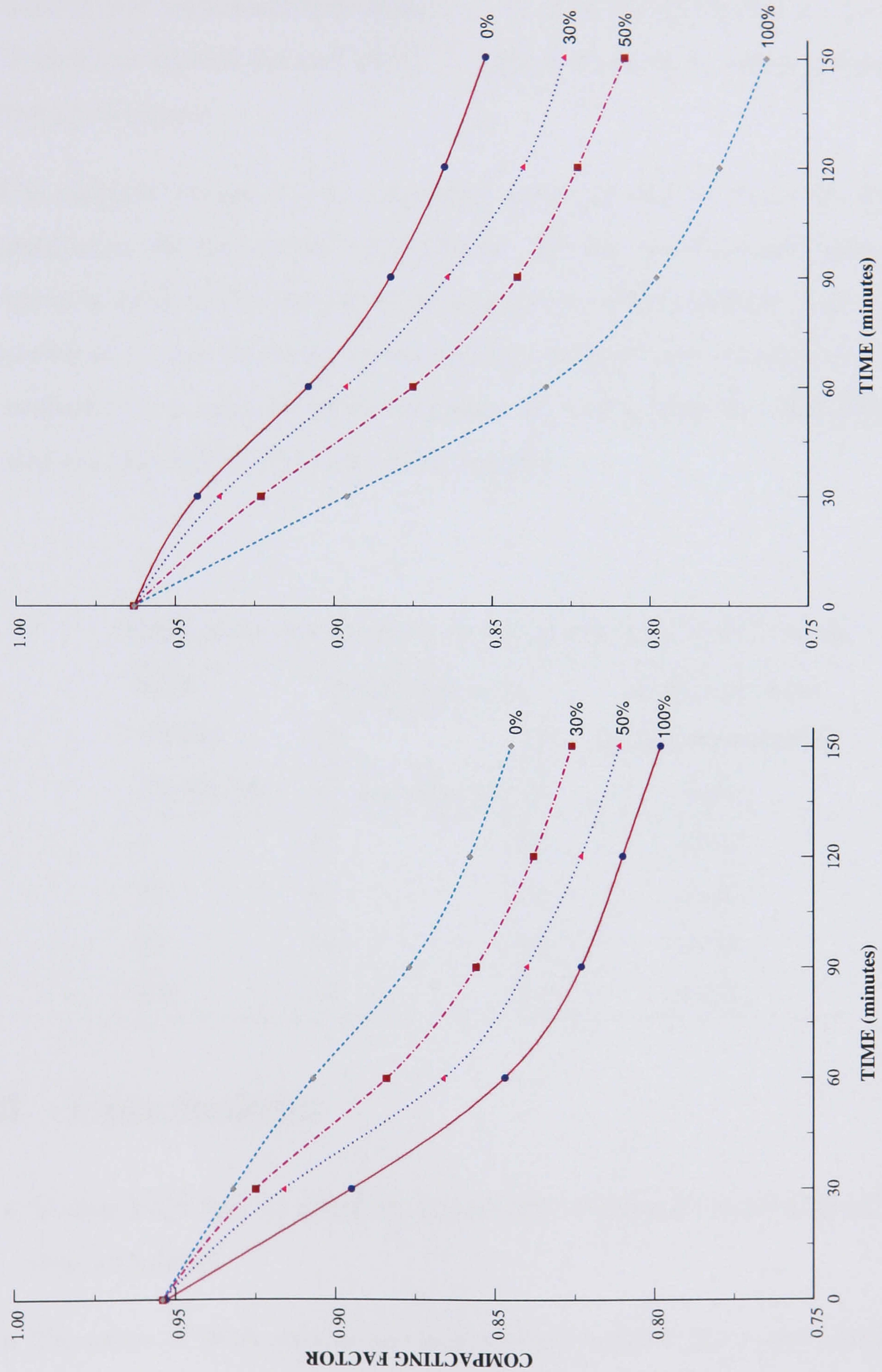
6.3.1 Loss of workability

The effect of RCA on loss of workability was measured using the compacting factor test. The procedure was to repeatedly measure the CF of the concrete at 30 minute intervals starting immediately after mixing and continuing up to 150 minutes. The results are shown graphically in *figures 6.2(a)* and *6.2(b)*.

The general trend was the same for the PAV and GEN series of mixes tested. It was evident that the loss of workability for RCA concrete occurs at a faster rate than NA concrete. The higher the proportion of RCA, the greater the discrepancy. This was mainly due to the higher water absorption of the RCA particles which continued to absorb the extra water added to satisfy this characteristic, over the test period of 150 minutes.

According to findings by the author, given in *table 5.5*, between 70-90% of the water absorption capacity of aggregate particles was satiated between 30 and 120 minutes after immersing the aggregate into water. Evidence here suggests that absorbing the required amount of water within the mix, is a slower process compared to immersing the aggregate directly into water, nevertheless it can be concluded that a reduction of the total water content due to the absorptive capability of the aggregates occurs. The loss of workability for RCA concrete was higher than that of NA concrete, and the effect increased with increased RCA content. It is likely that fresh cement paste surrounding the aggregate particles seals up the surface thus reducing subsequent water movement into the particles. Further, the cement hydration will initiate on contact with water, resulting in cement paste being gradually less permeable to water as it hydrates. Clearly, several factors are simultaneously causing loss of workability. Very importantly, thw w/c adjustment result in increased cement content and therefore increased hydration processes which consume the free water.

In any case, it is very important to know the rate at which workability of a concrete batch is lost over time. According to BS 8500 Part 1 [8] and BSEN 206 Part 1 [10], the workability needs to be examined at the time of delivery and therefore the producer will need to consider loss of workability in order to deliver a product meeting the fresh properties specified.



(a) PAV1 loss of workability

(b) GEN3 loss of workability

Figure 6.2: Effect of RCA content on the loss of workability over time for PAV1 and GEN3 concrete.

6.3.2 Entrained air stability

In order to assess the effect of coarse RCA content on the maintenance of entrained air content over time, tests were carried out as described in *Section 4.3.6.1* of *Chapter 4*. Testing was carried out on the PAV1 designated mixes to assess requirements for paving applications.

The required dosage of air entraining agent to achieve a 5% air content was established at 360 ml per 100 kg of cement. The air entrained and subsequent loss are given in *table 6.2* for various RCA proportions. The variation in air content was measured at 15 and 60 minutes after mixing and produced a negligible reduction in air content over a range of RCA inclusions. It is clear that the capability to retain air was not affected at all by the RCA content.

Table 6.2: Retention of air entrainment for PAV1 mixes.

MIX	**TIME** (minutes)		**LOSS OF AIR**
TYPE	15	60	**ENTRAINMENT**
(% RCA)	Air entrainment (%)		(%/hr)
0	5.5	5.3	0.267
30	5.9	5.5	0.533
50	5.1	5.0	0.133
100	5.5	5.4	0.133

6.4 Conclusions

- Coarse RCA had no effect on workability measured immediately after mixing was completed.
- The effect of RCA content on the loss of workability was evident with increases in RCA content. This was due to the higher absorption of RCA resulting in a longer period needed for the aggregate to absorb the extra water, which was provided to compensate for the water absorption. In this manner the mix

continued to lose workability for longer and at a higher rate when compared to NA concrete.

- Increased cement content due to w/c adjustment results in faster setting of the concrete.

- There was no bleeding observed in any of the mixes regardless the RCA content.

- Handling and finishing was carried out as for any NA concrete and no requirements for change in practice were identified due to the inclusion of RCA.

- The inclusion of RCA did not have any significant effect on the cohesiveness of concrete mixes. Compaction was carried out in same manner as for NA concrete and no indication of segregation was identified.

- The retention of entrained air was not affected by the inclusion of any proportion of RCA. In addition the dosage required to achieve an air content of 5% did not require any adjustment due to the RCA content.

CHAPTER 7

ENGINEERING PROPERTIES OF RCA CONCRETE

7.1 INTRODUCTION

Testing concrete in the hardened state is of prime importance since it reveals whether the material performs according to the specifications and requirements set by the relevant standards. In this part of the study, RCA and NA concretes have been thoroughly investigated establishing their engineering properties. The direct and indirect effects of the inclusion of coarse RCA as NA replacement in the mix, have been established. The concretes under investigation were designed for equivalent strength, through adjustment of cement content for RCA mixes containing RCA in excess of 30%, as explained in *paragraph 7.2*. The constituent materials were proportioned as given in *paragraph 4.3.3* using the DOE/BRE method.

Results of the engineering properties are summarised in *tables* 7.1 and 7.2 for ease of comparison. However, subsequently, each particular property is individually analysed and reference to the summary tables can assist the reader.

Table 7.1: Engineering properties of GEN series mixes at 28-days.

PROPERTY	**GEN0**					**GEN1**					**GEN3**				
	RCA content (%)														
	0	**30**	**50**	**75**	**100**	**0**	**30**	**50**	**75**	**100**	**0**	**30**	**50**	**75**	**100**
Compressive strength															
$f_{cube}(N/mm^2)$	8.0	9.0	10.5	9.5	9.5	11.0	13.5	12.0	11.5	12.0	22.5	22.5	23.0	23.0	23.5
f_{cyl} (N/mm^2)	5.5	6.5	8.0	7.5	7.0	8.5	10.5	9.5	9.5	9.5	16.5	16.0	17.5	17.0	16.0
Flexural strength (N/mm^2)	1.9	2.3	1.9	2.2	1.9	2.0	2.5	2.3	2.0	2.0	3.9	4.5	4.6	4.6	4.5
Static modulus of elasticity (kN/mm^2)	22.3	21.0	21.0	20.5	19.0	24.5	25.5	21.0	18.0	18.5	35.5	33.0	29.0	25.0	22.5
Long term deformation															
Shrinkage (90-days $\mu\epsilon$)	-	-	-	-	-	-	-	-	-	-	234	256	334	377	519
Swelling (90-days $\mu\epsilon$)	-	-	-	-	-	-	-	-	-	-	125	109	132	139	142

Table 7.2: Engineering properties of RC30 and PAV series mixes at 28-days.

PROPERTY	**RC30**					**PAV1†**					**PAV2†**				
	RCA content (%)														
	0	**30**	**50**	**75**	**100**	**0**	**30**	**50**	**75**	**100**	**0**	**30**	**50**	**75**	**100**
Compressive strength															
$f_{cube}(N/mm^2)$	34.0	34.0	35.5	35.5	36.5	34.0	35.0	37.0	35.0	32.5	38.5	35.5	37.5	37.0	36.5
f_{cyl} (N/mm^2)	23.5	25.0	29.0	28.0	26.5	26.5	26.5	27.0	27.0	27.5	28.0	28.0	28.5	28.5	29.0
Flexural strength (N/mm^2)	5.2	5.1	5.2	5.2	5.2	5.2	5.2	5.2	5.1	5.1	5.6	5.6	5.7	5.7	5.7
Static modulus of elasticity (kN/mm^2)	36.8	34.6	28.8	24.2	21.6	30.0	33.6	32.2	31.2	31.0	32.2	27.6	29.8	29.0	30.2
Long term deformation															
Shrinkage (90-days $\mu\epsilon$)	405	435	722	686	790	425	416	646	640	776	387	434	798	737	825
Swelling (90-days $\mu\epsilon$)	117	92	120	130	153	67	87	128	130	154	116	112	120	137	129

† Nominal air content 5.0%.

7.2 Design for equivalent strength concrete

Equivalent 28-day compressive cube strength was achieved using the method developed by Limbachiya et al [2] involving the adjustment of the w/c ratio in order to compensate for the strength loss due to inclusion of coarse RCA in excess of 30% by weight. The adjustment was achieved by increasing the cement content resulting in lower w/c ratios and so improving the compressive strength. The factors reported by Limbachiya et al and validated and used in this study ranged from 0.975 to 0.93 for 50% and 100% RCA inclusion respectively. 75% RCA concrete required an adjustment factor of 0.95 as shown in *figure 7.1*.

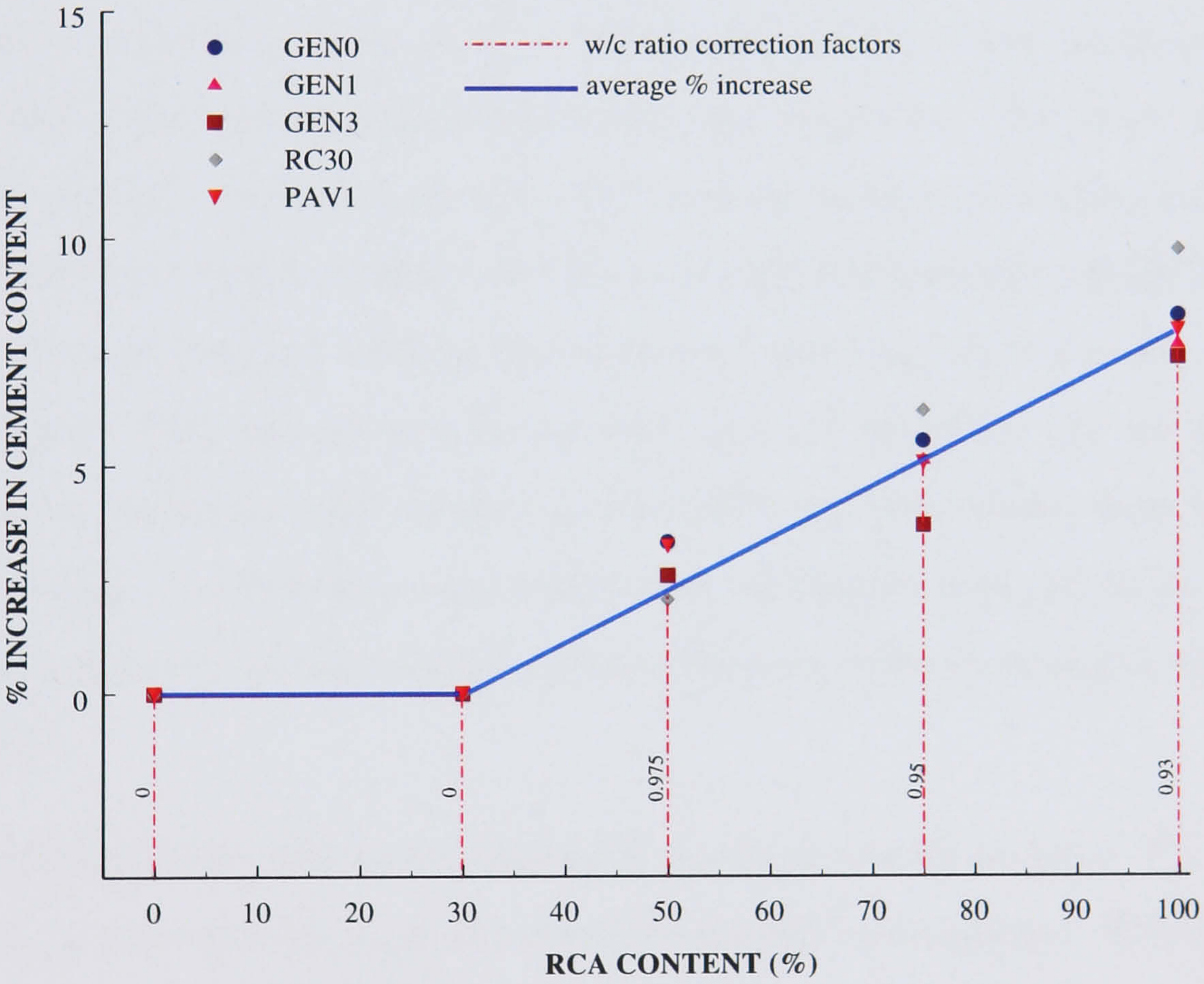


Figure 7.1: Required adjustment for the achievement of equivalent strength concrete, and percentage increase in cement content.

Intermediate RCA contents' factors can be extracted form the graph and are also valid.

Figure 7.1 shows the required percentage increase of cement content for all concretes used in the study with a range of RCA content from 0% to 100%. The average % increase ranged between 2.5 and 8.0% of the NA mix cement content. For example the extra cement required for a PAV1 series concrete mix containing 100% RCA in order to be of equivalent strength, was 27.6 kg/m^3 of concrete.

7.3 Compressive strength

7.3.1 Relationship between cube and cylinder strengths

Results for cube and cylinder strengths are given in *tables 7.1* and *7.2* and plotted in *figure 7.2* in order to examine their relationship.

The 28-day cube and cylinder compressive strengths when plotted, showed a clear positive correlation with an $R^2 = 0.993$ representing a very small scatter and verifying the direct relationship between the two properties. The high correlation factor also provides confidence for the validity of the results. It is important here to observe that the strength results used for this correlation included, all RCA and NA concrete strength findings without distinction so implying corresponding strengths are equivalent. This can be seen by the fact that the spread of the results on the graph has no particular pattern and neither RCA nor NA results form individual isolated groups. It can thus be concluded that equivalent strength RCA shows no difference in behavior to NA concrete as far as the cube cylinder strength relationship is concerned.

The cylinder/cube, compressive strength ratios are shown in *figure 7.3*. Cylinder strength $f_{c,cyl}$ was found to range between 70% and 80% averaging at 76% of the cube strength ($f_{c,cube}$) for all RCA and NA concrete mixes. This was in agreement with table 7 of EN 206 Part 1 [10], which gives cylinder $f_{ck,cyl}$ and corresponding cube $f_{ck,cube}$ characteristic strengths, the ratios of which are around 0.8 (80%). Neville [11] reviewing the same and other standards agrees.

The inclusion of RCA in the concrete caused minor fluctuations to the $f_{c,cyl}/f_{c,cube}$ ratio, with negligible reductions but considerable increases in the ratio in most cases. In the GEN series of mixes the inclusion of RCA improved the ratio overall, with the exception of 30% and 100% RCA in GEN1 and GEN3, where a small decrease was

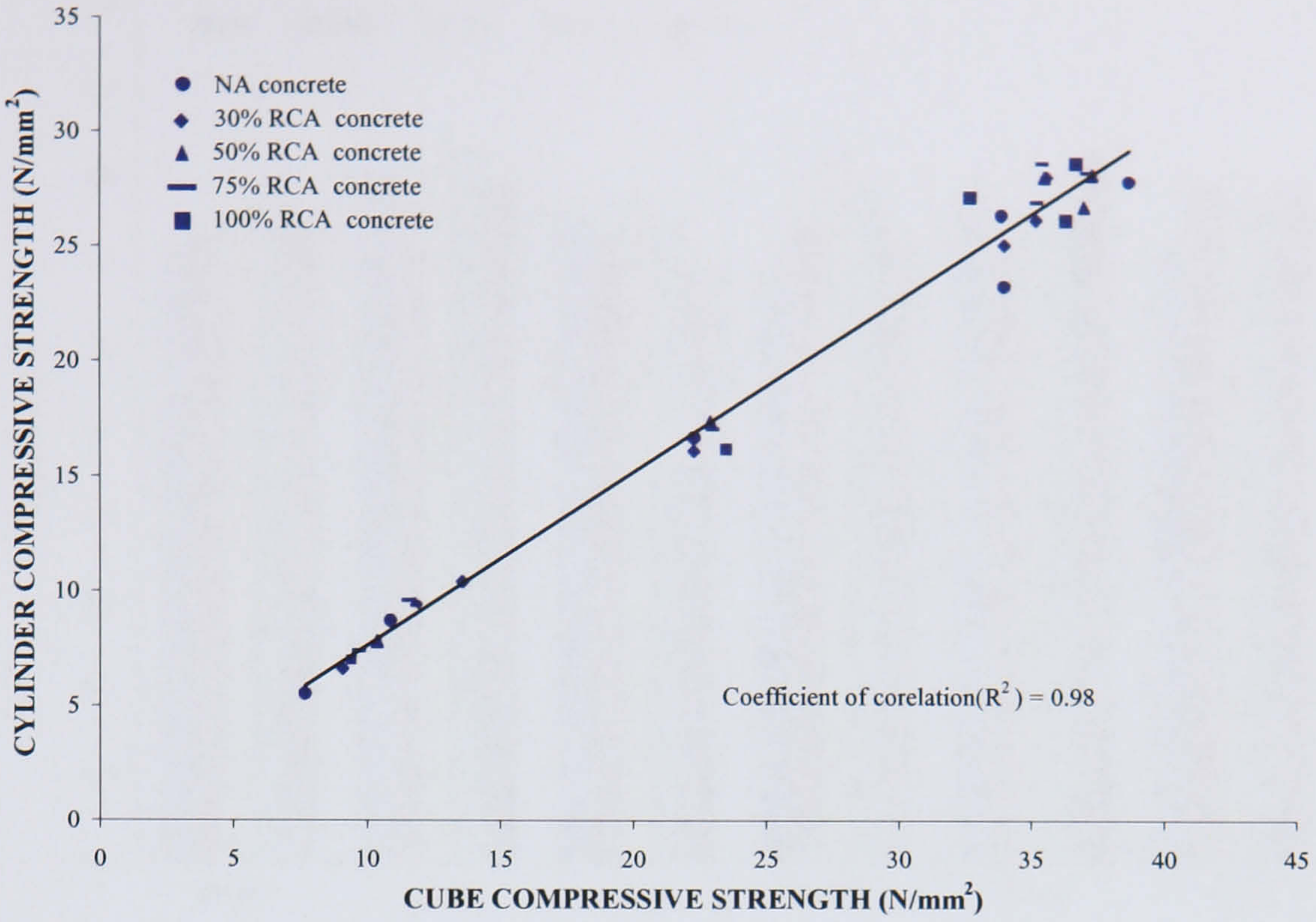


Figure 7.2: Relationship between cube and cylinder compressive strength at 28 days.

observed. In RC30, the increase in RCA content resulted in considerable improvement of the ratio especially for the 50% and 75% inclusions. The air-entrained PAV series of concretes showed similar behaviors with PAV1 ratios dropping slightly for contents between 30% and 75% and improving considerably for 100%. RCA content increase in PAV2 resulted in increases to the ratio.

Overall, based on the results of this investigation, it cannot be definitively concluded that RCA has a clearly predictable effect on the $f_{c,cyl}/f_{c,cube}$ ratio. But it can be concluded that, for this test programme, the overall effect was small with 75% of the results showing increases due to RCA inclusion whilst the rest showed small decreases of the ratio.

7.3.2 Cube compressive strength development

The strength of concrete is directly related to the time elapsed after the casting was completed and increases with increase in time. The rate at which the concrete strength develops is largely related to the hydration process of the cement which in

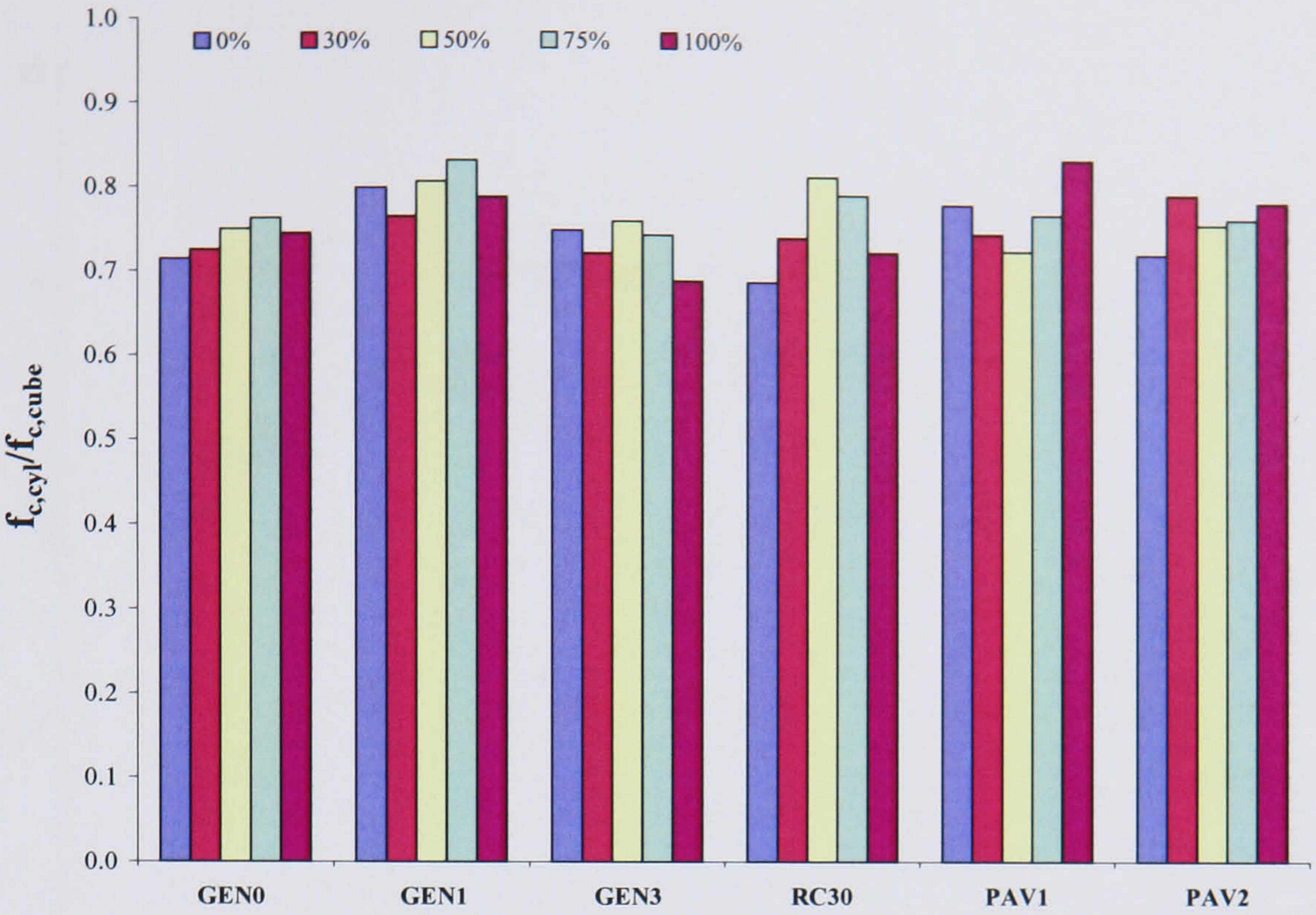
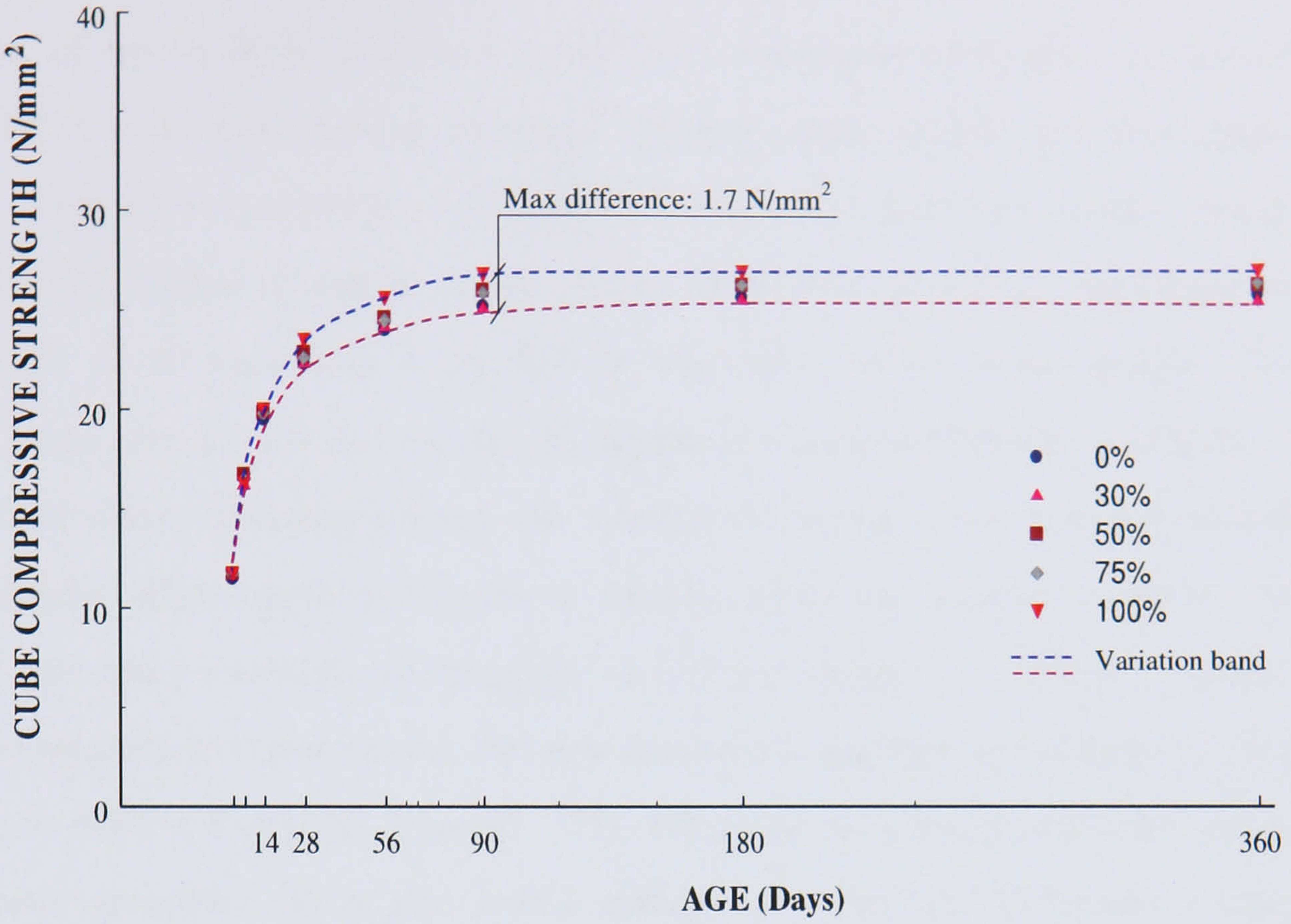


Figure 7.3: Cylinder over cube, 28-day compressive strength ratio for NA and RCA concrete mixes used in the study.

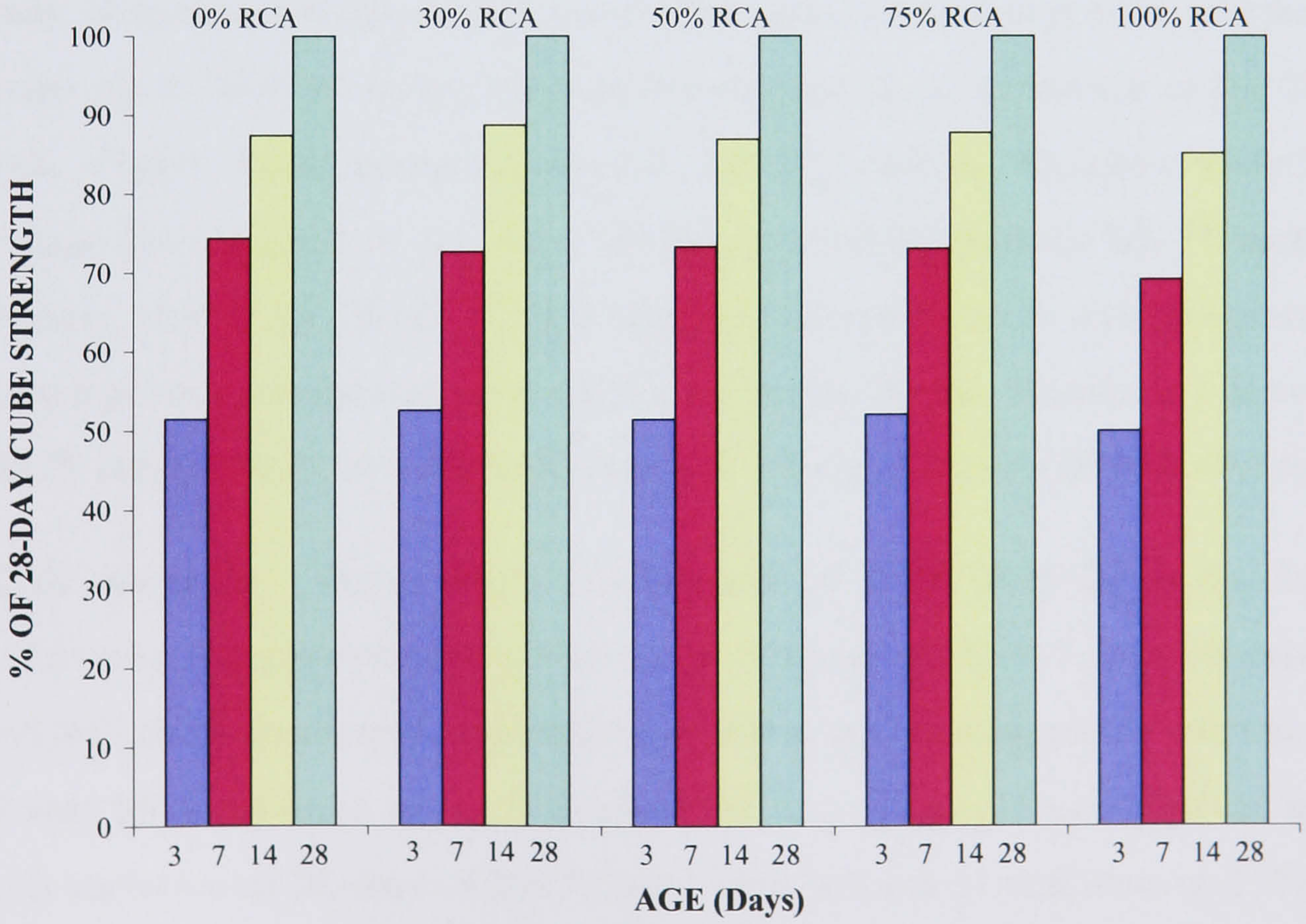
turn depends mainly on the tricalcium silicate C_3S content of the cement. In the context of this study it is not intended to cover how cement chemistry is related to strength but rather to examine the engineering aspect of it.

Traditionally, when specifying concrete for particular applications, the main requirement is the characteristic strength at 28-days of age. In order to be able to design a concrete mix capable of reaching this strength in time, it is necessary to understand how concrete strength increases with time. This is of great importance for structural concrete when a structure is to be subjected to full service loads after construction. The following paragraphs deal with the interpretation of the strength-age relationship of RCA and NA concretes as well as the effect of RCA content on strength development. It is worth remembering at this point that RCA concretes with a maximum of 30% RCA were not subject to any adjustment related to strength.

GEN3 concrete - *Figure 7.4* consists of two graphs covering the compressive strength of the GEN3 (C16/20) concrete. In *figure 7.4(a)* the strength development of this concrete is depicted, for RCA and NA mixes tested.



(a) Compressive strength development showing the range of variation.



(b) Percentage of the 28-day strength for various RCA contents.

Figure 7.4: GEN3 cube compressive strength results for equivalent strength RCA and NA concrete.

It is generally accepted today in the concrete research community, that the inclusion of up to 30% RCA has no effect on concrete strength. In fact NA and 30% RCA concretes showed identical strength magnitudes and development patterns. Concretes containing 50% and 75% RCA also had very similar development and slightly higher strength values whilst 100% RCA concrete was found to be the strongest of all and with a parallel development to the other mixes. This may have been due to the w/c ratio adjustments being somewhat generous. Having said that these adjustments are not considered wrong since it is impossible to define precise adjustment factors for a complex material such as concrete. Although there was some variation in strength, it did not exceed 1.7 N/mm^2, which is relatively insignificant considering the mix design was carried out assuming a margin of $k \times \sigma = 1.64 \times 4 = 6.56$ N/mm^2. The adjustments clearly achieved the expected concrete strengths. It is also worth noting here that the difference between test results of specimens taken from the same sample was well within the 9% value as stated in table 1 of BS 1881 Part 116 [100].

A way of assessing further how concrete strength develops over time and more in particular up to 28-days, is by assessing the strength as a percentage of the 28-day strength. *Figure 7.4(b)* shows this for NA and RCA mixes. Results revealed that on average the strength at 3, 7 and 14-days was approximately 50, 75 and 85% respectively, that of the 28-day result being satisfactory for such concrete according to values reported previously by Neville [11] reviewing others. Therefore, it is evident that RCA content does not effect the strength development of GEN3 concrete.

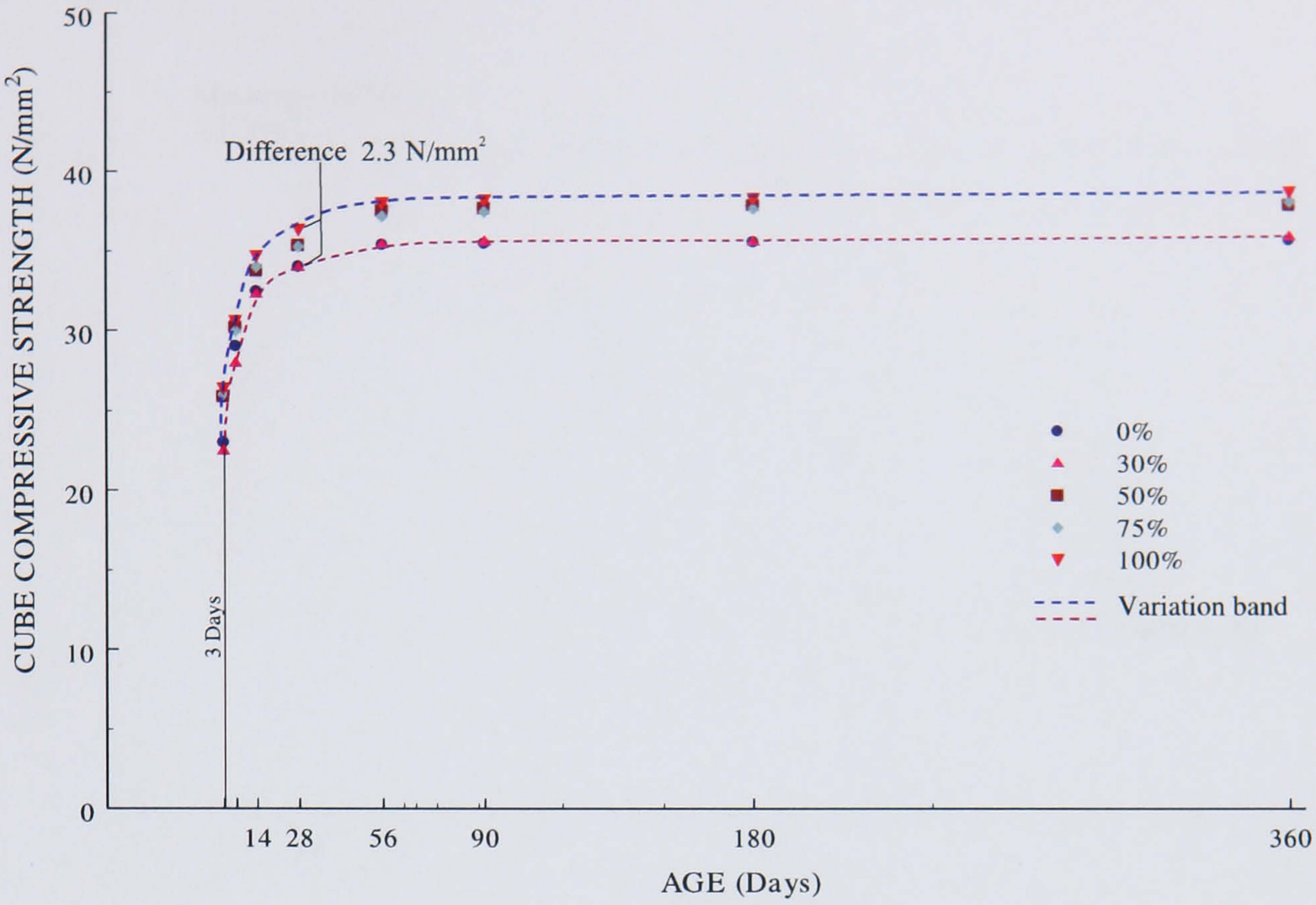
RC30 concrete - The strength development of RC30 (C25/30) is depicted in *figure 7.5* with strength development up to a year shown in *figure 7.5(a)*. As expected NA and 30% RCA concretes had identical strengths and development patterns. Also 50, 75 and 100% concrete strength results were very similar, if not identical with a strength variation at 28-days of 2.3 N/mm^2 with maximum variation of 3 N/mm^2 occurring at 360-days. Both these values were well within the designed allowance for variation of $k \times \sigma = 1.64 \times 4 = 6.56$ N/mm^2 implying that equivalent strength concrete was achieved through the adopted design method. Strength development for RCA and NA concretes was very similar regardless of the RCA content used.

Also in this case the test results of specimens taken from the same sample showed a variability well within the value of 9% as stated in BS 1881 Part 116 [100].

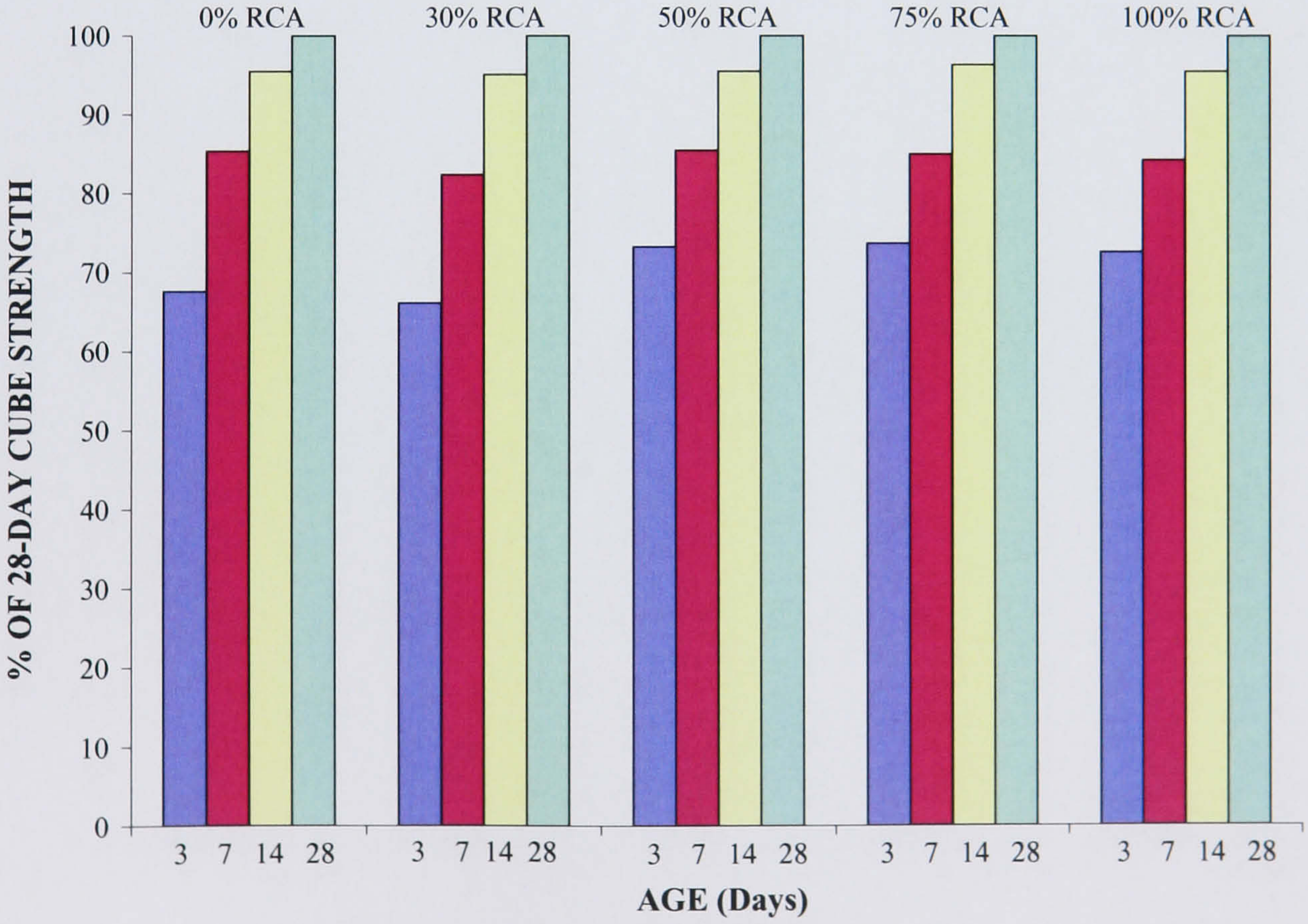
When assessing the strength development as a percentage of 28-day strength *(figure 7.5(b))* at 3, 7, and 14-days, it was found that RCA content did not have any negative effects and the ratios as percentages were, 70, 85 and 95% of the 28-day strength respectively. These values were higher by about 20% at 3-days and by 10% at 7, and 14-days when compared to the GEN3 results discussed earlier, and this finding is in agreement with values reported previously [11], and agrees with the fact that in concrete with higher w/c ratios the strength development progresses slower. Although the results indicated that RCA content increase corresponded to a more rapid strength development at 3-days, it cannot be claimed that this is a general rule as in the other series of concretes investigated the results were found to be similar regardless the RCA content. Summarising, the RCA content did not have any effect on strength magnitude or development pattern over time.

PAV1 concrete - The strength results for PAV1 (25/30) concrete are depicted in *figure 7.6*. Strength results shown in *figure 7.6(a)* revealed very similar strength development patterns up to a year, with no effect due to RCA content. The max variation in strength was at 28-days at 3.5 N/mm^2 comfortably within the variability of 6.56 N/mm^2 allowed by the mix design.

The NA and 30% RCA concretes had very similar development patterns and their strength results were found to be approximately 2 N/mm^2 below the 50% and 75% RCA concretes and about 1 N/mm^2 above 100% RCA concrete. These variations are insignificant and are believed to occur due to the fact that the PAV concrete was air-entrained and therefore if the air contents varied so would the strength results. As a rule of thumb a 1% variation in air content corresponds to a 5% strength variation which in this case could mean a reduction of approximately $1.75-2$ N/mm^2 considering results average at 35 N/mm^2. Summarising, despite the variations in RCA content, equivalent strength concretes were achieved and strength developed in a very similar way whether RCA or NA concrete was concerned. Test

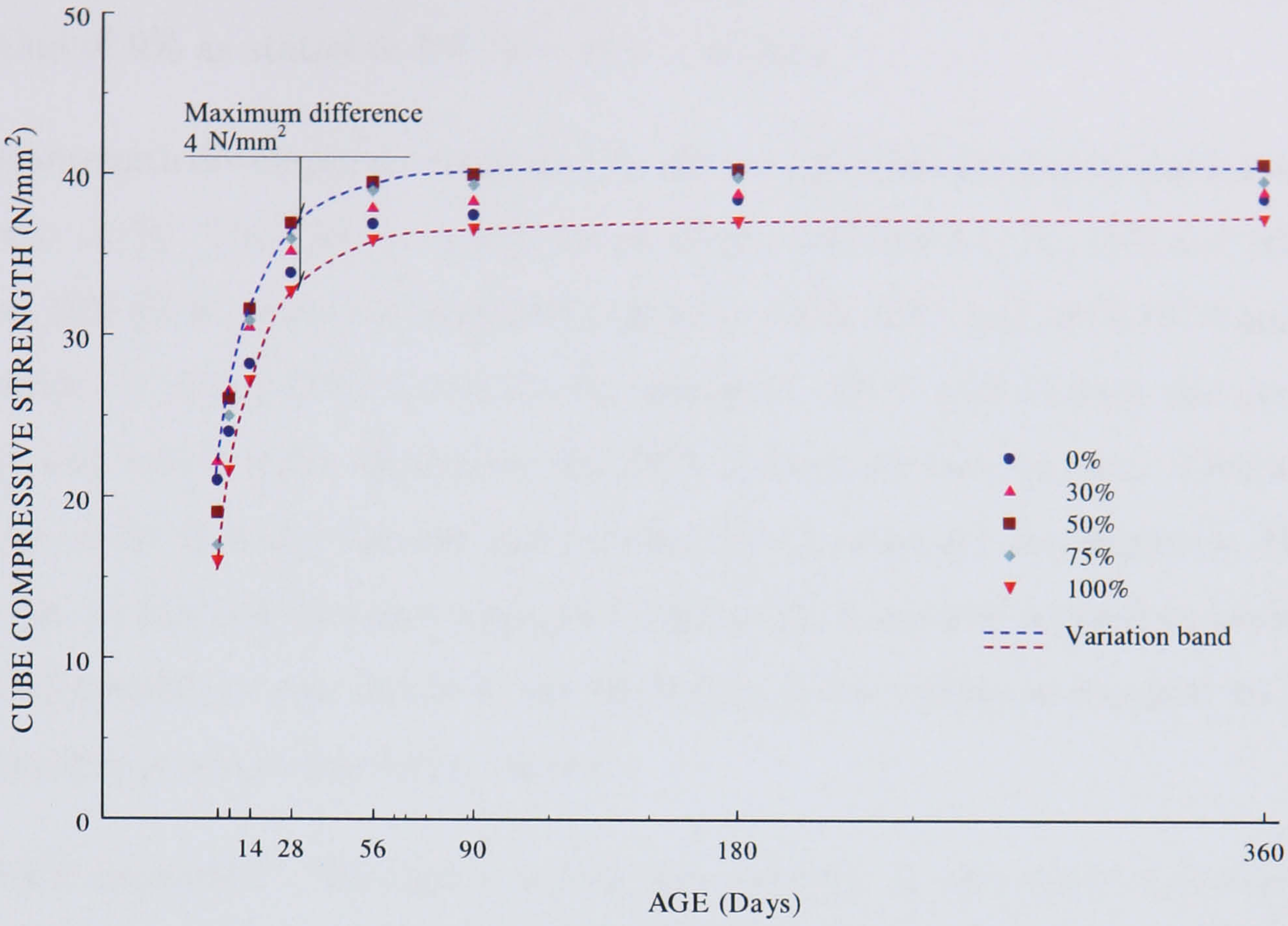


(a) Compressive strength development showing the range of variation.

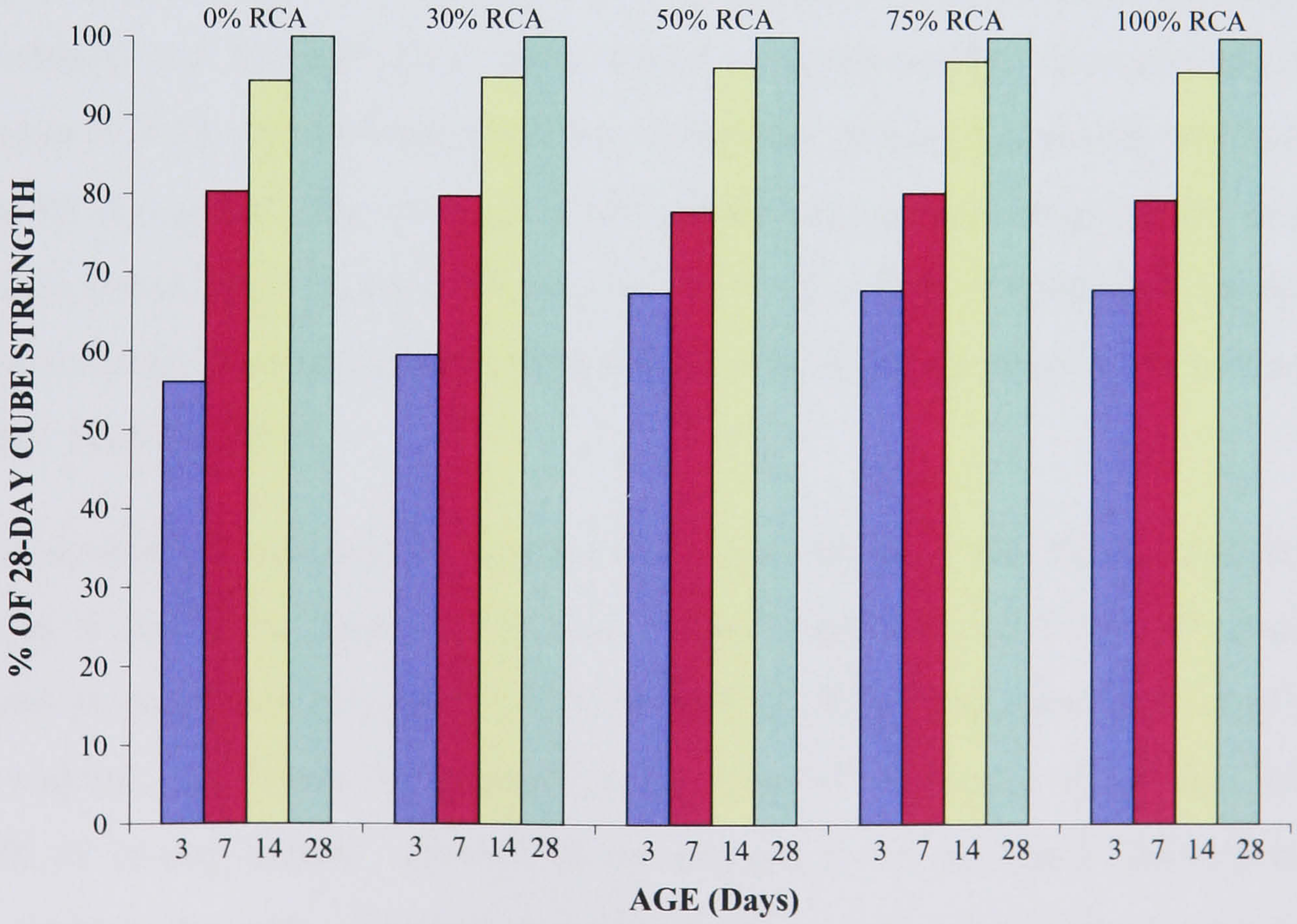


(b) Percentage of the 28-day strength for various RCA contents.

Figure 7.5: RC30 cube compressive strength results for equivalent strength RCA and NA concrete.



(a) Compressive strength development showing the range of variation.



(b) Percentage of the 28-day strength for various RCA contents.

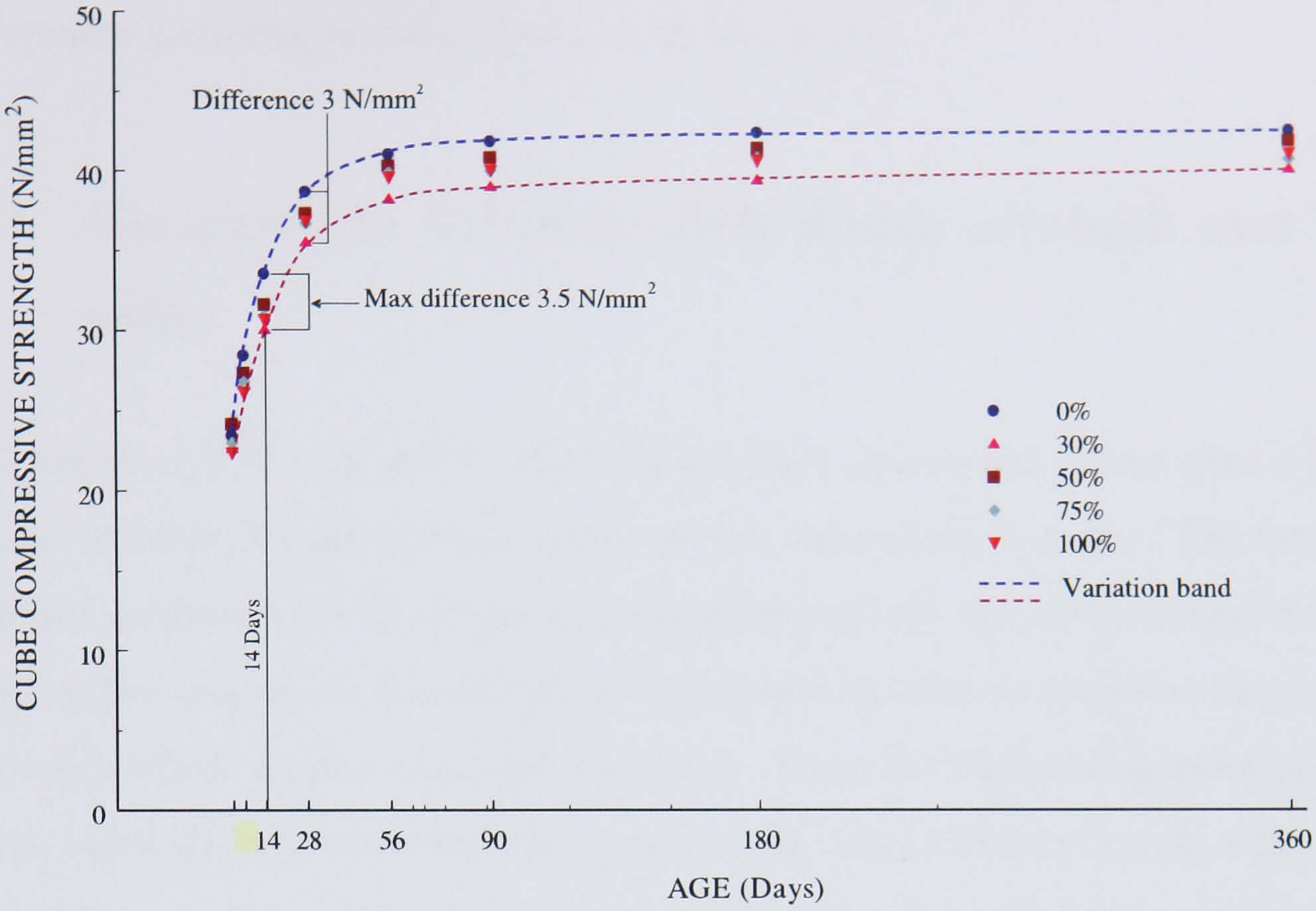
Figure 7.6: PAV1 cube compressive strength results for equivalent strength RCA and NA concrete.

results of specimens taken from the same sample showed a variability well within the value of 9% as stated in BS 1881 Part 116 [100].

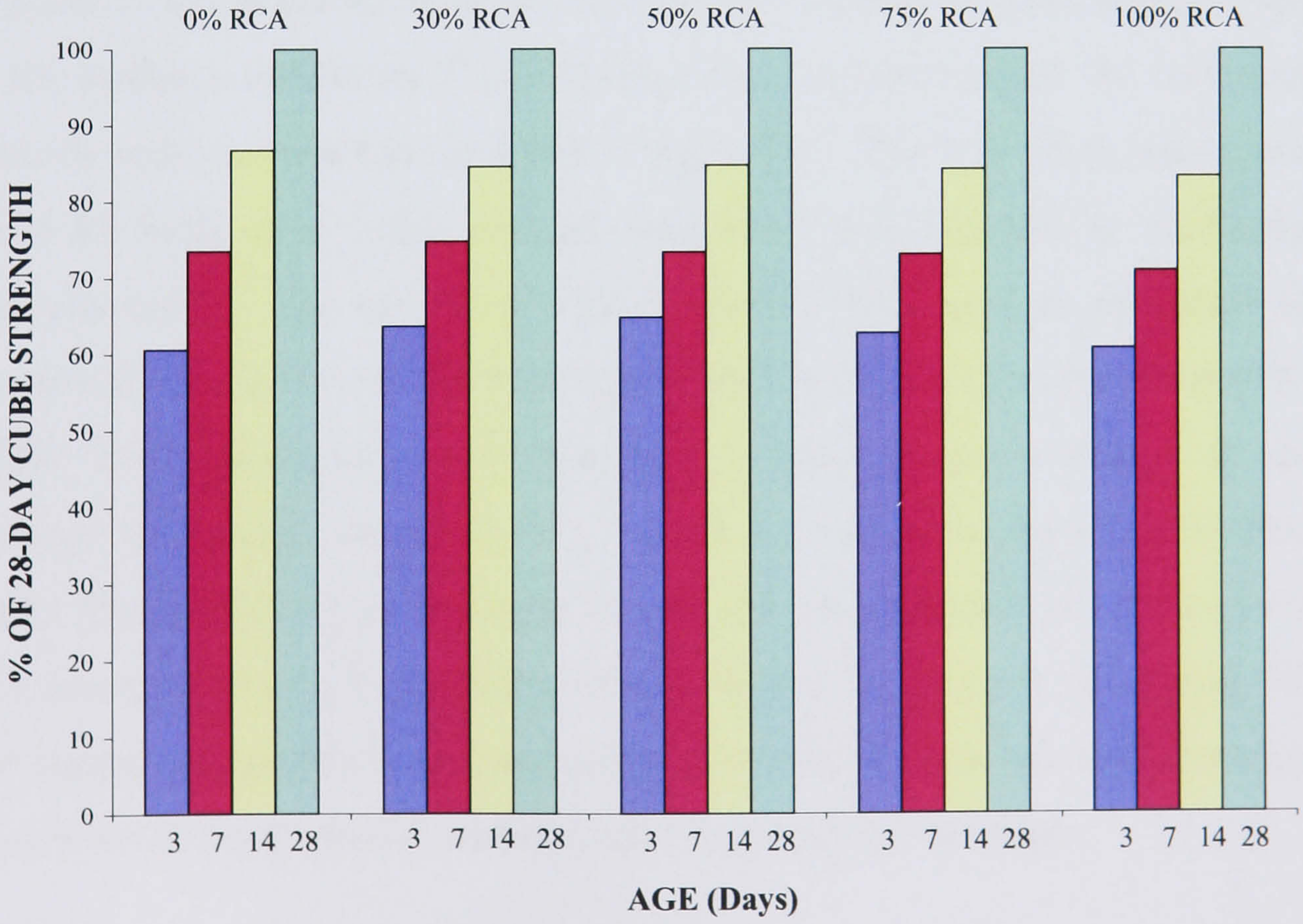
The strength development expressed as percentage of the 28-day strength is shown in *figure 7.6(b)*. The 3-day compressive strength was found to be 55% and 60% for 0% and 30% RCA concrete respectively while for 50%, 75%, and 100% RCA concrete was stable at about 70% of the 28-day strength. At 7 and 14-days the strength gained was very similar regardless the RCA content of the concrete. Overall the inclusion of RCA at any content had no effect on the strength development. Having said that, in the case of early strength (3-days) RCA content seemed to accelerate the development as was observed for RC30 but more testing is required to assess whether this is valid observation or not.

PAV2 concrete - The last concrete mix assessed in this study was also from the PAV series. PAV2 (28/35) strength results are graphically shown in *figure 7.7*. Assessing the findings in *figure 7.7(a)* it was found that the maximum variation in strength was 3.5 N/mm^2 and occurred at 14-days while at 28-days the difference was reduced to 3 N/mm^2. Both these values are much smaller than the mix design allowance of 6.56 N/mm^2 and therefore equivalent strength concrete was achieved at any RCA content. The strength development pattern was identical for all PAV2 concretes regardless of their RCA content. All test results of specimens taken from the same sample had variability conforming to the limiting value of 9% as stated in BS 1881 Part 116 [100].

The strength development expressed as a percentage of the 28-day compressive strength is shown in *figure 7.7(b)* and it was found that at 3-days all concretes achieved strengths of between 61-65% of that of 28-day old concrete regardless of RCA content. At 7-days the strength was between 71-75% and at 14-days between 83-87% of 28-day values. Overall there appears to be no effect associated with RCA content the mix. Another observation that can be made which also applies to PAV1 results, is that although both concretes have lower w/c ratios than RC30, their strength development rate decreased. This is related to the air-entrainment admixture used which results in slower rates of strength development. Summarising,



(a) Compressive strength development showing the range of variation.



(b) Percentage of the 28-day strength for various RCA contents.

Figure 7.7: PAV2 cube compressive strength results for equivalent strength RCA and NA concrete.

there was no evidence showing any affect due to the RCA content to either strength development patterns, or compressive strength results.

7.3.3 Relationship between compressive strength and w/c ratio

There are several factors which affect the strength of concrete, some play a major role and therefore in engineering practice are very important to assess. The two most important properties are the degree of compaction and the w/c ratio of concrete. It is important for concrete to be sufficiently compacted in order to minimise the content of air voids which result in strength reduction. From the engineering practice point of view, using the w/c ratio rule which states that, when concrete is fully compacted (ie. air-voids $\approx 1\%$) the strength can be considered to be inversely proportional to the w/c ratio is very useful [11].

In order to assess the effect of RCA on the relationship between strength and w/c ratio the strength results for 7 and 28-days were plotted against the corresponding w/c ratios and the result is depicted in *figure 7.8*. The w/c ratio rule appears to be valid for both early 7-day strength and the 28-day strength at which the mix design was based. The concretes which included RCA were no exception to this fundamental rule and so can be considered valid for mix designs containing RCA up to 100%. Both curves are nearly hyperbolic in form as reported in most concrete technology textbooks. In conclusion, it can be said that since the results form a nearly hyperbolic curve, strength is inversely proportional to w/c ratio and it can be assumed that the mix design was adequate for concrete containing RCA as coarse aggregate and that the compaction of the specimens was sufficient resulting in minimum air void content without compromising the strength.

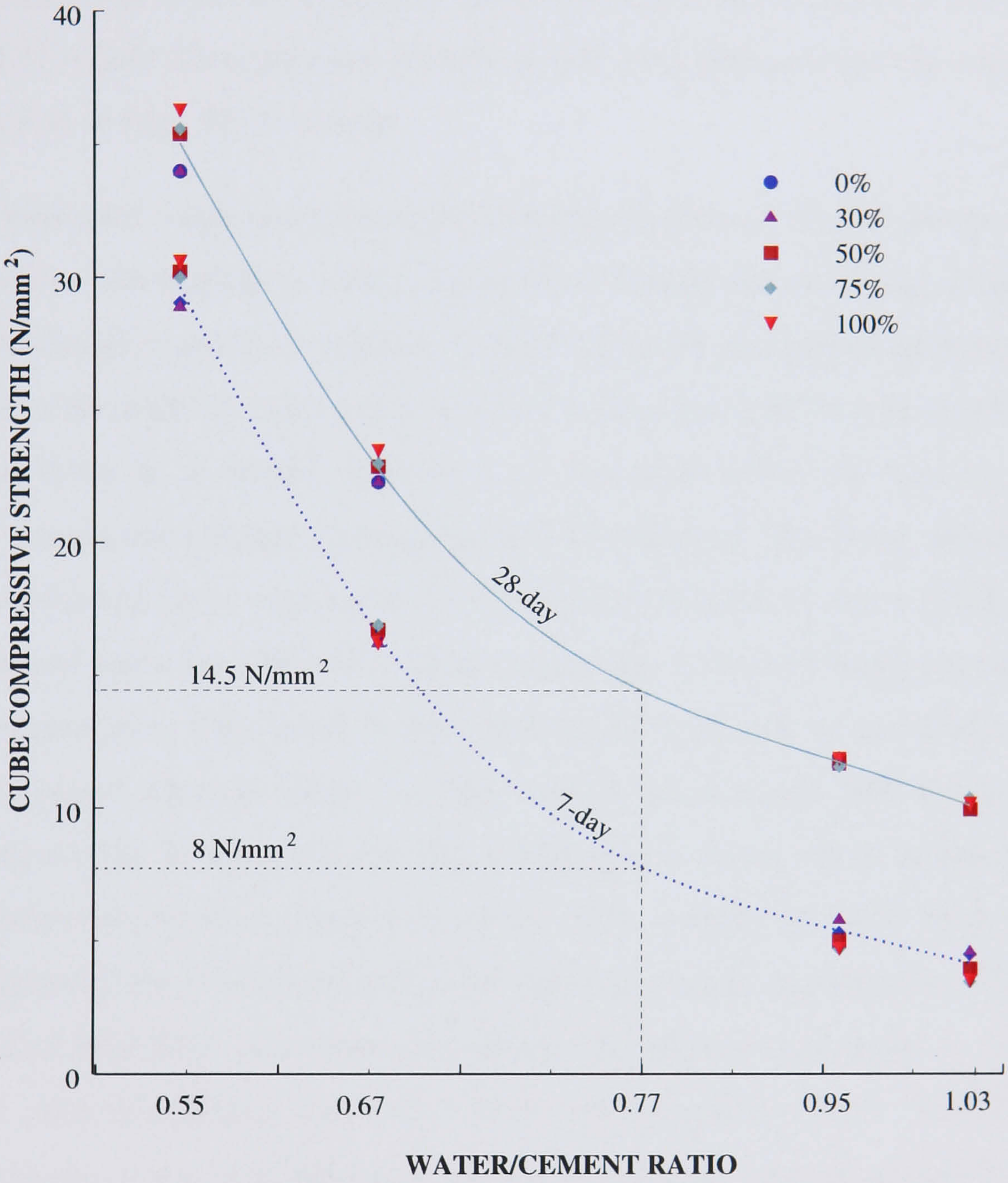


Figure 7.8: Relationship between cube compressive strength and w/c ratio for concretes used in the study.

7.4 High Strength RCA Concrete (Ceiling Strength).

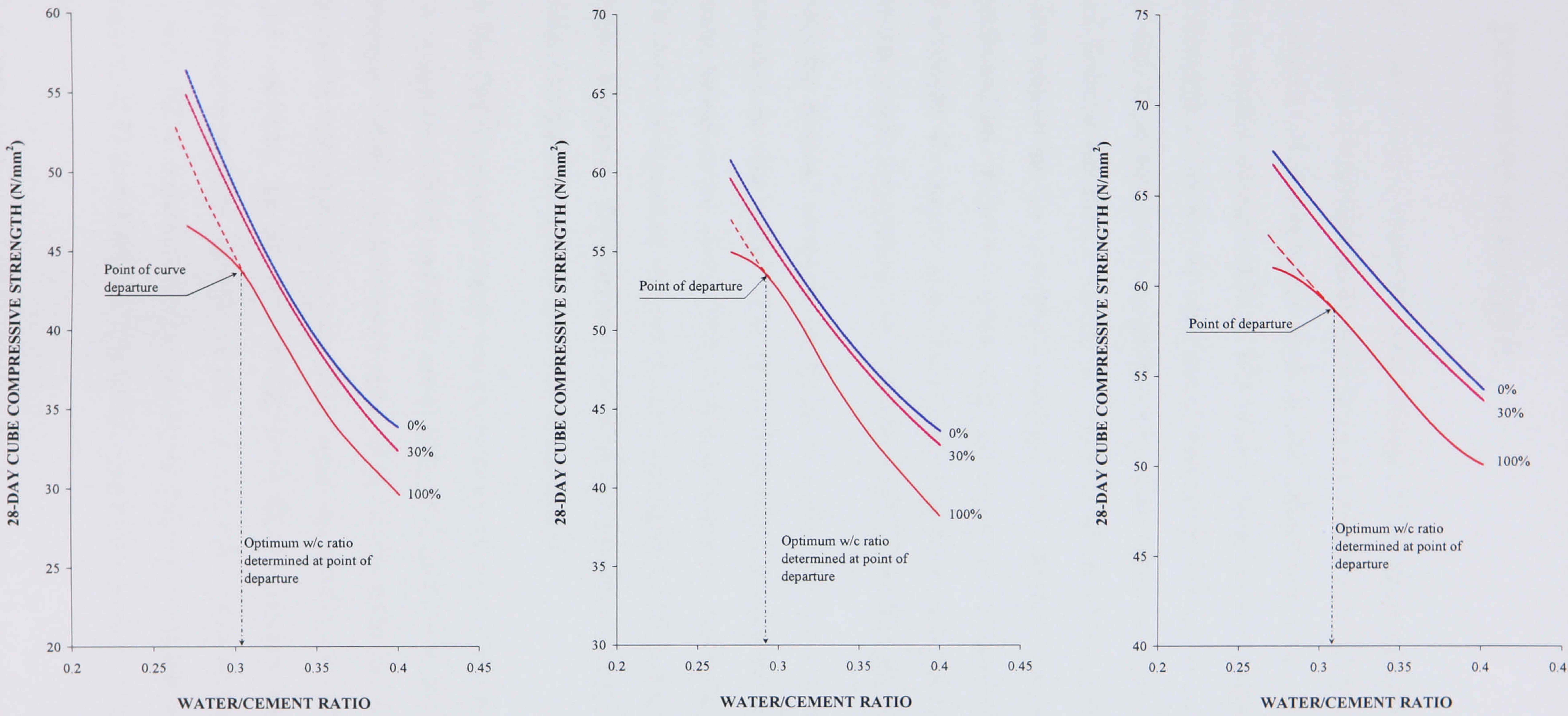
The effect of RCA content on the ceiling strength was investigated and the results are shown in *figure 7.9* which depicts the relationship between the compressive cube strength and w/c ratio for 3, 7, and 28-day results. In this part of the study the w/c ratio adjustments were not applied to the 100% RCA concrete in order to assess the behavior of ceiling strength more clearly as well as to demonstrate the reduction in strength due to high RCA content.

The results for 3-day concrete strength shown in *figure 7.9(a)* reveal as expected an hyperbolic relationship between compressive strength and w/c ratio in agreement with established concrete properties. Theoretically the continuous reduction of the w/c ratio will result in continuous increase of the strength, but in reality this is only true down to a certain value of w/c ratio after which the rate of strength increase decays until higher strength cannot be achieved. The point indicating the commencement of decay is identified in *figure 7.9(a)* around the value of 0.3 at which point the real curve for 100% RCA concrete departs from the theoretical one shown by the broken line. This point is also referred [2, 5, 111] to as the start of ceiling strength (upper strength limit). In the case of the NA and 30% RCA concrete this characteristic is not visible in this range of w/c ratios but it is believed that similar behaviors occur at lower w/c ratios. The strength of 100% RCA concrete was consistently lower by about 4 N/mm^2 down to a water cement ratio of 0.31 than the NA and 30% RCA concretes after which the difference increased to 6 N/mm^2 at a w/c ratio of 0.29 and about 10 N/mm^2 for w/c ratio of 0.27. The 30% RCA concrete strength was very similar to NA within a narrow band of around 2 N/mm^2.

At 7-days a similar relationship is shown in *figure 7.9(b)* where the 100% RCA concrete is once again displaced downwards by about $4-6$ N/mm^2 down to a w/c ratio of around 0.36 after which the difference reduces to $3-4$ N/mm^2 until the decrease is more evident at about $6-7$ N/mm^2 for w/c of 0.27. The point of departure or start of the ceiling strength is identified approximately at 0.29 very similar to the 3-day result.

Similarly the 28-day relationship is shown in *figure 7.9(c)* where the difference between the 100% RCA strength results and the other two is reasonable constant at about 4 N/mm^2 between w/c ratios of 0.4 and 0.29 after which this significantly increases to around 7 N/mm^2 when compared to NA concrete strength. The point of departure is identified at 0.31 again very similar to the 3 and 7-day results. Once again the 30% and NA concretes show continuously increasing behaviors but it is believed that further reduction of w/c ratio will reveal their ceiling strength.

Overall it can be concluded that the effect of RCA at high contents, is negative to both the strength as well as the maximum strength achieved. The ceiling strength identified by the point of the curve where departure occurred is at a w/c ratio of around 0.3 for all 3, 7 and 28-day results as reported in other studies [2, 5]. Concrete containing 100% RCA reached maximum 3-day strengths of around 46 N/mm^2 compared to over 55 N/mm^2 achieved by NA and 30% RCA concrete. Similarly at 7-days 100% RCA reached maximum strengths of just around 55 N/mm^2 compared to over 61 N/mm^2 achieved by NA and 30% RCA concrete. Finally, and most importantly the 28-day results showed similar variations due to RCA content and maximum strength achieved by 100% RCA concrete was over 60 N/mm^2 around 7 N/mm^2 lower when compared to the 67 N/mm^2 acieved by NA and 30% RCA concrete.



(a) 3-day compressive cube strength

(b) 7-day compressive cube strength

(c) 28-day compressive cube strength

Figure 7.9: Effect of RCA on the optimum w/c ratio of high strength concrete.

7.5 Flexural strength and relationship with compressive strength

Although concrete is a material used mainly for its high compressive strength capacity, it is also of importance for structural engineers to be able to determine other strength aspects of the material such as the tensile strength. Tensile strength of concrete is usually between 10% to 20% of the compressive strength. Measuring the flexural strength is one way of establishing indirectly the tensile strength of concrete which is also expressed as its modulus of rupture (MR) in N/mm^2. The determination of flexural strength is useful in assessing the quality of concrete pavements but is less important for structural concrete were tensile capacity is provided by steel reinforcement. Since the shape and surface texture of aggregates influence the flexural strength of concrete more than the compressive strength [11] it is within the scope of this study to examine the influence of RCA on this property.

Results for flexural strength are given in *tables 7.1* and *7.2* for all designated concretes used in this study. The flexural strength results for the GEN series of mixes were found to be about 20% of the compressive strength results. The RC and PAV series of concretes showed flexural strengths at 15% of their corresponding compressive strength. The inclusion of RCA has shown no negative effects at any proportion and for any type of concrete investigated.

With the GEN0 concrete there was an increase by up to 20% in flexural strength for RCA contents of 30% and 75% while NA, 50% and 100% RCA content results were identical. GEN1 concrete had similar flexural strengths for NA, 75% and 100% RCA concretes but improved for an RCA inclusion of 30% by 15% when compared to the NA concrete. In the case of GEN3 all RCA concretes had improved their flexural strength by 15%. Results for the RC and PAV series of concretes were very similar, with RCA concrete having improved flexural strength by about 2% with the exception of 75 and 100% RCA which dropped its value by 2% compared to NA concrete.

Overall, RCA inclusion in concrete was found to either have beneficial or no effect on the flexural strength. These findings are in agreement with previous studies [35, 57, 40].

The relationship between flexural and compressive strength was also assessed in order to establish if a clear correlation exists. *Figure 7.10* depicts the relationship which if assumed linear had a reasonable coefficient of correlation of $R^2 = 0.94$. Close examination of results indicated the relationship was non linear but exponential, and represented by a 2^{nd} order polynomial curve with a coefficient of correlation of 0.96. This relationship shows that as the compressive strength of concrete increases so the relative flexural strength slowly decreases a relationship which was not unexpected and is described in most concrete technology text books. Another important observation is that the scatter of results is equivalent for both RCA and NA concrete.

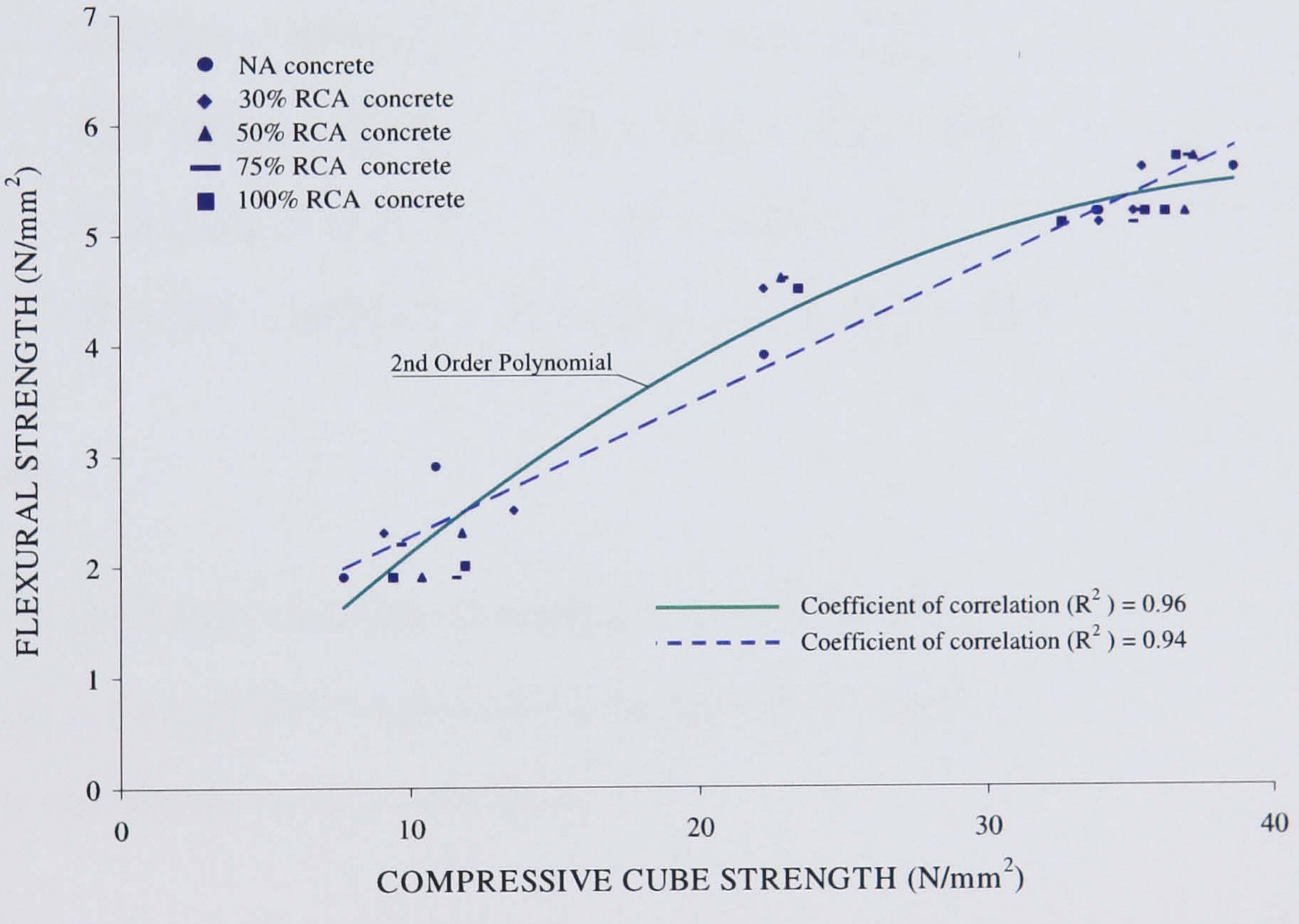


Figure 7.10: Relationship between cube compressive strength and flexural strength for concretes used in the study.

7.6 Static Modulus of Elasticity

In common with all structural materials, concrete is elastic and clearly the degree of elasticity is important. In this section the static modulus of elasticity, of concrete has been examined as a function of stress σ and strain ε. In any material the application of stress results in consequent strain, which if it completely disappears after removal of the load implies the material is perfectly elastic. The relationship of σ vs ε is however, not always linear and this is certainly the case in concrete. When assessing the concrete modulus of elasticity according to the procedure described in *4.3.6.2*, the modulus of elasticity is taken to be the gradient of the stress-strain curvature and expressed in kN/mm^2.

The results for the static modulus of elasticity for all concretes investigated in the study are given in *tables 7.1* and *7.2* and to ease comparison also in *table 7.3* against theoretically calculated values using four widely accepted formulae shown in *equations 7.1* to *7.4*.

$$ACI\ 318-02^1[112]: \quad E_c = 4.73 \times f_{c,cyl}^{0.5} \tag{7.1}$$

$$ACI\ 363R-9[113]: \quad E_c = 3.32 \times f_{c,cyl}^{0.5} + 6.9 \tag{7.2}$$

$$Kakizaki\ et\ al.[114] \quad E_c = 3.65 \times f_{c,cyl}^{0.5} \tag{7.3}$$

$$ACI\ 318-02^2[112]: \quad E_c = 43 \times \rho^{1.5} \times f_{c,cyl}^{0.5} \times 10^{-6} \tag{7.4}$$

Where:

- E_c is the Static modulus of elasticity in (kN/mm^2)
- $f_{c,cyl}$ is the cylinder compressive strength in N/mm^2
- ρ is the density of concrete in kg/m^3

The first observation to be noted is that the results obtained through testing were somewhat higher than expected especially for the GEN0 and GEN1 series of concretes, the second being that increased RCA content in concrete reduced the modulus of elasticity. For this reason it was decided to calculate the theoretical values using three formulae developed and recommended for structural design calculations by the American Concrete Institute (ACI) and one, reported in a study by Kakizaki et al [114]. Immediately it was obvious that all experimental values were considerably higher than the theoretical ones.

The GEN0 and GEN1 concretes were found to have moduli, which decreased by between 6-15% and 14-23% respectively, as the RCA content increased which was in line with results reported in previous studies [33, 52, 54, 63]. Following a similar but more marked trend the values decreased by between 6-37% for GEN3 and by 6-40% for RC30 as was also reported previously [52, 59]. It can also be observed that as the concrete strength increased so the effect of RCA on elastic modulus increased.

Conversely, the affects shown from the PAV series of results, which are of very similar strength to RC30, are less dramatic. In fact the elasticity of PAV1 was the only which increased as a result of including RCA, showing values increasing by between 3-12% compared to NA concrete. PAV2 was negatively affected by the RCA content showing results which decreased by between 6-14% when comparing to the NA concrete. In general including RCA in PAV concrete mixes had little influence when compared to the other mixes which may be related to the air-content, as the PAV and RC mixes are of similar strength.

The big difference between theoretical values calculated and those from experimental testing can be explained by the fact that the formulae are based on empirical data. These data were for structural concrete, i.e. strengths between 20-60 N/mm^2 as included in BS 8110 and therefore the formulae may not be suitable for prediction of static modulus of elasticity for lower strengths such as 8 and 10 N/mm^2 corresponding to GEN0 and GEN1 respectively.

Overall it can be concluded that since the elastic modulus of concrete is affected by the elastic moduli of the aggregate and cement paste combined, it is to be expected that the inclusion of a different aggregate (ie. RCA) will cause variations to the concrete's static modulus of elasticity. The concretes used in the study were shown generally to be negatively affected by the inclusion of RCA and this affect became more evident with increase in RCA content. Having said that, when comparing the actual test values with theoretically established values, it was found that even the lowest values, associated mainly with high RCA content concretes, were acceptable in terms of the range for e-values suggested in BS 8110.

Table 7.3: Theoretical and measured static modulus of elasticity results for concretes used in the study.

CONCRETE TYPE	$f_{c.cyl}$ (N/mm^2)	THEORETICAL MODULUS (kN/mm^2)				ACTUAL RESULT (kN/mm^2)
		Formulae developed by:[†]				
		ACI 318-02[1]	ACI 363R-92	Kakizaki et al	ACI 318-02[2]	
GEN0						
%RCA 0	5.5	11.1	14.7	8.6	11.4	22.3
30	6.6	12.2	15.4	9.4	12.5	21.0
50	7.8	13.2	16.2	10.2	13.6	22.0
75	7.4	12.9	15.9	9.9	13.2	20.6
100	7.0	12.5	15.7	9.7	12.9	19.0
GEN1						
%RCA 0	8.7	14.0	16.7	10.8	14.4	24.3
30	10.4	15.3	17.6	11.8	15.7	25.4
50	9.5	14.6	17.1	11.3	15.0	20.8
75	9.6	14.7	17.2	11.3	15.1	18.2
100	9.4	14.5	17.1	11.2	14.9	18.6
GEN3						
%RCA 0	16.7	19.3	20.5	14.9	19.9	35.4
30	16.1	19.0	20.2	14.6	19.5	33.2
50	17.4	19.7	20.7	15.2	20.3	29.2
75	17.1	19.6	20.6	15.1	20.1	25.2
100	16.2	19.0	20.3	14.7	19.6	22.4
RC30						
%RCA 0	23.4	22.9	23.0	17.7	23.5	36.8
30	25.2	23.7	23.6	18.3	24.4	34.6
50	28.8	25.4	24.7	19.6	26.1	28.8
75	28.2	25.1	24.5	19.4	25.8	24.2
100	26.3	24.3	23.9	18.7	25.0	21.6
PAV1						
%RCA 0	26.5	24.3	24.0	18.8	23.9	30.0
30	26.3	24.3	23.9	18.7	23.8	33.6
50	26.9	24.5	24.1	18.9	24.1	32.2
75	27.1	24.6	24.2	19.0	24.2	31.2
100	27.3	24.7	24.2	19.1	24.3	31.0
PAV2						
%RCA 0	28.0	25.0	24.5	19.3	24.6	32.2
30	28.2	25.1	24.5	19.4	24.7	27.6
50	28.3	25.2	24.6	19.4	24.7	29.8
75	28.4	25.2	24.6	19.5	24.8	29.0
100	28.8	25.4	24.7	19.6	25.0	30.2

[†] Source: Neville A. N. Properties of concrete 1995 [11].

[1,2] See equations 7.1 to 7.4.

7.7 Concrete Deformations

Concrete is subject to deformations due to changes in volume and this happens both in the plastic state and after the material has set. Deformations are mainly related to water being lost, absorbed and being involved in the cement hydration process. The determination of the magnitude of concrete deformations is of importance to structural engineering and this study has concentrated on the drying shrinkage and swelling of concretes containing RCA and identified the effect of the latter. Drying shrinkage was assessed to establish the contraction of concrete due to drying out after setting occurred, and swelling to establish the expansion due to the water absorption by the concrete.

In the following sections, discussion of the results takes place for the GEN3, RC and PAV series of mixes. Maximum deformation values at 90-days are given in *tables 7.1* and *7.2* . GEN0 and GEN1 concretes were deliberately excluded from this assessment due to the nature of their application being insignificantly affected by deformation effects. Results were expressed in micro strain ($\mu\varepsilon$) representing the ratio of the change in length of the specimen tested over the original length and were calculated using *equation 7.5.*

$$Strain\ in\ \mu\varepsilon :\ \frac{\Delta l}{L}\ (ie.\ \frac{0.045mm}{300mm} = 150\mu\varepsilon) \tag{7.5}$$

Where:

- Δl is the change in length of the specimen in *mm*.
- L is the original length measured immediately after de-molding in *mm*.

7.7.1 Drying shrinkage and swelling of GEN3 concrete.

Swelling - The findings from the investigation on GEN3 concrete prisms are depicted in *figure 7.11* and include the shrinkage and swelling profiles established up to 90-days. Expansion due to swelling was found to range between 110 and 140 $\mu\varepsilon$ and these values are within the range suggested in concrete textbooks [11]. Including RCA up to 30% had no effect when compared to NA concrete although the results suggest an insignificant 12% decreased expansion. Clearly with RCA content exceeding 30% the concrete showed expansions of 130 to 140 $\mu\varepsilon$, an increase between 6% to 16% when compared to NA concrete results.

The main factor governing the swelling magnitude is the cement content. When concrete is placed in water, it starts absorbing water causing the cement paste particles to move apart resulting in a build up of swelling pressure and therefore expansion. In this programme the inclusion of RCA in excess of 30% means extra cement due to the w/c ratio adjustment applied in mix design. Therefore, the increase in expansion for 50%, 75% and 100% RCA was mainly the result of their higher cement content, developing higher swelling pressures resulting in increased expansion. The water absorption of the aggregate is unlikely to have played a significant role since its water demand was compensated during mixing of the concrete.

The results have also clearly indicated that although the magnitude of swelling was affected by the RCA content, there was no effect at all on the development pattern of such deformation and, as shown in *figure 7.11*, the development of swelling was almost completely stabilised after two weeks for all concretes regardless of their RCA content, after which increase in swelling continued at very small rates.

Following this discussion it can be concluded that having up to a 30% RCA content has no effect on the swelling, but with increases above that, increased swelling values were observed which were the result of the extra cement required in order to achieve equivalent strength concrete. Therefore, higher RCA contents were not directly responsible for the increases. Also it was concluded that the swelling development of all concretes regardless of RCA content was identical and swelling was almost fully developed within two weeks from immersion in water. Nevertheless the magnitude of swelling of both RCA and NA concretes was within the values expected for concrete with a cement content of 270 kg/m^3.

Drying shrinkage - Drying shrinkage showed similar effects to swelling due to RCA content but clearly on a larger scale. The inclusion of RCA up to 30%

had no influence on the drying shrinkage of the concrete. RCA content of 50% resulted in shrinkage being 43% higher than that of NA concrete. The difference was even higher at 60 and 120% for 75 and 100% RCA contents respectively. As with swelling, the mixes containing RCA in excess of 30% will have a decreased *w/c ratio* due to increased cement content which will also result in a small reduction in the *aggregate/cement ratio.*

Both w/c and aggregate/cement ratios are the main governing factors in shrinkage with the first being directly proportional and the second inversely proportional to it. Despite this the major influence in this case is believed to be the saturated RCA in the mix which due to its higher moisture capacity when compared to NA shrinks considerably more when exposed to low RH, and consequently concrete containing it also shrinks more. Although the maximum of 520 $\mu\varepsilon$ associated with 100% RCA concrete was considerably higher than NA, it should be noted that a concrete with a w/c ratio of 0.67 and aggregate/cement ratio of 7, as is the case with GEN3, will be expected to show shrinkage values between 400 $\mu\varepsilon$ and 500 $\mu\varepsilon$ when conditioned at 50%RH [11]. The specimens in this study were subjected to 35-45% RH in a laboratory environment and therefore the values found were the expected ones. Lastly, the major part of the shrinkage development took place during the first 45-days after exposure to 35%-45%RH and 21^oC environment and this was regardless of RCA content.

Summarising for drying shrinkage, although the magnitude of the linear contraction of the concretes was clearly affected by the RCA content, this effect was associated with an increased cement content due to w/c ratio adjustments as well as the consequent aggregate/cement ratio reduction, but the main cause is believed to be the initial high moisture content of the RCA and subsequent loss of water while drying. The values observed, irrespective of RCA content, are of a magnitude expected by the w/c and aggregate/cement ratios of this designated mix.

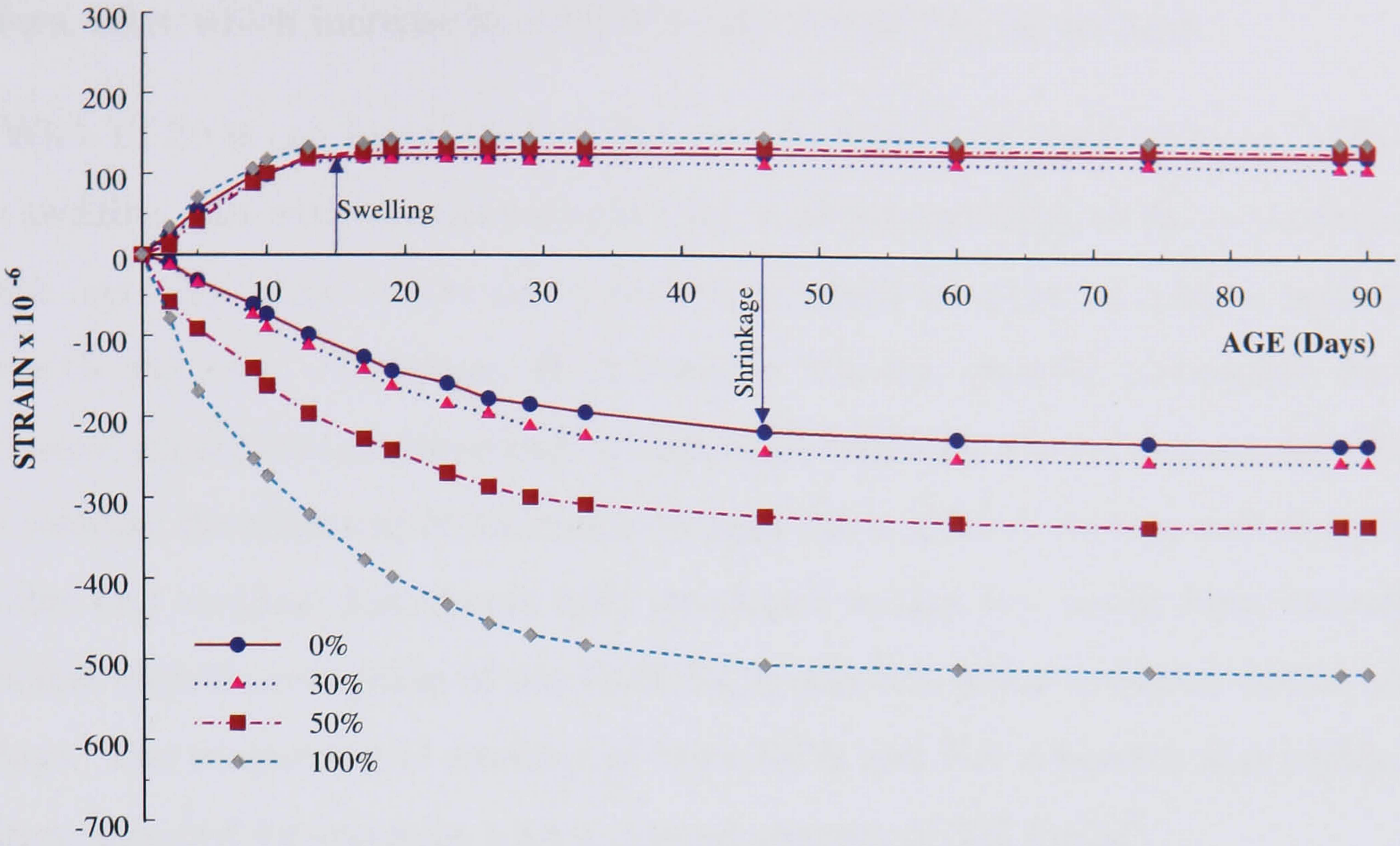


Figure 7.11: Effect of RCA content on deformation of GEN3 concrete.

7.7.2 Drying shrinkage and swelling of RC30 concrete.

Swelling - As shown in *figure 7.12*, expansion due to swelling was found to range between 92 and 153 $\mu\varepsilon$ and these values were within the guide range suggested in concrete textbooks [11]. With up to 50% RCA content there was limited affect, the results showing a 12% decreased expansion. With RCA content exceeding 50% the concrete showed expansions of 130 to 153 $\mu\varepsilon$, an increase of between 11-31% when compared to NA concrete results.

The inclusion of RCA in excess of 30% meant extra cement due to the w/c ratio adjustment applied in mix design. Therefore, the increase in expansion at 75% and 100% RCA was mainly the result of their higher cement contents developing higher swelling pressures and increased expansion.

The results have also clearly indicated that, although the magnitude of shrinkage was affected by the RCA content, there was no effect at all on the development pattern of such deformation and as shown in *figure 7.12*, development was almost completely stabilised after two weeks for all concretes regardless of their RCA content, except the 100% RCA in which most of its deformation occurred in the first

8-days, after which increase in swelling continued at very small rates.

With RC30 it can be concluded that up to a 50% RCA content has no effect on the swelling, but with increases above that, increased swelling values were observed which were the result of the extra cement required in order to achieve equivalent strength concrete. Therefore, RCA content was not directly responsible for the increased expansion corresponding to high RCA contents. Also it was concluded that the swelling development of all concretes regardless of RCA content was reasonably similar and swelling was almost fully developed within two weeks from immersion in water with the exception of the 100% RCA concrete which occurred within about 8-days. The magnitude of swelling of both RCA and NA concretes was within the values expected for concrete with a cement content of 335 kg/m^3.

Drying shrinkage - The inclusion of up to 30% RCA had an insignificant effect on the drying shrinkage of the concrete when compared to NA concrete. With RCA contents at 50% and 75%, shrinkage was 78% and 70% respectively, higher than for NA concrete. The difference was even higher, at 95% for 100% RCA content. Mixes containing RCA in excess of 30% will have a decreased *w/c ratio* due to increased cement content which will also result in small reductions to the *aggregate/cement ratio* but the factor mostly causing these discrepancies is that of the moisture content of the RCA.

Although the maximum shrinkage of 790 $\mu\varepsilon$ associated with 100% RCA concrete was considerably higher than for NA concrete, it should be noted that a concrete with a w/c ratio of around 0.55 and aggregate/cement ratio of 5, as is the RC30 case, would be expected to show shrinkage values between 600 $\mu\varepsilon$ and 750 $\mu\varepsilon$ when conditioned at 50%RH [11]. The specimens in this study were subjected to between 35-45% RH in a laboratory environment and therefore the values found were the expected ones. Lastly, most of the shrinkage development took place during the first 70-days for concrete with RCA contents up to 30% and during the first 80-days for those exceeding 30%, after exposure to 35-45%RH and 21°C environment and this was regardless of RCA content.

Summarising for drying shrinkage, although the magnitude of the linear contraction of the concretes was clearly affected by the RCA content, this effect was associated with the increased cement content due to w/c adjustments as well as the consequent aggregate/cement ratio reduction, but the main cause is believed to be the high moisture content as a result of high water absorption of the RCA which when drying causes higher shrinking when compared to NA concrete.The values observed irrespective of RCA content are of a magnitude expected by the w/c and aggregate/cement ratios of this designated mix.

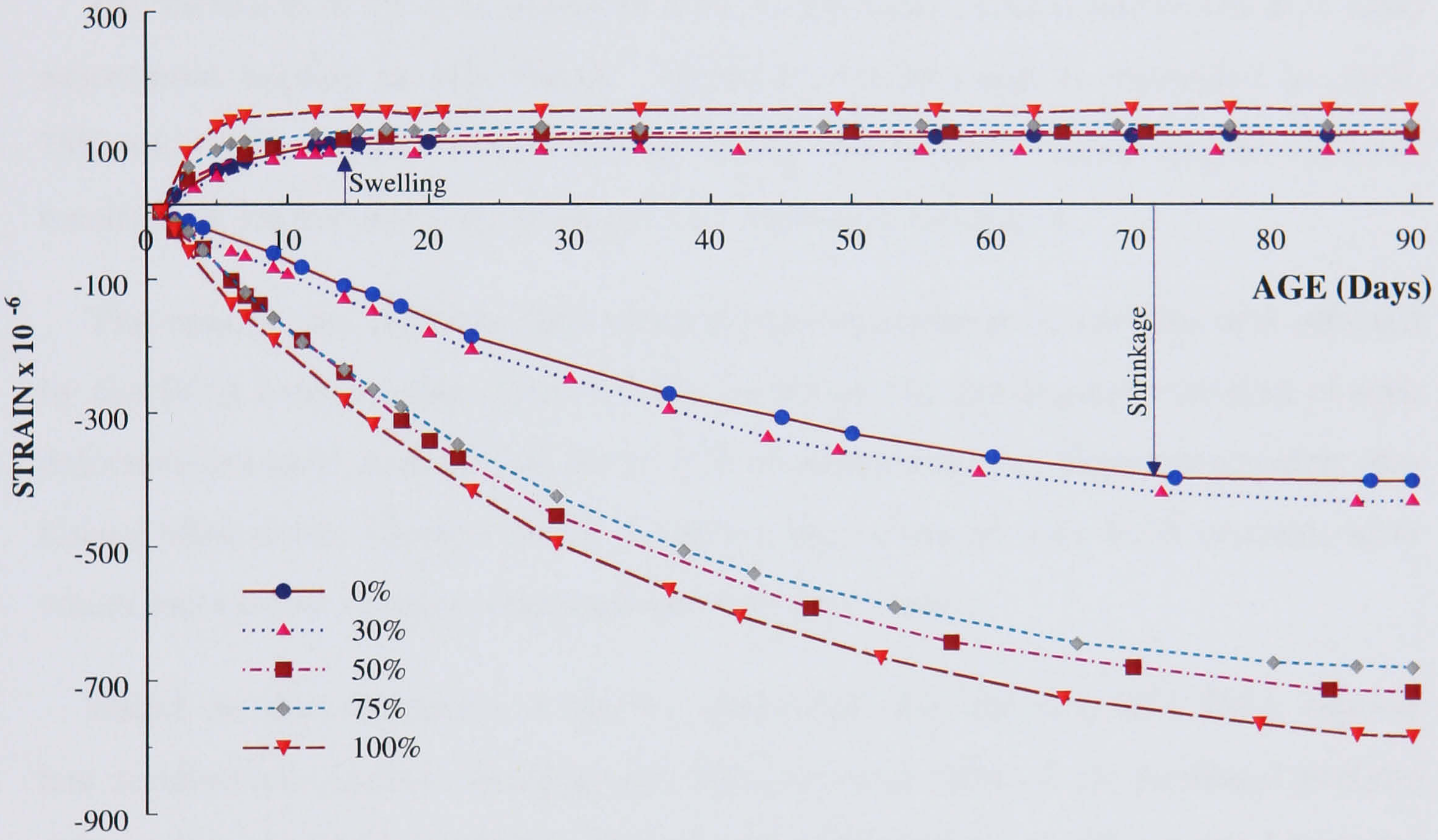


Figure 7.12: Effect of RCA content on deformation of RC30 concrete.

7.7.3 Drying shrinkage and swelling of PAV1 concrete.

Swelling - *Figure 7.13*, indicates expansion due to swelling ranged between 85 and 154 $\mu\varepsilon$ and these results were similar to those suggested in concrete textbooks [11]. With up to 30% RCA content there was no effect compared to NA concrete swelling and it is worth noting that the results for 0% and 30% RCA were somewhat low (usually 100 – 150 $\mu\varepsilon$). Clearly with RCA contents at 50 and 75% the concrete showed increased expansions of 128 and 130 $\mu\varepsilon$ respectively, an increase of around

50% compared to NA concrete. Concrete made with 100% RCA showed the maximum swelling compared to others at 154 $\mu\varepsilon$, an increase of 80% when compared to NA swelling.

These observations were almost identical to the RC30 results with the exception of a lower swelling of NA concrete. This was expected since both designated mixes have similar w/c ratios, cement contents and aggregate contents, the latter accounting for about 80% of the concrete volume.

The inclusion of RCA in excess of 30% meant extra cement due to the w/c ratio adjustment applied in mix design. Therefore, the increase in expansion for 50%, 75% and 100% RCA concretes was primarily due to their higher cement contents resulting in higher swelling pressures and increased expansion.

The results also indicate that although the magnitude of swelling was affected by the RCA content, there was no effect at all on the development pattern of such deformations and, as shown in *figure 7.13*, development was almost completely stabilised after about 10-days for all concretes regardless of their RCA content, after which increase in swelling continued at very small rates.

Based on this discussion it can be concluded that up to a 30% RCA content has no effect on concrete swelling, but with increases above that, increased swelling values were observed which were the result of the extra cement required in order to achieve equivalent strength concrete. The inclusion of RCA therefore indirectly caused increased expansion. The swelling development of all concretes regardless of RCA content was found to be very similar while swelling was almost fully developed within 10-days from exposure to 100%RH conditions. Nevertheless the magnitude of swelling for both RCA and NA concretes was within the values expected for concrete with a cement content of 345 kg/m^3.

Drying shrinkage - Drying shrinkage had similar but opposite effects due to RCA content but on a much larger scale. The inclusion of up to 30% RCA resulted in insignificant effects on the drying shrinkage of the concrete. However, an RCA content of 50% and 75% resulted in shrinkages 78% and 70% respectively, higher than for NA concrete. The difference was even higher, at 95% for 100% RCA content. As explained earlier the water content of the fully saturated RCA in the mix is considerably higher than that of NA and therefore when drying out it shrinks more transferring this effect to the surrounding concrete hence the more RCA is included in the mix the greater the effect. In addition to this cause concrete mixes containing RCA in excess of 30% will have a decreased *w/c ratio* due to increased cement content which will also result in small reductions to the *aggregate/cement ratio* which partly accounts for the increased shrinkages.

Although the maximum shrinkage of 776 $\mu\varepsilon$, associated with 100% RCA concrete was considerably higher than for NA concrete, it should be noted that a concrete with a w/c ratio of 0.48 and an aggregate/cement ratio of around 5, as in this case, will be expected to show shrinkage values between 600 $\mu\varepsilon$ and 700 $\mu\varepsilon$ when conditioned at 50%RH [11]. The specimens in this study were subjected to a much drier environment at 35% to 45% RH and therefore the values found were only slightly higher than the expected ones. Shrinkage development largely, took place during the first 55-days for all concretes regardless of RCA content.

Summarising for drying shrinkage, the magnitude of shrinkage was clearly affected by the RCA content, this effect was firstly associated with the high moisture content capacity of the RCA which when drying out resulted in increased shrinkage strains, and secondly with the increased cement content which was a direct consequence of w/c ratio adjustments as well as the consequent aggregate/cement ratio reduction. The values observed, irrespective of RCA content, were of an expected magnitude for a concrete of this water content and aggregate/cement ratio.

7.7.4 Drying shrinkage and swelling of PAV2 concrete.

Swelling - *Figure 7.14*, depicts the deformation results for PAV2 concretes. It can be observed that expansion due to swelling ranged between 112 and 137 $\mu\varepsilon$ and these values are within the guide values suggested in concrete technology textbooks [11]. The increase in RCA content had insignificant effects on the swelling behavior

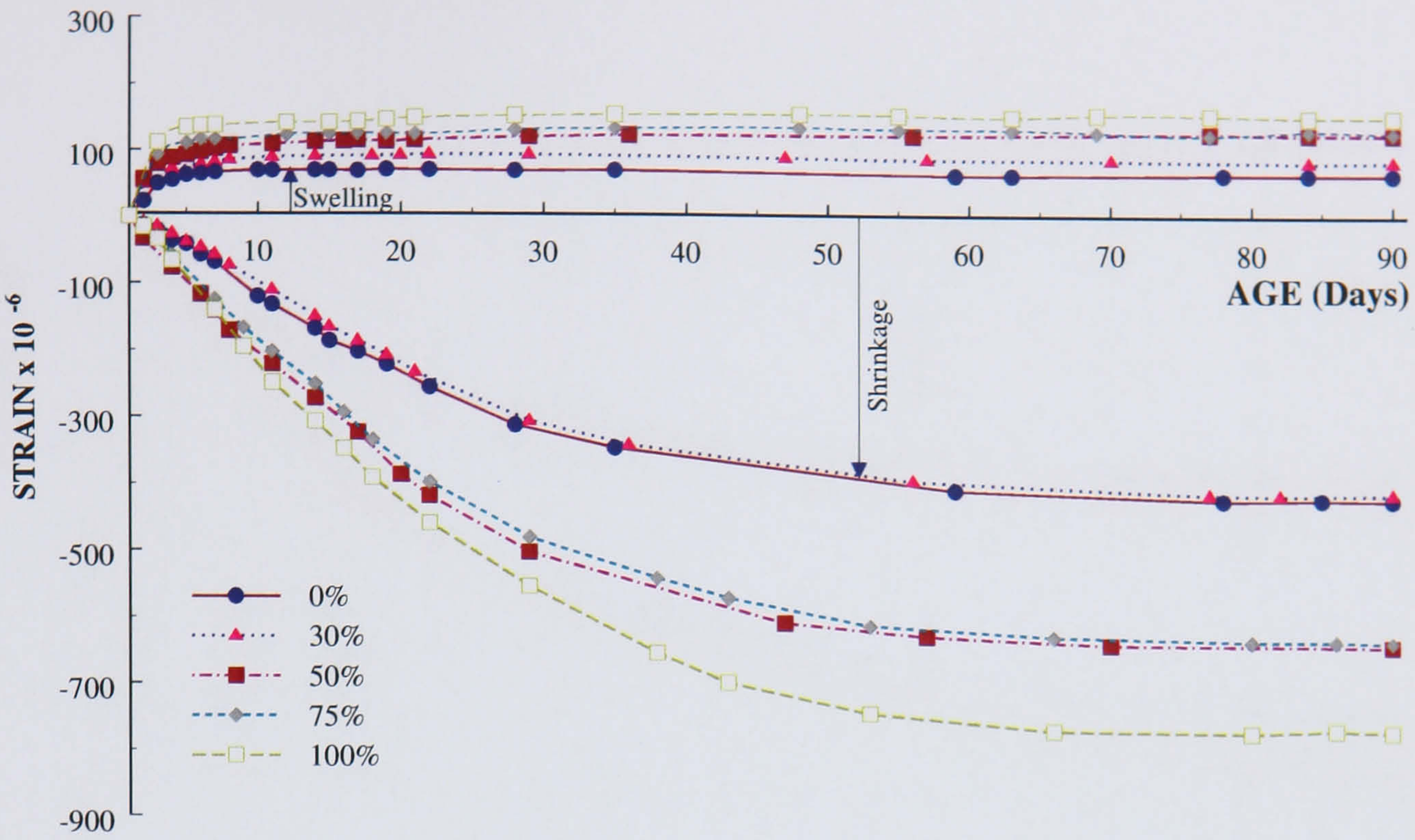


Figure 7.13: Effect of RCA content on deformation of PAV1 concrete.

of this concrete. The biggest variation was concrete with 75% RCA which showed an increase of 18% in swelling when compared to NA concrete.

All results were comfortably in the expected range of 100 to 150 $\mu\varepsilon$ for this concrete. The results have also clearly indicated that there was no effect at all on the development pattern of swelling expansion due to including RCA and as shown in *figure 7.14* the development largely took place over the first 10-days, after which increase in swelling continued at very small rates.

Drying shrinkage - Drying shrinkage showed effects due to RCA content were similar to RC30 and PAV1 concretes. The inclusion of RCA up to 30% showed a minor increase of 12%, on the drying shrinkage of concrete when compared to NA concrete results. RCA contents of 50, 75 and 100% resulted in shrinkages of 106 90 and 113% higher than NA concrete respectively. These variations partly relate to the fact that when RCA is used in excess of 30% the w/c ratio is adjusted down by increasing cement content, which also resulted in a small reduction in the aggregate/cement ratio. The main reason for shrinkage increase was the water absorption characteristic of the RCA being considerably higher than NA. This resulted in higher moisture contents retained by the saturated RCA in the concrete which

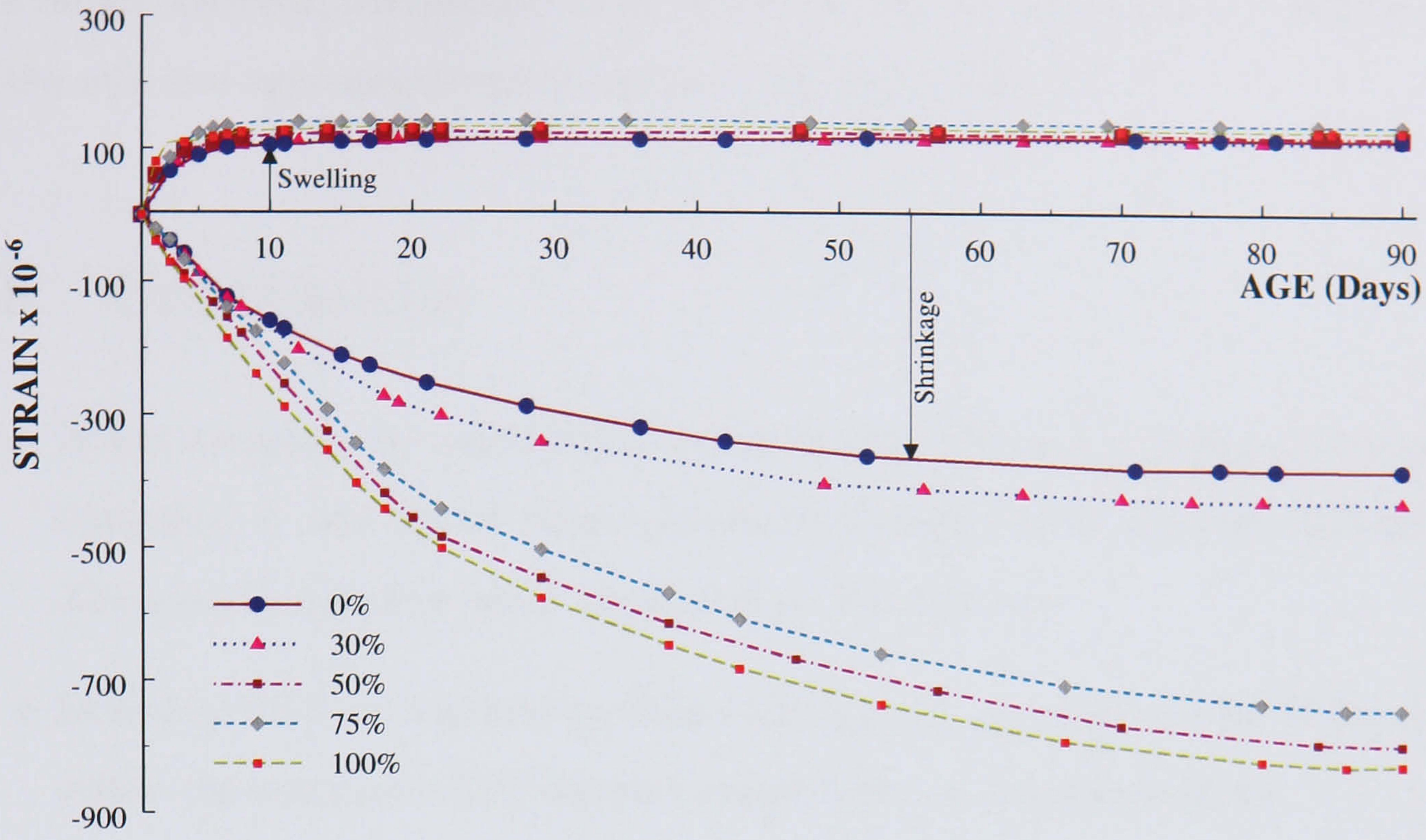


Figure 7.14: Effect of RCA content on deformation of PAV2 concrete.

when started to drying out caused considerably higher shrinkages to the concrete containing it.

Although the maximum shrinkage of 825 $\mu\varepsilon$ associated with 100% RCA concrete was considerably higher than for NA concrete, it should be noted that a concrete with w/c ratio of 0.42 and aggregate/cement ratio of 4.5, as in this case, will be expected to show shrinkage values of between 450 and 650 $\mu\varepsilon$ when conditioned at 50%RH [11]. The specimens in this study were subjected to a drier environment of between 35% and 45% RH which will result in a somewhat higher shrinkage to that resulting from exposure to 50%RH. Nevertheless a value of 825 $\mu\varepsilon$ is high. Lastly most of the shrinkage development took place during the first 55-days for concrete with RCA contents up to 30% and within 80-days for those exceeding 30%, after exposure to 35-45%RH and 21^oC environment and this was regardless of RCA content.

Summarising for drying shrinkage. Drying shrinkage was related to the RCA content, primarily in connection to its increased water retention capacity and consequent moisture loss when drying. Secondly to the increased cement content due to w/c ratio adjustment as well as the consequent aggregate/cement ratio reduction.

The values observed, irrespective to RCA content are of a magnitude to be expected by the w/c and aggregate/cement ratios of this designated mix.

7.8 Conclusions

- When assessing the relationship between the cube and cylinder compressive strengths, it was found that equivalent strength RCA concrete showed no difference in behavior when compared to NA concrete.
- Including RCA in concrete increases the $f_{c,cyl}/f_{c,cube}$ ratio in 75% of the cases whilst the remainder 25% showed insignificant or no change at all.
- Analysis of cube compressive strength results revealed that equivalent strength concretes can be achieved through the mix design modification involving the reduction of the water cement ratio. Strength development of RCA and NA concretes show near identical patterns regardless of the RCA content.
- From assessment of the relationship between compressive strength and w/c ratio, it can be concluded that the rule of strength being inversely proportional to w/c ratio is valid for RCA concrete as is the case for traditional concretes with natural aggregates.
- RCA inclusion in concrete was found to either have beneficial or no effect on flexural strength results.
- RCA concrete strengths over 60 N/mm^2 can be achieved. It was also found that RCA had a negative effect on the ceiling strength of concrete identified to commence at w/c ratios of around 0.3 which, was considerably before the 30% RCA and NA concretes showed any ceiling strength effects.
- Comparing flexural and compressive strength results gave a high coefficient of correlation (0.96) providing confidence in the results. The relationship was non linear showing that as compressive strength increases so does the flexural strength but its ratio over compressive strength decreases. No distinction between RCA and NA concrete results was evident in the scatter.

- Overall the static modulus of elasticity was decreased by up to 40% due to the inclusion of RCA as has been reported by other studies [33, 52, 63]

- The swelling of concrete containing up to 30% coarse RCA was very similar to that of NA concrete. Generally with increase of the RCA content in excess of 30% there was some increase in expansion due to swelling but such increases were very small with values always being in the range of those expected for the concrete Generally most swelling expansion occurred within 2-weeks.

  On the other hand, drying shrinkage was insignificantly affected by RCA contents up to 30% while exceeding this proportion resulted in increase that ranged between 35 and 120% compared to NA concrete.

CHAPTER 8

DURABILITY PERFORMANCE OF RCA CONCRETE

8.1 INTRODUCTION

Durability of concrete can be defined as its capability to withstand the processes of deterioration whether these are physical such as freeze-thaw action and abrasion, or chemical such as carbonation, chloride ingress, and sulphate attack. Concrete is not designed to withstand all deterioration processes at all grades of severity. According to the intended application certain measures should be taken during design to minimise and slow the deterioration processes in order for concrete to remain serviceable for the intended design life period. Minimum cement contents, w/c ratios, restrictions to cement compositions such as sulphate content, are only some of the requirements a designer encounters and which can be used to ensure adequate durability.

For the purposes of this study the designated mixes investigated so far have been selected for durability assessment according to the deterioration processes associated with their intended applications. The PAV series of concretes for example, are expected to be exposed to freeze-thaw cycling and chloride induced corrosion since they can be used in pavement construction outdoors. Other tests not directly related to a particular concrete application are good indicators of durability, such as the I.S.A.T. and have been included for all series of concretes in this study. In the following sections the results of these investigations will be discussed and the durability performance established emphasising how RCA content affects each property. A summary of all the results is given in *table 8.1* for ease in comparing results during the discussion, in addition to the graphical representation.

Table 8.1: Durability performance results summary.

PROPERTY	DESIGN STRENGTH (N/mm^2)	NA	COARSE RCA (%)			
			30	50	75	100
ISAT-10 ($ml/m^2/sec$)	GEN0-8	1.68	1.70	1.81	-	1.89
	GEN3-20	0.79	0.80	0.83	-	1.00
	RC30-30	0.56	0.55	0.59	-	0.71
	PAV1-30	0.61	0.60	0.63	-	0.72
	PAV2-35	0.48	0.48	0.53	-	0.64
Carbonation depth (mm)	GEN3-20	25.0	24.5	23.5	-	24.0
	RC30-30	22.0	22.0	24.5	-	25.0
	PAV1-30	22.5	24.5	21.5	-	25.0
Abrasion depth (mm)	RC30-30	0.44	0.41	0.62	0.55	0.64
	PAV2-35	0.47	0.57	0.65	0.54	0.50
Freeze-thaw resistance[†](kg/m^2)						
28 cycles	PAV1-30	0.047	0.037	0.030	-	0.052
56 cycles[‡]		**0.079**	**0.069**	**0.061**	-	**0.057**
128 cycles		0.104	0.102	0.109	-	0.105
28 cycles	PAV2-35	0.025	0.021	0.024	-	0.026
56 cycles[‡]		**0.028**	**0.025**	**0.026**	-	**0.029**
128 cycles		0.091	0.086	0.094	-	0.092
Expansion due to exposure to sulphate solution[♯]($\mu\varepsilon$)						
60-days	GEN0-8	48.7	54.7	51.5	-	58.6
60-days	GEN1-10	44.0	49.9	63.7	-	56.6
60-days	GEN3-20	36.0	37.8	49.0	-	58.5
Chloride ion content at 20 mm depth[§](% wt of sample)						
	GEN3-20	0.13	0.14	0.13	-	0.15
	PAV1-30	0.07	0.06	0.10	-	0.09
	PAV2-35	0.08	0.07	0.08	-	0.08

[‡] Resistance to freeze-thaw based on 56-days according to EN 12390.

[†] Cumulative surface scaled material in kg/m^2.

[♯] Exposure to 0.3g/l sodium sulphate Na_2SO_4 solution. Exposure class DS1 according to BS 8500-1.

[§] Continuous exposure to 1 mol NaCl solution for 3-months.

8.2 Near Surface Absorption (I.S.A.T.)

As mentioned earlier the near surface absorption, here assessed via the I.S.A.T. method, is a good indicator of concrete durability. It assesses effectively, the area of concrete acting as cover for reinforcement. The capacity of absorbing liquids which can carry hazardous ions (i.e. chlorides) through the concrete cover is directly related to corrosion of reinforcement due to chloride ingress or other agents. It is generally accepted [11] that an initial absorption after 10-minutes greater than 0.5 $ml/m^2/sec$ is considered high while bellow 0.25 $ml/m^2/sec$ is low. However, this will depend on the moisture content of the concrete which when high, results in low I.S.A.T. values and vice versa. In order to overcome this difficulty and ensure consistency, all the specimens were oven dried to a constant mass removing all moisture present before testing. This would be very difficult for site testing. The values reported in the following analysis were higher than 0.5 $ml/m^2/sec$ in most cases due to the drying process. A spot check on two RC30 specimens, not oven dried showed values half those of oven dried specimens and this puts the following results in perspective.

8.2.1 GEN0 series concrete.

Near surface absorption of GEN0 concrete was measured at 10, 30 and 60 minutes and the results are shown in *figure 8.1.* Most important are the 10 minute absorption results (*table 8.1*) which were found to be identical for NA and 30% RCA concrete while a small increase was observed for 50% and 100% RCA concretes at 7% and 12% respectively. Results from subsequent 30 minute tests show a greater difference in absorption with values increasing by 20% and 28% for concrete containing 50% and 100% RCA while at 60 minutes the increase was at 30% and42% when compared to NA concrete results. RCA with up to 5 times the absorption of NA, absorbed more water and consequently resulted in higher results for concrete containing it.

Another aspect of interest when comparing RCA and NA concretes was the rate at which the absorption decayed over time. When comparing the 10, 30 and 60 minutes absorption values it was found that regardless of the RCA content the rate drop between 30 and 60 minutes was about 45% when compared to that between 10 and 30 minutes. This revealed that RCA concrete absorption rates decay in the same way as NA concrete not requiring more time to reach full saturation and consequently minimum absorption values.

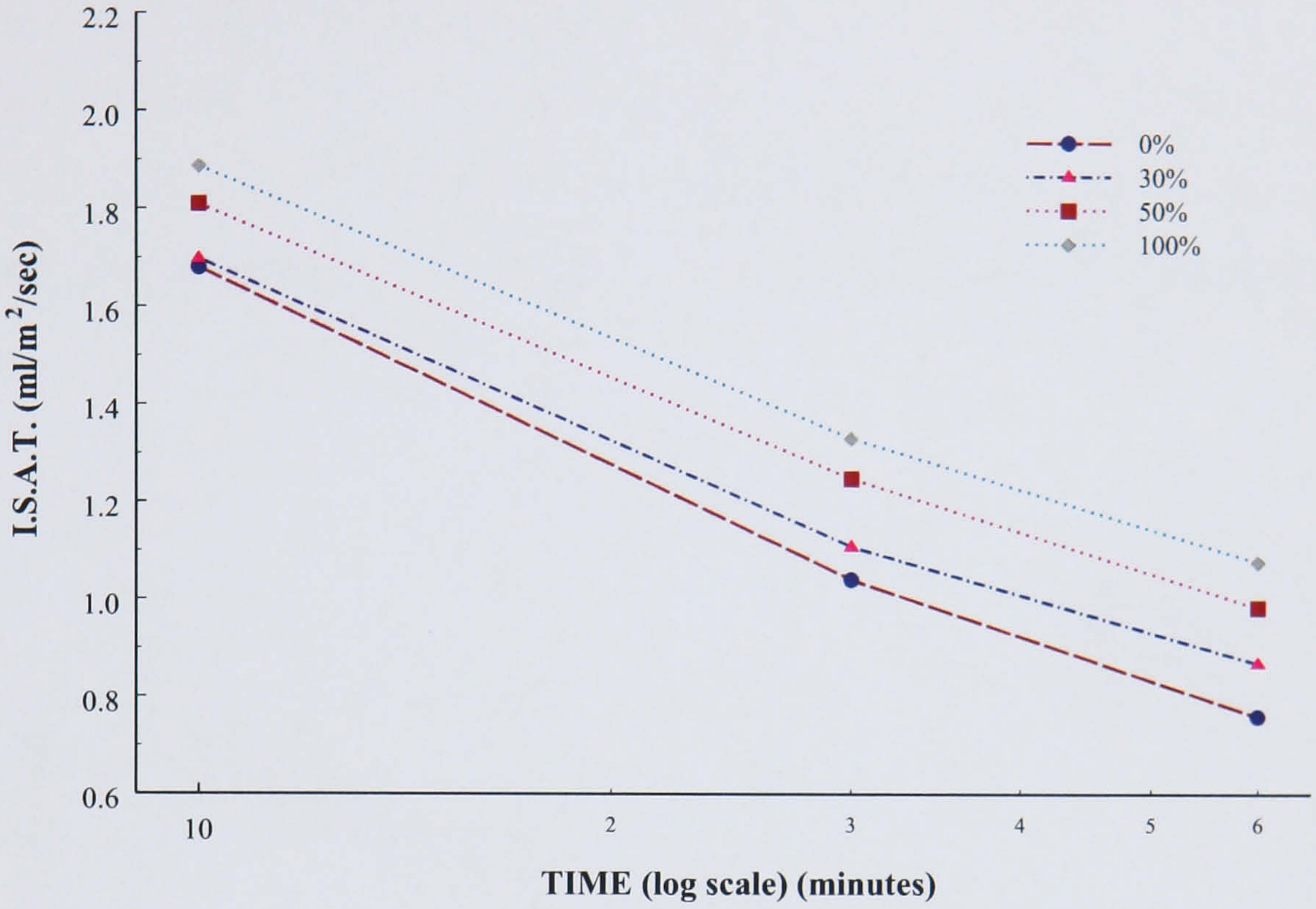


Figure 8.1: Effect of RCA content on the surface absorption of GEN0 concrete.

Overall, RCA content had a very small effect on the 10 minute initial surface absorption but as time passed the RCA concrete having a high water absorption aggregate, resulted in higher I.S.A.T. values. Finally, the decay of the absorption rates decreased in the same manner regardless of the RCA content.

8.2.2 GEN3 series concrete.

Results for GEN3 concrete are shown in *figure 8.2* with the effect of RCA being somewhat clearer than in GEN0. Concrete containing 100% RCA showed higher absorptions at all test times while all other results were very similar. Concrete containing 30 and 50% coarse RCA had almost identical water absorptions at all three test intervals while 100% RCA concrete showed values rising to 1 $ml/m^2/sec$ at 10 minutes and 0.63 $ml/m^2/sec$ at 30 minutes corresponding to a 27% increase compared to NA concrete results. The highest increase in I.S.A.T. value was observed for 100% RCA at 60 minutes which was about 36% higher than the corresponding NA concrete result.

It was also observed that the absorption rate, decayed in a similar manner for concretes with RCA content up to 50% showing a rate between 30 and 60 minutes which was about 55 to 60% lower when compared to that between 10 and 30 minutes. Concrete with 100% RCA had a faster decay during the first 10-30 minute interval, but this was reduced by 70% in the 30-60 minutes interval showing that the water absorption despite the high RCA content was largely satisfied during the first 30 minutes.

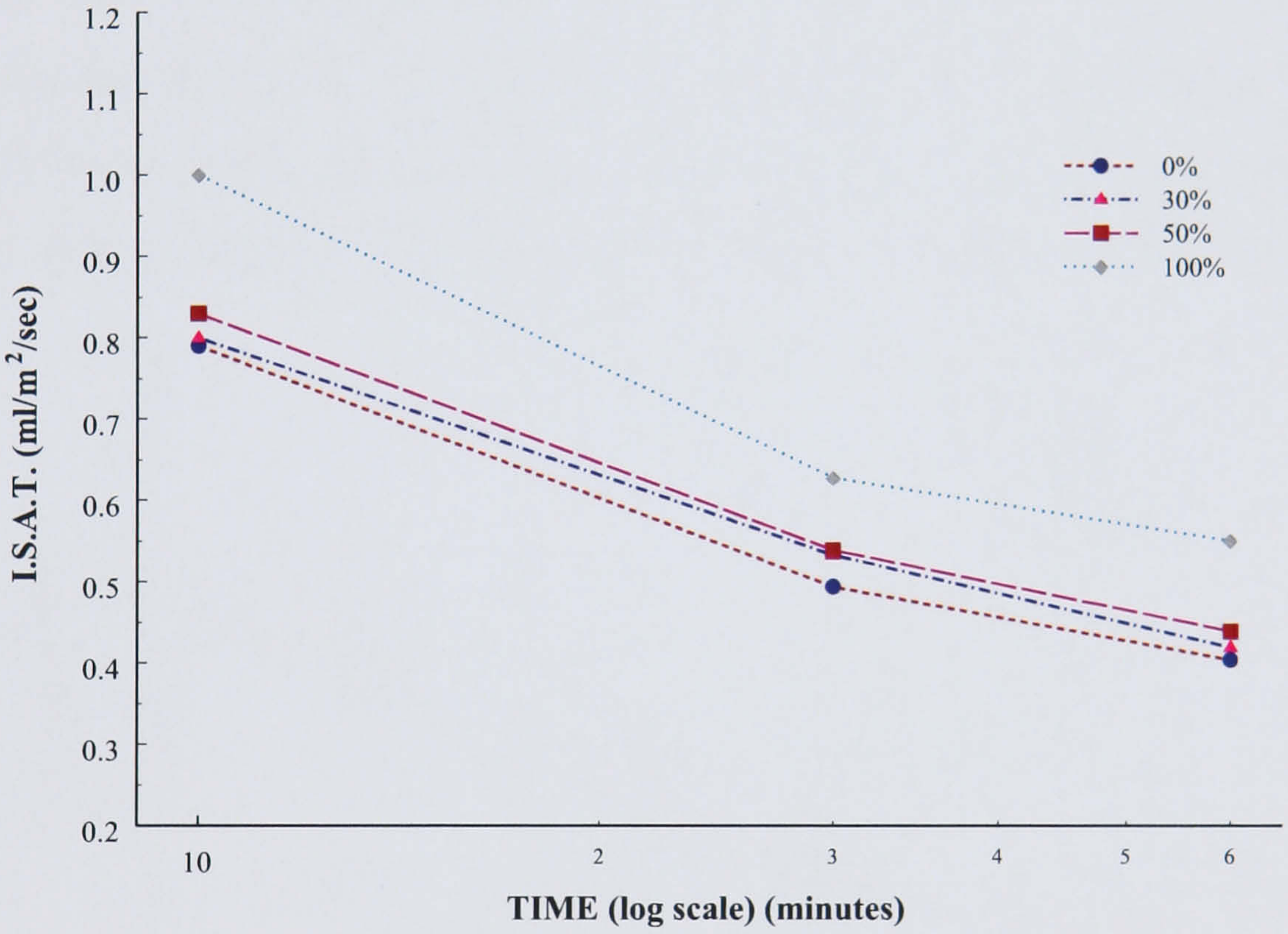


Figure 8.2: Effect of RCA content on the surface absorption of GEN3 concrete.

Overall, with up to 50% RCA content the effect on initial surface absorption was very small while concrete containing 100% RCA clearly showed the effect due to the higher water absorption of the aggregate indicating significantly higher absorption values.

8.2.3 RC30 series concrete.

These I.S.A.T. results are shown in *figure 8.3* from which it can be said that concrete containing 100% RCA was clearly affected by the high water absorption of the recycled aggregate which caused the high absorption results at all test intervals. The increase was about 27% for ISAT-10 results compared to NA concrete, but it increased to 40% and 45% at the 30 and 60 minute tests respectively.

Nevertheless the most important results, ISAT-10 (*table 8.1*) were identical for NA and 30% RCA concrete with 50% RCA also being very similar only showing an increase of about 5%. This observation was also valid for the results obtained from the subsequent 30 and 60 minute tests which remained within a very small band of 0.03 $ml/m^2/sec$. With respect to the decrease in the decay of absorption rate, it was very similar at 47% for all concretes tested regardless their RCA content.

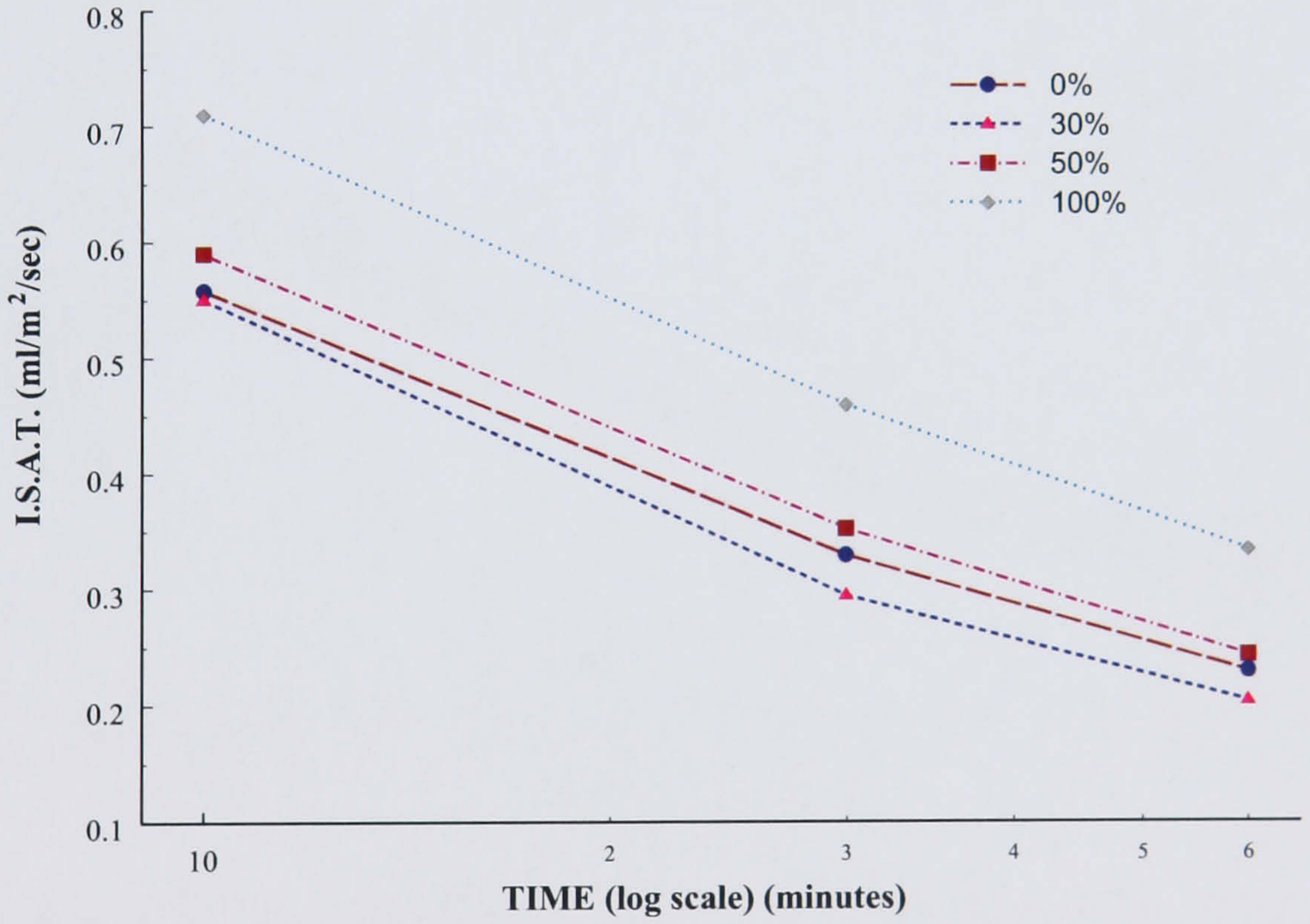


Figure 8.3: Effect of RCA content on the surface absorption of RC30 concrete.

Overall an inclusion of up to 50% RCA resulted in very small variations in the near surface absorption of this concrete throughout the 1 hour test. The rate at which the absorption rate decayed was almost identical regardless of the RCA content implying that NA and RCA concretes require similar durations to reach similar moisture states.

8.2.4 PAV1 series concrete.

The PAV1 concrete results were almost identical to those produced by RC30 concrete which was to be expected since both designated mixes have the same characteristic strength (30 N/mm^2). The only difference in their mix design was the air entrainment of the PAV series which, based on these results did not affect the initial surface absorption of the concrete.

Considering the PAV1 results shown in *figure 8.4*, it can be observed that with up to 50% RCA inclusion the results were very similar especially for 30% RCA concrete which showed identical results to NA concrete. Only when 100% RCA was included did the results increase by about 20% when compared to NA concrete. These observations were valid for all test intervals throughout the 1 hour procedure.

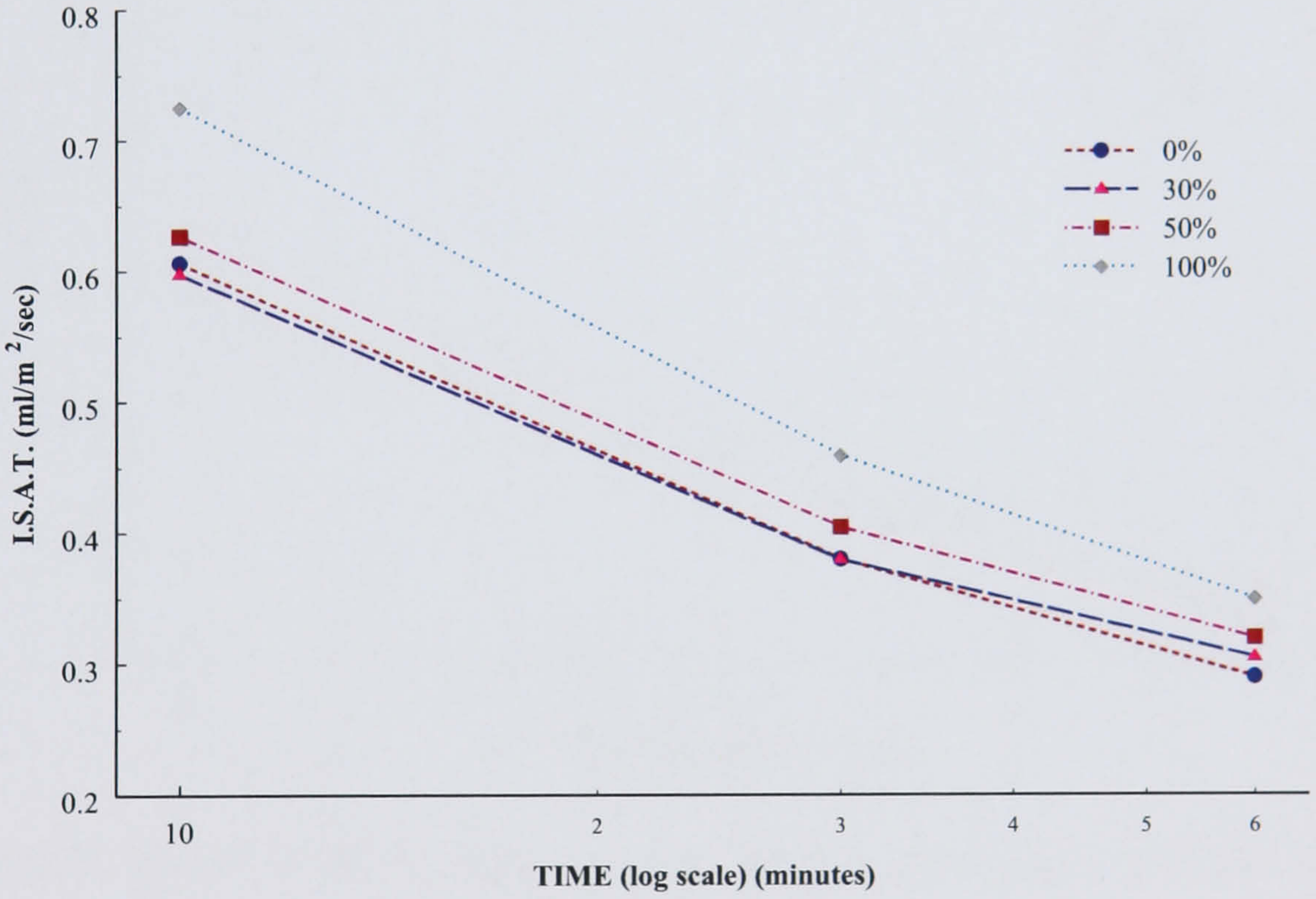


Figure 8.4: Effect of RCA content on the surface absorption of PAV1 concrete.

Summarising, RCA contents up to 50% had very small effects on surface absorbtion especially at 30% where identical results to NA concrete were observed. ISAT-10 was very similar up to 50% RCA inclusion with only 100% RCA concrete showing significantly increased values. The decay of absorption rate was also very similar, being about 50% for all concretes tested regardless of their RCA content.

8.2.5 PAV2 series concrete.

Results for PAV2 concrete are shown in *figure 8.5.* In common with the RC30 and PAV1 series results it was found that inclusions of up to 30% RCA had no effect on the ISAT-10 results while a 50% content showed only a small increase in surface absorption. Including 100% RCA resulted in 33% higher initial surface absorption at 10 minutes when compared to NA concrete. Similar observations were also valid for the 30 and 60 minute tests which showed that results for concrete containing up to 50% RCA remained within a small band of 0.03 $ml/m^2/sec$. RCA content at 100% resulted in increased surface absorption of about 34% and 31% for 30 and 60 minutes respectively, when compared to NA concrete results.

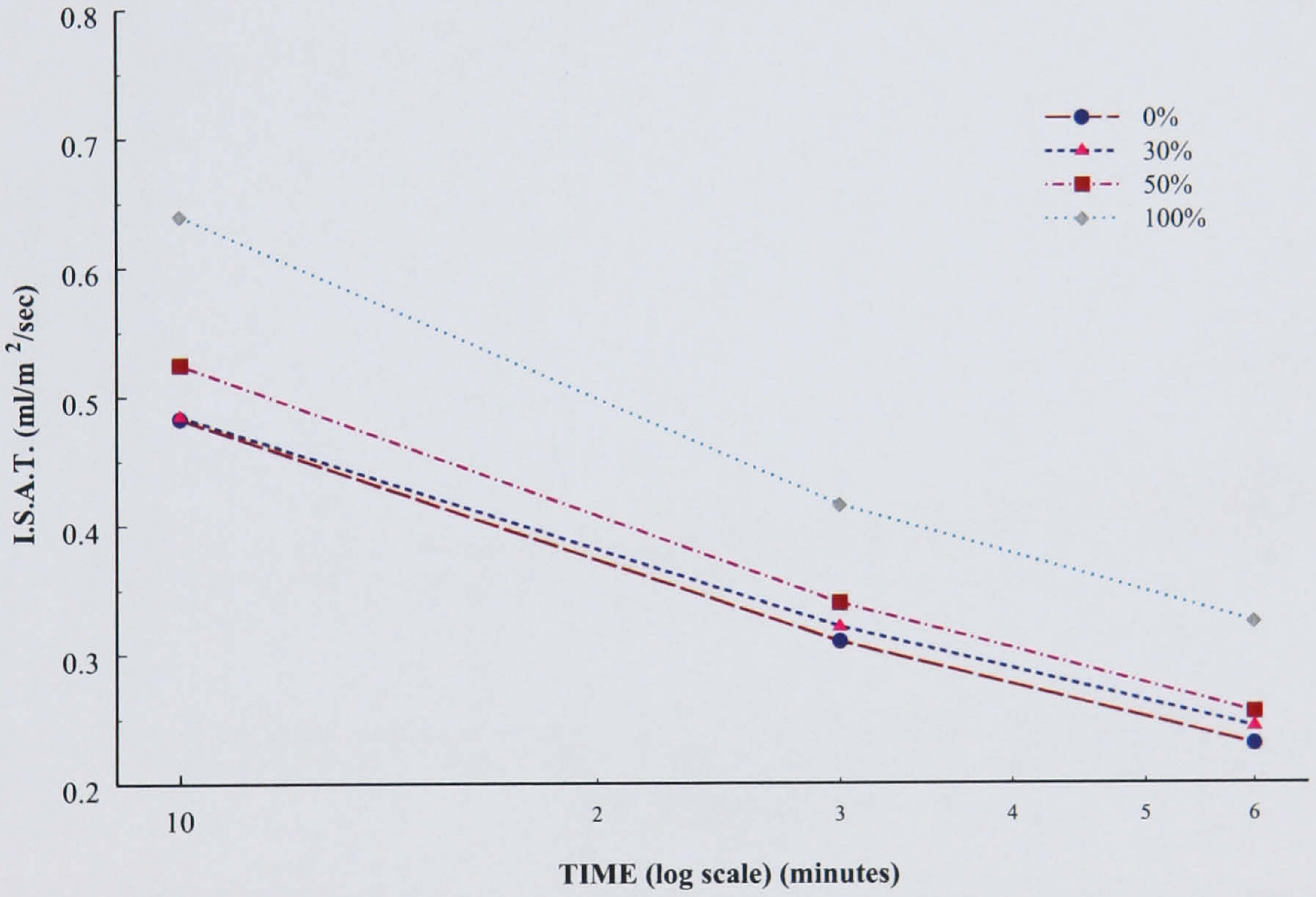


Figure 8.5: Effect of RCA content on the surface absorption of PAV2 concrete.

The decay rates of surface absorbtion were very similar for all RCA and NA concretes showing a 45% decrease during the 30-60 minutes interval when compared to the 10-30 minute interval.

Concluding, a 30% RCA content showed identical ISAT-10 and very similar results throughout the 60 minutes of testing, when compared to NA concrete. 50% RCA produced insignificant variations while 100% RCA inclusion resulted in significantly higher surface absorptions.

8.2.6 Effect of RCA content on ISAT-10.

As mentioned earlier the initial surface absorption after the first 10 minutes (ISAT-10) is of most importance so is discussed in more depth in this section.

All the ISAT-10 results were plotted against RCA content in order to identify more clearly the effect of RCA on this characteristic. The result is shown in *figure 8.6* which indicated that including up to 30% RCA had no effect at all on the ISAT-10 results. A relatively small increase was observed with RCA at 50% while a high content of 100% was found to have significant effects on the ISAT-10 value.

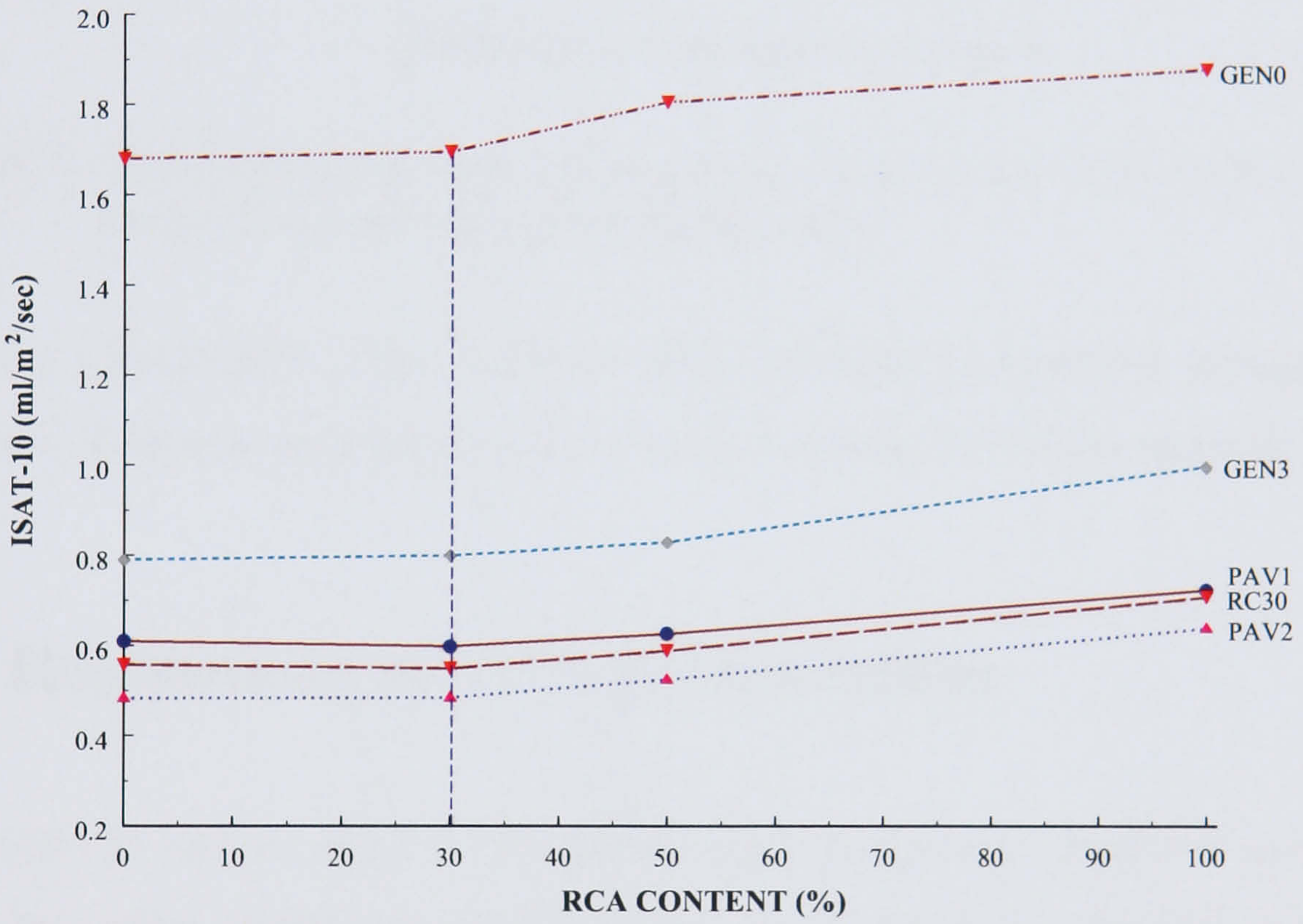


Figure 8.6: Effect of RCA content on the ISAT-10 results of GEN, RC30 and PAV series of concretes.

It was also clearly shown that the higher the strength of concrete the lower the I.S.A.T. results. This was due to the increased cement content in higher strength concrete resulting in a less permeable cement paste and consequently lower I.S.A.T. values. In order to check whether or not a relationship exists between the two properties, compressive cube strength results were plotted against the corresponding ISAT-10 results and the result is shown in *figure 8.7*.

A best fit curve was applied and a high correlation coefficient of 0.99 clearly

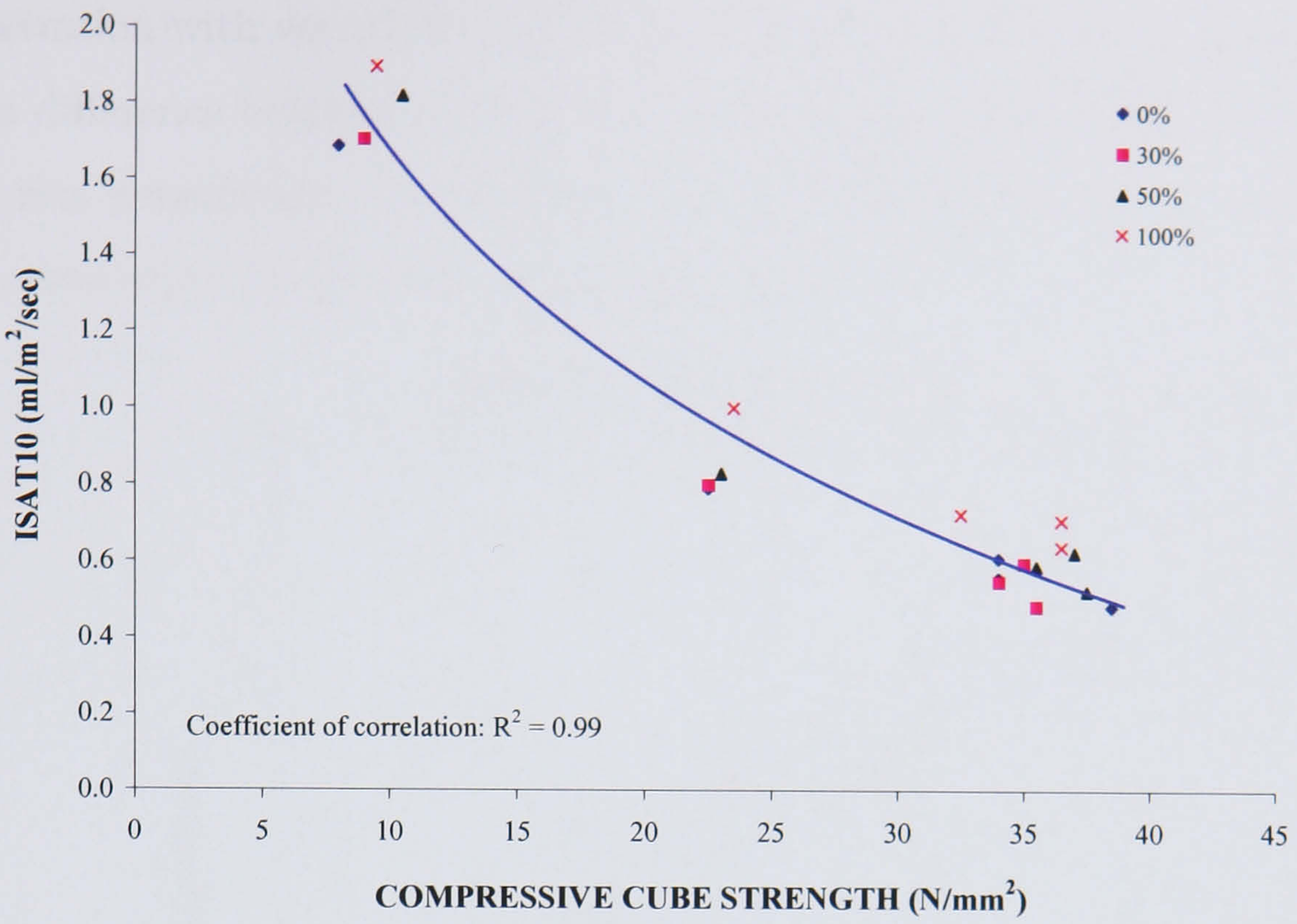


Figure 8.7: Relationship between compressive strength and ISAT-10 for all designated concretes used in the study.

indicates a relationship exists between ISAT-10 and compressive strength. The fitted curve showed a logarithmic relationship between the two properties.

8.3 Resistance to CO_2 Penetration

As explained in *section 3.2.4.3* CO_2 penetration in concrete results in increases of strength but when reinforcing steel is present could result in corrosion and further durability problems. Consequently this investigation focuses on two of the designated concretes, RC30 and PAV1 that can include steel reinforcement as well as GEN3 and aims to establish any effects due to RCA use.

8.3.1 GEN3 series concrete.

The results of CO_2 penetration are shown in *figure 8.8* on a graph that on the lower x-axis shows the real exposure duration in weeks while a second upper x-axis shows the corresponding simulated duration in years. Looking at the results it can be observed that both NA and RCA concretes showed similar resistances to

CO_2 penetration with variations that are unlikely to be due to RCA presence. The maximum difference between results was observed after 8-weeks when NA concrete had a 19 mm penetration, 3 mm more than for 100% RCA concrete. At all other ages the variation in results did not exceed 2 mm.

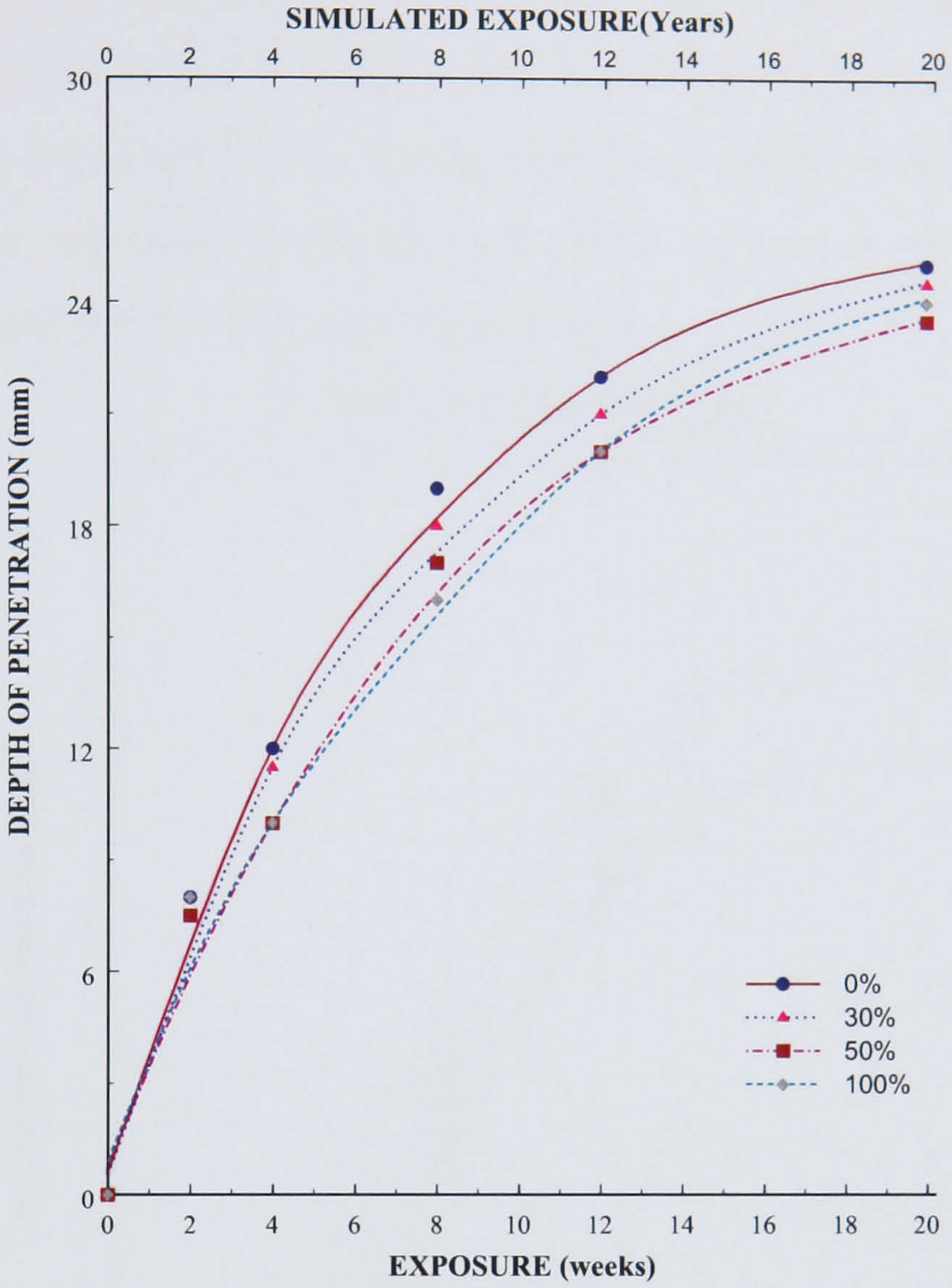


Figure 8.8: Effect of RCA content on the resistance to CO_2 penetration for GEN3 concrete.

Throughout the exposure period the highest depths of penetration were observed in NA concrete while concrete containing RCA consistently showed lower values. The maximum penetration results after 20 weeks (years) are also given in *table 8.1* were it is clear that the maximum CO_2 depth of penetration was very similar for all mixes but with very small decreases for RCA concrete. However, the small reduction with RCA concrete does not warrant the claim that RCA in concrete improves resistance to CO_2 penetration but it can be concluded with confidence that this particular set of results proved that including RCA had no negative effects.

8.3.2 RC30 series concrete.

Results showing resistance to CO_2 penetration for RC30 concrete are shown in *figure 8.9.* It can be observed that 0% and 30% RCA concretes had identical depths of penetration as did 50% and 100% RCA. The latter pair showed an increased penetration of around 3 mm at most, when compared to NA and 30% RCA concretes. However, it cannot be concluded that the increase in RCA content has a negative effect on carbonation depths since these variations could be due to the simple expected variability when testing concrete.

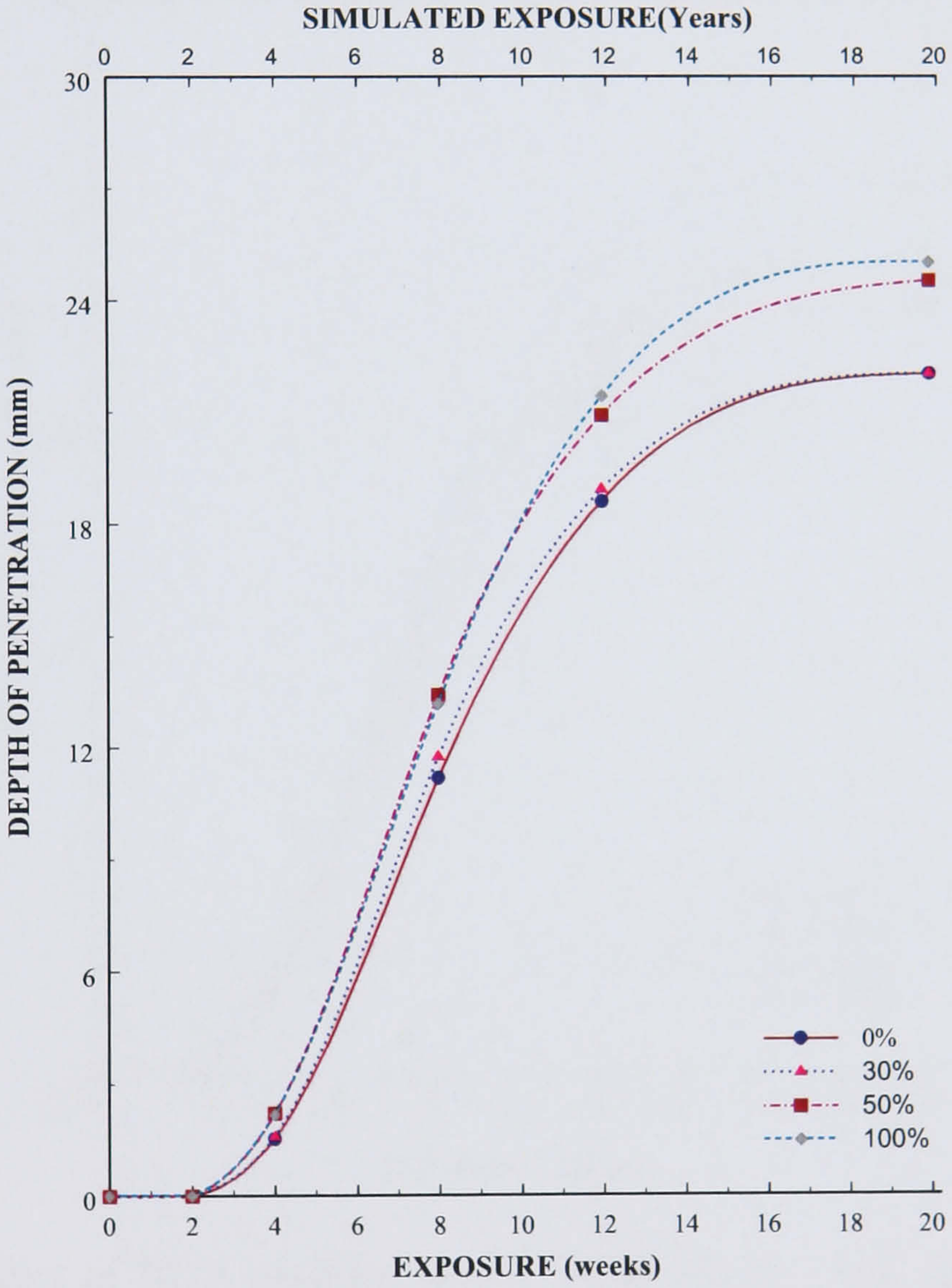


Figure 8.9: Effect of RCA content on the resistance to CO_2 penetration for RC30 concrete.

8.3.3 PAV1 series concrete.

Results of CO_2 penetration for the PAV1 series are shown in *figure 8.10.* In this case the 30% and 100% RCA concrete had identical results and NA and 50% RCA concrete had very similar depths of penetration. It is worth noting that in support of the observation made earlier regarding variability, the 50% RCA concrete showed the lowest depths in CO_2 penetration by at least 1 mm throughout the whole duration of the exposure when compared to NA concrete.

Overall the inclusion of RCA in concrete showed no negative effects on the resistance of concrete to CO_2 penetration and it is assumed that differences in results were mainly due to variability.

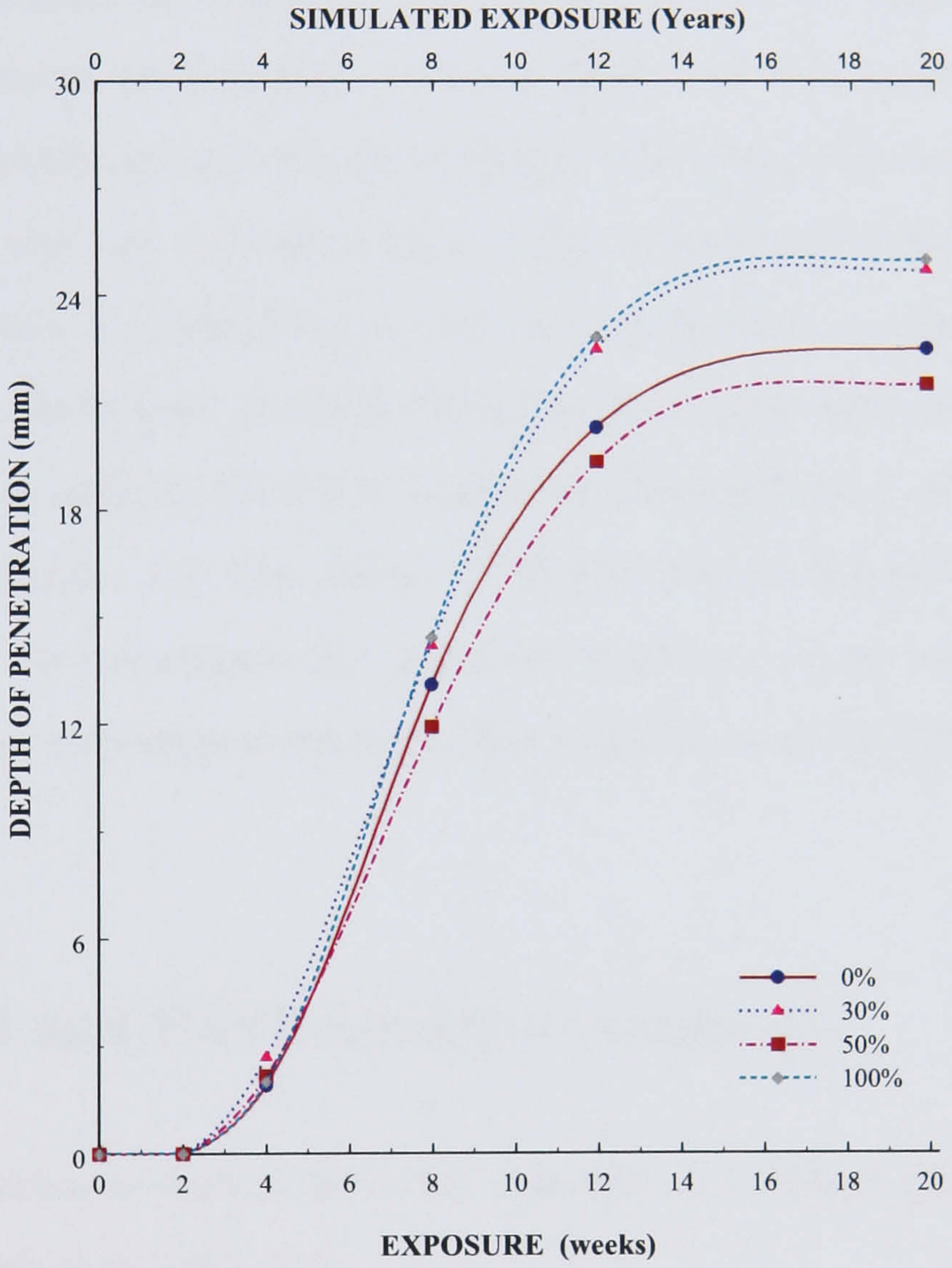


Figure 8.10: Effect of RCA content on the resistance to CO_2 penetration for PAV1 concrete.

8.4 Abrasion Resistance

Concrete destined for use in applications subject to wheel and heavy foot traffic needs to possess good resistance to abrasion. The assessment of abrasion resistance is very difficult since results will depend on many factors, one of the most important being the quality of the concrete finish, which will vary according to the method of finish and the experience of the operator. Another very important factor is the curing method and duration and this is emphasized by the recommendation of the draft ENV 206 in clause 7.3.1.4 [115] to double the duration of curing in order to improve abrasion resistance.

In this study the main focus is on the likely effects that RCA may have on the abrasion resistance of concrete. The results need to be taken as indicators of comparative abrasion performance between RCA and NA concretes, and not as values strictly classifying concrete according to BS 8204 [108] (see *table 4.16*). The reason for this is the fact that the author is not experienced in finishing pavements and this may result in variability as well as classification outside the AR values. Nevertheless all efforts were made to finish the specimen surfaces in a consistently identical manner in order to be able to assess the effect of RCA content, not finishing, on abrasion resistance. For this study RC30 and PAV2 designated concretes were selected in order to investigate the abrasion resistance of an industrial pavement concrete as well as a structural concrete that could be used for light foot and trolley traffic.

8.4.1 RC30 and PAV2 abrasion resistance.

The abrasion resistance results for both concretes are shown graphically in *figure 8.11* and summarised in *table 8.1*.

The wear depths for RC30 concrete ranged between 0.44 and 0.64 mm with the lowest depth of wear achieved with 30% RCA and the highest for 100% RCA concrete. Pavements containing 50 and 75% RCA were found to have wear depths 0.18 and 0.11 mm deeper than NA concrete. Considering that the classifications of *table 8.11* are divided at most by an interval of 0.2 mm it is evident that the increases in depth due to RCA were high compared to NA, the only exception being concrete with 30% RCA.

Generally it can be concluded that the inclusion of RCA in concrete affected the resistance to wear in a negative way but it was not seriously detrimental. Although the concrete containing 30% RCA, showed an improved wear resistance it cannot be claimed for certain that RCA up to this content improves performance and further testing would be needed to verify this.

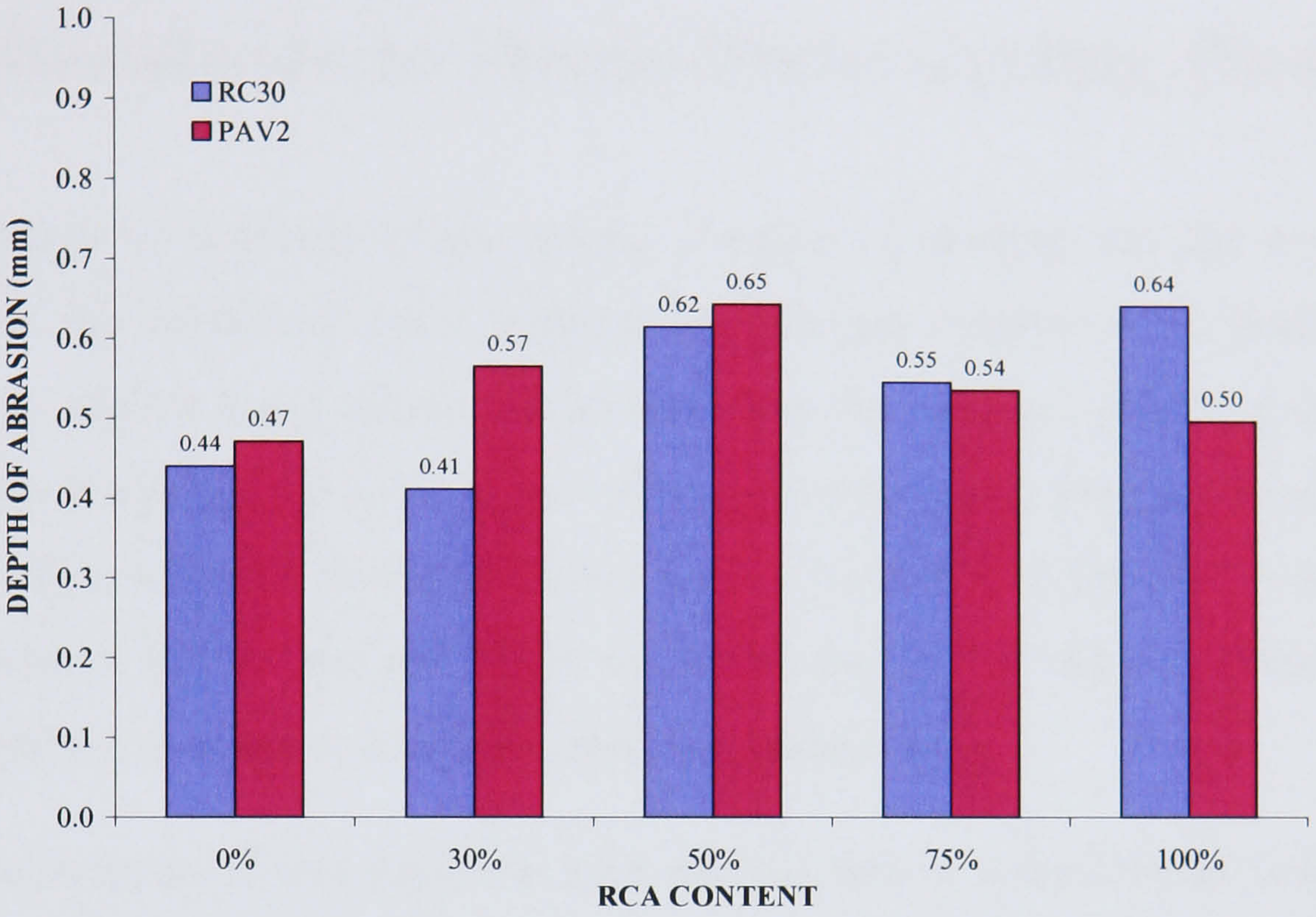


Figure 8.11: Effect of RCA content on the abrasion resistance of RC30 and PAV2 series concretes.

PAV2 concrete wear depth results ranged between 0.47 and 0.65 mm with the lowest depth of wear being for NA and the highest for 50% RCA concrete. The difference was about 0.18 mm, similar to that for RC30 concrete. Pavements containing 30 and 75% RCA were found to have depths 0.10 and 0.07 mm deeper than NA concrete. Pavement specimens containing 100% RCA were found to have a wear resistance not that different to NA concrete with values about 0.03 mm higher. Once again putting these differences in perspective and noting that the classifications of *table 8.11* for heavy duty pavements are divided by intervals between 0.05 to 0.1 mm, it is evident that the increases in depth were considerable when compared to NA but not excessive.

Summarising, once again the inclusion of RCA in concrete affected the abrasion resistance negatively but the effect was not seriously detrimental. As observed with the RC30 specimens, a clear pattern due to RCA inclusion was not established and in order to fully understand the effect that RCA has on abrasion resistance, it will be necessary to carry out an extensive experimental programme involving experienced operators and the production of a high number of specimens.

8.5 Resistance to Freeze-Thaw Cycling (Scaling)

Frost damage to concrete results mainly because of freezing and the consequent increase in the volume of water contained in the pore system of the hardened cement paste and/or water which has diffused from the surface. The frost resistance of concrete is studied by freeze-thaw cycling because, when freezing occurs cracks develop, which when the thaw part of the cycle is reached are filled with fresh water. This new water will in turn add to the expansion during the following freezing cycle causing further damage to concrete which is cumulative.

For the purposes of this study the PAV series of mixes, which in practical circumstances would be exposed to freeze-thaw cycles, were selected for the investigation of their freeze-thaw resistance and to determine the effect that RCA inclusion may have. The test method is based on quantifying the mass of cumulative scaled material after freeze-thaw cycling and the results are expressed in kg/m^2.

8.5.1 PAV1 series concrete.

Freeze thaw performance results for PAV1 concrete are graphically shown in *figure 8.12*. Although performance is based on the 56-day cumulative scaled material it was decided to show also results after 28 and extend the exposure to 128-cycles for a more in depth understanding of the effect of RCA.

Results after 28-cycles showed an increase in freeze-thaw resistance of the 30% and 50% RCA concretes, by 21% and 36% respectively compared to NA concrete. A small reduction was observed for concrete containing 100% RCA at about 10%.

Most important were the results after 56-days which define the freeze-thaw performance of the concretes tested. It was found that RCA concrete had better freeze thaw resistance and scaled material was reduced by 13% for 30% RCA, 23% for 50% RCA and by 28% for 100% RCA concrete. Finally, extended tests exposing the specimens up to 128-cycles showed that the inclusion of various proportions of RCA in concrete has little effect on the degree of scaling.

Overall it can be concluded that there was no indication from the results that RCA had any negative effect. In fact the presence of RCA in the mix often improved the freeze-thaw performance and therefore scaling resistance of concrete.

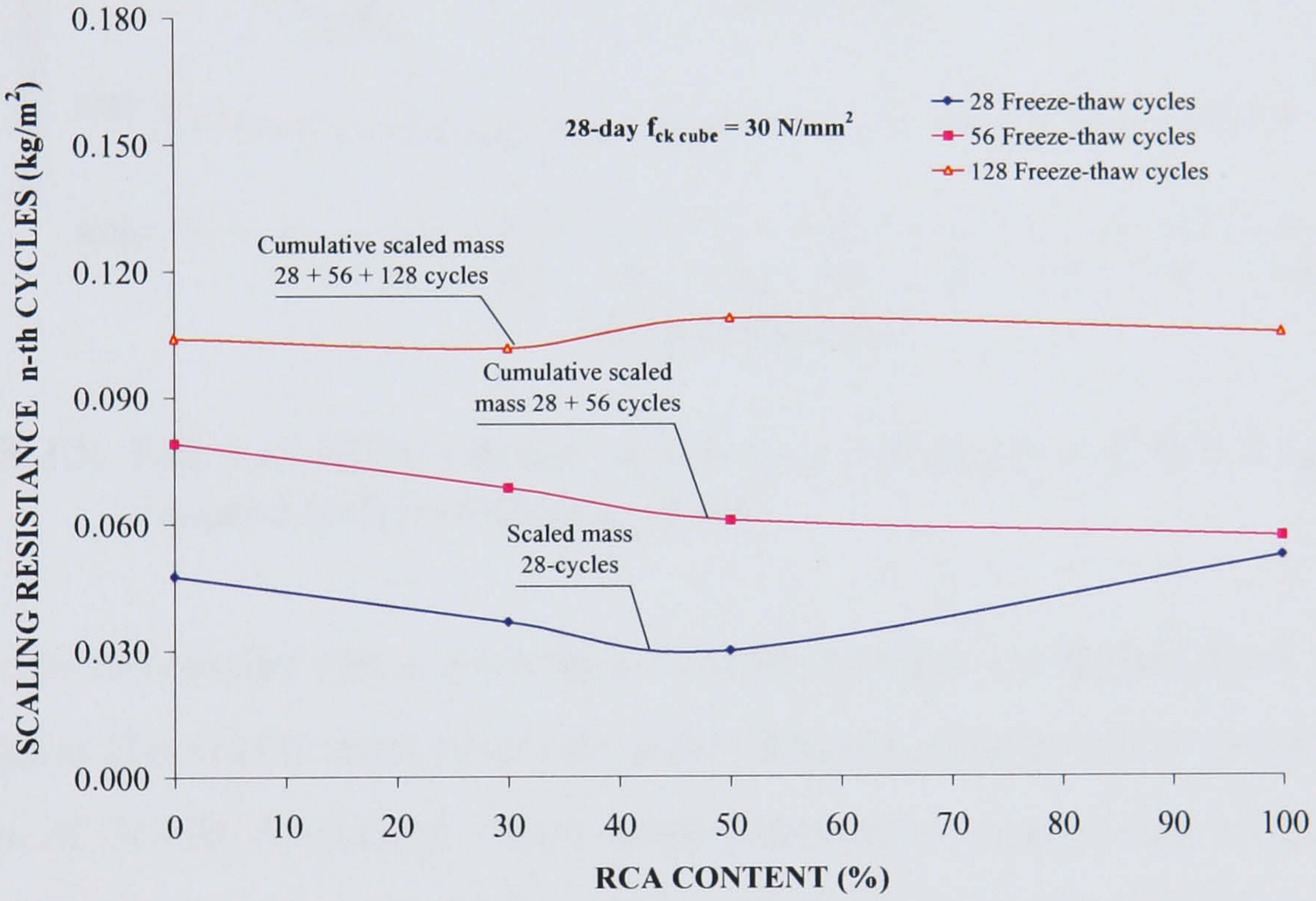


Figure 8.12: Effect of RCA content on the scale resistance of PAV1 concrete exposed to freeze-thaw cycling.

8.5.2 PAV2 series concrete.

The results obtained with PAV2 concrete are shown in *figure 8.13*. Exposure to freezing and thawing for 28-cycles showed very similar results for all RCA and NA concretes tested. Specifically a decrease in resistance of around 15% was observed for 30% RCA and only 4% for 50% RCA when compared to NA concrete performance. An improvement in freeze thaw resistance by 4% was observed for 100%

RCA concrete. These variations were very small and do not indicate a particular effect due to RCA inclusion but do highlight that, the inclusion of RCA in concrete does not have negative effect.

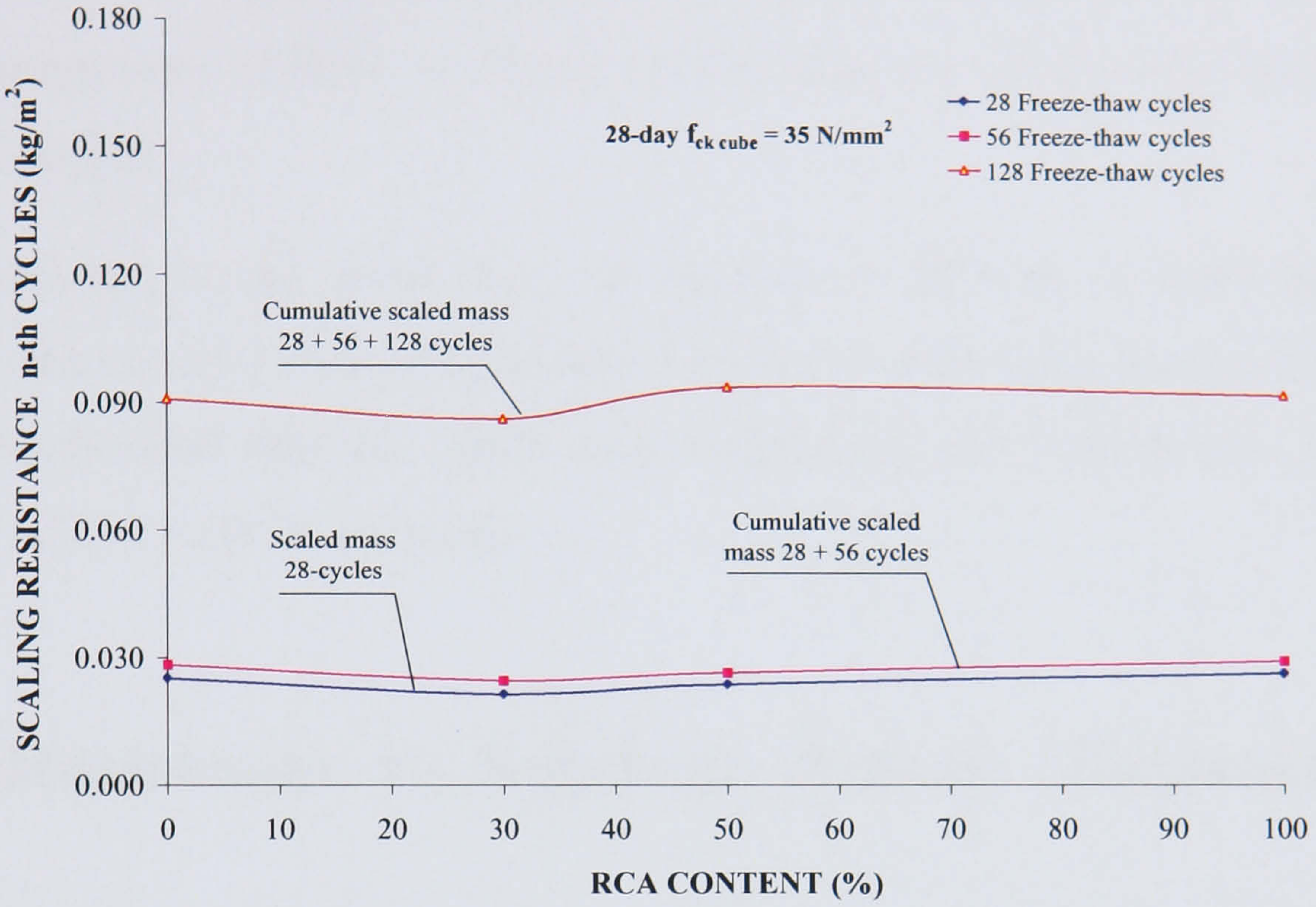


Figure 8.13: Effect of RCA content on the scale resistance of PAV2 concrete exposed to freeze-thaw cycling.

As mentioned earlier the authoritative result defining the freeze-thaw resistance of concrete is the scaled mass after 56-cycles. Results were found to be very similar regardless of the RCA content. Very small reductions in resistance to freeze-thaw were observed for concrete containing 30% and 50% RCA at 11% and 7% respectively while 100% RCA concrete showed an improvement of 4%. The same statement regarding variability of results is also valid in this case and there is no indication of negative effects due to RCA inclusion. It is also worth noting the very small increase in scaled material at 56-cycles when compared to 28-cycles resulted in cumulative scaling just above that of 28-cycles. This suggests that this particular concrete released the energy built up due to dilation in early stages creating cracks which accommodated some further expansion without significant additional damage. This small loss of scaled material, however, was followed by increased scaling after 128-cycles bringing up the scaled quantity of material to levels comparable to PAV1 concrete.

In fact after exposure to 128-cycles, scaled material reached around 0.90 kg/m^2 just 0.10 kg/m^2 below the PAV1 results. Reduction was expected from a concrete of higher strength better able to resist the expansion pressures of the freezing water. At 128-cycles variations in scaled masses were low indicating that the inclusion of various proportions of RCA in PAV2 concrete does not significantly influence the degree of scaling.

Summarising, it was found that the inclusion of RCA up to 100% had a non negative effect on the freeze-thaw performance of concrete and in cases improve it. Variations observed between results were insignificant and indicated no particular patterns related to RCA inclusion.

8.6 Resistance to Sulphate Attack (Expansion)

Sulphate attack on concrete is the result of a reaction between sulfate present in water in contact with concrete and the products of hydration. The products of this reaction result in expansion of concrete and consequent cracking and spalling ultimately destroying completely the concrete element. The severity of sulphate attack depends mainly on the concentration of sulphates in the water and the cement content. The type of attack investigated in this study was that of sodium sulphate (Na_2SO_4) reacting with calcium hydroxide ($Ca(OH)_2$) and calcium aluminate hydrate ($3CaO.Al_2O_3.12H_2O$) according to the reactions shown below [11]:

Sodium sulfate attacking calcium hydroxide:

$$Ca(OH)_2 + Na_2SO_4.10H_2O \longrightarrow CaSO_4.2H_2O + 2NaOH + 8H_2O$$

Sodium sulfate attacking calcium aluminate hydrate:

$$2(3CaO.Al_2O_3.12H_2O) + 3(Na_2SO_4.10H_2O) \longrightarrow$$
$$3CaO.Al_2O_3.3CaSO_4.32H_2O + 2Al(OH)_2 + 6NaOH + 17H_2O$$

The effect of RCA content was assessed via the expansion of concrete exposed to a mild sulphate environment (DS1) [8] as described in *section 4.3.6.2*. The GEN series of concretes were been selected for this investigation and results are discussed in the following sections.

8.6.1 GEN0 series concrete.

The deformation development of GEN0 concrete exposed to sulphate was assessed up to 60-days and results are shown graphically in *figure 8.14*. Maximum deformations at the end of the exposure period are also given in *table 8.1* at the beginning of the chapter.

Results revealed a tendency towards higher expansion values for concrete containing RCA. Concrete containing 30% RCA had a 12% (0.002mm) increase in strain compared to NA aggregate concrete while a 50% inclusion showed only a 6% (0.0008mm) increase in strain. Extending the RCA content to 100% showed concrete having strain values about 20% (0.003mm) higher than NA concrete. Although these increases appear significant it is worth considering an example which indicates actually how much the length of specimens changes. For instance, with the 100% RCA concrete the maximum increase in length of 0.018 mm compared to 0.015 mm of the NA concrete gives a small difference of 0.003 mm. In general it can be said that expansions of RCA and NA concrete were broadly similar [2].

The small increase in expansion is unlikely to be directly related to RCA due to the fact that, aggregates do not have a decisive effect on sulphate resistance [116]. In order for aggregates to significantly contribute to sulphate related expansion, they need to have high SO_3 contents but in this case, as found in the chemical-mineralogical characterisation, SO_3 contents were very low. However, concrete containing RCA in excess of 30% contains a higher amount of cement due to w/c ratio adjustments as discussed earlier. This will result in higher quantities of the products of hydration, most importantly calcium hydroxide and calcium aluminate hydrate both of which take part in the sulphate attack reactions and it is believed in this case that these are the governing factors in the expansion results.

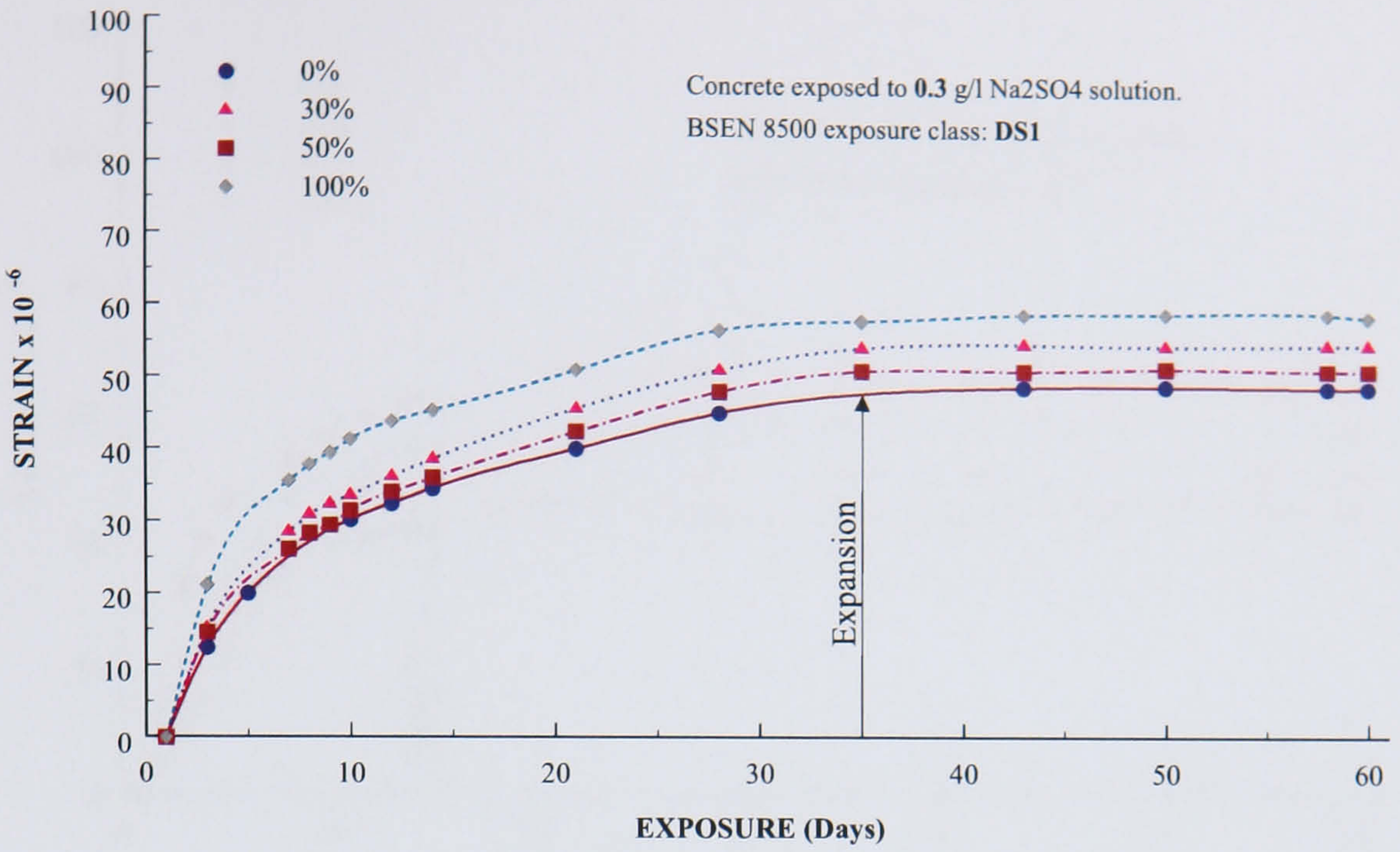


Figure 8.14: Effect of RCA content on GEN0 concrete expansion due to sulphate attack.

8.6.2 GEN1 series concrete.

GEN1 deformations due to sulphate attack are shown in *figure 8.15* and maximum deformations at 60-days are given in *table 8.1.*

Expansion of 30% RCA concrete was found to be similar to NA concrete showing only a 13% (0.0018mm) increase most likely related to natural variations in results. Increase of RCA content to 50% and 100% resulted in increased strain values by 45% (0.006mm) and 30% (0.004mm) respectively. As discussed earlier it is not believed that the recycled aggregates are directly responsible for these increases, due to their insignificant sulphate content and it is more likely that the increased products of hydration caused a more intense reaction with the sodium sulphate solution causing increased expansions. Overall the increase in expansions, as well as their absolute values in general were not considered to be excessive [2].

8.6.3 GEN3 series concrete.

Results obtained from the investigation of GEN3 concrete are shown in *figure 8.16* and maximum expansions are given in in *table 8.1.*

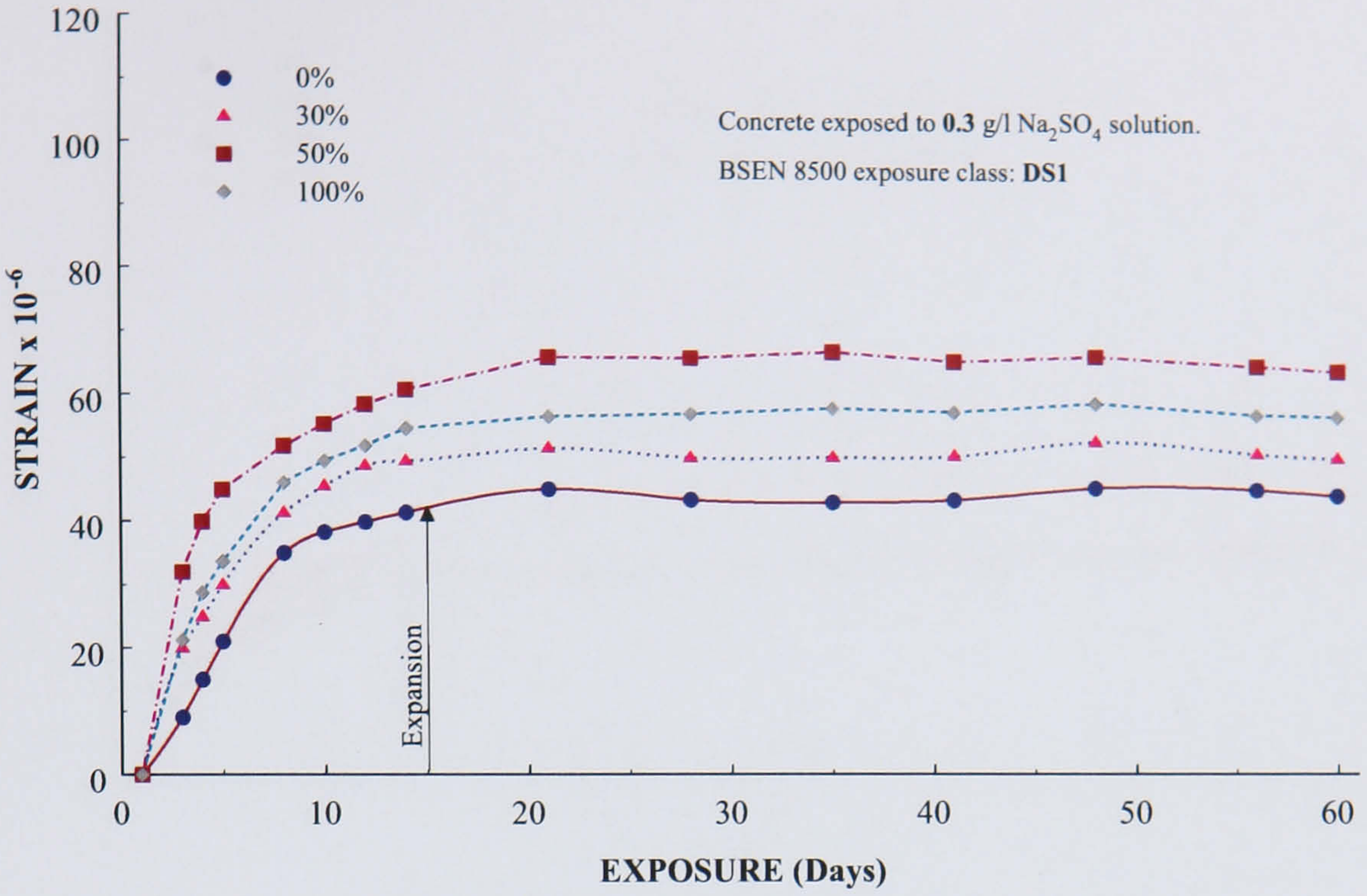


Figure 8.15: Effect of RCA content on GEN1 concrete expansion due to sulphate attack.

Inclusion of RCA up to 30% requiring no w/c ratio adjustments, showed no effects when compared to NA concrete expansion. The increase in expansion of 30% RCA concrete was insignificant, just 5% resulting in an extra increase in length of 0.0005mm. By including RCA at 50% and 100% contents the increase in strain was found to be about 36% (0.005mm) and 63% (0.007mm) respectively. From these results it can be concluded that the observation made previously regarding the w/c ratio adjustment and consequent increase in hydration products are not unfounded. In fact the 50% and 100% RCA concretes were both subject to cement content increases and showed increased strain values.

In conclusion, although there are variations indirectly related to RCA content, in general the expansions observed are low for concrete and not dissimilar between concrete containing NA and RCA.

8.7 Resistance to Chloride Ingress

One of the most common causes of reinforced concrete (RC) deterioration is due to steel corrosion resulting in increased steel volumes and consequently, cracking

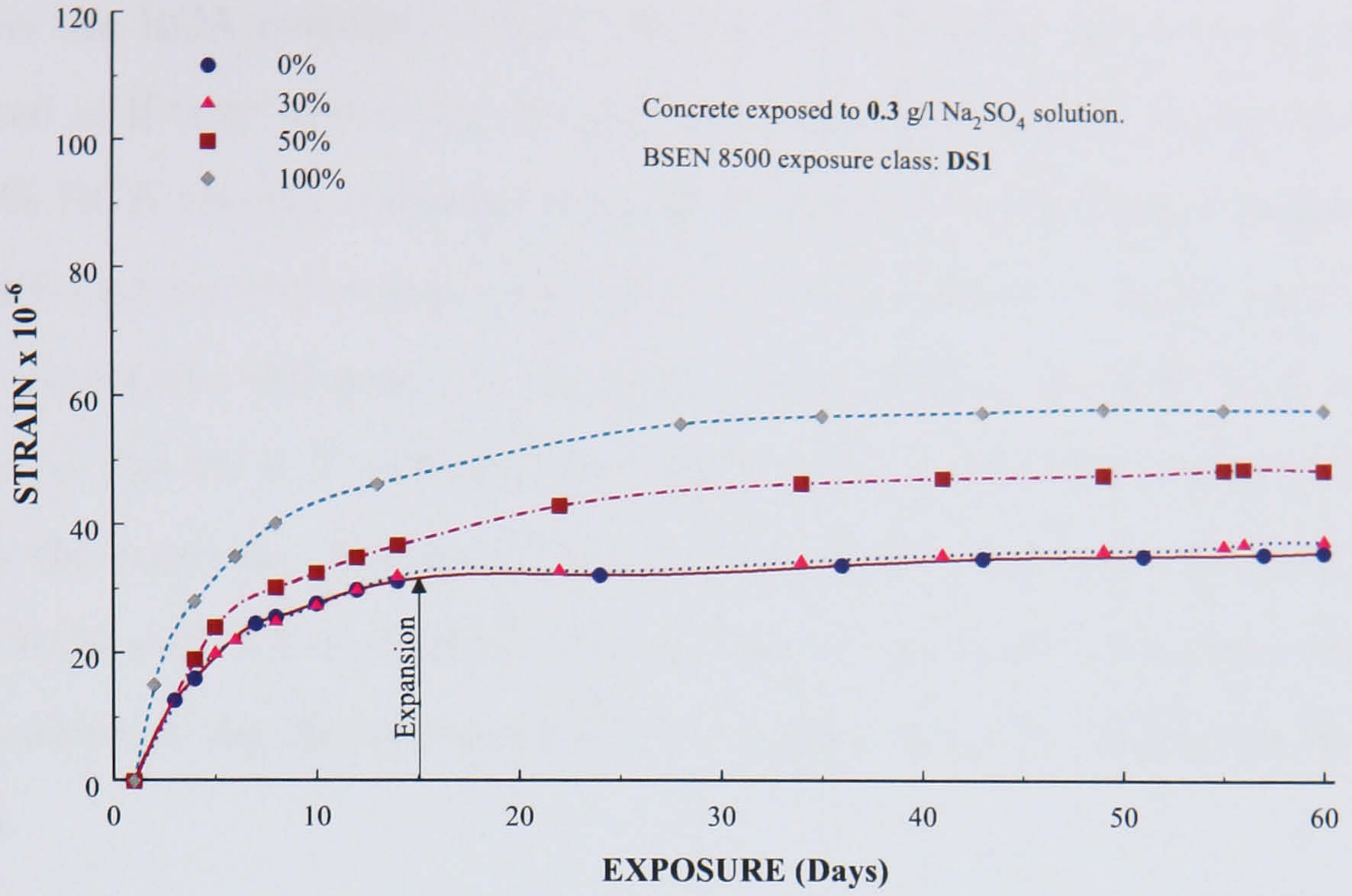


Figure 8.16: Effect of RCA content on GEN3 concrete expansion due to sulphates.

of concrete, allowing the ingress of more harmful substances to assist in further deterioration. A common cause of steel reinforcement corrosion is the ingress of chlorides through the concrete cover penetrating to the reinforcement and so causing rusting. Chlorides do not cause concrete degradation directly but by causing rusting of reinforcement the concrete is damaged. Chloride ion ingress depends on the way that chlorides can enter the concrete through the finished surface. Micro-cracks and increased permeability of concrete can assist in the diffusion of chloride ions.

In this study GEN3 and the PAV series of designated concretes were assessed for their resistance to Cl^- ingress up to a depth of 20 mm from the surface when exposed to a 1-mol NaCl solution.

8.7.1 GEN3 series concrete.

Results obtained from the investigation of GEN3 concrete are graphically shown as diffusion profiles in *figure 8.17* and for ease in comparing results, the Cl^- concentrations at 20-mm depth are given in *table 8.1.*

As a first observation it can be said that the diffusion profiles were very similar regardless the RCA content, indeed with up to 50% RCA concrete the results are distributed as if they were from the same concrete showing just expected variations. The 100% RCA results, although somewhat detached and slightly higher than the others, still had concentrations very similar to NA concrete. A factor that is believed to have caused this difference is the higher permeability of 100% RCA concrete as indicated by the I.S.A.T. investigation which would assist the transport of chloride ions into the concrete. It is important to emphasize that concentration variations between RCA and NA concretes decline as depth increases resulting in very similar concentrations at the 20-mm depth which importantly is the minimum cover usually specified.

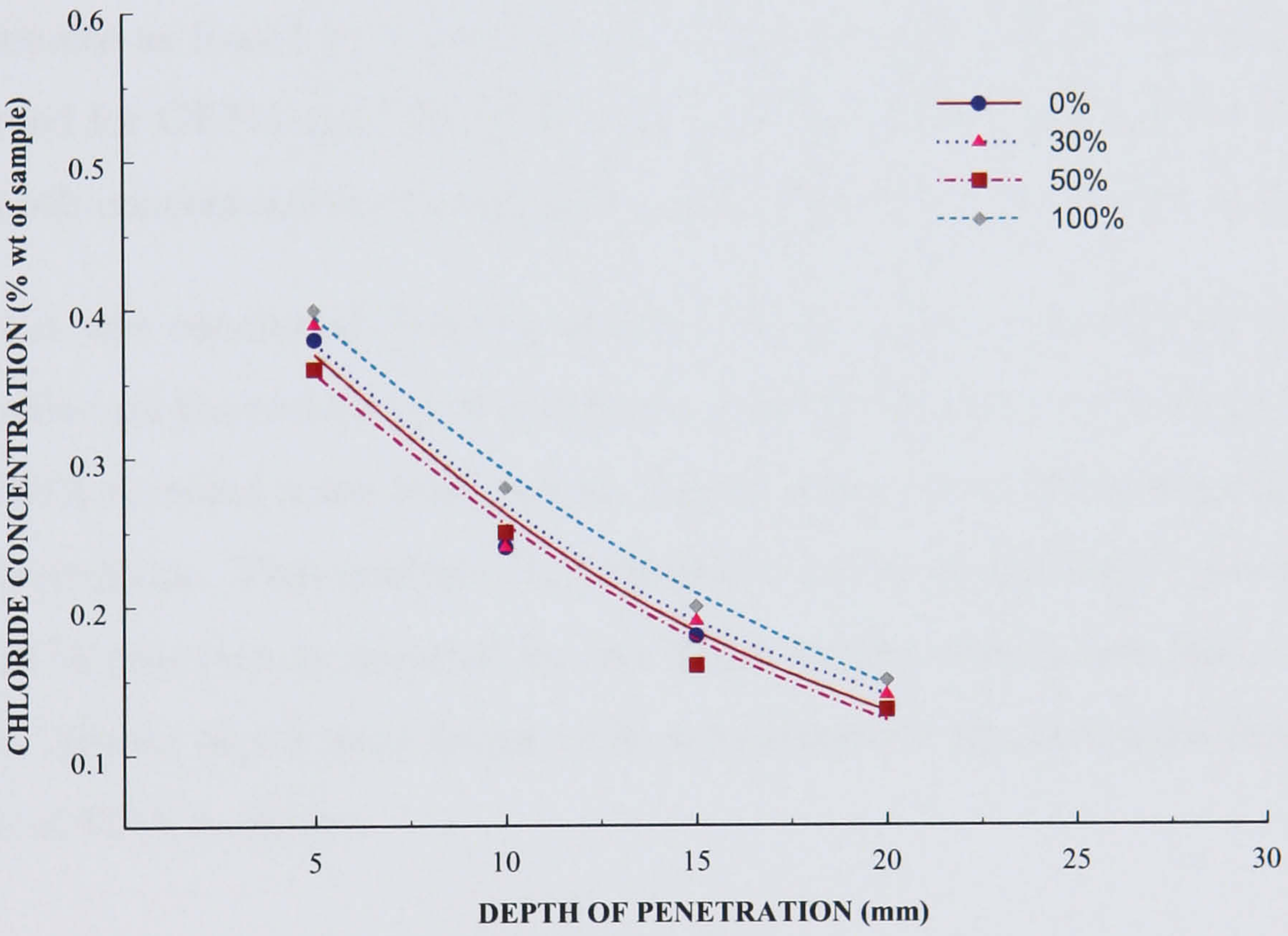


Figure 8.17: Chloride diffusion profiles for NA and RCA GEN3 concrete exposed continuously to 1 mol NaCl solution for 3 months.

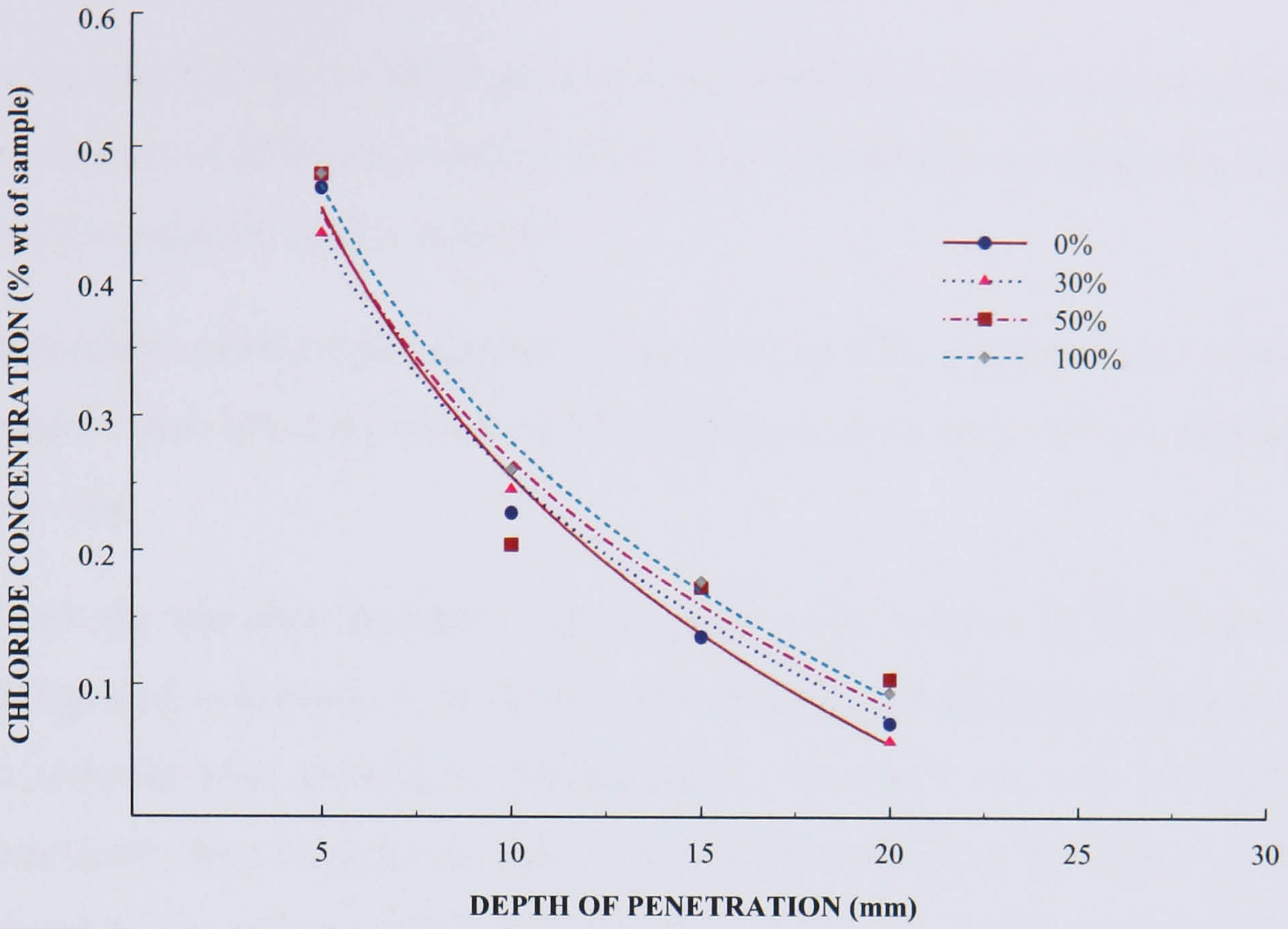
8.7.2 PAV series concrete.

Chloride diffusion profiles obtained from the PAV series of concretes are shown in *figure 8.18* and concentrations at 20-mm depth are given in *table 8.1*.

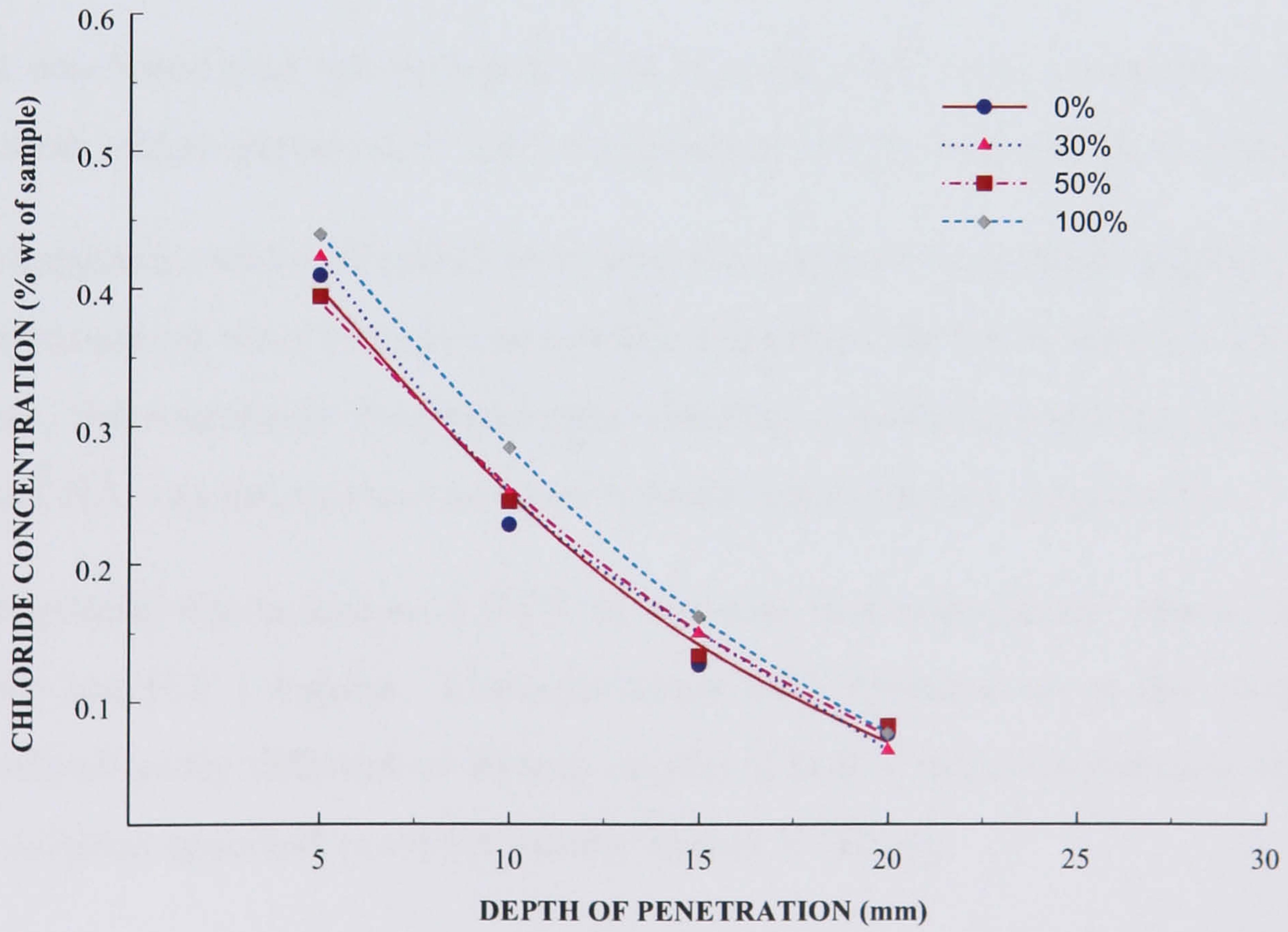
Investigation of chloride ingress in the PAV1 series concrete showed chloride diffusion profiles (*figure 8.18(a)*) very similar for all concrete specimens tested regardless of their RCA content. The maximum range of results was 0.06% observed at 10-mm depth while at 20-mm depth this reduced to about 0.05%. Overall there was no particular pattern related to RCA content although the 100% RCA concrete tended to be at the upper end of the results.

With the PAV2 results (*figure 8.18(b)*), chloride diffusion profiles were almost identical for concretes containing up to 50% RCA, with concrete containing 100% RCA showing marginally higher chloride concentration except at the 20-mm depth where results were again almost identical for all specimens regardless of RCA content. The tendency was again for 100% RCA concrete to have concentrations in the upper range of the results which can be associated with the higher permeability of this concrete as found from the I.S.A.T. investigation earlier in this chapter. As was observed for GEN3 and somewhat less evidently for PAV1, the PAV2 concrete, 20-mm depth concentrations were found to be almost identical as well as low.

Overall it was concluded that the affect of RCA content was limited having no practical effect on the resistance of concrete to chloride ingress. Only the inclusion of RCA at 100% revealed some tendency to slightly higher but still practically acceptable concentrations. This tendency is believed to be due to the higher permeability of 100% RCA concrete as revealed by the initial surface absorption tests. Concentrations at 20-mm depth were found to be very similar and sometimes identical for all ranges of RCA inclusion.



(a) PAV1 chloride diffusion profile.



(b) PAV2 chloride diffusion profile.

Figure 8.18: Chloride diffusion profiles for NA and RCA PAV series concrete exposed continuously to 1 mol NaCl solution for 3 months.

8.8 Conclusions.

- Including RCA up to 50% had a very small affect on initial surface absorption. In the case of 30% inclusion the results were identical and sometimes improved when compared to NA concrete.

- Simulation of 20-years exposure of concrete to CO_2 resulted in no evidence to suggest that the proportion of RCA affects resistance to CO_2 penetration in any way.

- From the abrasion resistance investigations carried out on RC30 and PAV2 designated concretes, it is evident the inclusion of RCA in concrete, results in reduced wear resistance. Nevertheless, the effect was not very significant practically but in order to clearly assess and establish the effect of RCA it would be necessary to carry out extensive testing on pavement specimens prepared by experienced operators, so eliminating the variability in the quality of surface finish, which is fundamental in any abrasion testing method used.

- It was found that the inclusion of RCA in the PAV series of concretes investigated, either improved or had no significant effect on freeze-thaw resistance.

- Expansion results obtained from concrete exposed to a mild sulphate (DS1) environment were broadly comparable regardless the RCA content. Nevertheless, the magnitude of expansions in concrete containing combinations of RCA and NA was not unexpected and broadly similar for all proportions.

- In general the inclusion of RCA in concrete had insignificant effects on chloride ion (Cl^-) ingress. Concentrations were identical or in the worst case insignificantly different at 20-mm depths, a fact of great importance since the minimum specified cover for reinforcement is 20 mm.

CHAPTER 9

ON-SITE DEMONSTRATIONS

9.1 Introduction

Following the successful completion and generally positive outcomes of the analytical work covered in previous chapters, it was decided to take a step further in order to assess the suitability of RCA in real conditions and thereby ensure that results from the laboratory testing under controlled conditions are representative of those really occurring on the construction site. In order to assess the performance of RCA concrete under real construction conditions, two full scale construction demonstrations were planned in association with DAY Group Ltd. and London Remade and carried out at the Day Group Ltd. site in Greenwich, London.

To assess fresh concrete performance on site in an identical way to that of laboratory concrete was not possible. The main objective was to assess the slump, stability, handling and placing of concrete and to cast specimens on site for laboratory testing after 28-days. Discussions with experienced site personnel placing the concrete during construction also gave important insights into the fresh properties of site concrete.

9.2 Full Scale Construction 1.

Production of quality RCA was demonstrated at the beginning of this construction demonstration as described in *section 5.2.* Then mix design to BS 8500 and EN 206 was carried out for heavy duty pavements (PAV2) and using the required concrete constituent proportions trial mixes were made in the laboratory. The mix proportions used, given in *table 9.1*, were entered into the onboard computer of a mobile volumetric batch plant for concrete production as shown in *figure 9.1*.

Table 9.1: Demonstration 1 mix proportions.

MIX PROPORTIONS(kg/m^3)					
			RCA		**AEA**†
	Cement	**Water**	**Sand**	**Coarse**	ml/100 kg
			<5 mm	*5 - 20 mm*	of cement
100% RCA - Batch 1	345	158	517	1353	360
100% RCA - Batch 2	350	153	512	1365	360

† Air entraining admixture providing nominal air content of 5% by volume of concrete.

Figure 9.1: Volumetric batching plant used in the demonstration .

This initial demonstration was undertaken prior to an extended full scale demonstration and for this reason the location selected for the pavement construction was an area subject to light foot and rubber tyre traffic only. Two predefined strips were prepared, the formwork put in place as shown in *figure 9.2* and the existing ground surface cleaned from foreign materials and levelled. At this point concrete pouring commenced and slump tests and stability observations were carried out. During the pouring process specimens for compressive, Young's modulus and flexural tests were cast (*figure 9.3*) for testing in the laboratory after 28-days.

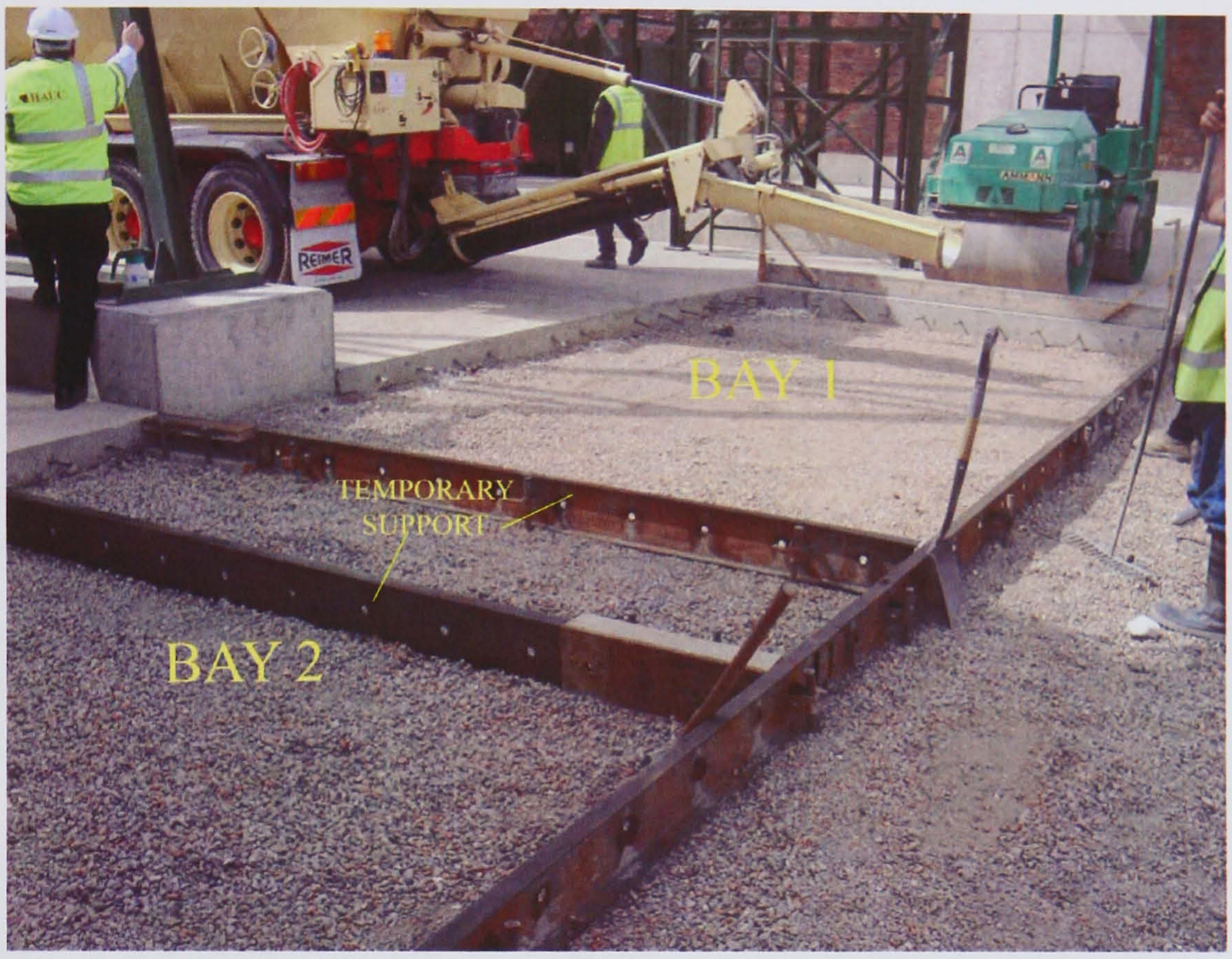


Figure 9.2: Predefined strips at the location selected for the 1^{st} preliminary demonstration.

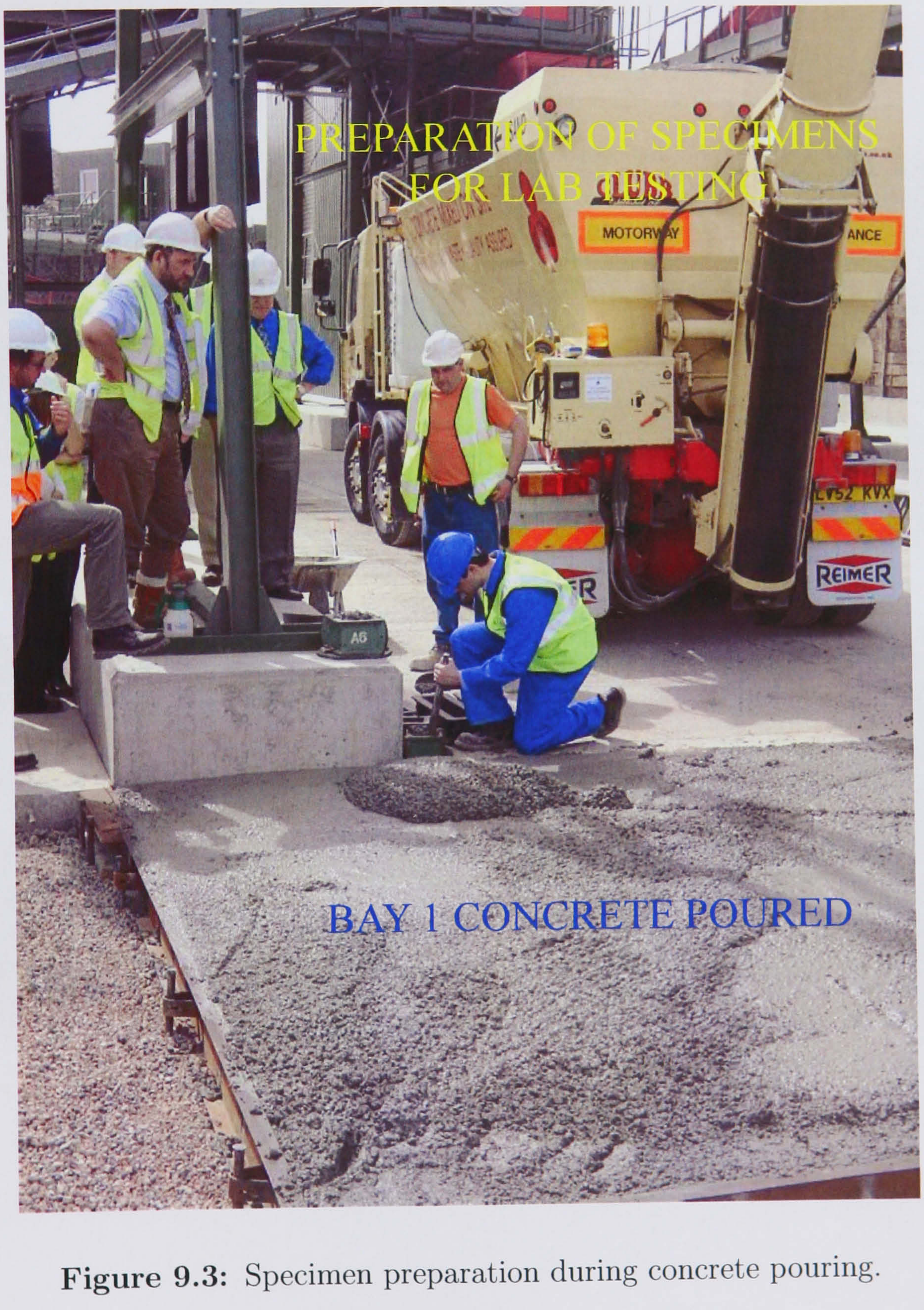


Figure 9.3: Specimen preparation during concrete pouring.

(a) Placing concrete. (b) Placing concrete.

(c) Surface finishing. (d) Surface finishing.

Figure 9.4: Placing, handling and finishing of concrete pavement.

Figure 9.5: Completed pavement using 100% RCA concrete.

9.2.1 Key findings.

- During construction of the pavements, slump tests showed values ranging between 55 and 75 mm (Class S2) within the allowed tolerance of ±20 mm required by EN 206 Part 1 [10].
- Tests on the slumped cones showed very cohesive concrete with gradual further slump when tamped at the sides. From these observations the cohesiveness class was established at 2a according to the classification of *Table 4.13.*
- During the placing, compacting and finishing of concrete there was no indication of bleeding.
- From discussion with the operators it was found that no difficulties were encountered during the compaction, placing and finishing of the concrete and identical practice to that for NA concrete was utilised.
- Three months after construction, visual inspections revealed no problems and the surface appeared to have a texture similar to surrounding pavements from

conventional concrete. The same observations remained valid when a second visit was carried out 1 year and 2 months after construction.

- The results from cube compressive tests on three 100 mm cubes showed strengths above the characteristic design strength. Flexural strength and static modulus of elasticity were also assessed and found to be comparable to those obtained in the laboratory based research. Results for the three specimens tested are given in *table 9.2*.

Table 9.2: Results obtained from site cast specimens tested in the laboratory at 28-days.

LABORATORY TESTING RESULTS			
	Compressive strength (N/mm^2)	Flexural Strength (N/mm^2)	Static Modulus of Elasticity (kN/mm^2)
Specimen 1	36	4.9	27
Specimen 2	42	5.3	32
Specimen 3	39	5.1	29

9.3 Full Scale Construction 2.

Following the successful completion of the preliminary construction demonstration, full scale construction of three predefined pavement areas was planned. This time, with confidence gained from the first demonstration, the location selected was an area subject to everyday activity where heavy duty equipment was operating as shown in *figure 9.6*.

The mix proportions used for the construction of these pavements are given in *table 9.3* and in this case, in order to increase workability and ease the placement of concrete, water reducing admixtures were used. Due to the size of the pavements being considerably larger than in the first demonstration, reinforcement was provided in the form of XT fibres. Three concretes were designed and used containing 0%, 30% and 100% coarse RCA and three slabs were constructed as shown in *figure 9.6*.

Figure 9.6: Location selected for RCA concrete pavements.

Table 9.3: Demonstration 2 mix proportions.

MIX PROPORTIONS(kg/m^3)							
RCA content	**PC**	**Water**	**Sand**	**Coarse**†		**Admixtures**	**Reinforcement**
			< 5 mm	*NA*	*RCA*	*WRA* (l)	*XT Fibres*
0%	340	167	791	1100	0	1.02	0.9
30%	340	167	791	770	330	1.02	0.9
100%	360	180	750	0	1100	1.08	0.9

† 20 - 5 mm graded aggregate.

Pavement construction was carried out as for the first demonstration using a mobile volumetric batching plant and the fresh properties at the time of pouring were assessed using the slump and stability tests. The concrete met the 60 mm design slump requirement for class S2 with variations within the 20 mm tolerance permitted. By tamping the slumped cone further slump slowly occurred without any indication of shearing (stability class 2a) regardless of the RCA content.

The plan of the construction area showing the three pavements constructed as well as giving areas and volumes of concrete required are shown in *figure 9.7*. Due to the size and nature of use of the pavements it was necessary to ensure movement was allowed where discontinuity of construction occurred. For this reason expansion joints were installed at 300 mm c/c and a detailed section showing the joint detail is shown in *figure 9.8*.

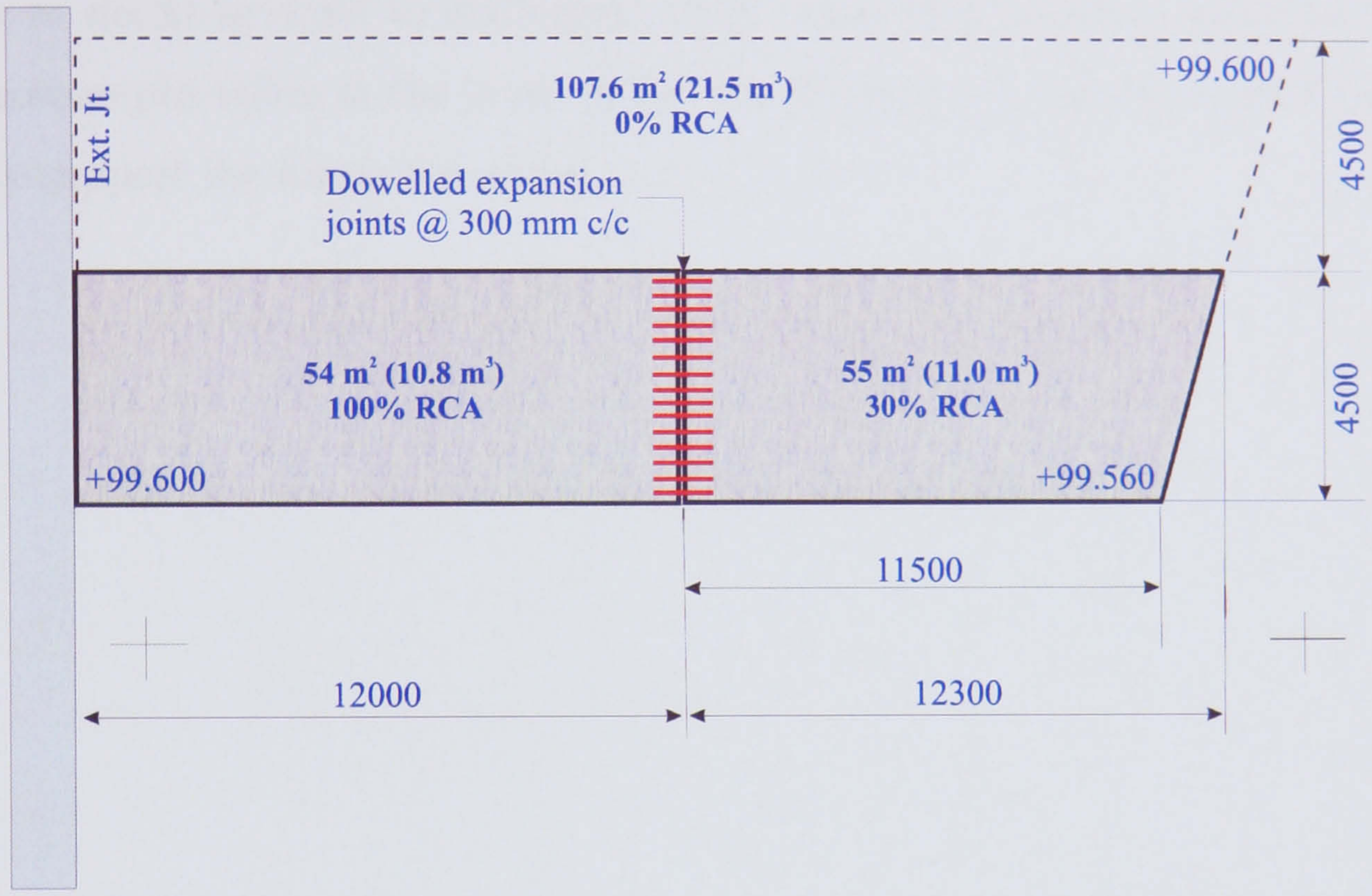


Figure 9.7: Plan showing the predefined concrete pavement strips constructed during the second demonstration.

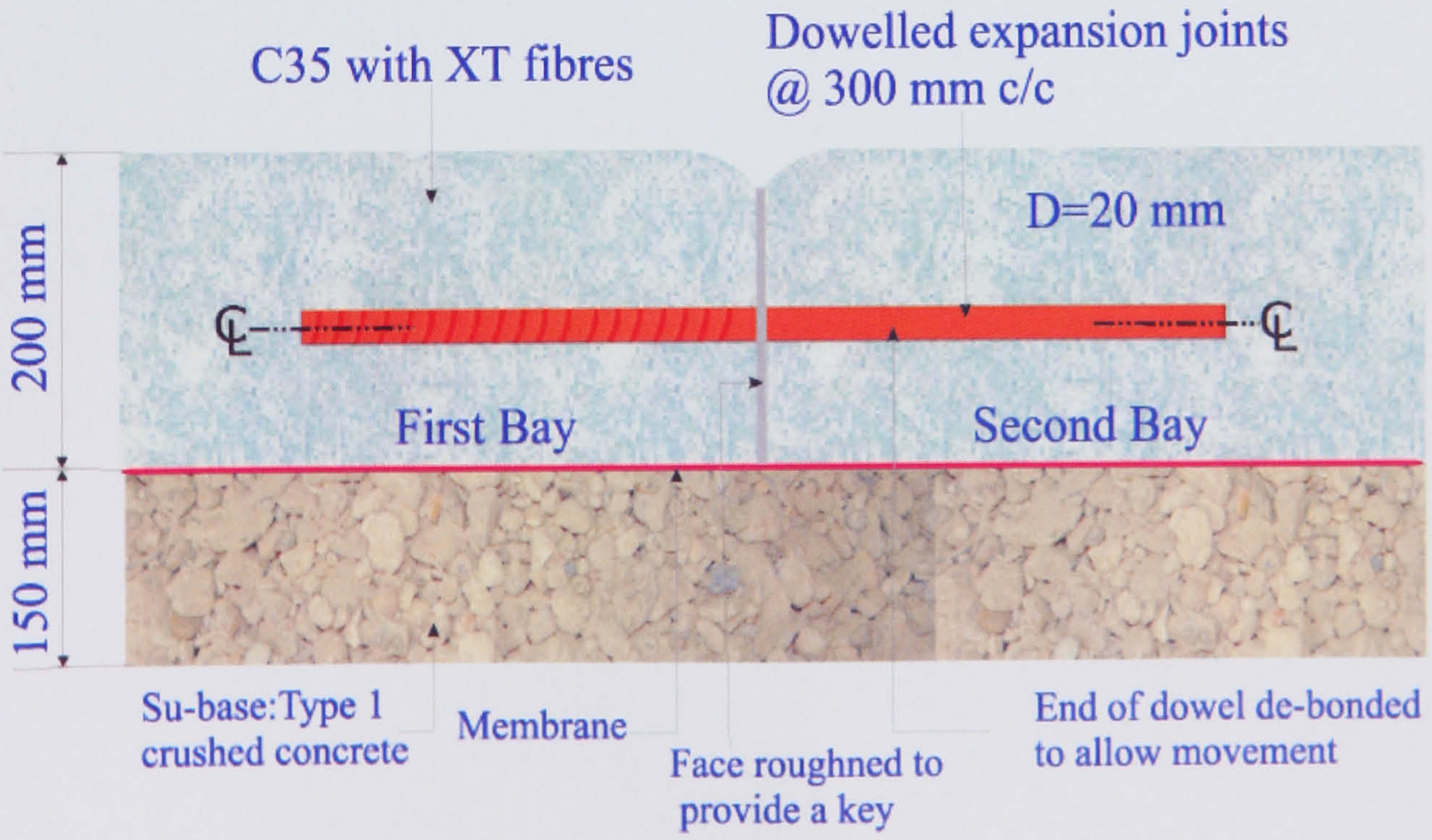
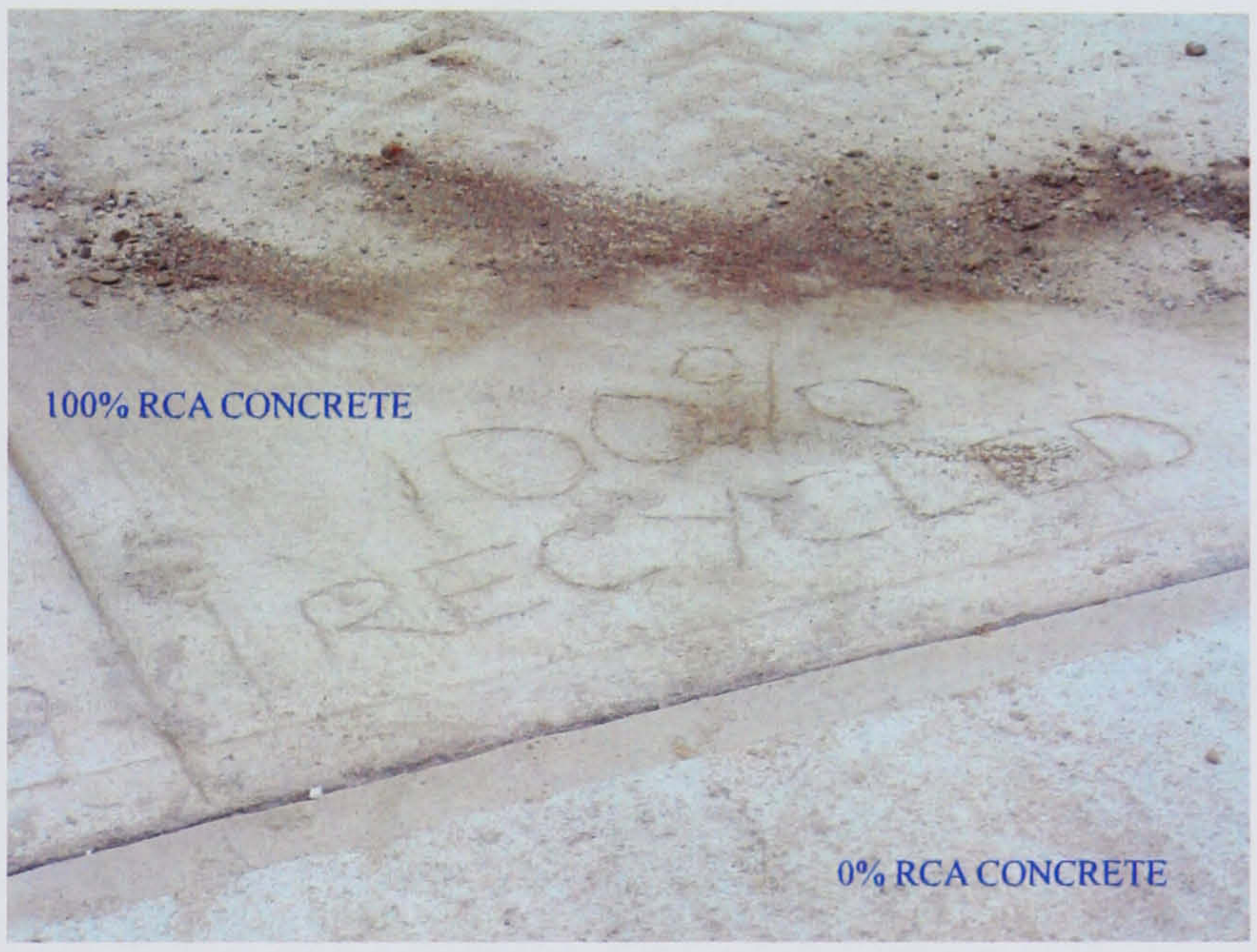


Figure 9.8: Detail of pavement section and expansion joint detail used in the second demonstration.

Six months after construction visual inspections were carried out to investigate the performance of the RCA pavements and compare them to the to NA pavement constructed. The results of these inspections indicated there was no distinction between any of the heavily used surfaces and in fact, it was necessary to locate the engraved marks in order to distinguish RCA from NA concrete pavements. Close up photographs taken at the joints of the various bays are shown in *figure 9.9* and clearly support the above discussion.

(a) Joint location between NA and 30% RCA concrete.



(b) Joint location between NA and 100% RCA concrete.

(c) Joint location between 100% and 30% RCA concrete.

Figure 9.9: Visual inspection photos between the surface finishes of NA and RCA concretes used in the second full scale demonstration.

9.4 Conclusions.

Two site demonstrations to show the feasibility of using RCA in concrete pavements have indicated the following conclusions:

- The production of quality recycled aggregates as well as the consistency of this quality is achievable regardless of the source of C&D debris provided that suitable methods are used for the processing of C&D debris.
- Fresh properties measured on site were similar to those identified in the laboratory. Most importantly, observations and discussions with experienced operators handling, placing and finishing the concretes used, revealed that no change in practice was necessary when using RCA concrete apart from alterations to the mix design, requiring adjustments to the w/c ratio.
- In the hardened state, the testing of small specimens cast on site showed that equivalent strength concrete was achieved through the w/c ratio adjustments. Flexural strength and modulus of elasticity results supported the laboratory findings presented in *chapter 7*.
- Through visits and visual inspections to the site over an extended period of time it was found that the performance of all pavements constructed was satisfactory especially in the case of those under heavy duty loads caused by heavy machinery.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

10.1 CONCLUSIONS

- All aggregates used in this study were characterised in order to identify their suitability as aggregates for use in concrete production. Constituent materials of RCA were found to conform to BS 8500 requirements and X-ray diffraction and X-ray fluorescence analysis, resulted in very similar mineralogical compositions between the three RCAs investigated, mirroring the constituent materials results. Physical properties of RCAs were found to be similar to natural aggregates with the exception of RCA water absorption which was found to be about 4 times higher than NA. Mechanical properties of RCA were found to be inferior with the exception of TFV, when compared to NA but all met the highest requirements for use in heavy duty concrete pavement applications.

  The chemical characterisation revealed that recycled aggregates had higher chloride contents especially in the case of acid soluble chlorides. However, for all aggregate combinations chloride content was still below the requirements set by BS 882. The sulphate content of recycled and natural aggregates used in the study were insignificant and conformed to the limits set in BSEN 12620 and BS 8500. Alkali content contribution from RCA was not significantly greater than that of NA and overall values were very small with minimal potential for ASR. All requirements to prevent ASR, as set in BS 8500 Part 2 regarding the use of RCA in concrete production, were met.

Overall, it was demonstrated that quality RCA for use in concrete can be produced meeting the requirements for not only RCA but also the stricter requirements for NA. The source of C&D debris was found to have no significant effects on the RCA characteristics.

- Fresh properties of equivalent strength RCA and NA concrete were investigated immediately after mixing and up to minutes after mixing so simulating transportation time. It was clearly identified that RCA content had no effect on the fresh properties of concrete immediately after mixing. However, increases in RCA content resulted in increased loss of workability over time but not in a detrimental way. Handling, placing and finishing of RCA concrete was carried out as for conventional concrete and no special care was required to achieve similar results. Inspections of the concrete mixes revealed no indication of bleeding or stability issues related to RCA content. The air entrainement requirement was met without any modification to the dosage of admixture required and investigation on the retention of air content over a period of 1-hr showed no effect due to the use of RCA.

- A selection of engineering properties were investigated in detail on concretes designed for equivalent strength containing up to 100% RCA. The compressive strength assessed on 100 mm cubes and standard cylinders was found to be equivalent to NA concrete strength demonstrating that the w/c ratio adjustments were suitable. The rate at which RCA concrete strength increased, expressed as a percentage of the 28-day strength, was similar and in most cases identical to NA concrete. In addition results conformed to the guide strength values given in BS 8110 Part 2. The ratio of cylinder to cube strength was found to be around 0.8 regardless of the RCA content, reflecting the strength classes as given in BSEN 206 Part 1, which gives cylinder strength to be around 80% that of cube strengths.

  The relationship between compressive strength and w/c ratio followed the general rule of strength being inversely proportional to w/c ratio for all RCA concrete mixes as will NA concrete. The relationship produced an hyperbolic curve consistent with the findings of other researchers. It was demonstrated that the mix designs used were suitable for both RCA and NA concretes. Compaction of the specimens was sufficient and did not compromise strength results.

The flexural strength of RCA and NA concretes was assessed and it was found that the inclusion of RCA had either a beneficial or no effect at all. Flexural strength was found to have a clear relationship to compressive strength producing a well fitting curve using all results regardless of RCA content. The curve had a correlation coefficient of 0.96. It was observed that with low strength concrete, the flexural strength corresponds to around 20% of the compressive strength but this drops to 15% for higher strength (around 30 N/mm^2) concrete.

The static modulus of elasticity was found to be significantly affected by the RCA content and reductions observed reached 40% when compared to NA concrete results. Despite this all results were higher than those calculated using the recommended formulae for structural design calculations given in standards and textbooks. Importantly, both RCA and NA results compared well to the typical ranges given in BS 8110 Part 2.

The effect of RCA on concrete deformations was assessed by examining both swelling and drying shrinkage. It was found that up to 30% RCA had insignificant effects on strains. Generally, with RCA content in excess of 30%, there was some increase in expansion due to swelling but such increase was considered small and the strain magnitude remained in the range of 100 $\mu\varepsilon$ to 150 $\mu\varepsilon$ as expected for the strength class of designated concretes investigated.

Results from drying shrinkage clearly showed the negative effect of RCA content. The inclusion of RCA up to 30% had no noticeable effect on concrete contraction but exceeding this content resulted in a considerable increase of shrinkage strains reaching values double those of NA concrete when 100% RCA was used. These increases are the result of two factors. Firstly, the increased moisture capacity of RCA resulted in higher moisture losses during the drying period. Secondly the inclusion of RCA in excess of 30% involved an increase of the cement content as part of the w/c ratio adjustment resulting in increased cement paste and, therefore, increased shrinkage.

- A range of durability properties were assessed on NA and RCA concretes. Assessment of the near surface absorption was found to be significantly affected only when use of RCA exceeded 50%. In the case of 30% RCA, results were identical with NA concrete and occasionally better. The decay of absorption rates was similar for both RCA and NA concretes regardless of the RCA content.

  The resistance of concrete to CO_2 penetration was investigated by simulating exposure up to 20 years, and it was found that the RCA content did not affect the depth of CO_2 penetration in any way. Results showed maximum variations of CO_2 penetration depths not exceeding 3 mm, between RCA and NA concrete which are believed to be due to natural variations.

  The abrasion resistance of RCA and NA concrete was studied on RC30 and PAV2 designated mixes. It was found that the inclusion of RCA significantly affected concrete resistance to wear and this was more evident when 30% RCA content was exceeded. The reductions in wear resistance were considerable when considering the performance classification given in *table 8.1*. However, the effect of RCA was not in any way practically detrimental.

  By exposing concrete specimens from the PAV series to severe freeze-thaw conditions in accordance to EN 12390 Part 9, it was found that the inclusion of RCA in concrete had no effect on the resistance of concrete to scaling. Results of RCA concrete occasionally showed improved resistance to scaling but the general finding was that RCA concrete had similar resistance to NA concrete.

  Resistance to sulphate attack by subjecting concrete to a mild exposure environment (DS1) was found to be similar when RCA and NA concrete results were compared. Small increases in expansion due to sulphate attack were observed for concretes with increased RCA contents but these, it is believed, are caused by the increase in cement content through adjustments to the w/c ratio which result in increased reaction activity between sulphates and the increased products of hydration and results in increased expansions.

The effect of RCA content on the resistance to chloride ion penetration into concrete was assessed on the GEN3 and the PAV series of designated concretes. The results indicated that the RCA content had no negative effects. Only with 100% RCA was there an insignificant increase in Cl^- concentration penetrating the concrete. This last finding seems to be in line with the near surface absorption results which showed increased permeability values for 100% RCA concrete a property which would assist the Cl^- diffusion. Results at the maximum depth of 20 mm were similar for all concretes regardless of RCA content, and this is of importance considering that the minimum concrete cover to reinforcement is usually specified as 20 mm.

- Through full scale demonstrations it was shown that quality RCA can be produced regardless of the source of the C&D debris and used for the production of quality RCA concrete. Findings from the laboratory based work were supported by observations during construction, performance inspections of concrete elements in service and the testing results of specimens cast on site during construction.

10.2 RECOMMENDATIONS FOR FUTURE WORK

- Due to the diverse nature of C&D debris it is necessary to control the quality of recycled aggregates throughout their production more closely than natural materials. The use of RCA in concrete is not widely accepted yet and it is believed that this is mainly due to fears that it will contain harmful substances, partly as a result of deterioration processes during the service life of buildings from which the debris originates. A study is proposed involving the application of techniques currently widely used in the ceramics industry, and earth sciences laboratories, involving chemical-mineralogical methodologies for the assessment of the mineral phases present in recycled aggregate and its composition using X-ray diffraction and X-ray fluorescence. It is recommended these techniques be used as a means of quality control in processing plants.

- Laboratory examination of the wear resistance of concrete pavements containing RCA carried out in this study provided a direct comparison between RCA and NA concrete but it was not representative of the real wear resistances of these concretes. This was due to the inexperience of technicians and the author in laying and finishing pavements techniques which require considerable experience. A laboratory study involving the construction of pavement specimens is proposed which will involve the training of the researcher and technical staff in concrete pavement construction in order to produce representative concrete specimens enabling the real wear resistance performance to be assessed.

- Further study of the use of RCA in high strength concrete as well as in reinforced concrete elements is recommended. This should involve the assessment of the bond between the reinforcement and the concrete and identify the effects of RCA through pull out testing on combinations of concrete strength and type of reinforcement bar.

- Durability of concrete is one of the most difficult aspects of this material to assess and understand. Over the last 50 years concrete technologists have continually investigated the durability performance of concrete but are still grey areas. With increased use of recycled materials in concrete, and due to their characteristics, it is very important to study further various aspects of durability in order to minimise associated problems with RCA concrete.

- Full scale constructions were found to be a successful way of attracting industrial interest and countering the myth that RCA is an inferior material. More demonstrations and real construction will help alleviate the reservations of concrete producers and specifiers and assist the creation of a market for recycled aggregates which will allow them to be used to their full potential.

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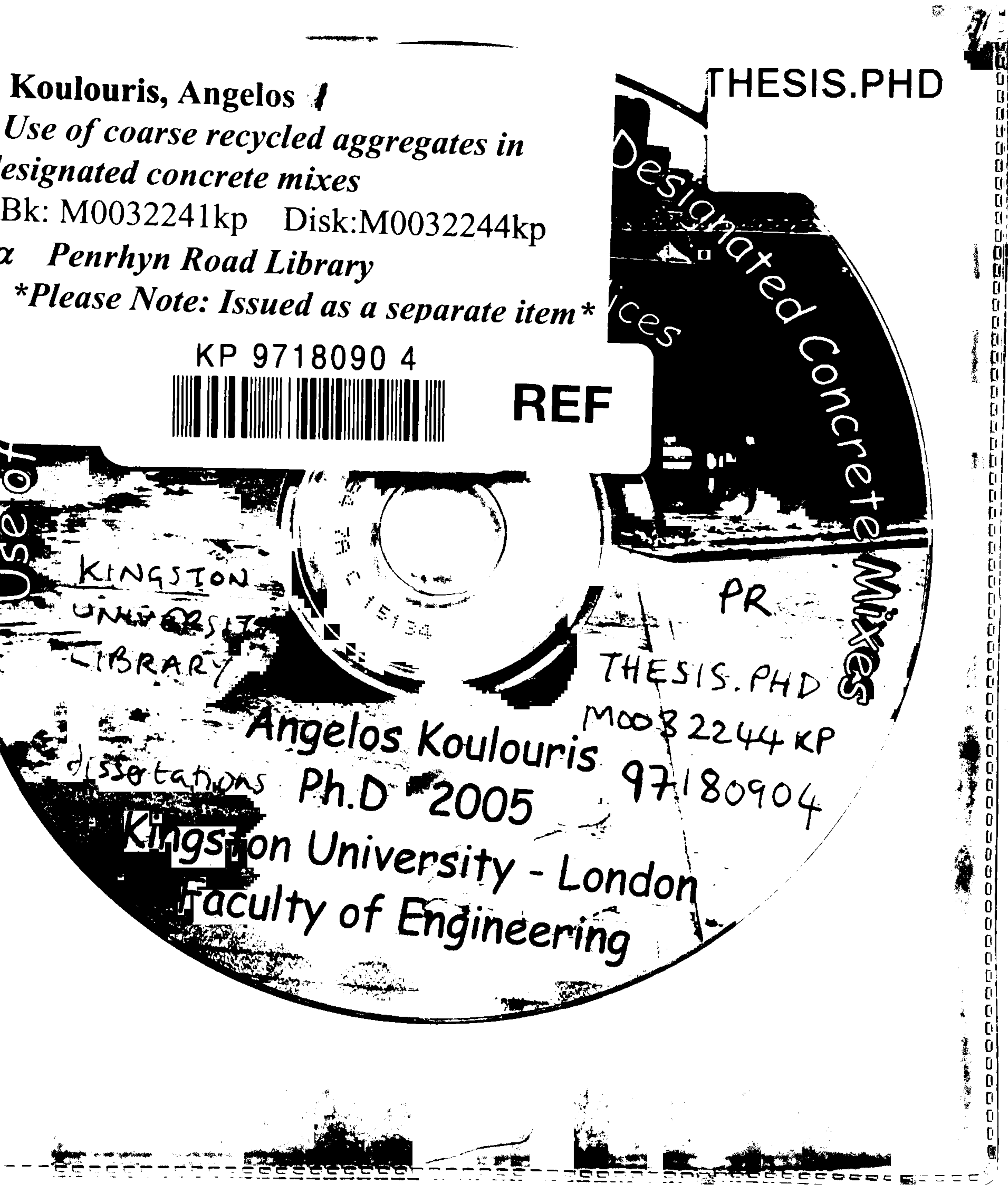

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