Kingston University London

Suitability of Recycled Concrete Aggregate for Use in Binary Cement Concrete

By

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DECLARATION

I hereby declare that the following thesis has been composed by me, that the work which it covers has been carried out by me, and has not been submitted in any form for another degree or diploma at the higher education level. Information derived from the work of others has been acknowledged in the text and a list of references is given.

Youssef Ouchagour

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In the name of Allah (God), the Most Gracious, the Most Merciful

They said: "Glory be to You, we have no knowledge except what you have taught us. Verily, it is You, the All-Knower, the All-Wise."

Quran (Chapter 2, Verse 32)

Firstly, all praises and thanks are due to God.

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PUBLICATIONS

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ABSTRACT

The principles of sustainable construction require the prudent use of natural resources and the maximum recycling and reuse of waste. In keeping with this approach, much research was undertaken to increase the use of recycled aggregates derived from construction and demolition wastes as an alternative to primary aggregates in construction. It is now increasingly recognised that the use of coarse recycled concrete aggregate (RCA) in concrete construction represents a further potential outlet for the material.

Several investigations have been made to study the effects of coarse RCA on the fresh and hardened properties of Portland Cement (PC) concrete. While these studies suggest the potential use of RCA in a range of concrete applications, issues relating to its suitability in binary cement concrete mixes, relevant to practice, have not been addressed. Against this background, the present study was undertaken to examine the suitability of using coarse RCA in BS 8500 designated concrete mixes produced using binary cements. The binary cements selected were (i) PC/PFA cement, a blend of 70% PC/ and 30% Pulverised Fuel Ash by mass and (ii) PC/SF cement, a blend of 90% PC and 10% Silica Fume by mass. The binary cements were blended in the mixer during concrete production. The effects on the fresh, engineering and durability properties of concrete, of replacing coarse natural aggregates (NA) by coarse RCA by up to 100% in concrete have been established. The RCA mixes were designed to achieve equal 28 day cube strengths as their corresponding NA mixes.

The aggregate characterisation results showed that concrete debris obtained from construction and demolition waste can be used to produce clean and properly graded RCA suitable for use in concrete production in accordance with the EN 12620 requirements. The results of the fresh properties of concrete showed that although the slump measurements remained within the allowable tolerances, the use of high RCA contents affected the workability and stability of the mixes. Studies of the hardened concrete properties, comprising the bulk engineering (Compressive cube and cylinder strength, flexural strength, modulus of elasticity, drying shrinkage and swelling deformations) and durability properties (near surface absorption, carbonation, chloride ingress, sulphate attack) showed that RCA concrete mixes made with binary cements had a comparable or better performance when compared to their corresponding concrete mixes made with PC only.

Practical implications derived from the findings of the study are also outlined for the use of RCA in binary cement concrete construction. Overall, the study has shown that RCA is suitable for the production of a wide range of designated mixes made with binary cements with a satisfactory engineering and durability performance, provided that the mixes are designed for equivalent 28 days cube strength.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The construction industry is one of the most important industries contributing to development worldwide. However, at the same time, it exerts huge strains on the world's environment through the consumption of energy and natural resources and the production of waste on a massive scale.

In keeping with the principles of sustainable development, many efforts were made to encourage the construction industry to reduce the amount of waste it produces through recycling and reuse and the amount of conventional natural materials it uses by increasing the use of alternative recycled materials.

Recycled aggregates derived from construction and demolition waste are widely used today by the construction industry. Initially, their use was mainly restricted to low value applications and very small quantities if none were used in high value applications such as concrete.

Several studies have looked at the effect of using recycled aggregates on the fresh, engineering and durability properties of concrete made with Portland cement. This has provided a better understanding of the effects of recycled aggregates on concrete and has somewhat helped to boost their use in concrete. Another boost to the use of recycled aggregates in concrete came with the recent inclusion of recycled aggregates in the latest European standards for aggregates and concrete.

Improving the engineering performance and durability of recycled aggregate concrete can further increase the use of recycled aggregates in concrete production and dispel the misconception that using recycled aggregates in concrete necessarily produces inferior quality concrete. Binary cements, which are blended cements composed of Portland cement and one type of supplementary cementitious material, have been used routinely in concrete to improve its quality. However, very few studies have examined the properties of concrete made with binary cements and recycled aggregates.

Against this background, a complete research programme has been devised to examine the suitability of using recycled concrete aggregate (RCA) in a range of BS 8500 designated mixes made with the following binary cements:

- PC/PFA cement; composed of 70% Portland Cement (PC) + 30% Pulverised Fuel Ash (PFA) by mass.
- PC/SF cement; composed of 90% Portland Cement (PC) + 10% Silica Fume (SF) by mass.

Part of the research programme was to examine the existing European and British standards covering the use of RCA and binary cements in concrete as well as the published work on this area. This was achieved through the collection of literature through searches at the libraries and on the online databases of national and international research establishments and universities.

1.2 OBJECTIVES

The prime objective of the research is to examine the suitability of recycled concrete aggregates for use in concrete produced using binary cements. In particular to study:

- The production procedure of RCA and their characteristics,
- The effect of RCA on the fresh, engineering and durability properties of binary cement designated concrete mixes,
- The practical implications for the use of RCA in binary cement concrete.

1.3 SCOPE OF THE STUDY

In order to achieve the objectives set above, the research programme was divided into three phases. An outline of the research programme is presented in Figure 1.1

Phase 1: Production and characterisation of RCA

The first phase looks at the method of production of the RCA used in the study and examines their characteristics. The RCA were produced in a concrete recycling plant comprising primary and secondary crushers and screens. The physical and mechanical characteristics of coarse RCA were determined and compared with those of the coarse natural aggregate (NA) used in this study. These include the particle size distribution, the shape and texture, the relative and loose bulk densities, the water absorption, the aggregate crushing value (ACV), the aggregate impact value (AIV) and the 10% fines value (TFV).

Phase 2: Use of RCA in binary cement designated concrete mixes

The RCA produced was used to establish its influence on the fresh, engineering and durability properties of binary cement designated concrete mixes. The control concrete mixes, containing NA, were proportioned for a range of BS 8500 designated mixes. Equal strength RCA concrete mixes made with Portland cement and binary cements were then proportioned by replacing of 30, 50 and 100% by mass of the total content of coarse aggregate with RCA.

The influence of the different RCA contents on the fresh properties of Portland cement and binary cement concretes were examined and compared. The fresh properties included the workability and stability of the mixes. The engineering and durability properties of Portland cement and binary cement designated NA and RCA concrete mixes were examined selectively and compared. The engineering properties included the compressive and flexural strength, the modulus of elasticity, the drying shrinkage and swelling deformations. The durability properties included the initial surface absorption, the resistance to carbonation, sulphate attack and chloride ingress.

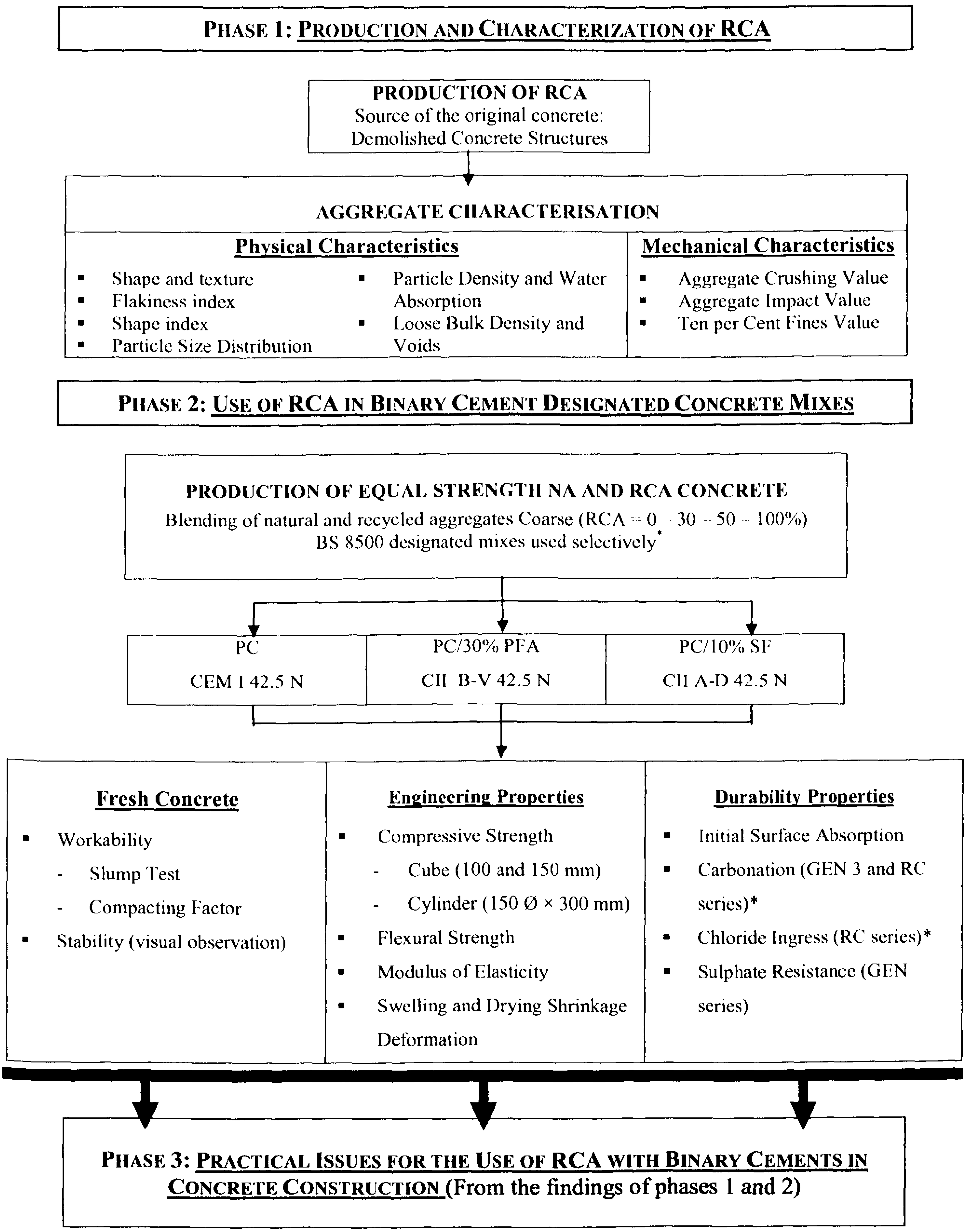
Phase 3: Practical implications for the use of RCA with binary cements in concrete construction

The last phase of the study is devoted to examining the practical implications of using RCA with binary cements in concrete construction.

1.4 THESIS OUTLINE

Chapter 2 presents the findings of the desk study carried out to review:

- The use of natural aggregates and recycled aggregates derived from construction and demolition waste in the UK.
- The existing European and British standards covering the use of RCA in concrete
- Previous studies looking at the physical and mechanical characteristics of RCA



* GEN series include GEN 1 and GEN 3 designated mixes
RC series include RC 30, RC 35 and RC 40 designated mixes

Figure 1.1 Outline of research programme.

- Previous studies looking at the effect of RCA on the fresh, engineering and durability properties of PC concrete.
- The Production and the history of use of the binary cements selected for the study
- The existing European and British standards covering the use of the binary cements selected for the study in concrete
- Previous studies looking at the fresh, engineering and durability properties of NA and RCA concretes made with binary cements.

A description of the experimental programme is given in chapter 3, followed by the presentation of the experimental details including the test materials, the mix proportions, the preparation of test specimens and the testing procedures of the aggregates and the concrete used in this study.

Chapter 4 describes the procedures used for the production of the RCA used in the study. The physical and mechanical properties of the NA and RCA used in the study are also presented and compared.

Chapter 5, 6 and 7 show the findings of the study of the effect of RCA on Portland cement and binary cement designated concretes' fresh, engineering and durability properties respectively. RCA mixes with equivalent design strength were considered.

Conclusions and practical implications of the use of RCA in Portland cement and binary cement designated concrete mixes are drawn from the research findings and are given in chapter 8 together with recommendations for further study.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter presents a comprehensive review of the literature related to the use of recycled aggregates and binary cements in concrete. It is divided into 4 parts; the first part presents an insight into the current state of the UK concrete sector in the light of the worldwide drive for a more sustainable construction. The second part looks at the current European and British standards covering the use of recycled aggregates in concrete and presents a review of previous studies on the characteristics of RCA and their effect on the properties of RCA concrete. The third part presents the current European and British standards covering the use of binary cements in concrete, the history of use of the binary cements selected for the study and a review of previous studies on their effect on the properties of natural and RCA concretes.

2.2 SUSTAINABLE CONSTRUCTION

In 1987, the World Commission on Environment and Development published a report entitled '*Our Common Future*', also known as The Bruntland report, which introduced for the first time the concept of "Sustainable Development" onto the international agenda. This report was released because of growing concerns over the detrimental effects of the rapid economic development of the last century on the environment.

Sustainable development is defined in the report as a "development that meets our needs without compromising the ability of future generations to meet their own needs" [1].

The goal of sustainable development is to balance our economic, environmental and social needs, allowing prosperity for now and for future generations. This means securing economic development, social equity and justice and environmental protection simultaneously.

In addition to setting the guiding principles of sustainable development, The Brundtland report highlighted the fact that countries all around the world have a shared responsibility to act immediately on a global, national and local level to achieve sustainable development. The report provided the inspiration of many actions that followed its publication, such as the Earth summit held at Rio de Janeiro in 1992 where the representatives of nearly 180 countries met to discuss how to achieve sustainable development. One of the recommendations of this summit was that every country should produce a national sustainable development strategy.

The United Kingdom became one of the first countries to come up with a strategy by publishing in January 1994, *Sustainable Development: the UK Strategy* [2]. Following the change of Government in 1997, it was announced that a new strategy will be prepared. In 1999, the government published *A Better Quality of Life – A Strategy for Sustainable Development for the United Kingdom*, its new revised strategy for sustainable development in the UK [3].

The strategy set four main objectives to be achieved simultaneously, these are:

- Social progress which recognises the needs of everyone;

- Effective protection of the environment;
- Prudent use of natural resources;
- Maintenance of high and stable levels of economic growth and employment.

This strategy was reviewed in 2005 to take account of developments in the UK since 1999 such as the changed structure of government in the UK with devolution to Scotland, Wales and Northern Ireland. It also takes account of new policies announced since 1999, in particular the 2003 Energy White Paper that sets a long-term goal of achieving a low carbon economy, as well as the renewed international push for sustainable development from the World Summit on Sustainable Development in Johannesburg in 2002, and the Millennium Development Goals set out in 2000 [4].

The 2005 strategy was presented in the report entitled *Securing the Future, Delivering UK Sustainable Development Strategy* [4]. The goal of sustainable development as defined by the 2005 strategy is to enable all people throughout the world to satisfy their basic needs and enjoy a better quality of life, without compromising the quality of life of future generations.

In its latest strategy, the UK Government, the Scottish Executive, the Welsh Assembly Government and the Northern Ireland Administration have agreed upon a set of principles that provide a basis for sustainable development policy in the UK. For a policy to be sustainable, it must respect all five principles. These are shown in Figure 2.1.

The 2005 strategy has also highlighted the following issues as the main priority areas for immediate action in the UK:

- Sustainable Consumption and Production
- Climate Change and Energy
- Natural Resource Protection and Environmental Enhancement
- Sustainable Communities

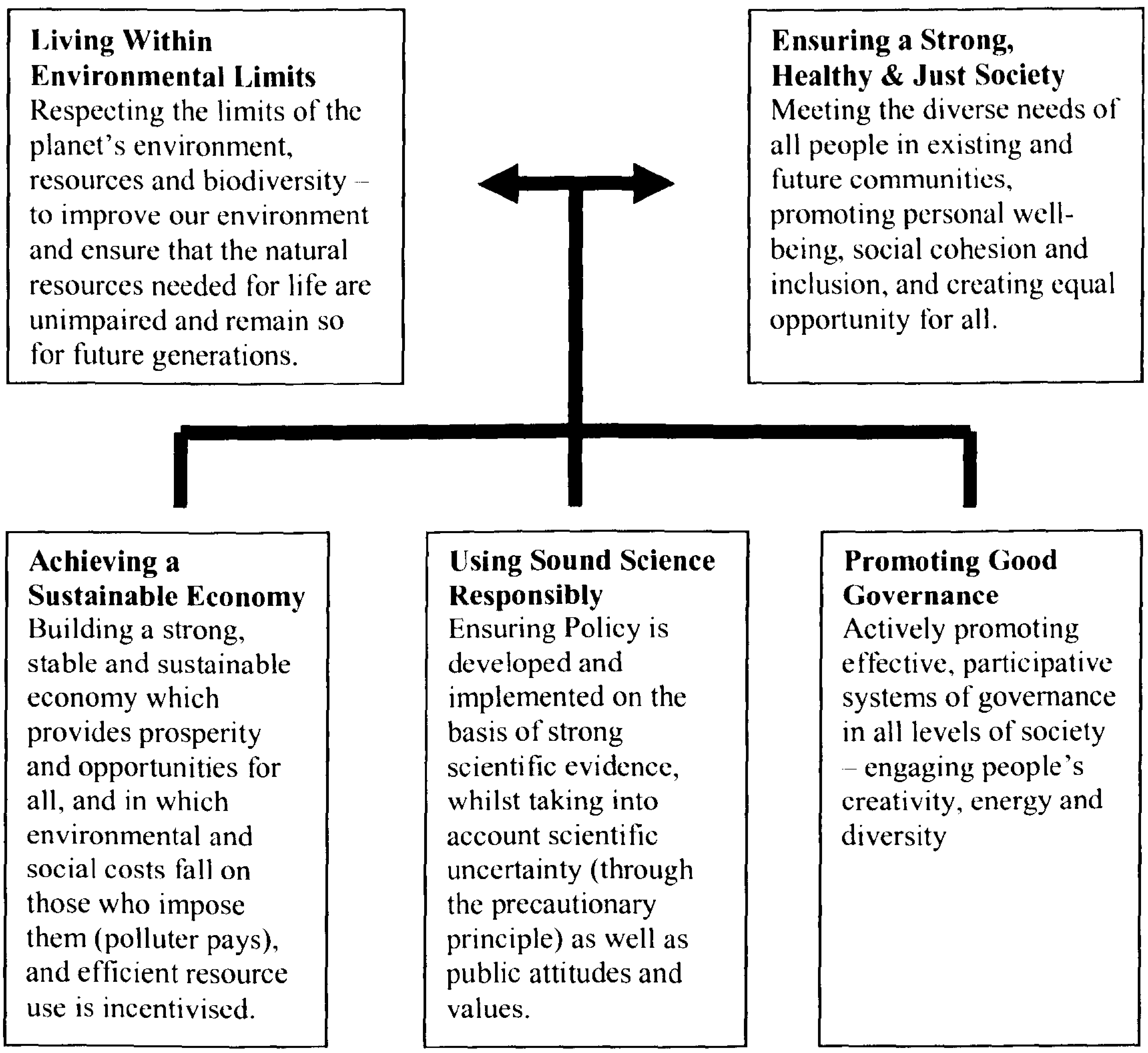


Figure 2.1 Set of principles representing the basis for sustainable development in the UK [4].

The construction industry has a great impact on the quality of life of people. In the UK, construction is a major sector of the economy and a significant employer. The broad construction sector, including building materials and associated professional services accounts for at least ten per cent of gross domestic product and provides employment for around two million people. Socially, the performance of the construction industry determines the quality not just of housing, but of the whole of the built environment including access to services and recreation. Environmentally, the construction, use, maintenance and renewal of the country's infrastructure and buildings, consume energy and material resources and generate waste on a massive scale. This represents a major contribution to climate change, resource depletion and pollution at a global level [5, 6].

Sustainable Construction is the application of Sustainable Development principles to the construction industry. It is widely recognised that the economic, social and environmental benefits that can flow from a more efficient and sustainable construction industry are potentially immense. In April 2001, the UK government published *Building a Better Quality of Life,* its strategy for a more Sustainable Construction [5].

The purpose of the report was to create a framework within which the Construction Industry can contribute to the better quality of life signalled by the UK government's Sustainable Development strategy. For this reason, this strategy built upon the framework and priorities of sustainable development set out in the 1999 UK strategy for sustainable development.

The report states that the construction industry can contribute to achieving sustainable development by:

- Being more profitable and more competitive,
- Delivering buildings and structures that provide greater satisfaction, well-being and value to customers and users,
- Respecting and treating its stakeholders more fairly,
- Enhancing and better protecting the natural environment,
- Minimising its impact on the consumption of energy (especially carbon-based energy) and natural resources.

2.2.1 THE CONCRETE SECTOR

Concrete is the most used construction material in the world. Consequently, the concrete sector represents one of the largest construction industry sub-sectors. Concrete is made by mixing cement, water, sand and coarse aggregate with or without admixtures, additions, fibres or pigments, to produce a concrete proportioned and engineered to the specific job for which it is intended. Aggregates account for a large proportion of the total volume of concrete as a result; the concrete industry consumes large quantities of aggregates.

Every year, around 210 million tonnes of primary aggregates are used in the UK as raw construction materials. An extra 20 million tonnes of aggregates will be needed each year by 2012 if the demand in the UK increases by 1% per year as it is expected [7].

43% of the total amount of primary aggregates consumed annually in the UK is destined for the concrete industry. It is estimated by the Portland cement association that ready mix concrete accounts for 75% of all concrete products in the USA. It is also assumed that ready mix concrete accounts for a similar proportion of all UK concrete products [7]. Figure 2.2 shows the UK's annual consumption of primary aggregates and the annual consumption of primary aggregates by a range of concrete products.

In the *Guidelines for Aggregates Provision in England MPG 6* [8], published in April 1994, the government provides advice to the mineral planning authorities and the minerals industry on how to ensure that the construction industry receives an adequate and steady supply of material at the best balance, of social, environmental and economic cost, whilst ensuring that extraction and development are consistent with the principles of sustainable development.

The report states that in keeping with the Government's commitment to a sustainable approach to the supply of aggregates it is in the national interest that aggregates, and products manufactured from aggregates, should be recycled wherever possible. It is also important that mineral and construction wastes should be used where they are technically, economically and environmentally acceptable as substitutes for primary materials. This can afford considerable savings of raw materials and can reduce the areas worked for new materials as well as those used for the dumping of wastes.

In this report, the government has set as a target to increase the use of recycled and secondary materials in England to 40 million tonnes per year by 2001 and 55 million tonnes per year by 2006.

In 2002/2003, the total waste produced in the UK was estimated at 333 million tonnes. Figure 2.3 shows the estimated total annual waste produced by each sector. The construction and demolition waste was estimated to be around 106 million tonnes. This includes excavated soil and miscellaneous materials as well as hard materials, such as brick, concrete and road planings [9]. A large percentage of the Construction and demolition waste arisings in the UK has the potential to be recycled into aggregates.

Today, 65 million tonnes of the amount of aggregates used in the UK are derived from recycled or secondary sources. The UK has an aggregates' recycling rate of nearly 2.5 times the European average. It has now established itself as the leader of the European aggregates recycling league; 17% of its aggregates need is satisfied through recycling. The UK is then followed by Holland and Germany with 14.6 and 8.5% respectively [10].

However, a large proportion of recycled aggregates produced is thought to be mainly used as low value fill, with some used for intermediate value applications such as capping and unbound sub-base in road foundations. The full potential of recycled aggregates to be used for high value applications such as coarse aggregates in concrete is yet to be fulfilled.

2.2.2 Environmental taxes

Economic instruments are one of the means Governments use to achieve sustainable development. The most common type of economic instruments used is environmental taxation. Taxation can influence prices and provide an incentive for the industry sectors affected by the taxes to adopt more sustainable practices. In the UK, fiscal

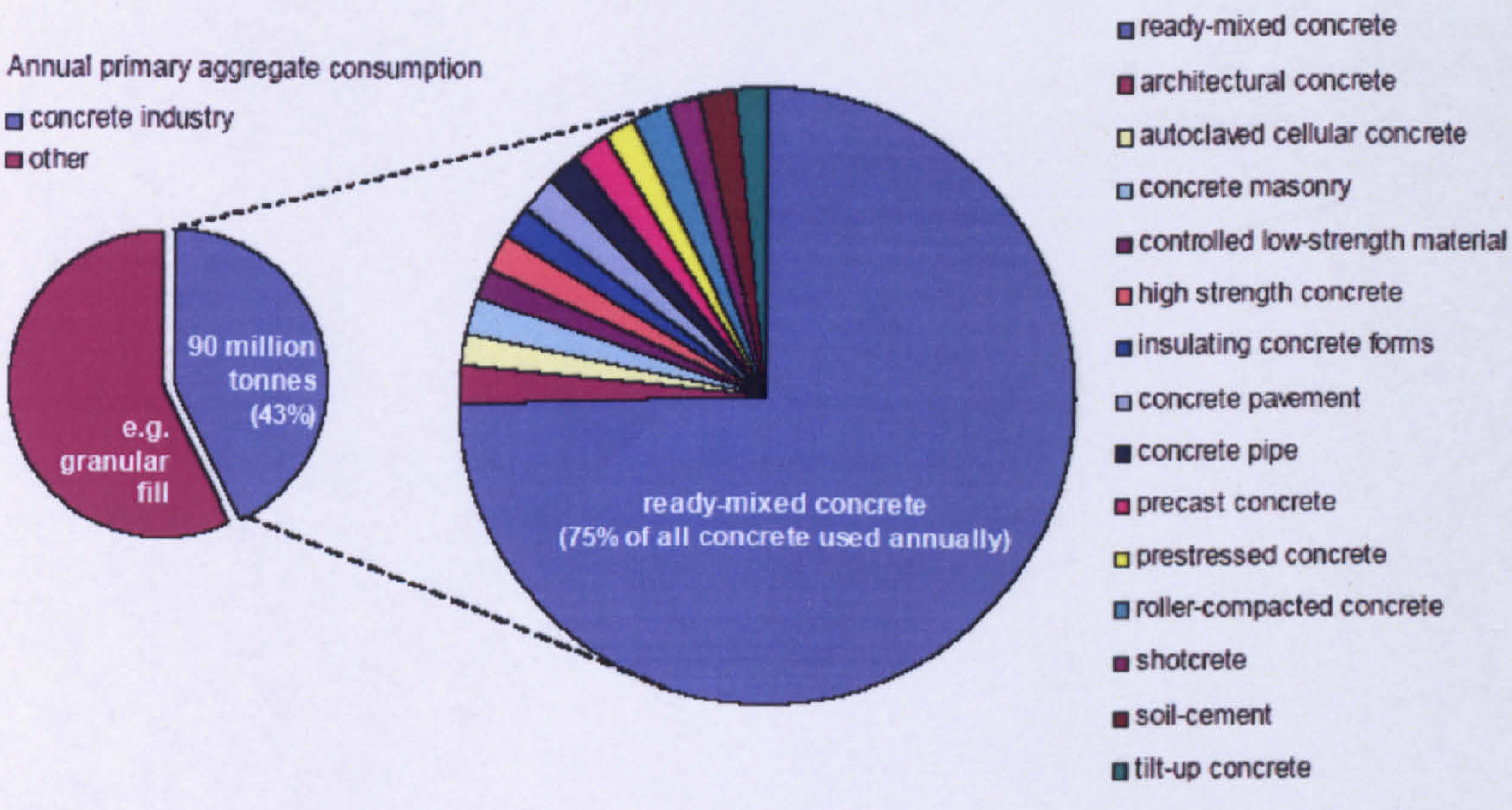


Figure 2.2 Annual consumption of primary aggregates by a range of concrete products (Source: QPA, BCA, Portland cement association) [7].

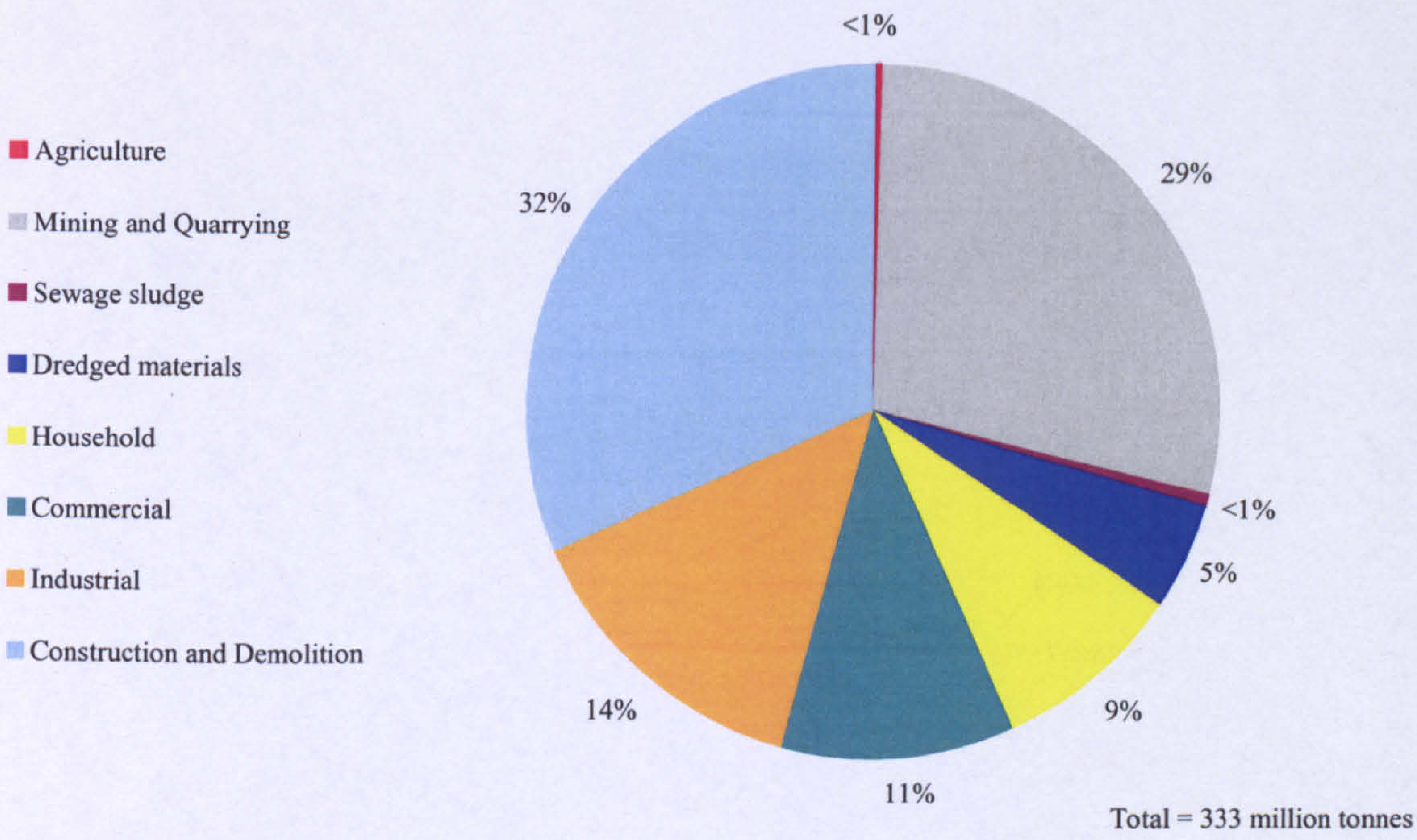


Figure 2.3 Estimated total annual waste arisings by sector in the UK for 2002/2003 (Source: Defra, ODPM, Environment agency, Water UK) [9].

measures such as the Aggregates levy and the Landfill Tax were introduced. These taxes are of high relevance to the concrete sector.

Aggregates Levy

The Aggregates Levy aims to reduce the demand for primary aggregates by increasing their cost and make the use of recycled and secondary materials more viable. The levy of £1.60 per tonne of aggregates (Sand, gravel, rock with some exceptions) was implemented in April 2002 and will increase to £1.95 in April 2008.

An Aggregates Levy Sustainability Fund was also introduced in April 2002; this fund uses revenue from the Aggregates Levy to reduce the environmental impacts of aggregates extraction and helps to stimulate the market for recycled and secondary materials.

Landfill Tax

The Landfill Tax was introduced in October 1996 to reduce the levels of waste going to landfill and encourage the development of more sustainable waste management practices.

The Landfill Tax is paid on top of normal landfill fees by businesses and local authorities that want to dispose of waste using a landfill site. There are two rates of tax:

- The lower rate - £2 per tonne (increasing to £2.50 in April 2008) for inactive waste such as rocks and soil.

- The standard rate - £24 per tonne for all other landfilled waste increasing by £8 each year from April 2008 until at least 2010/2011.

The introduction of the Landfill Tax provides an incentive for the construction industry to reduce the amount of construction and demolition waste being landfilled through its recycling and reuse.

In the light of the drive for a more sustainable construction, it is clear that the concrete industry today faces a new challenge and once again concrete has to adapt to our current needs as it did in many occasions since its first use.

2.3 USE OF RECYCLED CONCRETE AGGREGATE

2.3.1 STANDARDS FOR USE OF RCA

The fact that the use of recycled aggregates in concrete has to be maximised is increasingly being acknowledged by the national and international standards bodies. On the 1st of June 2005, the BS 882 'specification for aggregates from natural sources of concrete' [11] was withdrawn and replaced by the European standard, EN 12620 – 1 'aggregates for concrete' [12].

The BS 882 specified the quality and grading requirements of aggregates for use in concrete obtained only by processing natural materials, whereas, the EN 12620, specifies the properties of aggregates and filler aggregates obtained by processing natural, manufactured or recycled materials and mixtures of these aggregates for use in concrete.

This new standard defines natural aggregates as aggregates from mineral sources which have been subjected to nothing more than technical processing, and recycled aggregates as aggregates resulting from the processing of inorganic material previously used in construction [12].

A very important aspect of this European standard is that it mainly focuses on the fitness of purpose of aggregates and does not discriminate between different sources. As this European standard applies to all aggregates for use in concrete produced in Europe, it has been created to be flexible enough to allow the specification of a wide range of aggregates with a number of properties [14].

For the UK, in addition to the introduction of some new tests, the main differences between the old and new standard are the introduction of a new grading classification, a category system to describe performance and a new set of sieves.

The EN 12620 makes use of a classification system to describe the aggregates properties, with each category indicating the level of an aggregate property. Therefore, it is these categories that will be used to specify aggregates and to demonstrate aggregates are fit for purpose.

The EN 12620 states that the requirements in the standard are based upon experience with aggregate types with an established pattern of use and that care should be taken when considering the use of aggregates from sources with no such pattern of use, e.g., recycled aggregates and aggregates arising from certain industrial by-products. Such aggregates, which should comply with all the requirements of EN 12620, could have other characteristics not included in the standard that do not apply to the generality of aggregates types with an established pattern of use and when required, provisions valid at the place of use can be used to assess their suitability [12].

On the 1st of December 2003, the British Standard for concrete BS 5328 [15] was withdrawn to be replaced by the European Standard EN 206-1 [13]. In the UK, the EN 206-1 is complemented by the BS 8500 which includes provisions for a number of items relevant to UK concrete industry and materials and procedures not covered by the European standard (e.g. minimum cement contents or maximum water cement ratios for different exposures conditions, the use of recycled aggregates, procedures to minimise alkali aggregate reaction). The BS 8500: Concrete - Complementary British standard to EN 206-1, was published in March 2002 and is in two parts:

- BS 8500-1: Methods of specifying and guidance for the specifier [16].
- BS 8500-2: Specification for constituent materials and concrete [17].

The main differences between the BS 5328 and the new concrete standards EN 206 – 1 and BS 8500 are in the terminology used (e.g. the term 'workability' is replaced by the term 'consistence') and the way concrete is specified (e.g. Strength is specified by a strength class rather than a minimum characteristic cube strength and Consistency is specified by a class rather than a target value) and controlled (The producer is required to ensure conformity of the concrete supplied as per EN 206 – 1).

In the EN 206 – 1, the general suitability to be used as an aggregate in concrete is only established for:

- Normal and heavy-weight aggregates conforming to EN 12620.
- Lightweight aggregates conforming to EN 13055.

Provisions for recycled aggregates are not yet included in EN 206, however the standard states that until provisions for recycled aggregates are given in the European technical specifications, their suitability should be established through:

- A European Technical Approval which refers specifically to the use of the recycled aggregates in concrete conforming to EN 206-1,
- A relevant national standard or provisions valid in the place of use of the concrete which refers specifically to the use of recycled aggregates in concrete conforming to EN 206-1.

The BS 8500 – 2 covers the use of recycled aggregates in concrete in Clause 4.3. It introduces two categories of coarse recycled aggregates:

- Recycled Concrete Aggregate (RCA) consisting primarily of crushed concrete.
- Recycled Aggregate (RA) which may include a higher proportion of masonry.

The BS 8500 – 2 also defines the compositional requirements for RCA and RA and the limitations on their use in different exposure conditions. These are shown in Table 2.1 and Table 2.2 respectively. Whilst the use of coarse recycled aggregates is permitted, BS 8500 – 2 does not cover the use of fine RCA or RA.

RA is limited to use in concrete with a maximum strength class of C16/20 (i.e. equivalent to a characteristic cube strength of 20 N/mm^2) and only in the mildest exposure conditions, whereas RCA can be used up to strength class C40/50 (i.e. equivalent to a characteristic cube strength of 50 N/mm^2) and in a wider range of exposure conditions. RCA is not generally permitted in concrete exposed to sea water, de-icing salts, severe freezing and thawing or in very aggressive ground.

Table 2.1 BS 8500 – 2 requirements for coarse RCA and coarse RA [17].

Type of Aggregate	Requirement [a] and Maximum Content (by Mass Fraction %)					
	Masonry Content	Fines	Lightweight Material [b]	Asphalt	other Foreign Material [c]	acid soluble sulphate (SO_3)
RCA	5	5	0.5	5.0	1.0	1.0
RA	100	3	1.0	10.0	1.0	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] Material with a density less than 1000 kg/m^3

[c] e.g. glass plastic, metals

Table 2.2 BS 8500 – 2 limitations on the use of coarse RCA and coarse RA [17].

Type of aggregate	Limitations on use	
	Maximum strength class	Exposure classes [b]
RCA [a]	C40/50	X0, XC1, XC2, XC3, XC4, XF1, DC-1
RA	C16/20	X0, DC-1

[a] Material obtained by crushing hardened concrete of known composition that has not been contaminated by use may be used in any strength class.

[b] These aggregates may be used in other exposure classes provided it has been demonstrated that the resulting concrete is suitable for the intended environment, e.g. freeze/thaw resisting, sulphate-resisting, etc.

For designated mixes, the aggregates used shall be normal-weight and shall conform to EN 12620 and to any specified requirements for special properties. Any RCA or RA used in designated concretes GEN0 to GEN3 shall conform to 4.3. Where RCA or RA is not excluded by the specification for designated concretes RC25 to RC50, their proportions shall be not more than a mass fraction of 20 % of coarse aggregate except where the specification permits higher proportions to be used. Also unless otherwise specified, the maximum aggregate size shall be 20 mm and the aggregate drying shrinkage, tested in accordance with EN 1367 – 4, shall be less than 0.075 %.

2.3.2 RCA CHARACTERISTICS

2.3.2.1 Physical characteristics

Grading

Dhir et al [22] examined the grading of RCAs crushed in an existing plant for the production of crushed rock aggregate, comprising primary and secondary crushers and screens. The RCAs used in the study were derived from concrete samples from six different sources (Laboratory cast concrete, demolished concrete structure, rejected structural precast element, airport pavement, masonry concrete blocks and kerbs and paviers). No major differences were found between the particle size distributions of the RCAs from the different sources which were within the limits set for crushed-rock aggregates in the British standard used at that time this study was undertaken. The results of this study are shown in Table 2.3. O'mahony [19] also reported that the source of the concrete used to manufacture RCA has no influence on the grading of the RCA.

Katz [23] compared the particle size distribution of RCA prepared from an original concrete crushed at various ages (1, 3 and 28 days) therefore having various strengths (7.4, 14.4 and 28.3 MPa). The three types of RCA produced exhibited the same particle size distribution despite the differences in strengths of the original concretes they were made from. Similar results were reported in another study [91].

Hansen and Narud [21] reported that RCA prepared by crushing of a high, medium and low strength original concrete (56.4, 34.4 and 13.8 MPa respectively at 38 days) in a jaw crusher of 25 mm with the jaws in a closed position had a similar particle size distribution. The overall gradings of crusher products of the different RCAs tested in this study are shown in Table 2.4. These results show that crushing a low strength concrete produces a slightly higher quantity of fine particles (<5mm) compared to a concrete with higher strength. Similar findings were reported in another study [24].

Kaga et al [20 a] found that the particle size distributions of RCAs, derived from crushing concrete with a high, medium and low water/cement ratio, all met the requirements of the Japanese standards for crushed stone.

Comparing the grading of the crusher products of natural rock and hardened concrete from different studies showed that the crushing characteristics of the hardened concrete are similar to those of natural rocks and not significantly affected by the grade of the original concrete [51].

A study [25] by Japanese researchers found the percentage of fine aggregates produced from crushing concrete in a jaw crusher decreased with the increase in the size of the jaw opening. Similar results were reported in another study [91], where the

Table 2.3 Particle size distribution of coarse natural and recycled concrete aggregates derived from different sources [22].

Aggregate type	Percentage passing, by mass BS sieve size (mm)				
	37.5	**20.0**	**14.0**	**10.0**	**5.0**
BS 882 limits: (single sized 20 – 5 mm)	100	85-100	0-70	0-25	0-5
Natural Aggregate	100	95	23	5	1
RCA sources Demolished concrete structure (30-40 N/mm^2)	100	100	48	12	2
Rejected structural precast element (50-60 N/mm^2)	100	95	52	14	1
Airport pavement (50 N/mm^2)	100	98	56	16	2
Masonry concrete blocks (10-40 N/mm^2)	100	97	42	8	1
Kerb and paviers (30-50 N/mm^2)	100	90	30	10	3
Laboratory - cast concrete (10-70 N/mm^2)	100	100	63	8	2

Table 2.4 Overall grading of crusher products for RCAs derived from original concretes with different w/c ratios [21].

Size fraction, mm	Weight % of crusher products H (w/c = 0.40)	M (w/c = 0.70)	L (w/c = 1.20)
>30	3.0	4.2	3.2
30 – 20	27.4	31.9	27.6
20 – 10	35.9	33.2	33.5
10 – 5	14.7	13.4	13.2
<5	19.1	17.3	22.5

percentage of fine aggregates produced form crushing concrete in a jaw crusher was larger when the opening of the jaw crusher was reduced.

Particle Shape and Surface Texture

RCA are generally known to have a more angular particle shape and a rougher surface texture than NA. Dhir et al [22] after visually examining the shape and texture of the RCA used in their study described it as coarser, more porous and rougher but equidimentional when compared to the natural aggregates.

Collins [35 c] examined the flakiness value for RCA produced in a recycling plant and found that it was within the limits for the flakiness value set in the UK standards at the time of the study. Another study [20 p] showed that the particle shape index of RCA to be nearly the same as for natural coarse aggregates.

Ravindrajah and Tam [20 b] reported RCA particles to be more angular than crushed granite particles used in their study probably due to their ease of breaking in an irregular shape along the soft cement paste component in concrete.

Hansen and Narud [21] reported that crushing high, medium and low strength concrete produced RCA consisting mainly of more or less cubical particles.

Kaga et al [20 a] reported that the shape of RCA depends on the type of crushers used. RCA produced from crushing original concretes with different water/cement ratios using a jaw crusher was found to be harsh with cement paste still attached to it. However the particle shape could be improved by a secondary crush, which makes the surface of the RCA smooth.

Kikuchi et al [26 a] reported that the fraction shapes of RCA had the tendency to become more roundly as the water cement ratio of the original concrete increased and the mortar strength decreased. Similar results were reported in another study [96].

Kobayashi and Kawano [20 g] found that refining RCA produced by an impact crusher using a coarse aggregate refining machine resulted in aggregates with a rounder shape.

Meinhold et al [92] found that the material processed in a jaw crusher contained up to 40% flat shaped particles whilst for the material processed in an impact crusher this figure was about 10% and less.

Attached Cement Paste

RCA is composed of mainly two parts, the original aggregate and the cement paste attached to it. The attached cement paste is known to affect the RCA characteristics; this in turn has an effect on the fresh and hardened properties of concrete.

Investigations on the cement paste of RCA have shown that the amount of attached cement paste increased with the decrease in aggregate size [20 a-c, 21-23, 25, 26 b, 26 c].

Hansen and Narud [21] examined the amount of attached cement paste of RCA derived from original concretes with different water cement ratios made with the same cement and original aggregates, and found that the volume percentage of cement paste attached to the different RCA produced did not vary much. Same findings were reported in other studies [20 a, 20 c, 25, 93, 94].

Figure 2.4 shows the results from the analysis of the amount of attached cement paste in the different size fractions of RCAs derived from original concretes with different water cement ratios, from a study by Kaga et al [20 a].

Katz [23] determined the amount of attached cement paste in three size fractions (coarse, medium and fine) of RCA prepared from an original concrete crushed at various ages (1, 3 and 28 days) therefore having various strengths (7.4, 14.4 and 28.3 MPa). The amount of attached cement paste in each size group was not affected by the strength or crushing age of the original concrete.

A similar study [95] found that the amount of attached cement paste in RCA produced from a high, medium and low strength original concretes crushed at 1 month, 1 year and 2 years was not affected by the strength of the original concretes. However the amount of attached cement paste in RCA produced after 1 month of curing the original concrete was lower when compared to RCA produced after 1 and 2 years of curing.

Other studies have stated that RCA which originated from low strength concrete had slightly less attached cement paste when compared to RCA produced from higher strength concrete [28, 29].

Nagataki and Lida [93] determined the percentage of attached cement paste in 3 types of RCA. The first type was produced using a jaw crusher and an impact crusher, the second and third types were crushed further using an improved crusher with a strong grinding effect once and twice respectively. It was found that a higher level of crushing reduces the percentage of cement paste in the RCA produced. Similar findings were reported in another study [94].

Density

A range of density values obtained for NA and RCA in saturated and surface - dry conditions, from different investigations are summarized in Table 2.5. Generally RCA had bulk and relative densities lower than NA. This is mainly due to the low density old cement paste attached to the original aggregate particles.

Numerous studies have established that a correlation exists between the amount of attached cement paste in RCA and the density of RCA. The density of the RCA decreases with the increase in the attached cement paste. Figure 2.5 a and b show the relationship between the amount of attached cement paste and the specific and bulk densities of RCA respectively based on a study by Dosho et al [96].

Investigations on the density of RCA have shown that it decreased with the decrease in aggregate size [20 b, 20 d, 26 b]. This is not surprising as it is well known that the amount of cement paste increases in the RCA particles with the decrease in aggregate size.

Fujii [20 e] examined the bulk and relative densities of RCA obtained using different

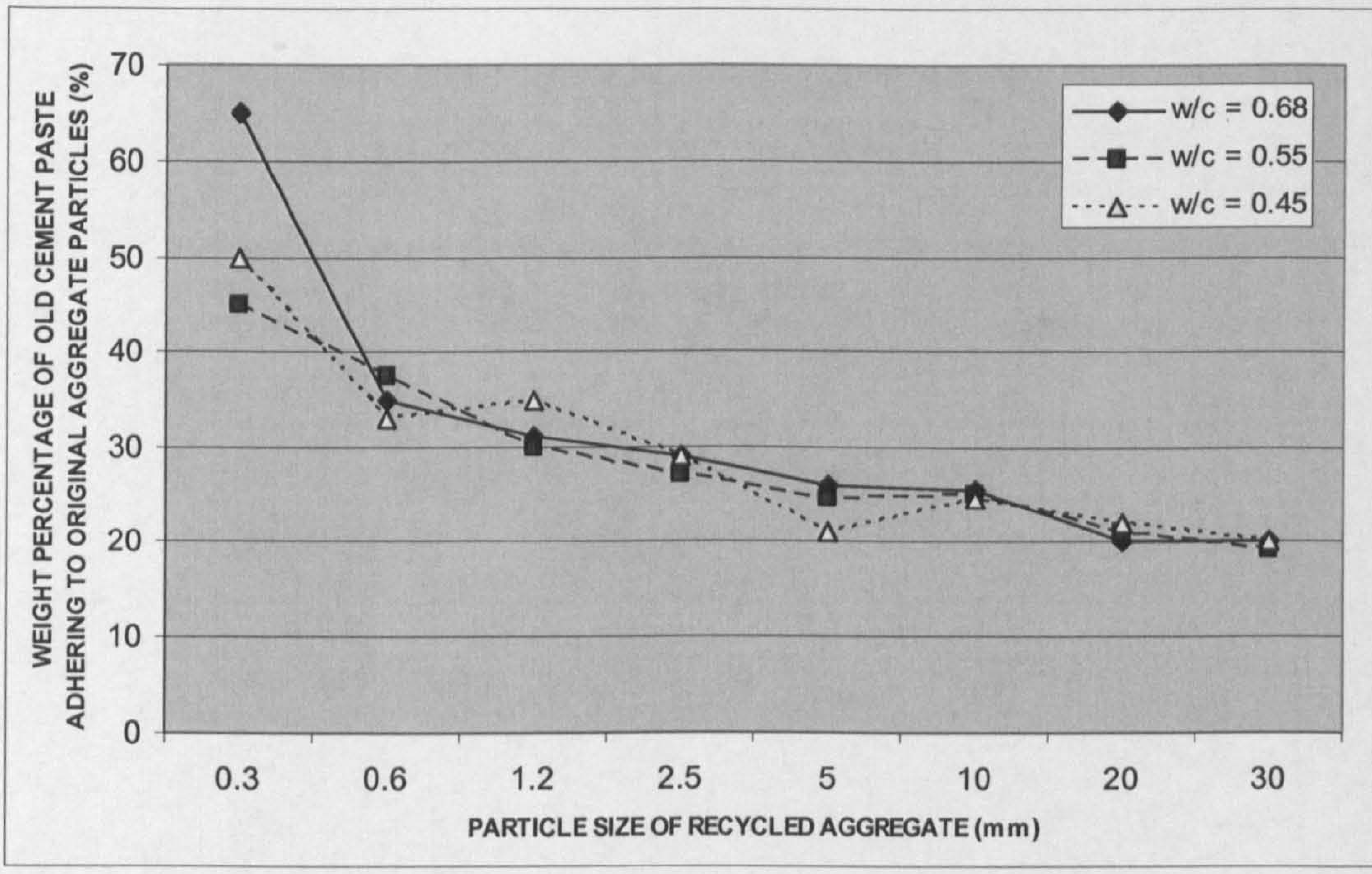


Figure 2.4 Weight percentage of cement attached to original aggregates in RCA produced from original concretes with different w/c ratios [20 a].

Table 2.5 Bulk and relative densities of coarse RCA and NA reported in different studies.

DENSITY (kg/m^3)				
Bulk		Relative		REFERENCE
NA	RCA	NA	RCA	
1360	940 - 1210	2600	2100 - 2640	[22]
1500 – 1580	1280 – 1370	2680 – 2710	2380 – 2460	[26 d]
1740	1350 – 1370	2670	2450 – 2460	[20 f]
1630	1320 – 1370	2650	2450 – 2370	[20 h]
1670	1410	2870	2410	[95]
1530 – 1620	1250 – 1320	2570 - 2700	2230 – 2360	[96]
1505	1258 – 1293	2872	2542 – 2589	[91]

crushers and found that the crusher type had no effect on the densities. Another study [20 c] also found no major difference in bulk density of RCA produced using a jaw crusher and a jaw and impact crusher combined.

However when Nagataki and Lida [93] compared the bulk density of 3 different types of RCA, the first type was produced using a jaw crusher and an impact crusher, the second and third types were crushed further using an improved crusher with a strong grinding effect once and twice respectively. It was found that the higher level of crushing, the higher the bulk densities of the RCA produced were. This was expected as additional refining of RCA through crushing or grinding removes the attached cement paste which influences the density of the RCA. Similar findings were reported by Kobayashi and Kawano [20 g]

Kakizaki et al [20 f] after examining the bulk and relative densities of RCA obtained from original concretes with different water cement ratios and therefore different strengths found that the w/c ratio or the strength of the original concrete did not have any influence on the RCA's density. Results from this study are shown in Table 2.6. Similar findings were reported by [20 a, 20 d, 20 i, 21, 24, 25, 28].

On the other hand, Dosho et al [96] found that the specific density of RCA showed a decreasing tendency as the water cement ratio of the original concrete increased, however the results for the bulk density of the RCA used in the same study were not affected.

Nagataki and Lida [93] compared the bulk and relative densities of RCA produced from a high, medium and low strength original concretes cured for 1 month, 1 and 2 years and found the bulk and relative densities of RCA were not affected by the age or the strength of the original concrete.

Table 2.6 Bulk and relative densities of RCAs derived from original concretes with different w/c ratios [20 f].

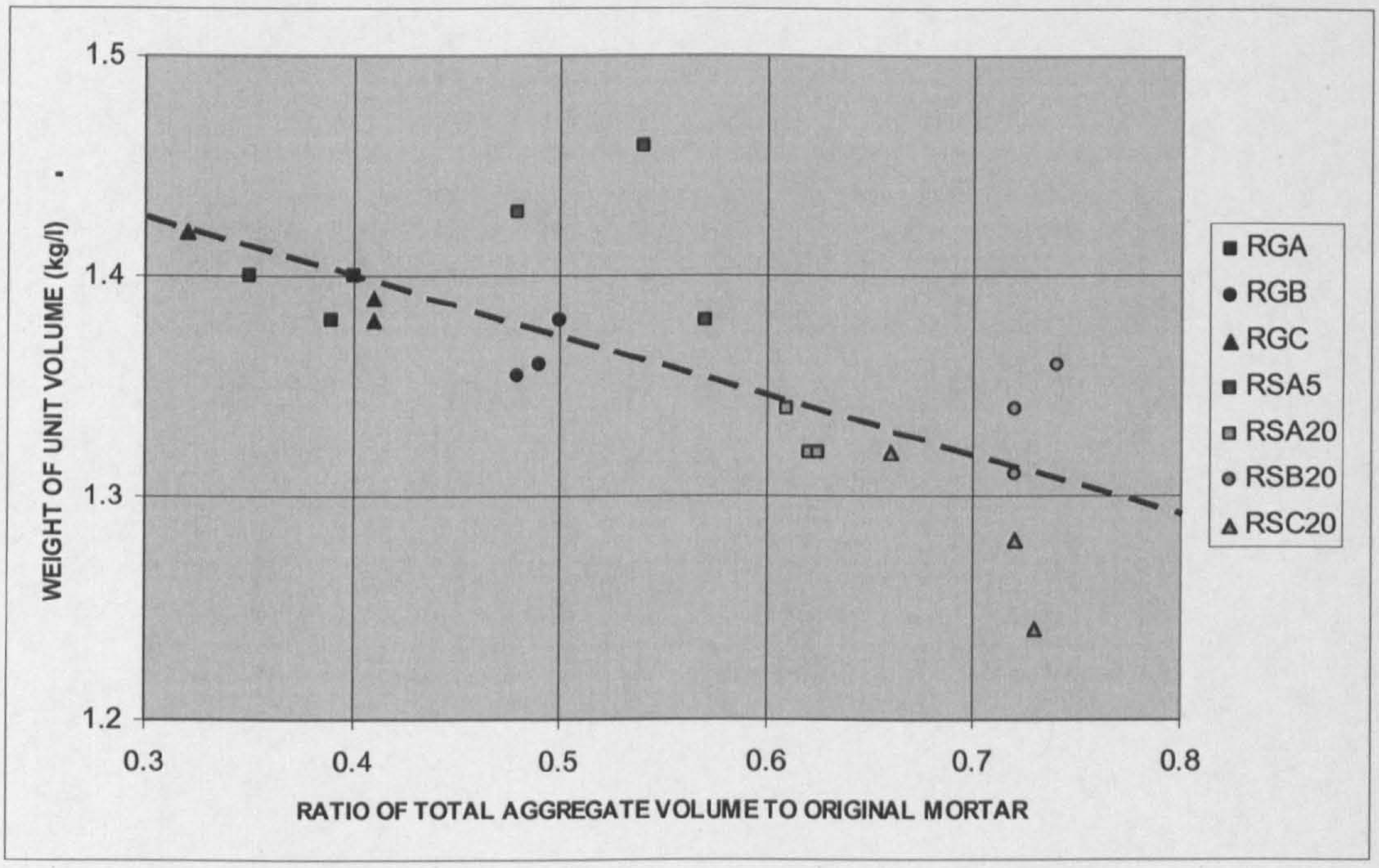
Aggregate type	Specific gravity		Bulk density (kg/l)
	Surface dry	Dry	
Natural aggregate	2.67	2.65	1.74
RCA (w/c = 0.45)	2.46	2.31	1.35
RCA (w/c = 0.55)	2.45	2.30	1.36
RCA (w/c = 0.68)	2.45	2.32	1.37

Water Absorption

Generally, the water absorption of RCA has been reported to be significantly higher than that of NA [51]. This is mainly due to the porosity of the old cement paste attached to the original aggregate particles. Table 2.7 shows water absorption values for coarse NA and RCA used in different studies.

It is widely recognized that as the amount of attached cement paste in RCA increases, its density tends to decrease whilst its absorption capacity increases [20 b, 20 g, 20 q, 30, 33, 35 b, 95, 96]. Figure 2.6 a and b show the relationship between the water absorption of RCA and the amount of attached cement paste and specific gravity respectively based on a study by Kobayashi and Kawano [20 g].

Meinhold et al [92] found that there was an excellent correlation of water absorption with the porosity of RCA. They found that the water absorption of RCA increases a.



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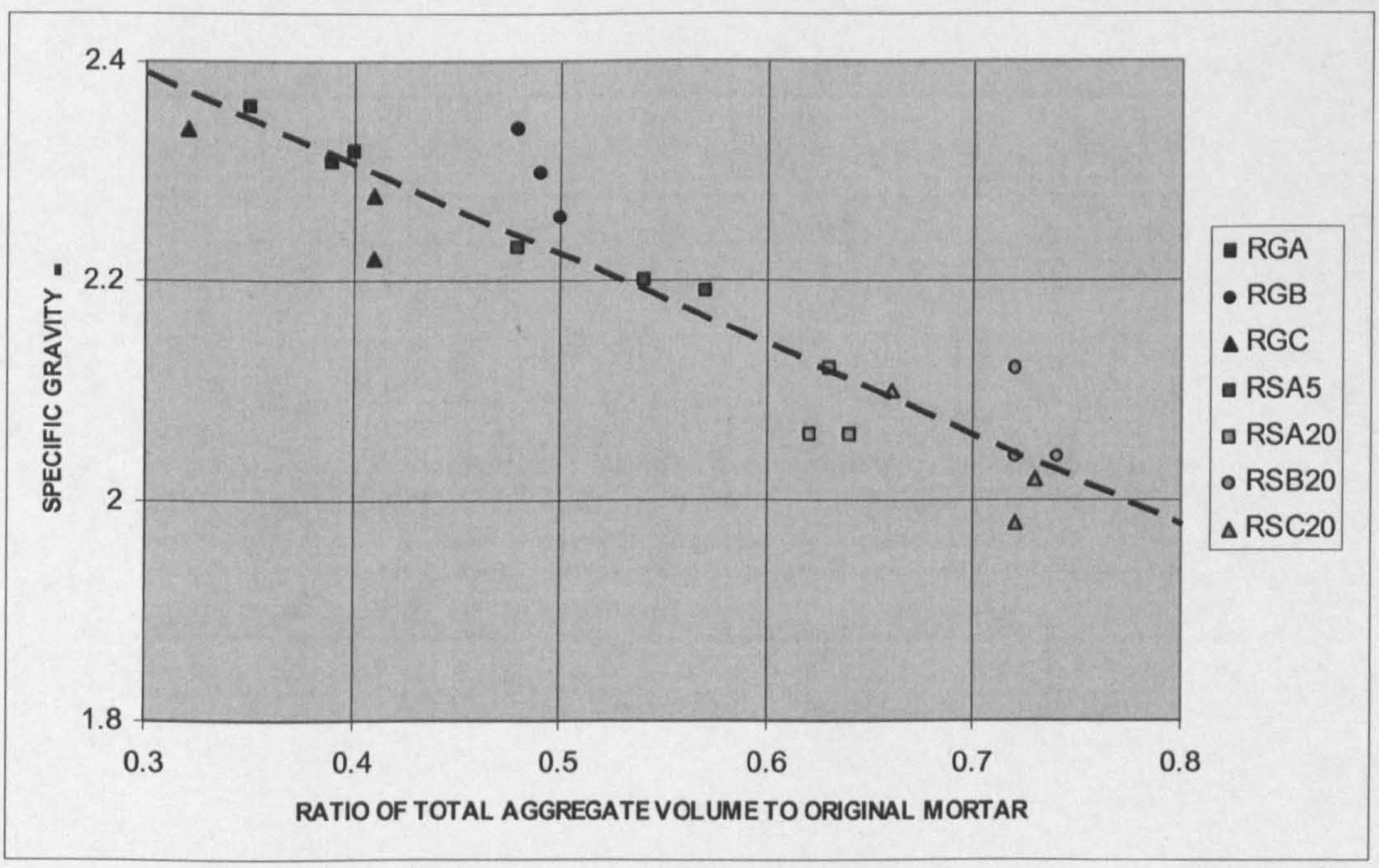


Figure 2.5 Relationship between the bulk and relative densities and the amount of attached cement paste for recycled aggregates [96].

with an increase in its porosity.

Nagataki et al [94] found a similar correlation after measuring the water absorption and the porosity of the attached cement paste of RCA from air entrained original concretes with a high, medium and low w/c value (0.63, 0.43 and 0.35). The results of this study showed that there were no big differences in the porosity characteristics of the mortars with original concretes with the low and medium w/c ratios however the porosity of the high w/c ratio original concrete was considerably higher.

Investigations on the water absorption of RCA showed that it increased with the decrease in the aggregate size [20 b, 20 d, 23]. This is not surprising as the amount of cement paste in RCA, which influences its absorption, increases with a decrease the aggregate size.

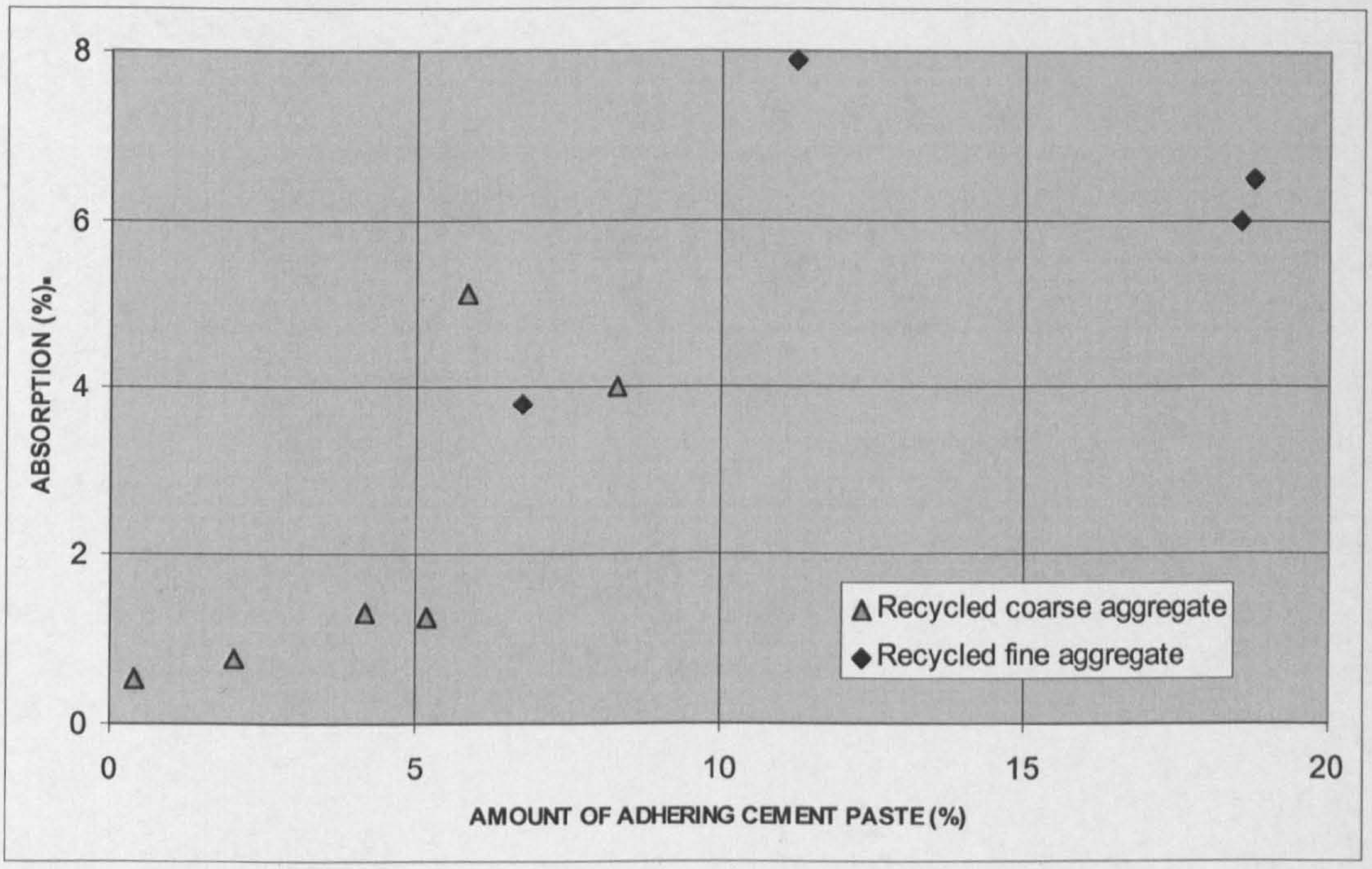
Fujii [20 e] examined the effect of using different type crushers on water absorption of RCA. It was found that the crusher type has a little influence on the water absorption of coarse RCA. Another study [20 c] showed that there are hardly any differences due to the methods of crushing, after comparing the water absorption capacity of RCA produced using a jaw crusher and RCA produced using a jaw and impact crusher.

Nagataki and Lida [95] determined the water absorption rate of 3 types of RCA. The first type was produced using a jaw crusher and an impact crusher, the second and third types were crushed further using an improved crusher with a strong grinding effect once and twice respectively. It was found that the higher level of crushing, the

Table 2.7 Water absorption values from several studies.

WATER ABSORPTION (%)		REFERENCE
NA	RCA	
0.68	3.47	[36]
0.65	7.58	[37]
0.4	3.0	[32]
0.4	9.25	[31]
0.2	5.5 – 6.5	[39]
1	5.6	[41]
2.5	3.2 – 14.6	[22]
0.5 – 1.6	4.0 – 5.7	[26 a]
0.53 – 0.86	6.22 – 7.66	[26 d]
1.4	5.85	[20 f]
0.8	6.7	[20 k]
0.85	5.7	[20 i]
0.6 – 1.1	3.3 – 10.05	[20 d]
0.6	4.5 – 5.3	[20 l]
0.58	5.63 – 6.50	[20 h]
0.8	5.82 – 6.40	[20 a]
0.86 – 1.62	7.6 – 7.7	[57]
0.94	3.30 – 4.96	[30]
0.5 – 1.6	4.3 – 6.0	[96]
0.8	6.4	[95]

a.



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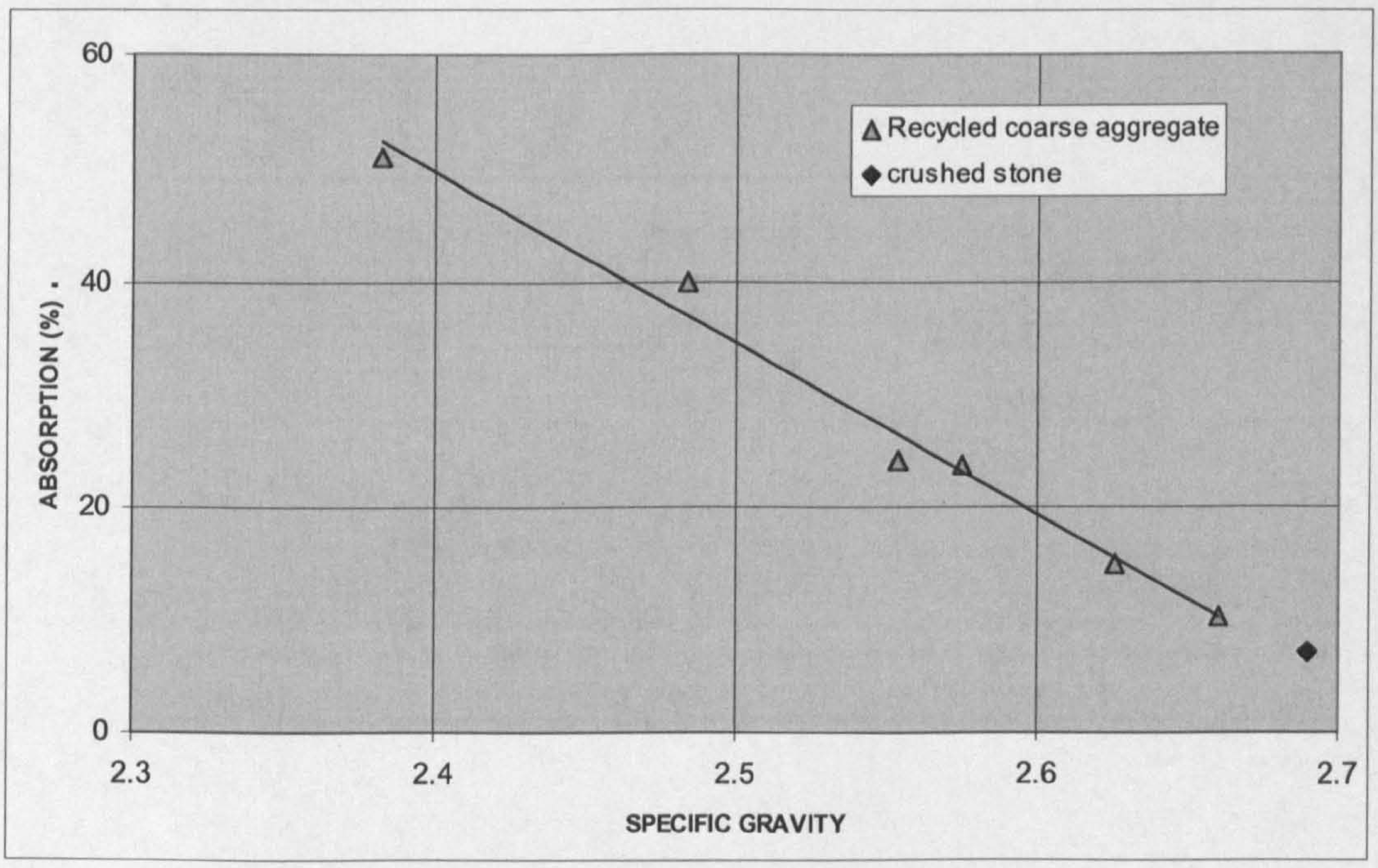

Figure 2.6 Relationship between the water absorption and the amount of attached cement paste and the relative density of recycled aggregates [20 g].

lower the water absorption rate of the RCA produced was. This was expected as additional refining of RCA through crushing or grinding removes the attached cement paste which influences the water absorption rate of the RCA. Similar findings were reported in another study [20 g].

Hasaba et al [28] compared the water absorption of RCA derived from concretes with different strengths and found that the original concrete's strength had no effect on the water absorption of RCA. Similar results were reported by several studies [20 c, 20 f, 20 i, 20 j, 21, 23, 24]. On the other hand, Kikuchi et al [35a] reported that RCA derived from high strength concrete had a lower water absorption compared to RCA derived from low strength concrete.

Poon et al [39] also found that RCA had lower water absorption when derived from high strength concrete containing mineral admixtures such as silica fume and fly ash compared to normal strength concrete. Kaga et al [20a] found that the water absorption rate of RCA is high when the water cement ratio of the source concrete is high. Similar findings were reported by other studies [94, 96].

2.3.2.2 Mechanical characteristics

Several studies have showed that the mechanical properties, including aggregate crushing value, aggregate impact value and 10% fine value of RCA were lower than those of NA. The results from some of these studies are shown in Table 2.8

Ravindrajah and Tam [20b] reported that the mechanical resistance of RCA decreases with the reduction in the maximum aggregate size. This is not surprising as the amount of the soft attached paste to the original aggregates increases as the size of the RCA particles decreases. These findings were confirmed by another study [96] which reported that the crushing value of RCA increased with an increase in the amount of cement paste attached in the RCA particles.

Poon et al [39] found that RCA derived from high strength concrete had a higher ten per cent fines value than RCA derived from normal strength concrete. Results of ten per cent fines values of RCA made from original concretes with different strengths presented in other studies [20 j, 26 c] show the same trend.

Kikuchi et al [35 a] also reported that the aggregate crushing value of RCA decreased with the increase in the strength of the original concrete. Same findings were reported in other studies [20 j, 21, 26 c, 96].

Table 2.8 Mechanical properties of RCA and NA from different studies [20 b, 20 j, 20 m, 26 a, 26 d, 35 a, 35 c, 38, 39, 42, 43, 96].

Aggregate type	Aggregate crushing value %	Aggregate impact value %	10% Fine Value, KN
RCA	18.4 - 33.4	22.5 - 29.0	60 - 175
NA	10.8 - 23.0	10.0 - 15.0	159 - 380
BS 882 limits for various applications	-	< 25.0 - 45.0	> 50 - 150

2.3.2.3 Impurities

One of the main problems related to the use of recycled aggregates in the manufacture of new concrete is the possibility of the contaminants in the construction and demolition debris used to produce these aggregates to be passed into the new concrete

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[51]. The types of impurities found in the RCA are related to the original concrete usage [42].

Hansen [51] listed the different contaminants that RCA may contain. These impurities may be bitumen, gypsum, organic substances, chlorides, chemical and mineral admixtures, soil and filler materials, metals, glass, fragmented brickwork and lightweight concrete, particles damaged by weathering or fire, particles susceptible to frost damage and alkali reaction, industrial chemicals and radioactive substances and high alumina cement.

These impurities can have detrimental effects on the properties of fresh and hardened concrete depending on the proportion and form in which they are present.

Hansen [51] after reviewing many studies on contaminants in RCA reported that:

- **Bitumen** has a detrimental effect on the strength of concrete.
- **Gypsum** can also have deleterious effects on RCA concrete due to sulphate expansions. It is recommended to use sulphate resistant Portland cement for the production of RCA concrete when it is known that the RCA is contaminated by large quantities of gypsum.
- **Organic substances** such as wood, textile fabrics, paper, joint seals and other polymeric materials are unstable in concrete when submitted to drying and wetting or freezing and thawing.
- **Chlorides** when present in RCA can result in severe reinforcement corrosion.
- **Chemical admixtures** have no effect on the fresh properties and compressive strength of RCA concrete if used in quantities not exceeding the dosages set by the manufacturer. Although no studies have been made, it is believed that the

presence of **mineral admixtures** will have no detrimental effects on RCA concrete.

- **Soil and filler materials** are expected to affect RCA concrete the same way as natural aggregate concrete. RCA should therefore not exceed the maximum allowable limits, where available, on contents of organic materials set for natural aggregates.
- **Metals** such as small amounts of reinforcing steel or bits of wire may cause staining or surface damage due to the rusting when close to the surface of RCA concrete. Zinc and aluminium may cause some cracking due to internal expansions or problems due to the release of hydrogen in fresh concrete. However Screening out and removal processes used during the production of RCA make it very unlikely that significant quantities of steel or other metals remain in RCA.
- **Glass** can be a dangerous contaminant because it can take part in alkali silica reactions.
- **Brickwork and lightweight concrete**, when present in RCA in high proportions can have an effect on the properties of the concrete. This effect is more pronounced with the durability properties of the concrete. The lower density of these materials when compared to concrete should make easy their removal from the RCA.
- **Particles damaged by weathering or fire**, such as RCA particles severely damaged by alkali or sulphate reactions, frost or other weathering agents, fire or other deleterious physical or chemical agents can have weak mechanical properties.
- **Particles susceptible to frost damage and alkali reactive aggregate particles**

  The natural aggregates used in the original concrete may be mechanically strong, but physically or chemically unsound. This may not have caused any problems in the original concrete, for example because of mild exposure, however when the RCA particles made from this concrete are introduced in new concrete exposed to severe exposure might give rise to problems. It is in particular, RCA particles which are susceptible to frost damage or alkali silica reactions which should be the cause of concern.

- **Industrial chemicals and radioactive substances**

  RCA particles derived from concrete used in chemical or industrial plants, may be contaminated by malodorous, toxic or radioactive substances and oil or water soluble chemicals which could affect the properties of concrete and also be a health hazard. Therefore, concretes from any plant where chemical or radioactive materials have been used should be considered suspect until proven innocuous.

2.3.3 RCA CONCRETE PROPERTIES

2.3.3.1 Fresh concrete

Workability

Hendricks and Pieterson [26 f] reported that the workability of concrete with a high level of aggregate replacement is less due to the high water absorption and angularity of the RCA particles. The authors found that adding water may increase workability, but this alters the water cement ratio which can in turn affect the strength and durability of the resulting concrete. Another alternative is to increase both water and cement, thereby keeping the water cement ratio constant or use superplasticisers which can be enough to improve the workability of the RCA concrete.

Dhir et al [22] and Limbachiya et al [26 g] found that the slump of RCA concrete decreased with an increase in the RCA content in the mix, however the values were within the specified tolerances. This is mainly due to the increasing amount of the high absorption attached cement paste with the increase of RCA in the mix. For the RCA and natural aggregate mixes to achieve the same slump, it was reported that an additional 5 l/m^3 of water was required in the RCA mixes.

Mulheron and O'mahony [20 m] found that RCA concrete when compared to natural aggregate concrete produced harsher and less workable mixes with lower values of compaction factor and slump and longer vebe times. It is thought that this was due to the more angular shape and rougher surface of RCA which resulted in an increased amount of inter particle interaction and locking. In the same study, when mixed demolition debris which consisted of rounder and less abrasive particles were used, the RCA concrete had a similar workability to the control. Similar findings were reported in other studies [20 n, 21].

Kawamura and Tori [20 n] found that due to the angularity of RCA particles which influences the consistence of concrete, RCA concrete requires 10 to 15% of extra water to obtain the same slump as the control concrete.

Yamato et al [20 o] found that using RCA with rounder particles than the natural aggregates used in the control mix resulted in the RCA concrete mixes having a higher slump than the natural aggregate mixes. This appears to confirm that the shape and texture of aggregates influences the workability of concrete.

Mukai et al [44] reported that RCA concrete required approximately 10 l/m^3 or 5%

more free water than control mixes produced with corresponding natural aggregates in order to achieve the same slump. Similar results were found by [21, 24, 45, 46, 62].

In another study, Ravindrajah and Tam [20 b] found that for a constant degree of workability, the water requirement for recycled aggregate concrete is about 10% more than that for a similar natural aggregate concrete. Another study [20 d] showed that to achieve an equal slump to natural aggregate concrete, an increase in the water content of 6% was necessary in RCA concrete.

Meinhold et al [92] reported that the water absorption up to the first 10 minutes by RCA is the amount that lowers the water during the concrete mixing process and therefore should be used to calculate the effective water/cement ratio.

Many studies looked at the effect of the moisture state of RCA prior to mixing on the fresh properties of concrete. Kashino and Takahashi [20 c] found that pre-wetting of recycled aggregates and adjustment of the water content was necessary when making ready mix recycled aggregate concrete. This was confirmed by Morlion et al [20 p] who reported that in order to prevent a rapid decrease in concrete workability of RCA concrete used for a new lock in the Belgian port of Antwerp, pre-soaking the RCAs used for one hour prior to mixing was a very efficient solution.

Knights [26 h] found that the workability of RCA concretes, when compared to similar concretes with natural aggregates, appears unchanged provided that the recycled aggregates are pre-soaked before mixing.

Dhir et al [22] examined the effects of aggregate conditions used in practice, wet and dry aggregates pre-treatments were investigated for their effect on the fresh properties of RCA concrete. Soaking aggregates in water for 24 hours showed a slight improvement in the fresh properties compared with corresponding mixes with dry aggregates where supplementary water was added to allow for aggregate absorption. This suggests that the influence of RCA preconditioning on the properties of fresh concrete is relatively minor.

Poon et al [38] studied the effect of moisture state (oven dried (OD), air dried (AD) and saturated surface dry (SSD)) of natural aggregates and RCA on the initial slump. When RCA are used in the air dried and the oven dried states at a high percentage replacement level, the initial slump increases. This is due to the higher amount of water added to the mix for saturating the aggregates leading to a larger amount of initial free water used in the mix. This is not surprising as the initial free water content influences strongly the initial slump. When the recycled aggregates are used in the saturated surface dry state, the replacement of natural aggregates by recycled aggregates resulted only in a small change in the initial slump of the concrete.

Loss of workability and setting times

Dhir et al [22] measured the effect of RCA on the retention of workability by measuring the compacting factor at 30 mins intervals up to 150 mins after mixing. The results obtained show that the loss of workability was of a uniform nature and a little less for the RCA mix compared with the NA mix.

Ravindrajah et al [49] and Hansen and Narud [21] found that the setting times of recycled aggregate concrete are slightly less than natural aggregate concrete.

Karaa [48] found that concrete made with dry RCA looses its workability and sets faster than concrete made with wet RCA. Poon et al [38] studied the effect of moisture state (oven dried, air dried and saturated surface dry) of natural aggregates and RCA on the initial slump and the rate of slump loss of concrete. Using recycled aggregates in OD state resulted in a quicker slump loss whilst using recycled aggregates in the SSD state resulted in a slower process of slump loss. Recycled aggregates in the AD state did not have a significant effect on the slump loss of concrete.

Kasai [47] found that the fineness modulus of RCA gradually decreases with the time of mixing in the concrete mixer thus increasing the fines content in the fresh RCA concrete which in turn leads to a decrease of the slump with the time of mixing in the concrete mixer. This is due to the attached cement paste being rubbed off the RCA particles when being mixed. Similar findings were reported in other studies [20 i, 22].

Stability

Poon et al [38] reported, based on observations during mixing and casting, that when RCA are used in high percentages (higher than 50%), the concrete mixtures are less cohesive when compared to concrete prepared with natural aggregates.

Dhir et al [22] and Limbachiya et al [26g] also found the concrete mixes with more than 50% coarse RCA to be harsher, less cohesive and exhibited a higher segregation tendency when compared to the corresponding NA concrete. A reduction in bleed water in the mixes with high RCA proportions beyond 50 mins was observed; the authors attribute this to the increase in fines in the mixes which comes from the rubbing off the attached cement paste from the surface of the RCA during mixing.

Hansen and Narud [21] reported that the RCA mixes are more cohesive the lower the quality of the recycled aggregates. The improved cohesion is attributed to the attrition of old mortar attached to the RCA which generates more fines during the mixing process.

Dhir et al [22] and Limbachiya et al [26g] carried out tests to improve the stability of concrete mixes containing 100% RCA. They reported that the problems caused by the inclusion of RCA could be overcome by using filler material, such as the coarse PFA to BS 3892 part 2 used in their study. Using Filler material in addition to superplasticiser in concrete containing 100% coarse RCA allowed a substantial reduction in water content without any adverse effect on the fresh properties. The results showed that the RCA mixes were more easily compacted, exhibited little bleeding and enabled a smooth trowelled surface finish to be achieved. These beneficial effects improved with increasing filler content within the range used. Similar results were reported by Wainwright et al [35 e] who investigated the effect of PFA when used as a filler material on fresh properties of RCA concrete.

2.3.3.2 Engineering properties

Compressive strength

The data available from studies looking at the effect of RCA on the compressive strength of concrete show that the strength of RCA concrete is somewhat lower when compared with the strength of the control mixes made with conventional aggregates. The compressive strength of the concrete was found to decrease with the increase of RCA content in the mix. [20 b, 20 h, 22, 26 g, 31, 51 - 54, 95].

Hansen [51] reviewed the findings from several investigations by Japanese researchers looking at the effect of RCA on the compressive strength of concrete. Generally, up to 30% replacement by weight had no effect on the compressive strength of RCA concrete. However the compressive strength of concrete starts decreasing gradually beyond this limit.

Dhir et al [22] tested the compressive strength of concretes made with different contents of RCA derived from concretes from different sources having different strength. They found that using up 30% RCA as a replacement for natural aggregates had no effect on the strength development but thereafter reductions in the strength increased with an increase in the RCA content. No significant variation was found in the strength of the different concretes made with the RCA from the different sources used in the study at a given RCA content.

A study by Poon et al [38] found that concrete made with RCA derived from high strength original concrete achieved a higher strength than concrete made with RCA derived from a low strength original concrete. Similar findings reported by another study [26 a] show the same trend.

Hansen and Narud [21] found that the compressive strength of RCA concrete depends on the strength of the original concrete and the strength of the RCA concrete when other factors are essentially identical. If the strength of the original concrete is the same or higher than the required strength for the RCA concrete, then the strength of the RCA concrete can be as good or higher than the design strength. If the strength of the original concrete is lower than the required strength for the RCA concrete, then the strength of the RCA concrete is lower than the design strength. Similar findings were reported by another study [55].

Several studies also reported that the reduction in strength was more noticeable in high strength RCA mixes using RCA derived from a lower strength original concrete rather than in low strength RCA mixes using similar RCA [20 d, 20 i, 26 a, 26 h, 30, 52, 96]. Figure 2.7 shows the influence of the strength of original concrete on the compressive strength of RCA concretes with various w/c ratios from a study by Dosho et al [96].

Chen et al [52] suggested that the main reason behind this phenomenon is that the strength of the paste greatly increases at low water cement ratios. According to the composite material theory, the RCA becomes the weak material and its bearing capacity is smaller thus leading to a decrease in concrete strength. RCA therefore behaves like lightweight aggregate in concrete. Nevertheless several studies reported that it is possible to obtain RCA concrete with higher compressive strength than the original concrete [20 d, 21, 35 a, 36, 45, 56, 96].

Dosho et al [96] reported that in addition to the compressive strength of the original concrete, the compressive strength of RCA concrete is also influenced by the crushing value and the water absorption capacity of the RCA. As the crushing value and absorption of the RCA increased, the compressive strength of the RCA concrete decreased. Similar findings were reported in another study [38]. Meinhold et al [92] reported that the difference in the strength between RCA and NA concrete depends on the quality of the RCA and more specifically its porosity. As it is well known that the w/c ratio and strength of the original concrete influence the properties of RCA, the findings of these studies seem to confirm the suggestion that the w/c ratio or strength of the original concrete influence the compressive strength of RCA concrete.

At the macroscopic level, concrete is a composite material consisting of discrete aggregates dispersed in a continuous cement paste matrix. As with other composites, the bond between these two major components influences the mechanical performance of concrete. Concrete therefore is a three phase system, this system comprises the coarse aggregate, the cement matrix and the interfacial zone between the aggregates and the cement matrix, sometimes called the interfacial transition zone (ITZ) [59]. The observation that cracking leading to the failure of concrete is initiated at the interfacial zone and that at failure the crack pattern includes the interfacial zone points to the importance of this part of the concrete [78]. Generally the interfacial zone is regarded as the weak link in concrete [59].

The structure of RCA concrete is different when compared to natural aggregate concrete. RCA concrete has two ITZs, the first is between the RCA and the new cement paste (New ITZ) and the second is between the original aggregates and the attached cement paste from the original concrete (Old ITZ). Figure 2.8 shows the different interfaces found in RCA concrete.

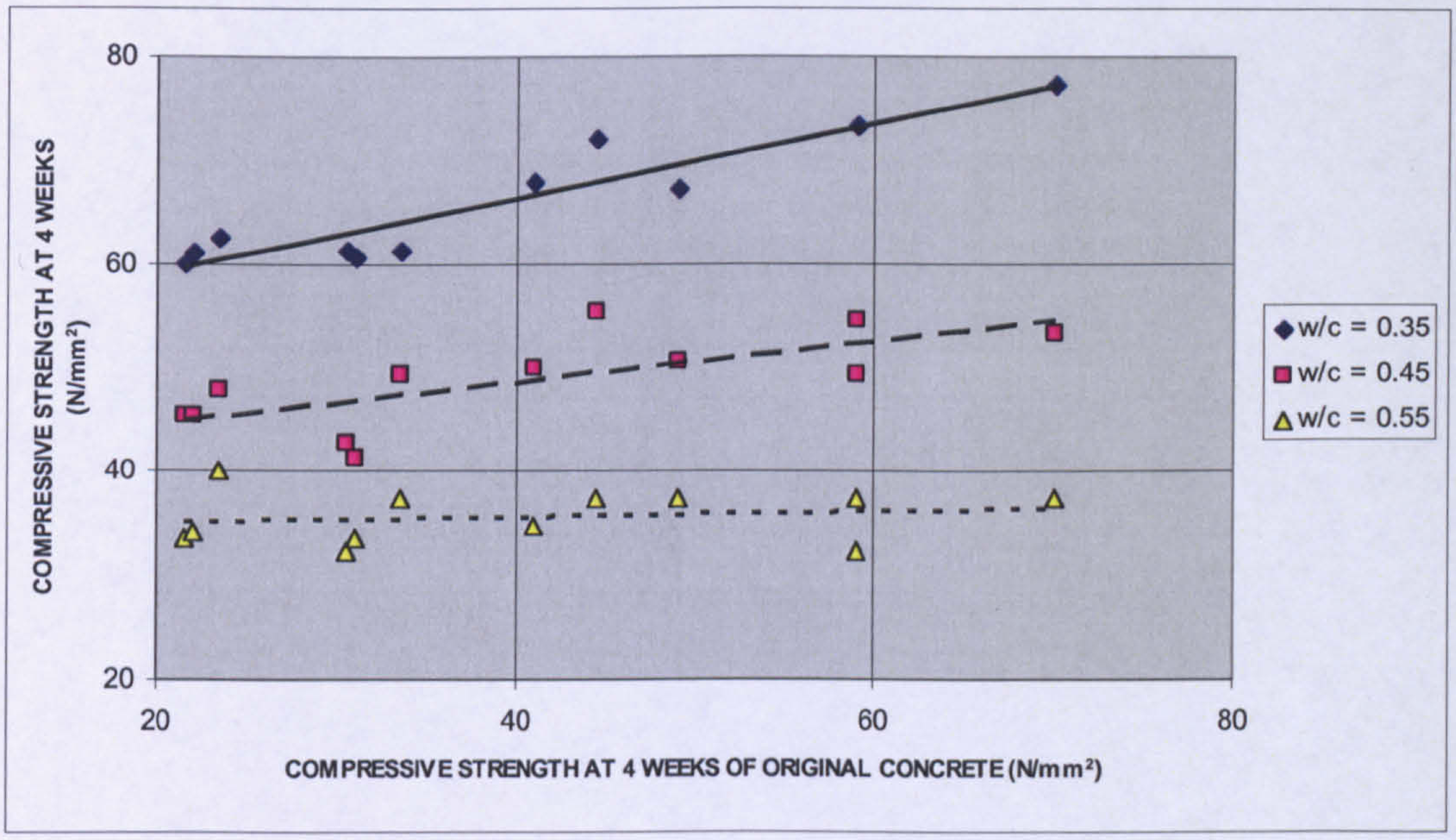


Figure 2.7 Relationship between the compressive strength of original concrete and the compressive strength of RCA concrete by [96].

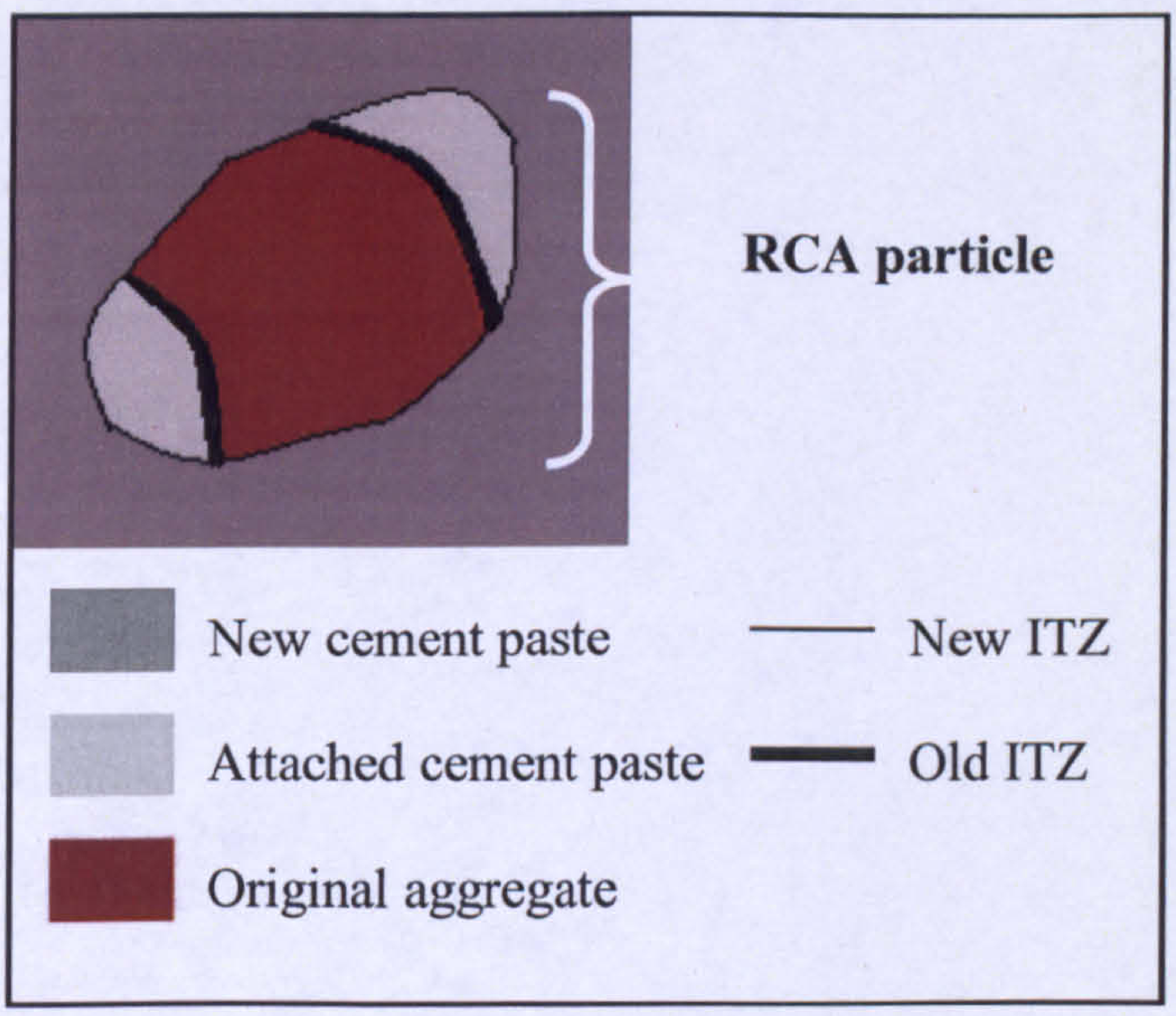


Figure 2.8 Cross section of RCA concrete showing RCA particle surrounded by the new cement paste.

Poon et al [39] reported that the interfacial zone of RCA concrete will be different from that of the natural aggregate concrete. When recycled aggregates with different properties are used in preparing concrete, different cement aggregate interfacial microstructures will results. It was found through, SEM observations, that the interfacial zone between RCA derived from normal strength concrete and the new cement paste consisted mainly of loose particles and was highly porous. For concrete made with RCA derived from high strength concrete, the new interfacial zone was barely distinguishable and was much denser resulting in a stronger bond and therefore higher compressive strength [39].

Ryu [30] used the Vickers hardness test to assess the strength of interfacial zones in the natural aggregate and RCA concrete. He found that the Vickers hardness in the aggregate vicinity increases, as the water cement ratio of the concrete decreases. The Vickers hardness of the ITZ of natural aggregate concrete and the new ITZ of RCA concrete were found to be almost the same. The results of this study [30] show that the strength of concrete depends on the relative quality of the old and new ITZ in RCA concrete. When the quality of the new ITZ is inferior to that of the old ITZ, the strength characteristic of the concrete receives the effect of the w/c ratio of the concrete without receiving the effect of the quality of recycled aggregate. Also when the quality of the new ITZ is better than the old ITZ, the strength characteristic of the concrete receives the effect of the old ITZ, namely the effect of the quality of the RCA.

Dosho et al [96] compared the compressive strengths at 1, 3 and 13 weeks of concrete made with RCA derived from original concretes made with 3 types of natural aggregates (Hard crushed sandstone, crushed limestone and river gravel). The results of the study show that the different types of original aggregates had no influence on the compressive strength of the RCA.

Nagataki and Lida [93] compared the compressive strength of concrete made with RCA derived from original concretes with different strengths and 1 month old. Three types of RCA were manufactured from each original concrete. The first type was manufactured using a jaw crusher and an impact crusher, the second and third types were crushed further using an improved crusher with a strong grinding effect once and twice respectively which resulted in decreasing the amount of cement paste in the RCA. It was found that the level of crushing had no appreciable effect on the compressive strength of RCA concrete.

Nagataki and Lida [93], in the same study compared the compressive strength of concrete made with RCA derived from a high, a medium and a low strength original concretes of different ages (1 month, 1 and 2 years). It was found that the age of the concrete at the time of crushing had no major effect on the compressive strength of concrete made with RCA derived from the high and medium strength concrete. On the other hand the low strength concrete made with RCA reclaimed at a year or 2 years had a higher compressive strength when compared to concrete made with RCA reclaimed at 1 month.

Hansen and Narud [21] found that there was little or no difference in compressive strength of RCA concrete produced with the aggregates in air dry or saturated surface dry condition when the free water cement ratios of the fresh concretes were the same.

Barra de Oliveira and Vasquez [57] studied the effect of three different recycled aggregates' moisture conditions (dry, saturated and semi-saturated) on the compressive strength of concrete and found the concretes produced using recycled aggregates had very similar compressive strength irrespective of the degree of moisture of RCA. Only a slight decrease is to be observed in concrete made in dry and saturated recycled aggregates respectively.

Poon et al [38] examined the compressive strengths of concretes made with air dry, Oven dry and surface saturated dry RCA. The RCA concretes had more or less similar strengths with the AD RCA achieving the highest strengths. The OD RCA concrete had a higher strength than the SSD RCA concrete. It is suggested that this might be due to the fact that when the OD RCAs are used, water may move from the cement paste towards the RCA resulting in an accumulation of cement particles which will in turn result in the formation of stronger bond between the new cement paste and the RCA particles. In contrast, when SSD RCAs are used, water may move from the particles toward the cement matrix creating a high w/c ratio at the interfacial zone which may result in a weaker bond.

Yanagi et al [20 1] found that there was a relationship between the quantity of impurities and the compressive strength of RCA concrete. It was found that increasing the amount of impurities causes a strength reduction in both air and water cured RCA concrete.

A report [58] by Japanese researchers showed that impurities had a detrimental effect on the compressive strength of concrete. The magnitude of the reduction in compressive strength caused by impurities was in the following order: PVAc paint > Asphalt > Gypsum Hydrate > Wood > Soil > Plaster.

Yanagi et al [35 d] studied the effect of different impurities on the compressive strength of RCA concrete. It was found only asphalt, plastic tile had an effect on the compressive strength of both air and water cured concrete with 100% RCA content. The impurities had no effect on the compressive strength of concrete at lower values of RCA replacement.

Chen et al [52] reported that washing away the impurities, powder and harmful materials from the RCA's surfaces results in a better bond effect. Concrete made using washed recycled aggregates had a higher compressive strength (30% and 10% lower than normal concrete for high and low water cement ratios respectively) than concrete using unwashed recycled aggregates (40% and 25% lower than normal concrete for high and low water cement ratios respectively). It was also found that the greater the brick and tile content in the recycled aggregates, the lower the compressive strength of the recycled aggregate concrete. Another study [20 l] found that washing the aggregates prior to use helped improve the compressive strength of RCA concrete.

Bairagi et al [97] found that the mix design method can influence the compressive strength of concrete after comparing the effect of different mix design procedures. Tam et al [59] showed that using a "two stage mixing approach" for making concrete containing up to 30% RCA concrete can help improve the strength of concrete by developing a stronger interfacial zone between the RCA and the new cement paste. This approach consists of mixing the fine aggregates and recycled aggregates in the mixer for 60 seconds then adding half of the water and mixing for another 60 seconds before adding the cement and mixing the contents again for 30 seconds then adding the remaining water and finally mixing for 120 seconds. This method divides the mixing process into two parts and proportionally splits the required water into two parts which are added at different times. The first stage of mixing, allows the formation of a thin layer of cement slurry on the surface of the RCA which will permeate into the porous attached cement paste of the RCA filling up any cracks and voids.

Yanagi et al [20 l] found that the initial curing environment has an effect on compressive strength of concrete. Concrete containing 100% RCA and natural sand cured in water at 20°C had a lower strength than when cured in air at 20°C and 60% RH. A later study [35 d] showed that concrete containing 100% RCA and natural sand cured in water at 20°C had a higher strength than when cured in air at 20°C and 60% RH. These latter results are in agreement with the findings of other studies [35 f, 40].

Dhir et al [22] examined the effect of air and water curing on the strength of conventional and RCA concretes and found the two curing conditions had exactly the same effect on both types of concrete. Concrete specimens cured in water had higher 28 day cube strengths when compared to air cured specimens.

Poon et al [53] investigated the effects of steam curing on the hardened properties of RCA concrete. The results show that the steam cured RCA concrete gained strength rapidly in the first 3 days and the corresponding strength was much higher than that of water-cured RCA concrete. However the situation was reversed beyond 28 days of curing. The 28 day compressive strength of concrete containing 100% RCA was the least affected by steam curing.

Several studies reported that the rate of strength development is similar for concretes regardless of whether or not they contain RCA [20 i, 24, 35 e, 36, 46, 60].

Studies have shown that an adjustment of the water cement ratio is required to compensate for the loss of strength in RCA concrete for a designed strength. This can be done by either increasing the cement content in the mix or reducing the water content [22, 95].

Similar observations were reported by Ravindrajah and Tam [20 b] who added that the use of pozzolanic additions such as fly ash and silica fume can also help in compensating the loss in the strength of RCA concrete. Similar findings were reported in a study [20 o] looking at the effect of the use of silica fume on RCA concrete.

Flexural strength

Ravindrajah and Tam [24] stated there is no great difference between the flexural strength of 100% coarse RCA concrete and NA concrete. Ikeda et al [20 i] also found 0% reduction in the flexural strength of RCA concrete compared to NA concrete.

Ravindrajah and Tam, reported in another study that the flexural strength of recycled aggregate concrete is consistently 10% lower than for NA concrete [49]. Several other studies also reported a reduction in flexural strength in RCA concrete [48, 54, 61].

Dhir et al [22] found a reduction in flexural strength in RCA mixes when compared to normal concrete and stated that this can be accounted for by the reduction in strength of the concrete due to the use of RCA.

Japanese researchers [25] found that the flexural strength of recycled aggregate concrete is somewhere between 1/5 and 1/8 of its compressive strength. This is similar to conventional concrete. However no experimental data are presented.

Kikuchi et al [35 a] reported that RCA concrete had a higher flexural strength than normal concrete in the case of high strength mixes (above 40 N/mm^2), however the opposite was observed for low strength mixes (below 40 N/mm^2).

Barra de Olivera and Vasquez [57] examined the flexural strength of RCA concrete made using dry, semi-saturated and saturated RCA. They found that the flexural strength of all RCA concretes was approximately 10% less than concrete made with conventional concrete except with saturated RCA which exhibited a higher reduction in flexural strength. The effect of the coarse RCA moisture on the flexural strength of concrete is illustrated in Figure 2.9 taken from the same study.

Chen et al [52] reported that the flexural strength of concrete made using washed recycled aggregates was higher when compared to the flexural strength of concrete using unwashed recycled aggregates regardless of the water cement ratio. The reduction in the flexural strength of RCA concrete when compared to conventional concrete was more obvious in the low water cement ratio mixes. With high water cement ratios (> 0.67), the flexural strength of RCA concrete made with washed RCA was higher than the reference concrete while the flexural strength of RCA concrete made with unwashed RCA reached up to 90% of that of normal concrete. The authors explain this phenomenon by the fact that under high water cement ratio conditions, the interface between the aggregate and the paste becomes a weak interface. The wash process cleans the RCA's interface thus leading to the enhancement of the bond between the RCA and the new cement paste.

Limbachiya et al [26 g] examined the flexural strength of equal strength mixes and found that the results show a negligible difference between RCA and NA mixes regardless of the amount of RCA used. Dhir et al [22] found that there exists a good correlation between the flexural and compressive strength of concrete regardless of the RCA content. Figure 2.10 shows the relationship between 28 day strength and flexural strength of RC 30 designated mix concrete with different RCA contents from the study by Dhir et al [22].

Modulus of elasticity

Due to the large amount of old mortar with a comparatively low modulus of elasticity which is attached to the original aggregate particles in recycled aggregates, the modulus of elasticity of recycled aggregate concrete is always lower than that of the corresponding control concrete made with conventional aggregates.

A review of the several studies on the effect of RCA on the modulus of elasticity of concrete reported that a reduction in the modulus of elasticity can be expected with an increase in the coarse RCA content [20 c, 31, 35 d, 53].

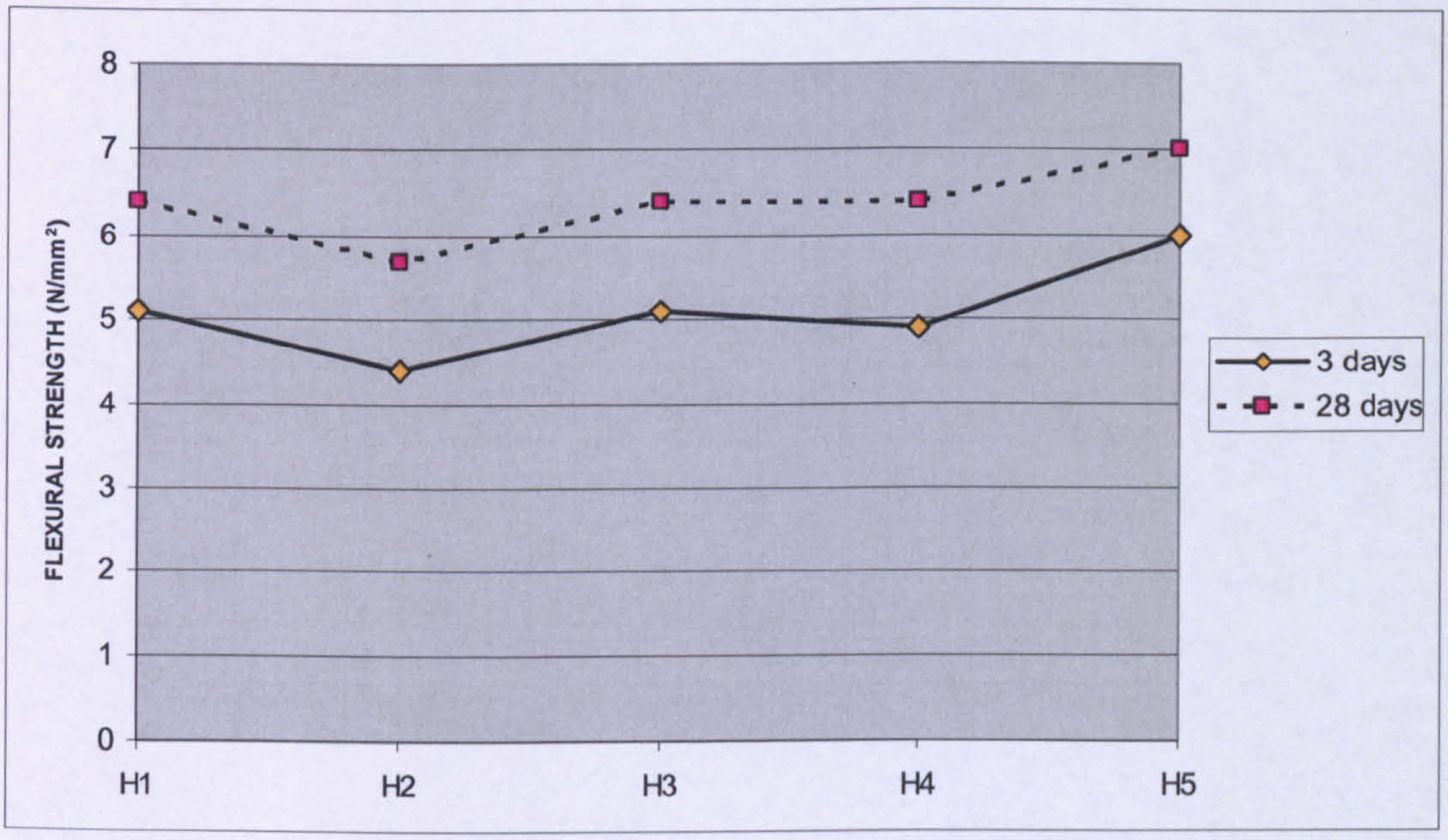


Figure 2.9 Flexural strength for concrete made with coarse RCA with different moisture conditions [H1: RCA, H2: saturated, H3: semi saturated (89.5%), H4: semi saturated (88.1%), H5: natural aggregate) [57].

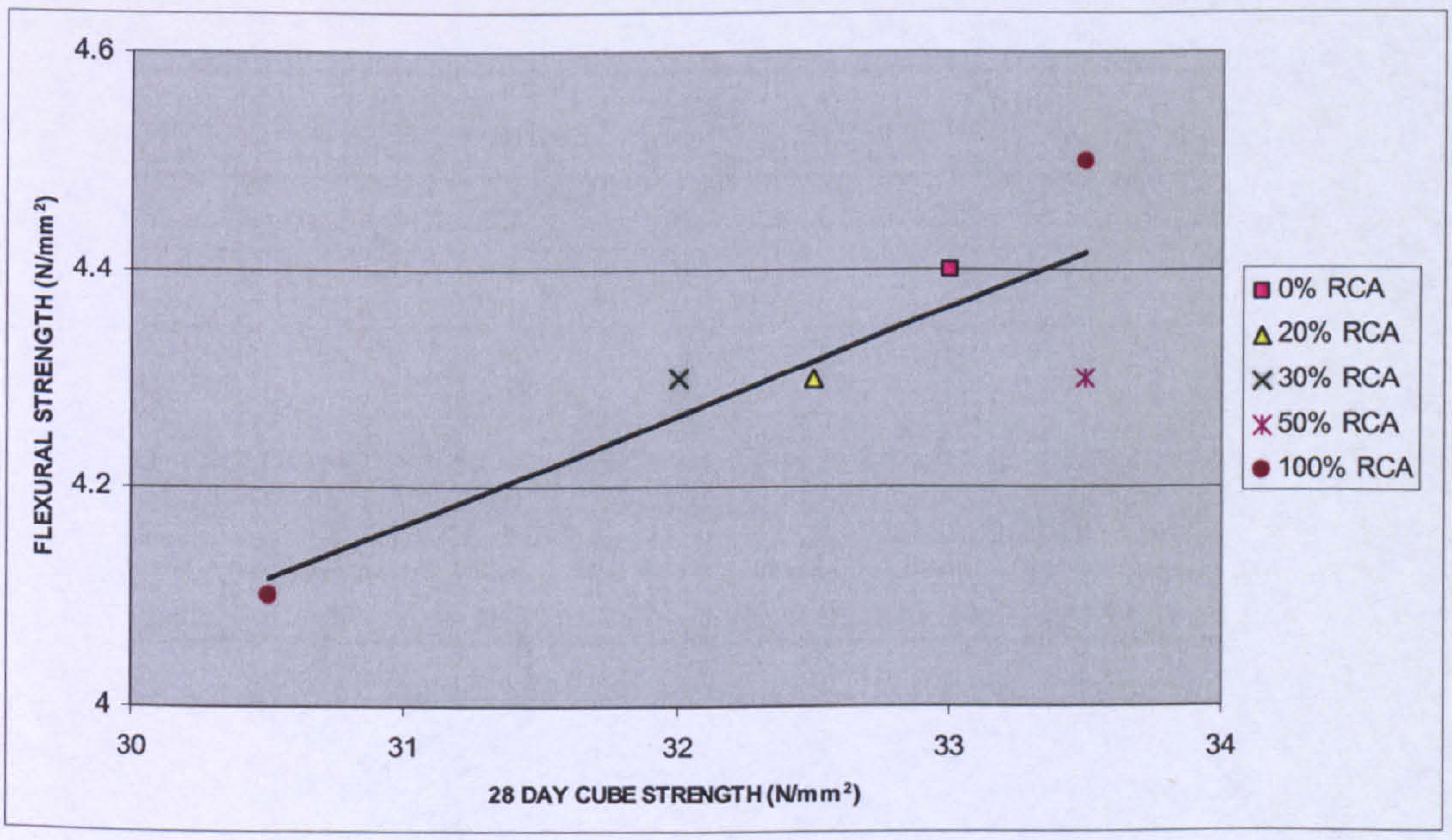


Figure 2.10 Relationship between 28 day strength and flexural strength of RC 30 designated mix concrete cured in water at 20°C with different RCA contents (RCA source: demolished concrete structure) [22].

Some studies have shown that up to 30% replacement of natural aggregates by RCA had no major effect on the modulus of elasticity of concrete. However, the reduction in the modulus of elasticity increased gradually beyond this limit with the increase in the RCA content of the mix [20 c, 22]. Figure 2.11 shows the effect of increasing the RCA content on the modulus of elasticity of concrete from a study by Kashino and Takahashi [20 c]. The reduction in the modulus of elasticity in RCA concrete as reported by several studies could be up to 40% when compared with a corresponding NA concrete [20 b, 20 c, 20 f, 20 j, 20 m, 31, 43, 51, 52, 62, 63, 91, 96].

Hansen [51] after reviewing the findings of several studies concluded that the low modulus of elasticity of RCA results in a RCA concrete with a low modulus of elasticity comparable to that of conventional lightweight aggregates concrete.

Kakizaki et al [20 f] also reported that the modulus of elasticity of RCA concrete shows the same tendencies as for lightweight aggregate concrete and attributed this to the state of bonding between the RCA and new cement paste, and cracks in the cement paste.

Hansen and Boegh [63] have found that concrete made with RCA derived from a high strength original concrete achieves a higher modulus of elasticity than concrete made with RCA derived from a low strength original concrete. Similar findings were reported by Dosho et al [96], these are illustrated in Figure 2.12.

Dosho et al [96] also found that in addition to the compressive strength of the original concrete, the modulus of elasticity of RCA concrete is also influenced by the crushing

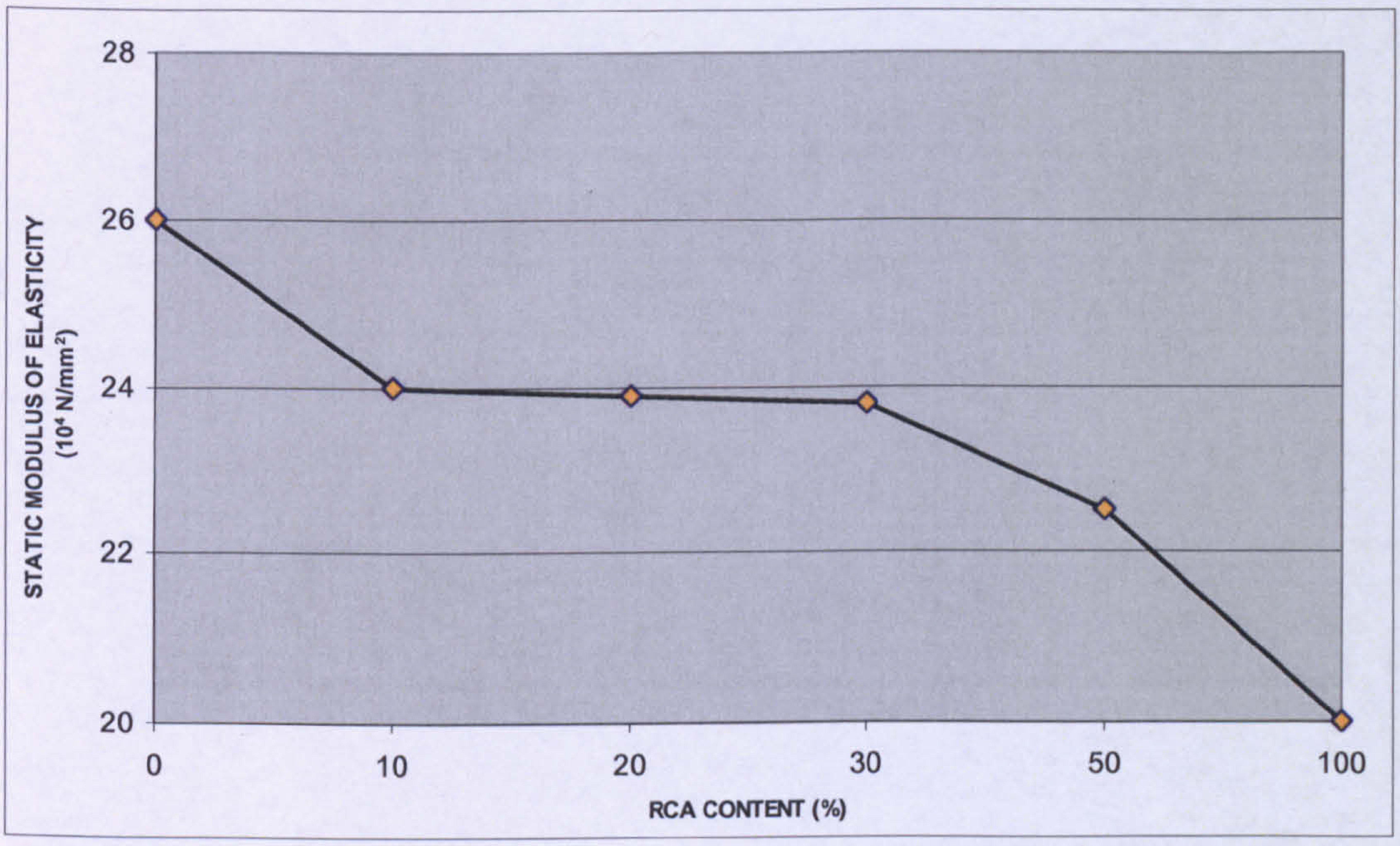


Figure 2.11 Static modulus of elasticity of concrete with various RCA contents [20 c].

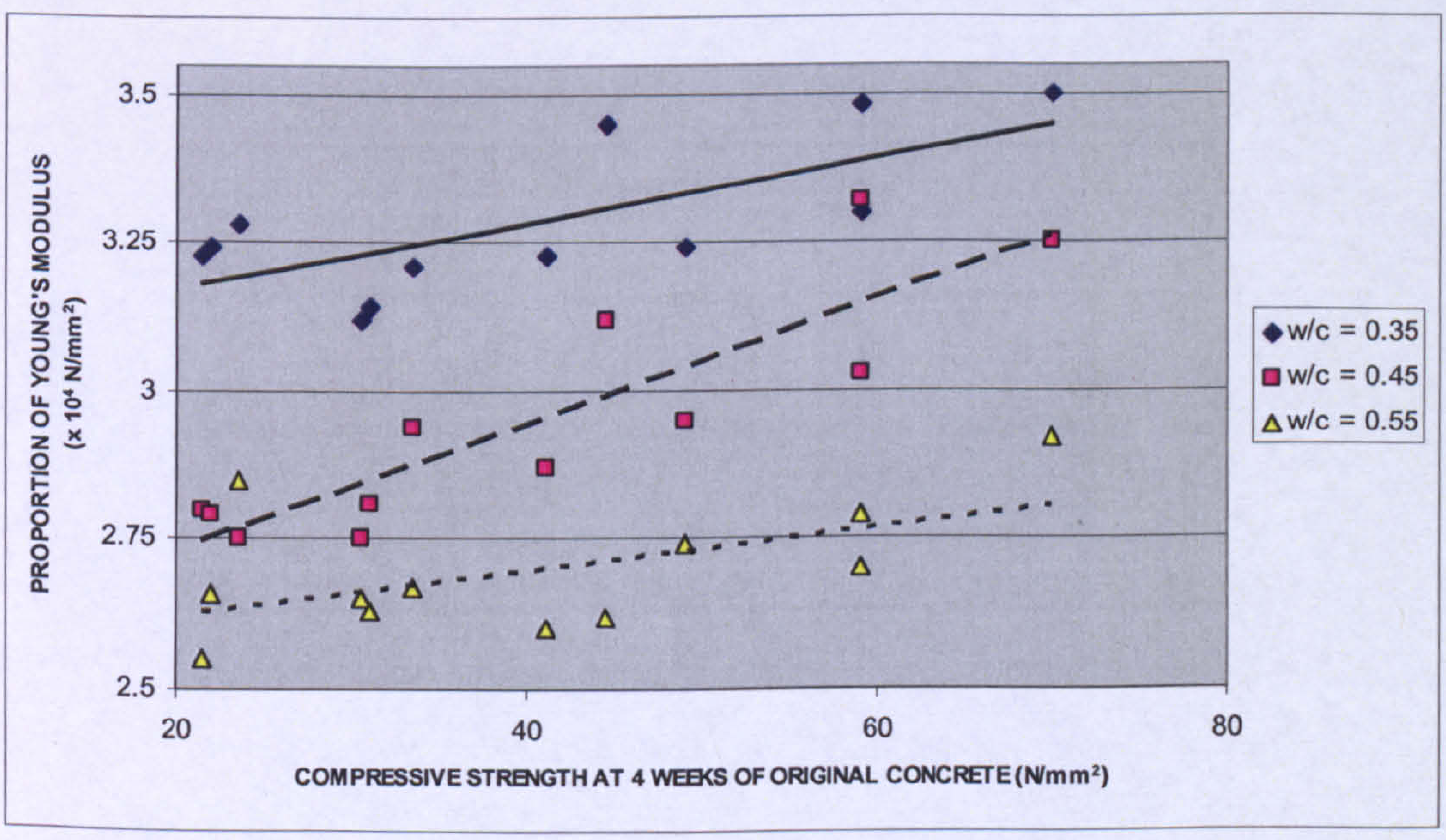


Figure 2.12 Relationship between the compressive strength of original concrete and the young's modulus of RCA concrete [96].

value and the absorption of the RCA. This is not surprising as it is well known that there exists a correlation between the compressive strength of the original concrete and certain mechanical and physical properties of RCA: as the compressive strength of the original concrete decreases, the crushing value and absorption of the RCA increases.

Butler and Machado Jr [91] reported that the modulus of elasticity of RCA concrete was 10 to 22% lower than normal concrete due to the larger porosity of RCA when compared to natural aggregates. Meinhold et al [92] also reported that the modulus of elasticity values of RCA concrete decrease with the increase in the porosity of RCA. This is again expected as a high porosity is generally associated with concrete with high water cement ratio and low strength.

Karaa [48] found that using dry or wet RCA in concrete with same free water cement ratio had no effect on the modulus of elasticity of RCA concrete. Another study [21] reported similar findings.

Barra de Olivera and Vasquez [57] examined the modulus of elasticity of RCA concrete made using dry, semi-saturated and saturated RCA. They found that the values of the modulus of elasticity of all RCA concretes were equally lower than concrete made with NA regardless of the moisture state of the RCA.

Chen et al [52] reported that the elastic modulus of concrete made using washed recycled aggregates and unwashed recycled aggregates were similarly low when compared to normal concrete regardless of the water cement ratio.

Yanagi et al [35 d] found that the modulus of elasticity of RCA concrete cured in water for 28 days to be lower when compared to natural aggregate concrete. This reduction increased with the increase of RCA in the mix. The static modulus of elasticity of RCA concrete cured in water with impurities was a little larger than that of no impurities. The reasons for this behaviour are unknown. RCA concrete cured in air behaved similarly except when natural aggregates were replaced by 100% RCA containing Plastic tiles, RCA containing Asphalt and RCA containing a blend of impurities in equal quantities which resulted in a slightly higher reduction in the modulus of elasticity of the RCA concrete compared to the other mixes in the study.

Poon et al [53] investigated the effects of steam curing on the hardened properties of RCA concrete. It was found that the values of modulus of elasticity of steam cured RCA concrete was lower than that of the water cured RCA concrete. The detrimental effect of steam curing at 28 days was diminished as the replacement level of RCA increased in the mix. The decrease in the modulus of elasticity due to the inclusion of RCA was more significant for normal water curing compared to steam curing. It was reported in another study [49] that for medium strength water cured concrete, the reduction in the modulus of elasticity was about 25% compared to 35% for air cured concrete.

Ravindrajah and Tam [24] found that the difference between the modulus of elasticity of RCA concrete and conventional concrete increases with the increase in the strength of the concretes.

It was found that there exists a linear relationship between the compressive strength and modulus of elasticity of RCA concrete; however this relationship is different from that of conventional concrete as the young's modulus of RCA concrete is lower than that of concrete with natural aggregates at the same compressive strength [20 b, 20 j, 22, 24, 98].

Shulz [20 q] in has demonstrated that in addition to the compressive strength of RCA, a relationship exists between the density of RCA and its elastic modulus.

Henrichsen and Jensen [99] found that the stress strain relationship for recycled aggregate concrete is similar in shape to that of ordinary concrete. Hansen [51] stated that as a result of this finding, structures from RCA concrete should be designed according to the theory of plasticity just like structures made from ordinary concrete. Limbachiya et al [26 g] examined the modulus of elasticity of equal strength RCA mixes and found that the results show a negligible difference between RCA and NA mixes. Another study [20 b] reported that for equal strength mixes, RCA concrete shows lower values for modulus of elasticity than those of conventional concrete.

Long term deformations

- ***Drying shrinkage***

Drying shrinkage of RCA concrete is always larger than in concrete made with natural aggregates [20 e, 20 j, 42, 53, 56, 95]. Research has shown that the drying shrinkage in RCA concrete increases with an increase in the content of RCA. This is not surprising considering that RCA concrete contains more cement paste than conventional concrete and that drying shrinkage generally increases with an increase in the cement paste content in concrete [20 e, 35 a, 53].

Gomez Soberon [100] analysed the shrinkage of RCA concrete using different percentages of replacement of natural aggregate with RCA (0, 15, 30, 60 and 100%) with test conditions of 50% RH and 20°C. The results showed an increase of the shrinkage values of RCA proportional to the amount of RCA used as a replacement. The author reported that the increase in the shrinkage values of RCA concrete corresponds to the high porosity and permeability of the RCA compared to natural aggregates.

Butler and Machado [91] attributed the increase in the drying shrinkage of RCA concrete to the lower stiffness of RCA, the great quantity of attached mortar in the RCA which increases the water absorption capacity of the RCA and the fact that RCA used in the study tended to be finer than the natural aggregates used.

Gomez Soberon [100] reported that the increase in the shrinkage values of RCA concrete starts only when the percentage of RCA in the total aggregate content exceeds 30%. Results from another study [26 j] show a similar trend.

Hansen [51], after reviewing a number of studies, stated the drying shrinkage of RCA concrete to be 20 to 70% higher than that of concrete made with conventional aggregates.

Other studies showed that this increase may sometimes exceed 70%. In one study [96], it was found that the drying shrinkage values of RCA concrete to be nearly double those of natural aggregate concrete due to the higher absorption and lower stiffness of the RCA particles.

Hansen and Boegh [63] found the drying shrinkage of RCA concrete was approximately 40 to 60% higher than the corresponding concrete made with conventional aggregates regardless of the mix proportions and the type of RCA used. On the other hand, Kikuchi et al [26 a] found that the compressive strength of the original concrete has an effect on the drying shrinkage of RCA concrete. The RCA concrete's drying shrinkage values increased with the decrease of the compressive strength of the original concrete. Similar findings were reported in other studies [35 a, 96]. The results from one of these studies [35 a] are shown in Figure 2.13.

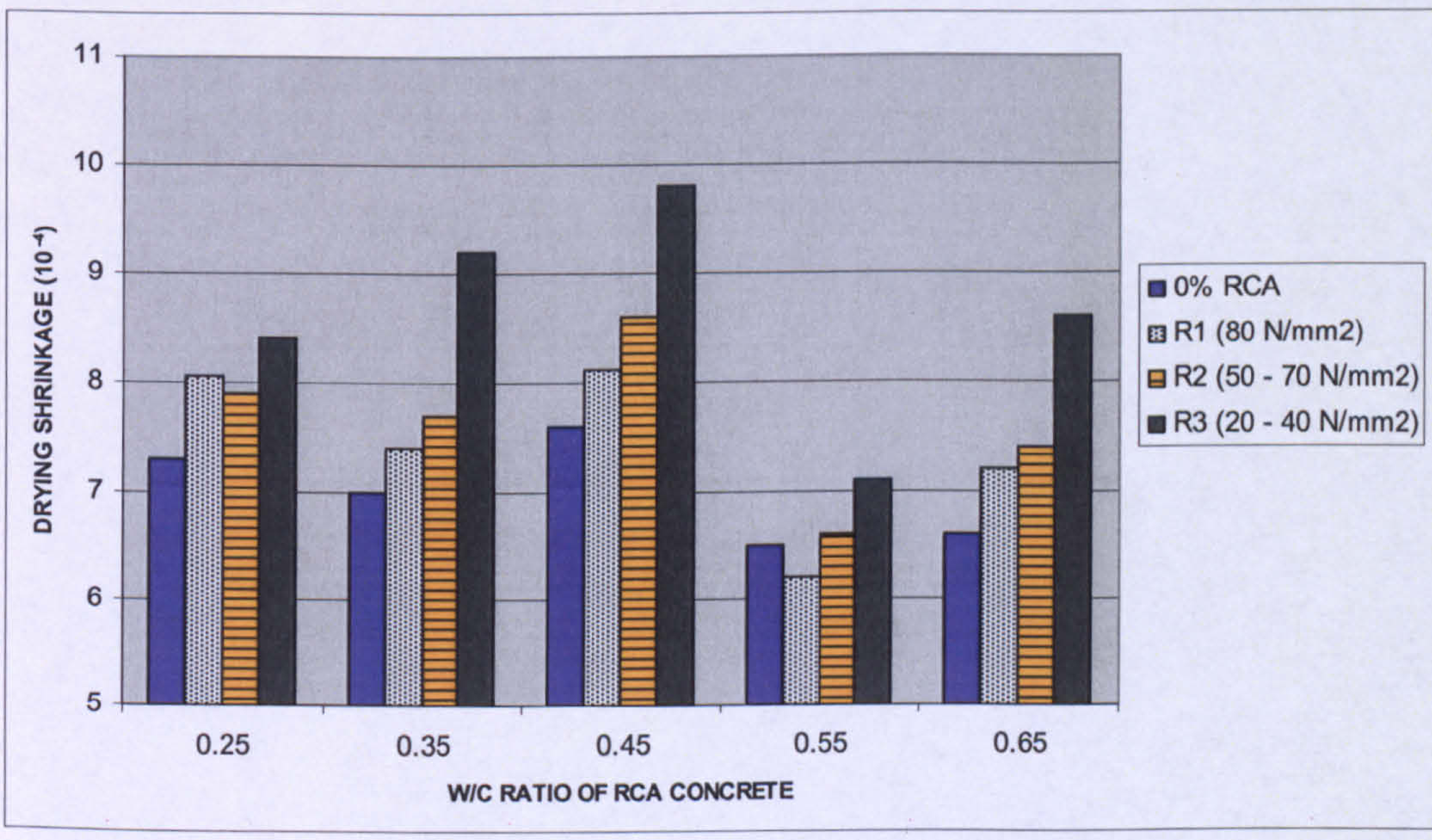


Figure 2.13 Effect of the strength of original concrete on the drying shrinkage of RCA concretes with various water cement ratios [35 a].

Dosho et al [96] found that in addition to the compressive strength of the original concrete, the drying shrinkage of RCA concrete is also influenced by the crushing value and the absorption of the RCA. This is not surprising as several studies found that there exists a correlation between the compressive strength of the original concrete and certain mechanical and physical properties of RCA. Dosho et al [96] showed that as the crushing value and absorption of the RCA increased, the drying shrinkage values of the RCA concrete also increased. Similar findings were reported by another study [101]. Meinhold et al [92] reported that shrinkage values of RCA concrete increases with the increase in porosity of RCA.

Fujii [20 e] compared the shrinkage of concrete made with RCA derived from a 1 month and a 23 year old concrete and found that the shrinkage of concrete which used RCA obtained from the older source was about half the shrinkage of concrete using RCA from the newer source. In this respect, RCA obtained from older concrete is preferable from the view point of shrinkage. If the age of original concrete is younger; the attached cement paste on the RCA is less hydrated and therefore causes larger shrinkage. Fujii [20 e] also reported that the process used in the production of RCA also influences the shrinkage of concrete. A high level of refinement or elimination of the attached cement paste in the RCA results in a reduction of shrinkage. In this study concrete that used RCA crushed twice by a jaw crusher first followed by a threader showed smaller shrinkage than those of other concretes which used RCA crushed once.

Tavakoli and Soroushian [101] reported that dry mixing of RCA prior to the addition of the other mix constituents in the mixer frees the RCA from some of the attached cement paste which may help in reducing the shrinkage of RCA concrete.

A study [95] has shown that the drying shrinkage of RCA concrete can be decreased to the same shrinkage level as the natural aggregate concrete by reducing the water cement ratio of the mix or by using a shrinkage reducing agent as an addition in the mix or through the impregnation of the specimens with the shrinkage reducing agent.

Some studies [24, 64] have shown that the difference between the drying shrinkage values of NA and RCA concrete was greater for higher grade concretes than for low grade concretes. On the other hand, Hansen and Boegh [63] measured the shrinkage of a high strength (w/c = 0.40), a medium strength (w/c = 0.70) and a low strength (w/c = 0.40) RCA concretes and found that the increase in the drying shrinkage of RCA concrete to be generally between 40 to 60% when compared to conventional concrete regardless of the RCA concrete's strength.

Yanagi et al [20 l] found that there was a relationship between the quantity of impurities and the drying shrinkage of RCA concrete. It was found that increasing the amount of impurities causes an increase in the drying shrinkage values of RCA concrete. Washing the aggregates did not seem to have a significant effect on the shrinkage of the RCA concrete.

Yanagi et al [35 d] found that from a wide range of impurities, plastic tile and gypsum increased the drying shrinkage of RCA concrete with a 100% RCA content. Increasing the amount of soil in RCA was also found to increase the drying shrinkage of RCA concrete.

Poon et al [53] investigated the effects of steam curing on the hardened properties of RCA concrete. It was found that the steam curing reduced the drying shrinkage of the concrete compared to normal water curing.

Fujii [20 e] also found that the drying shrinkage values of RCA concrete can be affected when cured in different curing conditions. The results of the study show that concrete cured first in water at 20°C for one week then indoors (at 10–31°C and 53–84% RH) showed the smallest drying shrinkage. RCA concrete cured in a curing room (at 20°C and 50–60% RH) and RCA concrete cured indoors (at 10–31°C and 53–84% RH) showed similarly higher drying shrinkage values.

Meinhold et al [92] found that there was no difference in the time dependent curves for shrinkage of natural and RCA concrete, however the latter developed higher values. These higher values were still in the range of ordinary concrete mixtures.

Sagoe – Crentsil [42] showed that although RCA concrete had higher drying shrinkage values when compared to conventional concrete, the drying shrinkage of all specimens increased with time and stabilized at about 91 days following similar trends reported by several researchers [51]. Adding 5% extra cement to the RCA concrete was found to slightly increase the drying shrinkage strains of the concrete. This is probably due to the increase of the volume of cement paste in concrete which may lead to an increase in drying shrinkage.

- ***Swelling***

Merlet and Pimienta [35 f] found that the expansion of RCA concrete immersed in water for 60 days was higher when compared to the expansion of conventional concrete.

Gomez and Soberon [100] compared the expansion of concretes made with different

RCA contents. The results show that the expansion increased with the RCA content in the mix. RCA concretes with 0, 15 and 30% RCA had similar expansions in the order of 0.045mm/m. On the other hand, the expansion of RCA concretes with 60 and 100% RCA had an expansion in the order of 0.109 mm/m, which, in comparative terms represents an increase of 2.5 times greater expansion.

Gomez and Soberon [100], in the same study, after curing the RCA concrete specimens to measure their expansion, put the specimens in a climatic chamber to assess their shrinkage behaviour. It was found that the RCA concretes containing 60 and 100% RCA rapidly recovered the expansion undergone in the first stage in short period of time to reach and then exceed the shrinkage strains of the other mixes with lower RCA contents. Concrete with high RCA contents was thus found to have great levels of expansion recovery.

Sagoe - Crentsil [42] examined the variation of swelling strain with time for both RCA and conventional concretes. Reference concrete made with basalt had a marginally lower expansion when compared to the RCA concrete. Adding 5% extra cement to the RCA concrete resulted in a reduction in the expansion values, the authors attribute this to the lower w/c ratio and improved quality of the cement paste.

2.3.3.3 Durability properties

Initial surface absorption

A review of studies, on the effect of RCA on the permeability of RCA concrete, shows that an increase in the permeability of concrete is expected with an increase in the RCA content [51]. It is thought that the increase in the initial surface absorption of concrete is due to the increased proportion of cement paste in RCA concrete which gives it a high water absorption rate [22].

This increase was reported by Gomez et al [102] to be proportional to the percentage of replacement of natural aggregates with RCA in the mix and is affected by the amount of paste adhering to the natural aggregate in the RCA which gives it high porosity levels that facilitate the flow of water inside the concrete.

It is well known that the structure of the porosity of concrete influences greatly its permeability. Nagataki et al [94] examined the total volume of permeable pores of RCA concrete and found it was 20 to 111 per cent higher compared to the control concrete. They also found that decreasing the amount of attached cement paste in the RCA used helped reduce the porosity of the RCA concrete and that using RCA derived from a low quality original concrete increased the permeable pore volume when compared to high and medium quality concrete.

Sagoe - Crentsil [42] reported that replacing coarse natural aggregates in concrete by RCA increased the water absorption of the concrete by an average of 25%. This was attributed to the attached cement paste serving as a potential conduit for moisture transport.

Wirquin et al [65] reported that a study of water absorption in recycled aggregate concretes showed that the processes of water absorption in recycled aggregate and natural aggregate concretes are similar and obey the same laws.

Levy and Helen [66] examined the effect of different RCA contents on the water absorption of equal strength mixes; they reported that up to 20% RCA replacement of NA has no effect on the absorption rate of concrete. Above this limit, the concrete's water absorption increased with the RCA content. Similar findings were reported by Dhir et al [22] who found that up to 30% replacement of natural aggregates by RCA has no influence on the initial surface absorption of concrete.

Rasheeduzzafar and Khan [55] reported that reducing the w/c ratio of the RCA mixes by 0.05 to 0.10 is necessary to achieve the same permeability as the conventional concrete mixes.

Wainwright et al [35 e] found that RCA concrete made with RCA derived from a low strength concrete (high permeability) had a higher permeability than RCA concrete made from RCA derived from a high strength concrete (low permeability). Similar results were reported by Rasheeduzzafar and Khan [55].

A study [40] on the surface permeability of RCA concrete reported that water curing RCA mixes resulted in a better permeability when compared to various air curing methods.

Dhir et al [22] examined the effect of air and water curing on the initial surface absorption of conventional and RCA concrete. The curing methods had exactly the same effect on both types of concrete; water curing improved the permeability of both the NA and RCA concretes.

Carbonation resistance

The carbonation of RCA concretes of different cement ratios containing 0, 30, 50 and 100% RCA was examined by Kasai et al [20 h]. The results show that the carbonation depth increased as the water cement ratios increased; however increasing the RCA content in the mix had no significant effect on the carbonation of RCA concrete. The results from this study are shown in Figure 2.14. Similar findings were reported by [26 a, 35 a, 42, 96].

Sakata and Ayano [98] reported that the carbonated thickness of concrete in which coarse RCA was used is almost the same as that with natural aggregates. Meinhold et al [92] reported a slight tendency to a higher carbonation rate in RCA concrete when compared to concrete made with natural aggregates. However the absolute difference after two years was only 1 – 2mm at a total range of 10mm. Similar findings were reported by Ryu [30].

Kikuchi et al [35 a] examined the carbonation resistance of concrete made with RCA derived from concretes of different strengths. The authors reported an increase in the carbonation depth with an increase in the water cement ratio of the RCA concrete. However the strength of the original concretes had only a small effect on the carbonation resistance of the RCA concrete. Similar results were reported by Ryu [30] who tested the carbonation resistance in concretes made with RCA with varying amounts of attached cement paste and derived from original concretes with different strengths.

Yanagi et al [20 l] found that there was a relationship between the quantities of impurities and the carbonation resistance of RCA concrete. It was found that increasing the amount of impurities causes a decrease in the carbonation resistance of RCA concrete. They also found that the carbonation of washed RCA concrete is larger than the carbonation of non-washed RCA concrete.

Yanagi et al [35 d] found that the carbonation depth was 1.7 times higher in RCA concrete when compared to natural aggregate concrete and that it increased with an increase in the RCA content. The carbonation depth of concrete made with RCA containing a wide range of impurities was found to be similar to clean RCA concrete except for RCA containing plastic tile or soil which exhibited slightly higher carbonation depths.

A study [25] by Japanese researchers found that the rate of carbonation of concrete made with RCA from an original source that has already suffered carbonation was 65% higher than that of a control concrete made with natural aggregates.

Dhir et al [22] examined the carbonation resistance of equal cement and water content RCA mixes and equal strength RCA mixes. For the first type of mixes, the results showed that up to 50% coarse RCA had a negligible influence on carbonation rates, and thereafter a slight increase in carbonation depths was observed. However, the carbonation resistance improved with an increase in the RCA content in equal strength concrete mixes. The authors attributed the improvements to the quantity of calcium hydroxide in the RCA concrete which increased with the content of the attached hydrated cement paste, as well as to the increase in the cement content in the RCA concrete to achieve equal strength which increased the alkalinity of the concrete.

Results from another study [64] also showed that NA and RCA concretes can have equal carbonation resistance when designed to have equal strength. Levy and Helene [66] also reported that RCA concretes can sometimes have a better carbonation resistance than normal concrete due to the increase in cement content of the RCA concretes to achieve the same compressive strength of natural aggregates concrete. This higher alkaline reserve acts by protecting the concrete surface against carbonation mechanisms.

Dhir et al [22] reported that the carbonation resistance of both the RCA and NA concretes increased with strength. A good correlation between the compressive strength and the carbonation depth was found regardless of the amount of RCA used in the mixes, suggesting that the use of RCA in concrete has no effect on its resistance to carbonation.

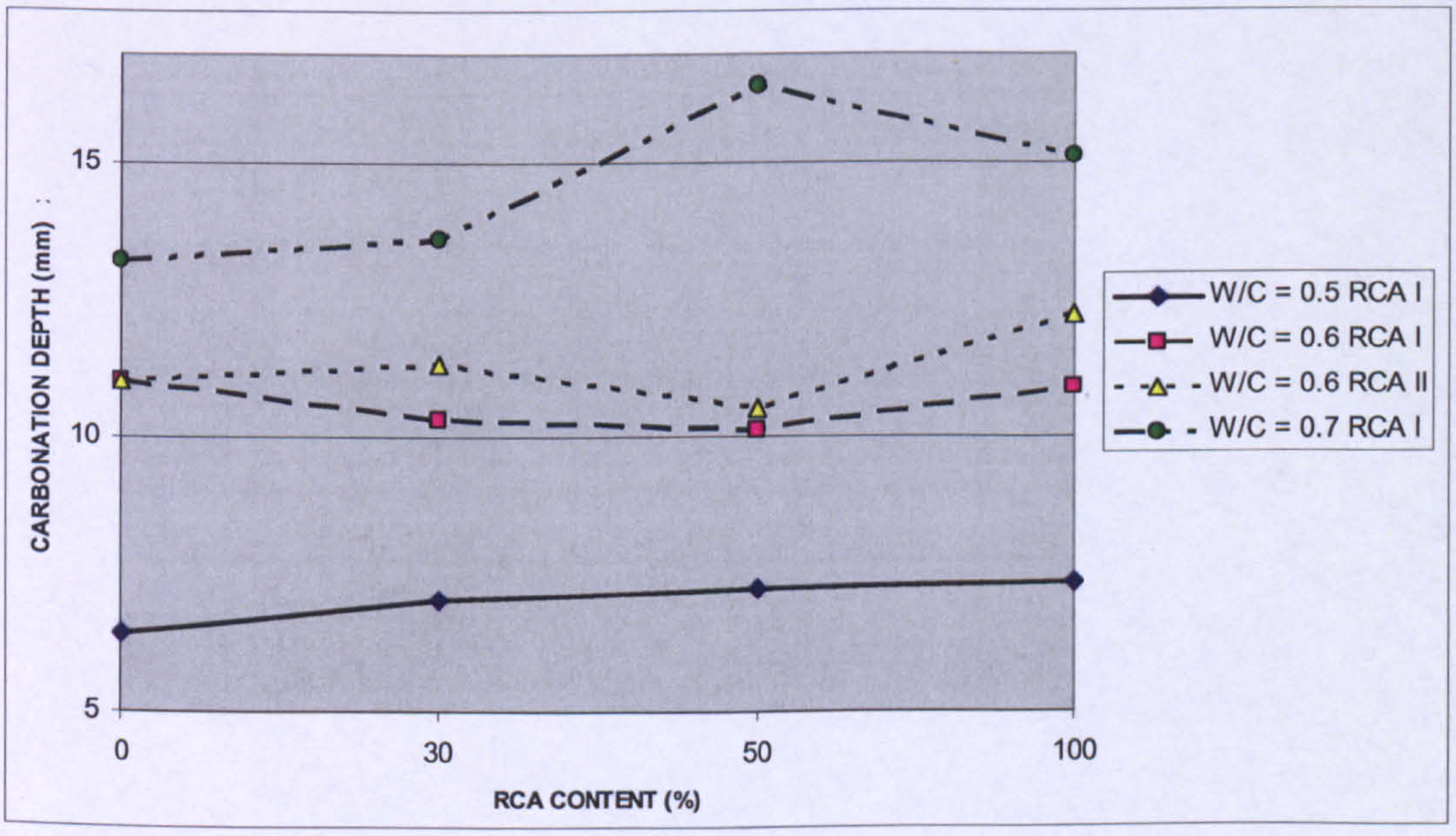


Figure 2.14 Effect of the original concrete's strength and RCA contents on the carbonation of RCA concrete with various water cement ratios [20 h].

Chloride penetration

The effect of RCA content on the chloride penetration depth was discussed by Kikuchi et al [35 a]. Results from this study show that the depth of chloride penetration slightly decreased when 100% RCA was used.

On the other hand, Poon et al [53] reported that the resistance against chloride ion penetration slightly decreased with increasing RCA contents. This agrees with the findings of Otsuki et al [67].

Similar to conventional concrete, the chloride resistance of RCA concrete was found to increase with the reduction in the w/c ratio of the mix and with the increase in curing age [35 a, 53].

Friedl et al [103] found that the type of RCA does not influence the chloride penetration significantly as only a slight increase was identified with an increase of the proportion of RCA in the mix regardless of the type of RCA used.

Kikuchi et al [35 a] reported that the chloride penetration was slightly higher in the concrete containing RCA derived from a low strength concrete when compared to concretes containing RCA derived from high strength concretes. The results of this study are shown in Figure 2.15.

Poon et al [53] investigated the effects of steam curing on the hardened properties of RCA concrete. It was found that the steam curing increased the resistance to chloride ion penetration of the concrete compared to normal water curing. Steam curing can create a tortuous interconnecting network of capillary pores which improves the chloride resistance of the concrete.

In addition to the penetration of chloride from outside, Friedl et al [103] reported that chloride contaminated recycled aggregate particles can release, into the surrounding mortar matrix in the RCA concrete, a sufficient amount of chlorides to cause serious corrosion. Using carbonated and/or pre-moistened RCA causes a higher re-distribution of chlorides in the concrete matrix. Also the higher the porosity of RCA the more chlorides are released in the concrete matrix.

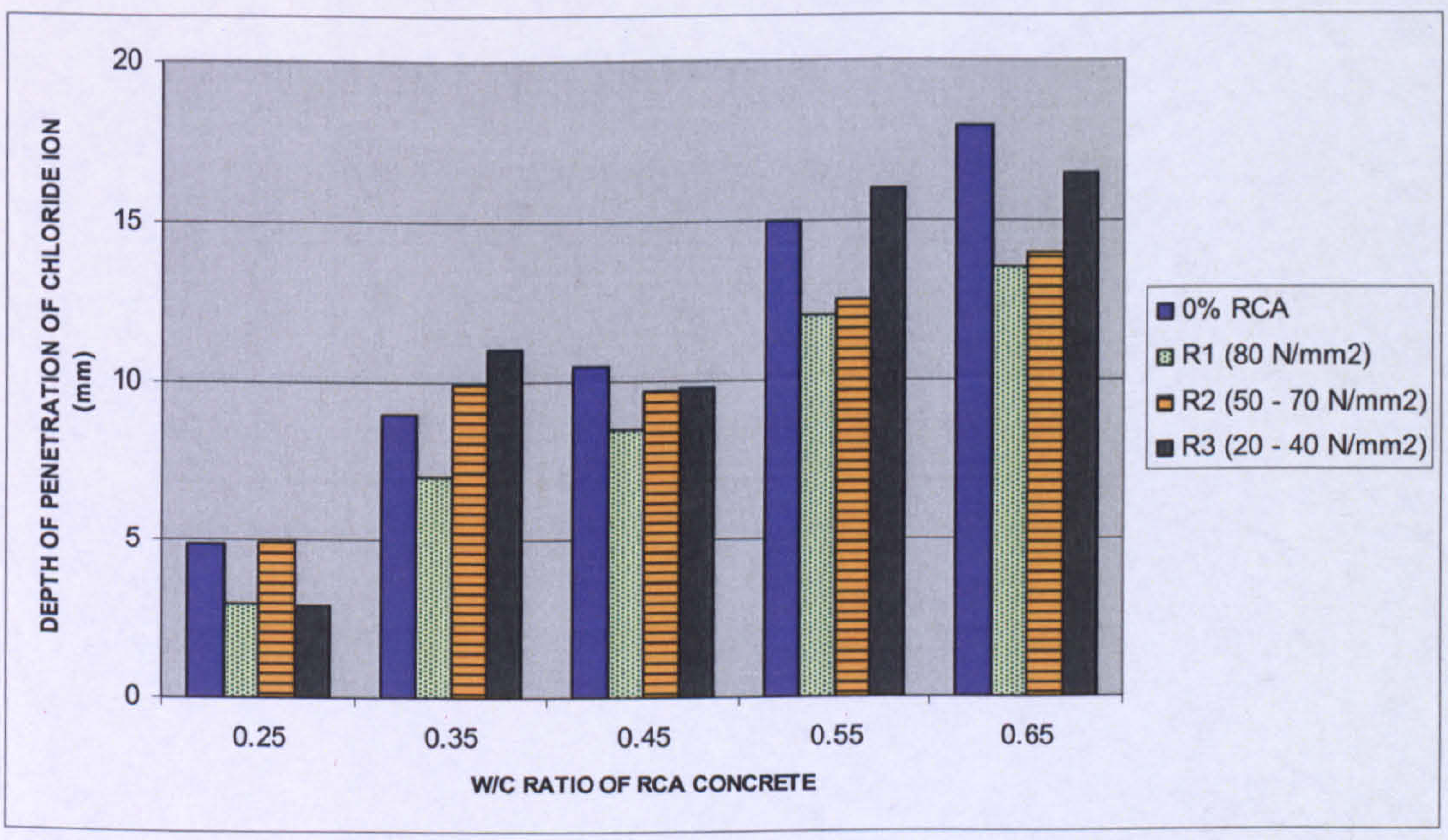


Figure 2.15 Effect of the strength of original concrete on the chloride resistance of RCA concretes with various water cement ratios [35 a].

Sulphate attack

The effect of RCA content on sulphate resistance was studied by Nishibayashi and Yamura [20 j]. During the testing concrete samples were subjected to 24 hr repeated cycles between immersion in a mixed solution (Na_2SO_4 and MgSO4 at 20°C) and drying in an oven at 70°C. Findings show equal or slightly lower sulphate resistance for concrete containing up to 100% coarse RCA than the corresponding NA concrete.

Dhir et al [22] assessed the sulphate resistance of equal strength air and water cured GEN 3 concrete mixes. Using up to 30% RCA had very little effect on the sulphate resistance of concrete. Thereafter, expansion due to sulphates increased with an increase in the RCA content, however the difference remained in a narrow band. The sulphate resistance of water cured specimens was higher when compared to air cured specimens.

2.4 USE OF BINARY CEMENTS

Since its invention in the 19th century, Portland cement has been and remains today the main cementitious material in concrete. There are many other cementitious materials available which are often used with Portland cement and constitute a portion of the total amount of cementitious material in concrete. Common terms used to describe such materials are 'supplementary cementitious materials', 'mineral admixtures' or 'additions'.

Blended cements are cement mixtures containing Portland cement and at least one type of supplementary cementitious material. Other terms used to describe blended cements are 'composite cements' or 'combination cements'. Blended cements can be blended in the concrete mixer or blended or inter-ground in cement plants. Binary cements are cement mixtures containing Portland cement and one type of supplementary cementitious material [78].

Pozzolanas from both natural (such as volcanic ash, pumice) and artificial sources (such as fly ash, silica fume and blastfurnace slag) have been widely used as supplementary cementitious materials. Pozzolanas are natural or artificial materials containing silica in a reactive form. Although Pozzolanas are referred to as cementitious, this is only true in latent form. In fact, they possess little or no cementitious value. This means they do not gain strength when mixed with water, however in finely divided form and in the presence of moisture; they chemically react with the calcium hydroxide produced by the hydration of Portland cement to form compounds possessing cementitious properties [78].

The term "Pozzolana" is derived from the name of a small village in the region around Vesuvius in Italy, called Pozzuoli, where a fine sandy volcanic ash, a natural occurring pozzolana, was originally discovered and dug by the Romans who mixed it with lime, broken tiles, crushed stone or bricks, sand and water to make the oldest known type of concrete. When other materials reacting with lime were discovered in other countries, the term pozzolana or pozzolan was used. Thus today Pozollana or Pozzolan indicate any pozzolanic material regardless of its origin or chemical composition [78].

The original reason for introducing pozzolanas in Portland cement concrete was mainly economic, as they were cheaper than Portland cement, because most of these materials either existed abundantly in nature and required little or no processing or were by-products or wastes of industrial processes that rapidly became available in large quantities also requiring little or no processing. Another boost for the use of these materials came from the rising cost of energy which represents a large proportion of the cost of production of Portland cement, and from the growing concerns about the detrimental impacts on the environment caused by:

- The manufacture of Portland cement which consumes huge amounts of natural raw materials and releases large quantities of greenhouse gases.
- And the disposal of large quantities of industrial waste materials such as fly ash, silica fume or blastfurnace slag in landfills.

In addition to the economic and environmental reasons mentioned hitherto, one of the main reasons behind the use of pozzolanas in concrete is the improvement in the concrete's performance that can be achieved when these materials are used at optimum levels in the manufacture of concrete [78].

2.4.1 STANDARDS

The use of additions in concrete is covered by the EN 206 – 1. The standard defines an addition as a finely divided inorganic material used in concrete in order to improve certain properties or to achieve special properties. It also divides additions in to two types:

- Nearly inert additions called Type I additions which include: filler aggregates conforming to EN 12620 and pigments conforming to EN 12878;
- Pozzolanic or latent hydraulic additions called Type II additions which include Fly ash conforming to EN 450 and silica fume conforming to EN 13263 [79].

The EN 206 – 1 states that the quantities of type I and type II additions to be used in concrete shall be covered by the initial tests in Annex A. The standard defines initial tests as tests used to check, before the production starts, how a new concrete or concrete family shall be composed in order to meet all the specified requirements in the fresh and hardened states. Where the producer or specifier can demonstrate an adequate design, based on data from previous tests or long-term experience, this may be considered as an alternative to initial tests.

Type II additions may be taken into account in the concrete composition with respect to the cement content and the water/cement ratio if the suitability is established. General suitability as type II addition is established in EN 206 1 for Fly Ash conforming to EN 450 and Silica Fume conforming to EN 13263 using the *k* value concept laid out in clause 5.2.5.2. [79].

_k_ – value concept

The *k* – value concept permits type II additions to be taken into account:

- By replacing the term "water/cement ratio" with "water/(cement + $k \times$ addition) ratio"
- In the minimum cement content requirement.

<u>Fly ash conforming to EN 450</u>

The maximum amount of fly ash to be taken into account for the k-value concept shall meet: fly ash/cement ≤ 0.33 by mass. If a greater amount of fly ash is used, the excess shall not be taken into account for the calculation of the water/(cement + $k \times$ fly ash) ratio, and the minimum cement content.

The following *k*-values are permitted for concrete containing cement type CEM I conforming to EN 197 – 1:

CEM I 32.5 $k = 0.2$

CEM I 42.5 and higher $k = 0.4$

The minimum cement content for the relevant exposure class (see 5.3.2) may be reduced by a maximum amount of $k \times$ (minimum cement content 200) kg/m^3 and additionally the amount of (cement + fly ash) shall not be less than the minimum cement content required in accordance with clause 5.3.2.

<u>Silica fume conforming to EN 13263</u>

The maximum amount of Silica Fume to be taken into account for the water/cement ratio and the cement content shall meet the requirement: Silica fume/cement ≤ 0.11 by mass. If a greater amount of Silica Fume is used, the excess shall not be taken into account for the k value concept.

The actual value of k depends on the specific addition. The following k-values are permitted to be applied for concrete containing Portland Cement CEM I conforming to EN 197-1:

- For specified water/cement ratio < 0.45

  $k = 2.0$

- For specified water/cement ratio > 0.45

  $k = 2.0$ except for exposure Classes XC and XF, where $k = 1.0$

The amount of (cement + $k \times$ Silica Fume) shall be not less than the minimum cement content required for the relevant exposure class in clause 5.3.2. The minimum cement content shall not be reduced by more than 30 kg/m^3 in concrete for use in exposure classes for which the minimum cement content is ≤ 300 kg/m^3.

The EN 206 – 1 permits the use of other concepts, additions or combination of additions if their suitability has been established. Their suitability should be established using the relevant national standard or provision valid in the place of use of the concrete which refers specifically to the use of the addition in concrete conforming to EN 206 – 1.

In addition to the k – value concept, the EN 206 – 1 lays out another concept in clause 5.2.5.3, the equivalent concrete performance concept. This concept may be applied to a combination of any specific addition and specific cement for which the manufacturing source and characteristics are clearly defined and documented.

Equivalent concrete performance concept

For the equivalent concrete performance concept, it shall be proven that the concrete has an equivalent performance especially with respect to environmental actions and to its durability when compared with a reference concrete with the requirements for the relevant exposure class. The principles for the assessment of the equivalent concrete performance concept are given in Annex E of the EN 206 – 1.

In the UK, the BS 8500 provides national provisions where required or permitted by the EN 206 – 1. It covers materials, methods of testing and procedures that are outside the scope of the EN 206 – 1, but within national experience.

BS 8500 combinations

BS 8500 – 1 defines a combination as a restricted range of Portland cement and additions which, having been combined in the concrete mixer, count fully towards the cement content and water/cement ratio in concrete. A procedure for establishing the suitability of combinations is specified in BS 8500 – 2, Annex A.

In the BS 8500 – 2, in addition to the additions listed in EN 206-1, 5.1.6 (i.e. silica fume conforming to EN 13263 and fly ash conforming to EN 450), general suitability as a Type II addition is established for the following:

- GGBS conforming to BS 6699;
- PFA conforming to BS 3892 – 1 [18];
- Metakaolin with an appropriate Agrément Certificate;
- Limestone fines conforming to BS 7979.

Provided that the combination of CEM I cement and the type II addition fulfils early age and 28 day strength requirements, which are set out in BS 8500 – 2 Annex A, and which takes into account source variability, the only additions that should count fully towards the cement content and Water/Cement ratio in concrete according to BS 8500 – 2 are:

- Fly ash conforming to EN 450 with a loss of ignition no more than 7%;
- GGBS conforming to BS 6699;
- Limestone fines conforming to BS 7979;
- PFA conforming to BS 3892 – 1 [18].

The BS 8500 – 2 requires that the equivalent concrete performance concept (EN 206 – 1, 5.2.5.3) shall only be used where the producer's proposals for demonstrating equivalence and ensuring conformity have been approved by the specifier. It also requires that when the *k* – value concept (EN 206 – 1, 5.2.5.2) is used, the starting point for limiting values shall be those specified in the specification for a CEM I cement concrete. Table 2.9 summarises the different ways specific additions may be used in concrete conforming to EN 206 - 1 and BS 8500.

2.4.2 FLY ASH / PULVERISED FUEL ASH

2.4.2.1 PFA production

Coal is a mineral substance of fossil origin used as a source of energy. It consists of carbon, volatile organic materials and a mixture of various minerals (shales, clays, sulphides and carbonates). The coal with the highest carbon content is the best and cleanest type of coal to use. As the carbon content decreases, the heat it gives out decreases and the dirtiness of the fuel increases. There are four types of coal:

- Anthracite (85 - 98 % carbon)
- Bituminous coal (45 - 85 % carbon)
- Sub - bituminous coal (35 - 45 % carbon)
- Lignite coal, also known as brown coal (25 - 35 % carbon)

Coal is used as a solid fuel in power stations, where it is burnt to heat water to produce steam. The steam, at tremendous pressure, flows into a turbine, which spins a generator to produce electricity. The by-product of coal combustion in coal fired power stations is known as Fly Ash. In the modern UK coal fired power stations, pulverised coal combustion is the most commonly used method of combustion. Hence the name Pulverised Fuel ash given in the UK to Fly ash produced using this technique.

Table 2.9 A summary of the different ways specific additions may be used in concrete conforming to EN 206 – 1 and BS 8500 [70].

Addition	Standard for addition	Type	Use in concrete permitted by	Route to count towards cement content and water/cement ratio$^{(1)}$
Fly ash/ pulverised fuel ash	EN 450	II	EN 206 – 1, 5.1.6	EN 206 – 1, 5.2.5.2.2 or BS 8500 – 2, 4.4
	BS 3892 – 1	II	BS 8500 – 2, 4.4	BS 8500 – 2, 4.4
	BS 3892 – 1	I	BS 8500 – 2, 4.4	No route
Ground granulated blastfurnace slag	BS 6699	II	BS 8500 – 2, 4.4	BS 8500 – 2, 4.4
Silica fume	EN 13263	II	EN 206 – 1, 5.1.6	EN 206 – 1, 5.2.5.2.3
Metakaolin	Agrément Certificate	II	BS 8500 – 2, 4.4	No route
Limestone fines	BS 7979	I or II	BS 8500 – 2, 4.4	BS 8500 – 2, 4.4
Filler aggregates	EN 12620	I	EN 206 – 1, 5.1.6	No route
Pigments	EN 12878	I	EN 206 – 1, 5.1.6	No route

(1) The "equivalent concrete performance concept" in 5.2.5.3 of EN 206 – 1 provides an additional route for any type II addition to effectively count towards the cement content and the water/cement ratio (by permitting amendments to the recommended values).

Pulverised coal combustion consists of burning the coal by grinding it to a fineness similar to cement and then blowing it into the boiler furnace with air. The coal particles burn within 3 to 4 seconds leaving the ash as molten beads of approximately spherical form. The ash particles then pass out of the furnace area with the flue gas, cooling as they do so. The boiler is designed so that the ash particles are below their melting temperature as the gas leaves the furnace. The ash becomes a solid bead transported with the combustion gases through the remainder of the boiler. Finally, the Fly ash particles are captured from the flue gas, electro-statically using precipitators, before the gas is allowed to pass to the atmosphere. The Fly ash is collected in hoppers beneath the precipitators. From here Fly ash can be withdrawn as a dry product for direct use or further processing. It is sometimes "conditioned" by mixing it with up to 18% water. In this form it can be more easily transported to a variety of uses, or stored awaiting sale [69]. Figure 2.16 shows a schematic layout of a pulverised coal fired power station furnace.

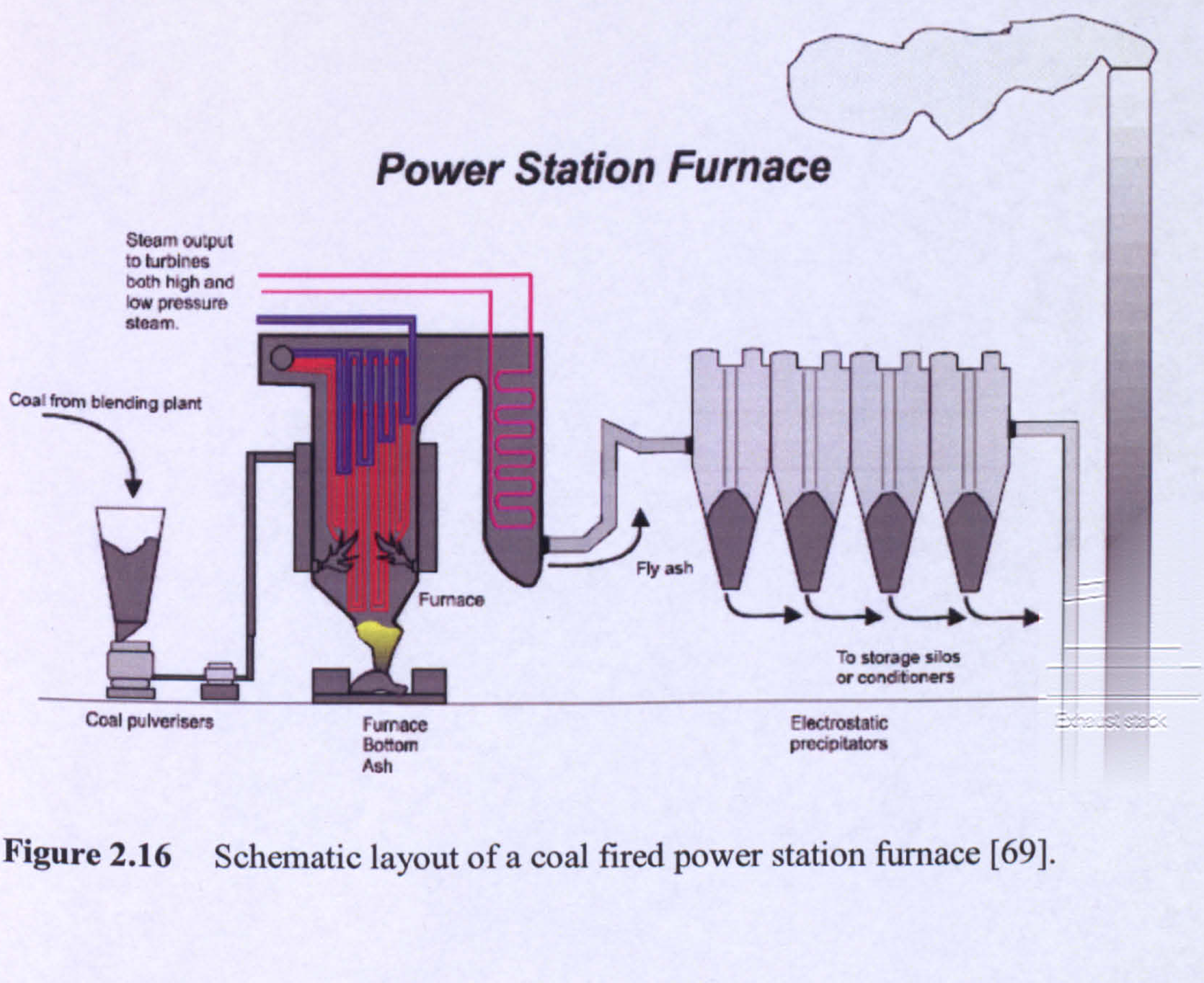


Figure 2.16 Schematic layout of a coal fired power station furnace [69].

The ash from pulverised fuel combustion is significantly different in its properties from ash produced by other methods of combustion. The coal grinding process gives the PFA fine particles of reasonably consistent size, the high temperature combustion releases and destroys the hydrocarbons and the ash is molten before solidifying into spherical PFA particles [69].

The production of PFA has not changed much over the years. Environmental improvements on UK power stations have concentrated on reducing gaseous emissions in recent years. These improvements have not changed the nature of PFA produced, except a slight increase on loss on ignition (LOI) [69].

PFA has been used for a wide range of construction applications. It is extensively used in concrete by the UK concrete industry for technical, environmental and economic reasons. About 25% of the ready-mixed concrete produced in the UK contains a binder consisting typically of 30% PFA and 70% Portland cement [69].

2.4.2.2 History of PFA

The idea of utilising coal fly ash in concrete emerged in the United States of America in the 1930's. The introduction of pulverised coal steam raising plant in the UK, particularly after the 1939 – 1945 war, resulted in the production of fly ash. It was in the 1940's that research into the use of fly ash began in the UK [68].

By the mid 1950's fly ash from coal combustion became known as Pulverised fuel ash within the UK to differentiate it from fly ashes produced using other processes. The first time PFA was used in concrete in the UK was for the construction of mass concrete dams in 1954 (Lednock, Clatworthy and Lubreoch Dams) following research at the University of Glasgow, as a replacement for Portland cement. The control criteria were somewhat crude using only the colour and the gritty feel of the ash. It was found that the variability of the fly ash both in fineness and in carbon content was problematical. The power station supplying the ash used some 20 differing coal sources during the period of construction and carbon content was not monitored or controlled in any manner. However, the subsequent durability of the structure has been found excellent [68].

Although PFA was accepted for use in concrete by British standards; it was not until 1965 that the first standard for PFA for use in concrete was introduced. PFA was treated as a fine aggregate having three classes of fineness based on the specific surface area. However, at a time when ready-mixed concrete suppliers were producing ever more technically demanding concretes of higher strength and lower water cement ratios, variability in quality and the supply problems of PFA when taken directly from the power stations meant that PFA was not fully accepted by the ready mixed concrete industry [68].

A solution to this problem was introduced within the UK in 1975 by Pozzolan Ltd who supplied PFA with controlled fineness. The production of a tightly controlled fineness PFA was achieved through either classification of the ash, to remove the coarse fractions or through selection of the finer material by continual monitoring of the ash quality. Using finer ash results in a better consistency and improves water reduction as well as the pozzolanicity of the fly ash resulting in a better strength and durability performance. An agrément board certificate (Agrément certification is designed specifically for new building products and processes that do not yet have a long history of use and for which published national standards do not yet exist) was obtained for classified or selected PFA in 1975 [68].

This development in the use of fly ash in concrete resulted in the division of the BS 3892 into two parts initially:

- Part 1 covering classified PFA for use in concrete, with PFA counting fully towards the cement content of the mix.
- Part 2 covering the run of station ash for use in concrete and grouts, with the ash being considered as an inert filler.

PFA for use in grouts was later taken out from BS 3892 Part 2 and was put in a separate part, BS 3892 Part 3. Also selection as a method of producing finer ash was removed for PFA conforming to Part 1 of the BS 3892 as this has proven to be unreliable.

In 1995, EN 450, the harmonised European standard for fly ash for concrete was introduced. EN 450 allows a very wide range of fineness when compared to BS 3892 – 1. This is not a surprise as this reflects the situation of the use of fly ash in Europe where apart from the UK and Ireland, no other European country classifies fly ash for use in concrete [68].

It is known that the fineness of PFA conforming to BS 3892 is very consistent and is not dependent on the source of the fly ash. However for fly ash conforming to EN 450, the differences in the fineness of the material between different sources is more noticeable and can affect the concrete consistency. However the natural variation found in fly ash conforming to EN 450 from the same source does not affect concrete in a major way. Therefore once Fly ash from a new source is to be used the concrete mix designs should be adjusted accordingly [68].

Fly ash or pulverised fuel ash used in concrete may therefore conform to one or several of the following standards:

- EN 450, Fly ash for concrete – Definitions, requirements and quality control;
- BS 3892 – 1, Pulverised fuel ash – Part 1: Specification for pulverised-fuel ash for use with Portland cement; or
- BS 3892 – 2, Pulverised fuel ash to be used as a Type I addition.

The requirements of each one of these standards are shown in table 2.10.

2.4.2.3 PFA concrete

2.4.2.3.1 Pozzolanic properties of PFA

The main compounds formed from the hydration of cement are hydrated calcium silicate and calcium hydroxide. Calcium hydroxide is water soluble and has no cementitious value. The main constituent of fly ash is silica SiO_2. Glassy amorphous forms of silica, alumina and iron found in PFA chemically combine with calcium hydroxides and other soluble alkalis such as potassium and sodium hydroxides to produce calcium-silicate-hydrate (C-S-H). The C-S-H strengthens the cement paste and fills the voids improving the permeability of the concrete.

The pozzolanic reaction of PFA does not start immediately after mixing. This is because the glass material in the fly ash is broken down only when the pH value of

Table 2.10 Requirements for fly ash and pulverised fuel ash conforming to BS 3892 – 1, BS 3892 – 2 and EN 450 [71].

Property	**Standards and requirements**		
	BS 3892 – 1	**BS 3892 – 2**	**EN 450**
Moisture Content, max	0.5%	0.5% unless conditioned ash used	Dry
Fineness (retained @45 μm), max	12%	60%	40% ± 10% of declared mean value
Particle Density (kg/m^3)	>2000	-	± 150 Kg/m^3 from the declared mean value
Water Requirement, max	95% for 30% PFA+70% CEM I	-	-
Initial Setting Time (minutes)	>initial setting time of PC	-	-
Soundness (mm), max	10 for 30% PFA+70% CEM I	-	10 for 50% Fly Ash+50% CEM I
Strength Factor, min	0.8 at 28 days	-	-
Activity Index, min	-	-	75% at 28 days and 85% at 90 days for 25% Fly Ash+75% CEM I
Chemical properties			
Sulphuric Anhydride (SO_3), max	2.0%	2.5%	3.0%
Loss of Ignition, max	7%	12%	7%
Chloride (Cl^-), max	0.10%	-	0.10%
Calcium Oxide (C_aO), max	<10.0%	-	1.0% or 2.5% if soundness is satisfactory

the pore water is at least about 13.2, and the increase in the alkalinity of the pore water requires that a certain amount of hydration of Portland cement in the mix has taken place [72].

The reaction products of Portland cement precipitate on the surface of the PFA particles, which act as nuclei. When the pH of the pore water has become high enough, the products of reaction of the PFA are formed on the PFA particles and in their vicinity. With time further products diffuse away and precipitate within the capillary pore system; this results in a reduction in capillary porosity and therefore a finer pore structure [78].

The influence of curing on PFA concrete is higher when compared with Portland cement concrete. Because of the slow reactions of PFA in concrete, prolonged wet curing is essential [78].

2.4.2.3.2 Fresh properties

The main influence of the use of PFA in concrete is on water demand and workability. For a constant workability, PFA requires less water when compared to a Portland cement only mix having the same cementitious material content [78].

PFA makes concrete more cohesive and less prone to segregation and reduces its bleeding capacity. The effect PFA has on the fresh concrete properties is due to the shape of the PFA particles. The reduction in water demand of concrete caused by the presence of PFA is usually attributed to their spherical shape, this being called 'ball bearing effect' [78].

Another mechanism to which this reduction in water demand is ascribed to is the mechanism by which finer PFA particles become absorbed on the surface of the cement particles due to electrical charges. If enough particles are available to cover the surface of the cement particles, which therefore become deflocculated, the water demand for a given workability is reduced [72].

2.4.2.3.3 Engineering properties

Compressive strength

In addition to its pozzolanic properties, fly ash has a physical effect on improving the microstructure of the hydrated cement paste and therefore the strength of the concrete. The main physical action is that of packing of the PFA particles at the interface of the coarse aggregate particles. One beneficial effect of packing on strength is a reduction in the volume of entrapped air in the concrete, but the main contribution of packing lies in a reduction in the volume of large capillary pores.

The coarse particles of PFA can be considered as 'micro-aggregates' which improve the density of the hydrated cement paste. This is beneficial with respect to strength, resistance to crack propagation and stiffness. This also results in system of capillary pores which is better able to retain water which can be used for long term hydration [73].

Concrete using fly ash as a partial replacement of Portland cement can be expected to have a slower strength development at early ages due to the reduced Portland cement content. Where early age strengths are needed, other ingredients such as chemical accelerators or silica fume can be used to improve the rate of strength development of the concrete at early ages.

However, the rate of strength development of concrete with fly ash at a later age is greater than for Portland cement concrete as a result of the continued pozzolanic reaction. For equal 28 day strength fly ash and Portland cement concretes, the ultimate strength of fly ash concrete is greater.

Sani et al [104] reported that the use of RCA causes a decrease in the strength of concrete which can be attenuated by fly ash addition. Ravindrajah and Tam [20 b] studied the effect of PFA as an addition (10% by mass of cement) on RCA concrete. The addition of fly ash helped in compensating the reduction in compressive strength that occurs when RCA is used in Portland cement concrete made with no addition. RCA concrete containing PFA even achieved a higher compressive strength than ordinary concrete. 10% addition of fly ash resulted in RCA concrete having a compressive strength 8 % and 23% higher than the natural aggregate concrete and RCA concrete with no addition respectively at 90 days. The 28 day compressive strength results of the mixes from this study [20b] are shown in Table 2.11.

Kou et al [105, 106] examined the effect of using various contents of RCA, on concretes of equal w/c ratio (0.45) where 0, 25 and 35% of the cement content was replaced by weight with fly ash. The results show that the compressive strengths of concrete at all curing ages decreased with an increase in the recycled aggregates content.

Kou et al [105, 106] also reported that the compressive strengths of concrete were reduced as the fly ash content increased. However at 90 days the concrete containing 25% showed equal or higher strength than the concrete prepared with no fly ash. This late strength development is typical of fly ash concrete.

Kou et al [106] also examined the effect of water and steam curing usually used in the precast concrete industry on RCA concrete containing PFA. For water curing, specimens were cured in air for 24 hours before being de-moulded and then they were cured in a water tank at 27°C. For steam curing, the specimens were cured in a steam bath at 65°C for 8 hours and then they were de-moulded and cured in water. Up to day 7, the strength of steam cured specimens was higher than the strength of water cured specimens. However the opposite was observed for the 28 and 90 days strengths.

Corinaldesi and Moriconi [107] looked at the effect of fly ash when used in RCA concrete as a replacement of a proportion of fine aggregate equivalent to 30% of the cement mass of the RCA concrete with no fly ash. The authors found that the strength development of the RCA concrete without Fly ash (w/c ratio = 0.40) slowed down after 14 days with respect to the reference concrete made with natural aggregate (w/c ratio = 0.56), thus achieving a lower compressive strength at a later age. On the other hand, this effect was not evident in RCA concrete made with fly ash (w/c ratio = 0.40). The fly ash due to its pozzolanity helped improve the compressive strength of RCA concrete to equal the reference concrete.

Another study [108] showed that the loss in compressive strength that occurs when using RCA can be mitigated by reducing the w/c ratio of the mix or by replacing 50%

of the amount of fine aggregates in the mix by fly ash. Fly ash was found to be very effective in decreasing the macro pores in the RCA concrete, which are detrimental to the strength of concrete. This was due to the higher paste content as a result of the fly ash addition. Figure 2.17 shows the effect of fly ash on the pore structure after 28 days of curing of natural and RCA concrete from a study by Corinaldesi et al [108]

Corinaldesi et al [108] made two equal strength mixes; the first was made with natural aggregates and the second with recycled aggregates. The second series of mixes consisted of the same mixes; however in the first mix with the conventional aggregates an amount fly ash equivalent to the amount of cement was added. In the second mix an amount of its fine aggregate content was replaced with fly ash by an amount equivalent to the amount of cement used. It was found that the fly ash had a positive effect on the strength in the presence of both natural and recycled aggregates especially at longer ages. The use of fly ash helped increase the compressive strength of NA concrete with no fly ash by 56%. The use of fly ash in the RCA concrete only helped to achieve the same strength as the conventional concrete as the weakness of the RCA had more influence on the compressive strength of the concrete as the cement matrix became stronger.

Flexural strength

Ravindrajah and Tam [20 b] studied the effect of fly ash as an addition (10% by mass of cement) on RCA concrete and reported that the addition of fly ash helped in compensating the reduction in flexural strength that occurs when RCA is used in concrete. The use of fly ash improved the flexural strength of RCA concrete at 28 days by up to 27% and 50% when compared to natural aggregate concrete and RCA concrete with no addition respectively. The results of this study [20b] are shown in Table 2.11.

Modulus of elasticity

Ravindrajah and Tam [20 b] studied the effect of PFA as an addition (10% by mass of cement) on RCA concrete and reported that the use of fly ash did not bring any improvements to the modulus of elasticity of RCA concrete as this is mainly affected by the aggregate modulus. The results of this study [20b] are shown in Table 2.11.

Similar findings were reported by Corinaldesi and Moriconi [107] who stated that the static modulus is not significantly influenced by the presence of mineral admixture used but depended substantially on the compressive strength of the concrete. On the other hand, another study [108] showed that if the addition of fly ash in RCA concrete results in an increase in the paste content, the modulus of elasticity decreases more than in RCA concrete with no fly ash as a result.

Kou et al [105, 106] reported that the modulus of elasticity of recycled aggregate concrete decreased with an increase in the recycled aggregate content in concrete made with and without fly ash. At 28 and 90 days the modulus of concrete_containing 100% RA was 20% lower than that of concrete containing natural aggregates. In the mixes using fly ash, the modulus of elasticity decreased as the fly ash content increased. However the influence of fly ash on the static modulus of elasticity of concrete prepared with 100% RA was not significant.

Kou et al [106] reported that for concretes made with Portland cement, steam curing

Table 2.11 Effect of 10% fly ash addition on the engineering properties on RCA concrete [20 b].

Property [test age in days]	Mix (w/c = 0.57)		
	NA PC	**RCA PC**	**RCA 10% FA**
Compressive strength (MPa) [28]	33.8	28.0	32.5
Flexural strength (MPa) [28]	4.88	4.15	6.21
Static modulus (GPa) [28]	29.0	21.5	21.3
Shrinkage (Microstain) [91]	204	430	360

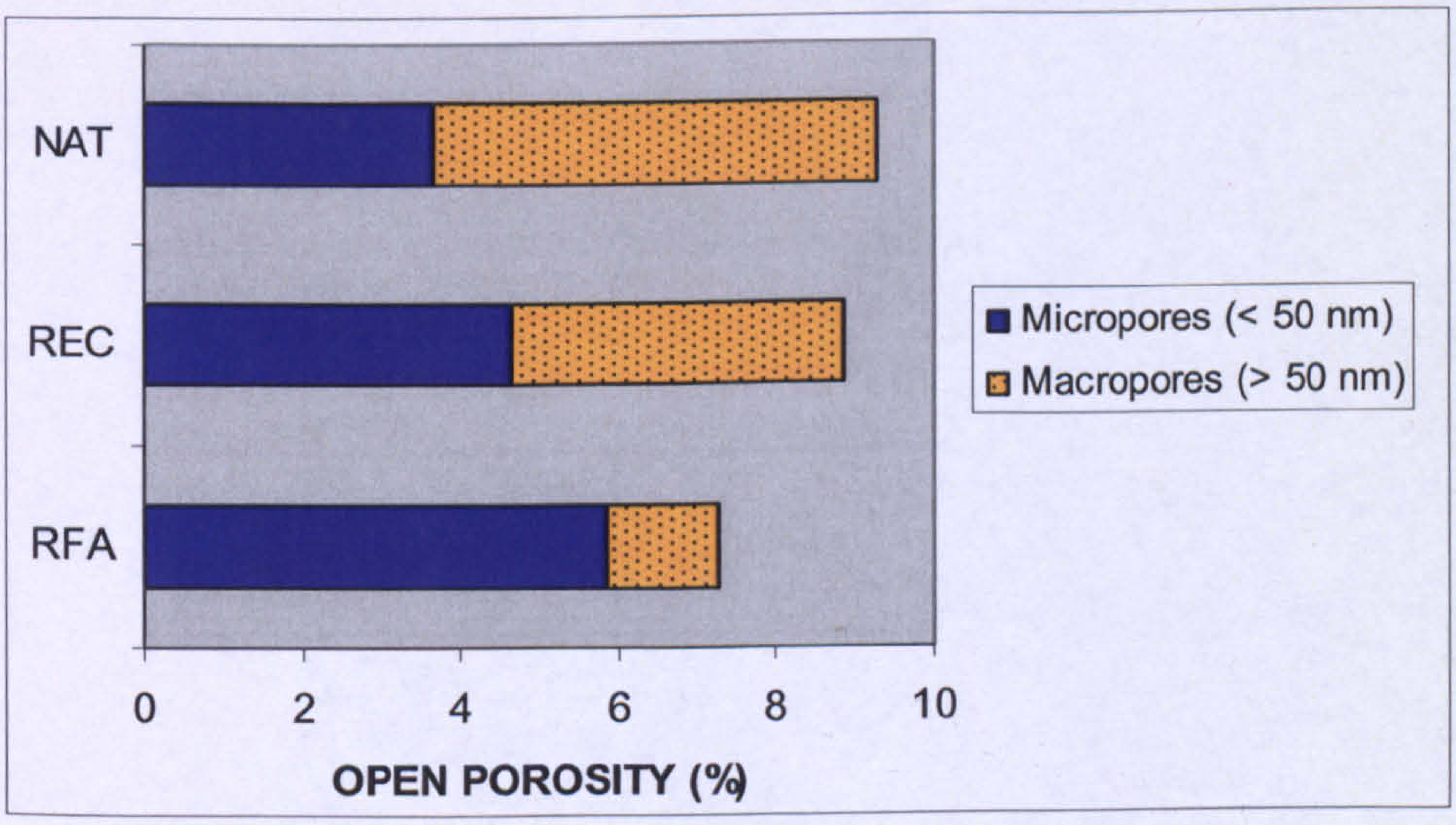


Figure 2.17 Effect of fly ash on the pore structure after 28 days of curing of natural and RCA concrete [108].

had a detrimental effect on the static modulus of elasticity of NA concrete, but it had no effect on the modulus of elasticity of RA concrete. However for Fly ash concrete, steam curing increased the modulus of elasticity of RA concrete when compared to water cured concrete.

Long term deformations

PFA is generally known to reduce the drying shrinkage and swelling deformations in concrete. Ravindrajah and Tam [20 b] found that the addition of fly ash reduced the increase in the drying shrinkage associated with RCA concrete by 30%. The results of this study [20b] are shown in Table 2.11.

Kou et al [105, 106] showed that drying shrinkage increased with an increase in recycled aggregate content. The introduction of fly ash as a partial replacement of cement reduced the drying shrinkage values of concrete. An initial steam curing regime also reduced the drying shrinkage of concrete containing recycled aggregates [106]. The results from this study [106] are shown in Figure 2.18.

On the other hand a study by Corinaldesi et al [108] where 50% of the amount of fine aggregates in RCA concrete was replaced by fly ash showed that fly ash increased the amount of micro pores in the pore structure of the concrete, because of the higher paste content as a result of the fly ash addition, which caused the increase of the shrinkage of concrete.

No data was available on the effect of fly ash on the swelling of RCA concrete.

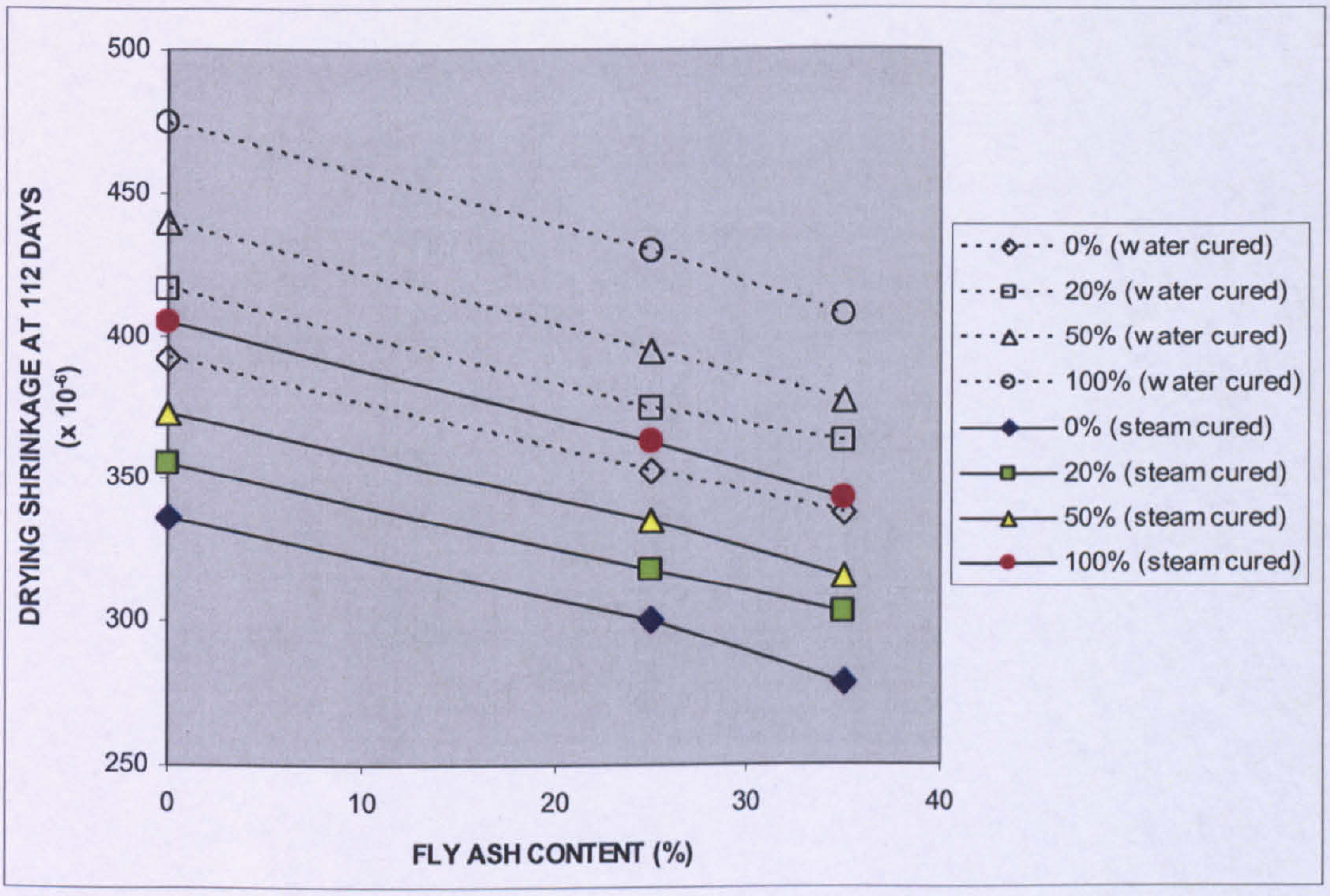


Figure 2.18 Drying shrinkage (at 112 days) of concrete (water and steam cured) prepared with different fly ash and RCA contents [106].

2.4.2.3.4 Durability properties

Initial surface absorption

The permeability of fly ash concrete was reported to be substantially lower than Portland cement concrete. This is due to the pore refinement that occurs as a result of the long term pozzolanic action of fly ash as well as its physical contribution. Initially fly ash concrete can have a higher permeability than Portland cement concrete with a similar water/cement ratio (on the basis of total cementitious material). This is due to the slow reaction of fly ash in the concrete. However with time fly ash concrete becomes less permeable [74]. The reduced permeability of concrete can reduce the rate of entry into concrete of water, corrosive chemicals, oxygen and carbon dioxide.

Ravindrajah and Tam [20 b] stated that fly ash is capable of modifying the pore structure of the cement paste matrix resulting in a decrease in permeability of RCA concrete. Sani et al [104] also reported that the use of RCA causes an increase in the total porosity of concrete which can be attenuated by fly ash addition.

Carbonation depth

The silica in the fly ash reacts with calcium hydroxide $Ca(OH)_2$ resulting from the hydration of cement. As a result of this fly ash concrete has a lower $Ca(OH)_2$ content in the hardened cement paste. Thus, a smaller amount of CO_2 is required to remove all the remaining $Ca(OH)_2$ which may entail a more rapid carbonation in fly ash concrete. However the use of fly ash also results in a cement paste with a denser structure which can also slow the carbonation of concrete down. Therefore the rate and extent of carbonation of fly ash concrete will depend on which of these two effects is dominant, which in turn depends on various factors, such as the method and period of curing [78].

Corinaldesi et al [109] found that replacing a portion of the fine aggregate content by fly ash has a strong positive contribution to the carbonation resistance of NA concrete due to the refinement of the pore system resulting in very low permeability. RCA concrete with and without fly ash had lower carbonation depths than conventional concrete but higher than conventional concrete made with fly ash. Using fly ash in RCA concrete slightly reduced its carbonation resistance.

Corinaldesi et al [109] made two equal strength mixes; the first was made with natural aggregates and the second with recycled aggregates. The second series of mixes consisted of the same mixes; however in the first mix with the conventional aggregates an amount fly ash equivalent to the amount of cement was added. In the second mix an amount of its fine aggregate content was replaced with fly ash by an amount equivalent to the amount of cement used. It was found that the fly ash had positive effect on the carbonation resistance in the presence natural aggregates more than recycled aggregates. The use of fly ash in the RCA concrete increased slightly the carbonation depth of the concrete. Results from this study [109] are graphically illustrated in Figure 2.19.

Chloride penetration

Fly ash concrete is generally more resistant to chloride ingress when compared with Portland cement concrete due to its reduced permeability thus reducing the rate of corrosion of steel in concrete [78].

Kou et al [105, 106] showed that the resistance of concrete against chloride ion penetration decreased as the recycled aggregates content increased, however the incorporation of fly ash as partial cement replacement increased the resistance to chloride ion penetration. This was significantly apparent at 90 days. It was also found that initial steam curing increased the resistance of recycled aggregate concrete with or without fly ash.

Corinaldesi et al [109] reported that using recycled aggregates has a detrimental effect on the concrete permeability to chloride due to their porosity. Reducing the water/cement ratio of RCA concrete to compensate for the loss in strength has a positive influence on the resistance against chloride penetration. In fact the chloride resistance of concrete with a water/cement ratio of 0.3 made solely of recycled aggregates was twice as high as the chloride resistance of concrete with a water cement ratio of 0.6 made solely of natural aggregates. Replacing a portion of the fine aggregate content in the mix by fly ash reduced the depth of penetration of chloride in concrete made with either natural or recycled aggregates. Results from this study are graphically illustrated in Figure 2.20.

In another study [108], it was found that the addition of fly ash as replacement of fine aggregates, even in the presence of concrete cracks decreased the corrosion rate values in very porous concrete (w/c ratio = 0.8) to equal those obtained in good quality concrete (w/c ratio = 0.45). This is attributed to the pozzolanic action of fly ash which lowers the pore solution alkalinity, rather than its effect on reducing the concrete's porosity.

Sulphate attack

Alumina and lime especially when present in the glass part of the fly ash may provide a long term source of material which can react with sulphates to form expansive ettringite [75]. However, using fly ash in concrete improves its sulphate resistance mainly through the removal of calcium hydroxide, resulting in the decrease of Calcium hydroxide available for reaction with sulphates. Moreover fly ash improves the permeability of concrete preventing the ingress of sulphates into the concrete [78].

No data was available on the effect of fly ash on the resistance of RCA concrete to sulphate attack.

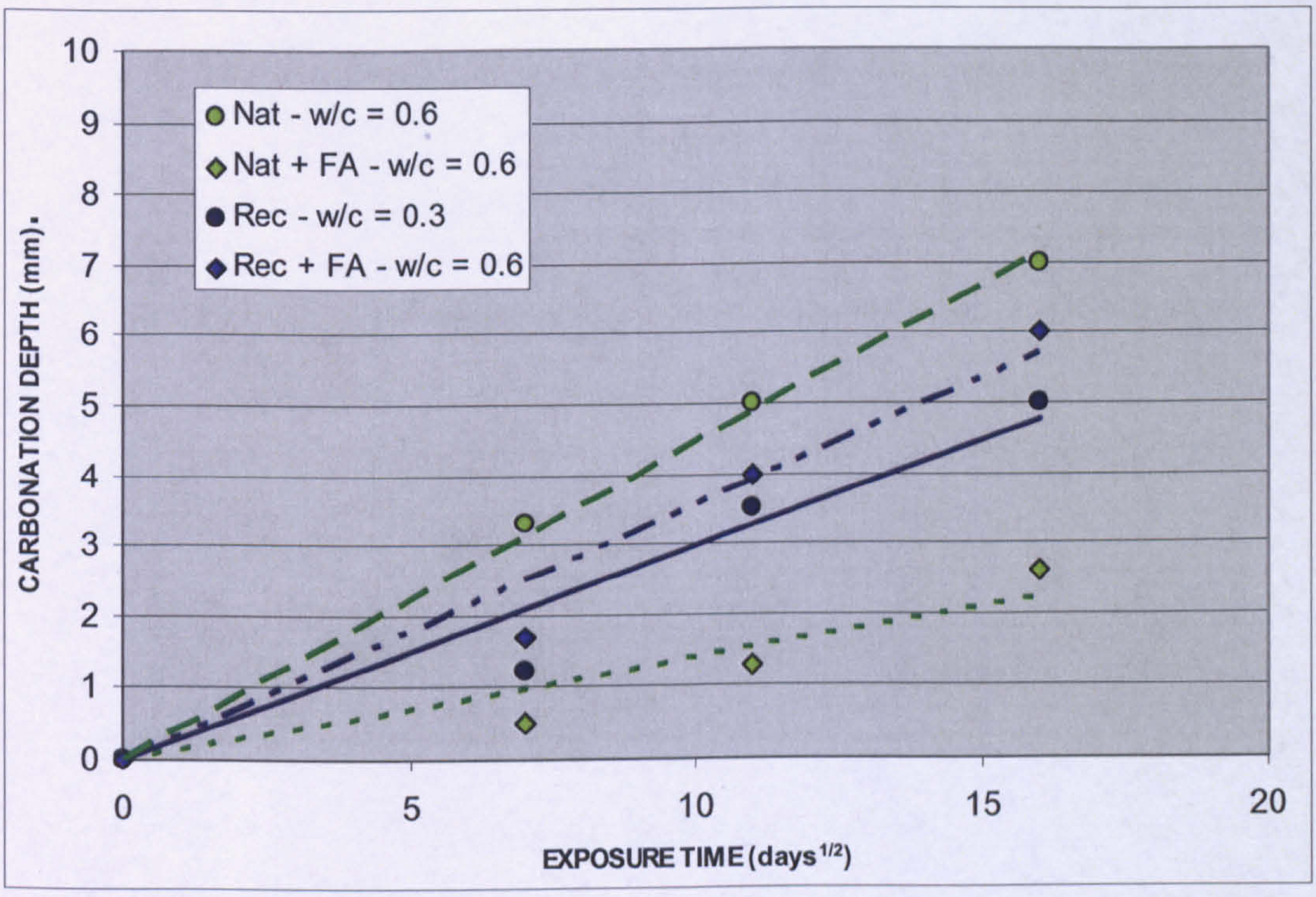


Figure 2.19 Effect of fly ash on the carbonation of natural and RCA concrete [109].

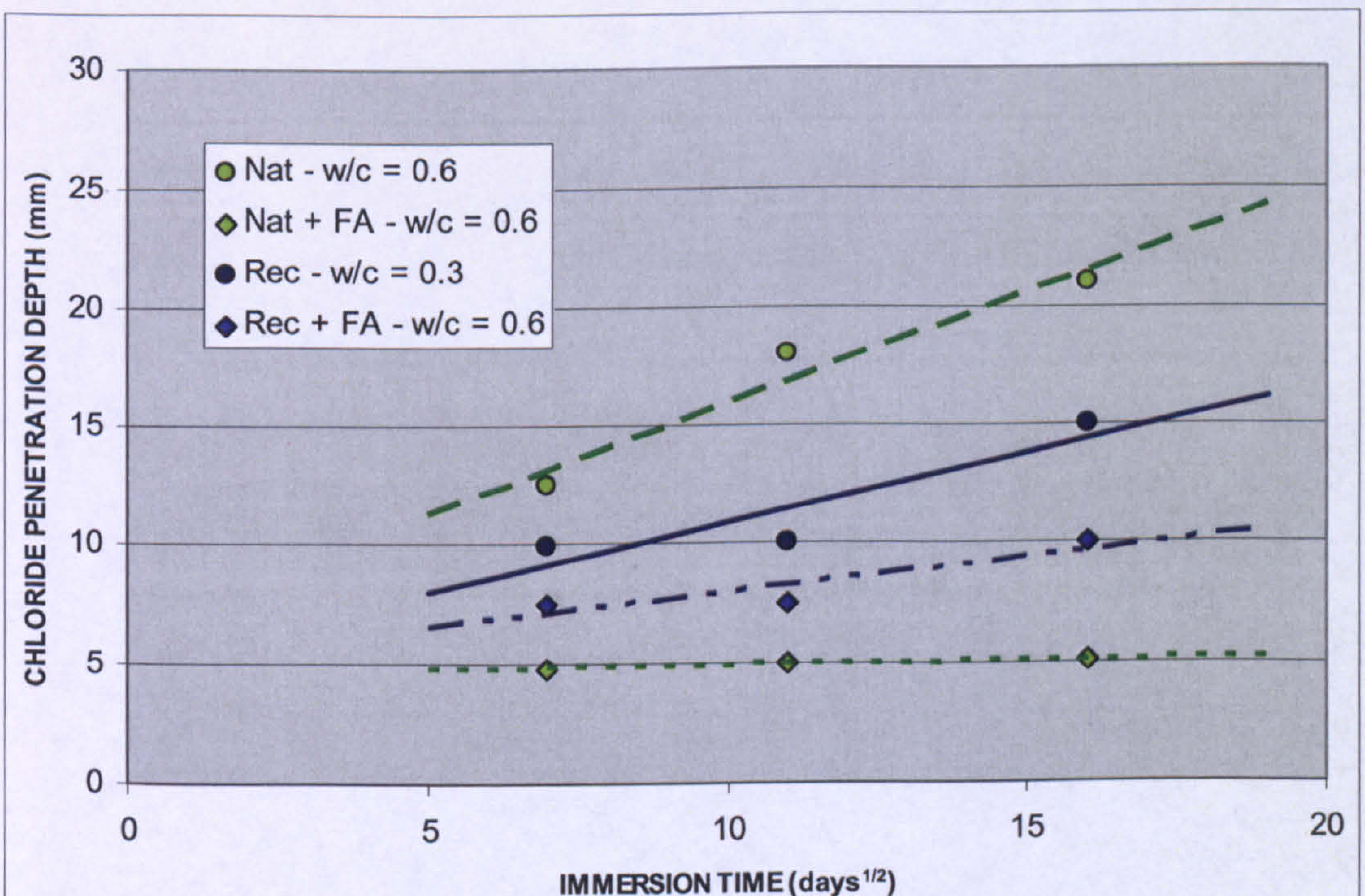


Figure 2.20 Effect of fly ash on the chloride resistance of natural and RCA concrete [109].

2.4.3 SILICA FUME

2.4.3.1 Silica fume production

Silica fume, also known as microsilica or condensed silica fume is a by-product of the manufacture of silicon and ferrosilicon alloys from high purity quartz and coal in electric arc furnaces. These metals are used in many industrial applications including aluminium and steel production, computer chip fabrication, and the production of silicones, which are widely used in lubricants and sealants [104]. The silica fume is formed, when the Silicon monoxide (SiO) gas escaping from silicon and ferrosilicon alloys plants resulting from the reduction of high purity quartz in the electric arc furnaces at temperatures of over 2000°C mixes meets oxygen in the upper parts of the furnace. The escaping SiO gas oxidises and condensates in the form of extremely fine particles of amorphous silicon dioxide (SiO_2) forming the major part of the smoke or fume from the furnace. Hence the different names given for the material, silica fume or condensed silica fume. The silica fume is collected in large bags in the baghouse and sold [77].

Figure 2.21 shows the schematic of Silica fume production and Figure 2.22 shows the schematic of a smelter for the production of silicon metal and ferrosilicon alloy [77].

Because of its very high fineness, silica fume has a very low bulk density (200 to 300 kg/m^3) and is therefore difficult and expensive to handle. For this reason it is supplied in the densified form of micropellets, which are agglomerates of the individual particles produced by aeration (bulk density of 500 to 700 kg/m^3) or it is supplied in the form of a slurry containing equal parts of water and silica fume by mass (bulk density of 1300 to 1400 kg/m^3).

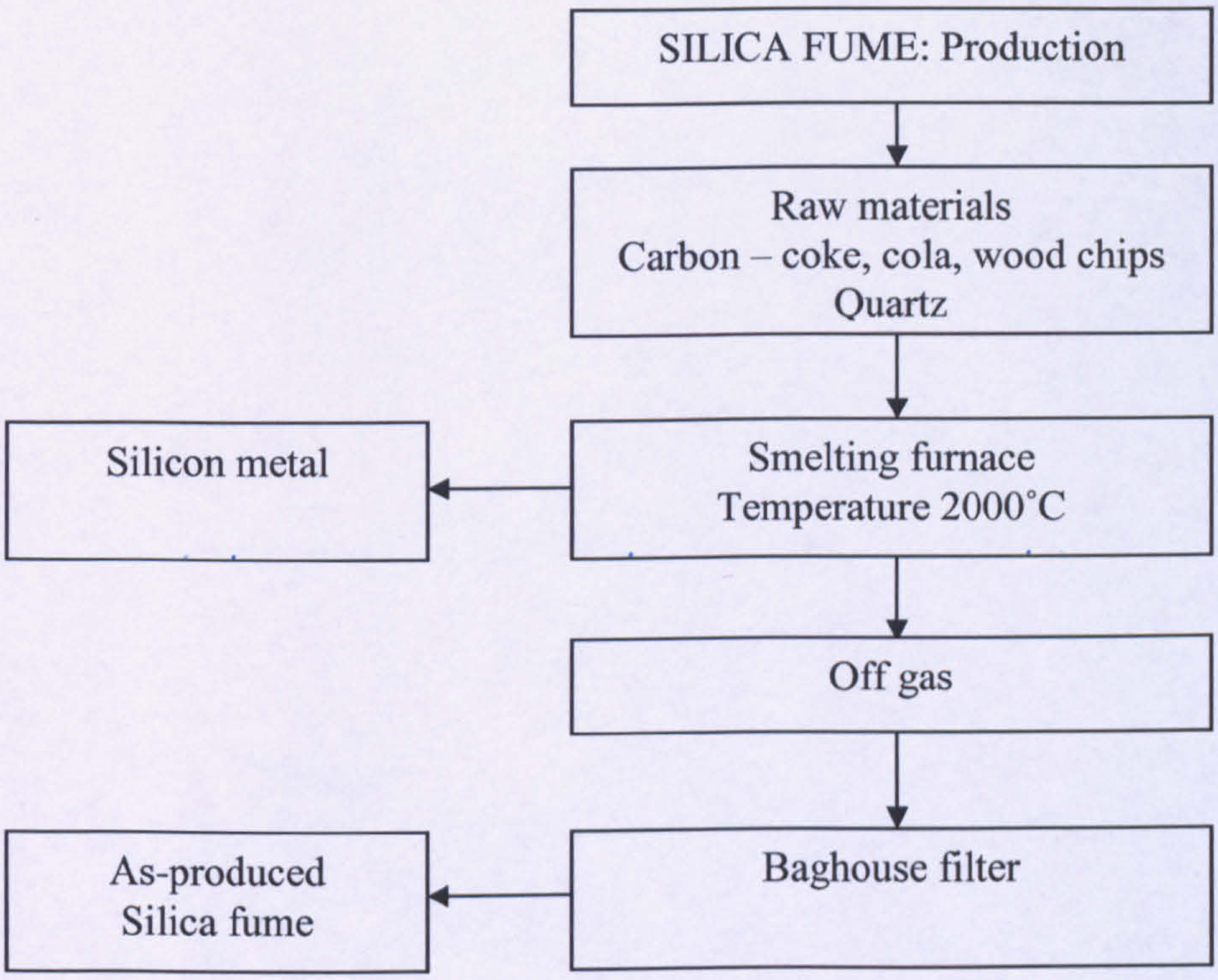


Figure 2.21 Schematic of silica fume production [77].

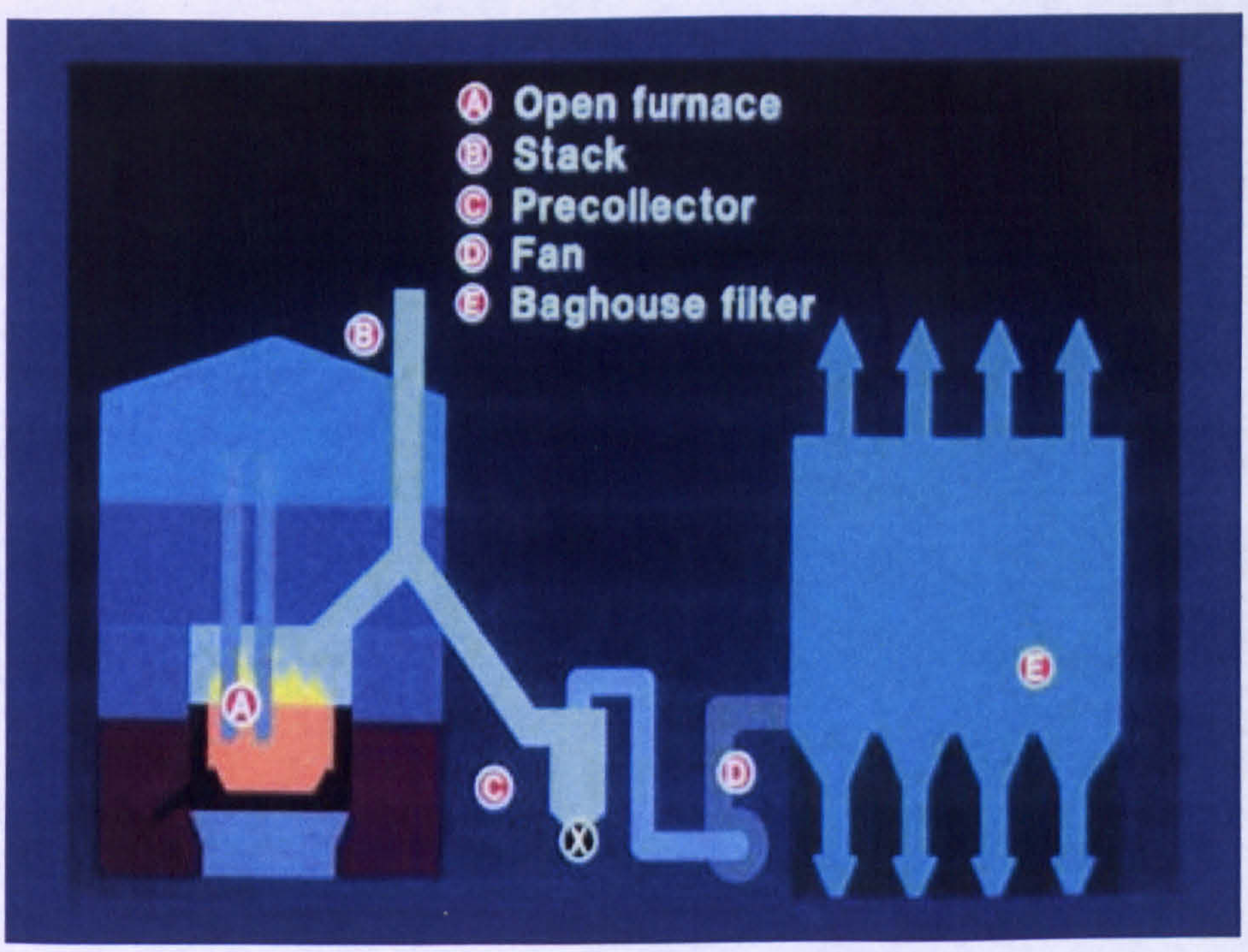


Figure 2.22 Schematic of a smelter for the production of silicon metal and ferrosilicon alloy [77].

Silica fume particles are extremely small, with more than 95% of the particles being less than 1μm. The ACI 234 R, Guide for the use of silica fume in concrete, estimates that for a 15% silica fume replacement of cement, there are approximately 2,000,000 particles of silica fume for each grain of Portland cement. The particle size and the high amorphous silicon dioxide content (>85%) of silica fume are the main factors contributing to the physical and chemical contributions of silica fume in concrete [77].

2.4.3.2 History of Silica Fume

In 1948, Researchers in Norway identified the potential of silica fume to be used as a concrete admixture. The first field experiment on the use of silica fume in concrete involved the Blindtarmen Tunnel in Oslo in 1952 and the first standard on the use of condensed silica fume as an addition of 10% by mass of cement was permitted in Norway in 1976 [76].

Before the mid 1970s, nearly all silica fume was discharged into the atmosphere. After environmental concerns necessitated the collection and landfilling of silica fume, it became economically justified to use silica fume in various applications. Silica fume has been used as an addition to concrete for some 30 years. However until recently only a few international standards have been available for the specification of the material. In the UK, non-UK National Standards for silica fume were used until 2005, when the EN 13263, a harmonised European standard for silica fume, was introduced.

This standard is new to the UK industry and sets out the minimum requirements to ensure the production of Silica Fume of suitable quality for use as a type II addition in concrete as per EN 206-1 and BS 8500. The requirements set in this standard for silica fume are shown in Table 2.12.

Table 2.12 Requirements for silica fume given in EN 13263 1 [79].

Property	EN 13263 – 1 Requirements	Method of Determining Requirement
Chemical Requirements		
Silicon Dioxide (SiO_2), min	85%	BS EN 196 2
Element Silicon (Si), max	0.4%	ISO 9286
Free Calcium Oxide, (C_aO), max	1.0%	BS EN 451 1
Sulfate (SO_3), max	2.0%	BS EN 196 2
Total Content of Alkalis, "Na_2O Equivalent"	Shall be declared by producer	BS EN 196 2
Chloride (Cl^-), max	0.3%	BS EN 196 2
Loss on Ignition, max	4.0%	BS EN 196 2
Physical Requirements		
Specific Surface m^2/g	15 to 35	ISO 9277
Dry Mass Content in Slurry Variation, max	±2 %	5.3.2 of BS EN 13263 1
Activity Index, min	100%	5.3.3 of BS EN 13263 1

2.4.3.3 Silica Fume concrete

2.4.3.3.1 Pozzolanic properties of Silica fume

Because of its chemical properties (high amorphous silicon dioxide SiO_2 content), silica fume is a very reactive pozzolan. As the Portland cement in concrete begins to react chemically, it releases calcium hydroxide. The silica fume reacts with the calcium hydroxide to form additional binder material called calcium silicate hydrate

(C-S-H). This additional binder material improves the hardened properties of silica fume concrete.

Silica fume dissolves in a saturated solution of calcium hydroxide within few minutes [82]. As soon as the pore water is saturated with calcium hydroxide, calcium silicate hydrate is formed on the surface of the silica fume particles. This reaction proceeds at a high rate. For concrete containing 10% silica fume by mass of the total mass of the cementitious material, one half of the silica fume was observed to react in 1 day, two thirds during the first 3 days however the remaining reaction is very slow with only three quarters reacted after 90 days [83].

2.4.3.3.2 Fresh properties

It is well known that the water demand in concrete increases as the size of particles of sand used in the mix becomes smaller as more water is needed to wet the sand particles. Silica fume particles are very small, for this reason the surface area of silica fume is very large. Similarly to the sand, the large surface area of the silica fume particles when used in concrete increases the capacity of the mix to absorb water resulting in an increase in water demand. To maintain the required w/c ratio and workability of a silica fume mix, it is necessary to use a water reducing admixture or a superplasticizer especially in low w/c ratio concretes [78].

Using silica fume makes the mix more cohesive and therefore less prone to segregation when compared to concrete with no silica fume. As a consequence of the strong cohesiveness, silica fume concrete exhibits very little bleeding or even none because of the high surface area of silica fume and the usually very low water content of silica fume concrete [77]. Unless preventive measures are taken, the reduction in bleeding can lead to plastic shrinkage cracking under drying conditions [78].

The cohesiveness of the silica fume concretes also affects the slump. A Silica Fume mix needs a slump 25 to 50 mm higher than a Portland cement mix only to be capable of similar compaction [77, 80, 81]. Silica fume mixes can also be very sticky, however as soon as vibration is applied, the mix becomes 'mobile' [80].

2.4.3.3.3 Engineering properties

Compressive strength

In addition to the pozzolanic properties of silica fume, Silica fume contributes to the progress of hydration of the Portland cement due to the extreme fineness and the large surface area of its particles which provide nucleation sites for calcium hydroxide. This allows early strength development to take place [78].

The contribution of silica fume to the early strength development (up to 7 days) is also probably through acting as filler thus improving packing and the interfacial zone with the aggregate [85, 86]. This phenomenon is referred to as particle packing or micro – filling. Even if the silica fume did not react chemically, the micro filler effect would bring about significant improvements in the nature of concrete [77].

The high early reactivity of silica fume results in a faster use of the mix water which may cause self-desiccation. Also, the dense microstructure of the hydrated cement paste makes it difficult for the water to penetrate the concrete to reach the un-hydrated Portland cement and silica fume particles [84]. Consequently, the rate of compressive strength development of silica fume concrete is much slower than Portland cement concrete after 28 days [77].

Ravindrajah and Tam [20 b] studied the effect of silica fume on RCA concrete. The addition of silica fume helped in compensating the reduction in the compressive that occurs when RCA is used in concrete. In the first series of mixes made for the study, it was found that an RCA concrete (w/c = 0.57) with a 5% addition of silica fume by mass of cement achieved a 4% and 25% higher compressive strength at 28 days when compared to conventional concrete (w/c = 0.57) and RCA concrete (w/c = 0.57) with no silica fume respectively. Results of the engineering properties of the first series of mixes from this study [20b] are presented in Table 2.13.

The second series of mixes consisted of a conventional concrete (w/c = 0.55), an RCA concrete with a reduced water cement ratio (w/c = 0.48) and a third mix similar to the second one but including an addition of 10% silica fume by mass of cement. It was found that reducing the w/c ratio helps mitigate the loss of strength that occurs with the use of RCA, the RCA concrete with a reduced w/c ratio achieved a 9 and 14% higher compressive strength than conventional concrete at 28 and 90 days respectively. The 10% addition of silica fume to the RCA concrete helped increase the compressive strength even higher. RCA concrete with silica fume achieved a 12 and 19% higher compressive strength than conventional concrete at 28 and 90 days respectively. Results of the engineering properties of the second series of mixes from this study [20b] are presented in Table 2.14.

Similar findings were reported by Yamato et al [20 o] who investigated the effect of silica fume on the compressive strength of RCA concrete. Silica fume was found to improve the compressive strength of the RCA concrete which exceeded the compressive strength of the conventional concrete when the replacement of cement by silica fume in the mix was 10 or 20%.

Adjukiewicz and Kliszczewicz [56] reported that the replacement of 10% of the cement content by silica fume in concrete with natural or recycled aggregates resulted in an increase of the compressive strength. It was also found that the replacement of natural aggregates by recycled aggregates in concrete resulted in a decrease of compressive strength regardless of the type of cement used. Concrete made with RCA derived from low strength concretes had a slightly reduced compressive strength when compared to concrete made with RCA derived from high strength concretes.

Corinaldesi and Moriconi [107] looked at the effect of silica fume when used in RCA concrete as a replacement of proportion of fine aggregate equivalent to 15% of the cement mass of the RCA concrete with no silica fume. The authors found that the strength development of the RCA concrete without silica fume (w/c = 0.40) slowed down after 14 days with respect to the reference concrete made with natural aggregate (w/c ratio = 0.56), thus achieving a lower compressive strength at a later age. On the other hand, this effect was not evident in RCA concrete made with silica fume (w/c ratio = 0.40). The silica fume due to its densifying effect and pozzolanity help ed improve the compressive strength of RCA concrete to exceed the compressive strength of the reference concrete.

Flexural strength

Using silica fume in concrete as a cement replacement or addition will result in an increase of the compressive and flexural strengths of the concrete. However, the relationship between compressive and flexural strength of concrete is unaffected by the use of silica fume [80, 87].

Ravindrajah and Tam [20 b] studied the effect of silica fume on RCA concrete. The addition of silica fume helped in compensating the reduction in the flexural strength which occurs when RCA is used in concrete. In the first series of mixes made, it was found that an RCA concrete (w/c = 0.57) with a 5% addition of silica fume by mass of cement achieved a 29% and 44% higher flexural strength at 28 days when compared to conventional concrete (w/c = 0.57) and RCA concrete (w/c = 0.57) with no silica fume. Flexural strength results for the first series of concrete mixes are presented in Table 2.13.

The second series of mixes consisted of a conventional aggregate (w/c = 0.55), an RCA concrete with a reduced water cement ratio (w/c = 0.48) and a third mix similar to the second one but including an addition of 10% silica fume by mass of cement. It was found that reducing the w/c ratio or the use of silica fume as an addition resulted in an increase of the flexural strength of RCA concrete when compared to conventional concrete by 22 and 31% respectively. Flexural strength results for the second series of concrete mixes are presented in Table 2.14.

Modulus of elasticity

The modulus of elasticity of concrete containing silica fume was reported to be higher when compared to a Portland cement concrete of equal strength [80].

Ravindrajah and Tam [20 b] found that the use of silica fume as a cement replacement did not bring any improvements to the modulus of elasticity of RCA concrete as this is mainly affected by the aggregate modulus. The modulus of elasticity of RCA concrete was about 75 to 87% of that of natural aggregate concrete. Modulus of elasticity results for the various concrete mixes from this study are presented in Table 2.13 and 2.14.

Adjukiewicz and Kliszczewicz [56] reported a slight decrease in the modulus of elasticity of concrete containing 10% silica fume cement replacement when NA was fully substituted with RCA. This reflects the lower compressive strength of RCA concrete when compared to conventional concrete.

Similar findings were reported by Corinaldesi and Moriconi [107] who stated that the static modulus of RCA concrete is not significantly influenced by the presence of mineral admixture used but depended substantially on the compressive strength of the concrete.

Long term deformations

Shrinkage of concrete containing silica fume was reported to be to some extent larger than shrinkage of Portland cement concrete [84].

Ravindrajah and Tam [20b] found that the addition of silica fume reduced the increase in the drying shrinkage associated with RCA concrete. The drying shrinkage values of

Table 2.13 Effect of 5% fly ash addition on the engineering properties on RCA concrete [20 b].

Property [test age in days]	Mix (w/c = 0.57)		
	NA PC	RCA PC	RCA 5% SF
Compressive strength (MPa) [28]	33.8	28.0	35.1
Flexural strength (MPa) [28]	4.88	4.15	6.29
Static modulus (MPa) [28]	29.0	21.5	22.0
Shrinkage (Microstrain) [91]	204	430	306

Table 2.14 Effect of 10% fly ash addition on the engineering properties on RCA concrete [20 b].

Property [test age in days]	w/c = 0.55	w/c = 0.48	
	NA PC	RCA PC	RCA 10% SF
Compressive strength (MPa) [28]	35.5	38.7	39.8
Flexural strength (MPa) [28]	4.26	5.19	5.56
Static modulus (GPa) [28]	30.4	26.5	26.5
Shrinkage (Microstrain) [91]	360	532	508

RCA concrete with a 5% addition of silica fume was lower than RCA concrete with no silica fume by 29%. Shrinkage results for the various concrete mixes from this study [20b] are presented in Tables 2.13 and 2.14.

Adjukiewicz and Kliszczewicz [56] reported that the full replacement of NA by RCA in silica fume concrete resulted in an increase in shrinkage. However silica fume concrete had a significantly lower shrinkage when compared to PC concrete regardless of the RCA content.

No data was available on the effect of Silica fume on the swelling of RCA concrete.

2.4.3.3.4 Durability properties

Initial surface absorption

As the Portland cement in concrete begins to react chemically, it releases calcium hydroxide. The Silica fume reacts with the calcium hydroxide to form additional binder material called calcium silicate hydrate (C-S-H). The C-S-H improves the structure of the cement paste by filling the voids thus improving the permeability of the concrete.

The continuing pozzolanic activity of silica fume results in a reduced permeability especially under adequate curing conditions. It results in a reduction in the pore size of the hydrated cement paste thus reducing the permeability of concrete but not necessarily its total porosity [84]. Generally for concretes of equal strength, the reduction in permeability due to a longer period of curing is greater in silica fume concrete when compared to Portland cement concrete [88].

Ravindrajah and Tam [20 b] stated that pozzolanas are capable of modifying the pore structure of the cement paste matrix resulting in a decrease in permeability of concrete, thus in turn improving the durability of the RCA concrete.

Carbonation

Similarly to fly ash, The silica in the silica fume reacts with calcium hydroxide ($Ca(OH)_2$) resulting from the hydration of cement. As a result of this silica fume concrete has a lower $Ca(OH)_2$ content in the hardened cement paste. Thus, a smaller amount of CO_2 is required to remove all the remaining $Ca(OH)_2$ which may entail a more rapid carbonation in fly ash concrete. However the use of silica fume also results in a cement paste with a denser structure which can also slow the carbonation of concrete down. Therefore the rate and extent of carbonation of silica fume concrete will depend on which of these two effects is dominant, which in turn depends on various factors, such as curing method and period [78].

No data was available on the effect of silica fume on the carbonation resistance of RCA concrete.

Chloride penetration

Silica fume concrete, due to its low permeability, has a greater resistance to chloride ingress thereby reducing the corrosion of steel. Using 5 to 10% of silica fume in the total cement content reduces greatly the ingress of chloride ions into concrete [89, 90]. The reduced permeability of silica fume concrete can result in many years of extended life for a structure.

No data was available on the effect of silica fume on the chloride resistance of RCA concrete.

Sulphate resistance

The sulphate resistance of silica fume concrete is good, partly due to its low permeability and partly to a lower content of calcium hydroxide and alumina, which react with silica fume to create C-S-H [78].

No data was available on the effect of silica fume on the resistance of RCA concrete to sulphate attack.

2.5 SUMMARY OF MAIN FINDINGS

- The worldwide drive for a more sustainable construction had a great impact on the concrete sector. The use of secondary and recycled materials in the manufacture of concrete has significantly increased as a result of government and industry initiatives and research.

- RCA are made by crushing concrete debris derived from C&D waste. The grading of RCA was generally found to be within the limits set for aggregates to be used in concrete. It has been reported that the source of concrete used for the production of RCA does not affect the grading of RCA. Only few studies reported a slight increase in the fine particle fraction with the decrease in the strength of original concrete. On the other hand the grading of RCA can be affected by the type of crushers used.

- The particle shape of RCA was generally found to have a rougher surface and to be more angular than NA. The crushing method and crusher type used were found to influence the shape of RCA. Some studies reported that extra crushing or refinement of the RCA resulted in rounder particles with a smoother surface.

- RCA is composed of the attached cement paste and particles of the original aggregate. The amount of attached cement paste in RCA increases with the decrease in aggregate size. The amount of attached cement paste was generally reported not to be influenced by the source of the original concrete. On the other hand, few studies showed that RCA derived from low strength concrete had less attached cement paste than RCA derived from high strength concrete. The amount of attached cement paste can be reduced by extra crushing.

- The density of RCA is reported to be lower than the density of conventional aggregate. This is mainly attributed to the low density of the attached cement paste of the RCA. There exists a good correlation between the amount of attached cement paste and the density of RCA. The density of RCA was found to be neither affected by the source of concrete nor by the type of crusher used.

- The water absorption of RCA has been reported to be higher than that of NA. This is mainly attributed to the high water absorption and porosity of the attached cement paste of RCA. The type of crusher used was not found to have a great influence on the water absorption of RCA. Conflicting findings were reported regarding the effect of the source of aggregate on the water absorption of RCA.

- Although RCA was found to have a lower mechanical performance when compared to conventional aggregates, it generally satisfied the limitations set for aggregates to be used in concrete. This low mechanical performance is again due to the weak and soft attached cement paste of RCA.

- RCA can contain different types of contaminants, depending on the application the original concrete was used for, which could affect certain properties of the concrete made with these aggregates.

- RCA was reported to affect the workability of concrete, due the high water absorption and angularity of its particles. RCA concrete was generally found to be harsher, less workable and less cohesive compared to NA concrete. The workability of RCA concrete can be improved by pre-soaking the aggregates or using extra water in the mix to allow for the water absorption of RCA particles. RCA concrete was also reported to have a faster loss of workability and shorter setting times. No data was available on the effect of PFA or silica fume on the workability of RCA concrete.

- RCA was found to reduce the compressive strength of concrete when it is used to replace more than 30% of the natural coarse aggregate in the mix. The reduction in compressive strength increases gradually with the increase in the RCA content in the mix. Nevertheless the rate of strength development of RCA concretes is similar to conventional concrete. The reduction in compressive strength due to the use of RCA can be compensated for by reducing the water cement ratio of the mix or by using pozzolanic additions such as fly ash or silica fume.

- The compressive strength of RCA concrete is mainly affected by the strength of the original concrete used to produce the RCA. If the strength of the original concrete is the same or higher than the required strength for the RCA concrete, then the strength of the concrete can be as good or higher than the design strength. If the strength of the original concrete is lower than the required strength, then the strength of the RCA concrete will be lower than the required strength.

- Other factors reported to have a potential influence on the compressive strength of RCA concrete are the presence of impurities and the curing and mixing methods.

- The use of RCA was found to marginally affect the flexural strength of concrete. In fact it can be said that the flexural strength is the least affected engineering concrete property by the use of RCA. Most researchers reported a slight decrease in flexural strength; this can be simply accounted for by the reduction in compressive strength due to the use of RCA. The flexural strength of RCA concretes was found to be similar or higher than for equal strength NA mixes. The presence of impurities in RCA was reported to reduce the flexural strength of RCA concrete.

- The use of fly ash or silica fume in RCA concrete was found to improve its flexural strength, resulting in a higher flexural strength when compared to conventional concrete, this is attributed to the increase in the compressive strength of the concrete when fly ash and silica fume are used.

- The modulus of elasticity of RCA concretes was found to be always lower than the corresponding conventional concretes due to the low modulus of elasticity of the RCA particles. RCA were reported to behave like conventional lightweight aggregates. The reduction in the modulus of elasticity was reported to gradually increase when more than 30% of natural aggregates were replaced by RCA. The modulus of elasticity of RCA concretes was found to be lower even when compared to the modulus of elasticity of equal strength NA mixes.

- Other factors reported to have a potential influence on the modulus of elasticity of RCA concrete are the strength of the original concrete, the presence of impurities and the curing method.

- The use of additions such as fly ash and silica fume does not bring any improvements to the modulus of elasticity of RCA as this is mainly affected by the modulus of elasticity of the RCA.

- The drying shrinkage in RCA concrete was always found to be larger than in NA concrete. The drying shrinkage value of RCA concrete gradually increases with an increase in the RCA content in the mix. This increase starts when more than 30% of natural aggregates are replaced by RCA. Using shrinkage reducing agent was found to reduce the drying shrinkage values of RCA concrete to equal those of NA concrete.

- Other factors reported to have a potential influence on the drying shrinkage of RCA concrete are the age and strength of the original concrete, the presence of impurities and the curing method.

- The use of fly ash and silica fume can help reduce the increase in the drying shrinkage values associated with the use of RCA.

- The use of RCA was found to affect the swelling of concrete in a similar way to the drying shrinkage. No data was available on the effect of Fly ash or silica fume on the swelling of RCA concrete.

- The replacement of up to 30% of the amount of natural aggregates by RCA in the mix seems to have no effect on the initial absorption values of concrete. However above this limit, it was found that the use of RCA in concrete results in a gradual increase in the initial surface absorption values. This is mainly attributed to the increased proportion of cement paste in RCA which gives it a high water absorption rate.

- Many studies showed that the compressive strength of the original concrete and the curing method affect the initial surface absorption values of RCA concrete.

- Fly ash and silica fume were reported of being capable of decreasing the permeability of RCA concrete by modifying the pore structure of the cement paste matrix.

- Most of the studies looking at the effect of RCA on the carbonation resistance of concrete reported that the use of RCA in concrete has no effect on its carbonation resistance. Unlike other concrete properties, the carbonation resistance of RCA concrete was not found to be influenced by the compressive strength of the original concrete. However, the presence of certain impurities in RCA decreased the carbonation resistance of the concrete.

- Fly ash and silica fume react with $Ca(OH)_2$ (product of the hydration of cement) therefore lowering its content in the mix. For this reason, only a small amount of CO_2 is required to remove the remaining $Ca(OH)_2$ which can result in a rapid carbonation of concrete. On the other hand, the use of fly ash and silica fume in RCA concrete results in a cement paste with a denser structure which can slow down the penetration of CO_2 into the concrete. Therefore the effect of fly ash and silica fume on the carbonation of RCA concrete will depend on which of the two effects are dominant which in turn depends on many factors such as amount of addition used, the curing method and duration.

- Only a slight decrease in the chloride resistance was reported when Natural aggregates are replaced by RCA in concrete. The strength of the original concrete and the curing method were reported to affect the chloride resistance of RCA concrete.

- Fly ash and silica fume were reported to improve the chloride resistance of conventional concrete. Few studies showed that the use of fly ash can help improve the chloride resistance of RCA concrete. However, no data was available on the effect of using silica fume on the chloride resistance of RCA concrete.

- The use of RCA in concrete was found to affect the sulphate resistance of concrete in a similar way to its chloride resistance. Only the curing method was reported to influence the sulphate resistance of RCA concrete.

- Fly ash and silica fume were reported to improve the sulphate resistance of conventional concrete. However, no data was available on the effect of using fly ash or silica fume on the sulphate resistance of RCA concrete.

CHAPTER 3

RESEARCH PROGRAMME AND EXPERIMENTAL DETAILS

3.1 INTRODUCTION

This chapter briefly describes the experimental programme designed to establish the suitability of RCA for use in designated binary cement concrete mixes. The chapter is divided into two parts: The first part covers the different phases of the programme of work, whilst the second part describes the experimental details including materials used, mix proportions, preparation of specimens and testing procedures used for the testing of aggregates and concrete.

3.2 OVERALL RESEARCH PROGRAMME

The research programme was divided into three main phases (Figures 3.1 and 3.2) which are briefly described below. The main part of the research programme looks at the characteristics of RCA and the effect of various contents of RCA on equal strength BS 8500 designated concrete mixes made with binary cements.

Phase 1: Production and characterization of RCA

In the first phase, concrete rubble obtained from demolished concrete structures was crushed into RCA in a static recycling plant consisting of a primary and secondary crushers (Jaw and impact crushers respectively) and screens. The physical and mechanical properties of the NA and RCA used in the study were determined with the appropriate European and British standards. The characteristics of the RCA were compared with those of the NA used in the study as well as the requirements set in the current standards for aggregates to be used in concrete production.

PHASE 1: PRODUCTION AND CHARACTERIZATION OF RCA

PRODUCTION OF RCA

Source of the original concrete:

Demolished Concrete Structures

↓

AGGREGATE CHARACTERISATION

Physical Characteristics		Mechanical Characteristics
▪ Shape and texture ▪ Flakiness index ▪ Shape index ▪ Particle Size Distribution	▪ Particle Density and Water Absorption ▪ Loose Bulk Density and Voids	▪ Aggregate Crushing Value ▪ Aggregate Impact Value ▪ Ten per Cent Fines Value

Figure 3.1 Phase 1 of research programme.

Phase 2: Use of RCA in BS 8500 designated mixes made with binary cements

This phase examines the influence of various RCA contents on the fresh, engineering and durability properties of BS 8500 designated mixes made using binary cements.

The first stage of this phase was to design NA designated concrete mixes made with PC, PC/PFA and PC/SF cements.

The mix proportions for NA concrete mixes made with PC and PC/PFA were calculated using the conventional mix design method (BRE/DoE) for normal concrete [34].

For the NA designated concrete mixes made with PC/SF, A mix design method for

PC/SF mixes was developed based on the findings of a preliminary study of the effect of Silica fume, on the strength development of NA designated concrete mixes, when used as a substitute of 10% of the PC content by mass.

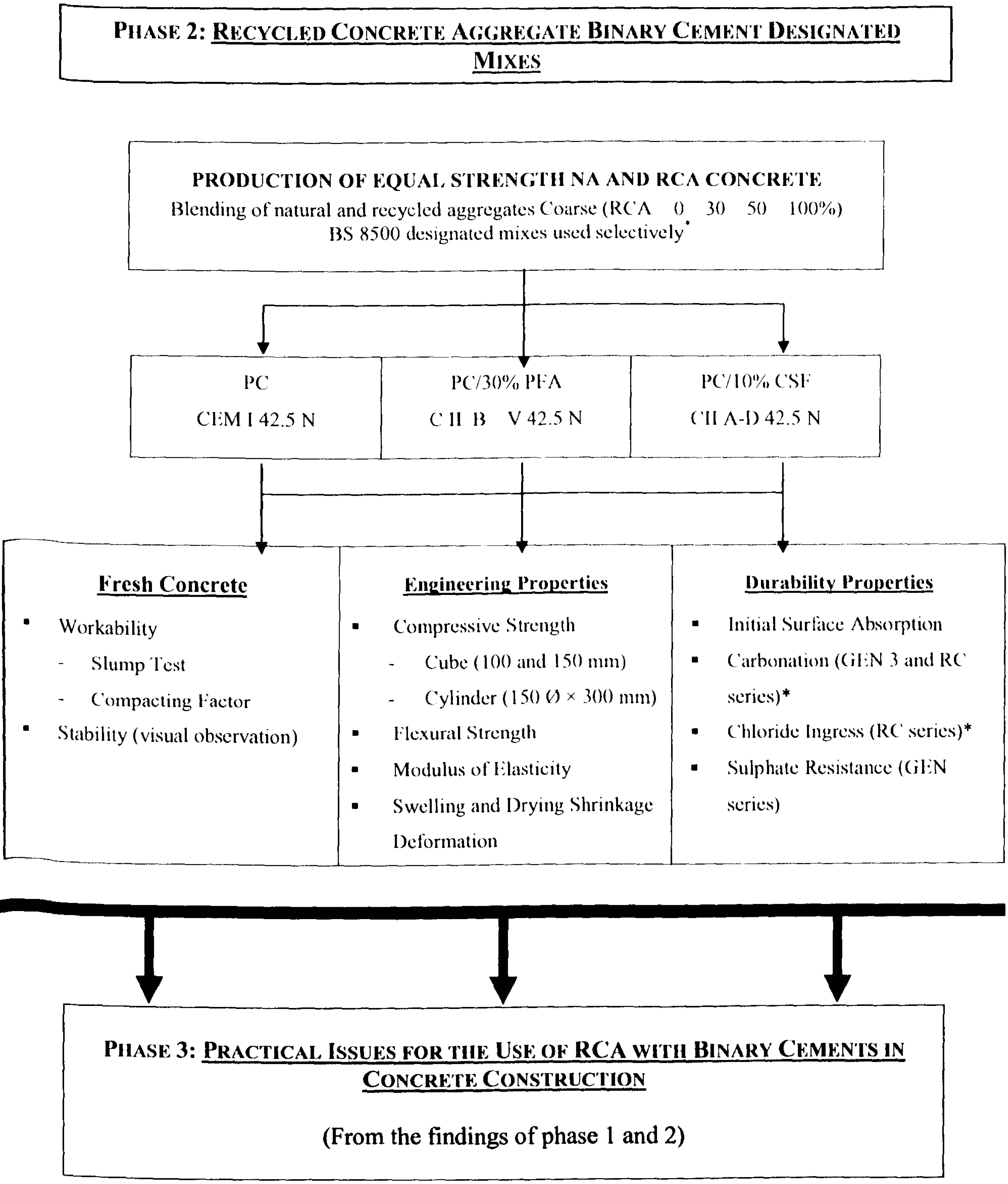
Thereafter, equal strength RCA designated mixes made with the cements selected for study were designed using a mix design method developed to take into account of the effect of RCA on the strength of concrete. This mix design method is based on the findings of previous studies looking at the effect of substituting NA with RCA in equal cement and water content concrete mixes [22, 26 g, 50].

Subsequently, a study was undertaken to determine the effect of RCA on the fresh, engineering and durability properties of equal strength RCA concrete mixes made with binary cements.

The fresh properties included workability (slump, compacting factor) and stability. The engineering properties included (i) Compressive Strength, (ii) Flexural Strength, (iii) Modulus of Elasticity, (iv) Drying Shrinkage Deformation and (v) Swelling Deformation. The durability properties included (i) Initial Surface Absorption, (ii) Carbonation Resistance, (iii) Chloride Ingress and (iv) Sulphate Attack.

Phase 3: Practical implications for the use of RCA in concrete construction

The last phase of the study is devoted to the practical implications of using RCA with binary cements in concrete construction. Instructions and guidelines for the use of RCA in PC and binary cement concretes are provided.



*GEN series include GEN 1 and GEN 3 designated mixes
RC series include RC 30, RC 35 and RC 40 designated mixes

Figure 3.2 Phases 2 and 3 of the research programme.

3.3 EXPERIMENTAL DETAILS

3.3.1 Materials

3.3.1.1 Cements

The composition and designation of the cements used in the study are shown in Table 3.1.

Portland Cement

Different batches of Portland cement (PC CEM I 42.5N), conforming to EN 197-1 from the same cement manufacturer, were used in this study. PC was ordered and delivered regularly, this has minimised the risk of using deteriorated cement.

Portland Cement / Pulverised Fuel Ash

A single batch of PFA conforming to BS 3892-1 [18] was used throughout the study (This is effectively an equivalent material to BS EN 450-1 : 2005 category S fly ash). The PFA was stored in air tight containers to minimise deterioration over time. The PC/PFA binary cement (CII-B-V) used in this study was a combination of PC conforming to EN 197-1 and 30% PFA conforming to BS 3892-1 [18] by mass, combined in the concrete mixer as per BS 8500.

Portland Cement / Silica Fume

A single batch of silica fume conforming to EN 13263-1 [79] was used throughout the study. The silica fume was used in a slurry form; the slurry was composed of 50% water and 50% silica fume powder by mass. The slurry was stored in air tight containers to minimise deterioration over time. The PC/SF binary cement (CII-A-D) used in the study was a combination 90% PC conforming to EN 197-1 and 10%

Silica fume conforming to BS EN 13263 1 by mass combined in the concrete mixer as per EN 206 - 1.

Table 3.1 Cements used in the study.

Cement composition	Designation
100% Portland Cement (100%)	CEM I 42.5 N (EN 197 1)
70% PC / 30% Pulverised Fuel Ash	CII B V 42.5 N (BS 8500)
90% PC / 10% Silica Fume	CII A D 42.5 N (EN 206 1)

3.3.1.2 Aggregates

Fine Aggregates

The fine aggregate used for all the mixes was natural sand with a size fraction ranging from 0 to 5mm.

Coarse Aggregates

Two types of coarse aggregates were used in the study, natural aggregate (NA) and Recycled Concrete Aggregate (RCA). Natural aggregate used was Thames Valley gravel with a size fraction of 20 5 mm. The RCA used was obtained from processing concrete debris from demolished concrete structures. The size fraction of the RCA was 20 - 5 mm. Details of the production procedures of RCA and the characteristics of the aggregates used are available in chapter 4.

3.3.1.3 Water

Normal tap water was used throughout the study in the manufacture of the concrete mixes. Distilled water was used where required for some tests (such as the initial surface absorption test and the chloride ingress test).

3.3.2 Mix Proportions

The study examined the use of RCA in the BS 8500 designated mixes. The designated mixes selected for the study are shown in Table 3.2. Concrete mixes proportioned using different proportions of RCA replacement (0, 30, 50, and 100 %) were used.

3.3.2.1 BS EN 206 – 1 Designated Mixes

PC Mixes

The conventional mix design method (BRE/DoE) was mainly used in the development of PC designated concrete mixes. The concrete mixes were proportioned to meet the requirements of minimum cement content and maximum water/cement ratio for designated mixes as per BS 8500 2 shown in Table 3.3.

The DOE method utilises British test data obtained at the Building Research Establishment, the Transport and Road Research Establishment, and the British Cement Association. It consists of 5 stages:

Stage 1 consists of determining the water cement ratio required to achieve the specified strength depending upon the coarse aggregates type and the cement type used.

Stage 2 consists of determining the free water cement content depending upon the type and maximum size of the aggregate to give a concrete of the specified slump.

Stage 3 determines the cement content of the mix from the water cement ratio and water content determined in the previous stages.

Stage 4 consists of determining an estimate of the density of the fully compacted concrete depending upon the free water content and the relative density of the combined aggregate in the saturated surface-dry condition (SSD). From this estimated density, the total aggregate content is estimated.

Stage 5 determines the fine and coarse aggregates contents depending upon the maximum size of the coarse aggregate, the required workability and the grading of the fine aggregate (defined by its percentage passing the 600 μm sieve).

Using modification factors obtained from previous studies on the effect of RCA on the strength of equal water cement ratio mixes, the w/c ratios of the NA concrete mixes were modified to take account of the effect of RCA on concrete in order to achieve equal strength RCA designated mixes [22, 26 g, 50]. The water cement ratio was adjusted only for mixes containing more than 30% RCA; the RCA when used below this limit does not affect the strength of the concrete. The water content of the mixes was unchanged, but the coarse and fine aggregates were adjusted to allow for the differences in cement content. The modification factors used for the PC RCA mixes and the mix proportions of the PC NA and RCA mixes used in the study are shown respectively in Table 3.4 and 3.5 respectively.

PFA mixes

The conventional mix design method (BRE/DoE) was mainly used in the development of PC/PFA designated concrete mixes. The DOE design method for PFA mixes regards the mass of PFA in a mix as providing strength equivalent to a smaller mass of cement and as a result uses a 'cementing efficiency factor', $k = 0.3$, where kF is the mass of Portland cement class 42.5 equivalent to a mass F of PFA.

Table 3.2 Designated concrete mixes from BS 8500 selected for the study.

BS 8500 Designated Mixes	DESIGNATED MIXES SELECTED		
	Mix	Characteristic Strength* N/mm^2	Specific Application from BS 8500 and Recommended Consistence
GEN Series (8 - 20 N/mm^2) ***Foundations, General Applications and Floors***	GEN 1	C8/10	General applications - Kerb bedding and backing (S1)* - Drainage works to give immediate support (S1)* - Other drainage works (S3)* - Over-site below suspended slabs (S3)* Foundations to be used in mild exposure - Blinding and mass fill concrete (S3)* - Strip footings (S3)* - Trench fill (S4)* and Mass concrete foundations (S3)* - House floors with no embedded metal: Permanent finish to be added e.g. a screed or floating floor (S2)*
	GEN 3	C16/20	- Garage floors with no embedded metal (S3)*
RC Series (25 - 50 N/mm^2) ***Reinforced, Pre-stressed Concrete and Floors***	RC 30	C25/30	- Fully buried reinforced foundations in mild exposure (S3)* - Wearing surface: light foot and trolley traffic (S2)*
	RC 35	C28/35	Use in moderate exposure
	RC 40	C32/40	Use in moderate exposure - Wearing surface: General industrial (S2)*

* Slump classes (for more detail refer to Table 5.1)

* $f_{c,cyl} / f_{c,cube}$

Therefore a mass of 42.5 Portland cement, C combined with a mass of PFA, *F* is equivalent to a mass of 42.5 Portland cement $C_1 = C + kF$.

The strength of the PFA concrete depends upon the water 'equivalent cement' ratio in the same way as Portland cement 42.5 concrete. PFA cement will have the same strength as a PC concrete of similar workability if:

$$W/(C + kF) = W_1/C_1$$

Where W, C, F are the free-water, cement and PFA contents respectively and W_1 and C_1 the free water and cement contents of the PC concrete.

As for the PC mixes, The DOE design method for PFA mixes utilises British test data obtained at the Building Research Establishment, the Transport and Road Research Establishment, and the British Cement Association. It also consists of 5 stages:

Stage 1 consists of determining the water 'equivalent cement' ratio required to achieve the specified strength depending upon the coarse aggregates type and the cement type used.

Stage 2 consists of determining the free water cement content depending upon the type and maximum size of the aggregate to give a concrete of the specified slump.

Stage 3 determines the PC and PFA contents of the mix from the water 'equivalent cement' ratio and water content determined in the previous stages.

Stage 4 consists of determining an estimate of the density of the fully compacted concrete depending upon the free water content and the relative density of the combined aggregate in the saturated surface-dry condition (SSD). From this estimated density, the total aggregate content is estimated.

Stage 5 determines the fine and coarse aggregates contents depending upon the the maximum size of the coarse aggregate, the required workability and the grading of the fine aggregate (defined by its percentage passing the 600 μm sieve).

Using modification factors obtained from previous studies on the effect of RCA on equal water cement ratio PC mixes, the w/c ratios of the NA concrete mixes were modified to take account of the effect of RCA on concrete in order to achieve equal strength RCA designated mixes [22, 26 g, 50]. The water cement ratio was adjusted only for mixes containing more than 30% RCA. The water content of the mixes was unchanged, but the coarse and fine aggregates were adjusted to allow for the differences in cement content. The modification factors used for the PFA RCA mixes and the mix proportions of the PFA NA and RCA mixes used in the study are shown in Table 3.4 and 3.6 respectively.

SF mixes

Silica fume is a relatively new material in concrete technology and no commonly used mix design method is available. Therefore the method used for the mix proportioning of PC/SF mixes consisted of a series of trial mixes. Firstly, the compressive strength development of PC concrete mixes using NA with different w/c ratios obtained using the conventional mix design method (BRE/DoE) was examined, when silica fume was used as a direct replacement of 10% of the PC content by mass. The 28 days strength results obtained were plotted against their corresponding w/c ratios and a best fit curve was applied. The results of these trial mixes are shown in Figure 3.3. From the curve obtained, the w/c ratios necessary to achieve the required strengths were established.

Using modification factors obtained from previous studies on the effect of RCA on equal water cement ratio PC mixes, the w/c ratios of the NA concrete mixes were modified to take account of the effect of RCA on concrete in order to achieve equal strength RCA designated mixes [22, 26 g, 50]. The water cement ratio was adjusted only for mixes containing more than 30% RCA. The water content of the mixes was unchanged, but the coarse and fine aggregates were adjusted to allow for the differences in cement content. However, the SF RCA mixes did not achieve the same compressive strengths as their corresponding NA mixes showing that the modification factors used were not suitable for the SF mixes.

Consequently, a study of the relationship between the water cement ratios and their corresponding 28 days compressive strengths of SF mixes with various RCA content was used to determine the water cement ratios needed to achieve the required strength at 28 days (Figure 3.4). From the curves obtained, the w/c ratios necessary to achieve the required strengths were established (Example in Figure 3.4 is given for an RC 30 designated mix – 30 N/mm^2) and the correct modifications factors to be used for the SF RCA mixes were calculated. The modification factors for the SF RCA mixes and the mix proportions of the SF NA and RCA mixes used in the study are shown in Table 3.4 and 3.7 respectively.

Table 3.3 BS 8500 – 2 requirements for cement content, water/cement ratio for designated mixes selected for the study.

Designated mix	Characteristic strength* N/mm^2	Minimum cement or combination cement content kg/m^3	Maximum W/C ratio
GEN 1	C8/10	180	N/A
GEN3	C16/20	220	N/A
RC 30	C25/30	260	0.65
RC35	C28/35	280	0.60
RC 40	C32/40	300	0.55

* $f_{c,cyl}$ / $f_{c,cube}$

Table 3.4 Modification factors used to achieve equal strength NA and RCA mixes.

RCA content	w/c ratio modification factors		
%	PC	PFA	SF
0	-	-	-
30	-	-	-
50	0.925	0.925	0.933
100	0.88	0.88	0.82

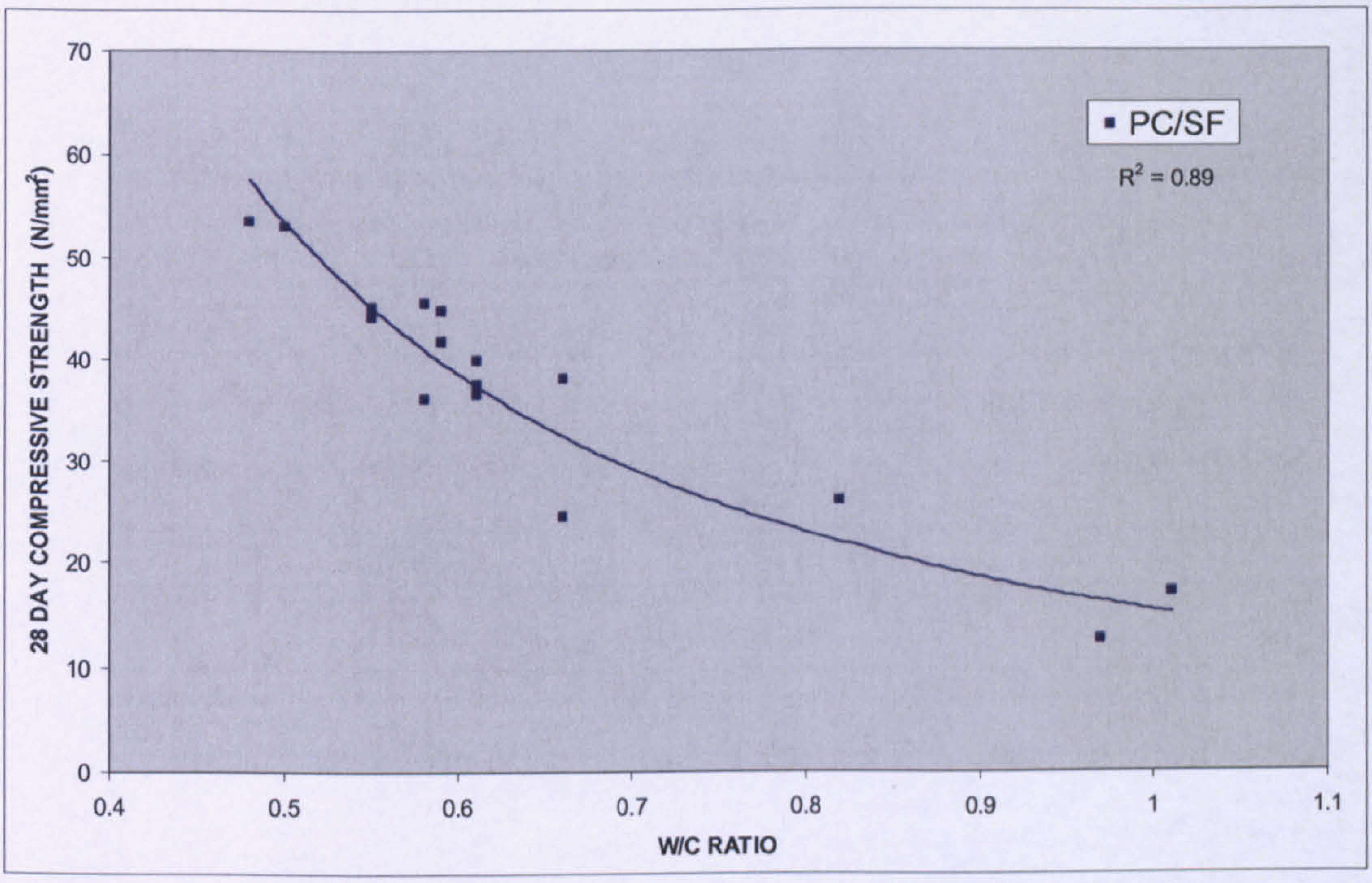


Figure 3.3 w/c ratio vs. 28 day cube compressive strength of PC/SF concrete.

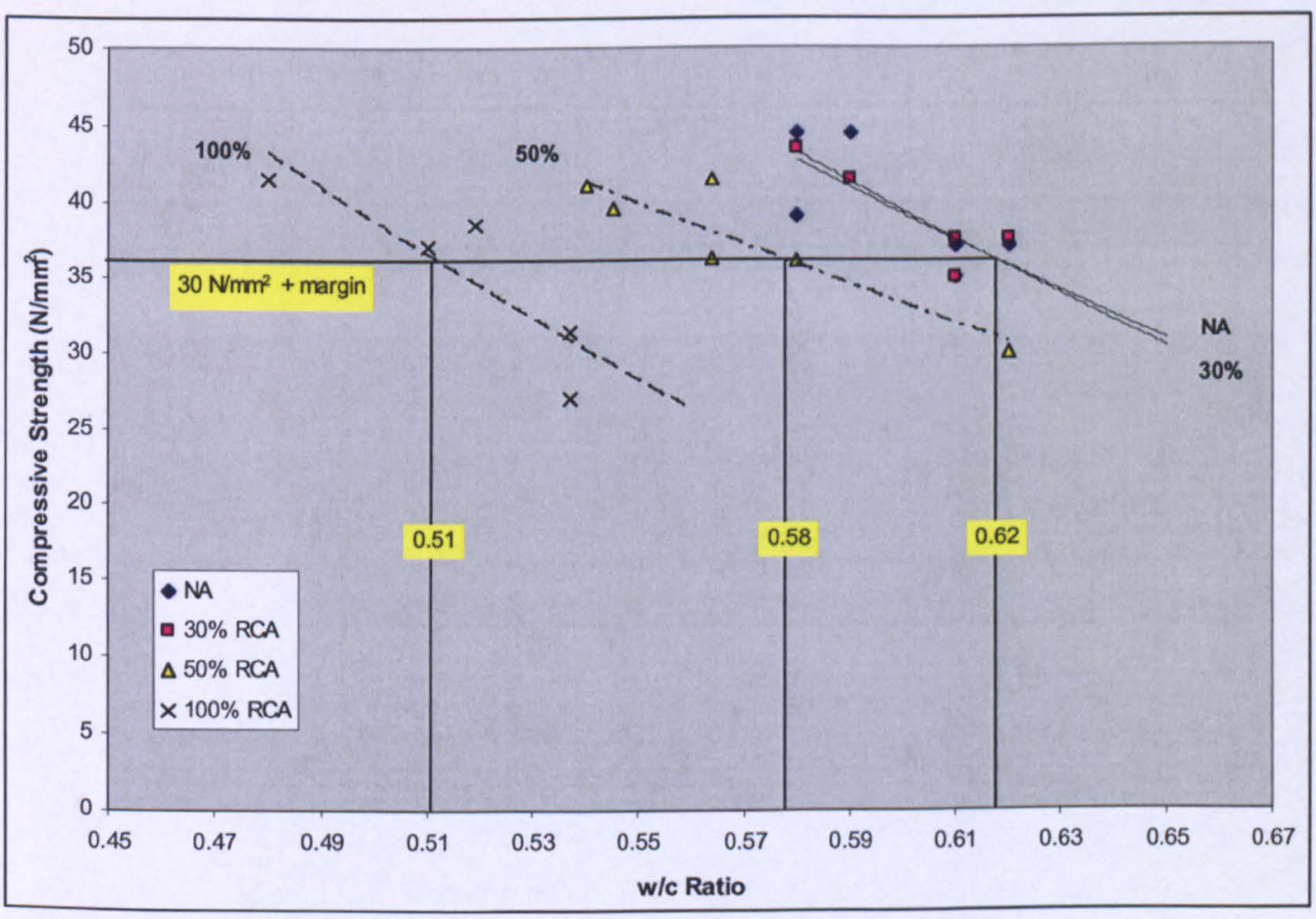


Figure 3.4 w/c ratio vs. 28 day compressive strength of SF mixes with different RCA contents.

Table 3.5 PC mix proportions.

Designated mix	RCA %	Mix Proportions kg/m³					W/C
		PC	Water	Aggregates			
				NA	RCA	Fine	
GEN 1	0	185	180	1225	0	750	0.97
	30	185	180	858	367	750	0.97
	50	200	180	618	618	725	0.9
	100	212	180	0	1247	701	0.85
GEN 3	0	275	180	1260	0	625	0.66
	30	275	180	882	378	625	0.66
	50	295	180	635	635	595	0.61
	100	310	180	0	1240	610	0.58
RC 30	0	330	180	1245	0	585	0.55
	30	330	180	872	373	585	0.55
	50	355	180	623	623	560	0.508
	100	372	180	0	1252	536	0.48
RC 35	0	355	180	1245	0	560	0.50
	30	355	180	872	373	560	0.50
	50	385	180	613	613	550	0.47
	100	409	180	0	1226	525	0.44
RC 40	0	375	180	1241	0	544	0.48
	30	375	180	869	372	544	0.48
	50	405	180	624	624	508	0.44
	100	426	180	0	1241	494	0.42

Table 3.6 PC/PFA mix proportions.

Designated mix	RCA %	Mix Proportions kg/m³						W/C
		PC	PFA	Water	Aggregates			
					NA	RCA	Fine	
GEN 1	0	145	65	160	1297	0	690	0.76
	30	145	65	160	908	389	698	0.76
	50	160	70	160	652	652	671	0.69
	100	166	71	160	0	1299	669	0.67
GEN 3	0	215	90	160	1311	0	589	0.52
	30	215	90	160	918	393	589	0.52
	50	230	100	160	657	657	562	0.48
	100	245	105	160	0	1280	575	0.45
RC 30	0	260	110	160	1285	0	550	0.43
	30	260	110	160	899.5	385.5	550	0.43
	50	280	120	160	641	641	523	0.4
	100	295	126	160	0	1267	517	0.38
RC 35	0	280	120	160	1282	0	523	0.40
	30	280	120	160	898	384	523	0.40
	50	300	130	160	631	631	514	0.37
	100	322	138	160	0	1257	488	0.34

Table 3.7 PC/SF mix proportions.

Designated mix	RCA %	Mix Proportions kg/m³						W/C
		PC	SF	Water	Aggregates			
					NA	RCA	Fine	
RC 30	0	261	29	180	1234	0	636	0.62
	30	261	29	180	864	370	636	0.62
	50	279	31	180	629	629	592	0.58
	100	318	35	180	0	1247	560	0.51
RC 35	0	279	31	180	1258	0	592	0.58
	30	279	31	180	881	377	592	0.58
	50	300	33	180	626	626	575	0.54
	100	338	37	180	0	1241	544	0.48

3.3.2.2 Portland cement savings

To compensate for the loss in the strength of concrete which occurs when RCA is used in high quantities, the water cement ratios of the mixes were reduced. For the PC mixes, this meant that the quantity of Portland cement in any given designated mix increased by 8 and 15%, when 50 and 100% RCA contents were used respectively. Choosing this option can defeat the purpose of the study which is to make concrete more sustainable by maximising the use of RCA in concrete. In fact, the environmental impacts of the production of Portland cement are becoming less acceptable and this can become a barrier to the use of RCA in concrete. However for the PFA and SF mixes, although the amount of cementitious material used in the mix increased with the increase in RCA, great savings on the quantities of Portland cement used in the mixes have been achieved when compared to the PC mixes:

- All the PFA and SF mixes used 21% less PC when compared to their corresponding PC mixes, except for the 100% RCA SF mixes where a saving of 16% was achieved.
- The 50% RCA mixes made with PFA and SF used 15% less Portland cement when compared to their corresponding NA PC mixes.

- The PFA and SF mixes with 100% RCA content used respectively 10 and 5% less Portland cement when compared to their corresponding NA PC mixes.

The use of additions in RCA concrete therefore represents a great sustainable alternative to Portland cement.

3.3.3 Preparation of Test Specimens

3.3.3.1 Mixing and Casting Procedures

A horizontal pan-type mixer of 0.05 m^3 capacity was used for concrete mixing. For the main part of the study the natural aggregates were kept in the laboratory at 20°C, 55% RH. The recycled aggregates were kept outdoors under a plastic sheet used as a cover. The amount of free water required for the mix was adjusted before mixing to take into consideration the water absorption by the aggregates that takes place when they are not fully saturated. Firstly, the batched aggregates were mixed for 1 minute, then half of the water was added and mixing continued for 1 minute. The mixing was then stopped and left for 8 minutes to allow the water absorption of the aggregates to take place. Then the cements were added and mixing was resumed for 1 minute. The remaining water was added and mixing was resumed for another three minutes. On completion, the mix was hand mixed to ensure uniformity. Following the assessment of the fresh properties of the concrete, test specimens were prepared in steel moulds and compacted on a vibrating table. The specimens were then covered by a polythene sheet for 24 hours. The following day, the specimens were demoulded, marked for identification and then transferred to the appropriate curing regimes selected.

3.3.3.2 Curing Environments

Two methods of moist curing were used for the study and these included curing at

20°C, 95% RH in a temperature and humidity controlled curing room and standard water curing at 20°C in water tanks. Limited moist curing for different tests was also used. Details of the different curing environments are presented in Table 3.8.

3.3.4 Test Procedures

3.3.4.1 Aggregates Properties

Prior to testing the aggregate samples were obtained and reduced using the quartering or/and the riffle box method, as described in EN 932-1 and EN 932-2.

RCA constituents

The percentage weight of the constituents of representative RCA samples were examined in accordance with Annex B of the BS 8500-2.

Table 3.8 Curing conditions for concrete test properties.

Code	Curing Condition	Test Property
CU1	Curing at 20°C, 95% RH	Compressive Strength, Flexural Strength, Modulus of Elasticity
CU2	Standard water at 20°C	Compressive Strength, Flexural Strength, Modulus of Elasticity, Swelling Deformation, Initial Surface Absorption, Sulphate Attack
CU3	Air at 20°C, 55% RH	Drying Shrinkage, Sulphate attack
CU4	CU2 for 28 days and CU3 for 14 days	Carbonation resistance
CU5	CU2 for 3 days and CU3 for 14 days	Chloride Ingress

3.3.4.1.1 Physical Characteristics

Particle Size Distribution

The coarse and fine aggregates samples were pre-conditioned through oven drying to constant weight prior to sieving, as per EN 933 1, into various size fractions. The grading of aggregates was determined based on the percentage by weight of the aggregates passing through standard sieve sizes.

Water Absorption and Relative Density

The water absorption and relative density of the aggregates were determined in accordance with EN 1097 6.

Aggregate Shape and Texture

The particle shape and texture of aggregates were visually examined. In addition, the shape of coarse aggregates was examined for the flakiness and shape indices, as per EN 933 3 and 4 respectively. The aggregates were then classified in accordance with the categories specified in EN 12620 for maximum values of flakiness and shape indices. The different categories for maximum values of flakiness and shape indices are shown in Tables 3.9 and 3.10 respectively.

Table 3.9 Categories for maximum values of flakiness index from EN 12620.

Flakiness Index	Category FI
≤ 15	FI_{15}
≤ 20	FI_{20}
≤ 35	FI_{35}
≤ 50	FI_{50}
> 50	$FI_{Declared}$
No requirement	FI_{NR}

Table 3.10 Categories for maximum values of shape index from EN 12620.

Shape Index	Category SI
≤ 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 loose bulk density and the percentage of voids of the aggregates were determined in accordance with EN 1097 – 3.

3.3.4.1.2 Mechanical Characteristics

Three different tests were carried out to assess the mechanical characteristics of the NA and RCA, these included the aggregate crushing value, the ten percent fines value and the aggregate impact value as per BS 812 – 110, 111, and 112 respectively.

3.3.4.2 Concrete Properties

3.3.4.2.1 Fresh Properties

Slump Test

The slump of fresh concrete was determined as per EN 12350 – 2. According to EN 206 – 1, if the slump test is used as a means to determine the consistence of concrete, the consistence can be specified by reference to one of the slump classes in Table 3 of EN 206 – 1 or, in special cases, by a target value. The different slump classes from Table 3 of EN 206 – 1 are shown in Table 3.11. All the designated mixes used in the study were designed to have a slump of 30 to 60 mm. The target slump value for the designated mixes used in the study falls within two classes from Table 3 of EN 206 1, namely S1 and S2. Table 3.12 shows the tolerances for slump target values according to EN 206 1. The range of acceptable slumps according to EN 206 1 for the designated mixes used in the study is therefore 20 to 80 mm.

Table 3.11 Slump classes from EN 206 1.

Class	Slump (mm)
S1	10 to 40
S2	50 to 90
S3	100 to 150
S4	160 to 210
S5	≥ 220

Table 3.12 Tolerances for target values for the slump test from EN 206 1.

Target value (mm)	Tolerance (mm)
≤ 40	± 10
50 to 90	± 20
≥ 100	± 30

Compacting Factor

The compacting factor of fresh concrete was determined as per BS 1881 103. This test however has now been replaced by the degree of compactability test described in EN 12350 – 4.

3.3.4.2.2 Engineering Properties

Compressive Strength

100 mm Cubes specimens were used to determine the compressive strength of the concrete. The samples were selectively cured under CU1 and CU2 and tested after 3, 7, 14, 28, 56, 90, 180 and 365 days as per EN 12390-3. Cylinders (150 mm Ø × 300 mm) were selectively cured under CU1 and CU2 and tested to determine the compressive strength of concrete at 28 and 56 days according to EN 12390-3.

Flexural Strength

Flexural strength of prism specimens of (100×100×500 mm) was determined under two point loading at 28 and 56 days as per EN 12390-5. The beams were selectively cured under CU1 and CU2 curing conditions.

Modulus of Elasticity

Cylinders (150 mm Ø × 300 mm) cured selectively under CU1 and CU2 curing conditions were used to determine the static modulus of elasticity at 28 and 56 days in accordance with BS 1881-121.

Swelling and Drying Shrinkage

Prism specimens (75×75×300 mm) with stainless steel DEMEC points, fixed on each of the 4 faces of the specimen (Figure 3.5), were used to monitor the expansion and shrinkage of concrete. The swelling and shrinkage samples were cured under CU2 and CU3 curing conditions respectively for 90 days and the change in length of the different faces of the specimens was measured everyday for the first week then once a week afterwards using a Digital DEMEC strain gauge. The specimens were stood upright and kept the same way throughout the testing period.

3.3.4.2.3 Durability Properties

Initial Surface Absorption

150 mm cubes were used to determine the initial surface absorption in accordance with BS 1881 208 at 28 days (Figure 3.6). The cubes were selectively cured under CU1 and CU2 curing conditions and then dried at 105 °C to constant mass (i.e. Weight change not exceeding 0.1% over a 24 hour period) prior to testing. The samples were then left to cool to the laboratory temperature. ISAT measurements were taken at 10, 30, 60 minutes.

Carbonation

100 mm cubes were cured under CU1 curing conditions and conditioned under CU3 curing conditions for 28 and 14 days respectively. The cubes were then sealed using wax on 5 faces and exposed in carbonation tanks to a CO_2 enriched atmosphere containing 3.5% CO_2 at a (21 ± 2) °C temperature and a relative humidity (RH) of (60 ± 10) % (Figure 3.7). The depth of carbonation in the concrete was measured by applying a phenolphthalein colour indicator solution on a freshly broken piece of the specimen at 2, 4, 8, 12 and 20 weeks. The carbonation depth, indicated by the colourless zone of the concrete, was measured after 24 hours at five points along the exposed surface (Figure 3.8). The internal air distribution in the carbonation chamber was constantly maintained by using dummy cubes in place of the specimens as they

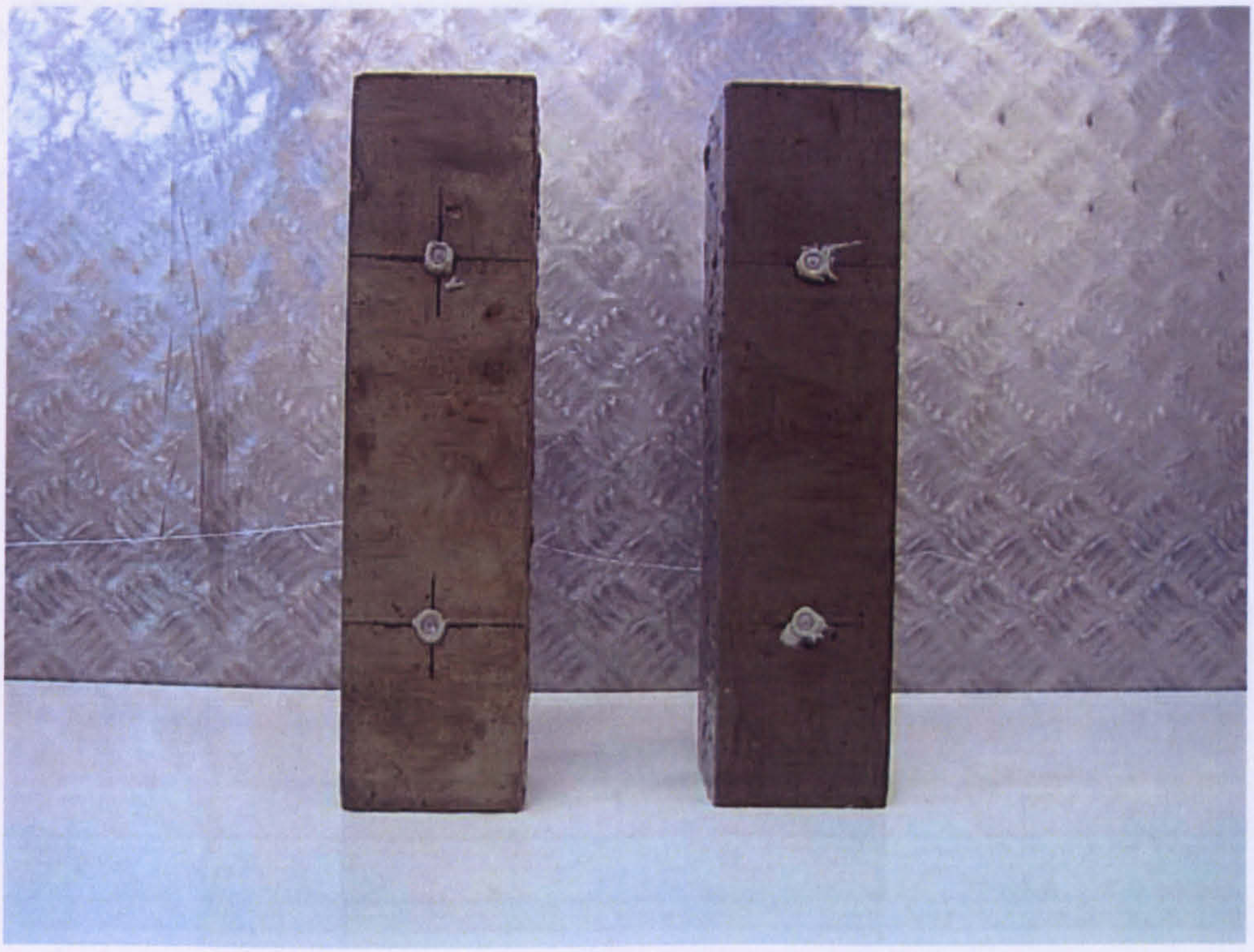


Figure 3.5 Prism specimens with fixed stainless steel DEMEC points.

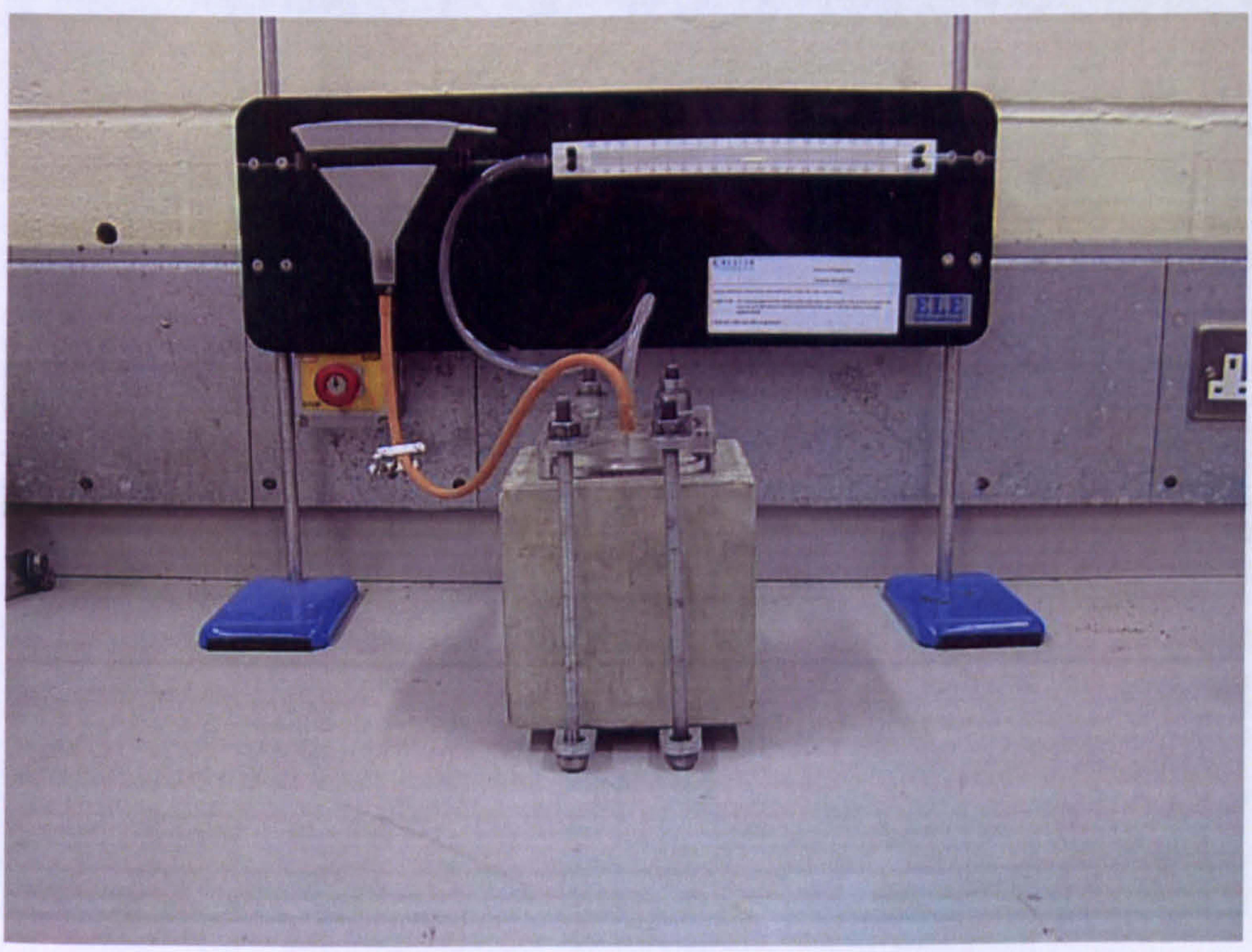


Figure 3.6 Initial surface absorption test apparatus.

Figure 3.7 Apparatus for carbonation resistance testing.

Figure 3.8 Concrete cubes after being sprayed by phenolphthalein solution to reveal the depth of carbonation.

were removed for testing. The 20 weeks period of exposure simulated 20 years of exposure to normal atmospheric conditions.

Chloride Diffusion

150 mm cubes were cured under CU1 then for CU3 curing conditions for 3 and 14 days respectively. All the faces of the cube specimens were sealed using a bituminous coating paint except the top face of the specimen on which a 1 mol sodium chloride solution (58.4g of NaCl per litre of distilled water) was ponded for 42 days allowing transmission of moisture and chloride through one surface only (Figure 3.9). At the end of the ponding period, the specimens were dried then drilled from the top face. Dust samples collected at different depths from the top face (5, 10, 15 and 20 mm) were then tested using the potentiometric method as per BS 1881 – 124 to determine their acid-soluble chloride content.

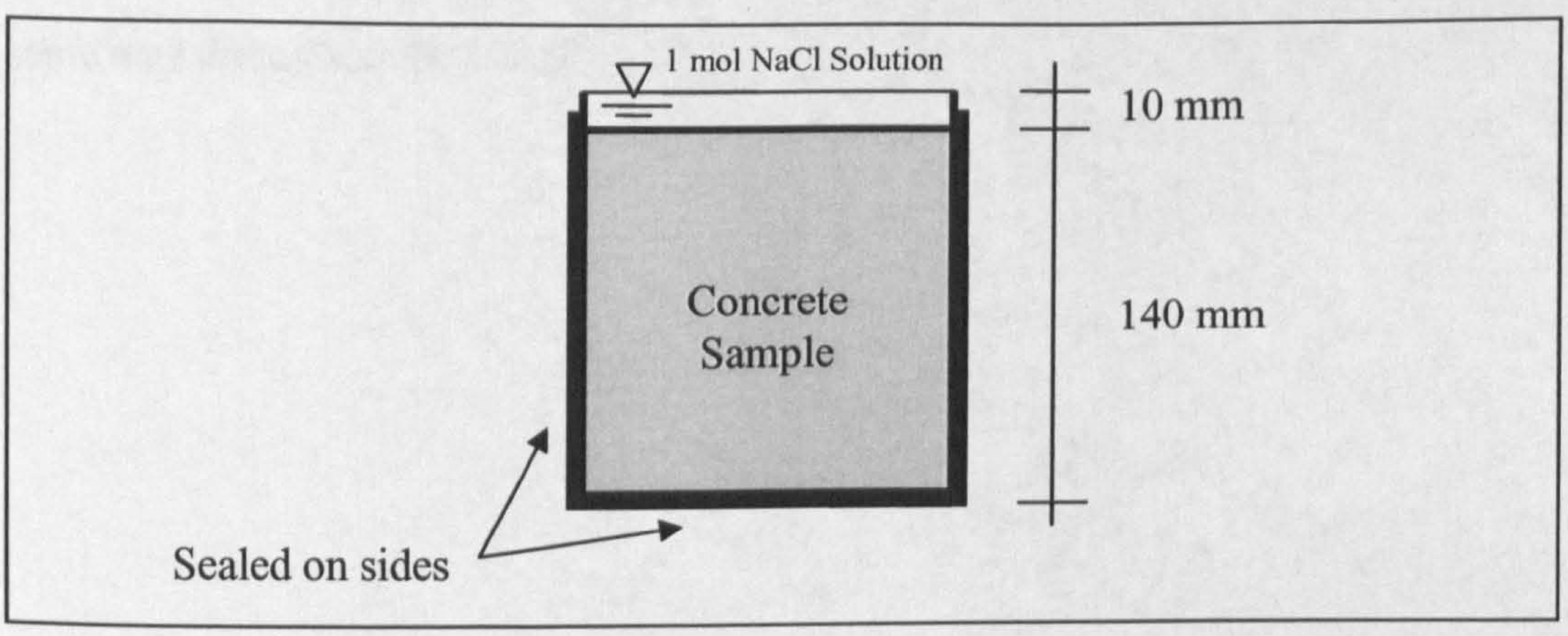


Figure 3.9 Chloride attack test setup.

Sulphate Attack

Prism specimens (75×75×300 mm) with stainless steel DEMEC points, fixed on each of the 4 faces of the specimen (Figure 3.5), were used to monitor the change in length of concrete exposed to a sulphate solution. Two specimens from each mix were cured under CU2 and another two under CU3 curing conditions for 28 days. After this curing period, the specimens were left in CU3 curing conditions for an extra week. Thereafter, the specimens were stored in tanks containing prepared solutions of 0.3g/l Sodium Sulphate (Na_2SO_4) at 20°C which corresponds to the Class 1 exposure condition as per EN 206 – 1. Care was taken in each case to allow the flow of the solution around the whole specimen and the level of the solution above the top surface of the specimens was kept constant to avoid differential pressure effects. In addition, the sulphate solution was refreshed each month. The specimens were kept in the Sulphate solution for 60 days. The change in length of the different faces of the specimens was measured everyday for the first week then once a week afterwards using a Digital DEMEC strain gauge. The specimens were stood upright and kept the same way throughout the testing period.

CHAPTER 4

PRODUCTON AND CHARACTERIZATION OF RCA

4.1 INTRODUCTION

Previous studies [20, 26, 35, 51] have showed that RCA have different characteristics to NA. This chapter examines the procedure used to manufacture the coarse RCA used in this study. The characteristics of the coarse NA and RCA used in the study are compared. The characteristics of the NA and RCA are also checked against the requirements in the existing standards for natural and recycled aggregates for use in concrete.

4.2 AGGREGATE PRODUCTION

During this study, a newly built plant designed for the recycling of demolition rubble was used to produce the RCA. The recycling plant is located in London and operated by the Day Group Ltd, who are suppliers of primary and recycled aggregates for the construction and landscape industry. The plant consists of primary and secondary crushers and screens. The process of recycling used is explained below and presented schematically in Figure 4.1. The original concrete used in the manufacture of the RCA consisted mainly of demolition debris from demolished concrete structures (Figure 4.2).

In the first stage of the recycling process, the large pieces of concrete debris are reduced to smaller pieces of 0.4m maximum size. The steel reinforcement is cut by hydraulic shears, where required. Thereafter, the material is crushed in a primary jaw crusher to produce debris of 75mm maximum size (Figure 4.3).

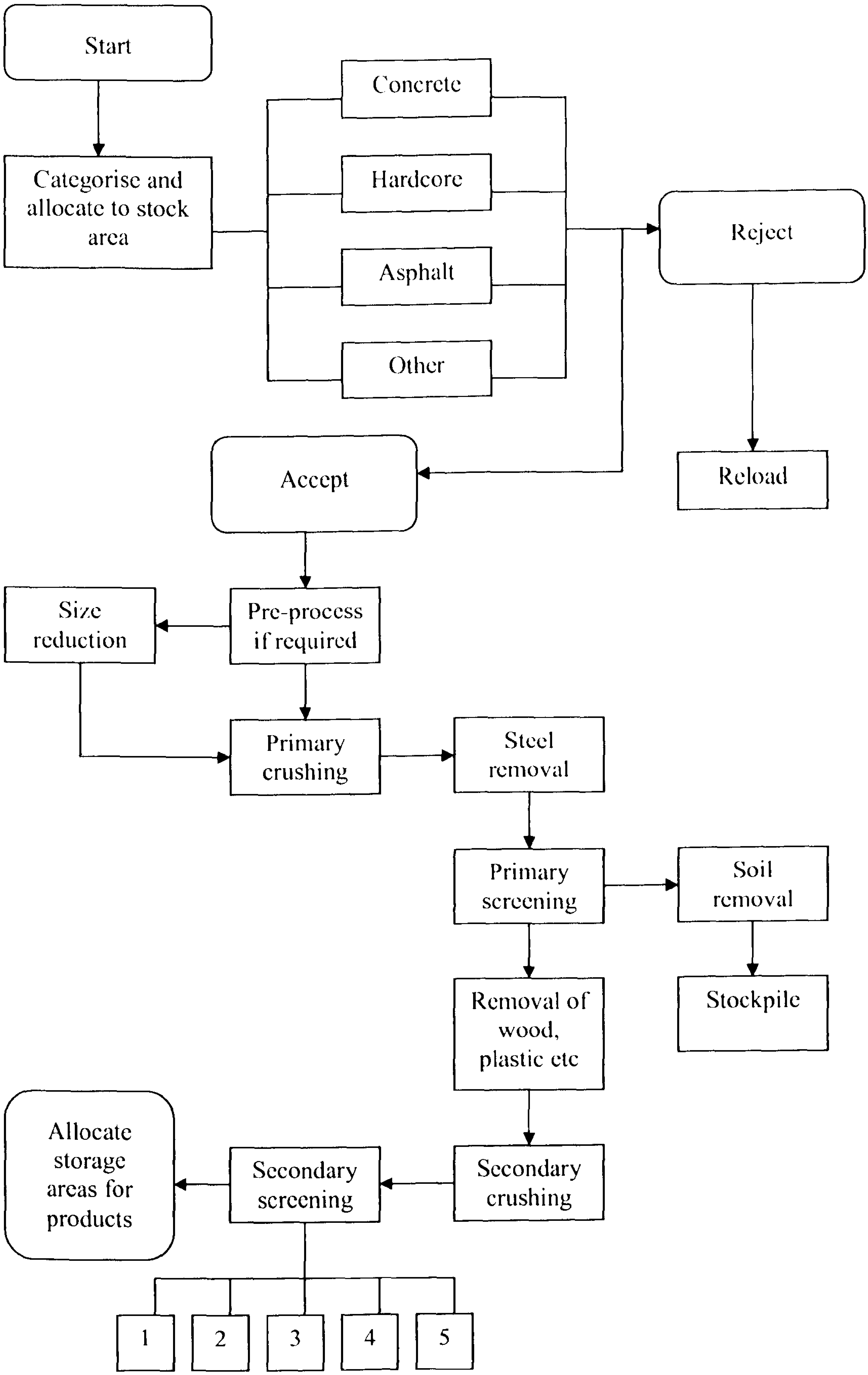


Figure 4.1 Flow chart for processing of construction and demolition waste. (Day Group Ltd)

The debris is then passed under an electromagnet which removes any left over reinforcement which is collected to be recycled (Figure 4.4). The debris is then screened through a series of suitable screens. In this primary screening, fine materials such as dirt and gypsum are separated and stockpiled to be recycled for other uses. The dirt free material is subsequently diverted on a conveyor belt to a manual sorting room where foreign materials such as wood, glass, bricks etc are manually removed (Figure 4.5). The cleaned concrete debris is then conveyed to a secondary cone crusher to reduce its size to 20 mm maximum. The Final products are then screened into various size fractions; 20 – 10 mm, 10 – 5 mm and <5mm; to give a clean and properly graded RCA (Figure 4.6).

Figure 4.2 Demolition waste consisting mainly of concrete stocked at the recycling plant.

Figure 4.3 Primary jaw crusher reducing C&D debris from 0.4 m to 75 mm.

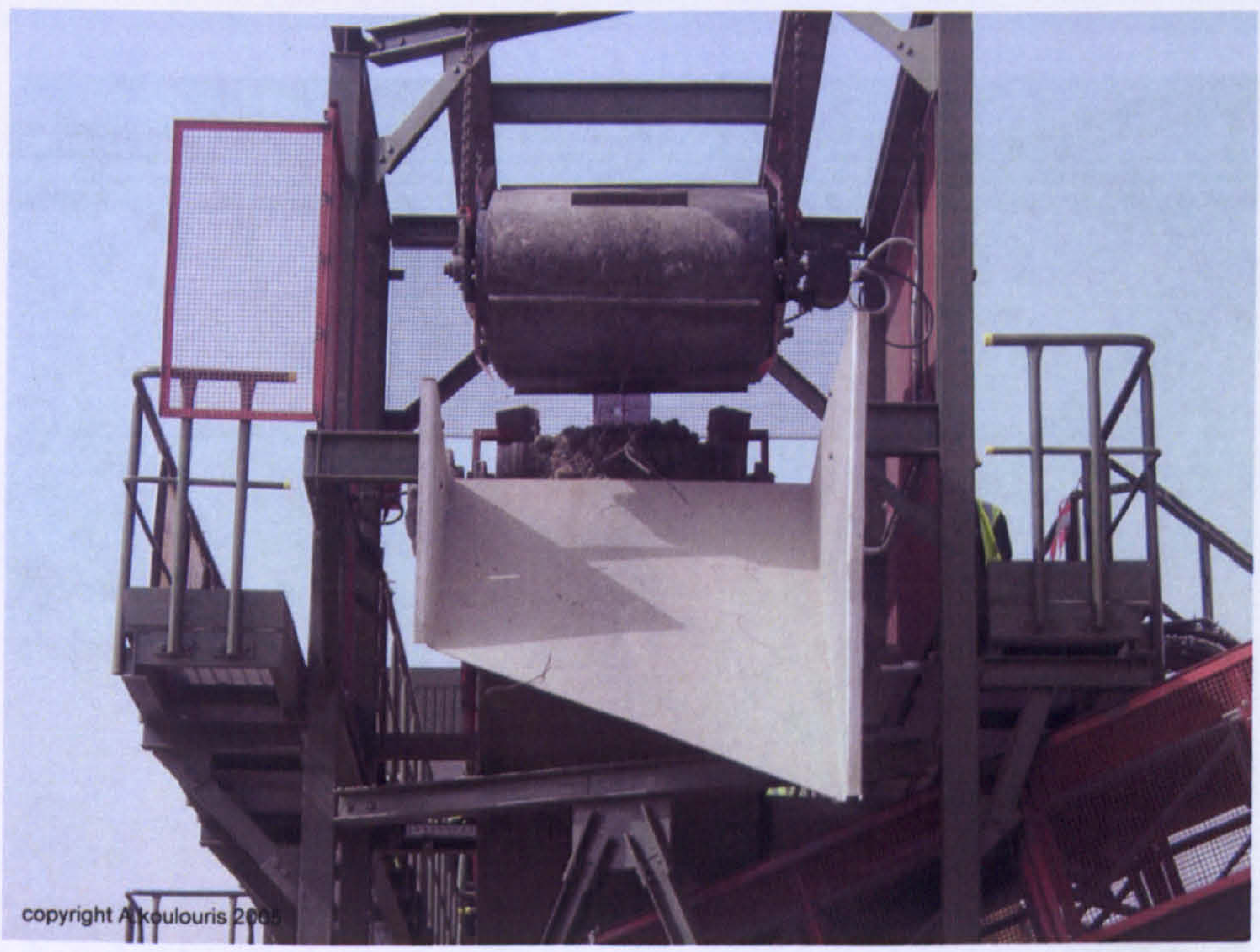


Figure 4.4 Electromagnet removing reinforcement from the 75mm debris.

Figure 4.5 Sorting room used for manual removal of foreign materials.

Figure 4.6 Stockpile of the clean and graded coarse RCA produced at the recycling plant.

4.3 AGGREGATE CHARACTERIZATION

4.3.1 RCA constituents

The constituents of the recycled aggregates used in the study were examined using the method laid out in Annex B of the BS 8500 2. The types and amounts of the different constituents of the recycled aggregates used in the study were then compared to the compositional requirements for Recycled concrete aggregates (RCA) set in Table 2 of the same standard.

Table 4.1 shows the proportions of different materials present in the Recycled aggregates used in the study. These results showed that these recycled aggregates satisfy the limits for Recycled Concrete Aggregates (RCA) for use in concrete.

Table 4.1 Constituents of the recycled aggregates used and the compositional requirements for RCA set in BS 8500 2.

Constituents present in RCA Source I	Proportions %	Maximum % allowed for coarse RCA
Concrete*	92.13	-
Masonry	1.56	5
Asphalt	1.57	5
Fines	3.41	5
Foreign materials**	0.85	1
Lightweight materials ***	0.48	0.5

* Requirements set in BS 8500 for coarse RCA:
Minimum of 83.5% for content of concrete

** Glass, timber, plastic metal etc.

*** Materials with $\rho<1000Kg/m^3$

4.3.2 Physical characteristics

The main physical characteristics of NA and RCA covered in the study included the particle size distribution, shape and texture, voids, relative and bulk densities and the water absorption. The results obtained for both types of aggregates were then compared with the requirements for natural aggregates set in EN 12620 and BS 882.

Particle size distribution

At the start of the study, the grading of the aggregates used in the study was compared to the limits set in the BS 882. It was found that particle size distribution of the coarse NA and RCA used was within the limits and allowed tolerances of BS 882 for 20–5 mm coarse aggregates for use in concrete. The natural sand used in the study also satisfied the limits set by BS 882 for fine aggregate (< 5mm) for use in concrete. The grading results are shown in Table 4.2 and 4.3.

Following the replacement of BS 882 with the new European standard for aggregates for concrete, EN 12620, the particle size distribution of the Coarse NA, RCA and fine sand used were also determined and compared to the limits set in the new standard. The grading of all the aggregates used satisfied the limits set and allowed tolerances. The grading results are shown in Table 4.4 and 4.5.

Comparing the grading of the NA and RCA used shows that the RCA had a slightly finer grading than the NA. This may be due to the attached cement paste in the RCA particles which can break away easily during the crushing process, thus increasing the amount of finer particles. Studies [25, 91] have found that the grading of RCA was finer when the size of the jaw opening of the crusher was reduced. RCA producers

Table 4.2 Particle size distribution of coarse NA and RCA used in the study and the requirements for grading for coarse aggregates from BS 882.

Aggregate type	Percentage passing, by mass BS sieve size (mm)					
	37.5	**20**	**14.0**	**10.0**	**5.0**	**2.36**
Coarse BS 882 Limits for graded aggregate 20 5 mm	100 90	90 100	40 80	30 60	0 15	-
NA	100	95	60	33	2	1
RCA	100	96	70	45	11	4

Table 4.3 Particle size distribution of natural sand used in the study and the requirements for the grading of fine aggregates from BS 882.

Aggregate type	Percentage passing, by mass BS sieve size (mm)						
	10.0	**5.0**	**2.36**	**1.18**	**0.6**	**0.3**	**0.15**
Fine BS 882 Limits for natural Sand <5mm	100	89 100	60 100	30 100	15 100	5 70	0 15
Natural Sand	100	98	89	80	65	15	2

Table 4.4 Particle size distribution of coarse NA and RCA used in the study and the requirements for grading for coarse aggregates from EN 12620.

Aggregate type	Percentage passing, by mass — BS sieve size (mm)					
	40.0	**28.0**	**20.0**	**10.0**	**5.0**	**2.5**
Coarse BS 12620 Limits for graded aggregate 20 - 5 mm	100	98 - 100	90 - 99	25 - 70	0 - 15	0 - 5
NA	100	100	95	47	4	2
RCA	100	100	98	55	8	2

Table 4.5 Particle size distribution of natural sand used in the study and the requirements for the grading of fine aggregates from EN 12620.

Aggregate type	Percentage passing, by mass — BS sieve size (mm)						
	8.0	**5.6**	**4.0**	**2.0**	**1.0**	**0.3**	**0.15**
Fine BS 12620 Limits for natural Sand <4mm	100	95 - 100	85 - 99	-	-	-	-
Natural Sand	100	98	91	85	70	16	3

can therefore improve the grading of the RCA by choosing a suitable size of jaw opening.

Particle shape and surface texture

The particle shape and surface texture of the coarse NA and RCA were visually examined and the flakiness and shape indices were classified. RCA were found to be rounder with few angular particles, rougher and more porous than the NA which had an irregular shape with a smoother and less porous surface (Figure 4.7). The strength of the concrete, especially the flexural strength is affected by the bond between the aggregate and cement paste. The bond is partly due to the interlocking of the aggregate and the hydrated cement paste due to the roughness of the surface of the aggregate. The porosity and roughness of the RCA therefore can potentially result in a better bond between the RCA and the cement paste [78]. Among the properties that may influence the workability of the RCA concrete are the shape and texture of the RCA particles: the rougher surface of the RCA particles may lead to a decrease in the workability of the mixes whilst the rounder shape of the aggregates may improve the workability [20 n, 20 o, 21].

The flakiness index of NA was between 13 and 16, classifying it as FI_{15} or FI_{20} according to EN 12620. The RCA had a flakiness index between 7 and 9, classifying it as FI_{15}. PD 6682 – 1 gives the recommended flakiness categories depending on the type of aggregates and the concrete's use for the UK concrete sector [110]. For uncrushed gravel, the maximum recommended flakiness category is FI_{50}. For crushed rock or crushed gravel, the maximum recommended flakiness category is FI_{35}. The NA and RCA satisfy both these limits.

The shape index of NA was between 20 and 22, classifying it as SI_{20} or SI_{40} according to EN 12620. The RCA had a shape index ranging between 14.4 and 16.2, classifying it as SI_{15}. The shape index of the RCA was just within the maximum shape index recommended by Neville [78], who reported that it is generally considered to be undesirable that more than 10 to 15% of the mass of coarse aggregate consists of non – cubical particles, however no standard limits are laid down for the shape index.

Overall, it was found that the flakiness and shape indices of the RCA were lower than the NA. The improvement in the particle shape of the RCA may be attributed to the use of a cone crusher for the secondary crushing which produces rounder particles [20 a, 20 g].

RCA **NA**

Figure 4.7 NA and RCA used in the study.

Relative and bulk densities

The results for the relative and loose bulk density tests are given in Table 4.6. The densities of the RCA in saturated and surface dry, oven dried and apparent states were slightly lower when compared to the NA used. This is due to the low density and high porosity of the attached cement paste found in RCA as well as the finer grading of RCA when compared to the NA. Numerous studies found that the density of the RCA decreases with the increase in the amount of attached cement paste and with the decrease in aggregate size [20 b, 20 d, 26 b, 96]. This is not surprising as it is well recognized that the amount of attached cement paste increases in the RCA particles with the decrease in aggregate size [20 a-c, 21-23, 25, 26 b, 26 c].

The apparent particle density of NA was less than 1% higher than the apparent density of the RCA. The particle density of NA in the saturated surface dry (SSD) state was 4.5 % higher when compared to RCA. The oven dry (OD) particle density of NA was 6% higher when compared to RCA. The relatively high difference in the particle density of NA and RCA on the OD state is not surprising as it reflects the high porosity of the RCA.

The loose bulk density in the oven dried state of the RCA was found to be 13.7 % lower than the NA. This does not mean that the NA particles were packed more densely than the RCA particles. In fact, the RCA particles due to their particular shape are expected to pack better than the NA particles. The percentage of voids of the RCA and NA was approximately the same, which indicates that they have a similar packing capacity. The low loose bulk density of the RCA particles was mainly due to the low density of the attached cement paste found in the RCA.

Table 4.6 Physical and mechanical characteristics of NA, RCA and natural sand used in the study.

Physical characteristics	Size fraction (mm)	Natural aggregate	Recycled concrete aggregate
		NA	RCA
Shape, visual	All	Irregular	Round
Flakiness Index %	28 – 6.3	13 – 16	7 – 9
Shape Index %	28 – 6.3	20 – 22	14.4 – 16.2
Voids %	20 – 5 (<5)	40.9 (36.9)	43.2 (-)
Texture, Visual	All	Smooth	Rough and porous
Apparent particle density Mg m^3	20 – 5 (<5)	2.603 (2.701)	2.585 (-)
Particle density (OD), Mg m^3	20 – 5 (<5)	2.511 (2.644)	2.342 (-)
Particle density (SSD), Mg m^3	20 – 5 (<5)	2.546 (2.665)	2.431 (-)
Loose bulk density (OD), Mg m^3	20 – 5 (<5)	1.483 (1.667)	1.28 (-)
Water absorption %	20 – 5 (<5)	1.4 (0.8)	5.3 (-)
Mechanical characteristics			
ACV %	14 – 10	12.4	23.4
AIV %	14 – 10	6.3 – 7.3	18.3 – 23
10% fine value, KN	14 – 10	155	131

Water absorption

The Water absorption of RCA concrete between the SSD and OD states was up to 5 times higher than the water absorption of the NA used. This is due to the high porosity of the cement paste surrounding the RCA particles. The results of the water absorption capacity of NA and RCA are presented in Table 4.6. If dry RCA are used in the manufacture of concrete, water will be absorbed from the mix to saturate the aggregates. This will affect the free water content and the w/c ratio of the mix and in turn the fresh and hardened properties of the concrete. Therefore, it is essential that the moisture content of the aggregates is determined prior to mixing to adjust the amount of water used in the mix and that the order of feeding the ingredients into the mixer allows the water absorption by the aggregates to take place (Refer to the mixing procedure used in the study in Chapter 3).

4.3.3 Mechanical properties

The mechanical characteristics of NA and RCA were determined in accordance with BS 812 and the results are presented in Table 4.6

Aggregate crushing value (ACV)

The ACV test is used to measure the resistance of the aggregates to pulverization [78]. A high ACV indicates the low strength of the aggregate. The ACV of the RCA was found to be nearly double that of the NA. The high ACV of the RCA is due to the weak attached cement paste found in the RCA which can be easily crushed.

Aggregate impact value (AIV)

The AIV test measures the resistance of the aggregates to failure by impact. Similarly to the ACV, a high value indicates the low strength of the aggregate The BS 812 112 prescribes the following maximum values for the AIV: 25% when the aggregate is to be used in heavy duty floors, 30% for concrete for wearing surfaces and 45% for other concretes [78]. The AIV of the all aggregates were within these maximum values. However, the AIV of the RCA (18.3% 23%) was found to be up to 3.5 times higher than the NA (6.3% 7.3%). The high AIV of the RCA shows that the RCA can be easily crushed by impact when compared to the NA, due to the weak attached cement paste found in the RCA.

10 % fines value (TFV)

The ten per cent fines value test was introduced as the crushing value test was rather insensitive to the variation in strength of weak aggregates (ACV · 25). Unlike the previous tests, a high value indicates the high strength of the concrete. The BS 812 111 prescribes the following minimum values for the TFV: 150 kN when the aggregate is to be used in heavy duty floors, 100 kN for concrete for wearing surfaces and 50 kN for other concretes [78]. The TFV of all the aggregates fall within these limits. The TFV of the RCA (131) was 15% lower than the value obtained for the NA (151) used.

Overall, the RCA showed a relatively poorer mechanical performance compared to NA. This was mainly due to the weak attached cement paste found in the RCA. The finer grading of the RCA also played a role in further reducing the mechanical performance of the RCA as it is widely accepted that the amount of attached cement paste in RCA increases with the decrease in the size of aggregates [20 b, 96].

4.4 PRACTICAL IMPLICATIONS

The study has shown that clean and graded RCA satisfying the requirements of EN 12620 and BS 8500 can be produced from concrete rubble. Clean concrete rubble should therefore be selected and diverted to recycling whenever it is feasible. The source of the concrete rubble should be investigated to avoid using contaminated concrete in the production of RCA.

The study has also shown that RCA have a higher water absorption capacity and a lower relative density when compared to NA. These properties have to be taken into account in the design of the RCA concrete and its production. The low relative density of RCA when compared to the NA should be taken into consideration when replacing NA with RCA in concrete and in the calculation of the mix proportions of RCA concrete. The high water absorption of the RCA particles should be taken into account when manufacturing the RCA concrete; as the high absorption of the RCA can affect the water cement ratio of the mix, which will in turn affect the fresh, engineering and durability properties of the RCA concrete.

4.5 CONCLUDING REMARKS

- Concrete debris obtained from demolished concrete structures can be used to produce clean and properly graded RCA suitable for use in concrete production in accordance with EN 12620. RCA was found to have a slightly finer grading compared to the NA.

- RCA was found to be rougher, more porous and less angular than NA. The porosity and roughness of the RCA therefore can potentially result in a better bond between the RCA and the cement paste. The rough surface of the RCA may also decrease the workability of RCA concrete; however this may be offset by the round shape which can improve the workability.

- Due to the cement paste attached to the RCA particles, RCA have a higher water absorption and lower density when compared to NA. These factors need to be taken into consideration in the design and manufacture of the RCA concrete mixes. The attached cement paste in the RCA was also behind the relatively poor mechanical performance of RCA.

CHAPTER 5

FRESH PROPERTIES OF RCA CONCRETE

5.1 INTRODUCTION

The workability of concrete is influenced by many interrelated factors such as the types and quantities of materials used in the mix and their characteristics. Many studies [20, 26, 35, 51] have been undertaken to study the effect of RCA on the fresh properties of Portland cement concrete due to the concern that the characteristics of RCA may detrimentally affect the fresh concrete properties. Although, it is well known that the use of additions, such as PFA and SF, can improve the workability and stability of fresh concrete, very few studies have looked at the combined effect of RCA and binary cements on the fresh properties of concrete.

Against this background, a study of the workability of equal strength NA and RCA concretes made with binary cements was undertaken. For this, BS 8500 designated mixes from the GEN and RC series were used. The fresh properties examined include the workability and stability of the mixes.

5.2 EXPERIMENTAL PROGRAMME

The experimental programme was divided into two parts. In the first part, the effect of RCA and binary cements on the workability of concrete was determined using the slump and compacting factor tests. The second part examined the effect of RCA and binary cements on the stability of the designated concrete mixes by assessing bleeding and segregation.

5.3 WORKABILITY

The slump of fresh concrete was determined as per EN 12350 2. All the designated mixes used in the study were designed to have a slump of 30 to 60 mm. The range of acceptable slumps according to EN 206 1 for the designated mixes used in the study is 20 to 80 mm. The compacting factor of fresh concrete was determined as per BS 1881 103. Table 5.1 gives the slump and compacting factor values of all the designated NA and RCA mixes used in the study.

5.3.1 Effect of RCA

PC mixes

The slump values of the PC mixes ranged from 20 to 120 mm; the majority of the slump values were within the specified tolerances of EN 206 1. The RCA and NA mixes generally had comparable slumps. However, some mixes containing 50 and 100% RCA were found to have slightly higher slump values than their corresponding NA mixes. This may be attributed to the shape of the RCA particles which tend to be rounder and less angular compared to NA, thus improving the workability of the RCA mixes [20n, 20 o, 21]. Another factor behind the high initial slumps measured in the RCA mixes, may be that the extra water added to the mixes, to achieve the complete saturation of dry aggregates, was not yet fully absorbed at the time of the test which increased the initial water content of the mixes [38]. The incomplete saturation of the aggregates is attributed to the slowing down of the water absorption by the dry aggregates due the coating of particles with cement paste [78].

The compacting factor values of the mixes ranged from 0.90 to 0.99. The use of RCA did not have any noteworthy influence on the compacting factor values of concrete.

Table 5.1 Slump and compacting factor values of designated mixes used in the study.

DESIGNATED MIX	COARSE RCA %	100% PC		70% PC / 30% PFA		90% PC / 10% SF	
		Slump (mm)	Compacting factor	Slump (mm)	Compacting factor	Slump (mm)	Compacting factor
GEN 1	0	70	0.98	40	0.96	-	-
	30	60	0.94	20	0.89	-	-
	50	50	0.96	80	0.98	-	-
	100	80	0.99	30	0.97	-	-
GEN 3	0	70	0.97	40	0.96	-	-
	30	70	0.98	20	0.95	-	-
	50	60	0.98	50	0.97	-	-
	100	40	0.96	30	0.91	-	-
RC 30	0	70	0.97	30	0.91	30	0.95
	30	60	0.98	20	0.86	40	0.95
	50	80	0.98	60	0.97	40	0.94
	100	120*	0.98	70	0.94	20	0.94
RC 35	0	40	0.95	10*	0.83	40	0.94
	30	20	0.95	30	0.92	30	0.93
	50	60	0.98	20	0.86	30	0.95
	100	50	0.95	20	0.92	20	0.92
RC 40	0	30	0.95	-	-	-	-
	30	10*	0.90	-	-	-	-
	50	40	0.96	-	-	-	-
	100	20	0.93	-	-	-	-

* Slumps outside the specified tolerances

PFA mixes

The slump values of the PFA mixes ranged from 20 to 80 mm; the majority of the slump values were within the tolerances of EN 206 1. The RCA and NA mixes generally had comparable slumps, only few RCA mixes were found to have considerably higher slump values than their corresponding NA mixes. This can be attributed to the round shape of the RCA particles and the high initial water content of the RCA mixes.

The compacting factors of the mixes ranged from 0.83 to 0.98. Despite the occasional discrepancies, the RCA mixes had similar or slightly higher compacting factor values when compared to their corresponding NA mixes.

SF mixes

The slump values of the SF mixes ranged from 20 to 40 mm; the slump values were all within the tolerances of EN 206 1. The RCA and NA mixes generally had comparable slumps. Unlike the PC and PFA mixes, using high contents of RCA did not have much influence on the slump values of SF mixes, the effect of using additional water to saturate the aggregates on the slump values may have been offset by the increase of the SF content in the RCA mixes; the amount of PC and SF in the RCA mixes was increased to compensate for the loss of strength that occurs when high contents of RCA are used in the mix. The SF increases the water demand of concrete as a result of the large specific area of the SF particles; the additional water was thus used to wet the extremely fine SF particles therefore reducing its effect on the slump values of the SF mixes.

The compacting factors of the mixes ranged from 0.92 to 0.95. The NA and RCA mixes generally had comparable compacting factor values.

5.3.2 Effect of cement constituents

PC/PFA

The use of PFA reduced the water demand of the mixes for equivalent slump when compared to the PC mixes. The reduction in water demand when PFA is used is due to the spherical shape of the PFA particles which provide a ball bearing effect and the increase of the cement paste volume in the PFA mixes which provides more cohesion and plasticity thus improving the workability of the concrete.

The PFA mixes had generally slightly lower compacting factor values when compared to their corresponding PC mixes. This may be due to the improved cohesiveness of the PFA mixes when compared to the PC mixes. However, to be fully compacted; mixes having low compacting factor values do not necessarily require a higher amount of work than mixes with high compacting factor values. In fact this will depend on the richness of the mix: leaner mixes will need more work than richer ones [78]. The PFA mixes had a higher content of cementitious material when compared to their corresponding PC mixes, they may therefore require the same amount of work to be fully compacted.

PC/SF

Contrary to PFA, SF greatly increases the water demand of concrete as a result of the large specific area of the SF particles. For the PC and SF mixes to have the same workability and ease of compaction, the SF mix needs a slump 25 to 50 mm higher than the PC mix [78]. The SF mixes had lower slumps when compared to their corresponding PC mixes; this indicates that the SF will not be as workable as the PC mixes and will require more work to be fully compacted.

The compacting factor values of SF mixes were slightly lower when compared to their corresponding PC mixes. This may be due to the improved cohesiveness and the typical stickiness of the SF mixes. This also confirms the lower workability of the SF mixes; unlike the PFA mixes, the SF mixes have a slightly lower content of cementitious material than the PC mixes, they may therefore require some additional amount of work to be fully compacted when compared to the PC mixes.

5.4 STABILITY

A visual observation of the concrete mixes was carried out to assess the effect of RCA and binary cements on the stability of concrete. The visual observation was made to examine the cohesiveness, bleeding, handling and compacting properties of the concrete mixes.

5.4.1 Effect of RCA

PC mixes

The majority of the PC mixes were found to be cohesive with no bleeding. Nevertheless, some of the RCA mixes were less cohesive when compared to their corresponding NA mixes and exhibited bleeding; this was more noticeable in concretes with high water cement ratios and high RCA contents.

Due to the higher gradual absorption of water by the RCA, the degree of bleeding initially observed immediately after mixing reduced with time in some RCA mixes. In addition, some of the low w/c ratio RCA mixes became harsher and slightly harder to handle and compact with time.

PFA mixes

The PFA mixes were found to be cohesive and exhibited no bleeding. Similar findings were reported in previous studies [22, 26 g, 35e] where PFA was used as a filler to improve the stability of RCA concrete. Some of the low w/c ratio RCA mixes became harsher and slightly harder to handle and compact with time, this may be due to the gradual absorption of water by the RCA.

SF mixes

The SF mixes were found to be cohesive and exhibited no bleeding. The majority of the SF mixes became difficult to handle and compact with time, this may be due to the gradual absorption of water by the RCA as well as the sticky nature and low workability of SF concrete. Thus, to avoid excessively sticky mixes and improve the workability of the SF concrete, it is recommended to use a superplasticizer.

5.4.2 Effect of cement constituents

PC/PFA

The use of PFA improved the cohesiveness of the concrete and eliminated bleeding. The elimination of bleeding is due to the increase in fines volume and the low water content of the PFA mixes. To be fully compacted, the PFA mixes required the same amount of work as the PC mixes. The fineness, void filling ability and the spherical shape of the PFA particles all contributed to increase the response to vibration energy and offset the low water content of the PFA mixes.

PC/SF

As a result of its fineness, the SF greatly improved the cohesiveness of the concrete thus eliminating the occurrence of bleeding. The SF concrete mixes were very sticky compared to the PC and PFA mixes. Some of the SF RCA mixes were slightly more difficult to handle and compact with time when compared to their corresponding PC and PFA mixes. Although as soon as the SF concrete was vibrated it became mobile, it needed more work to be compacted when compared to the PC and PFA concrete. It is therefore recommended to use a superplasticizer in SF concrete. The reduced bleeding of SF concrete may lead to plastic shrinkage cracking if precautions are not taken to prevent moisture evaporation from the surface of the concrete.

5.5 PRACTICAL IMPLICATIONS

The study has shown that the high water absorption of the RCA particles can affect the workability of the concrete if precautions are not taken. It was found that adding an amount of water in the mix, equal to the amount of water needed to fully saturate the RCA, in order to maintain the required slump of the RCA concrete is not practical. In fact, the RCA do not fully absorb the amount of water added; this is due to the slowing down of the absorption process caused by the coating of RCA particles with cement paste [78]. The amount of water which was not absorbed increases the free water content of the mix resulting in high initial slump values and the bleeding of some of the RCA mixes.

It is therefore important to determine the exact amount of water to be absorbed by the

RCA prior to mixing, in order to maintain the fresh concrete at the specified workability whilst also avoiding the loss of cohesion of the fresh concrete. Some studies suggested that the amount of water to be added should be equivalent to the amount absorbed by the RCA up to 10 minutes rather than the full amount needed to saturate the RCA particles as this is the amount which lowers the quantity of added water during the concrete mixing process [92]. If this solution is used, the mixing method of RCA concrete should be tailored so as to allow for the RCA particles to absorb the extra added water; the RCA particles with half of the water required for the mix should be mixed for 1 minute and then left to rest for 10 minutes before adding rest of the concrete constituents (fine aggregates, cement) followed by the rest of the water.

Other studies suggested that the pre-soaking or pre-wetting of the RCA before mixing (for 1 24 hours) is an efficient solution to achieve a workability similar to that of the NA concrete [20 c, 20 p, 36 h, 22]. This however is not very practical especially when high volumes of RCA concrete have to be produced.

PFA and SF should be used to improve the cohesiveness of RCA concrete and reduce the occurrence of bleeding. However when SF is used, it is necessary to use it with a suitable superplasticizer to improve the workability of concrete. The necessary precautions should also be taken to avoid plastic shrinkage cracking in SF concrete by preventing moisture evaporation from the surface of the concrete [77].

5.6 CONCLUDING REMARKS

- The use of high RCA contents (50 and 100%) resulted in the increase of the slump value of some of the PC and PFA mixes. This was due to the round shape of the RCA particles as well as the incomplete saturation of the RCA which resulted in an increase of the free water content of the mixes. On the other hand the use of RCA had no influence on the slump values of the SF mixes.

- The use of PFA decreased the water demand of the mixes, due to its contribution to improving the workability of the concrete. SF, on the other hand, increases the water demand of the mixes as a result of its fineness.

- The PFA and SF mixes had slightly lower compacting factor values than the corresponding PC mixes. This may be due to the improved cohesiveness of these mixes when compared to the PC mixes.

- The PFA mixes, due to their high cementitious content had the same workability as the PC mixes. On the other hand, the SF mixes were slightly more difficult to handle and compact compared to the PC and PFA mixes confirming the importance of using a superplasticizer in SF mixes.

- The high water content of the RCA mixes was behind the segregation and bleeding of some PC mixes. The use of PFA and SF in RCA concrete improved the cohesiveness of the mixes and eliminated the occurrence of bleeding.

CHAPTER 6

ENGINEERING PROPERTIES OF RCA CONCRETE

6.1 INTRODUCTION

Concrete is the most used material in construction. Structural design of concrete structures is mainly based on the compressive strength of concrete making it the most important single property of concrete. Other engineering properties of concrete used in structural design, such as the flexural strength, the modulus of elasticity, the drying shrinkage and swelling strains are also very important. These properties are influenced by the type and proportioning of materials used in making the concrete.

Several investigations were made on the effect of RCA on the engineering properties of Portland cement concrete. On the other hand very little research was undertaken to investigate the effect of RCA on the engineering properties of binary cement concretes. Additions, such as Fly ash and silica fume, have been used extensively by the concrete industry to improve the quality of conventional concrete. Such additions therefore have the potential to improve the engineering properties of RCA concrete.

Against this background, a study of the engineering properties of equal strength NA and RCA concretes made with binary cements was undertaken. For this, BS 8500 designated mixes from the GEN and RC series were used.

6.2 EXPERIMENTAL PROGRAMME

This part of the study will examine the engineering properties of equal strength Portland cement and binary cement concretes made with various contents of RCA (0, 30, 50 and 100%). The engineering properties examined include the compressive and flexural strengths, the modulus of elasticity and the drying shrinkage and swelling deformations.

6.3 COMPRESSIVE STRENGTH DEVELOPMENT

Compressive strength tests were carried out on cube (100 × 100 mm) and cylinder specimens (150 Ø mm × 300 mm). Cubes from each mix were tested at 3, 7, 14, 28, 56 90, 180 and 365 days. Cylinders were tested at 28 and 56 days.

6.3.1 Effect of RCA

6.3.1.1 PC mixes

The 100mm cube compressive strength results of all the PC designated mixes are presented in Table 6.1. Table 6.2 shows the strength of NA and RCA PC mixes at different ages as a percentage of the 28 day compressive strength of the mix.

GEN 1 – All the GEN 1 mixes reached the specified strength at 28 days regardless of the amount of RCA used in the mix. The GEN 1 mix containing 30% RCA had a lower compressive strength when compared to the other mixes. The maximum variation in strength between all mixes at 28 and 365 days was 7N/mm^2 and 10N/mm^2 respectively.

As can be seen from the results of the GEN 1 mixes in Table 6.2, the inclusion of RCA did not have an impact on the rate of strength development of the mixes.

GEN 3 – All the GEN 3 mixes reached the specified strength at 28 days regardless of

Table 6.1 Cube compressive strength results of NA and RCA PC mixes.

DESIGNATED MIX (Design Strength)	AGE (days)	COMPRESSIVE STRENGTH, (N/mm²) COARSE RCA CONTENT, %			
		0	**30**	**50**	**100**
GEN 1 (10 N/mm²)	3	9	6	10	8.5
	7	11.5	7.5	13	11
	14	13.5	8.5	15	13
	28	15	10	17	15.5
	56	17	11	19	17.5
	90	18.5	11.5	20	19
	180	20	13	22	21
	365	22	14	24	23.5
GEN 3 (20 N/mm²)	3	16.5	16.5	15.5	18.5
	7	20	19.5	19	20.5
	14	23	22	22.5	22.5
	28	25.5	25	25.5	24.5
	56	28.5	28	28.5	26.5
	90	30.5	30	30.5	27.5
	180	33	33	33.5	29.5
	365	36	36	37	31.5
RC 30 (30 N/mm²)	3	19.5	20	21.5	17
	7	24	24.5	26.5	21
	14	27.5	28.5	30	24
	28	31	32.5	34	27
	56	35	36.5	38	30.5
	90	37.5	39	41	32.5
	180	41	43	44.5	36
	365	44.5	47	48.5	39
RC 35 (35 N/mm²)	3	24	21.5	24.5	25.5
	7	29	25.5	30.5	32.5
	14	33.5	28.5	35.5	38.5
	28	37.5	31.5	40	44.5
	56	41.5	34.5	45	50.5
	90	44	36.5	48	54.5
	180	48.5	40	53	60.5
	365	52.5	43	58	66.5
RC 40 (40 N/mm²)	3	31	31	24.5	29
	7	37.5	37.5	30.5	35.5
	14	43	43	35.5	40.5
	28	48.5	48.5	40.5	46
	56	54.0	53.5	45.5	51
	90	57.5	57.5	49	54.5
	180	63	63	54	60
	365	68.5	68	59	65

Table 6.2 Strength of PC mixes as a percentage of 28 day cube compressive strength.

DESIGNATED MIX (Design Strength)	Age (days)	% OF 28 DAY CUBE STRENGTH			
		COARSE RCA CONTENT, %			
		0	30	50	100
GEN 1 (10 N/mm²)	3	60	60	59	55
	7	77	75	76	71
	14	90	85	88	84
	28	100	100	100	100
	56	113	110	112	113
	90	123	115	118	123
	180	133	130	129	135
	365	147	140	141	152
GEN 3 (20 N/mm²)	3	65	66	61	76
	7	78	78	75	84
	14	90	88	88	92
	28	100	100	100	100
	56	112	112	112	108
	90	120	120	120	112
	180	129	132	131	120
	365	141	144	145	129
RC 30 (30 N/mm²)	3	63	62	63	63
	7	77	75	78	78
	14	89	88	88	89
	28	100	100	100	100
	56	113	112	112	113
	90	121	120	121	120
	180	132	132	131	133
	365	144	145	143	144
RC 35 (35 N/mm²)	3	64	68	61	57
	7	77	81	76	73
	14	89	90	89	87
	28	100	100	100	100
	56	111	110	113	113
	90	117	116	120	122
	180	129	127	133	136
	365	140	137	145	149
RC 40 (40 N/mm²)	3	64	64	60	63
	7	77	77	75	77
	14	89	89	88	88
	28	100	100	100	100
	56	111	110	112	111
	90	119	119	121	118
	180	130	130	133	130
	365	141	140	146	141

the amount of RCA used in the mix. All the mixes had a similar strength at 28 days. The maximum variation in strength between all mixes at 28 and 365 days was 1N/mm^2 and 5.5N/mm^2 respectively.

As can be seen from the results of the GEN 3 mixes in Table 6.2, the inclusion of RCA did not have an impact on the rate of strength development of the mixes.

RC 30 – All the RC 30 mixes reached the specified strength at 28 days except the 100% RCA mix which had a strength 3N/mm^2 below the specified strength. The maximum variation in strength between all mixes at 28 and 365 days was 7N/mm^2 and 5.5N/mm^2 respectively.

As can be seen from the results of the RC 30 mixes in Table 6.2, the inclusion of RCA did not have an impact on the rate of strength development of the mixes.

RC 35 – All the RC 35 mixes reached the specified strength at 28 days except the 30% RCA mix which had a strength 3.5N/mm^2 below the specified strength. The maximum variation in strength between all mixes at 28 and 365 days was 7N/mm^2 and 5.5N/mm^2 respectively.

As can be seen from the results of the RC 35 mixes in Table 6.2, the inclusion of RCA did not have an impact on the rate of strength development of the mixes.

RC 40 – All the RC 40 mixes reached the specified strength at 28 days . The 50% RCA mix had a significantly lower strength compared to the other mixes. The maximum variation in strength between all mixes at 28 and 365 days was 8N/mm^2 and 9.5N/mm^2 respectively.

As can be seen from the results of the RC 40 mixes in Table 6.2, the inclusion of RCA did not have an impact on the rate of strength development of the mixes.

Overall, all the NA and RCA designated mixes reached the specified strength at 28 days showing the validity of the method used to take account of the effects of RCA on the compressive strength of concrete. The use of RCA did not have any effect on the rate of strength development of the PC designated mixes.

6.3.1.2 PFA mixes

The 100mm cube compressive strength results of all the PFA designated mixes are presented in Table 6.3. Table 6.4 shows the strength of NA and RCA PFA mixes at different ages as a percentage of the 28 day compressive strength of the mix.

GEN 1 – All the GEN 1 mixes reached the specified strength at 28 days regardless of the amount of RCA used in the mix. The GEN 1 mix containing 30% RCA had a lower compressive strength when compared to the other mixes. The maximum variation in strength between all mixes at 28 and 365 days was 5N/mm^2 and 9N/mm^2 respectively.

As can be seen from the results of the GEN 1 mixes in Table 6.4, the NA and 30% RCA mixes had a slower rate of strength development when compared to the 50 and 100% RCA mixes up to 14 days. However the opposite is observed after 14 days.

Table 6.3 Cube compressive strength results of NA and RCA PFA mixes.

DESIGNATED MIX (Design Strength)	AGE (days)	COMPRESSIVE STRENGTH, (N/mm²) COARSE RCA CONTENT, %			
		0	30	50	100
GEN 1 (10 N/mm²)	3	3.5	2.5	7	7
	7	8.5	6	10.5	10
	14	12.5	8.5	13	13
	28	16.5	11.5	15.5	15.5
	56	20	14.5	18	18.5
	90	23	16.5	20	20
	180	27	19	22.5	23
	365	31	22	25	25.5
GEN 3 (20 N/mm²)	3	10	12.5	14	15
	7	17.5	19	19.5	20
	14	23.5	24	24	24.5
	28	29.5	29.5	28.5	28.5
	56	35.5	34.5	33	33
	90	39.5	38.5	36.5	36
	180	46	43.5	41	40.5
	365	52	49	45.5	44.5
RC 30 (30 N/mm²)	3	14.5	17	18.5	21.5
	7	23	23.5	25	27.5
	14	30	29.5	30	32
	28	37.5	35	35	37
	56	44.5	40.5	40	42
	90	49	44	43.5	45
	180	56	49.5	48.5	50
	365	63.5	55.5	54	55
RC 35 (35 N/mm²)	3	18	25	20.5	22
	7	26	32	27.5	27.5
	14	32.5	37.5	33.5	31.5
	28	38.5	43	39.5	36
	56	45	48.5	45.4	40.5
	90	49.5	52	49.5	43.5
	180	56	57.5	55.5	48
	365	62.5	63.5	61.5	52.5

Table 6.4 Strength of PFA mixes as a percentage of 28 day cube compressive strength.

DESIGNATED MIX (Design Strength)	Age (days)	% OF 28 DAY CUBE STRENGTH			
		COARSE RCA CONTENT, %			
		0	30	50	100
GEN 1 (10 N/mm^2)	3	21	22	45	45
	7	52	52	68	65
	14	76	74	84	84
	28	100	100	100	100
	56	121	126	116	119
	90	139	143	129	129
	180	164	165	145	148
	365	188	191	161	165
GEN 3 (20 N/mm^2)	3	34	42	49	53
	7	59	64	68	70
	14	80	81	84	86
	28	100	100	100	100
	56	120	117	116	116
	90	134	131	128	126
	180	156	147	144	142
	365	176	166	160	156
RC 30 (30 N/mm^2)	3	39	49	53	58
	7	61	67	71	74
	14	80	84	86	86
	28	100	100	100	100
	56	119	116	114	114
	90	131	126	124	122
	180	149	141	139	135
	365	169	159	154	149
RC 35 (35 N/mm^2)	3	47	58	52	61
	7	68	74	70	76
	14	84	87	85	88
	28	100	100	100	100
	56	117	113	115	113
	90	129	121	125	121
	180	145	134	141	133
	365	162	148	156	146

GEN 3 – All the GEN 3 mixes reached the specified strength at 28 days regardless of the amount of RCA used in the mix. All the mixes had an approximately similar strength at 28 days. The maximum variation in strength between all mixes at 28 and 365 days was $1N/mm^2$ and $7.5N/mm^2$ respectively.

As can be seen from the results of the GEN 3 mixes in Table 6.4, the rate of strength development up to 14 days increased as the RCA content of the mixes increased. However after 14 days, the rate of strength development after 14 days began to decrease as the RCA content of the mixes increased.

RC 30 – All the RC 30 mixes reached the specified strength at 28 days regardless of the amount of RCA used in the mix. All the mixes had an approximately similar strength at 28 days. The maximum variation in strength between all mixes at 28 and 365 days was $2.5N/mm^2$ and $9.5N/mm^2$ respectively.

As can be seen from the results of the RC 30 mixes in Table 6.4, the rate of strength development up to 14 days increased as the RCA content of the mixes increased. However after 14 days, the rate of strength development after 14 days began to decrease as the RCA content of the mixes increased.

RC 35 – All the RC 35 mixes reached the specified strength at 28 days regardless of the amount of RCA used in the mix. The maximum variation in strength between all mixes at 28 and 365 days was $7N/mm^2$ and $11N/mm^2$ respectively.

As can be seen from the results of the RC 35 mixes in Table 6.4, the rate of strength development of all the RCA mixes up to 14 days was higher than the NA mix, with the 30 and 100% RCA mixes having a similarly higher rate development than the 50% mix. However after 14 days, the opposite was observed.

Overall, all the NA and RCA designated mixes reached the specified strength at 28 days showing the validity of the method used to take account of the effects of RCA on the compressive strength of concrete. For the PFA mixes, at the early ages (up to 14 days), the rate of strength development increased as the RCA content increased. At later ages (beyond 90 days), the rate of strength development decreased with the increase of the RCA content.

6.3.1.3 SF mixes

The 100mm cube compressive strength results of all the SF designated mixes are presented in Table 6.5. Table 6.6 shows the strength of NA and RCA SF mixes at different ages as a percentage of the 28 day compressive strength of the mix.

RC 30 – All the RC 30 mixes reached the specified strength at 28 days regardless of the amount of RCA used in the mix. All the mixes had an approximately similar strength at 28 days. The maximum variation in strength between all mixes at 28 and 365 days was 1.5N/mm^2 and 6.5N/mm^2 respectively.

As can be seen from the results of the RC 30 mixes in Table 6.6, the rate of strength development of all the RCA mixes up to 14 days was higher than the NA mix. After 28 days, the rate of strength development of the 50 and 100% RCA mixes was lower

Table 6.5 Cube compressive strength results of NA and RCA SF mixes.

DESIGNATED MIX (Design Strength)	AGE (days)	COMPRESSIVE STRENGTH, (N/mm^2) COARSE RCA CONTENT, %			
		0	30	50	100
	3	16	24	21.5	21
	7	24	29	27	27
	14	30.5	33.5	31.5	32
RC 30	28	37	37.5	36	37
(30 N/mm^2)	56	43.5	41.5	41	41.5
	90	47	47	42.5	43.5
	180	52	51	44.5	45.5
	365	51	53	46.5	47.5
	3	26	17	22	20.5
	7	33	28	29	28.5
	14	39	38	35	35
RC 35	28	44.5	43.5	41	41.5
(35 N/mm^2)	56	50.5	45	46	48
	90	52	47	47	47
	180	54.5	48	50	49
	365	57	48	50	51

Table 6.6 Strength of SF mixes as a percentage of 28 day cube compressive strength.

DESIGNATED MIX (Design Strength)	Age (days)	% OF 28 DAY CUBE STRENGTH COARSE RCA CONTENT, %			
		0	30	50	100
	3	43	64	59	57
	7	65	77	75	73
	14	83	89	87	86
RC 30	28	100	100	100	100
(30 N/mm^2)	56	118	111	113	112
	90	127	125	117	117
	180	141	136	123	123
	365	138	141	128	128
	3	58	39	54	49
	7	74	64	71	69
	14	88	87	85	84
RC 35	28	100	100	100	100
(35 N/mm^2)	56	113	103	112	116
	90	117	108	115	114
	180	123	110	122	118
	365	128	110	122	123

than the NA and 30% RCA mixes which had a more or less similar rate of strength development.

RC 35 – All the RC 35 mixes reached the specified strength at 28 days regardless of the amount of RCA used in the mix. The maximum variation in strength between all mixes at 28 and 365 days was 3.5N/mm^2 and 9N/mm^2 respectively.

As can be seen from the results of the RC 35 mixes in Table 6.6, unlike other mixes, it is not evident that the RCA content had an effect on the rate of strength development of the RC 35 SF mixes.

Overall, all the NA and RCA designated mixes reached the specified strength at 28 days showing the validity of the method used to take account of the effects of RCA on the compressive strength. No evident effect of RCA on the rate of strength development was established for the SF mixes.

6.3.2 Effect of cement constituents

6.3.2.1 PC/PFA

GEN 1 – Comparing the strength results of the GEN 1 PC and PFA mixes shown in table 6.1 and 6.3 respectively, it can be seen that the strength of the PFA mixes was lower than the corresponding PC mixes prior to 28 days. At 28 days, the strength the PFA and corresponding PC mixes was in the same range. The maximum variation at 28 days between a PFA mix and its corresponding PC mix was 1.5N/mm^2. However, beyond 28 days of curing, the strength of the PFA mixes exceeded the strength of the PC mixes. The maximum variation at 365 days between a PFA mix and its corresponding PC mix was observed in the NA mix and was 9N/mm^2.

Comparing the results for the GEN1 PC and PFA mixes shown in Tables 6.2 and 6.4 respectively. We find that the PFA mixes have a slower rate of strength development at early ages when compared to their corresponding PC mixes. However the opposite was observed at a later age.

GEN 3 – Comparing the strength results of the GEN3 PC and PFA mixes shown in Tables 6.1 and 6.3 respectively, it can be seen that the strength of the PFA mixes was lower than the corresponding PC mixes prior to 28 days. At 28 days, the strength the PFA was slightly higher than the corresponding PC mixes. The maximum variation at 28 days between a PFA mix and its corresponding PC mix was 4.5N/mm^2. Beyond 28 days of curing, the strength of the PFA mixes exceeded significantly the strength of the PC mixes. The maximum variation at 365 days between a PFA mix and its corresponding PC mix was observed for the NA mix and was 16N/mm^2.

Comparing the results for the GEN 3 PC and PFA mixes shown in Tables 6.2 and 6.4 respectively. We find that the PFA mixes have a slower rate of strength development at early ages compared to their corresponding PC mixes. However the opposite was observed after 28 days.

RC 30 – Comparing the strength results of the RC 30 PC and PFA mixes shown in Tables 6.1 and 6.3 respectively, it can be seen that the strength of the PFA mixes was lower than the corresponding PC mixes at early ages. At 28 days, the strength the PFA mixes was higher than the corresponding PC mixes. The maximum variation at 28 days between a PFA mix and its corresponding PC mix was 10N/mm^2. Beyond 28 days of curing, the strength of the PFA mixes exceeded significantly the strength of the PC mixes. The maximum variation at 365 days between a PFA mix and its corresponding PC mix was observed for NA mix and was 19N/mm^2.

Comparing the results for the RC 30 PC and PFA mixes shown in Tables 6.2 and 6.4 respectively. We find that the NA, 30, 50% RCA PFA mixes have a slower rate of strength development at early ages compared to their corresponding PC mixes. However the opposite was observed after 28 days. The 100% RCA PFA mix had an approximately similar rate of strength development as its corresponding PC mix.

RC 35 – Comparing the strength results of the RC 35 PC and PFA mixes shown in Tables 6.1 and 6.3 respectively, it can be seen that the strength of the PFA mixes was lower than the corresponding PC mixes at early ages. At 28 days, the strength of all the PFA mixes and PC mixes was in the same range except for the 30% PC mix which did not achieve the specified strength. The maximum variation at 28 days between a PFA mix and its corresponding PC mix disregarding the 30% mix was 8.5N/mm^2. Beyond 28 days of curing, the strength of the PFA mixes exceeded significantly the strength of the PC mixes. The maximum variation at 365 days between a PFA mix and its corresponding PC mix was observed for NA mix and was 19N/mm^2.

Comparing the results for the RC 35 PC and PFA mixes shown in Tables 6.2 and 6.4 respectively. We find that the NA, 30 and 50% RCA PFA mixes have a slower rate of strength development at early ages compared to their corresponding PC mixes. However the opposite was observed after 28 days. The 100% RCA PFA mix had an approximately similar rate of strength development as its corresponding PC mix.

Overall, the PC mixes had a higher rate of strength development when compared to their corresponding PFA mixes at early ages. However the opposite was observed at later ages. The slow rate of strength development of the PFA mixes is most probably due to the low PC content of these mixes.

6.3.2.2 PC/SF

RC 30 – Comparing the strength results of the RC 30 PC and SF mixes shown in Tables 6.1 and 6.5 respectively, it can be seen that the strength of the SF mixes was lower than the corresponding PC mixes at early ages. At 28 days, the strength the SF mixes was higher than their corresponding PC mixes. The maximum variation at 28 days between a SF mix and its corresponding PC mix was 10N/mm^2. Beyond 28 days of curing, the strength of the SF mixes remained higher than the strength of their corresponding PC mixes. The maximum variation at 365 days between a SF mix and its corresponding PC mix was observed for 100% RCA mix and was 8.5N/mm^2.

Comparing the results for the RC 30 PC and SF mixes shown in Tables 6.2 and 6.6 respectively, it is clear that the SF and their corresponding PC mixes have a similar rate of strength development at early ages except for the SF NA mix which had a slower rate than its corresponding mix. After 28 days of curing, the NA and 30% RCA SF mixes had an approximately similar rate of strength development as their corresponding PC mixes, whilst the rate of strength development of the 50 and 100% RCA SF mixes slowed down compared to their corresponding PC mixes.

RC 35 – Comparing the strength results of the RC 35 PC and SF mixes shown in Tables 6.1 and 6.5 respectively, it can be seen that the strength of the PC and their corresponding SF mixes was approximately the same at early ages. At 28 days, the strength the SF mixes was higher than their corresponding PC mixes. The maximum variation at 28 days between a SF mix and its corresponding PC mix was 12N/mm^2. Beyond 28 days of curing, the strength of the SF mixes remained higher than the strength of their corresponding PC mixes except for the 50 and 100% RCA mixes. The maximum variation at 365 days between a SF mix and its corresponding PC mix was observed for 100% RCA mix and was 15.5N/mm^2.

Comparing the results for the RC 35 PC and SF mixes shown in Tables 6.2 and 6.6 respectively, it is clear that the SF mixes have a slightly slower rate of strength development.

Overall, the PC mixes in general had a similar or slightly higher rate of strength development when compared to their corresponding SF mixes. The slow rate of strength development of the SF mixes is most probably due to the low PC content of these mixes.

6.3.3 Cube vs. Cylinder compressive strength

6.3.3.1 Effect of RCA

PC mixes

The cube compressive strengths of the PC mixes and their corresponding cylinder compressive strengths at 28 and 56 days are shown respectively in Table A.1 and Table A.2 of Appendix A. The relationships between the cube and cylinder strengths of all the PC mixes regardless of the RCA content at 28 days and 56 days are shown in Figures 6.1 and 6.2 respectively. These show that there is a good correlation between the cube and the cylinder compressive strength of PC mixes at both 28 (R^2 = 0.85) and 56 days (R^2 = 0.92).

Figure 6.3 compares the relationship between the cube and cylinder strength at 28 and 56 days. As can be seen from the graph, the cube and cylinder strength relationships at 28 and 56 days are similar. Therefore, the age of concrete does not affect the cube and cylinder strength relationship of the PC mixes.

The average cylinder – cube strength ratio of the PC mixes regardless of the RCA content and age was 81%. This is identical to the cylinder – cube strength ratio used in the EN 206 – 1 and BS 8500 (≈ 80%) for concrete at 28 days. The average ratios for the 0, 30, 50 and 100% RCA concretes regardless of age were 78, 79, 82 and 86% respectively. This shows that the inclusion up to 30% RCA in concrete does not affect the ratio, however beyond this limit; the cylinder – cube strength ratio increases with an increase in the RCA content.

PFA mixes

The cube compressive strengths of the PFA mixes and their corresponding cylinder compressive strengths at 28 and 56 days are shown respectively in Table A.3 and Table A.4 of Appendix A. The relationships between the cube and cylinder strengths of all the PFA mixes regardless of the RCA content at 28 days and 56 days are shown in Figures 6.4 and 6.5 respectively. These show that there is a good correlation between the cube and cylinder compressive strength of PFA mixes at both 28 (R^2 = 0.85) and 56 days (R^2 = 0.91).

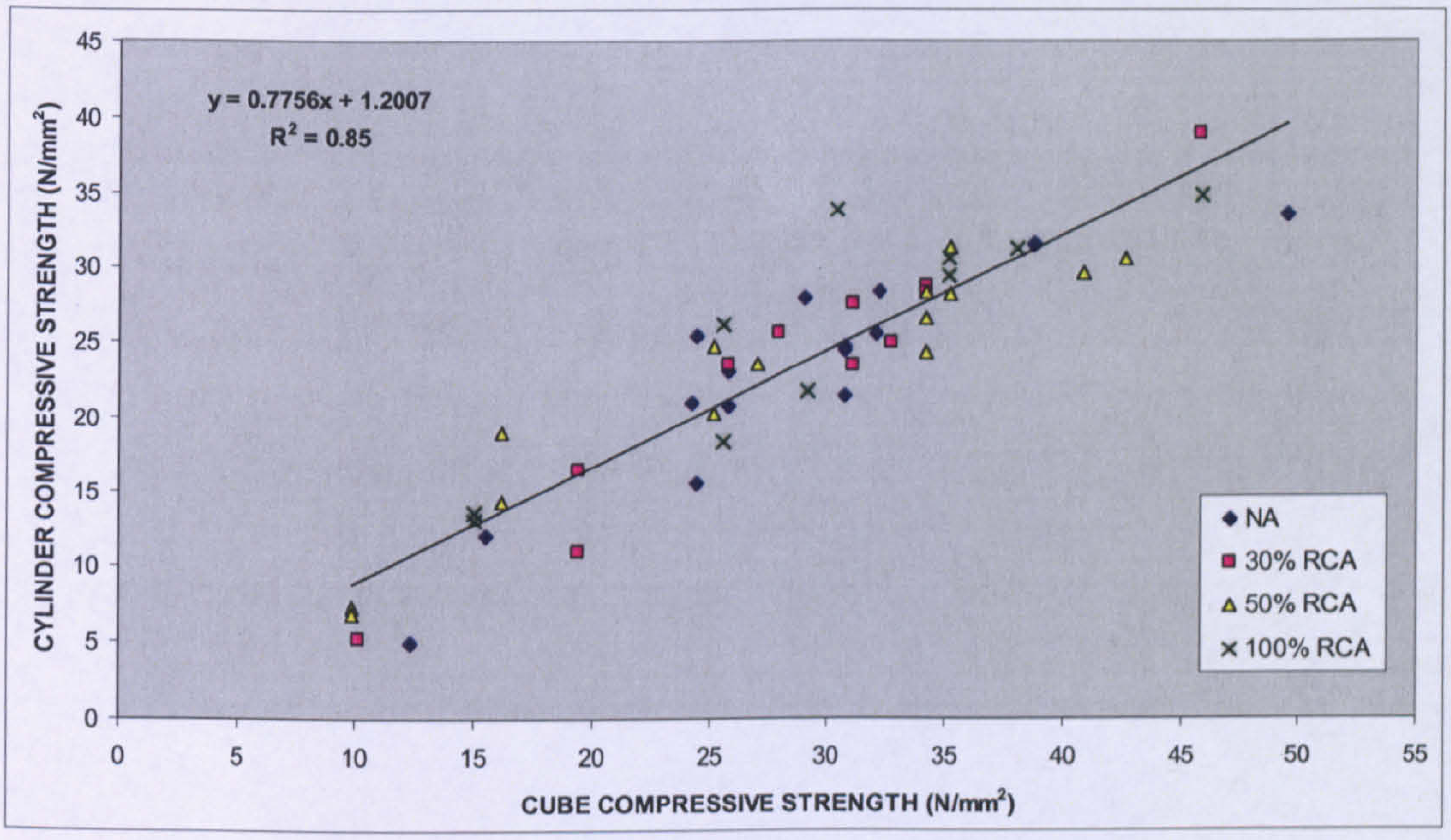


Figure 6.1 Cube vs. cylinder strength of PC mixes at 28 days.

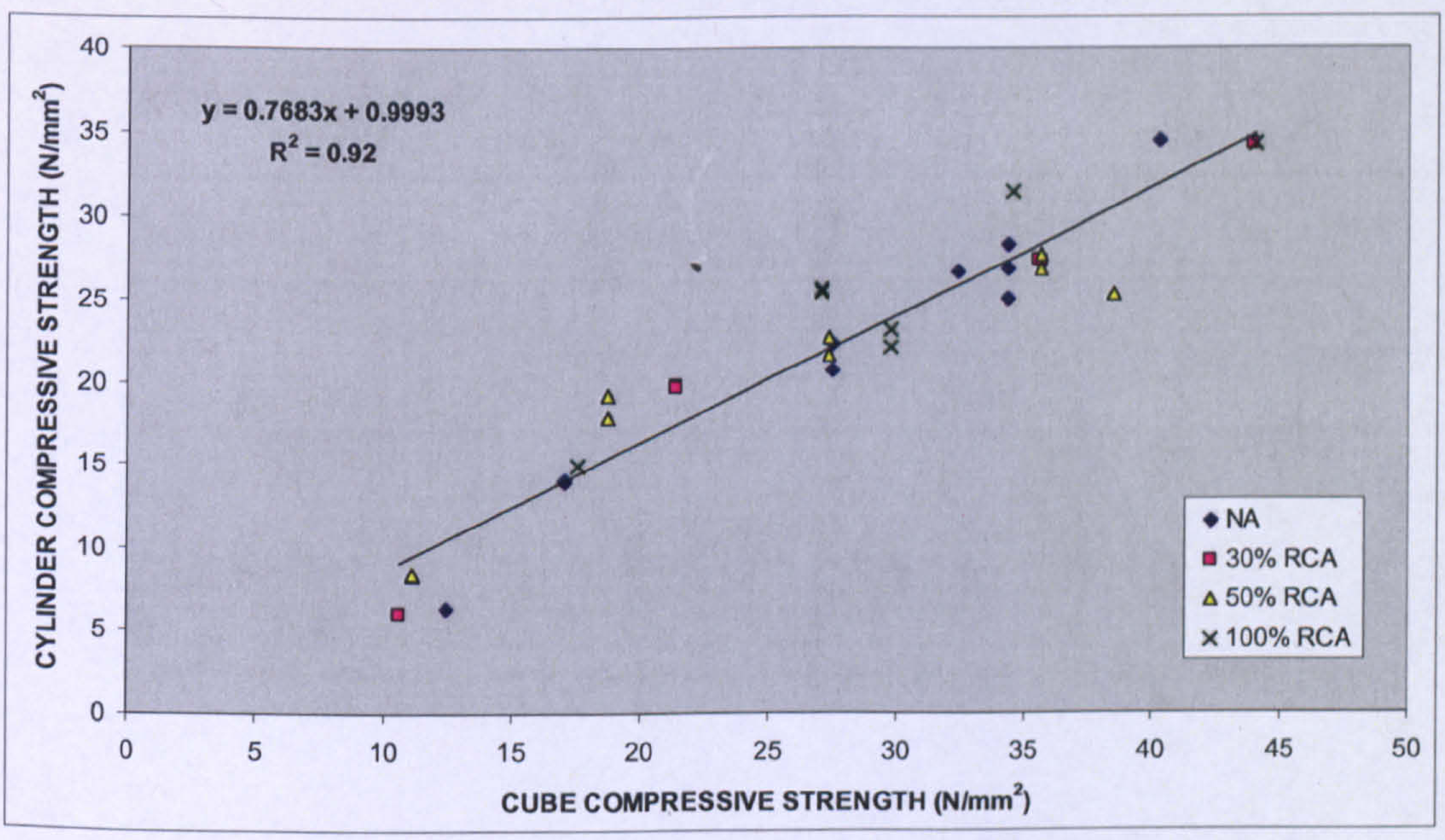


Figure 6.2 Cube vs. cylinder strength of PC mixes at 56 days.

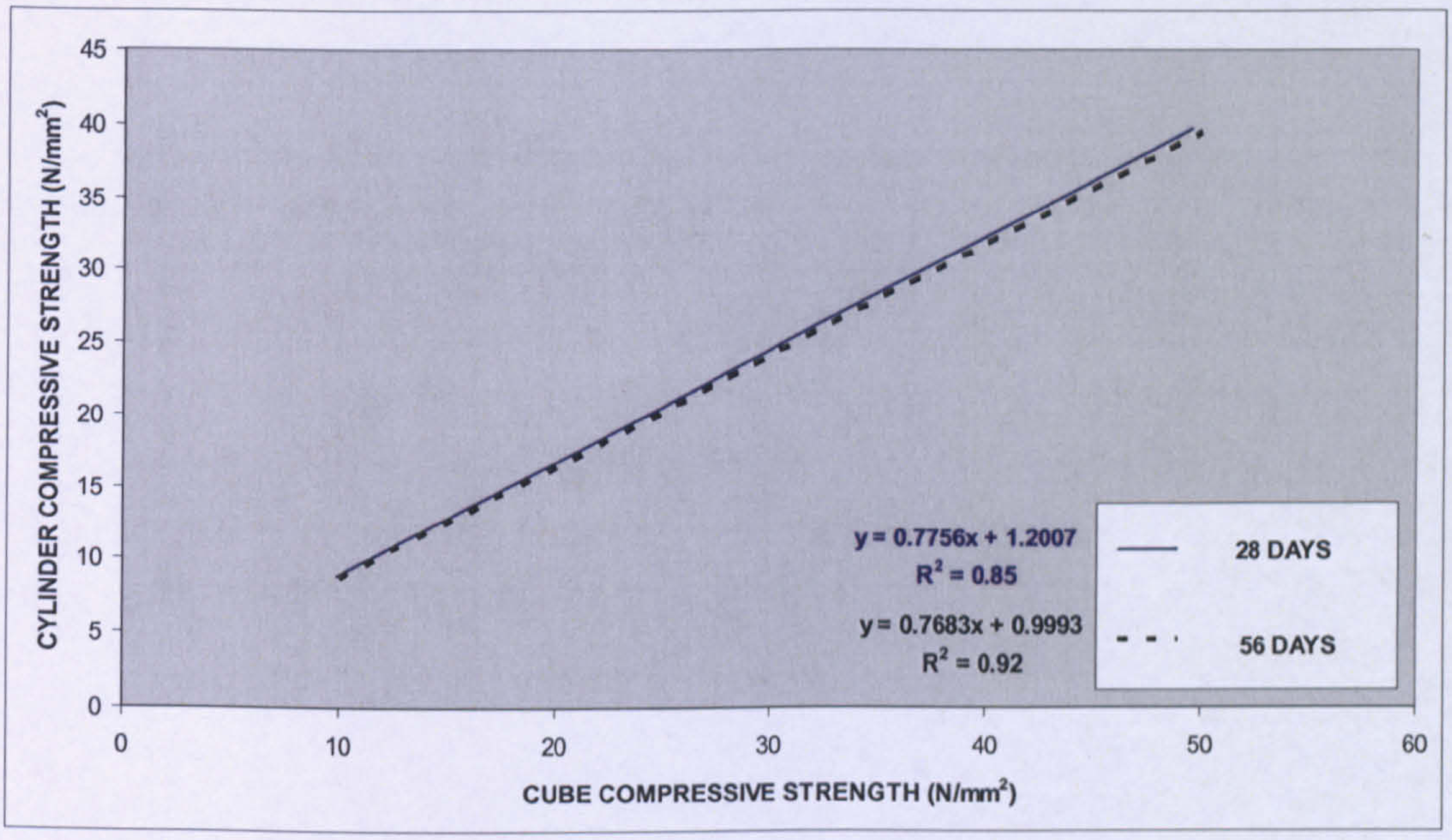


Figure 6.3 Comparison of the cube and cylinder strength relationship of PC mixes at 28 and 56 days.

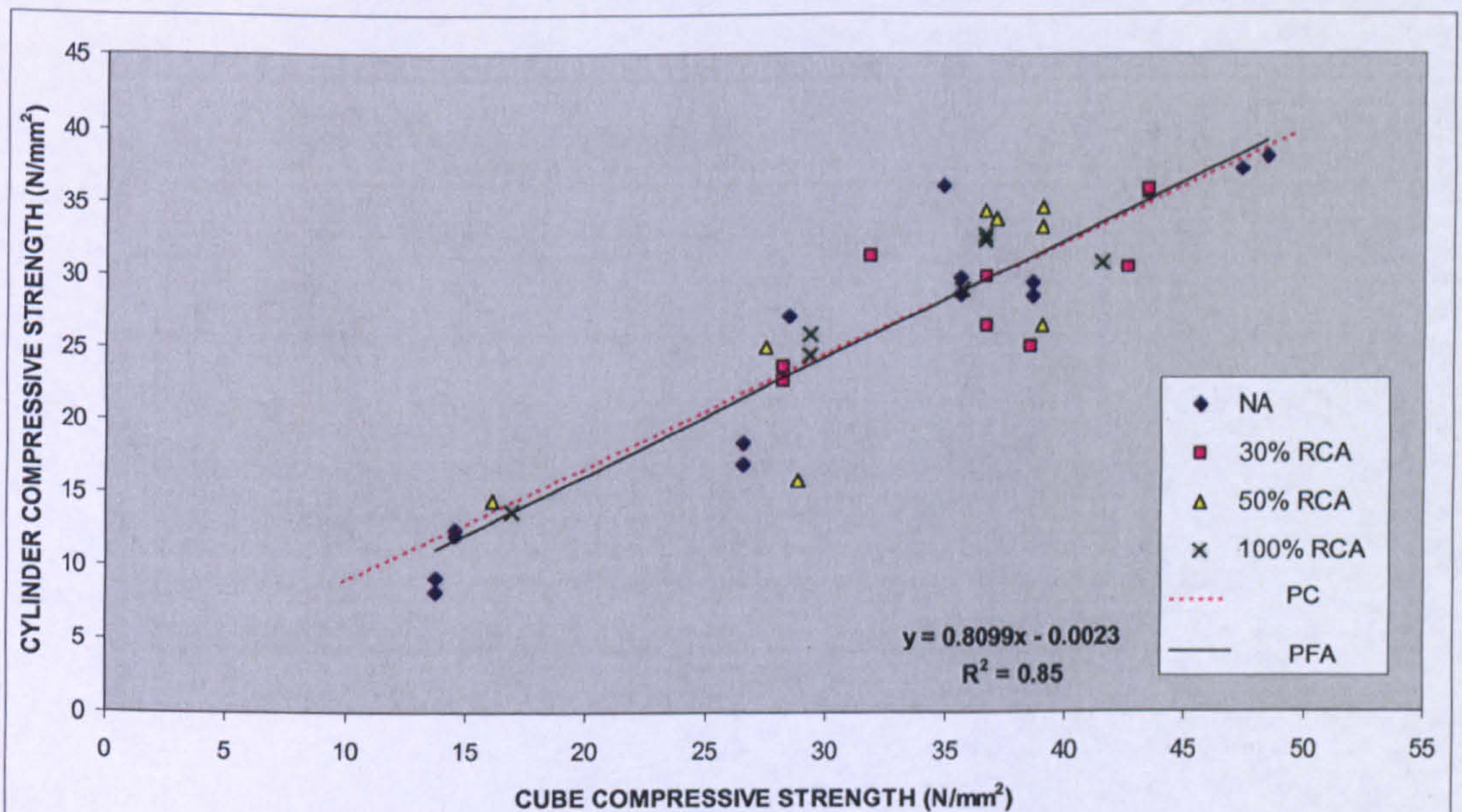


Figure 6.4 Cube vs. cylinder strength of PFA mixes + Comparison of the cube and cylinder strength relationship of PC and PFA concretes (at 28 days).

Figure 6.6 compares the relationship between the cube and cylinder strengths at 28 and 56 days. As can be seen from the graph, the cube and cylinder strengths relationships at 28 and 56 days are approximately identical. Therefore, the age of concrete does not significantly affect the cube and cylinder strength relationship of the PFA mixes.

The average cylinder/cube strength ratio of all the PFA mixes regardless of the RCA content and age was 80%. However when comparing the average cylinder/cube ratios of the mixes with different RCA contents, it was found that the cylinder/cube strength ratio increased when 100% RCA was used. The average ratio for the NA, 30 and 50% RCA PC mixes was 79%, while it was 83% for the 100% RCA mixes.

SF mixes

The cube compressive strengths of the SF mixes and their corresponding cylinder compressive strengths at 28 and 56 days are shown respectively in Table A.5 and Table A.6 of Appendix A. The relationships between the cube and cylinder strengths of all the SF mixes regardless of the RCA content at 28 days and 56 days are shown in Figures 6.7 and 6.8 respectively. These show that there is a good correlation between the cube and the cylinder compressive strengths of SF mixes at both 28 ($R^2 = 0.71$) and 56 days ($R^2 = 0.81$).

Figure 6.9 compares the relationship between the cube and cylinder strengths at 28 and 56 days. As can be seen from the graph, the cube and cylinder strengths relationships at 28 and 56 days are approximately the same. The cube and cylinder strengths relationship of the SF mixes is not affected by the age of the concrete.

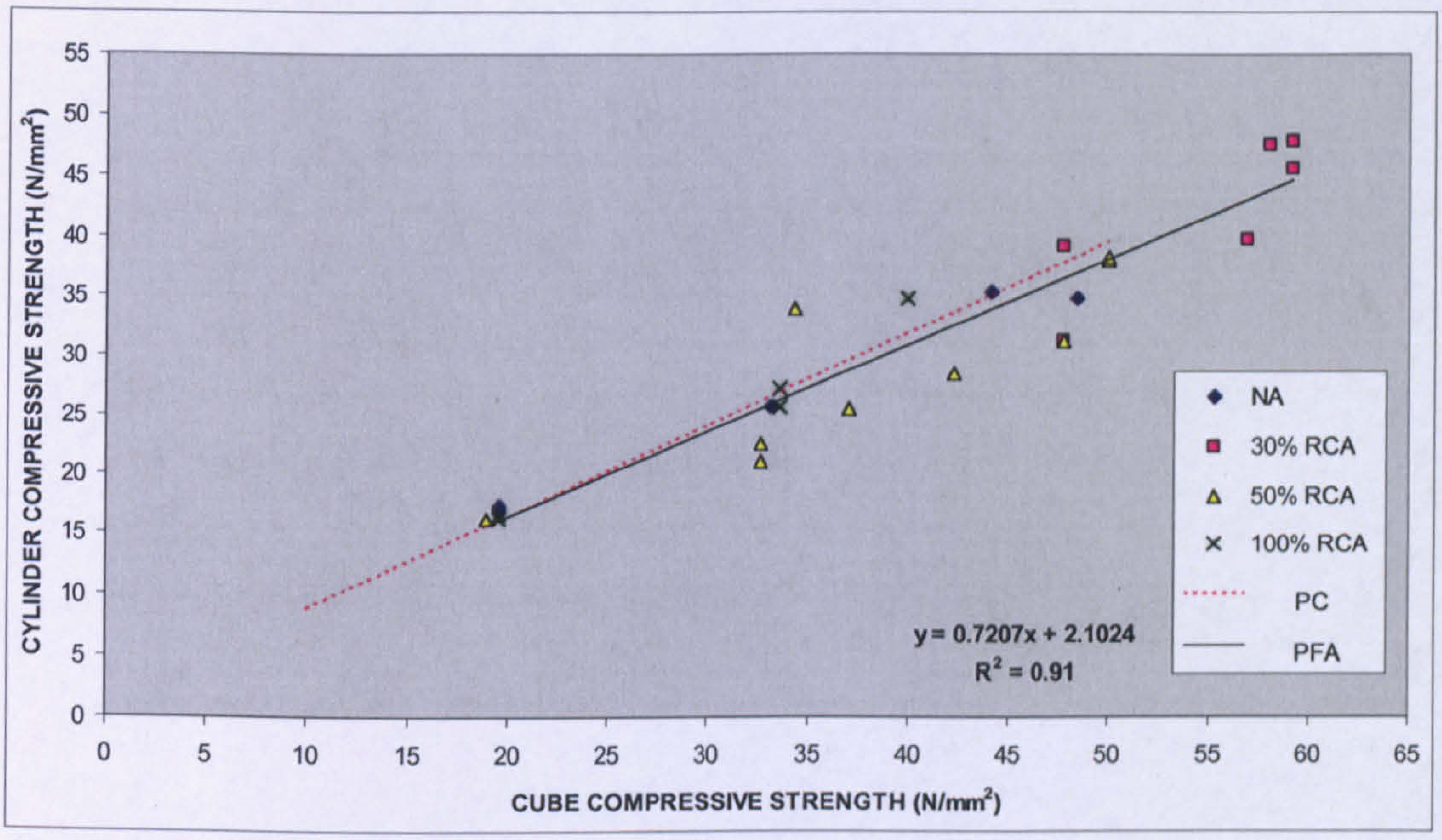


Figure 6.5 Cube vs. cylinder strength of PFA mixes + Comparison of the cube and cylinder strength relationship of PC and PFA concretes (at 56 days).

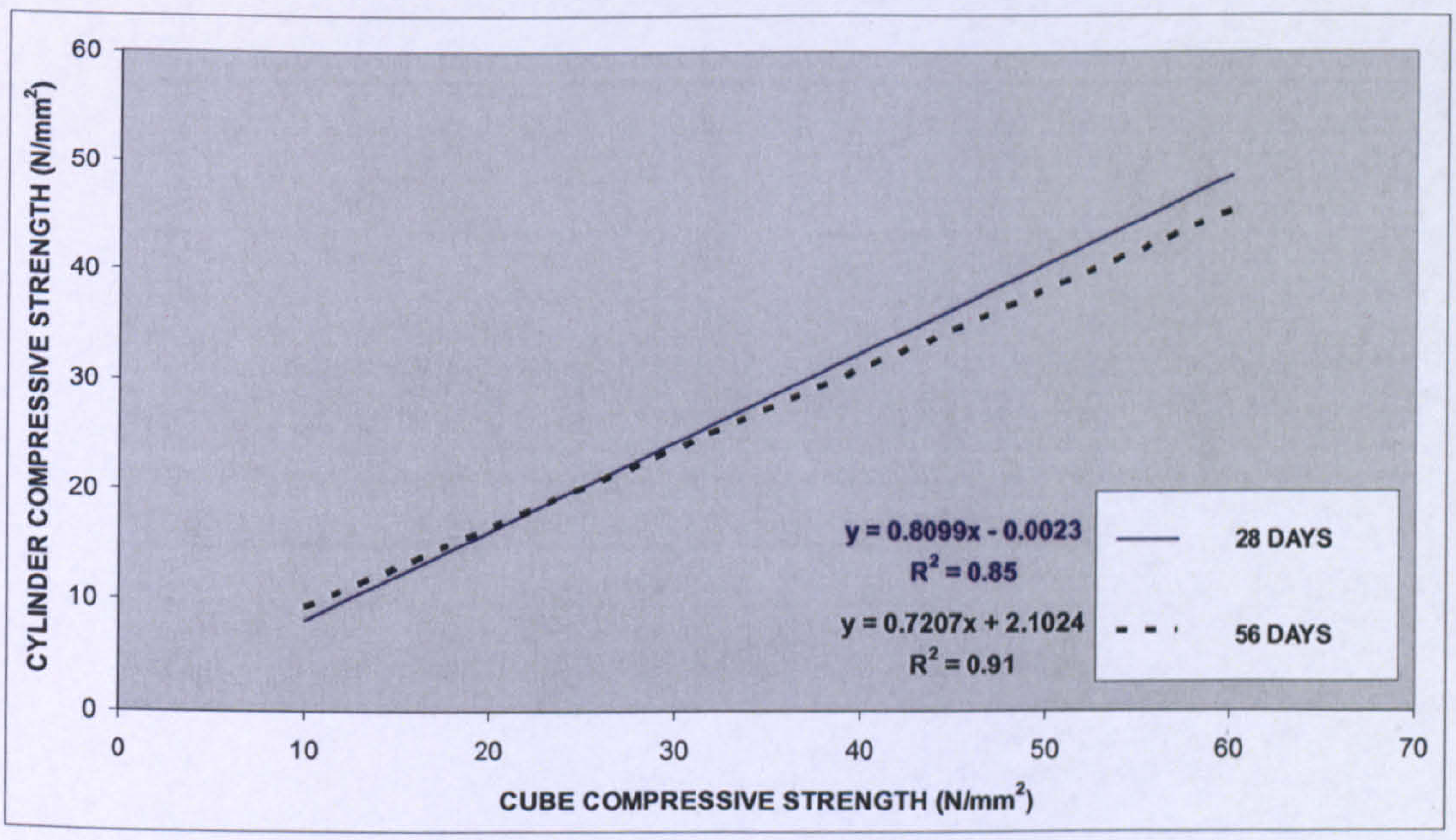


Figure 6.6 Comparison of the cube and cylinder strength relationship of PFA mixes at 28 and 56 days.

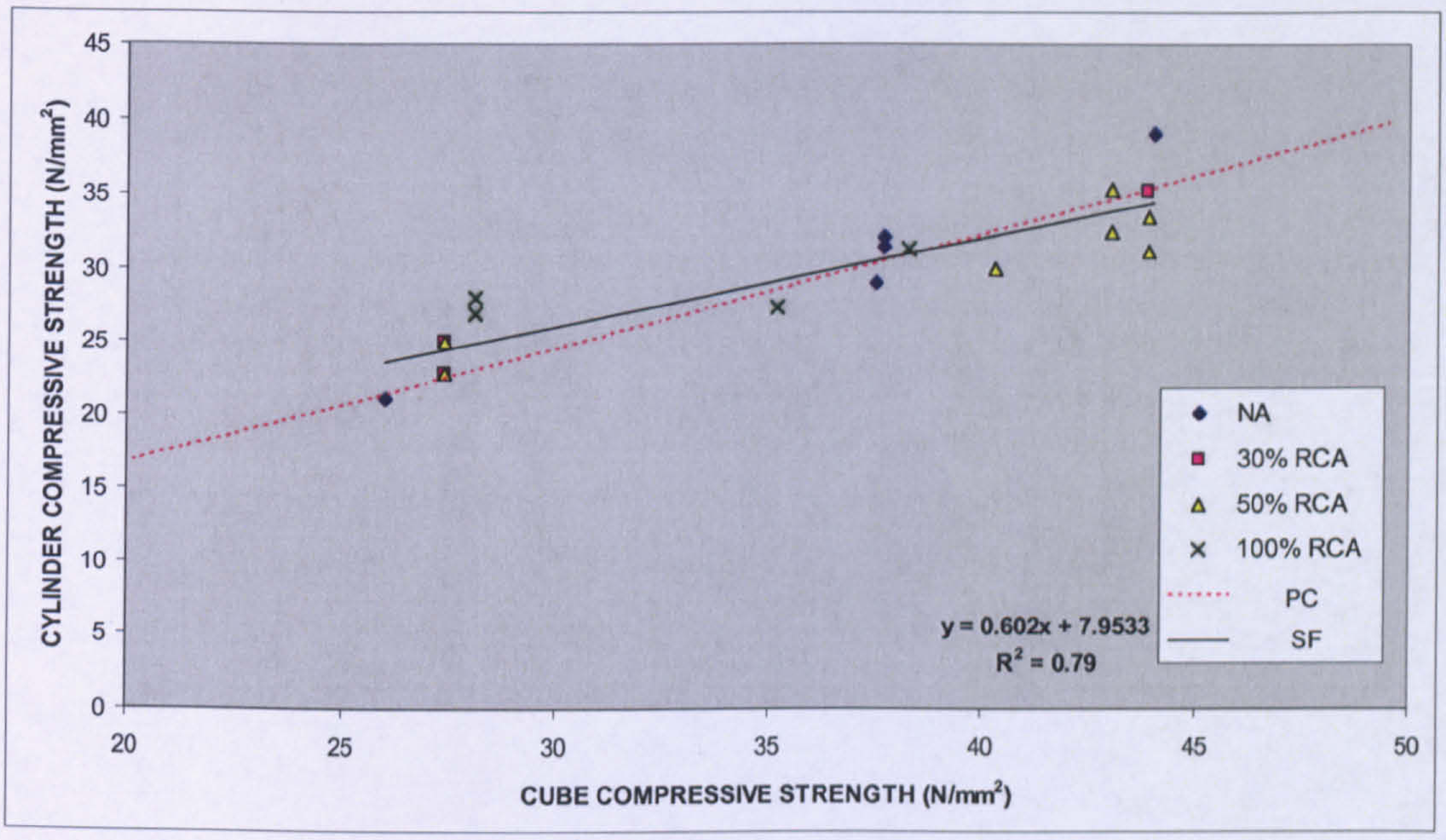


Figure 6.7 Cube vs. cylinder strength of SF mixes + Comparison of the cube and cylinder strength relationship of PC and SF concretes (at 28 days).

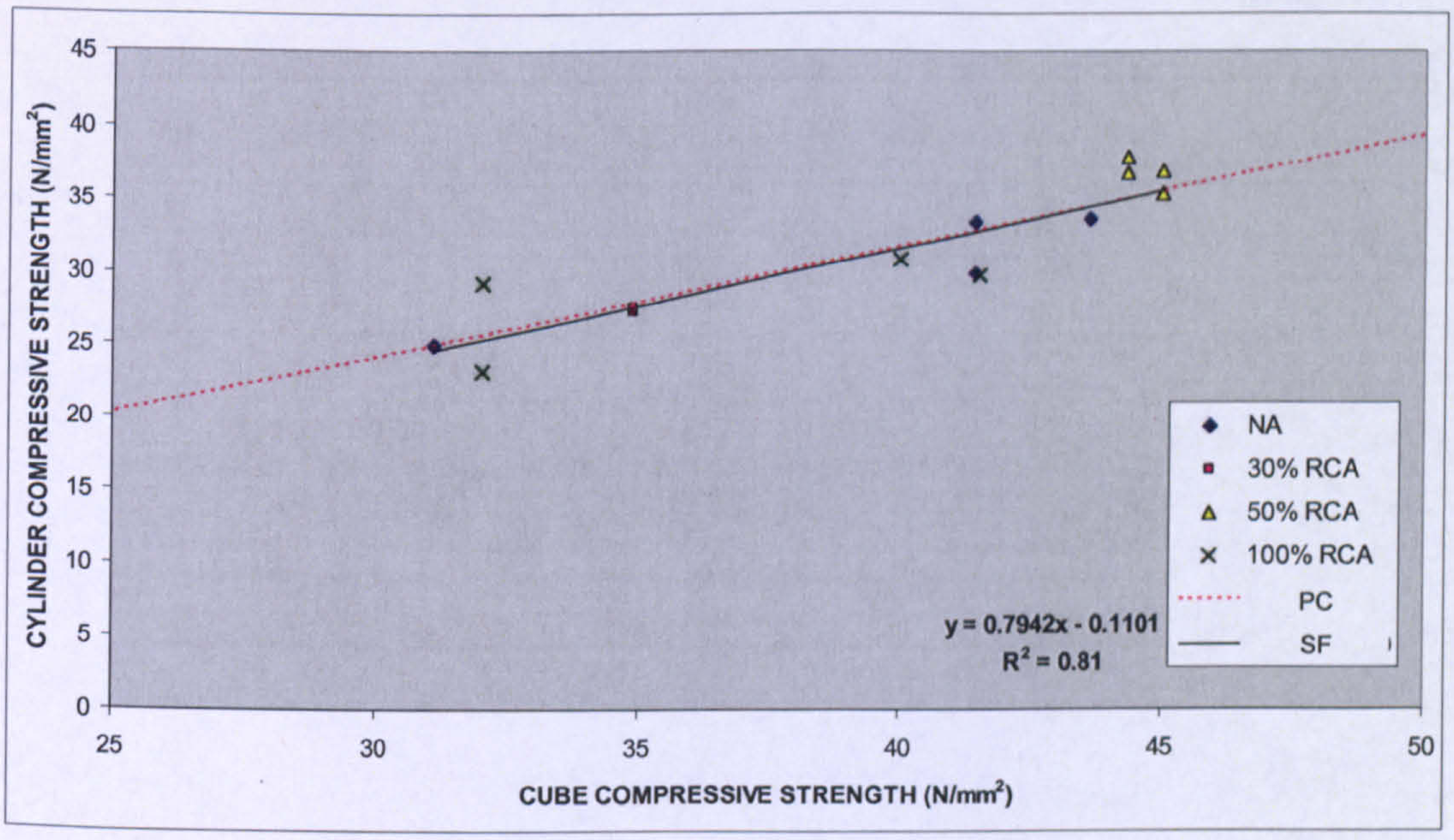


Figure 6.8 Cube vs. cylinder strength of SF mixes + Comparison of the cube and cylinder strength relationship of PC and SF concretes (at 56 days).

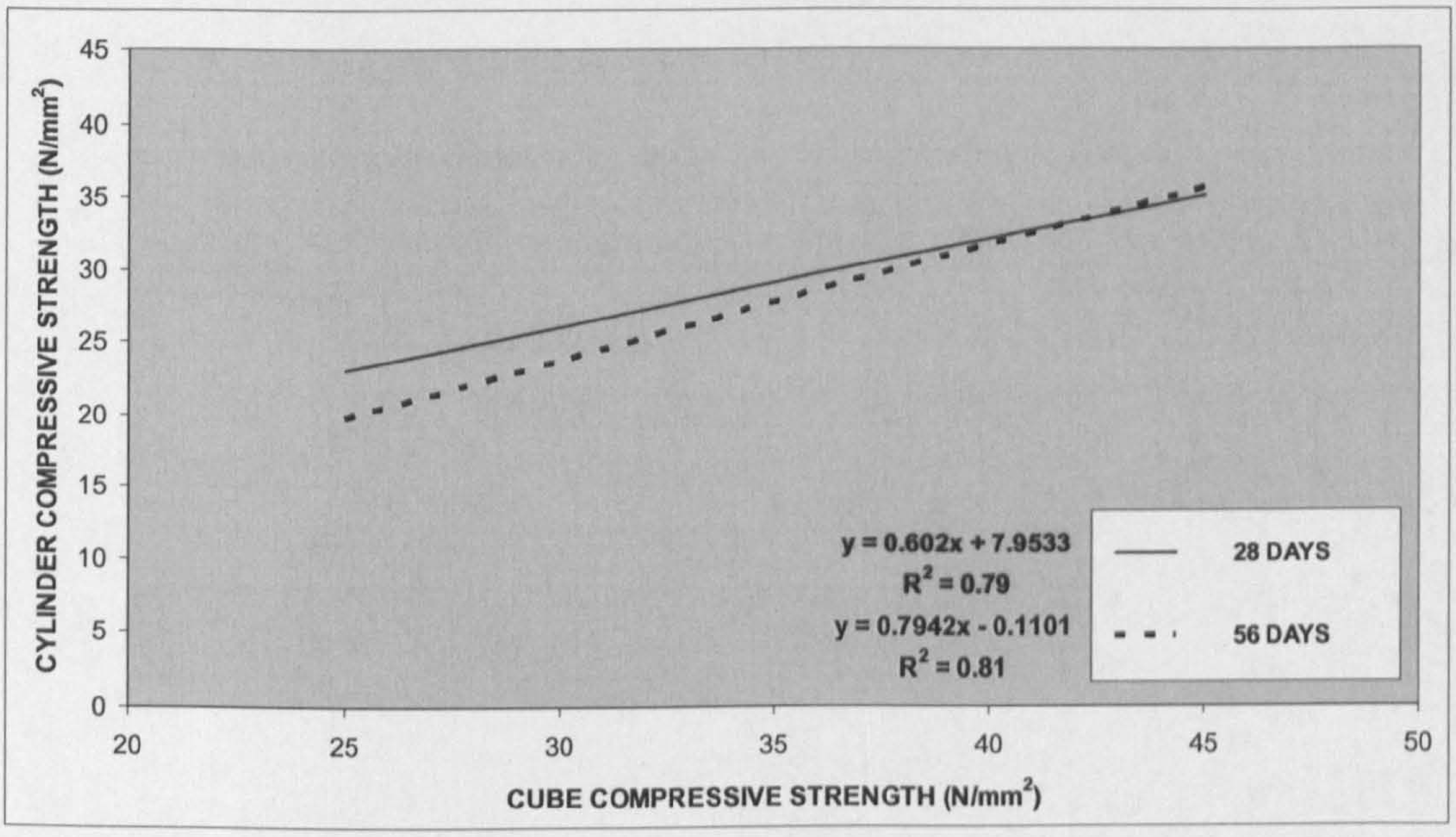


Figure 6.9 Comparison of the cube and cylinder strength relationship of SF mixes at 28 and 56 days.

The average cylinder – cube strength ratio of all the SF mixes regardless of the RCA content and age was 81%. However when comparing the average cylinder – cube strength ratios of the mixes with different RCA contents, it was found that the cylinder – cube strength ratio of the 100% RCA mixes was slightly higher than the other mixes. The average ratios for the NA, 30, 50 and 100% RCA concretes were 81, 81, 79 and 83% respectively.

6.3.3.2 Effect of cement constituents

PC/PFA

Figures 6.4 and 6.5 compare the relationship between the cube and cylinder strengths of the PC and PFA mixes at 28 and 56 days respectively. Figure 6.10 compares the relationship between the cube and cylinder strengths of PC and PFA mixes regardless of age and RCA content. All the graphs show a similitude between the PC and PFA mixes. This shows in general, that the inclusion of PFA does not greatly influence the cube and cylinder relationship of concrete. This is confirmed when comparing cylinder – cube strength ratios of the NA and RCA PC mixes with their corresponding PFA mixes, which were approximately the same.

PC/SF

Figures 6.7 and 6.8 compare the relationship between the cube and cylinder strengths of PC and SF mixes at 28 and 56 days respectively. Figure 6.11 compares the relationship between the cube and cylinder strengths of PC and SF mixes regardless of the age and RCA content. All the graphs show a similitude between the PC and SF mixes. This shows that in general, the inclusion of SF does not greatly influence the cube and cylinder relationship of concrete. When comparing cylinder – cube strength ratios of the PC mixes with their corresponding SF mixes, no clear effect of the use of SF on the cylinder – cube strength ratios of the NA and RCA mixes was established.

6.4 FLEXURAL STRENGTH

Flexural strength tests were carried out on beam specimens (100 × 100 × 300 mm). For each mix, the beams were tested at 28 and 56 days.

6.4.1 Effect of RCA

6.4.1.1 PC mixes

The cube compressive strengths of the PC mixes and their corresponding flexural strengths at 28 and 56 days are shown respectively in Table A.7 and Table A.8 of Appendix A. The relationships between the compressive and flexural strengths of all

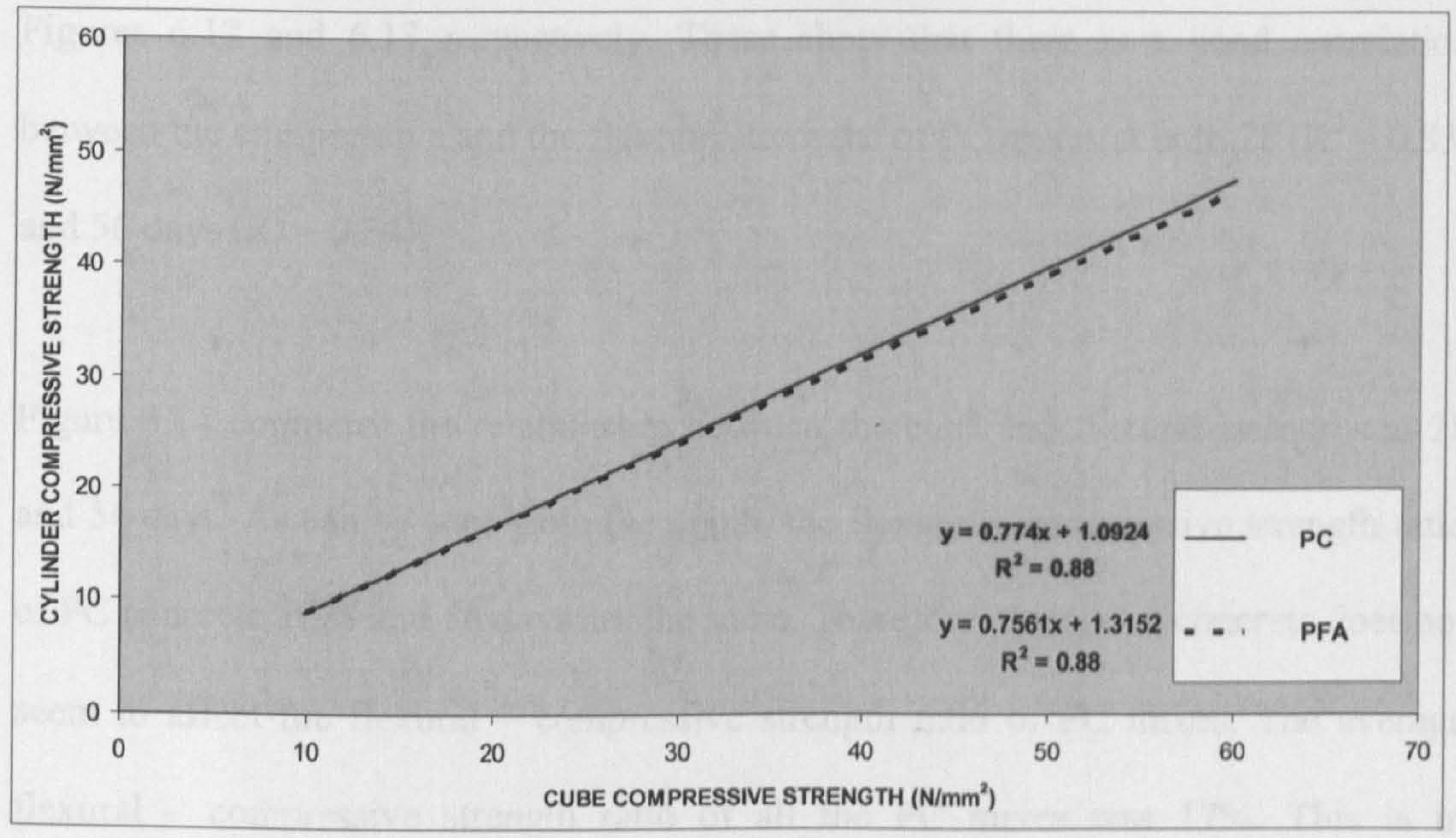


Figure 6.10 Comparison of the cube and cylinder strength relationship of PC and PFA mixes.

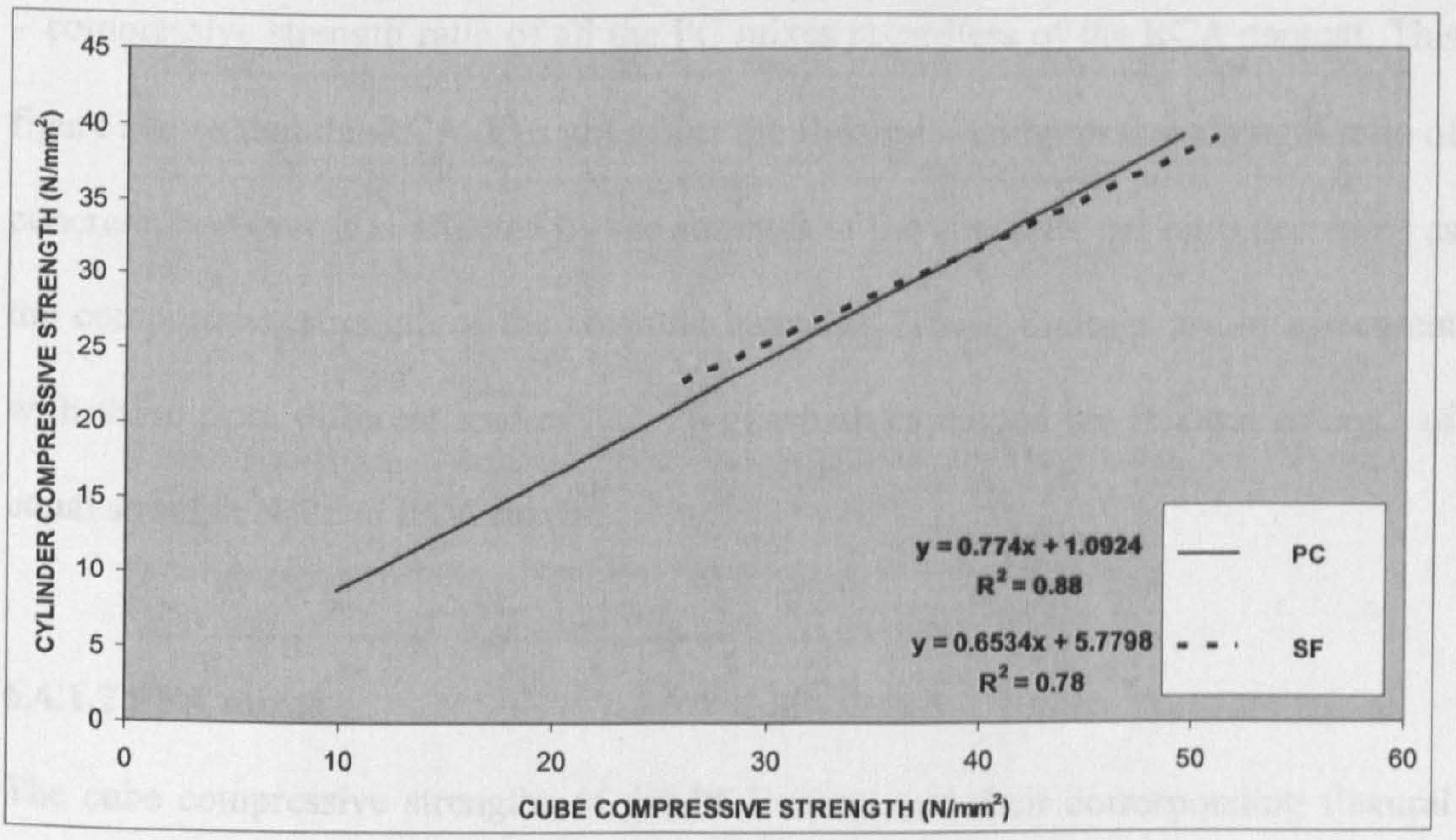


Figure 6.11 Comparison of the cube and cylinder strength relationship of PC and SF mixes.

the PC mixes regardless of the RCA content at 28 days and 56 days are shown in Figures 6.12 and 6.13 respectively. These show that there is a good correlation between the compressive and the flexural strengths of PC mixes at both 28 (R^2 0.83) and 56 days ($R^2 = 0.84$).

Figure 6.14 compares the relationship between the cube and flexural strengths at 28 and 56 days. As can be seen from the graph, the flexural compressive strength ratio of PC concrete at 28 and 56 days are the same. Therefore, the age of concrete does not seem to affect the flexural compressive strength ratio of PC mixes. The average flexural compressive strength ratio of all the PC mixes was 17%. This is in agreement with values found in the literature [25].

Figure 6.15 shows the relationship between the compressive strength and the flexural compressive strength ratio of all the PC mixes regardless of the RCA content. This figure shows that the RCA does not affect the flexural compressive strength ratio of concrete, however it is affected by the strength of the concrete; the ratio decreases as the compressive strength of the concrete increases. These findings are in agreement with those from different studies [22, 26 g] which examined the flexural strength of equal strength NA and RCA mixes.

6.4.1.2 PFA mixes

The cube compressive strengths of the PFA mixes and their corresponding flexural strengths at 28 and 56 days are shown respectively in Table A.9 and Table A.10 of Appendix A. The relationships between the compressive and flexural strengths of all the PFA mixes regardless of the RCA content at 28 days and 56 days are shown in

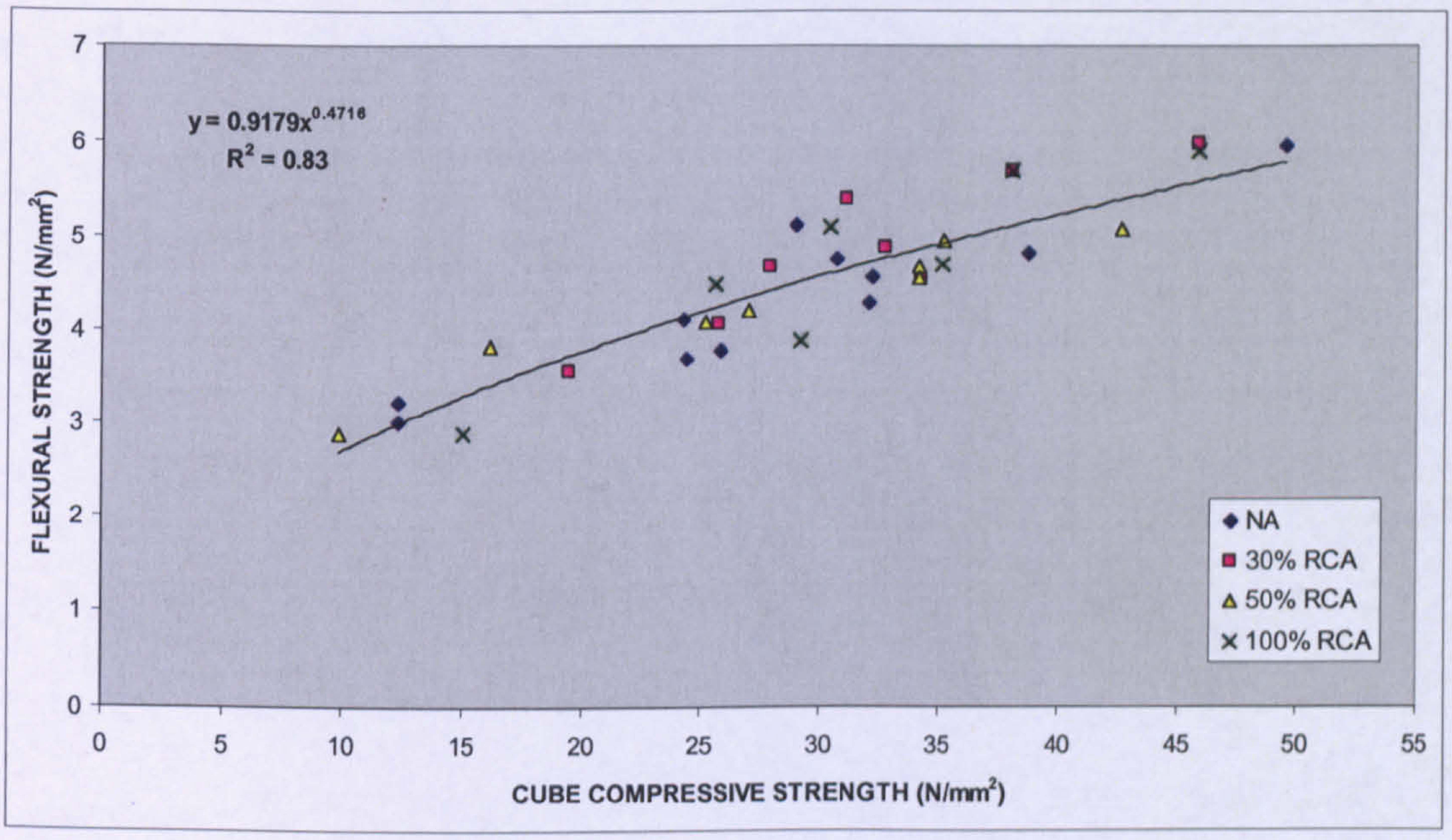


Figure 6.12 Compressive vs. flexural strength of PC mixes at 28 days.

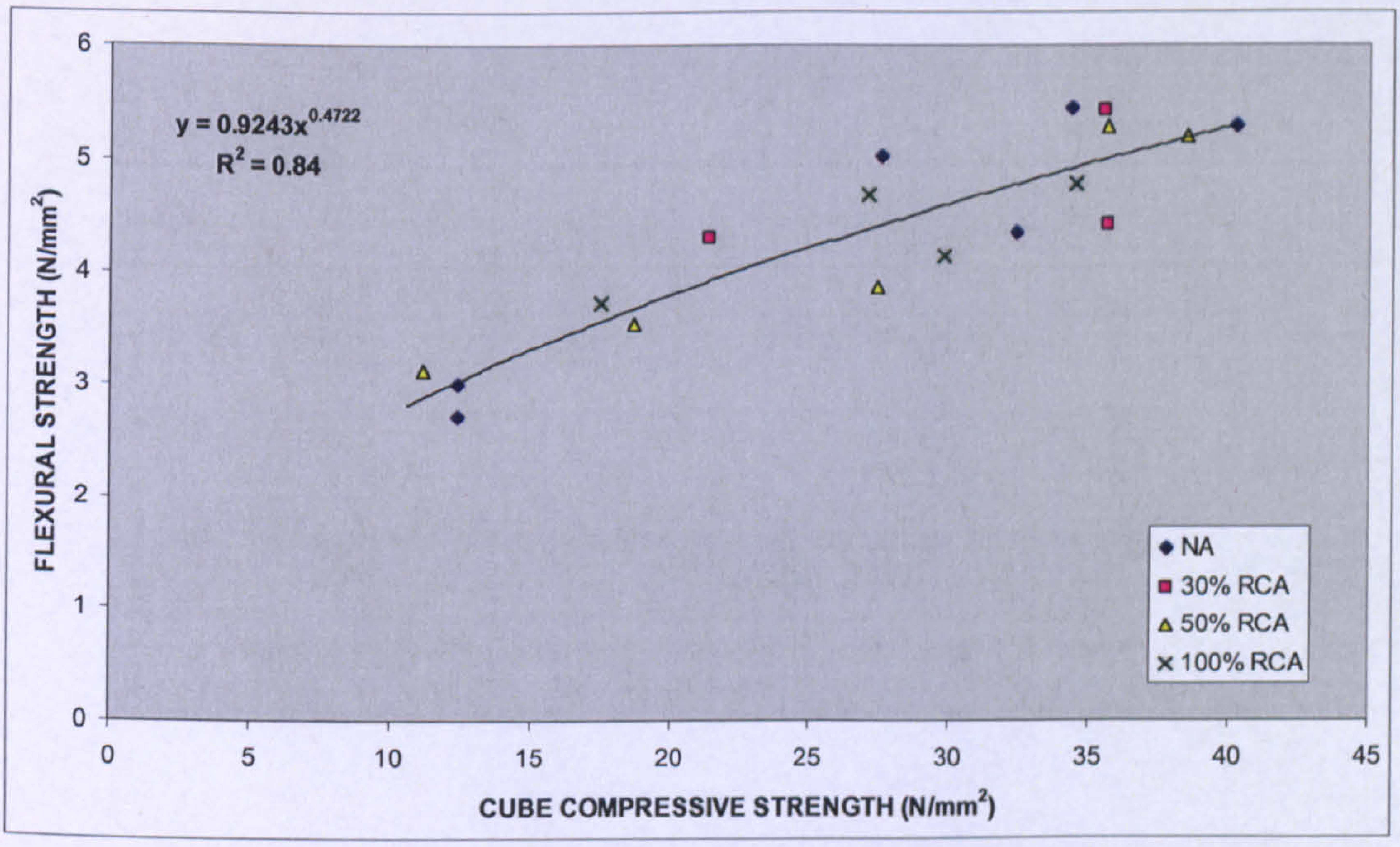


Figure 6.13 Compressive vs. flexural strength of PC mixes at 56 days.

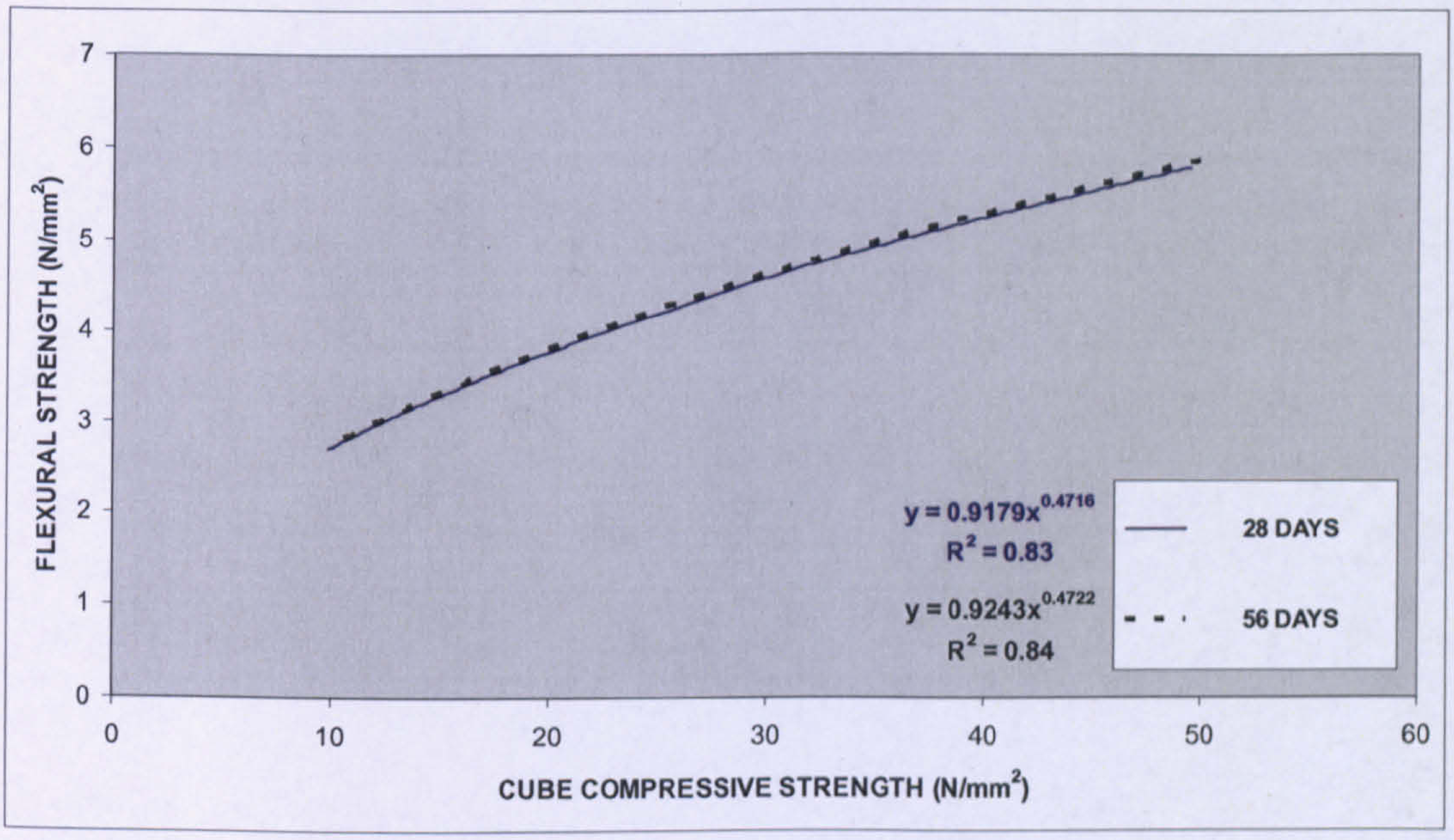


Figure 6.14 Comparison of the compressive and flexural strengths relationship of PC mixes at 28 and 56 days.

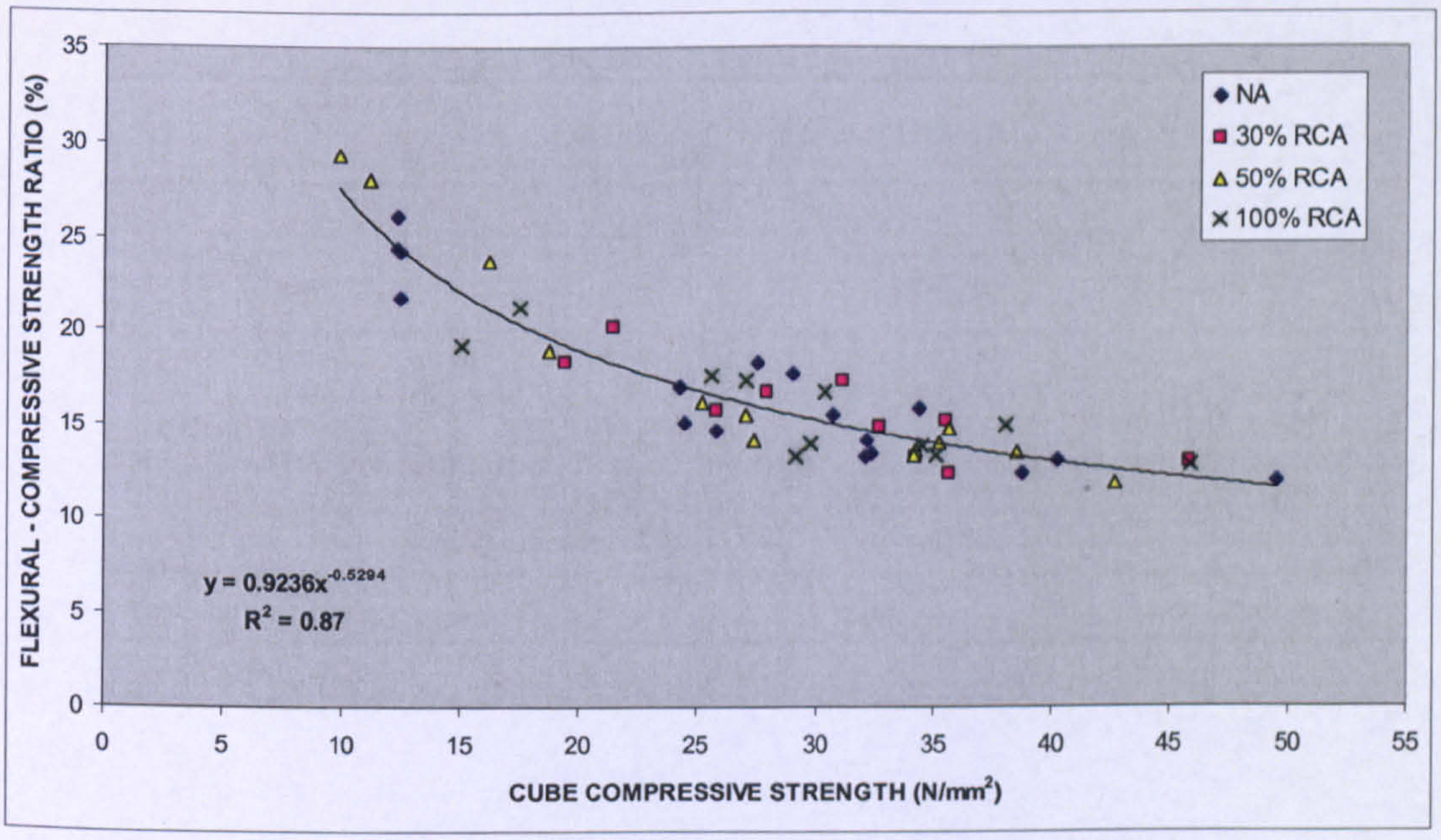


Figure 6.15 Compressive strength vs. the flexural – compressive strength ratio of PC mixes.

Figures 6.16 and 6.17 respectively. These show that there is a good correlation between the compressive and the flexural strengths of PFA mixes at both 28 (R^2 = 0.86) and 56 days (R^2 = 0.91).

Figure 6.18 compares the relationship between the cube and flexural strengths at 28 and 56 days. As can be seen from the graph, the flexural – compressive strength ratio at 28 is lower when compared to 56 days. Therefore, the age of PFA concrete does slightly affect the flexural – compressive strength ratio of the PFA mixes. The average flexural – compressive strength ratio of all the PFA mixes was 16%.

Figure 6.19 shows the relationship between the compressive strength and the flexural – compressive strength ratio of all the PFA mixes regardless of the RCA content. This figure shows that the RCA does not seem to affect the flexural – compressive strength ratio of concrete, however it is affected by the strength of the concrete; the ratio decreases as the compressive strength of the concrete increases.

6.4.1.3 SF mixes

The cube compressive strengths of the SF mixes and their corresponding flexural strengths at 28 and 56 days are shown respectively in Table A.11 and Table A.12 of Appendix A. The relationships between the compressive and flexural strengths of all the SF mixes regardless of the RCA content at 28 days and 56 days are shown in Figures 6.20 and 6.21 respectively. These show that there is a correlation between the compressive and flexural strengths of SF mixes at both 28 (R^2 = 0.75) and 56 days (R^2 = 0.68).

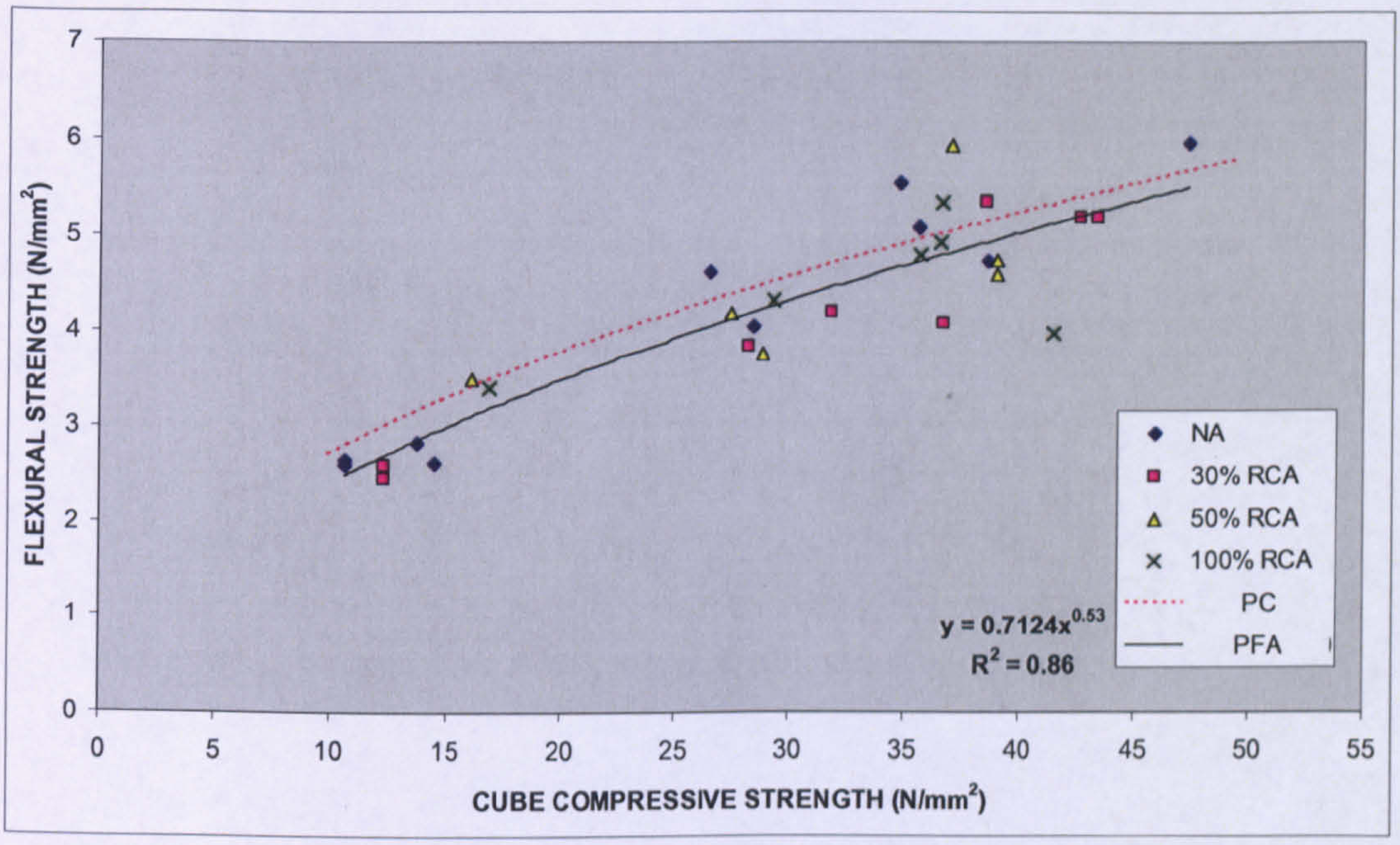


Figure 6.16 Compressive vs. flexural strength of PFA mixes + Comparison of the compressive and flexural strengths relationship of PC and PFA mixes (at 28 days).

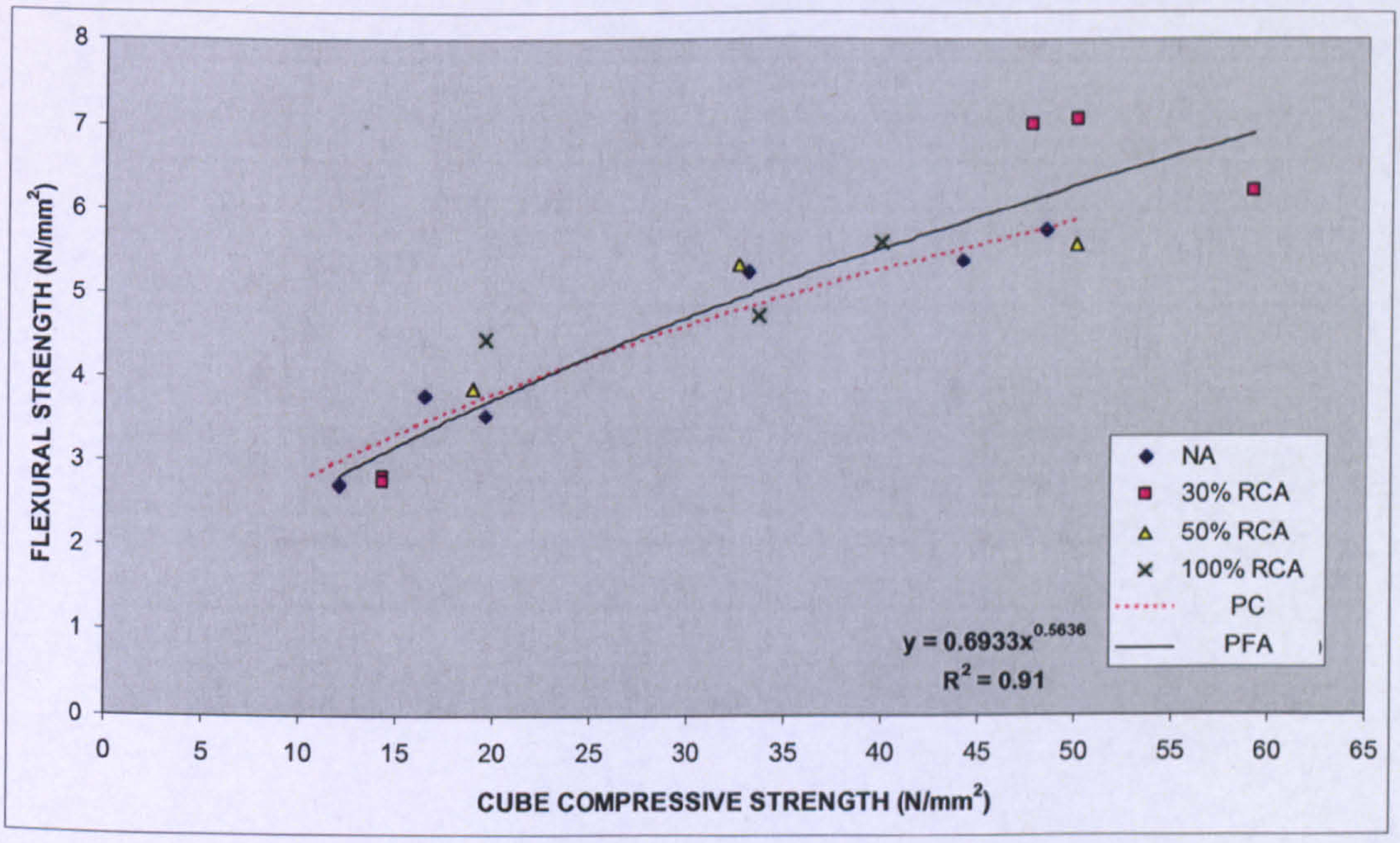


Figure 6.17 Compressive vs. flexural strength of PFA mixes + Comparison of the compressive and flexural strengths relationship of PC and PFA mixes (at 56 days).

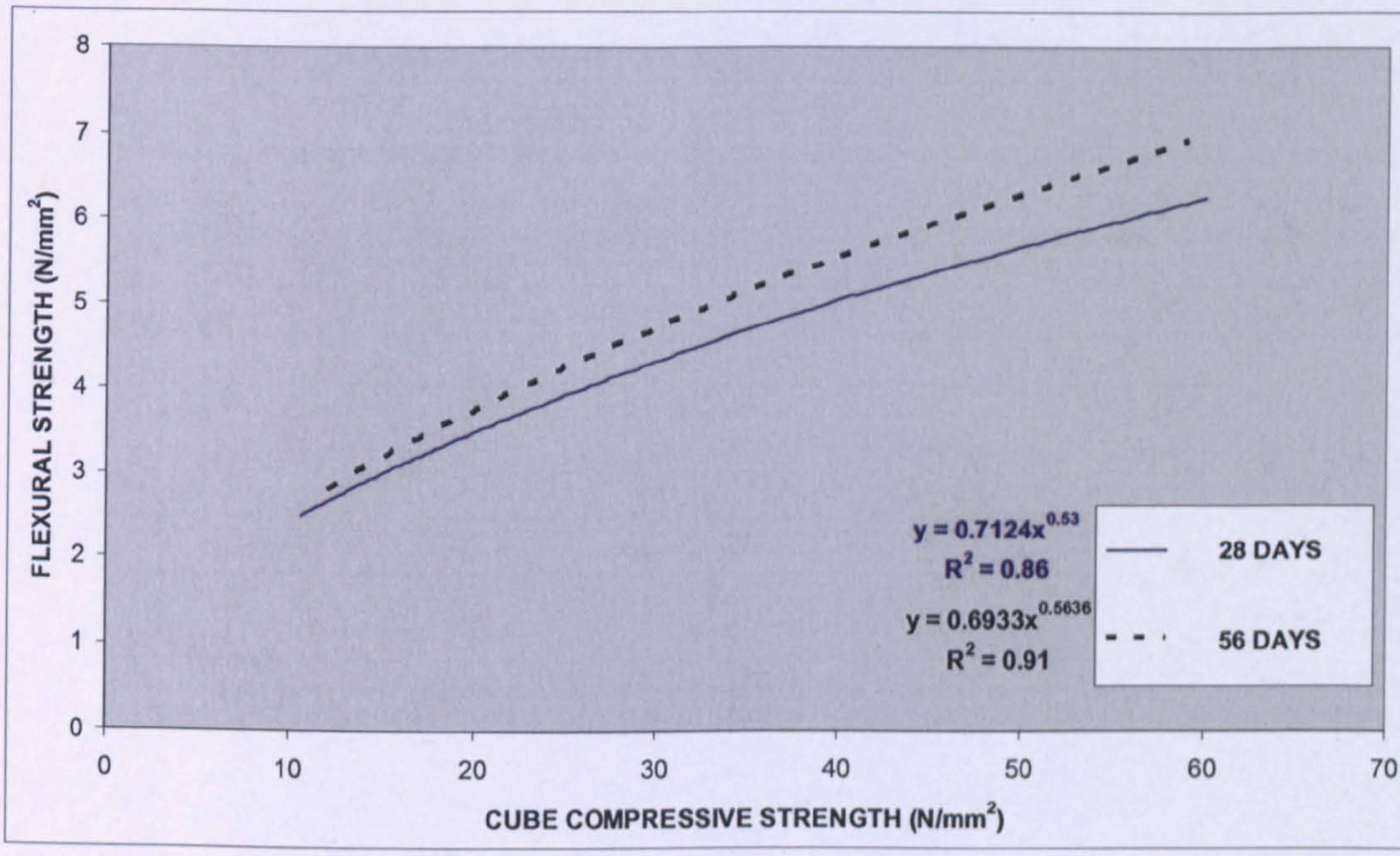


Figure 6.18 Comparison of the compressive and flexural strengths relationship of PFA mixes at 28 and 56 days.

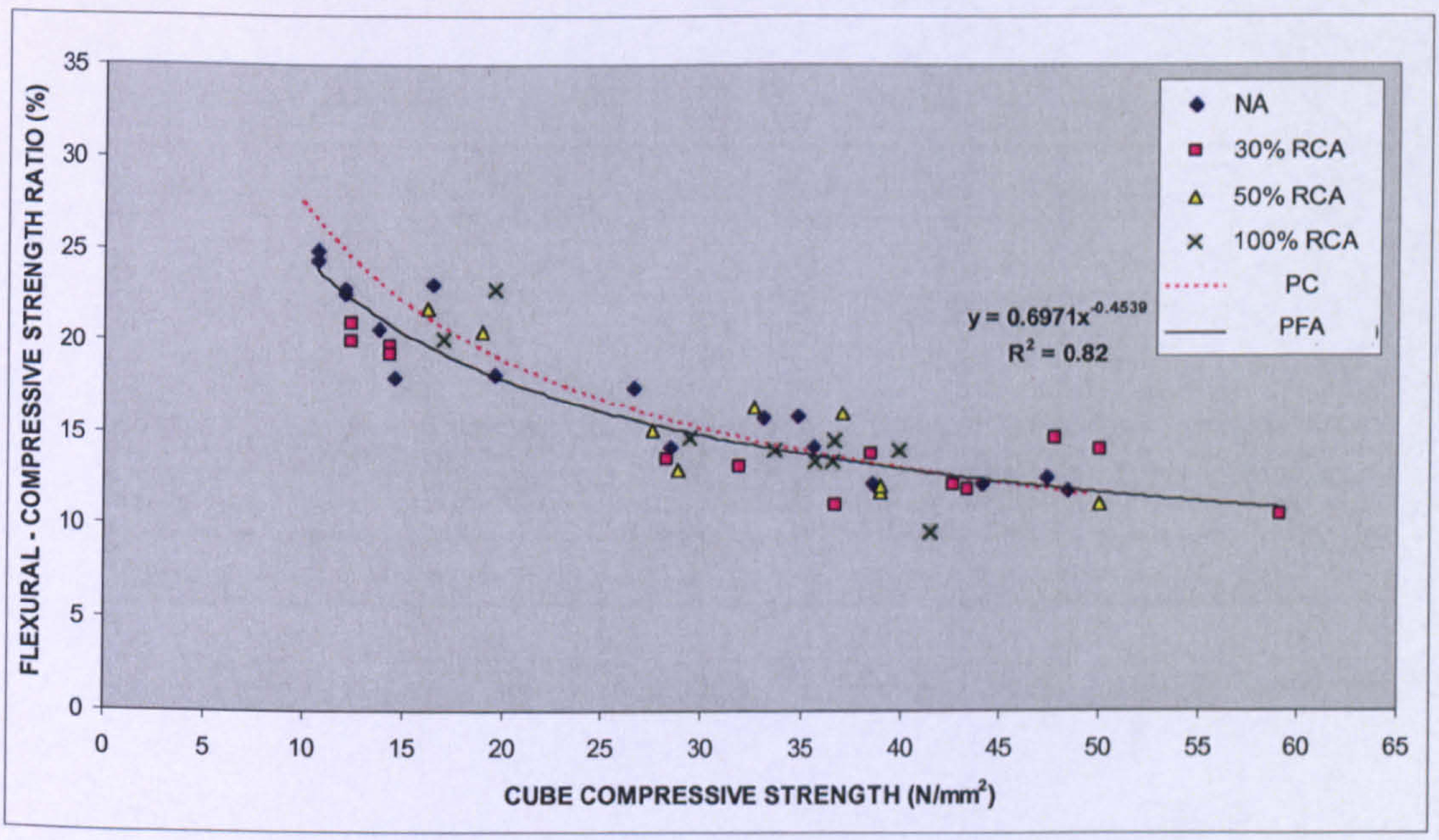


Figure 6.19 Compressive strength vs. the flexural – compressive strength ratio of PFA mixes + Comparison with the relationship established for PC mixes.

Figure 6.22 compares the relationship between the cube and cylinder strengths at 28 and 56 days. As can be seen from the graph, the flexural compressive strength ratio at 28 and 56 days are approximately the same. Therefore, the age of concrete does not significantly affect the flexural - compressive strength ratio of the SF mixes. The average flexural compressive strength ratio of all the PC mixes was 15%.

Figure 6.23 shows the relationship between the compressive strength and the flexural compressive strength ratio of all the SF mixes regardless of the RCA content. This figure shows that the RCA does not seem to affect the flexural compressive strength ratio of concrete, however it is affected by the strength of the concrete; the ratio decreases as the compressive strength of the concrete increases.

6.4.2 Binary cement concrete performance

6.4.2.1 PC/PFA

Figures 6.16 and 6.17 compare the relationship between the compressive and flexural strengths of PC and PFA mixes at 28 and 56 days respectively. Figure 6.24 compares the relationship between the compressive and flexural strengths of PC and PFA mixes regardless of age and RCA content. All the graphs show a similitude between the PC and PFA mixes. This shows that in general, the inclusion of PFA does not greatly influence the relationship between the compressive and flexural strengths of concrete.

Figure 6.19 shows the relationship between the compressive strength and the flexural compressive strength ratio of all the PC and PFA mixes regardless of the RCA content. The graph shows that the inclusion of PFA does not influence this relationship.

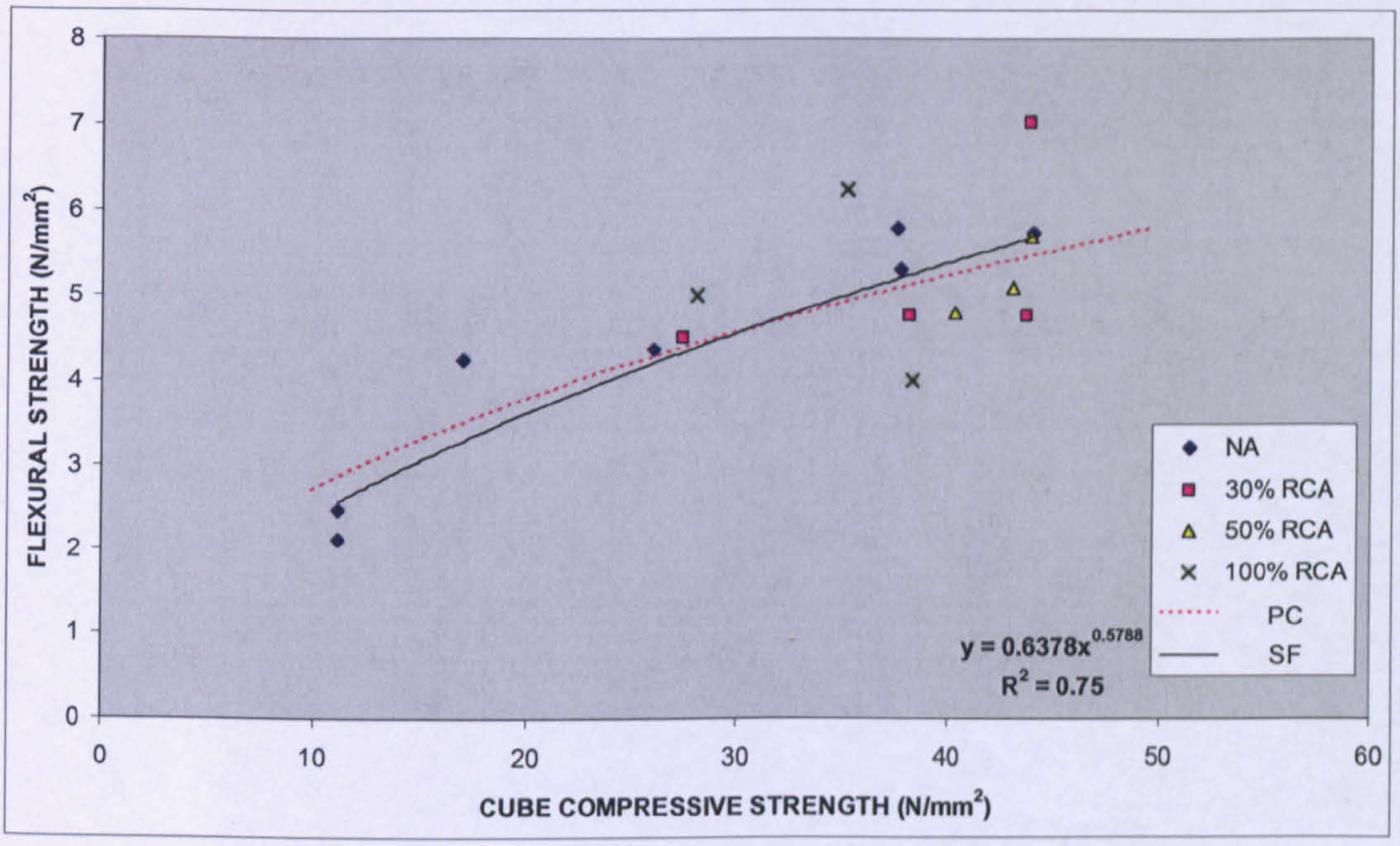


Figure 6.20 Compressive vs. flexural Strength of SF mixes + Comparison of the compressive and flexural strengths relationship of PC and SF mixes (at 28 days).

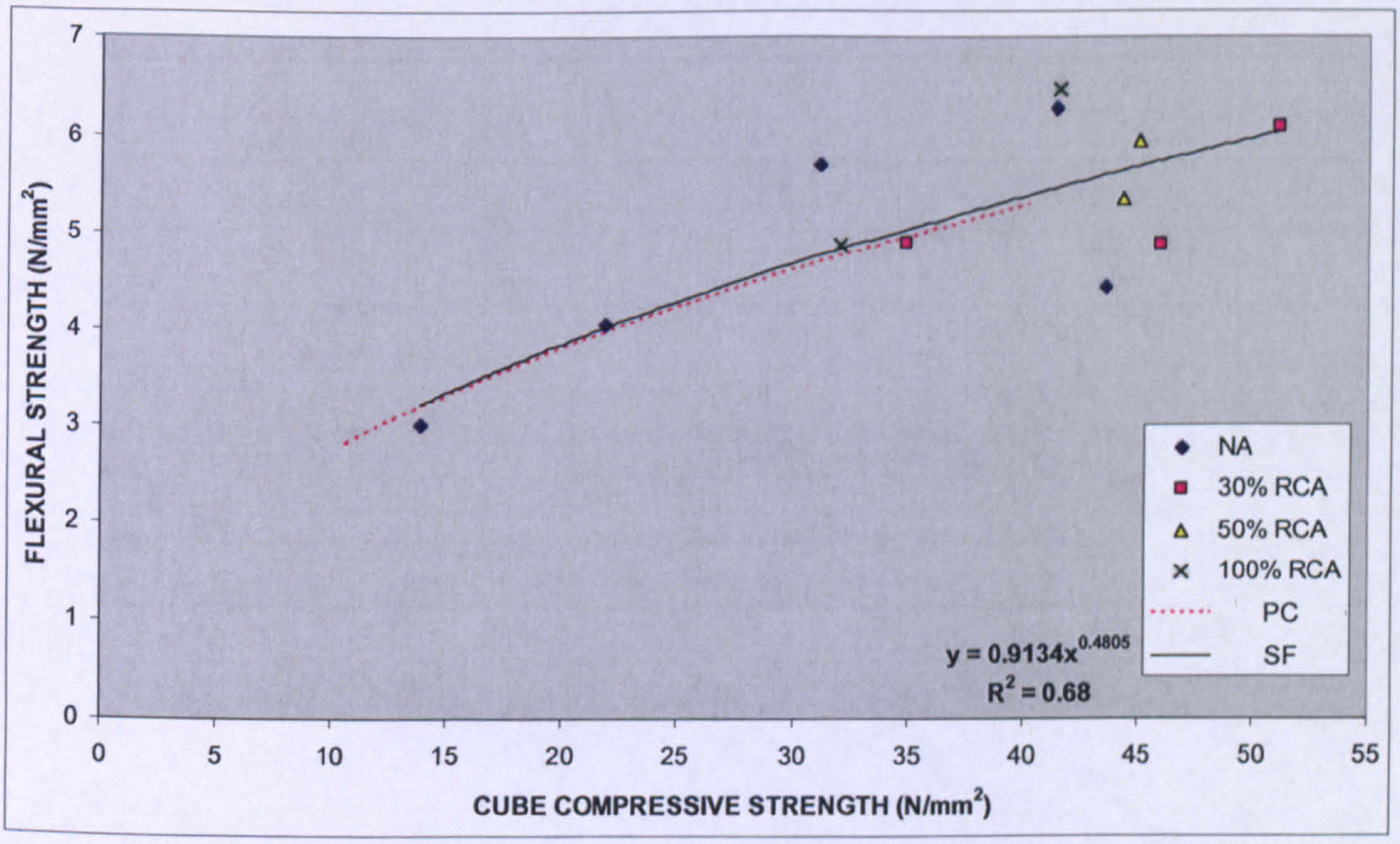


Figure 6.21 Compressive vs. flexural strength of SF mixes + Comparison of the compressive and flexural strengths relationships of PC and SF mixes (at 56 days).

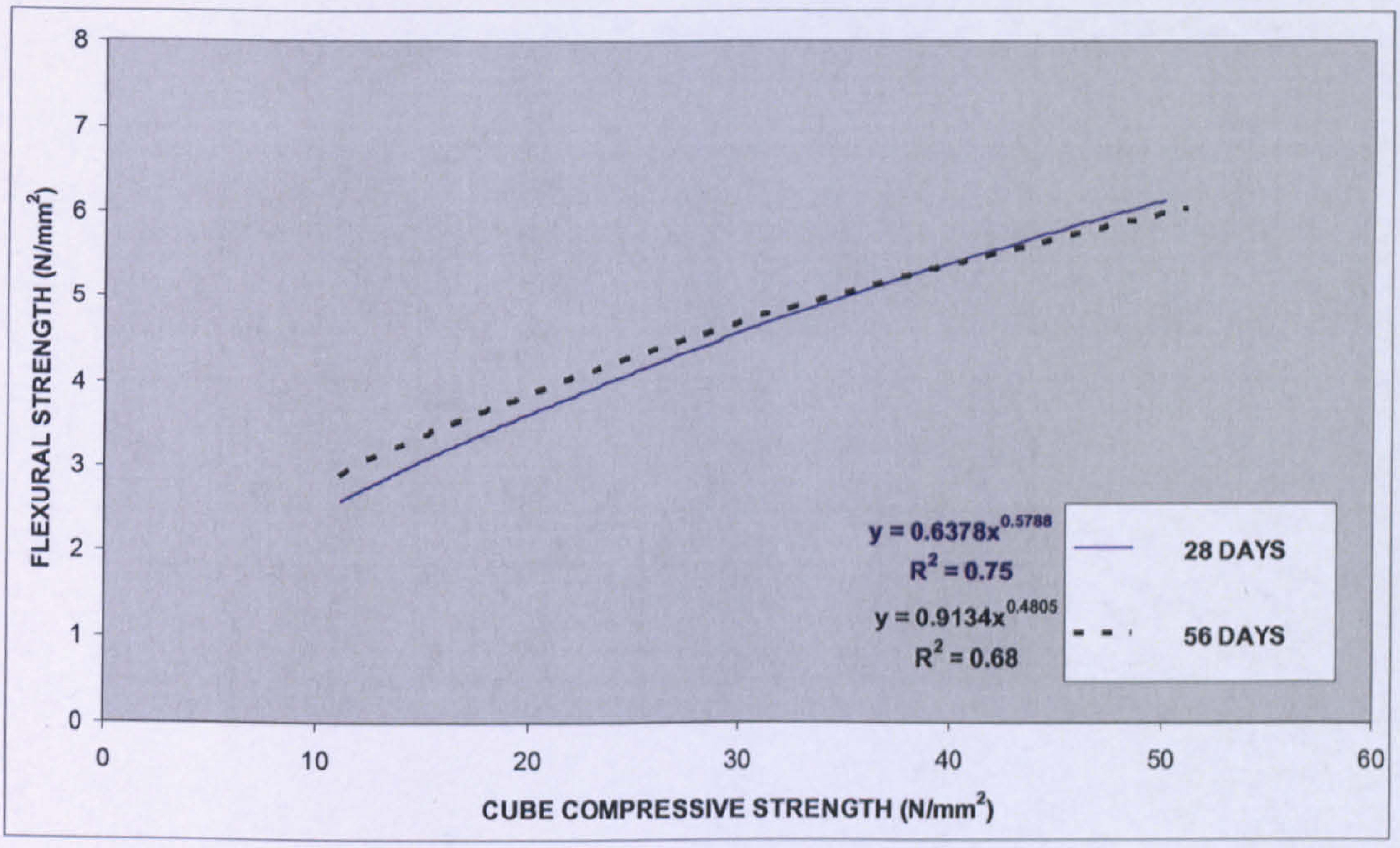


Figure 6.22 Comparison of the compressive and flexural strengths relationship of SF mixes at 28 and 56 days.

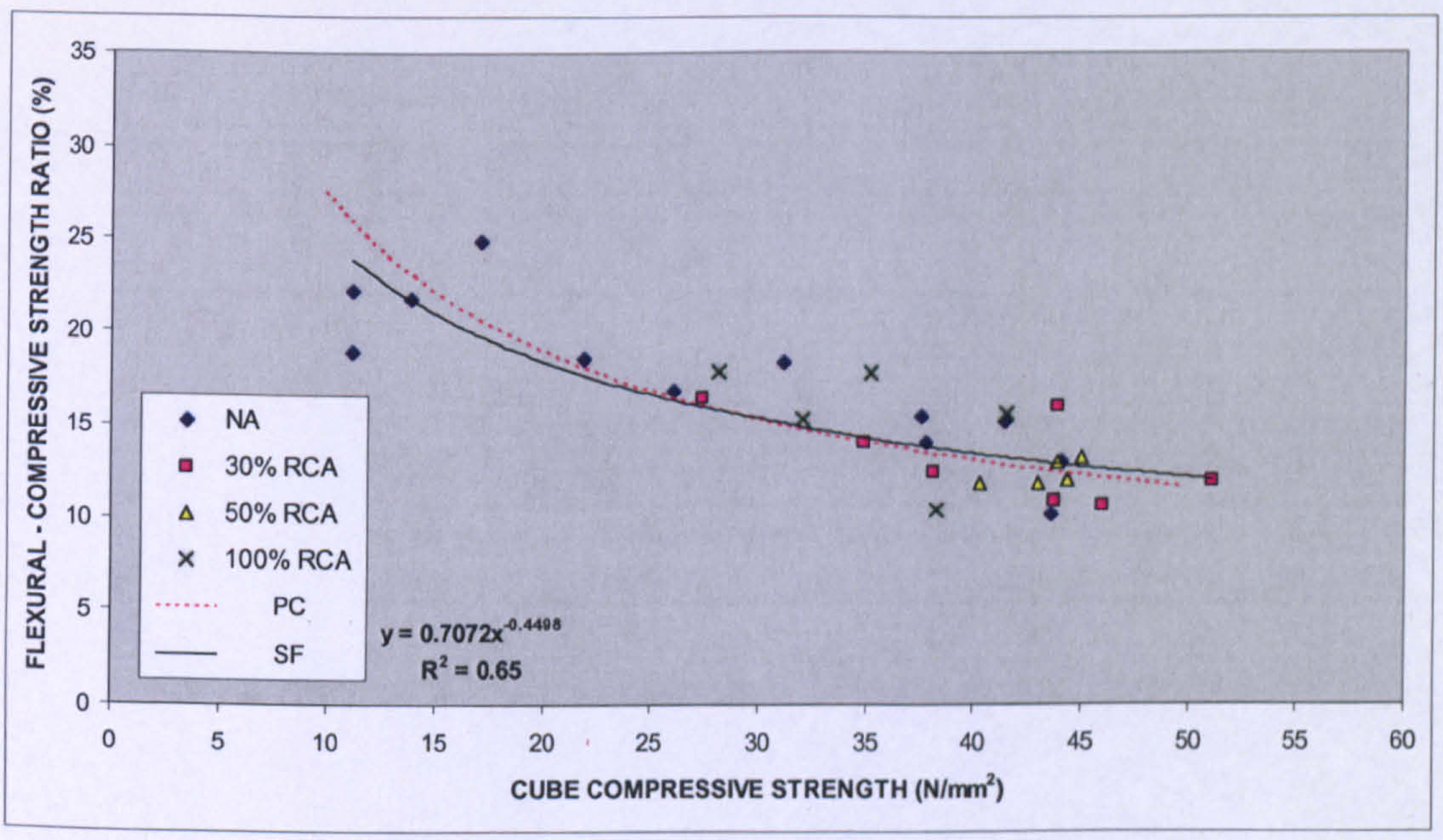


Figure 6.23 Compressive strength vs. the flexural – compressive strength ratio of SF mixes + Comparison with the relationship established for PC mixes.

6.4.2.2 PC/SF

Figures 6.20 and 6.21 compare the relationship between the compressive and flexural strengths of PC and SF mixes at 28 and 56 days respectively. Figure 6.25 compares the relationship between the compressive and flexural strengths of PC and SF mixes regardless of age and RCA content. All the graphs show a similitude between the PC and SF mixes. This shows that in general, the inclusion of SF does not greatly influence the relationship between the compressive and flexural strengths of concrete.

Figure 6.23 shows the relationship between the compressive strength and the flexural compressive strength ratio of all the PC and SF mixes regardless of the RCA content. The graph shows that the inclusion of SF does not influence this relationship.

6.5 MODULUS OF ELASTICITY

Cylinders (150 mm Ø × 300 mm) were used to determine the static modulus of elasticity at 28 and 56 days.

6.5.1 Effect of RCA

6.5.1.1 PC mixes

The cube compressive strengths of the PC mixes and their corresponding modulus of elasticity values at 28 and 56 days are shown respectively in Table A.13 and Table A.14 of Appendix A and plotted in Figure 6.26. The figure shows that concrete containing RCA has a lower modulus of elasticity when compared to conventional concrete of equal strength. The decrease in the modulus of elasticity is greater as the RCA content increases in the mix. The use of RCA as 30, 50 and 100% replacement of the NA in concrete resulted in an average reduction in the modulus of elasticity of

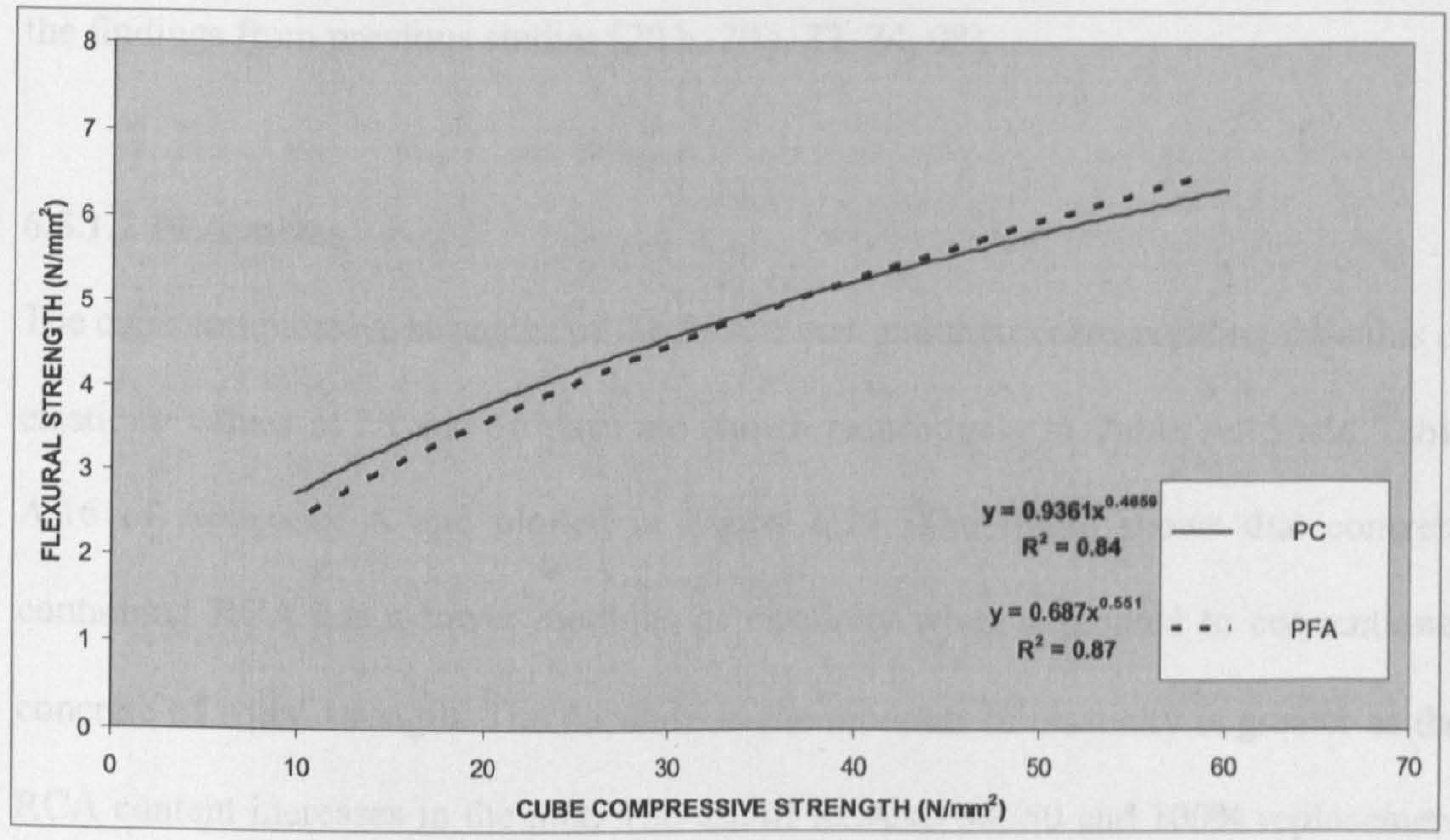


Figure 6.24 Compressive vs. flexural Strength of PC and PFA mixes.

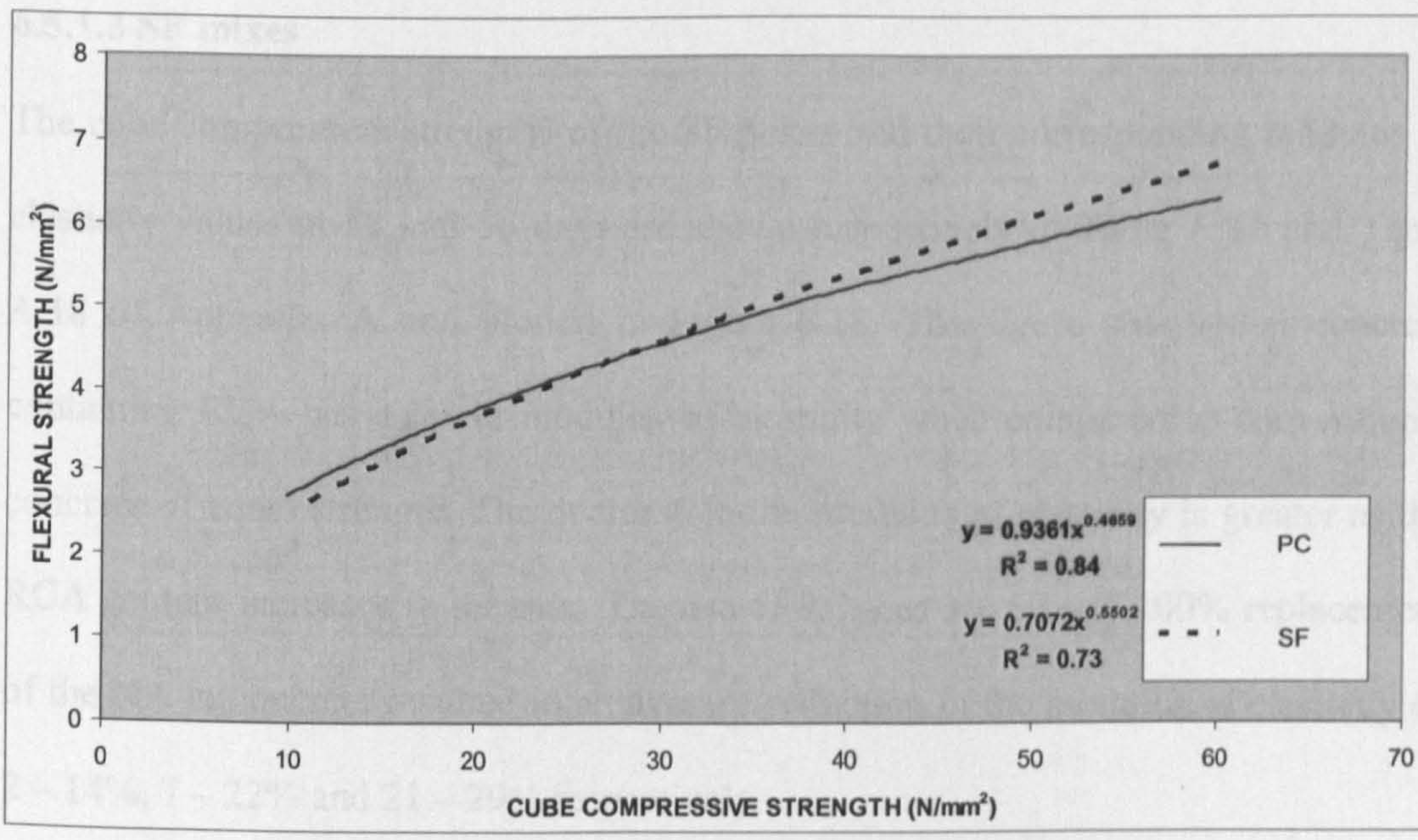


Figure 6.25 Compressive vs. flexural strength of PC and SF mixes.

13 – 14%, 18 – 21% and 25 – 40% respectively. These results are in agreement with the findings from previous studies [20 b, 20 j, 22, 24, 98].

6.5.1.2 PFA mixes

The cube compressive strengths of the PFA mixes and their corresponding modulus of elasticity values at 28 and 56 days are shown respectively in Table A.15 and Table A.16 of Appendix A and plotted in Figure 6.27. The figure shows that concrete containing RCA has a lower modulus of elasticity when compared to conventional concrete of equal strength. The decrease in the modulus of elasticity is greater as the RCA content increases in the mix. The use of RCA as 30, 50 and 100% replacement of the NA in concrete resulted in an average reduction in the modulus of elasticity of 11 – 13%, 17 – 19% and 27 – 40% respectively.

6.5.1.3 SF mixes

The cube compressive strengths of the SF mixes and their corresponding modulus of elasticity values at 28 and 56 days are shown respectively in Table A.17 and Table A.18 of Appendix A and plotted in Figure 6.28. The figure shows that concrete containing RCA has a lower modulus of elasticity when compared to conventional concrete of equal strength. The decrease in the modulus of elasticity is greater as the RCA content increases in the mix. The use of RCA as 30, 50 and 100% replacement of the NA in concrete resulted in an average reduction in the modulus of elasticity of 2 – 14%, 7 – 22% and 21 – 29% respectively.

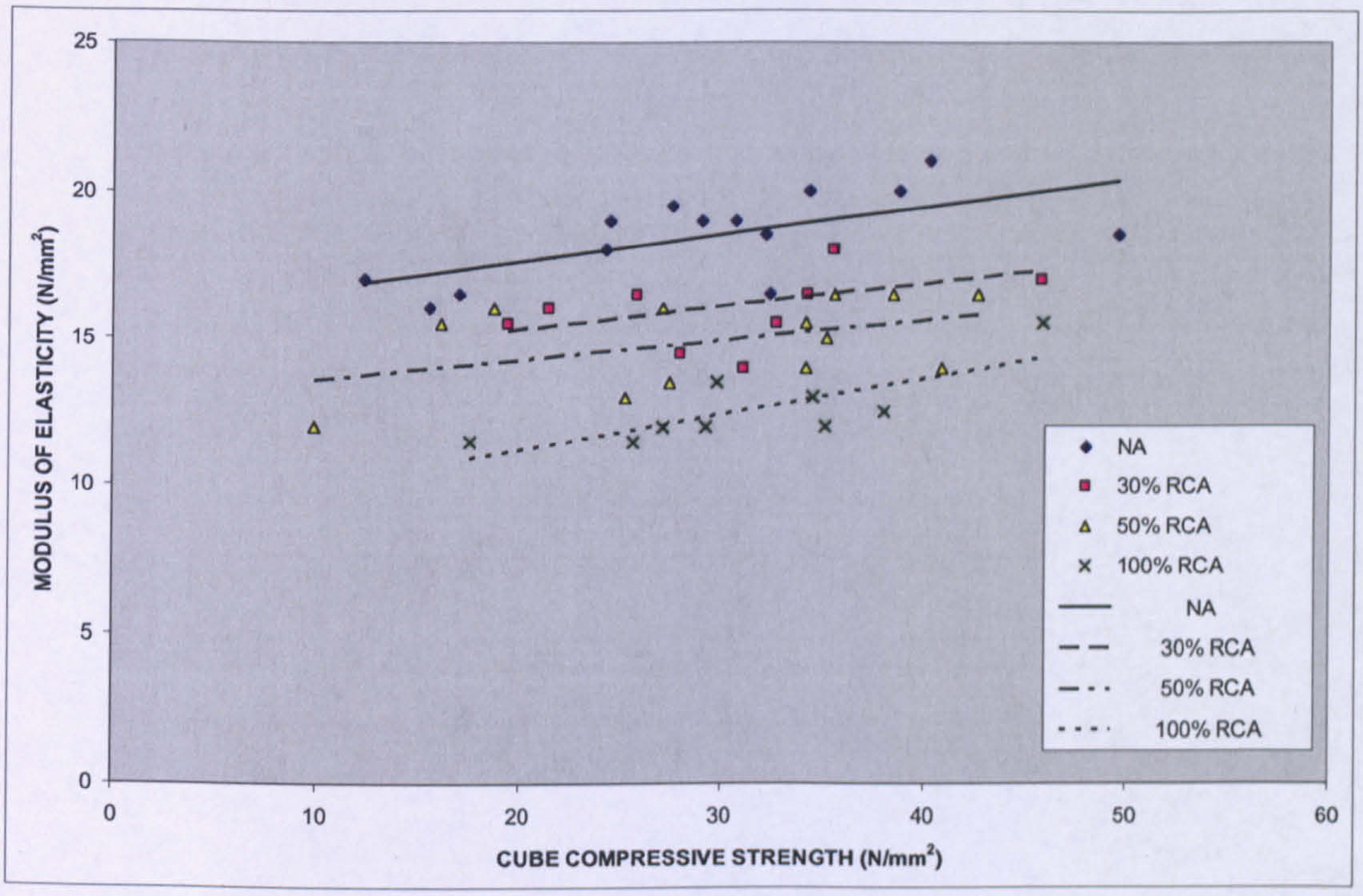


Figure 6.26 Cube compressive strength vs. modulus of elasticity of PC mixes.

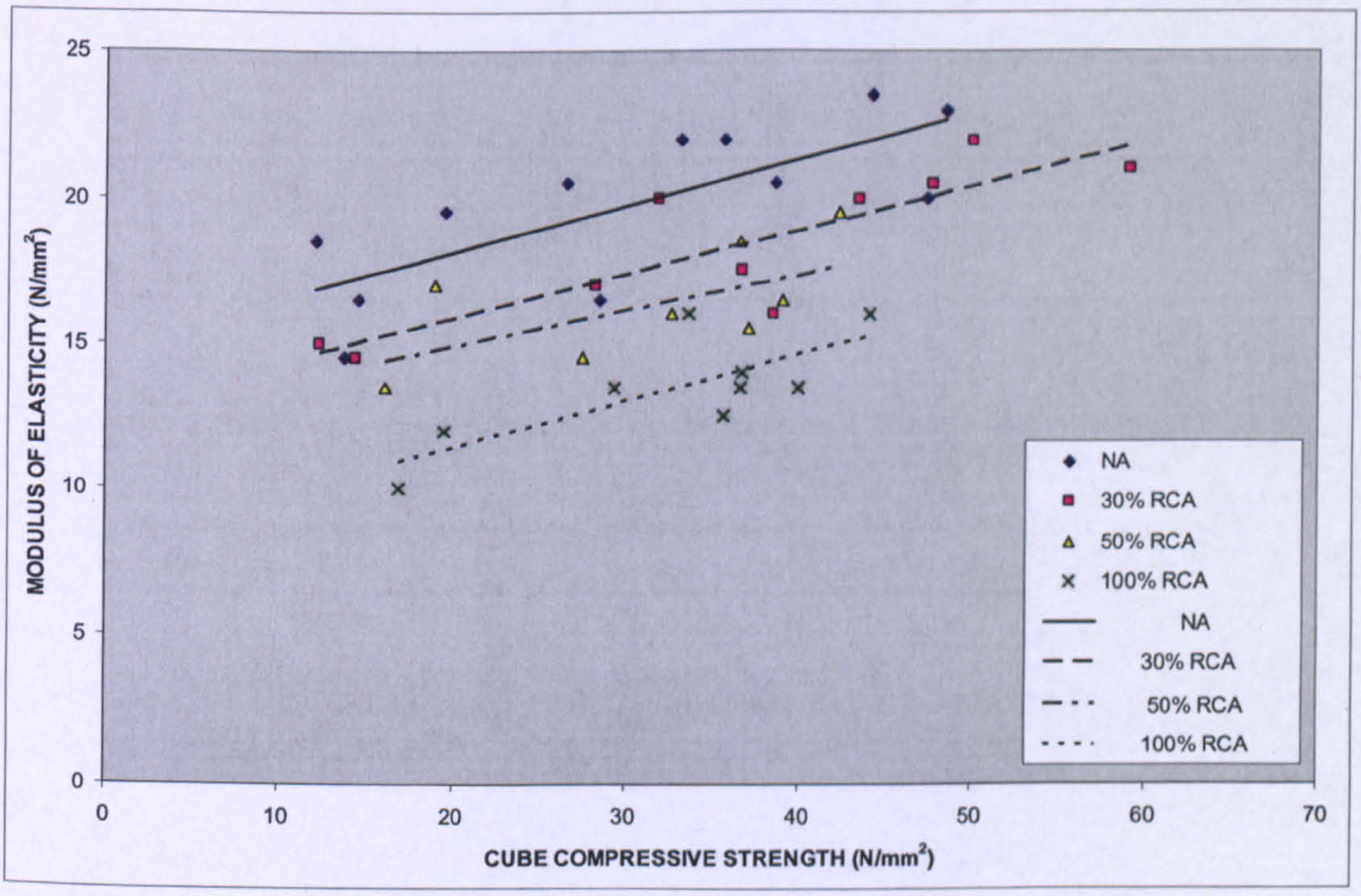


Figure 6.27 Cube compressive strength vs. modulus of elasticity of PFA mixes.

6.5.2 Binary cement concrete performance

Figure 6.29 shows the effect of the RCA content on the modulus of elasticity of 30 N/mm^2 PC, PFA and SF mixes.

6.5.2.1 PC/PFA

Figures 6.30 to 6.33 compare the relationship between the cube compressive strength and the modulus of elasticity of PC and PFA concrete mixes with different RCA contents. These figures show that PFA does not affect the modulus of elasticity of low strength mixes. However as the strength of the mixes increased, the PFA mixes had a slightly higher modulus of elasticity values when compared to their corresponding PC mixes.

6.5.2.2 PC/SF

Figures 6.34 to 6.37 compare the relationship between the cube compressive strength and the modulus of elasticity of PC and SF concrete mixes with different RCA contents. These figures show that SF had no major effect on the modulus of elasticity values of both NA and RCA concrete. The modulus of elasticity results of the SF mixes were within the same range as the results obtained for the PC mixes.

6.6 DRYING SHRINKAGE AND SWELLING DEFORMATIONS

Prism specimens (75×75×300 mm) were used to monitor the drying shrinkage and swelling deformations of concrete for 90 days.

6.6.1 Drying shrinkage deformation

6.6.1.1 Effect of RCA

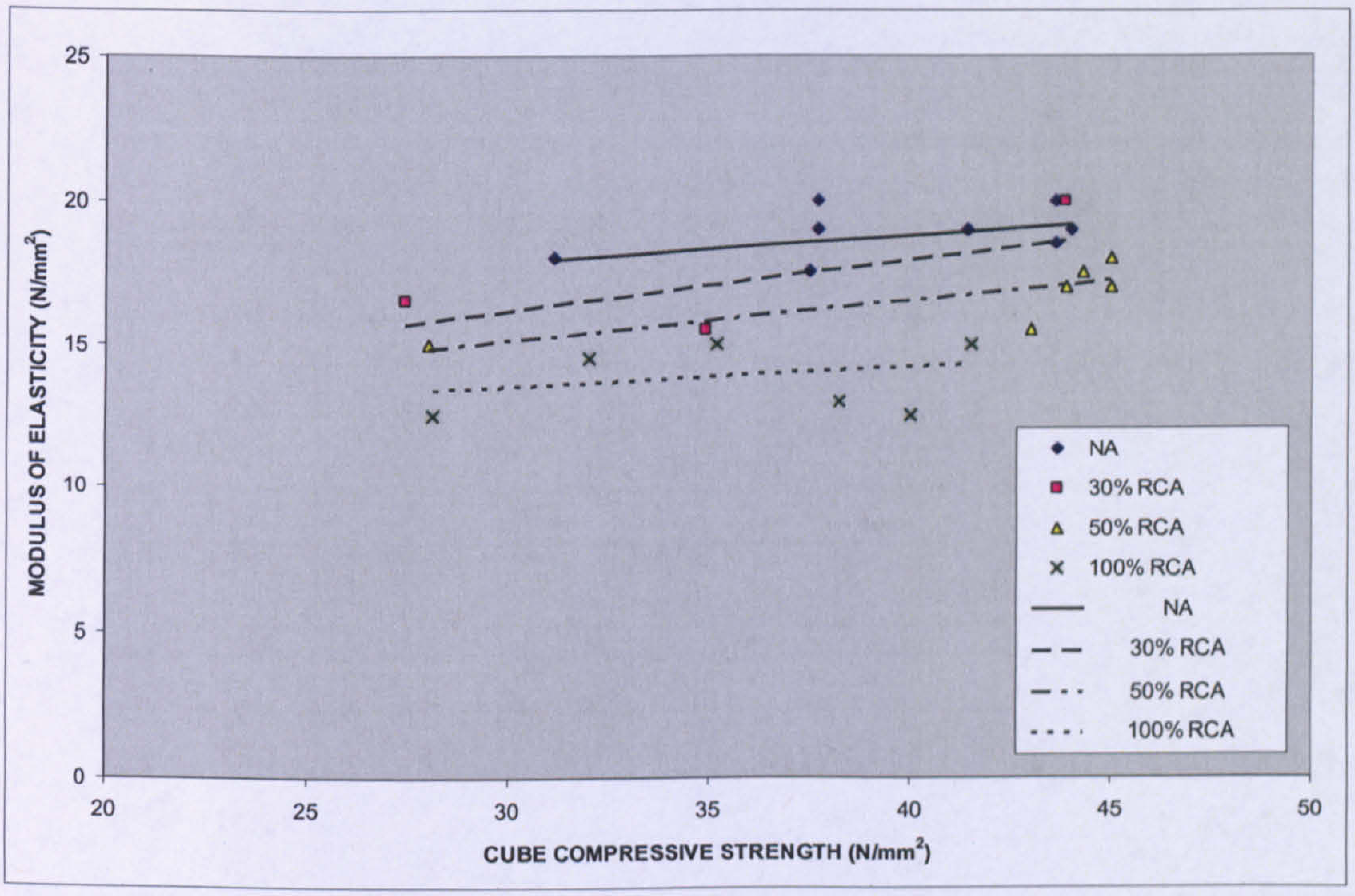


Figure 6.28 Cube compressive strength vs. modulus of elasticity of SF mixes.

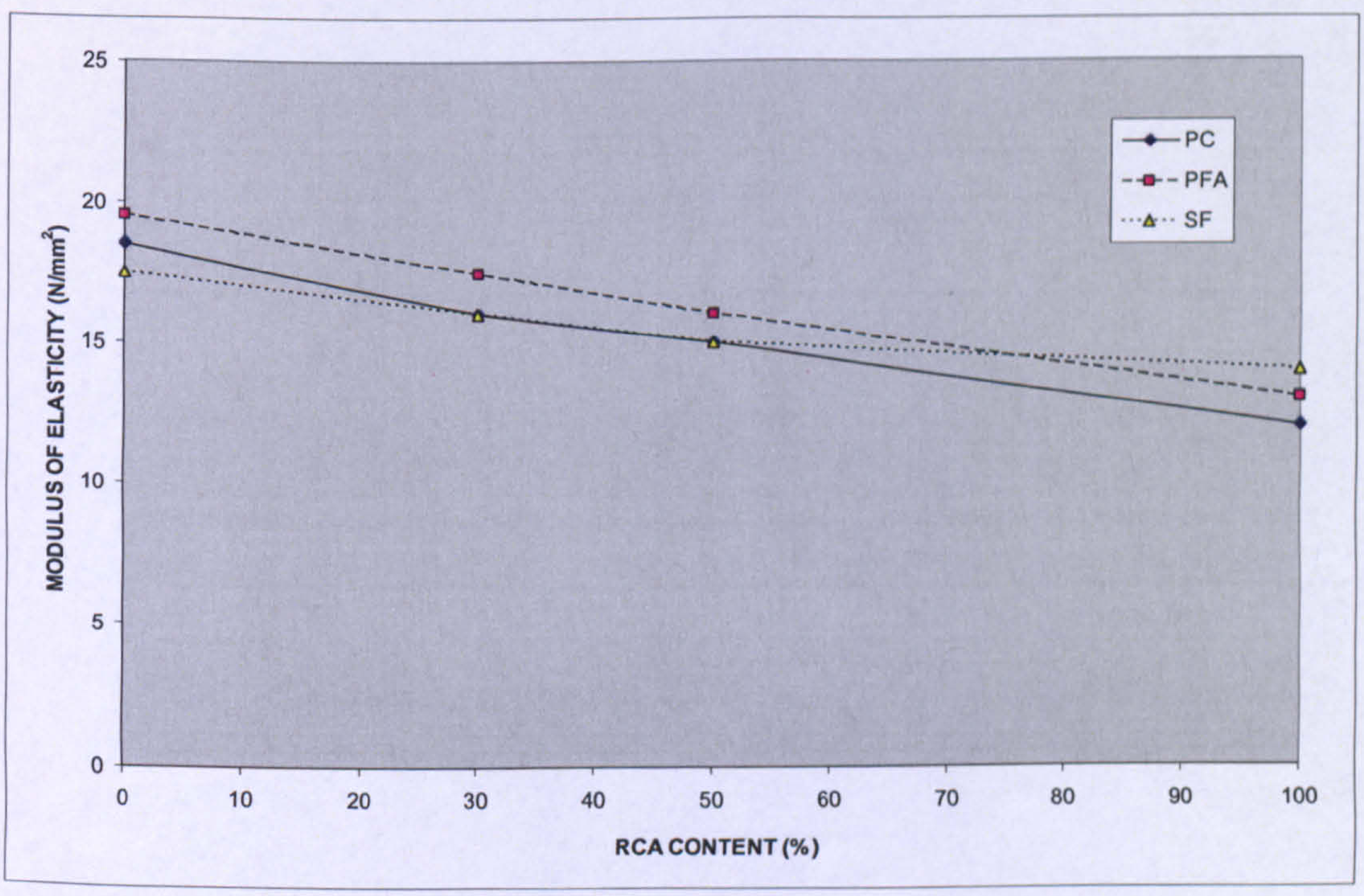


Figure 6.29 Effect of RCA on the modulus of elasticity of 30 N/mm^2 PC, PFA and SF mixes.

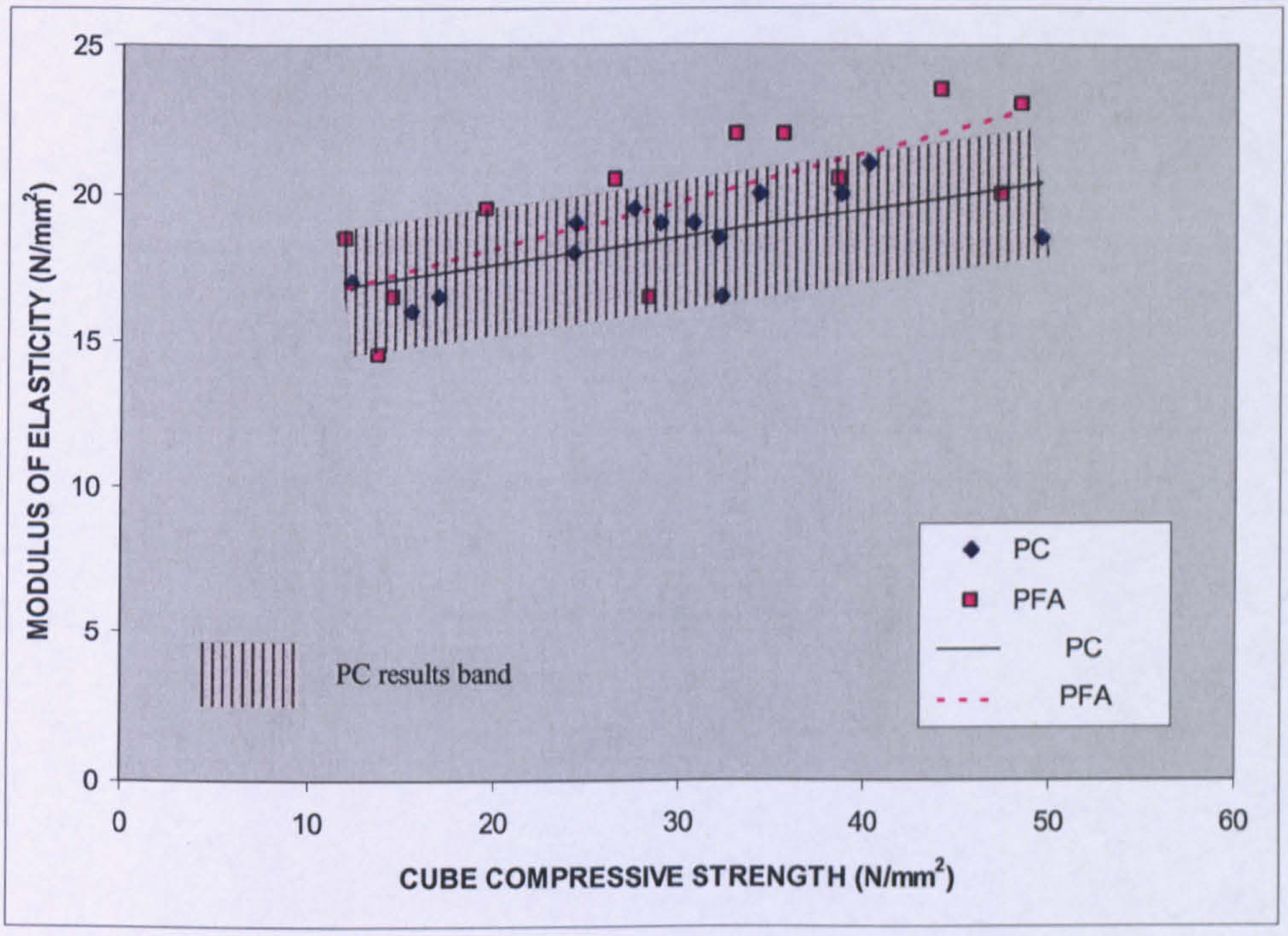


Figure 6.30 Cube compressive strength vs. modulus of elasticity of NA PC and PFA mixes.

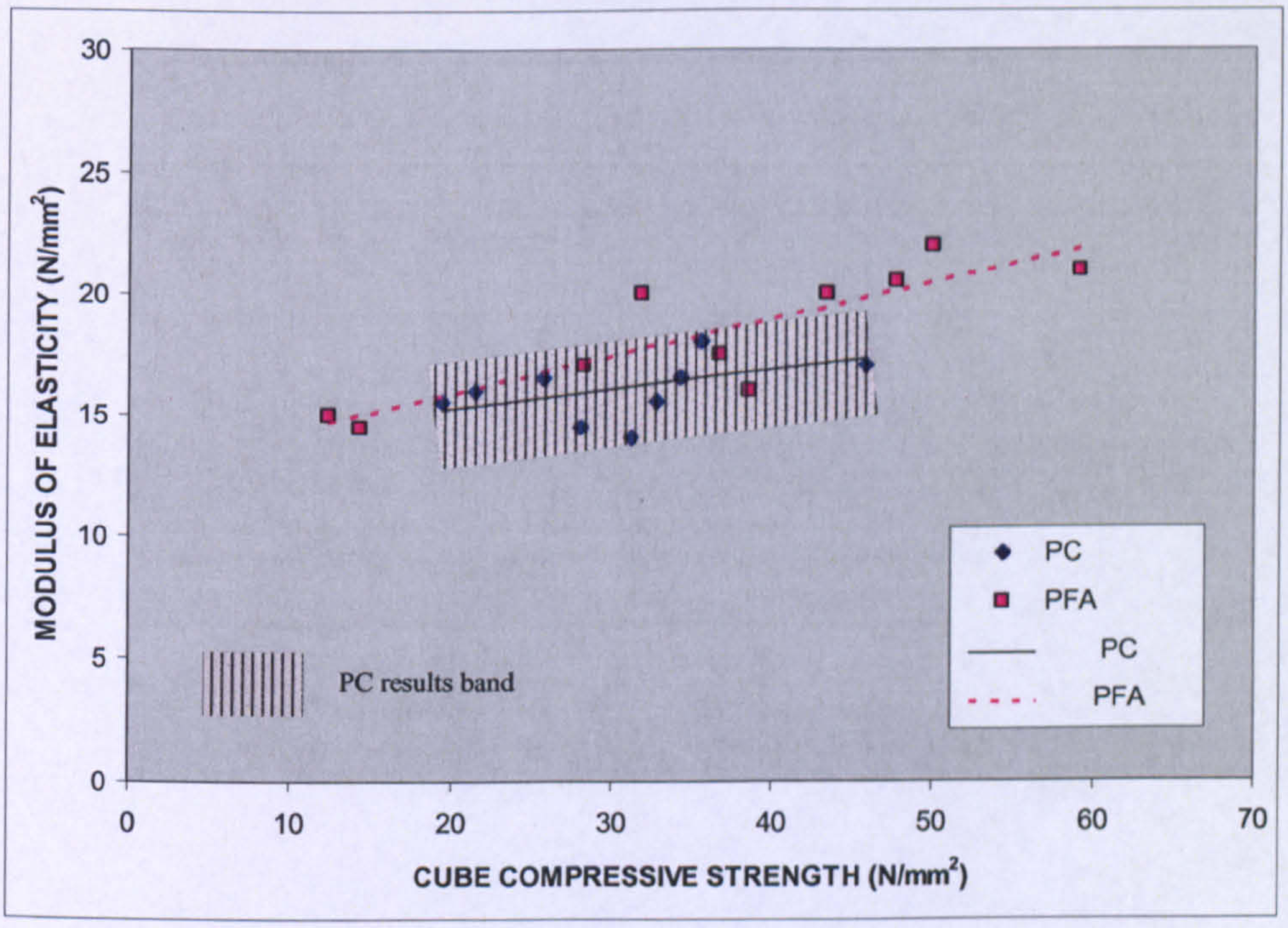


Figure 6.31 Cube compressive strength vs. modulus of elasticity of 30% RCA PC and PFA mixes.

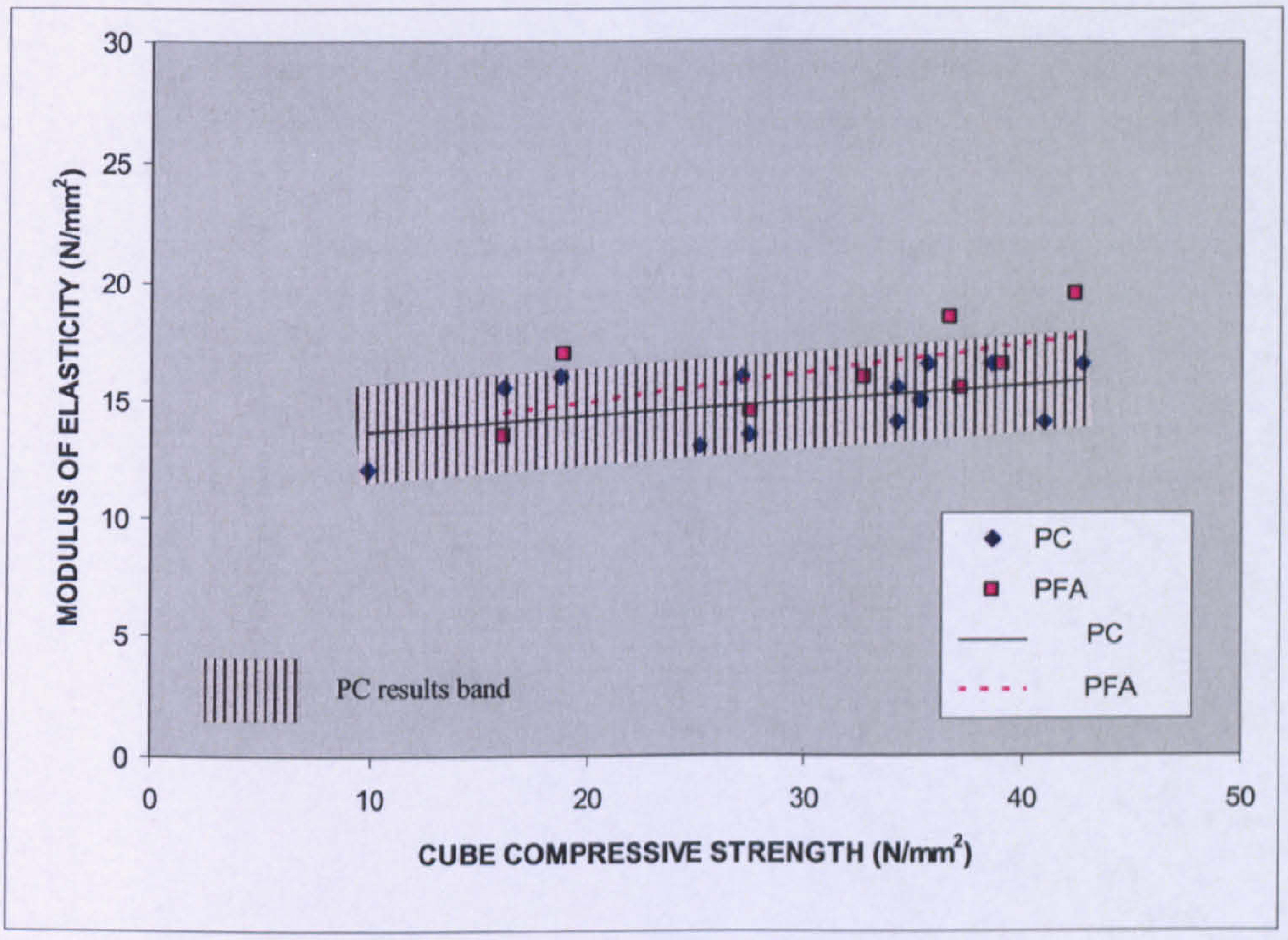


Figure 6.32 Cube compressive strength vs. modulus of elasticity of 50% RCA PC and PFA mixes.

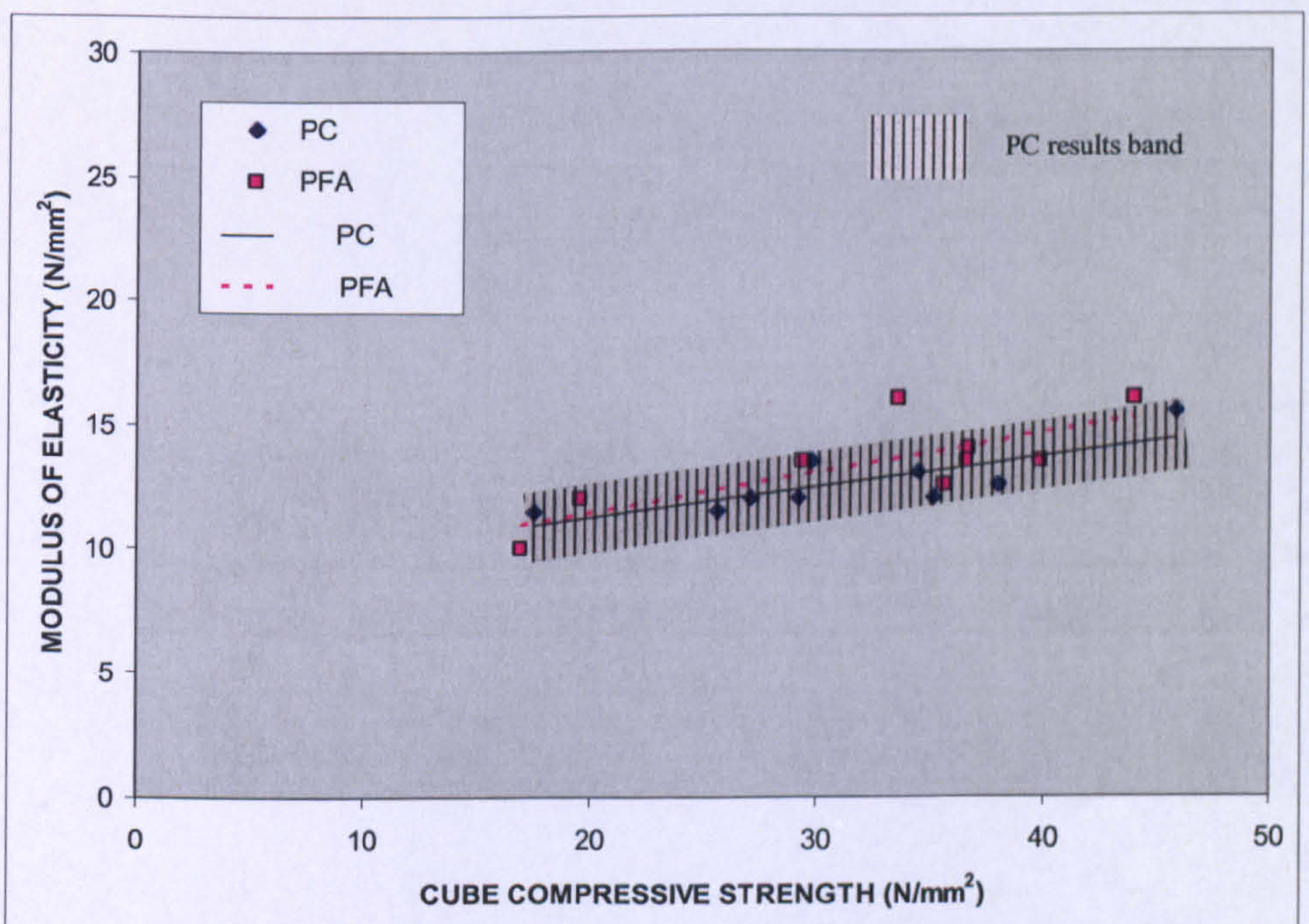


Figure 6.33 Cube compressive strength vs. modulus of elasticity of 100% RCA PC and PFA mixes.

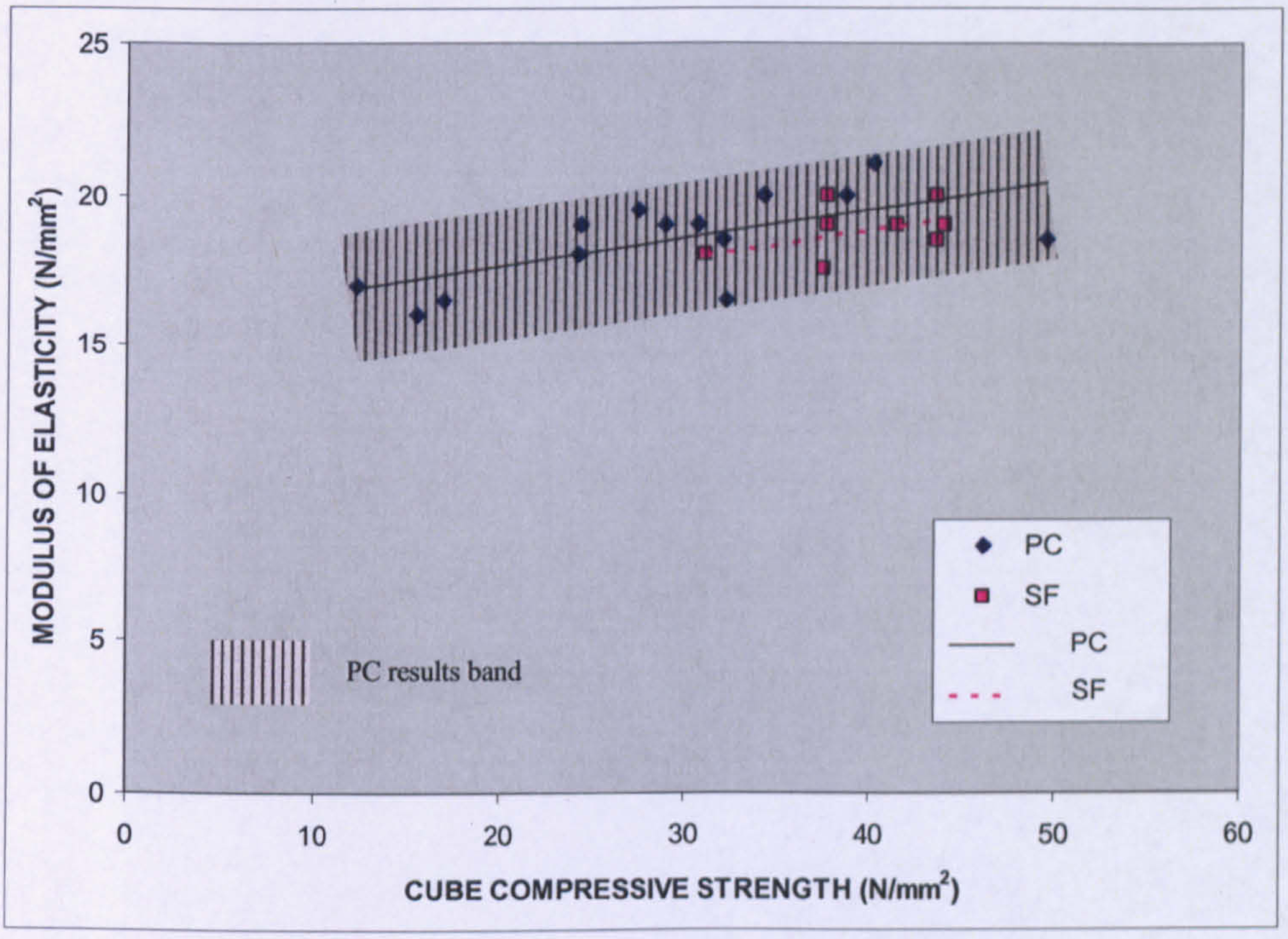


Figure 6.34 Cube compressive strength vs. modulus of elasticity of NA PC and SF mixes.

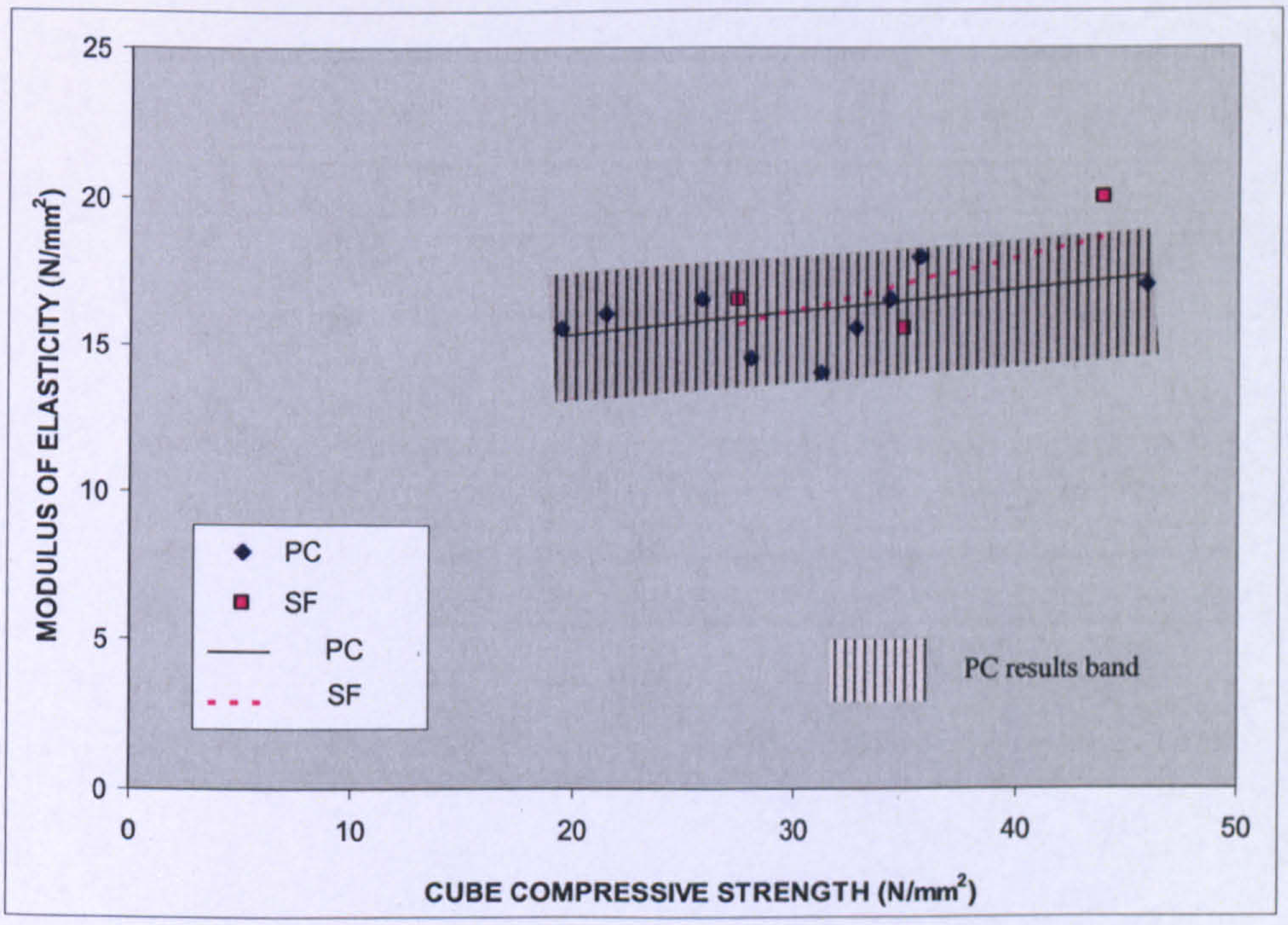


Figure 6.35 Cube compressive strength vs. modulus of elasticity of 30% RCA PC and SF mixes.

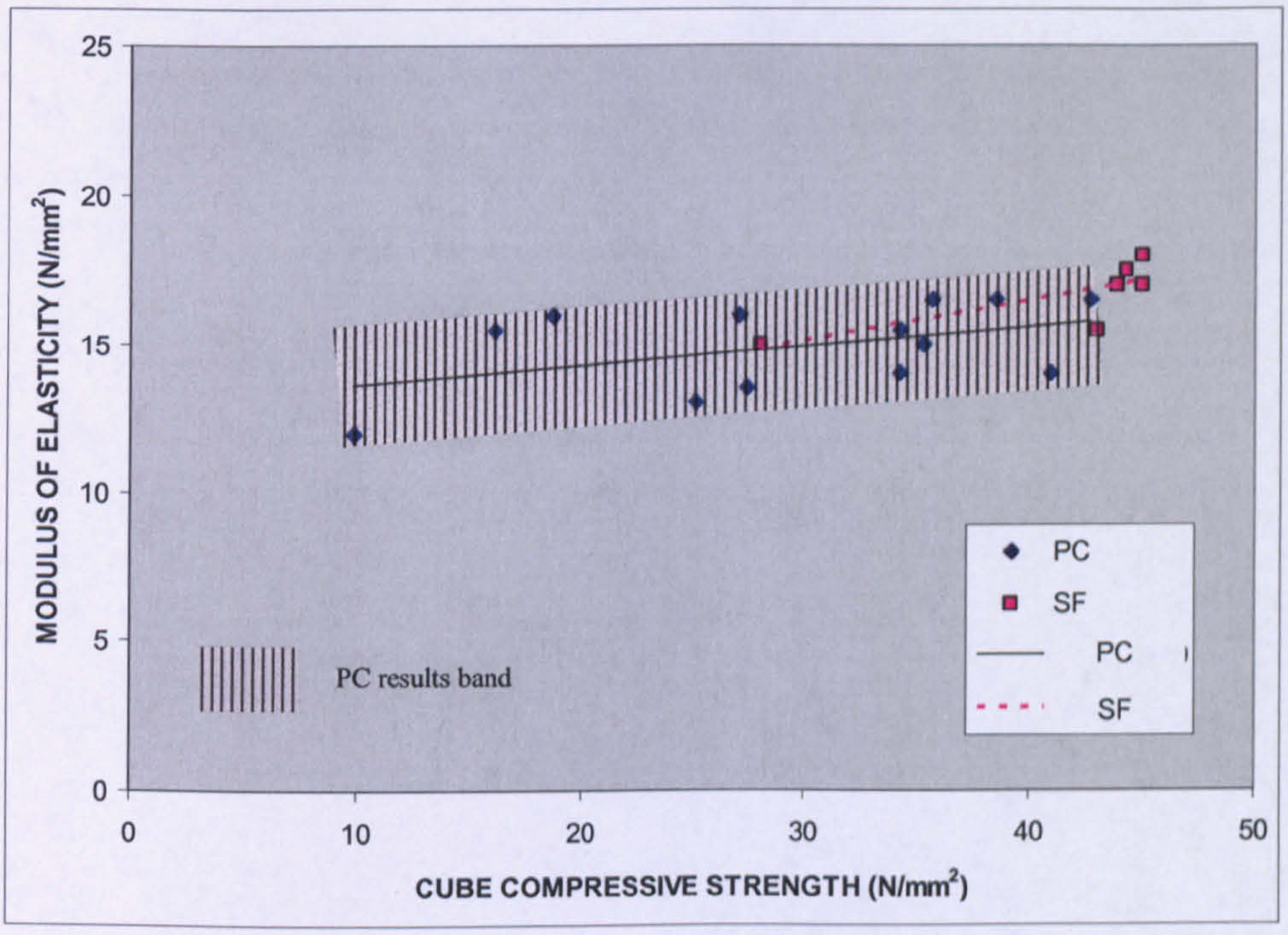


Figure 6.36 Cube compressive strength vs. modulus of elasticity of 50% RCA PC and SF mixes.

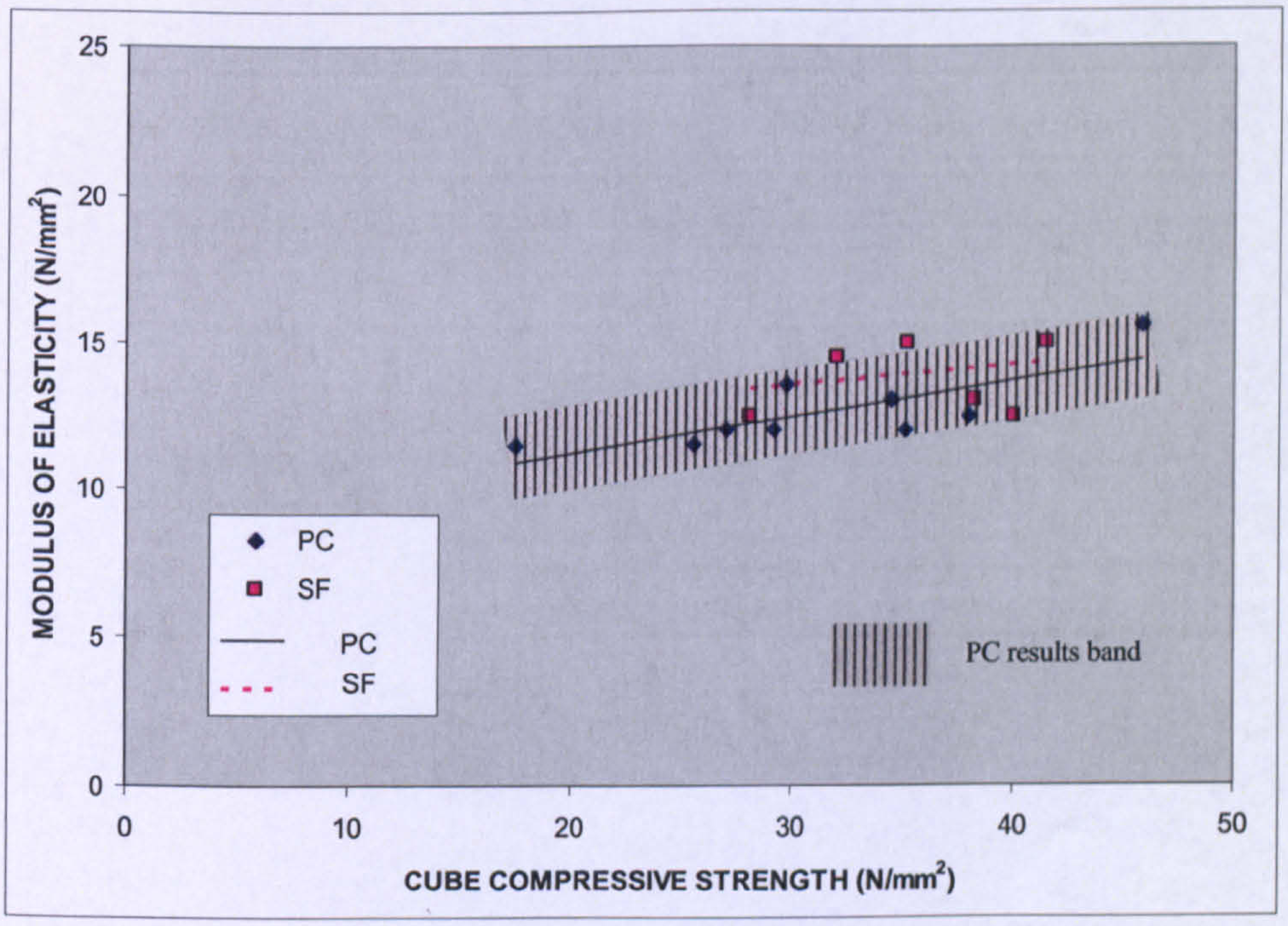


Figure 6.37 Cube compressive strength vs. modulus of elasticity of 100% RCA PC and SF mixes.

PC mixes

Table 6.7 shows the shrinkage values of all the PC mixes, after drying for 90 days at 20°C and 55% RH. Figure 6.38 shows the effect of the RCA content on the shrinkage deformation values of the different designated PC mixes.

GEN 1 – The shrinkage values ranged from 350 to 1150 με. There was an increase by 14, 31 and 229% in comparison with the NA mix in the shrinkage value for RCA contents of 30, 50 and 100% respectively.

GEN 3 – The shrinkage values ranged from 290 to 650 με. The results show an increase in the shrinkage value with the increase in RCA content in concrete. The increase was by 10, 55 and 124% for 30, 50 and 100% RCA contents respectively.

RC 30 – The shrinkage values ranged from 340 to 630 με. There was an increase by 53 and 85% in comparison with the NA mix in the shrinkage value for RCA contents of 50 and 100% respectively while the NA and 30% RCA mixes were almost identical.

RC 35 – The shrinkage values ranged from 280 to 810 με. There was an increase by 14, 52 and 189% in comparison with the NA mix in the shrinkage value for RCA contents of 30, 50 and 100% respectively.

Overall, the results showed that substituting 30% of the aggregate content in concrete with RCA had no major effect on the drying shrinkage of concrete. This confirms the findings of previous studies [26 j, 100]. Beyond this limit the use of RCA resulted in

Table 6.7 Shrinkage deformation values of PC mixes at 90 days.

Mix	Coarse RCA (%)	Drying shrinkage strain ($\times 10^{-6}$)
GEN 1	0	350
	30	400
	50	460
	100	1150
GEN 3	0	290
	30	320
	50	450
	100	650
RC 30	0	340
	30	340
	50	520
	100	630
RC 35	0	280
	30	320
	50	425
	100	810

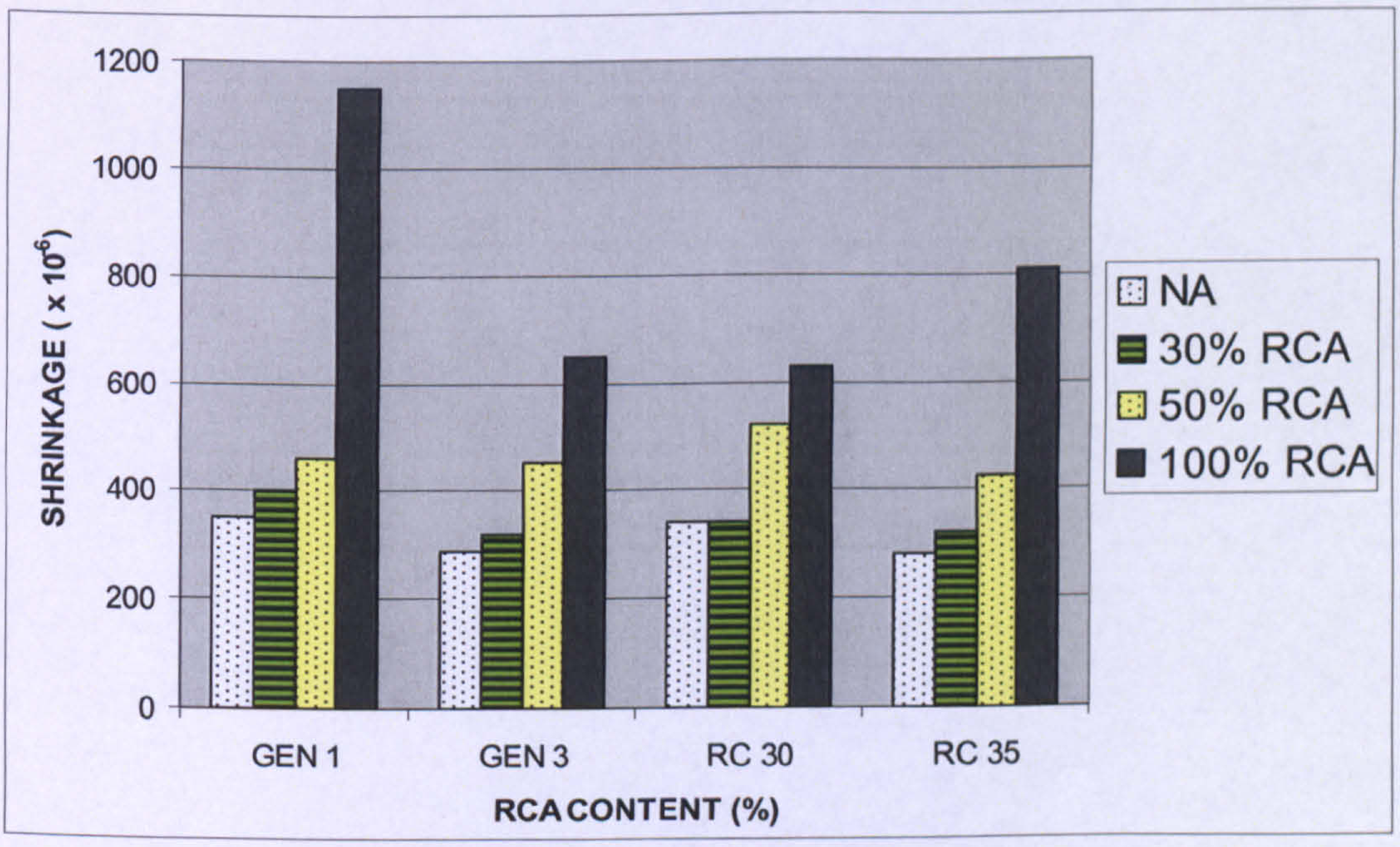


Figure 6.38 Effect of RCA content on the shrinkage of PC designated mixes.

an increase in the shrinkage values of the concrete.

Aggregates have a stiffening effect which hinders the shrinkage of the cement paste, this effect is greater the higher the modulus of the aggregates. RCA particles are composed of natural coarse aggregates and an attached cement paste; this results in the decrease of the volume of coarse aggregates available in the mix to counter the shrinkage of the cement paste; the natural coarse aggregates from the original concrete are the main elements countering the shrinkage of the cement paste in the RCA mixes. Another contributor to the increase of the drying shrinkage deformation values when RCA are used is the shrinkage capacity of the attached cement paste found in the RCA particles. The absorption of water by the RCA during the mixing process swells the attached cement paste of the RCA particles, which subsequently shrinks when the concrete is exposed to drying conditions. The high absorption rate of RCA is a warning sign that this type of aggregates has a high shrinkage capacity.

One of the mains reasons also behind the high shrinkage of the RCA mixes is the increase of the cement paste content and decrease of the aggregates/cement ratio as the RCA content of the mixes increased; this is due to the fact that the cement content was increased in the RCA mixes to compensate for the loss in strength that occurs when high proportions of RCA are used (> 30% RCA).

PFA mixes

Table 6.8 shows the shrinkage values of all the PFA mixes, after drying for 90 days at 20°C and 55% RH. Figure 6.39 shows the effect of the RCA content on the shrinkage deformation values of the different designated PFA mixes.

GEN 1 – The shrinkage values ranged from 190 to 450 με. There was an increase by 13 and 85% in comparison with the NA mix in the shrinkage value for RCA contents of 30 and 100% respectively while the NA and 50% RCA mixes were identical.

GEN 3 – The shrinkage values ranged from 270 to 510 με. There was an increase by 37 and 32% in comparison with the NA mix in the shrinkage value for RCA contents of 30 and 50% respectively while the increase for the 100% RCA mix was by 137%.

RC 30 – The shrinkage values ranged from 215 to 550 με. There was an increase by only 12% in comparison with the NA mix in the shrinkage value of the 30% RCA mix while the increase for the 50 and 100% RCA mixes was by 100 and 156% respectively.

RC 35 – The shrinkage values ranged from 195 to 695 με. There was an increase by 28% in comparison with the NA mix in the shrinkage value for the 30% RCA mix while the increase for the 50 and 100% RCA mixes was much higher with an increase of 118 and 256% respectively.

Overall, the results showed that substituting 30% of the aggregate content in concrete with RCA slightly increased the drying shrinkage of PFA concrete by up to 37%. For the GEN mixes, substituting 50% of the aggregate content in concrete with RCA had the same effect on the shrinkage as a 30% replacement, however for the RC mixes it resulted in doubling the shrinkage values of the mixes. Substituting 100% of the aggregate content in concrete with RCA increased considerably the shrinkage values of all the mixes; the 100% RCA mixes reached up to 3.5 times the shrinkage values

Table 6.8 Shrinkage deformation values of PFA mixes at 90 days.

Mix	Coarse RCA (%)	Drying shrinkage strain ($\times 10^{-6}$)
GEN 1	0	275
	30	310
	50	270
	100	510
GEN 3	0	190
	30	260
	50	250
	100	450
RC 30	0	215
	30	240
	50	430
	100	550
RC 35	0	195
	30	250
	50	425
	100	695

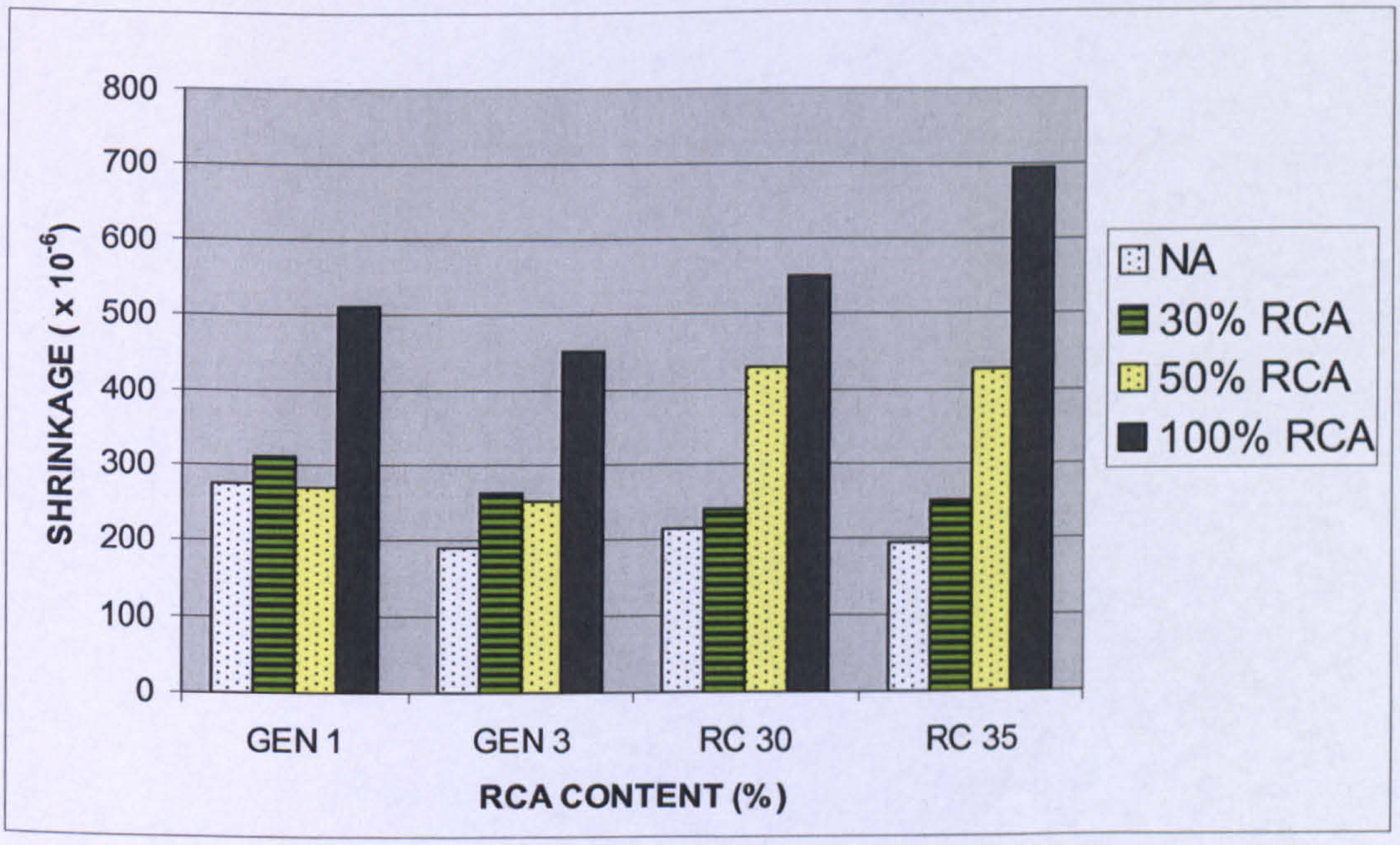


Figure 6.39 Effect of RCA content on the shrinkage of PFA designated mixes.

of their corresponding NA mixes. The increase in the drying shrinkage deformation values of the PFA mixes when RCA is used, as for the PC mixes, is due to the attached cement paste found in the RCA particles and its shrinkage capacity and the increase of the cement paste content in the RCA mixes.

SF mixes

Table 6.9 shows the shrinkage values of all the SF mixes, after drying for 90 days at 20°C and 55% RH. Figure 6.40 shows the effect of the RCA content on the shrinkage deformation values of the different designated SF mixes.

RC 30 – The shrinkage values ranged from 220 to 760 με. There was a gradual increase in the shrinkage value with the increase of RCA content in concrete. The increase was by 55, 95 and 245% for 30, 50 and 100% RCA contents respectively.

RC 35 – The shrinkage values ranged from 235 to 730 με. There was an increase in the shrinkage value by 64 and 175% for 50 and 100% RCA contents respectively while the shrinkage values of the NA and 30% RCA mixes were almost the same; the shrinkage value of the 30% RCA mix was lower by 11% when compared to the NA mix.

Overall, the results showed that substituting 30% of the aggregate content in SF concrete with RCA had a minor effect on the drying shrinkage of the concrete, however beyond this limit the use of RCA resulted in an increase in the shrinkage values of the concrete. Substituting 50 and 100% of the aggregate content in concrete increased considerably the shrinkage values of all the mixes to reach 1.5 to 3.5 times

Table 6.9 Shrinkage deformation values of SF mixes at 90 days.

Mix	Coarse RCA (%)	Drying shrinkage strain ($\times 10^{-6}$)
RC 30	0	220
	30	340
	50	430
	100	760
RC 35	0	265
	30	235
	50	435
	100	730

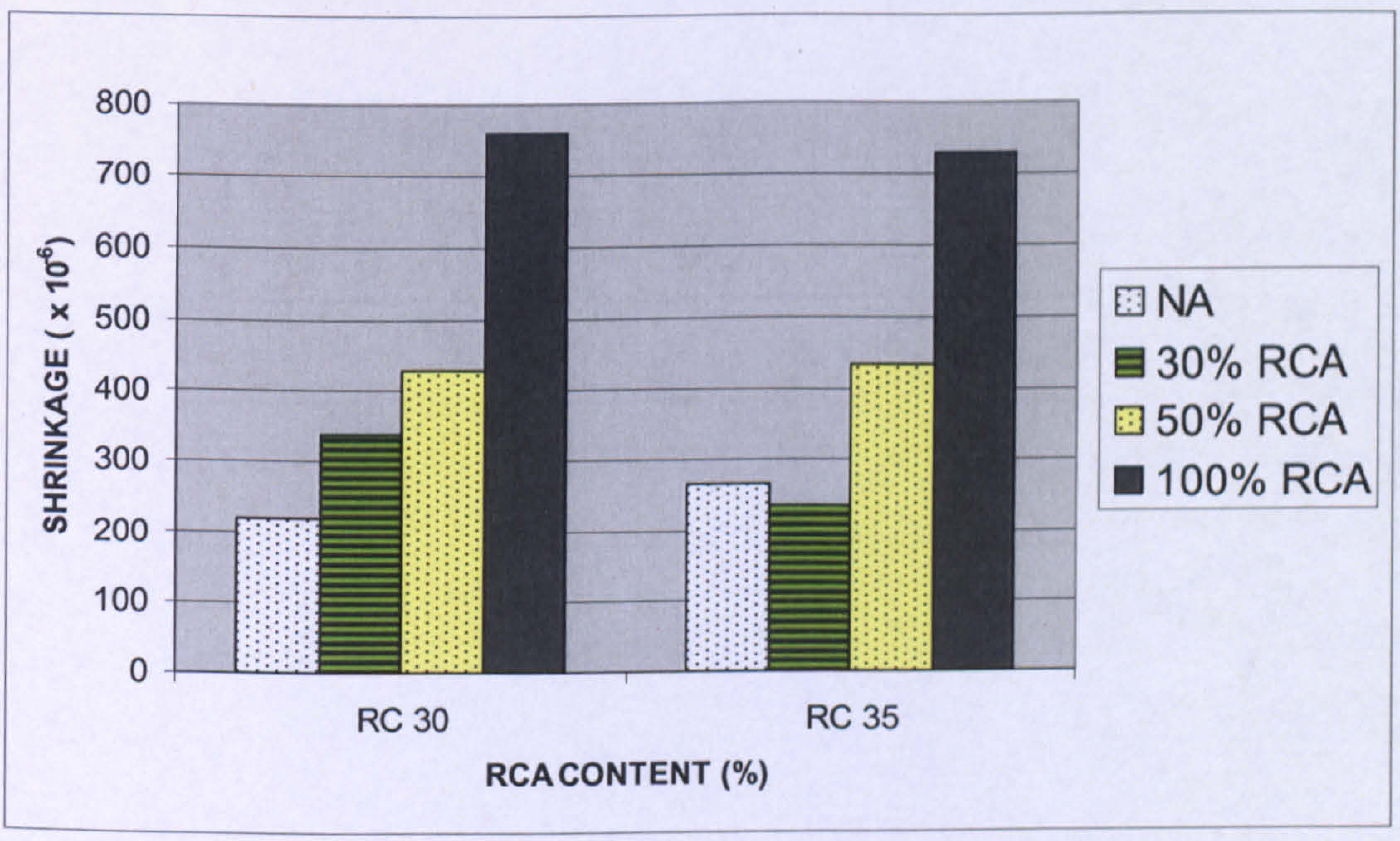


Figure 6.40 Effect of RCA content on the shrinkage of SF designated mixes.

the shrinkage values of their corresponding NA mixes. The increase in the drying shrinkage deformation values of the SF mixes when RCA is used, as for the PC mixes, is due to the attached cement paste found in the RCA particles and its shrinkage capacity and the increase of the cement paste content in the RCA mixes.

6.6.1.2 Binary cement concrete performance

Figures 6.41 to 6.44 compare the effect of the RCA content on the shrinkage deformation values of equal strength designated PC mixes and their corresponding PFA and SF mixes. Figure 6.45 shows the drying shrinkage deformations for the RC 35 mix using different levels of RCA and the different cements used in the study.

PC/PFA

GEN 1 – When comparing the shrinkage values of the PFA mixes with their corresponding PC mixes, we found that these were lower by 21, 23, 41 and 56% for the 0, 30, 50 and 100% RCA contents respectively.

GEN 3 – When comparing the shrinkage values of the PFA mixes with their corresponding PC mixes, we found that these were lower by 34, 19, 44 and 31% for the 0, 30, 50 and 100% RCA contents respectively.

RC 30 – When comparing the shrinkage values of the PFA mixes with their corresponding PC mixes, we found that these were lower by 37, 29, 13 and 17% for the 0, 30, 50 and 100% RCA contents respectively.

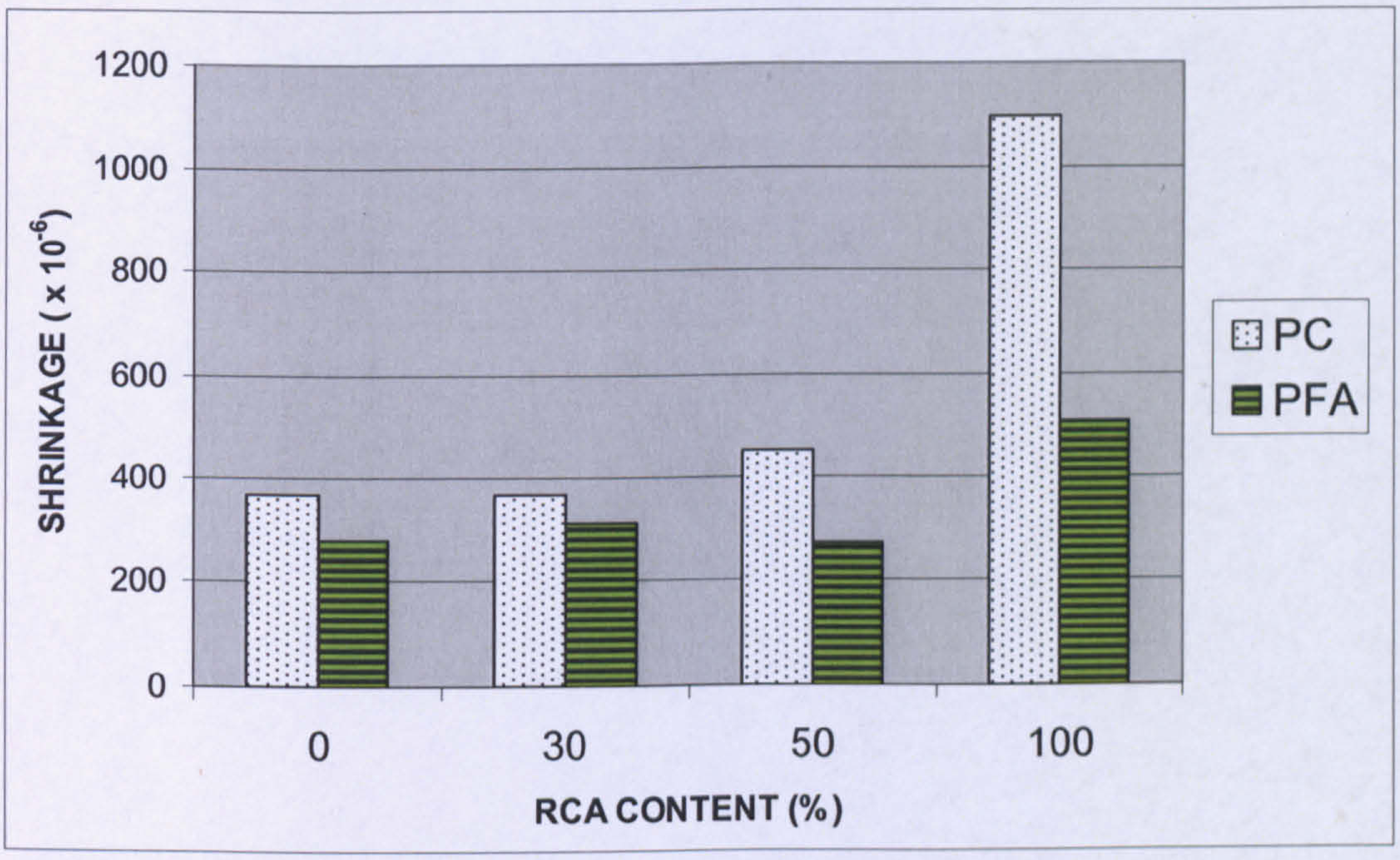


Figure 6.41 Effect of RCA content on the shrinkage of PC GEN 1 mix and its corresponding PFA mix.

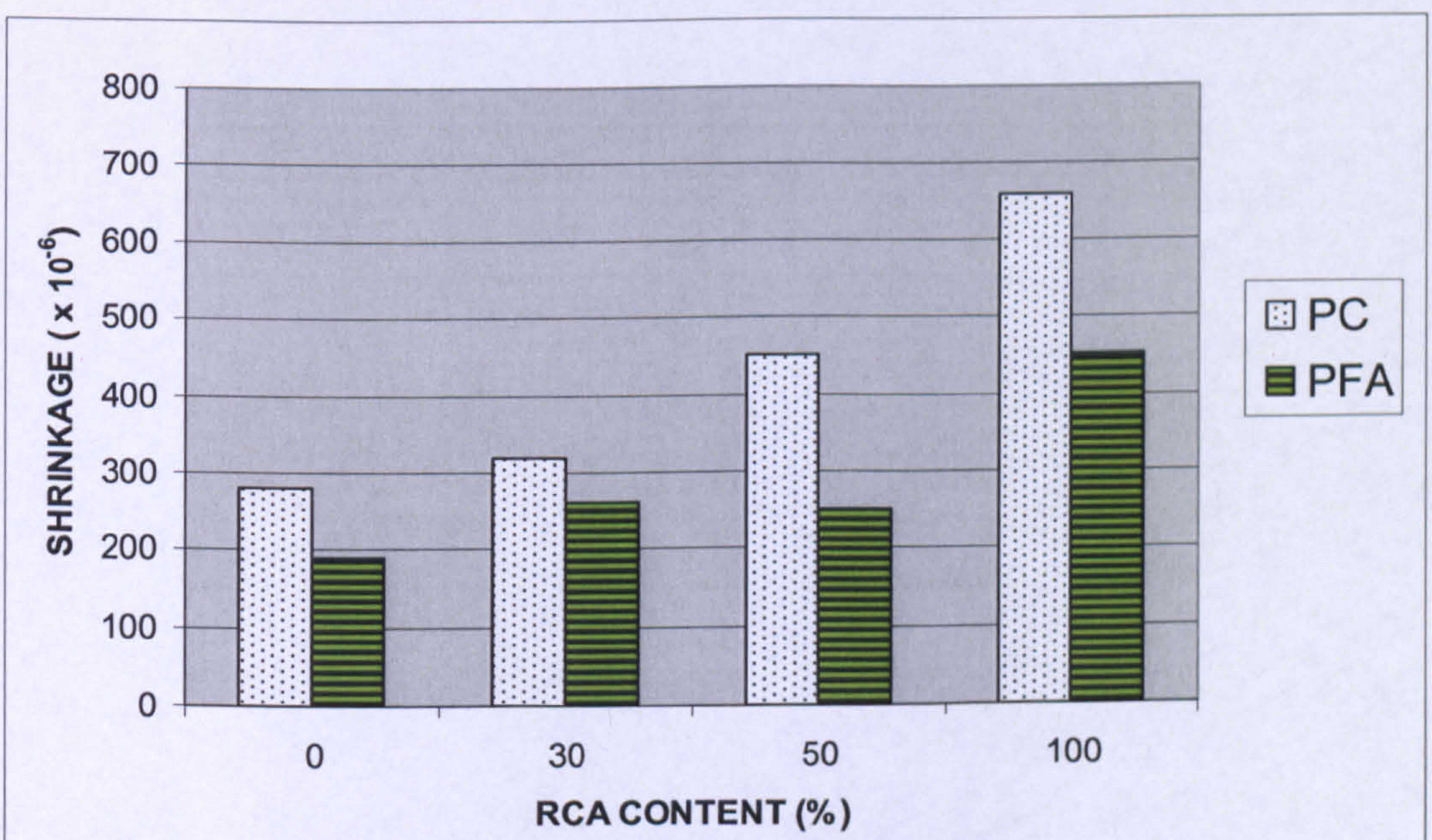


Figure 6.42 Effect of RCA content on the shrinkage of PC GEN 3 mix and its corresponding PFA mix.

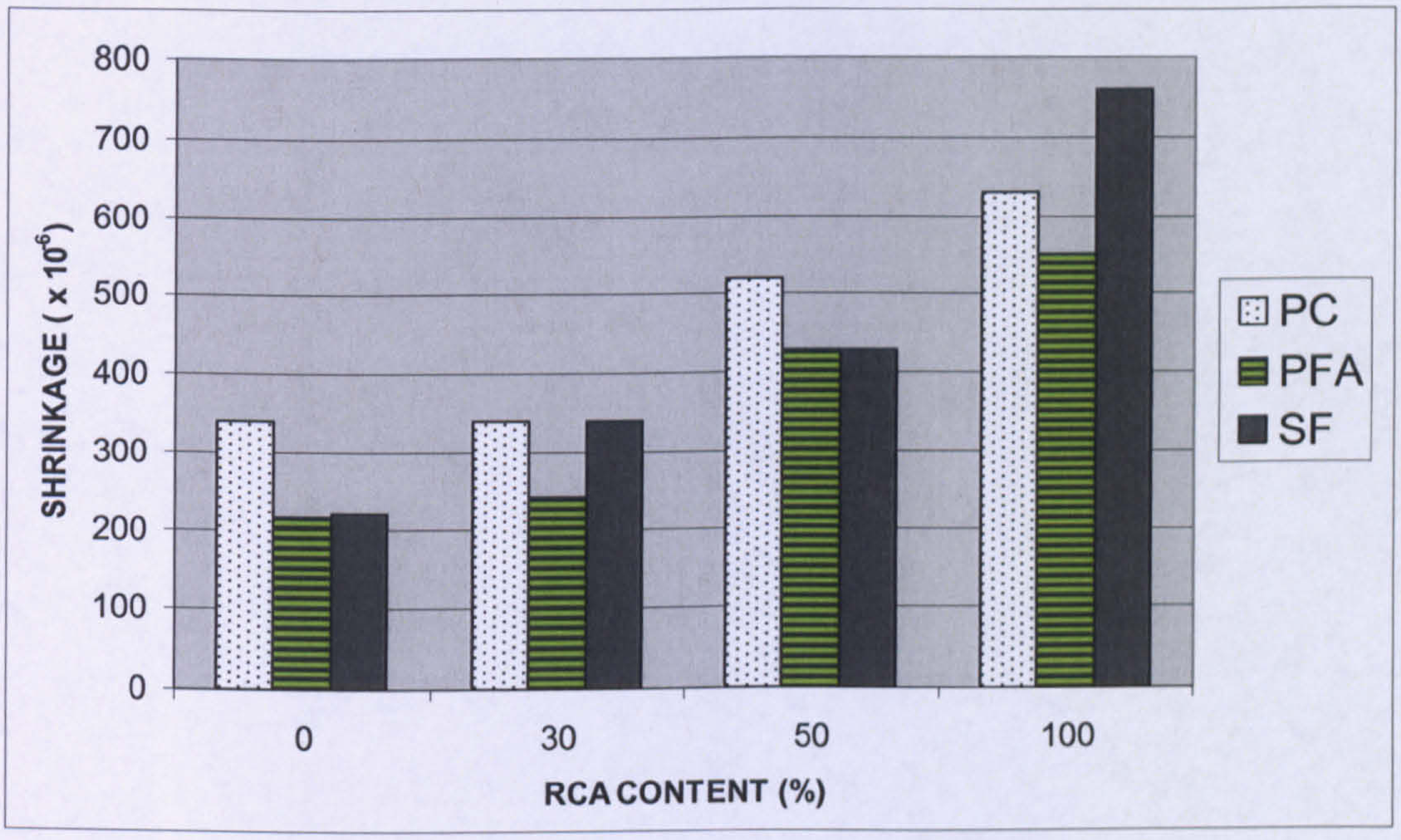


Figure 6.43 Effect of RCA content on the shrinkage of PC RC 30 mix and its corresponding PFA and SF mixes.

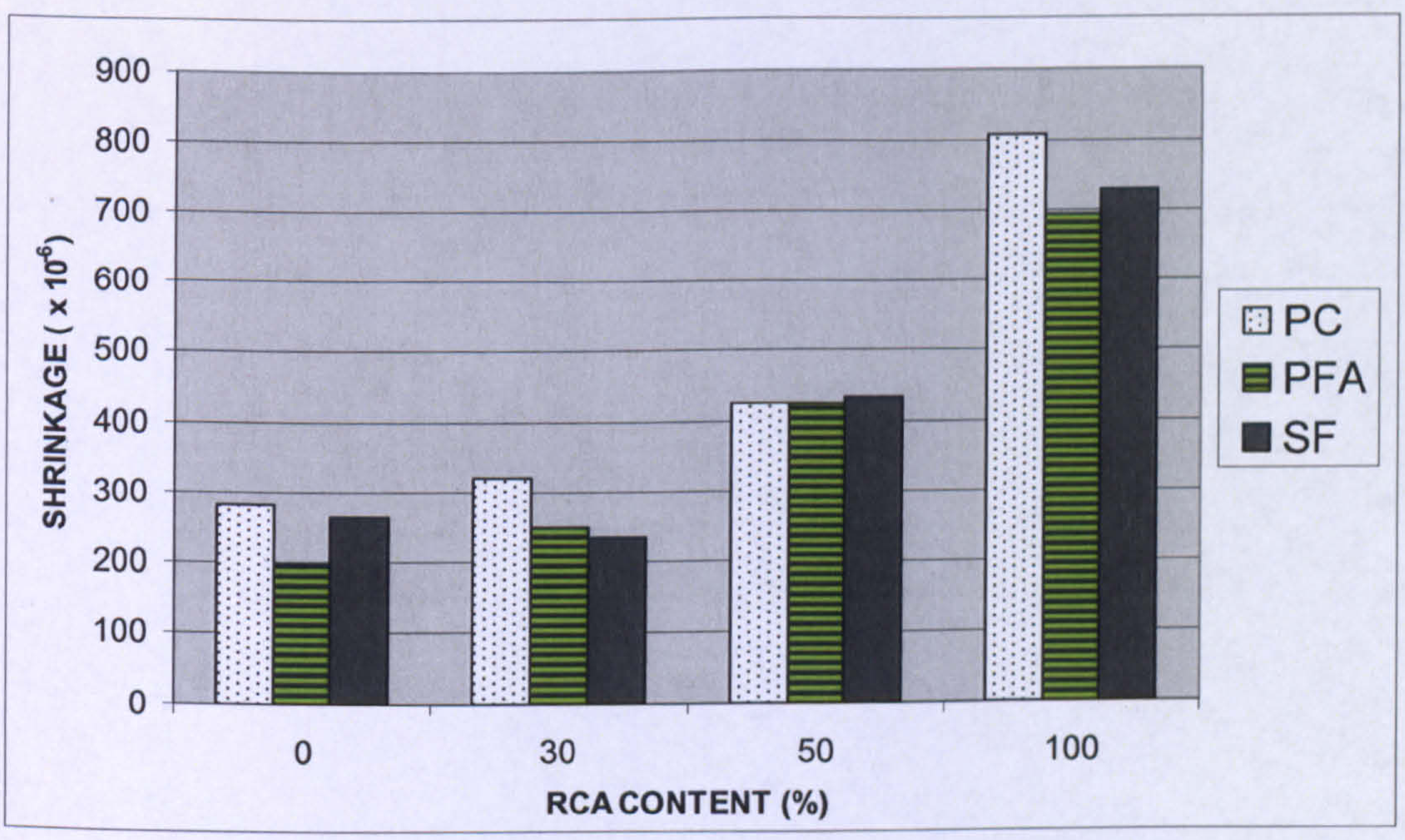


Figure 6.44 Effect of RCA content on the shrinkage of PC RC 35 mix and its corresponding PFA and SF mixes.

RC 35 – When comparing the shrinkage values of the PFA mixes with their corresponding PC mixes, we found that these were lower by 30, 22 and 14% for the 0, 30 and 100% RCA contents respectively while the shrinkage values of the 50% RCA PC and PFA mixes were similar.

Overall, the shrinkage values of the PFA designated mixes were lower compared to the PC designated mixes regardless of the RCA content. This is in line with the findings from other studies [20 b, 105, 106]. This is possibly due to the low water content, which leads to lower shrinkage, and the lower and finer porosity of the PFA mixes which can lower the rate at which water moves towards the surface of the specimens.

PC/SF

RC 30 When comparing the shrinkage values of the 0 and 50% RCA SF mixes with their corresponding PC mixes, we found that these were lower by 35 and 17% respectively while the 30% RCA content PC and SF mixes were similar. The shrinkage value of the 100% RCA content SF mix was higher than its corresponding PC mix by 21%. When comparing the shrinkage values of the SF mixes with their corresponding PFA mixes, we found that these were higher by 42 and 38% for the 30 and 100% RCA contents respectively. On the other hand, the shrinkage values of the 0 and 50% SF and PFA mixes were identical.

RC 35 - When comparing the shrinkage values of SF mixes with their corresponding PC mixes, we found that these were lower by 5, 27 and 10% for the 0, 30 and 100% RCA contents respectively. The shrinkage values of the 50% RCA content PC and SF

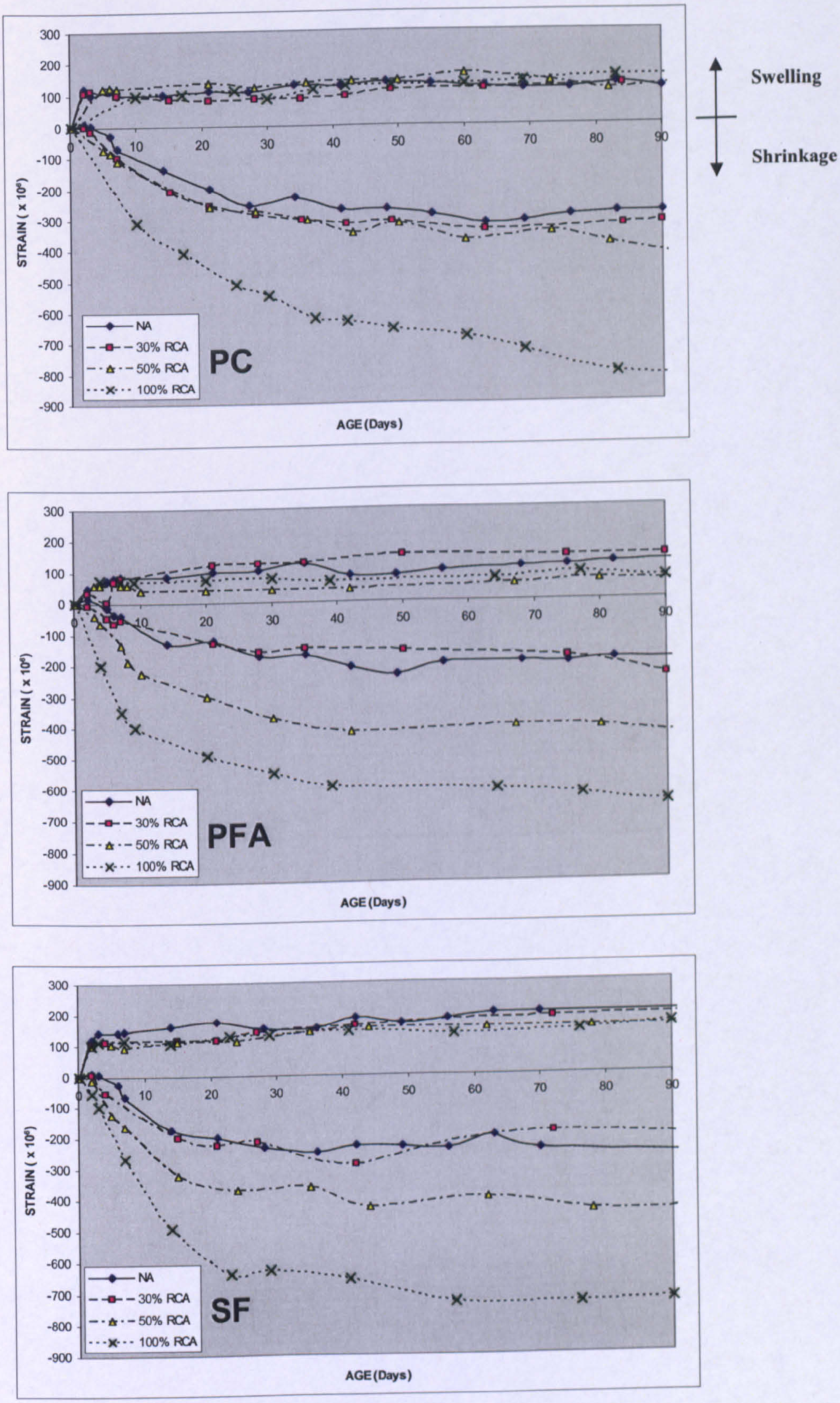


Figure 6.45 Effect of RCA on the drying shrinkage and swelling deformations of PC, PFA and SF RC 35 designated mixes.

mixes were identical. When comparing the shrinkage value of the NA SF mix with its corresponding PFA mix, we found that it was higher by 36%. The shrinkage values of the 30, 50 and 100% SF and PFA mixes were almost identical.

Overall, the shrinkage values of the SF designated mixes were slightly lower when compared to the PC designated mixes regardless of the RCA content. This is in line with the findings from other studies [20 b, 56]. This is possibly due to the lower content of cement paste, which leads to lower shrinkage, and the slightly higher content of fine aggregates of the SF mixes compared to the PC mixes which can help restrain the shrinkage of the cement paste.

6.6.2 Swelling deformation

6.6.2.1 Effect of RCA

PC mixes

Table 6.10 shows the swelling values of all the PC mixes, after 90 days storage in water at 20°C. Figure 6.46 shows the effect of the RCA content on the swelling deformation values of the different designated PC mixes.

GEN 1 - The expansion values due to swelling ranged from 115 to 180 με. There was an increase by 13 and 60% in comparison with the NA mix in the swelling value for RCA contents of 30 and 50% respectively while the NA and 100% RCA mixes were identical.

GEN 3 – The expansion values due to swelling ranged from 60 to 125 με. The results showed a decreasing swelling value with the increase in RCA content. The decrease

Table 6.10 Swelling deformation values of PC mixes at 90 days.

Mix	Coarse RCA (%)	Swelling strain ($\times 10^{-6}$)
GEN 1	0	115
	30	130
	50	180
	100	115
GEN 3	0	125
	30	110
	50	100
	100	60
RC 30	0	100
	30	120
	50	80
	100	80
RC 35	0	120
	30	130
	50	130
	100	140

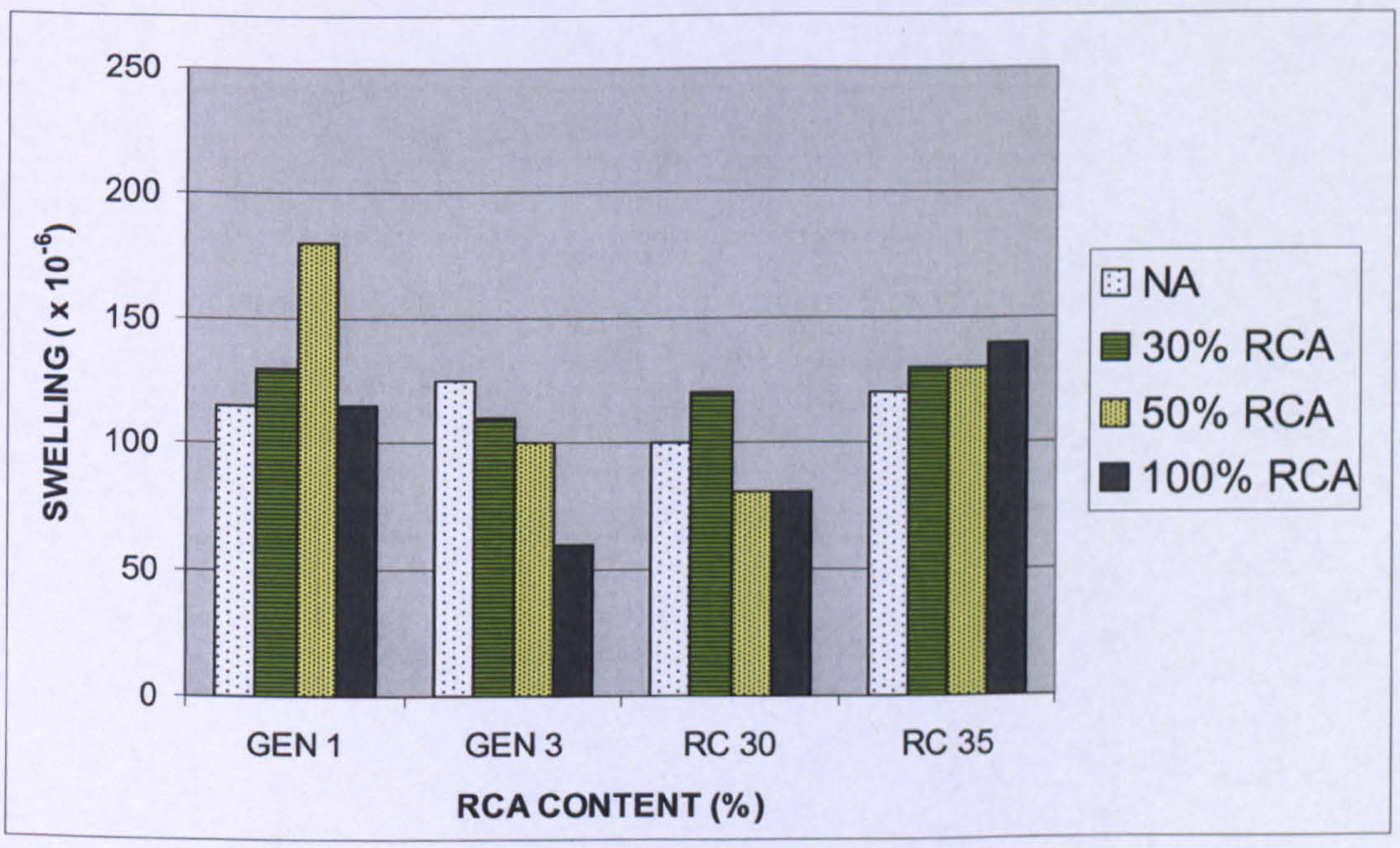


Figure 6.46 Effect of RCA content on the swelling of PC designated mixes.

was by 12, 20 and 52% for 30, 50 and 100% RCA contents respectively.

RC 30 – The expansion values due to swelling ranged from 80 to 120 με. There was an increase by 20% in the swelling value for 30% RCA mix and a decrease by 20% for both the 50 and 100% RCA mixes.

RC 35 – The expansion values due to swelling ranged from 120 to 140 με. The RC 35 mix results show a slight increase of 8% for both 30 and 50% RCA mixes and 17% for the 100% RCA content.

Overall, the different RCA contents had different effects on the swelling of the designated mixes. No clear correlation could be established between the swelling deformation and the RCA content of the PC designated mixes. The use of saturated RCA for producing concrete reduces the influence of the RCA to increase the swelling of the concrete as a result of the "pre-swelling" of the aggregate. The small differences in the swelling values of the mixes may be due to a difference in the degree of saturation of the RCA in the mixes.

PFA mixes

Table 6.11 shows the swelling values of all the PFA mixes, after 90 days storage in water at 20°C. Figure 6.47 shows the effect of the RCA content on the swelling deformation values of the different designated PFA mixes.

GEN 1 – The expansion values due to swelling ranged from 170 to 200 με. There was an increase by 14 and 9% in comparison with the NA mix in the swelling value for

Table 6.11 Swelling deformation values of PFA mixes at 90 days.

Mix	Coarse RCA (%)	Swelling strain ($\times 10^{-6}$)
GEN 1	0	175
	30	200
	50	190
	100	170
GEN 3	0	145
	30	190
	50	190
	100	220
RC 30	0	90
	30	145
	50	110
	100	135
RC 35	0	140
	30	140
	50	65
	100	100

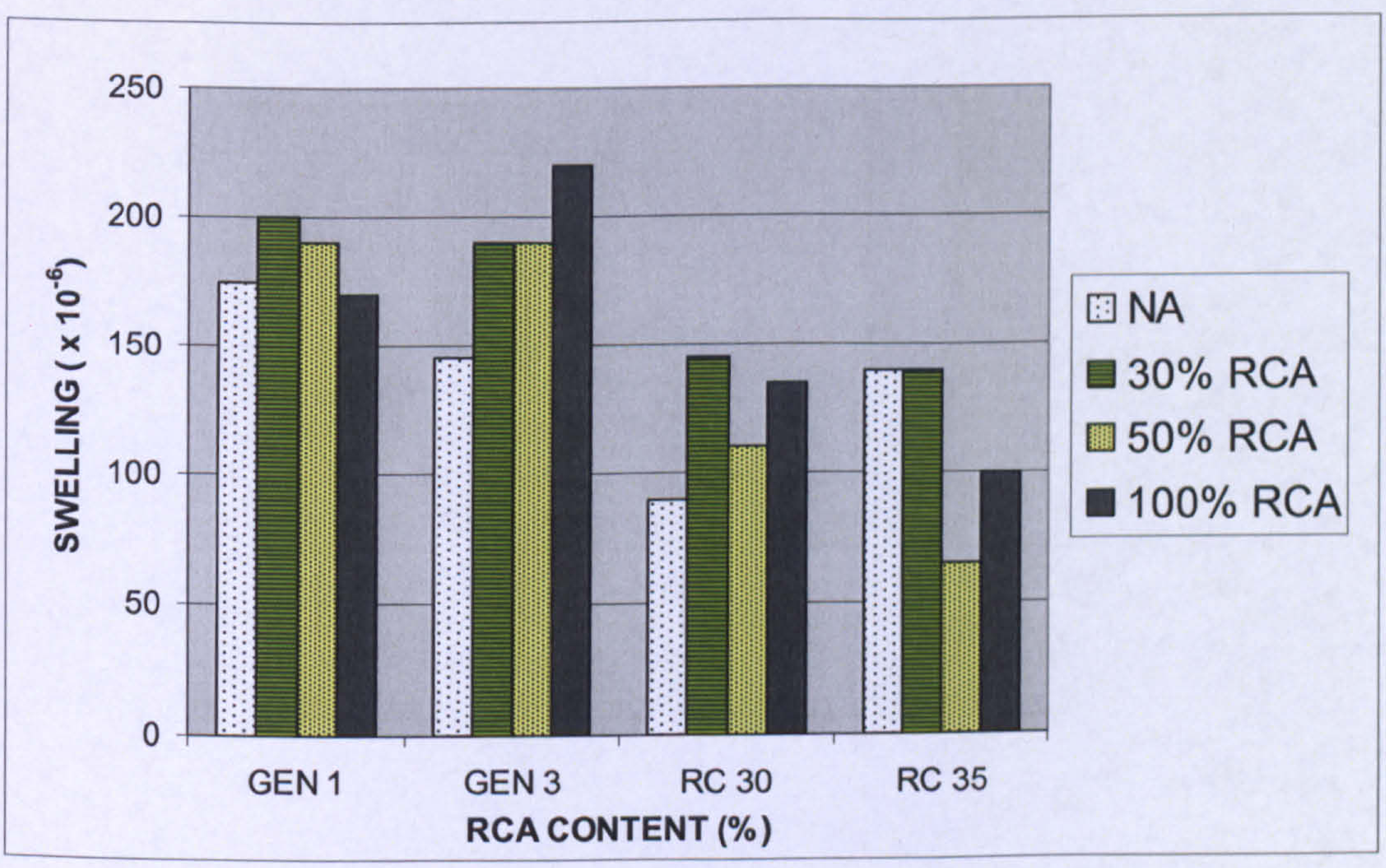


Figure 6.47 Effect of RCA content on the swelling of PFA designated mixes.

RCA contents of 30 and 50% respectively while the NA and 100% RCA mixes were almost identical.

GEN 3 – The expansion values due to swelling ranged from 145 to 220 με. The results showed an increasing swelling value with the increase in RCA content. The increase was by 31% for both the 30 and 50% RCA mixes and 52% for the 100% RCA content.

RC 30 – The expansion values due to swelling ranged from 90 to 145 με. There was an increase by 61, 22 and 50% in the swelling value for 30, 50 and 100% RCA contents respectively when compared to NA concrete.

RC 35 – The expansion values due to swelling ranged from 65 to 140 με. The RC 35 mix results show a decrease of 54 and 29% in the swelling value for the 50 and 100% RCA mixes respectively in comparison with the NA mix, while the values of the NA and 30% RCA mix were identical.

Overall, the results showed that the inclusion of RCA increased the swelling deformation of the PFA mixes. The increase in swelling with the use of RCA may be due to the higher content of the cement paste volume of the RCA mixes. The differences in the swelling values of the mixes may also be due to a difference in the degree of saturation of the RCA in the mixes.

SF mixes

Table 6.12 shows the swelling values of all the SF mixes, after 90 days storage in water at 20°C. Figure 6.48 shows the effect of the RCA content on the swelling deformation values of the different designated SF mixes.

RC 30 – The expansion values due to swelling ranged from 155 to 195 με. There was a decrease by 18, 13 and 21% in the swelling value of the 30, 50 and 100% RCA concretes respectively when compared to NA concrete.

RC 35 – The expansion values due to swelling ranged from 150 to 190 με. There was a decrease by 5, 21 and 16% in the swelling value of the 30, 50 and 100% RCA concretes respectively when compared to NA concrete.

Overall, the results showed that the inclusion of RCA did not have a major effect on the swelling of SF concrete. RCA only resulted in a slight decrease in the swelling deformation of SF mixes. The influence of RCA on the swelling behaviour of SF concrete could not be attributed to changes in the composition of the SF mixes. The small differences in the swelling values may be solely due to the different degree of saturation of the RCA in the mixes.

6.6.2.2 Binary cement concrete performance

Figures 6.49 to 6.52 compare the effect of the RCA content on the swelling values of equal strength designated PC mixes and their corresponding PFA and SF mixes. Figure 6.45 shows the swelling deformations for the RC 35 mix using different levels of RCA and the different cements used in the study.

Table 6.12 Swelling deformation values of SF mixes at 90 days.

Mix	Coarse RCA (%)	Swelling strain ($\times 10^{-6}$)
RC 30	0	195
	30	160
	50	170
	100	155
RC 35	0	190
	30	180
	50	150
	100	160

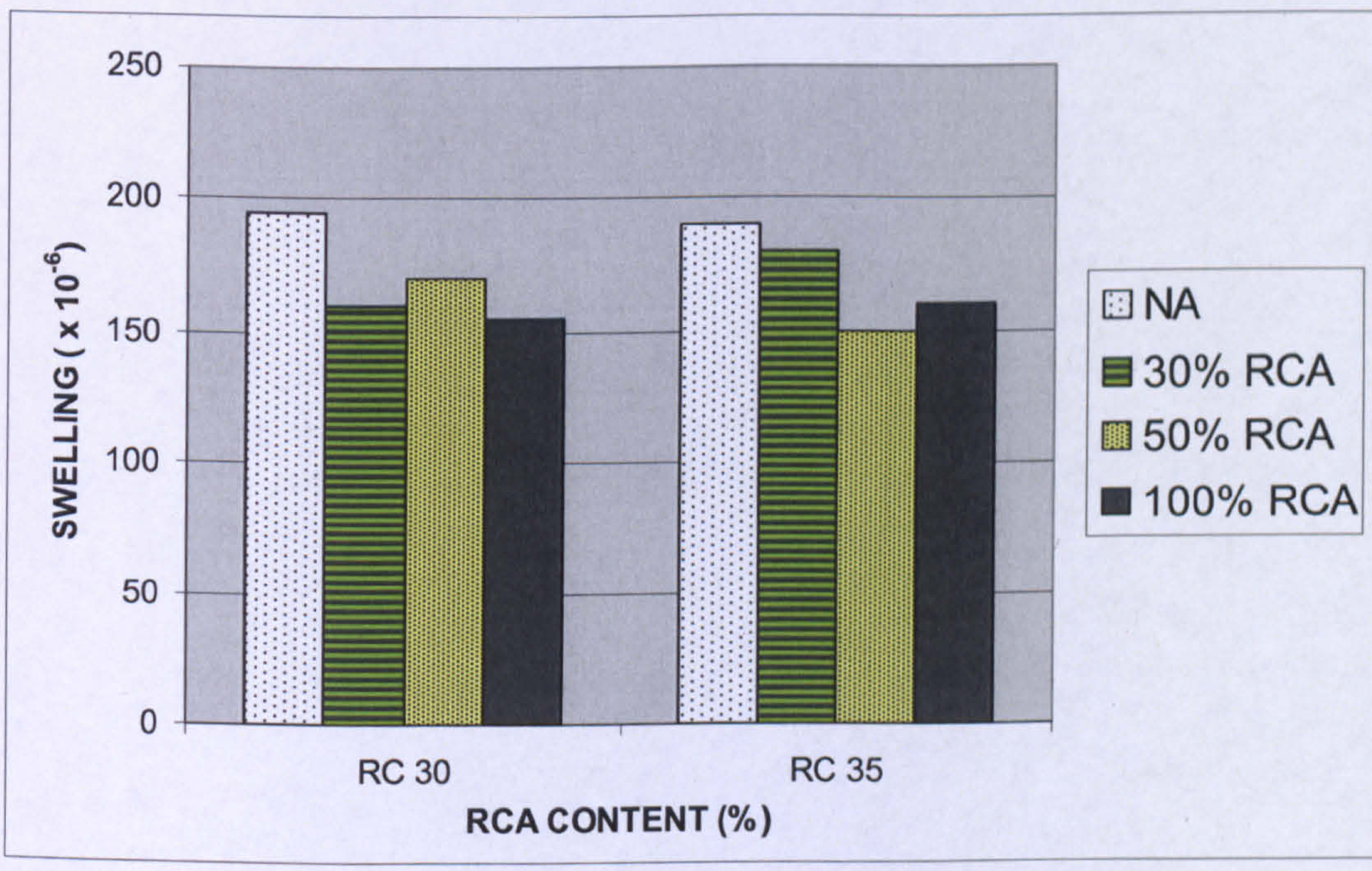


Figure 6.48 Effect of RCA content on the swelling of SF designated mixes.

PC/PFA

GEN 1 – When comparing the swelling values of the PFA mixes with their corresponding PC mixes, we found that these were higher by 52, 54, 6 and 48% for the 0, 30, 50 and 100% RCA contents respectively.

GEN 3 – The expansion due to swelling was in PFA mixes was higher when compared to their corresponding PC mixes by 16, 73, 90 and 267% for the 0, 30, 50 and 100% RCA contents respectively.

RC 30 – The expansion due to swelling of the PFA mixes was higher than for their corresponding PC mixes by 21, 38 and 68% for the 30, 50 and 100% RCA contents respectively, while expansion of the NA PC mix was higher than for its corresponding PFA mix by only 10%.

RC 35 – The expansion due to swelling of the PFA mixes was higher than for their corresponding PC mixes by 17 and 8% for the 0 and 30% RCA contents, while it was lower by 50 and 29% for the 50 and 100% RCA contents respectively.

Overall, the results showed that the use of PFA resulted in an increase in the swelling deformation of NA and RCA concrete when compared to PC concrete. This is possibly due to the low water content and w/c ratio of the PFA mixes as well as their low and fine porosity which increases capillary tension resulting in higher swelling. The PFA mixes also have a higher content of coarse aggregates which can increase the swelling and a lower amount of fine aggregates which decreases the ability of the concrete to restrain deformation. The high swelling of PFA concrete may also indicate

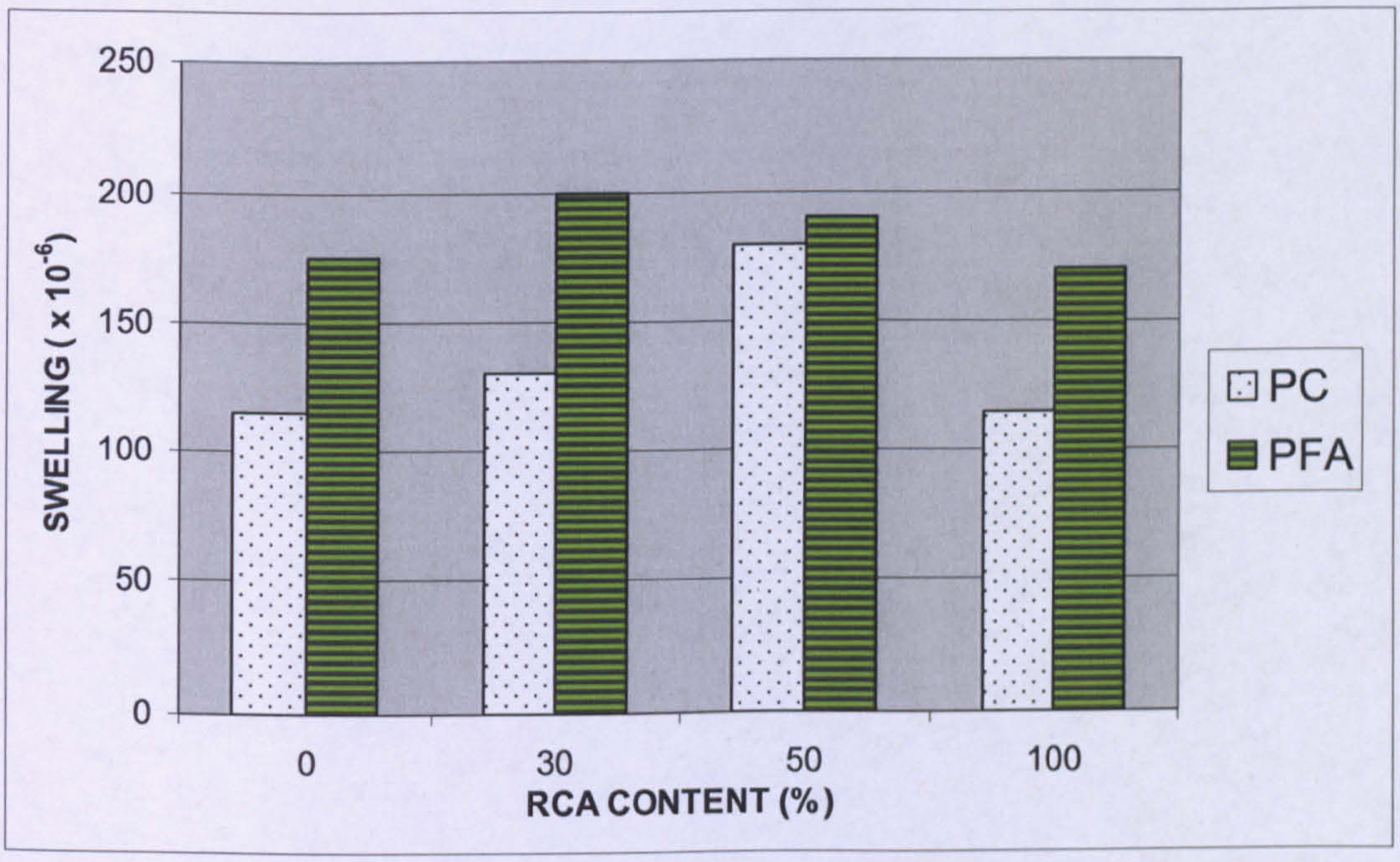


Figure 6.49 Effect of RCA content on the swelling of PC GEN 1 mix and its corresponding PFA mix.

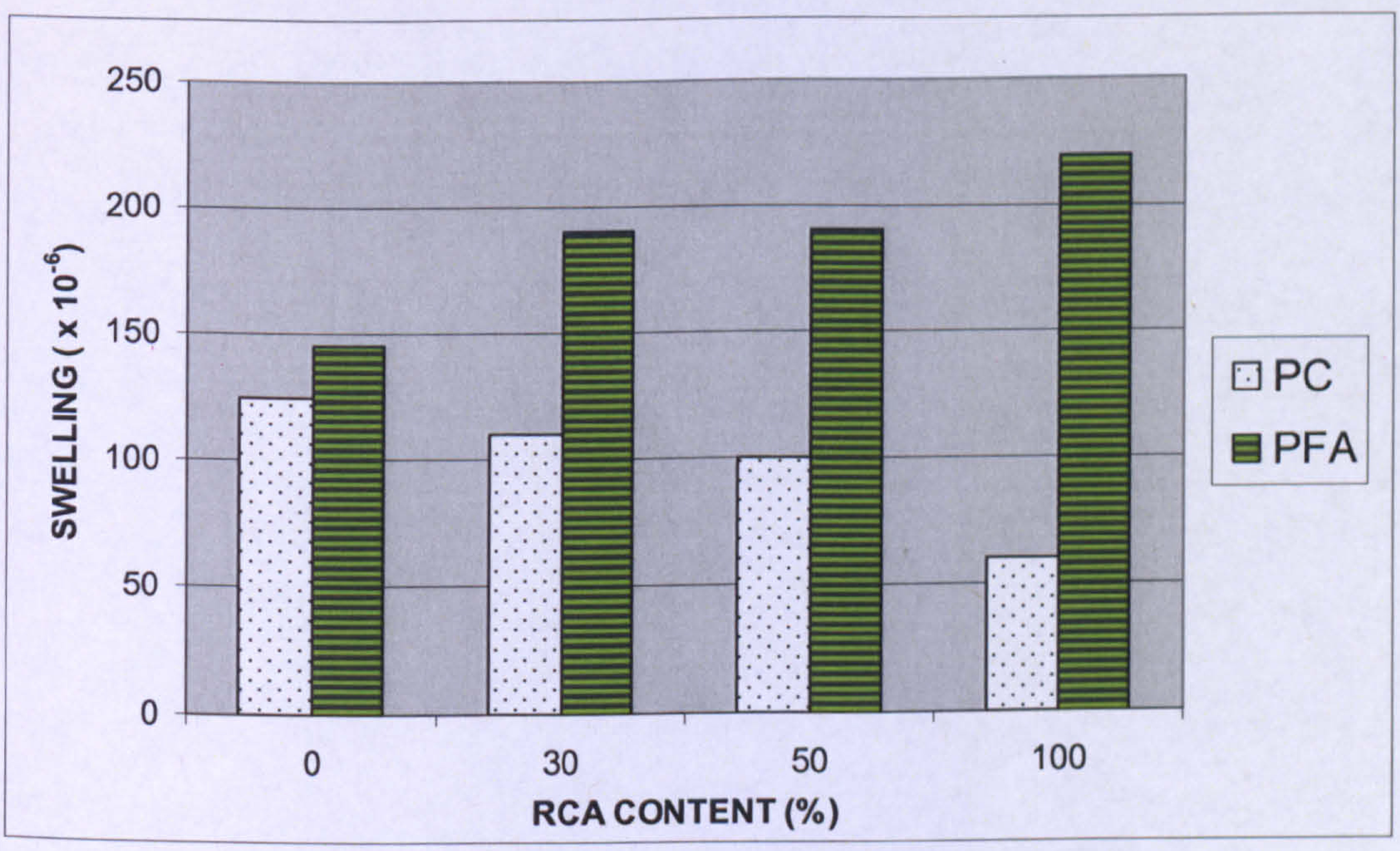


Figure 6.50 Effect of RCA content on the swelling of PC GEN 3 mix and its corresponding PFA mix.

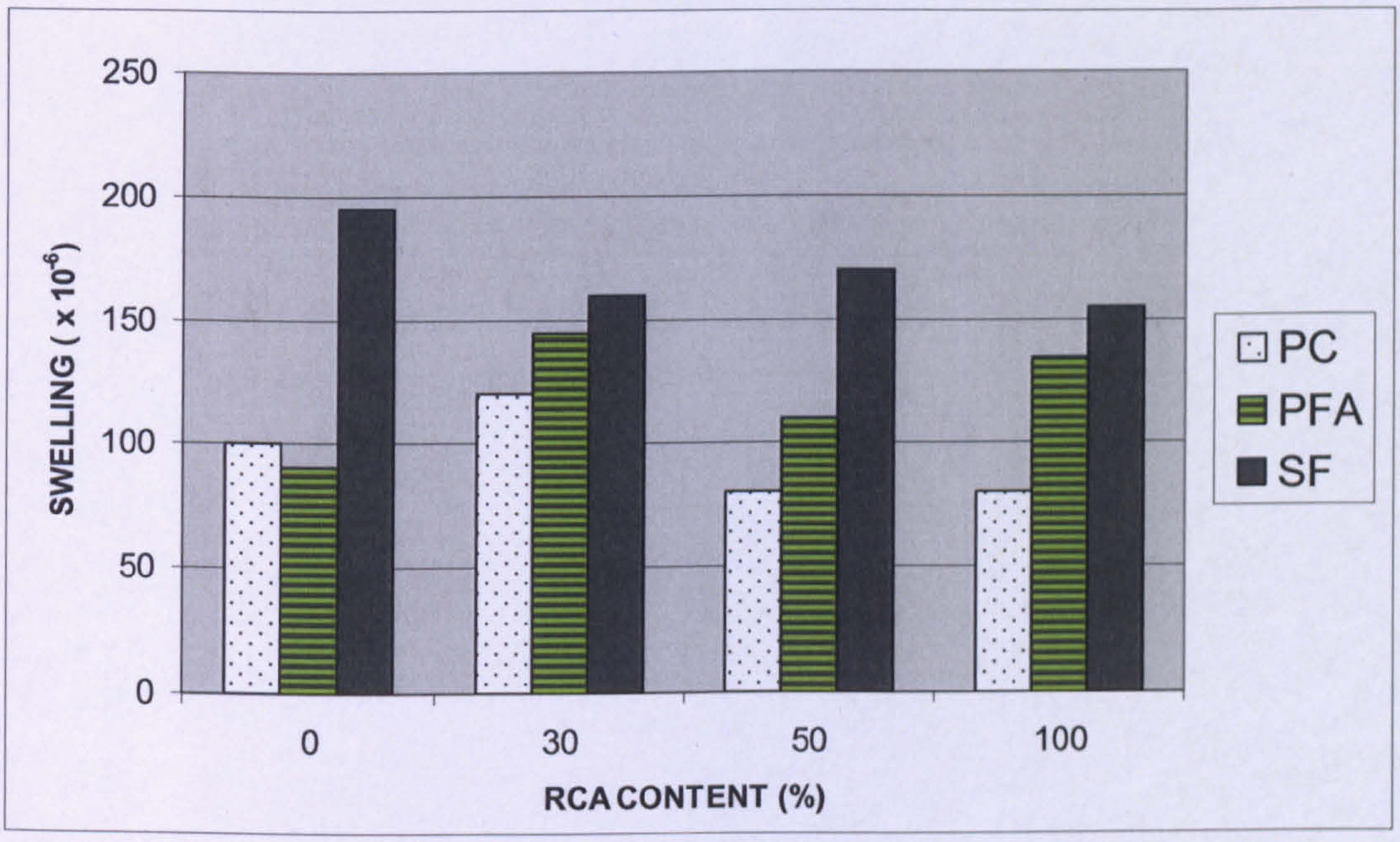


Figure 6.51 Effect of RCA content on the swelling of PC RC 30 mix and its corresponding PFA and SF mixes.

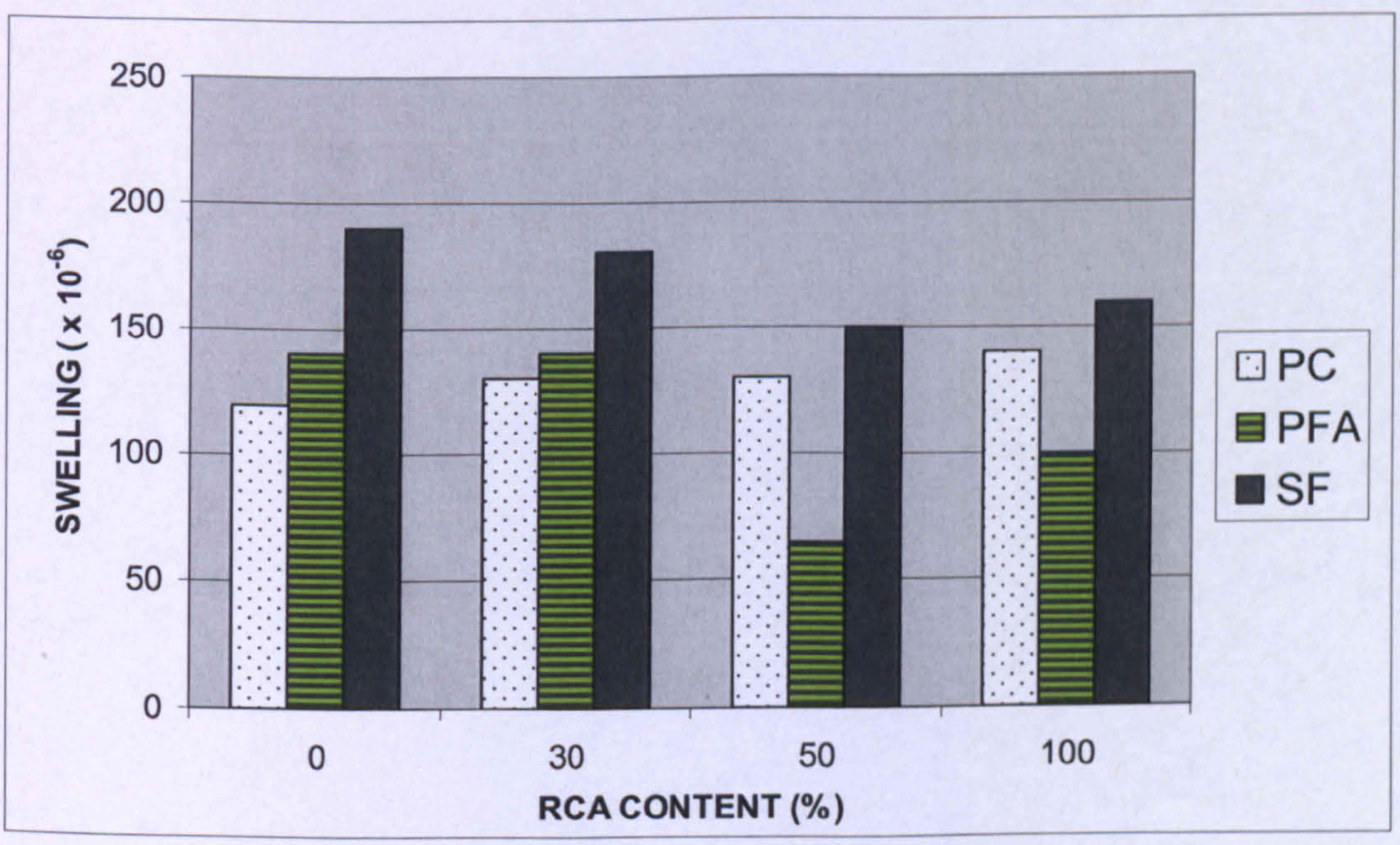


Figure 6.52 Effect of RCA content on the swelling of PC RC35 mix and its corresponding PFA and SF mixes.

that the RCA particles were less saturated in PFA concrete when compared to the PC concrete resulting in an increase in the swelling deformation.

PC/SF

RC 30 – When comparing the swelling values of the SF mixes with their corresponding PC mixes; it was found that these were higher by 95, 33, 113 and 94% for the 0, 30, 50 and 100% RCA contents respectively. When comparing the swelling values of the SF mixes with their corresponding PFA mixes, we found that these were higher by 117, 10, 55 and 15% for the 0, 30, 50 and 100% RCA contents respectively.

RC 35 – When comparing the swelling values of the SF mixes with their corresponding PC mixes; it was found that these were higher by 58, 38, 15 and 14% for the 0, 30, 50 and 100% RCA contents respectively. When comparing the swelling values of the SF mixes with their corresponding PFA mixes, we found that these were higher by 26, 29, 131 and 60% for the 0, 30, 50 and 100% RCA contents respectively.

Overall, the results showed that the use of SF resulted in an increase in the swelling deformation of NA and RCA concrete. This may well indicate that the RCA particles were less saturated in SF concrete when compared to the PC and PFA concretes, resulting in the increase in the swelling deformation in the SF mixes. Other possible reasons behind the high swelling of the SF mixes are the slightly higher content of coarse aggregates in the SF mixes compared to the PC mixes and the high permeability of SF mixes compared to the PFA mixes.

6.7 PRACTICAL IMPLICATIONS

The study has shown that RCA concrete can be designed to achieve the same strength as NA concrete by simply adjusting the water cement ratio of the mix. The use of RCA did not have any effect on the strength development of PC and SF concrete. On the other hand, an acceleration of the rate of strength development of PFA concrete was observed when RCA was used. This can reduce the minimum time before striking formwork of PFA concrete.

The flexural strength of concrete was unaffected by the use of RCA and binary cements providing RCA concrete was designed to have an equal strength as the NA concrete.

The gradual increase of the RCA content resulted in the decrease of the modulus of elasticity values of the concrete; the low modulus of elasticity values of RCA concretes should be taken into consideration in structural design to avoid excessive deformations and provide a satisfactory serviceability. The use of binary cements did not have any significant effect on the modulus of elasticity of the NA and RCA concretes.

The use of RCA increased the drying shrinkage values of concrete, the drying shrinkage of RCA concrete can be reduced by using a shrinkage reducing agent [95]. PFA and SF were also found to decrease the drying shrinkage deformations of concrete.

Whilst RCA had no major effect on the swelling deformation of PC and SF concretes, it slightly increased the swelling deformation of PFA concrete. PFA and SF were found to increase the swelling deformations of concrete.

The degree of saturation of the RCA used in concrete appears to be one of the major influences on the swelling and drying shrinkage of concrete. The pre-wetting of the RCA leads to the pre-swelling of the aggregates, which reduces the swelling of concrete when immersed in water and increases the drying shrinkage of concrete when exposed to drying conditions. The use of dry RCA has the opposite effect on the long term deformations of the concrete.

Any excessive deformations resulting from the use of RCA or binary cements should be taken into consideration to avoid the occurrence of cracking in concrete which can increase the rate of corrosion of the steel reinforcement and even lead to the premature failure of the structure.

6.8 CONCLUDING REMARKS

- All the NA and RCA designated mixes reached the specified strength showing the validity of the method used to take account of the effects of RCA on the compressive strength, which simply entails adjusting the water/cement ratio of the mix.

- The use of RCA did not have any effect on the rate of strength development of the PC designated mixes. For the PFA mixes, at the early ages (up to 14 days), the rate of strength development increased as the RCA content increased. However, at later ages (beyond 90 days), the rate of strength development decreased with the increase of the RCA content. For the SF mixes, no clear effect from the use of RCA on the rate of strength development was established.

- The PC mixes had a higher rate of strength development when compared to their corresponding PFA mixes at early ages. However the opposite was observed at later ages. The PC mixes in general had a similar or slightly higher rate of strength development when compared to their corresponding SF mixes. The slow rate of strength development of the PFA and SF mixes is most probably due to the low PC content of these mixes.

- The use of up to 30% RCA content in PC mixes did not affect the cube and cylinder strength relationship of PC mixes. However beyond this limit the cylinder – cube ratio gradually increased with an increase in the RCA content. For the PFA and SF mixes, the cube and cylinder strength relationship was not affected by the use of RCA as much as the PC mixes. The average cylinder/cube ratios of the PC mixes, PFA and SF regardless of the RCA content and age were 81, 80 and 81% respectively, which is in agreement with the cylinder/cube ratio used for designated mixes in EN 206 1 and BS 8500 (≈ 80%).

- The use of RCA and binary cements was not found to affect the compressive and flexural strengths relationship of the designated mixes. The relationship was only affected by the strength of the concrete; the flexural compressive strength ratio was found to decrease as the compressive strength of the concrete increased.

- The increase of RCA content in the PC, PFA and SF mixes resulted in the reduction of their modulus of elasticity. The 30 and 50% RCA contents reduced the modulus of elasticity of all mixes regardless of the type of cement used by up to 14 and 22% respectively. The 100% RCA content resulted in the reduction of the modulus of elasticity by up to 40% for both the PC and PFA mixes and 29% for the SF mixes.

- The modulus of elasticity of low w/c ratio PFA mixes were higher when compared to their corresponding PC mixes. On the other hand, for high w/c ratio mixes, the modulus of elasticity of the PFA and their corresponding PC mixes were within the same range. The modulus of elasticity of the majority of PC mixes and their corresponding SF were within the same range; SF does not appear to have any major effect on the modulus of elasticity of the mixes.

- Using up to 30% RCA has no effect on the shrinkage of PC concrete, beyond this limit the gradual increase of RCA resulted in a gradual increase in the shrinkage values of concrete. With the PFA and SF mixes, the gradual increase of RCA resulted in a gradual increase in the shrinkage values of concrete.

- The use of PFA and SF reduced the shrinkage values of the majority of the mixes regardless of the RCA content when compared to the PC mixes.

- While there was no apparent effect on the swelling of the PC mixes from the use of RCA, the swelling deformation values of the RCA PFA mixes were higher than their corresponding NA mixes. On the other hand, the use of RCA resulted in a slight decrease of swelling deformation in the SF mixes.

- The swelling deformation of PFA mixes was higher when compared to their corresponding PC mixes, while the swelling deformation of SF mixes was higher than both their corresponding PC and PFA mixes.

CHAPTER 7

DURABILITY PROPERTIES OF RCA CONCRETE

7.1 INTRODUCTION

In addition to withstanding the forces and loads it is subject to, concrete has to resist the corrosive physical and chemical attacks that can emanate from its environment. For this purpose many limitations have been introduced to improve the durability of concrete, these are based on long term experiences rather than a designed durability resistance. We therefore find that the durability of concrete is mainly controlled by specifying certain requirements for concrete composition, properties and composition of concrete constituents, casting and compaction procedures, curing and sometimes compressive strength. This approach may yield unsatisfactory results when new materials are used in concrete, hence it is crucial to assess the effect of new materials such as RCA on the durability of concrete.

Contrary to the case of the engineering properties of RCA concrete, very few studies have looked at the effect of RCA on the durability properties of concrete. Additions, such as Fly ash and silica fume, have been used extensively by the concrete industry to improve the quality of concrete. Such additions therefore have the potential to improve certain durability properties of RCA concrete.

Against this background, a study of the durability properties of equal strength NA and RCA concretes made with binary cements was undertaken. For this, BS 8500 designated mixes from the GEN and RC series were used.

7.2 EXPERIMENTAL PROGRAMME

This part of the study will examine the durability properties of equal strength Portland cement and binary cement concretes made with various contents of RCA (0, 30, 50, and 100%). The durability properties examined include the initial surface absorption and the carbonation, chloride and sulphate resistance of concrete.

7.3 INITIAL SURFACE ABSORPTION

150 mm cubes were used to determine the initial surface absorption (ISA) in accordance with BS 1881 – 208 at 28 days.

7.3.1 Effect of RCA

7.3.1.1 PC mixes

Table 7.1 shows the ISA – 10 results of the PC mixes. From the results obtained, it was found that there is a relationship between the ISA results and the cube compressive strength of the PC mixes. To assess the influence of RCA on the ISA of the mixes, the ISA results for the NA and RCA mixes were plotted against their corresponding cube compressive strengths. Figure 7.1 shows the relationship between the ISA – 10 results of the PC mixes and their corresponding cube compressive strengths.

It was found that using up to 30% RCA had a minor influence on the ISA – 10 results, just slightly increasing the ISA – 10 results by 17% on average. This agrees with the findings of previous studies [22, 66]. However beyond this limit the ISA results increased considerably with the increase of the RCA content, the ISA – 10 results for the mixes with 50% and 100% RCA contents were on average double the results

Table 7.1 ISA – 10 results of PC designated mixes.

Designated mix	ISA -10 ($\times 10^{-2}$ ml/m^2/sec)			
	Coarse RCA content, %			
	0	30	50	100
GEN 1	73	122	118	131
GEN3	46	54	94	102
RC 30	38	43	77	95
RC 35	32	44	67	63
RC 40	26	30	66	61

Table 7.2 ISA – 10 results of PFA designated mixes.

Designated mix	ISA -10 ($\times 10^{-2}$ ml/m^2/sec)			
	Coarse RCA content, %			
	0	30	50	100
GEN 1	81	100	100	107
GEN3	52	46	72	73
RC 30	40	36	62	59
RC 35	39	25	57	60

Table 7.3 ISA – 10 results of SF designated mixes.

Designated mix	ISA -10 ($\times 10^{-2}$ ml/m^2/sec)			
	Coarse RCA content, %			
	0	30	50	100
RC 30	57	53	63	70
RC 35	55	57	61	67

obtained for the NA mixes. The increase in the initial surface absorption of concrete when using RCA is mainly due to the porous cement paste attached to the RCA particles which increases the flow of water into the concrete.

The use of RCA had a similar effect on ISA – 30 and 60 results of the NA and RCA PC mixes. The ISA – 30 and 60 results obtained are shown in Table B.1 and B.2 in appendix B.

7.3.1.2 PFA mixes

Table 7.2 shows the ISA – 10 results of the PFA mixes. As for the PC mixes, a relationship between the ISA results and the cube compressive strengths of the PFA mixes was found. To assess the influence of RCA on the ISA of the mixes, the ISA results of the NA and RCA mixes were plotted against their corresponding cube compressive strengths. Figure 7.2 shows the relationship between the ISA – 10 results of the PFA mixes and their corresponding cube compressive strengths.

The results obtained for the different designated mixes show that up to 30% RCA had a minor influence on the ISA – 10 results. However beyond this limit there was an increase in the ISA – 10 results with the increase of the RCA content due to the porous cement paste attached to the RCA particles, the ISA – 10 results for the mixes with 50 and 100% RCA contents were up to 50% higher compared to the NA mixes.

The use of RCA however had a different effect on the ISA – 30 and 60 results of the PFA mixes. For the ISA – 30 results, the use of up to 50% RCA had a minor effect on the ISA results whilst using 100% increased the ISA results by a mere 15% on

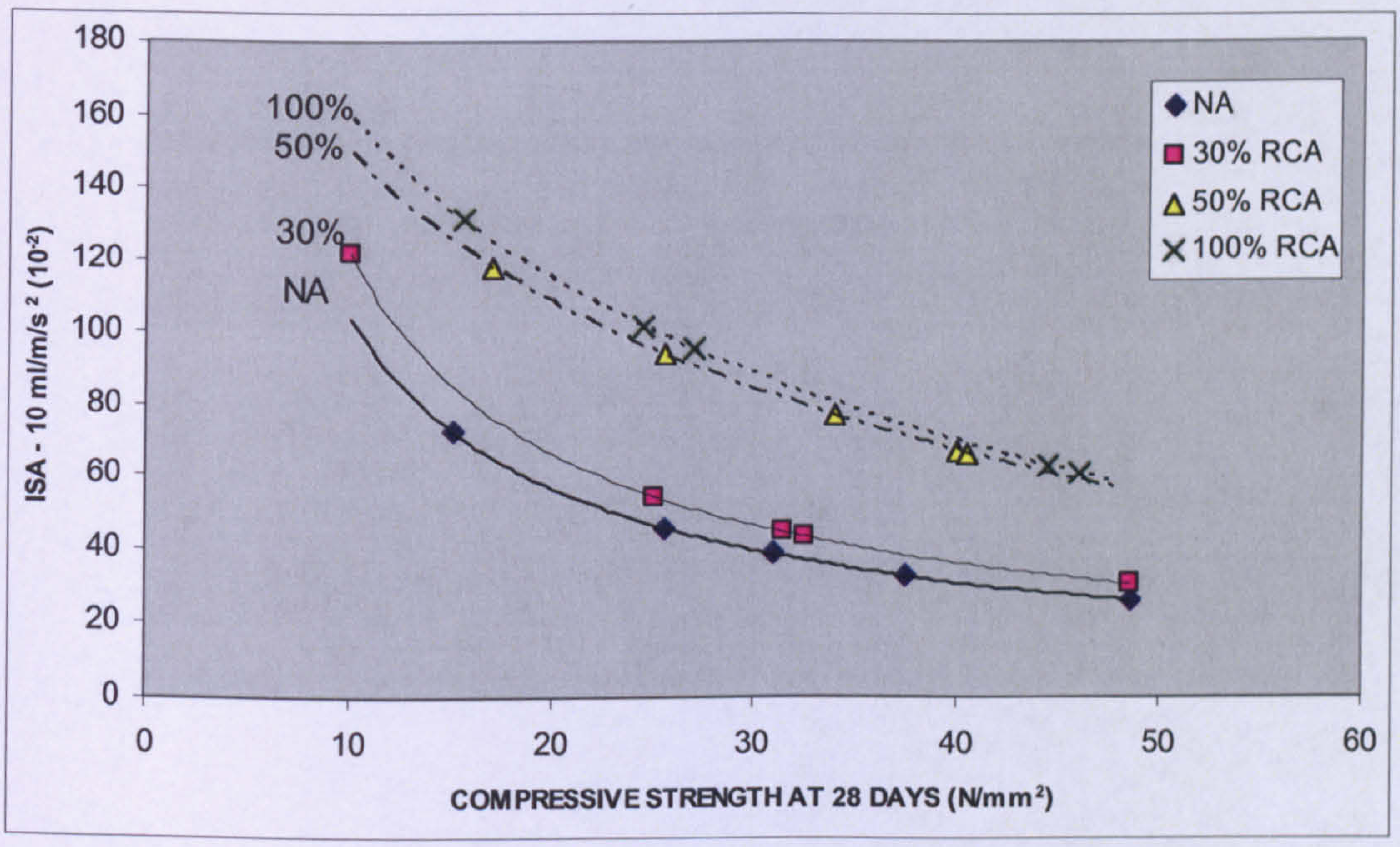


Figure 7.1 ISA – 10 vs. cube compressive strength of PC NA and RCA mixes.

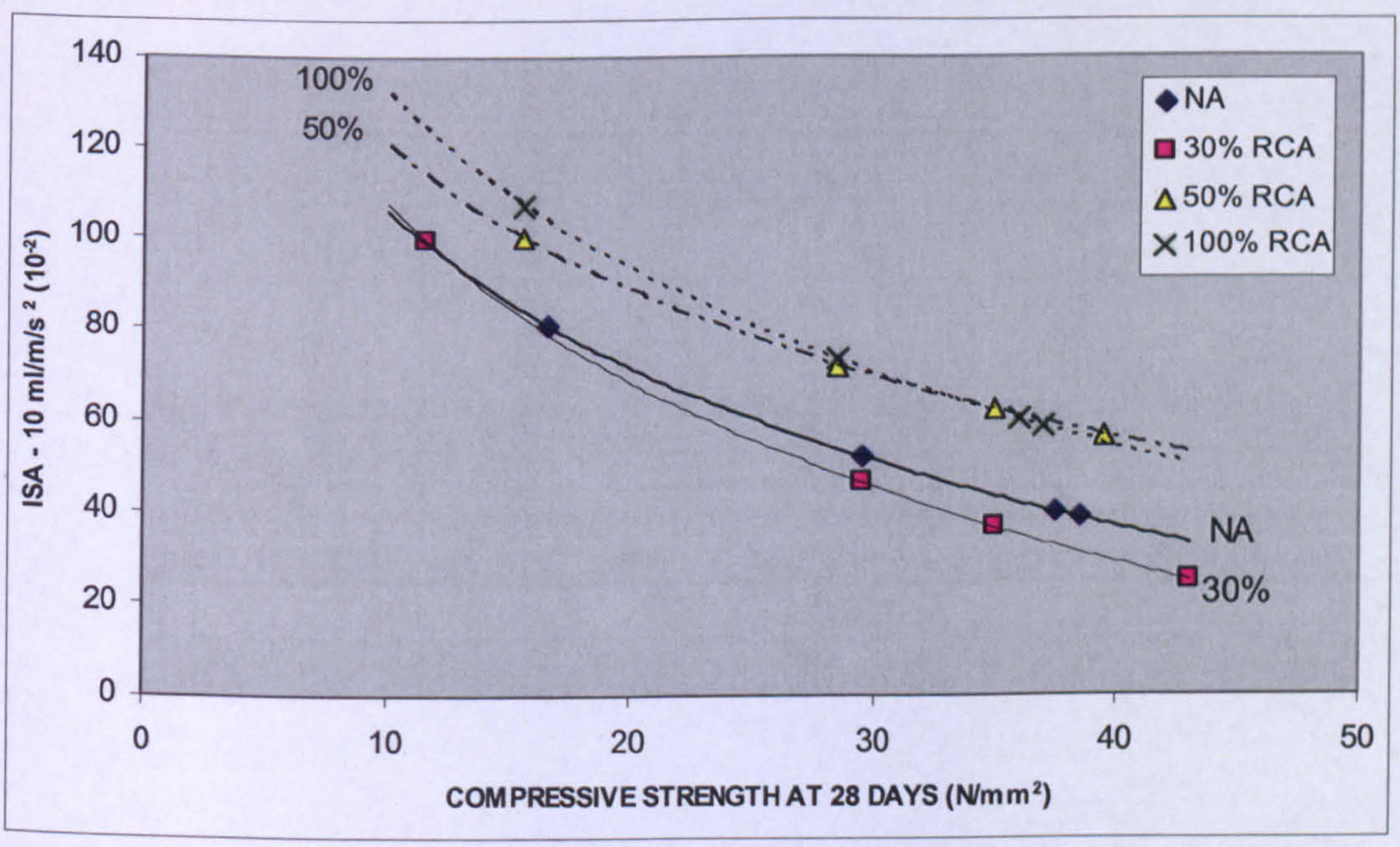


Figure 7.2 ISA – 10 vs. cube compressive strength of PFA NA and RCA mixes.

average. For the ISA – 60 results, the use of up to 30% RCA had no effect whilst using 50 and 100% RCA increased the ISA results by 20 % on average. The ISA – 30 and 60 results obtained are shown in Table B.3 and B.4 in appendix B.

7.3.1.3 SF mixes

Table 7.3 shows the ISA – 10 results of the SF mixes. A relationship between the ISA results and their corresponding cube compressive strengths could not be established for SF concrete as the range of the cube compressive strengths of the SF designated mixes in the study was small compared to the PC and PFA mixes.

However, the ISA – 10 results in Table 7.3 show that the use of up to 30% RCA had no effect on the ISA – 10 results of SF concrete. Using 50 and 100% RCA had a minor influence on the ISA – 10 results, increasing it only by 9 and 22% respectively.

The use of RCA had a similar effect on ISA – 30 and 60 results of the NA and RCA SF mixes. The ISA – 30 and 60 results obtained are shown in Table B.5 and B.6 in appendix B.

7.3.2 Binary cement concrete performance

Figures 7.3 to 7.6 compare the relationship between the ISA – 10 and the cube compressive strength results of the PC, PFA and SF mixes for the different RCA contents used in the study.

7.3.2.1 PC/PFA

For the NA mixes, the ISA – 10 results of the PFA mixes were higher than the PC mixes. For the mixes with 30% RCA content, the ISA results of the PC mixes were slightly higher than the PFA mixes. The results obtained for the NA and 30% PFA concrete were slightly higher than expected. In fact, for equal strength mixes, the replacement of part of the cement with PFA reduces the permeability of the concrete. This increase may have been caused by the slow strength development of the PFA concrete. However, the PFA mixes are expected to become less permeable than their corresponding PC mixes with time. For the mixes with 50 and 100% RCA content, the use of PFA resulted in a reduction of the ISA by up to 20% when compared to the PC mixes.

The reduction in the ISA results of the PFA RCA concretes is due to the reduction in water demand in the PFA mixes, the finer pore structure of the cement paste resulting from the pozzolanic action and the physical contribution of PFA. The use of PFA also improves the permeability of the interfacial transition zone between the RCA and the new cement paste thus reducing the effect of RCA on the initial surface absorption of the concrete. This is confirmed by the fact that the ISA results of the PC mixes were more affected, when high quantities of RCA were used, compared to the PFA mixes.

The ISA 30 and 60 results showed the same trend. However, the influence of PFA in reducing these ISA results for the 30, 50 and 100% RCA concretes was more important when compared to the ISA 10 results.

7.3.2.2 PC/SF

For the NA mixes, the ISA – 10 results of the SF mixes were, on average, 80% higher than their corresponding PC mixes. For the 30% RCA mix, the ISA results of the SF

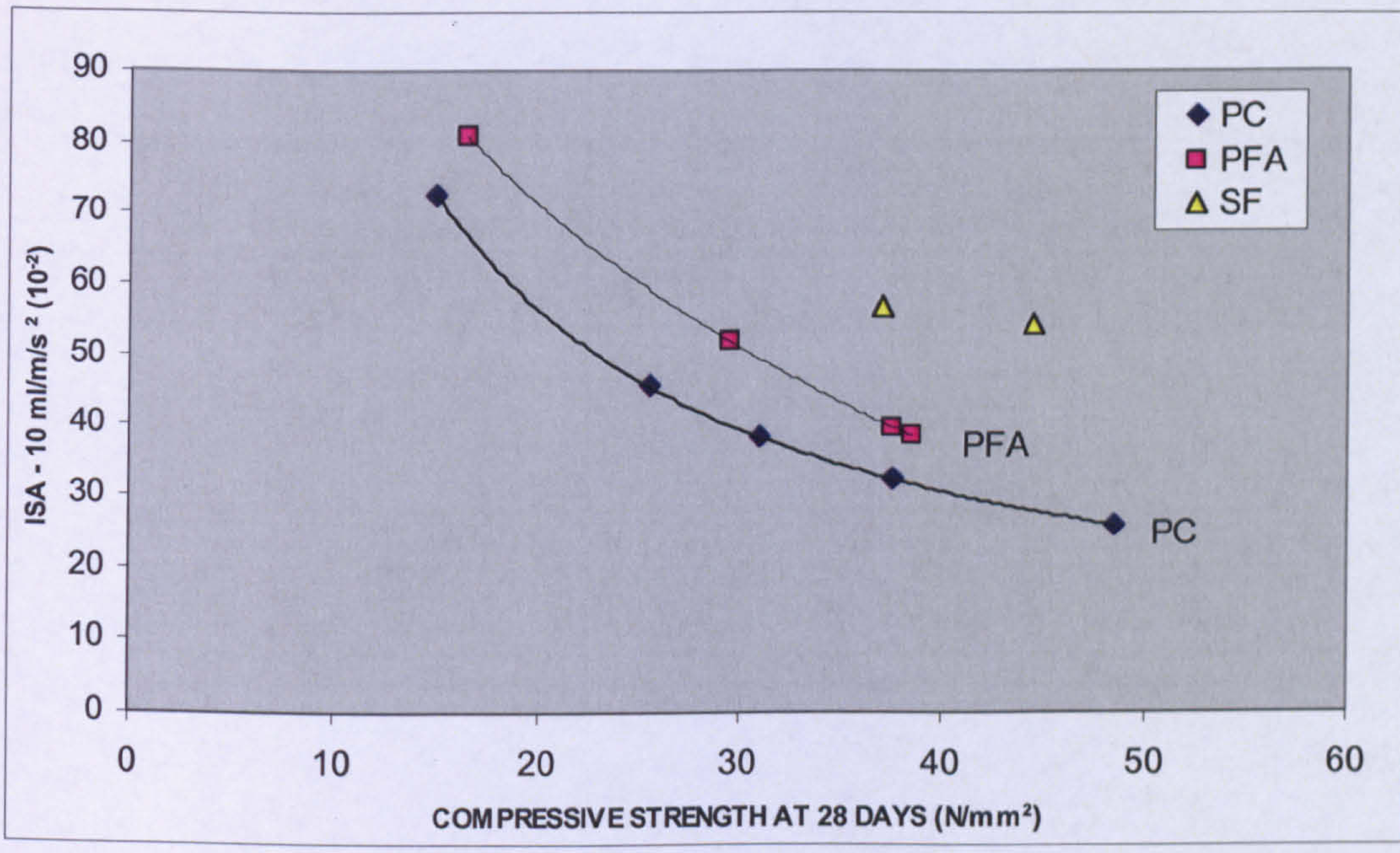


Figure 7.3 ISA – 10 vs. cube compressive strength of PC, PFA and SF NA mixes.

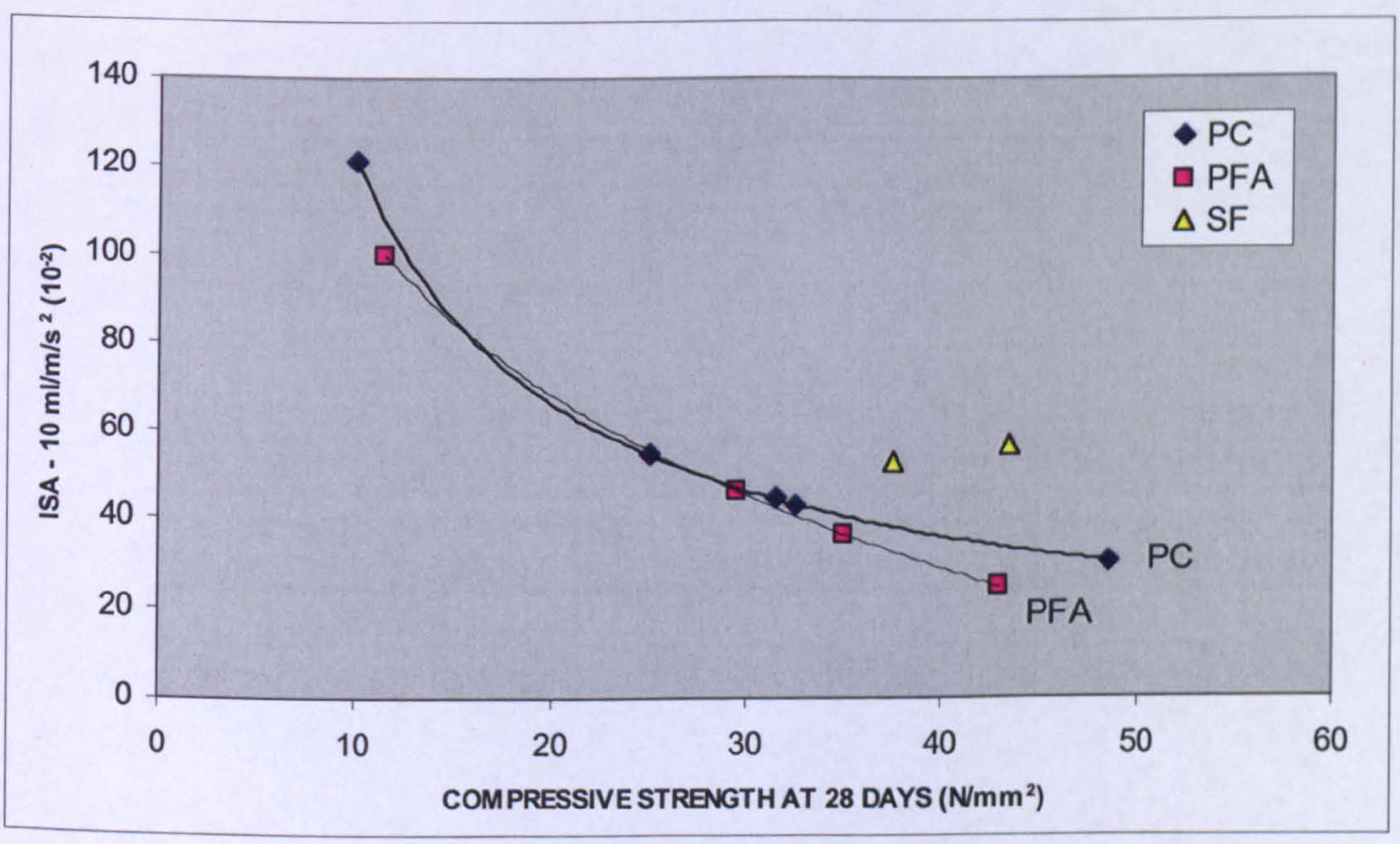


Figure 7.4 ISA – 10 vs. cube compressive strength of PC, PFA and SF mixes with 30% RCA content.

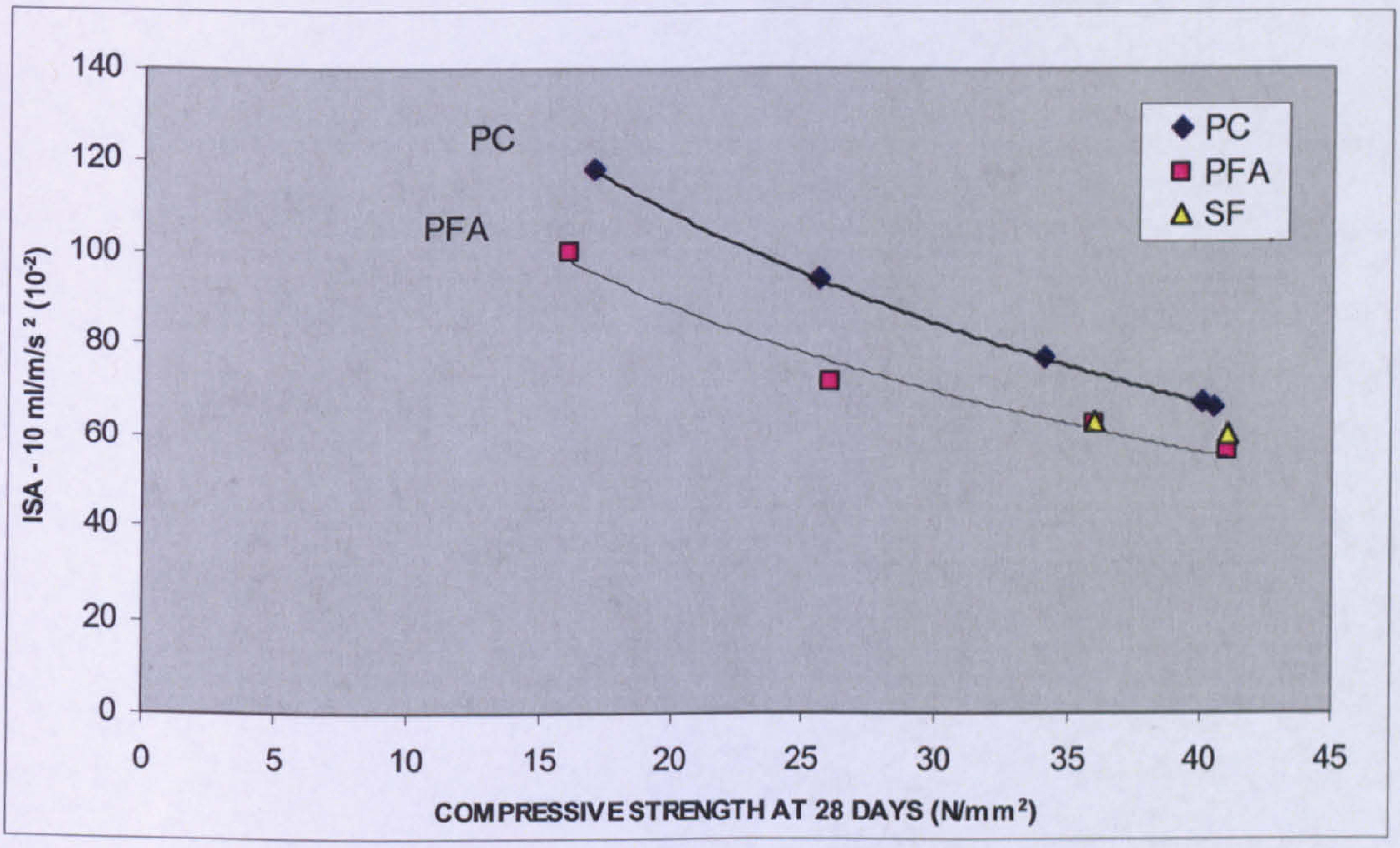


Figure 7.5 ISA – 10 vs. cube compressive strength of PC, PFA and SF mixes with 50% RCA content.

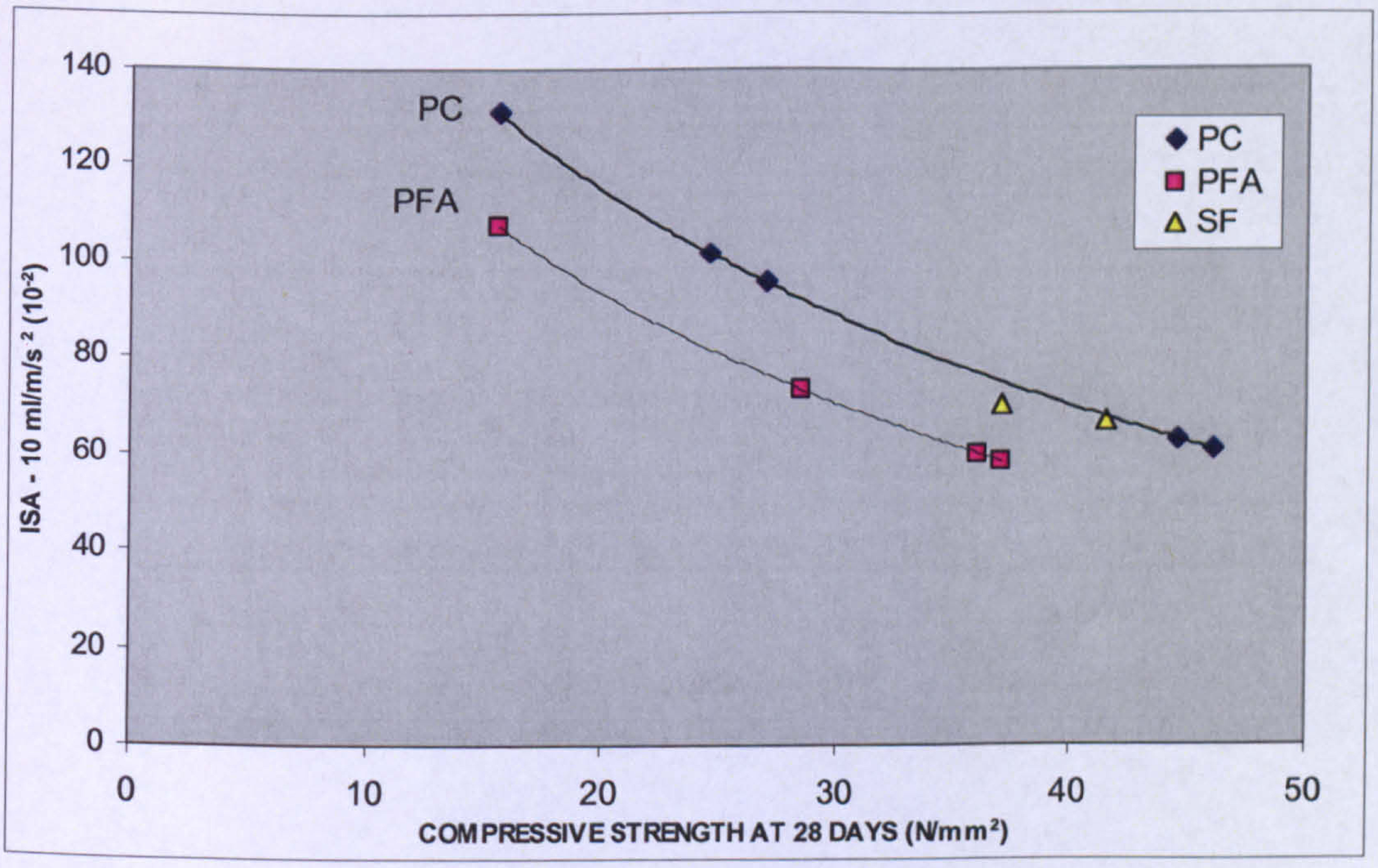


Figure 7.6 ISA – 10 vs. cube compressive strength of PC, PFA and SF mixes with 100% RCA content.

mixes were, on average, 40% higher than their corresponding PC mixes. The high ISA results of the SF mixes are due to their high w/c ratio. However for the 50 and 100% RCA contents, the ISA results of the SF mixes were the same as or slightly lower than the PC mixes. This is due to the increase of the cementitious material in the mixes resulting in a finer pore structure of the cement paste. In addition, the SF particles improved the permeability of the interfacial transition zone between the RCA and new cement paste, through the pozzolanic reaction and packing of the SF particles against the surface of the RCA, thus reducing the effect of RCA on the rate of initial surface absorption of the concrete. This is confirmed by the fact that the ISA results of the PC mixes were more affected, when high quantities of RCA were used, compared to the SF mixes. The ISA 30 and 60 results showed the same trend as the ISA 10 results.

7.4 CARBONATION RESISTANCE

During this study, 100mm cubes were exposed to a 3.5% CO_2 enriched environment for a period of 20 weeks. Each week of exposure simulated one year of exposure to normal atmospheric conditions. The samples were regularly tested to measure the depth of carbonation penetration.

7.4.1 Effect of RCA

7.4.1.1 PC mixes

The carbonation depths measured for the GEN 3, RC 30, RC 35 and RC 40 are shown in Figures 7.7, 7.8, 7.9 and 7.10 respectively.

GEN 3 – The NA and RCA mixes have an approximately equal resistance to carbonation. The variation between the results did not exceed 3 mm at all ages. The NA and 100% RCA mixes had exactly the same carbonation depth of 24 mm after 20 weeks of exposure, whilst the 30% and 50% RCA mixes had a carbonation depth of 25 and 22 mm respectively.

RC 30 – The NA and RCA mixes have an approximately equal resistance to carbonation. The maximum variation between the results was 4 mm at 2 weeks. The variation was 3 mm at all the other exposure durations. The 50% and 100% RCA mixes had the same carbonation depth of 16 mm after 20 weeks of exposure, whilst the NA and 30% RCA mixes had a carbonation depth of 14 and 17mm respectively.

RC 35 – The NA and RCA concrete mixes had an approximately equal resistance to carbonation. The NA, 50 and 100% RCA mixes exhibited a carbonation depth of 11, 12 and 13 mm respectively at 20 weeks. On the other hand, the 30% RCA content exhibited a carbonation depth of 21 mm which is significantly higher than the other mixes. This huge discrepancy can be attributed to the low compressive strength of the 30% RCA mix.

RC 40 – All the concretes had an approximately similar carbonation resistance regardless of the RCA content. The variation in the carbonation depths at all ages did not exceed 3mm. The carbonation depth measured for the NA, 30, 50 and 100% RCA concretes at 20 weeks was 6, 5, 8 and 7 mm respectively.

Overall, it was found that the use of RCA does not affect the carbonation of PC concrete. Figure 7.11 shows the carbonation depth results of the PC mixes at 20

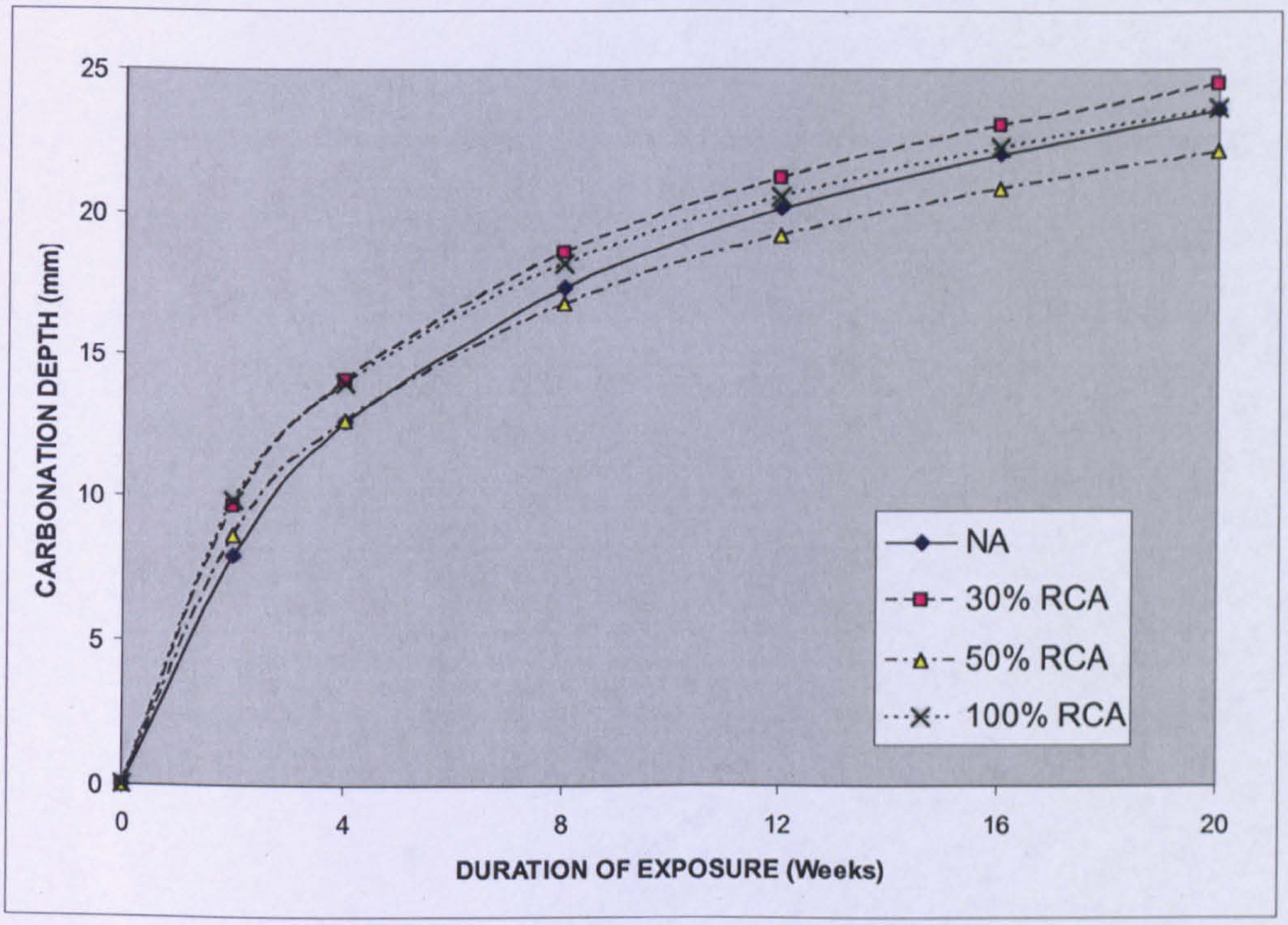


Figure 7.7 Effect RCA on the carbonation depth of GEN 3 PC concrete with time.

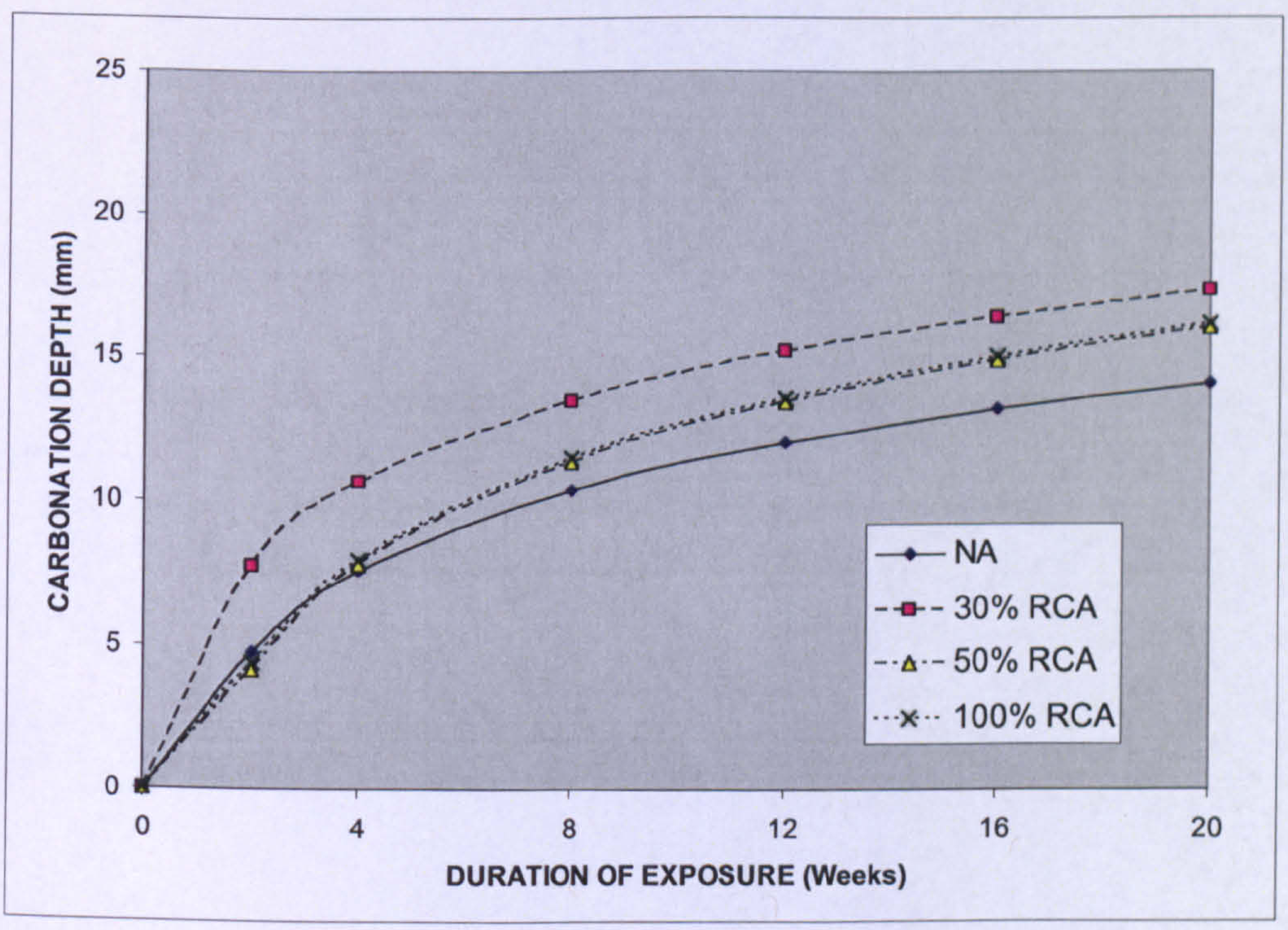


Figure 7.8 Effect RCA on the carbonation depth of RC 30 PC concrete with time.

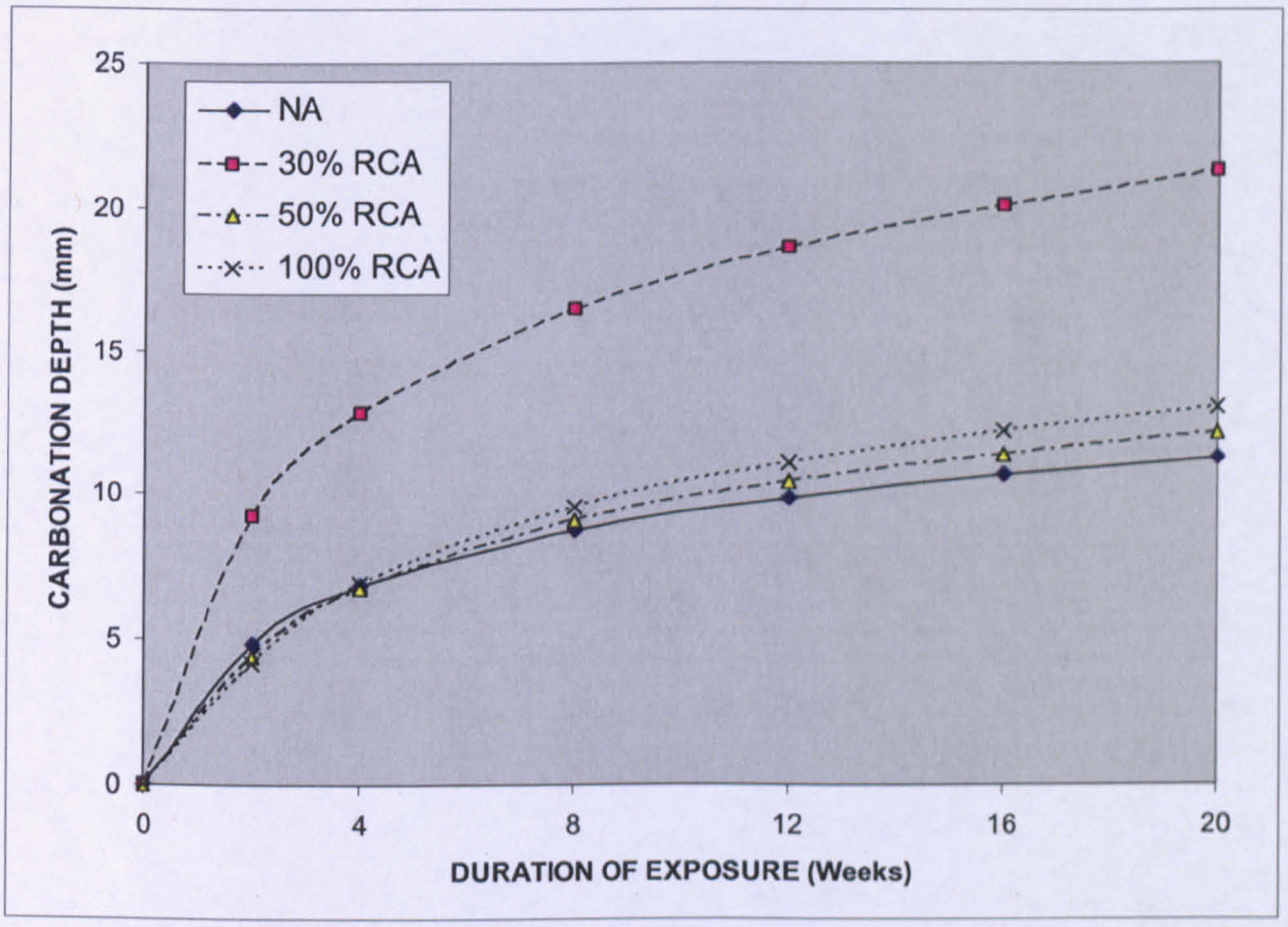


Figure 7.9 Effect RCA on the carbonation depth of RC 35 PC concrete with time.

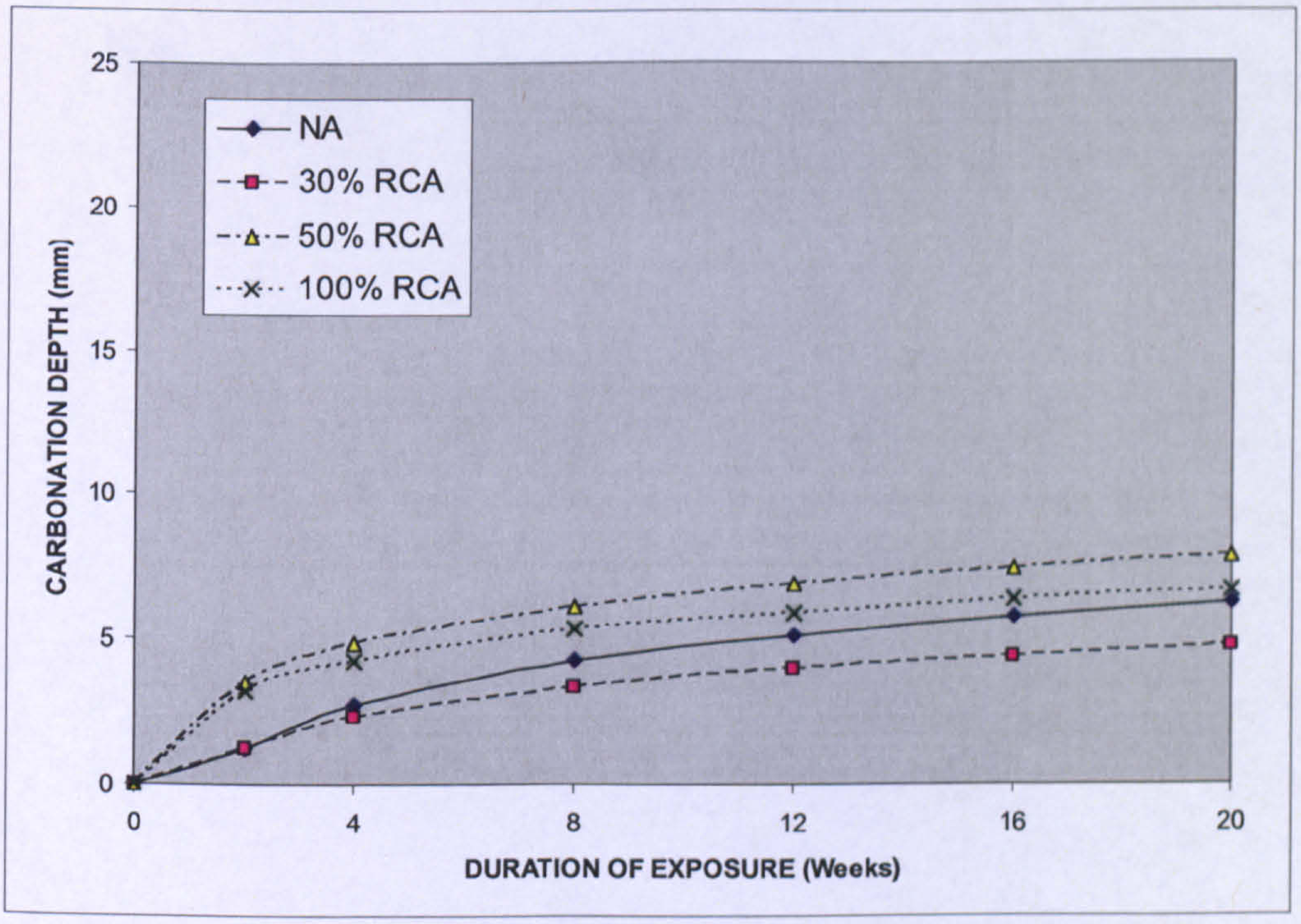


Figure 7.10 Effect RCA on the carbonation depth of RC 40 PC concrete with time.

weeks in relation to their 28 days cube compressive strengths. A strong correlation was found between the compressive strength of the concrete and its carbonation resistance regardless of its RCA content ($R^2 = 0.95$). The carbonation resistance of the NA and RCA concretes was found to increase with the increase in the strength of the concrete regardless of the amount of RCA used. Similar findings were reported in previous studies on the carbonation of equal strength NA and RCA PC mixes [22, 66].

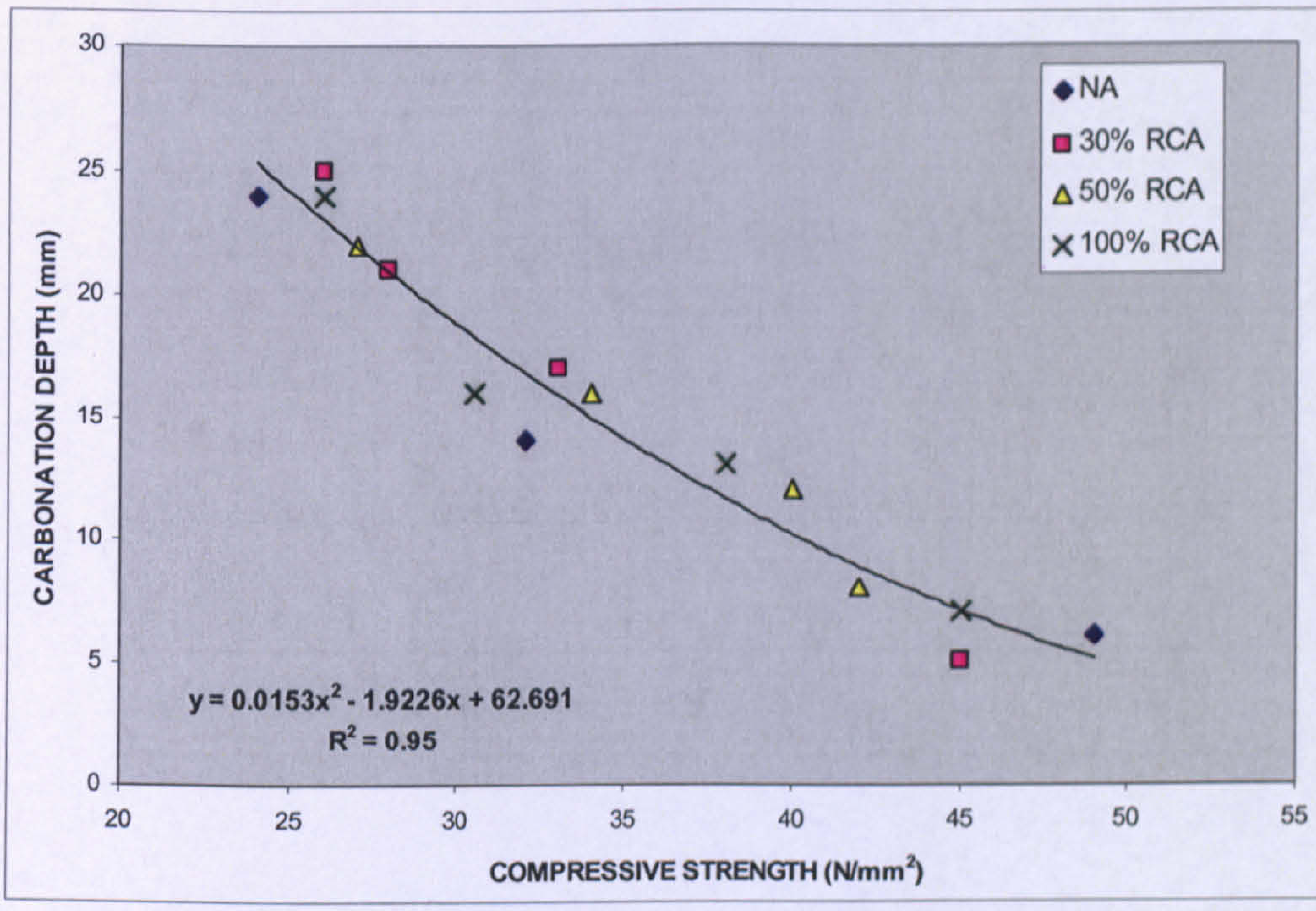


Figure 7.11 20 weeks carbonation depth vs. 28 day cube compressive strength of PC concrete with various RCA contents.

7.4.1.2 PFA mixes

The carbonation depths measured for the GEN 3, RC 30 and RC 35 are shown in Figures 7.12, 7.13 and 7.14 respectively.

GEN 3 – The NA concrete had the lowest carbonation resistance after 20 weeks of exposure as 26 mm of the sample was carbonated. The 50% and 100% RCA concrete had approximately the same carbonation depth with 25 and 24 mm respectively. The lowest carbonation depth, 21 mm, was measured in the 30% RCA mix.

RC 30 – At 20 weeks, the NA concrete had the lowest carbonation depth with 11 mm. 30 and 100% RCA mixes had a similar carbonation depth of 16 mm. The highest carbonation depth, 20 mm, was measured for the 50% RCA mix.

RC 35 – The NA concrete had the lowest carbonation depth with 11 mm at 20 weeks. On the other hand, the RCA concretes had similarly higher carbonation depths (16 17 mm).

Figure 7.15 shows the carbonation depth results of the PFA mixes at 20 weeks in relation to their 28 day cube compressive strengths. It was found that there exists a strong correlation between the compressive strength of the PFA concrete and its corresponding carbonation resistance regardless of its RCA content (R^2 0.90). The carbonation resistance of the PFA concrete was found to increase with the increase in the strength of concrete and was not affected by the amount of RCA used.

7.4.1.3 SF mixes

The carbonation depths measured for the RC 30 and RC 35 are shown in Figures 7.16 and 7.17 respectively.

RC 30 – The 0, 30 and 100% RCA concretes had similar 20 week carbonation depths (26 27 mm) while the 50% RCA concrete had a lower carbonation depth (22m).

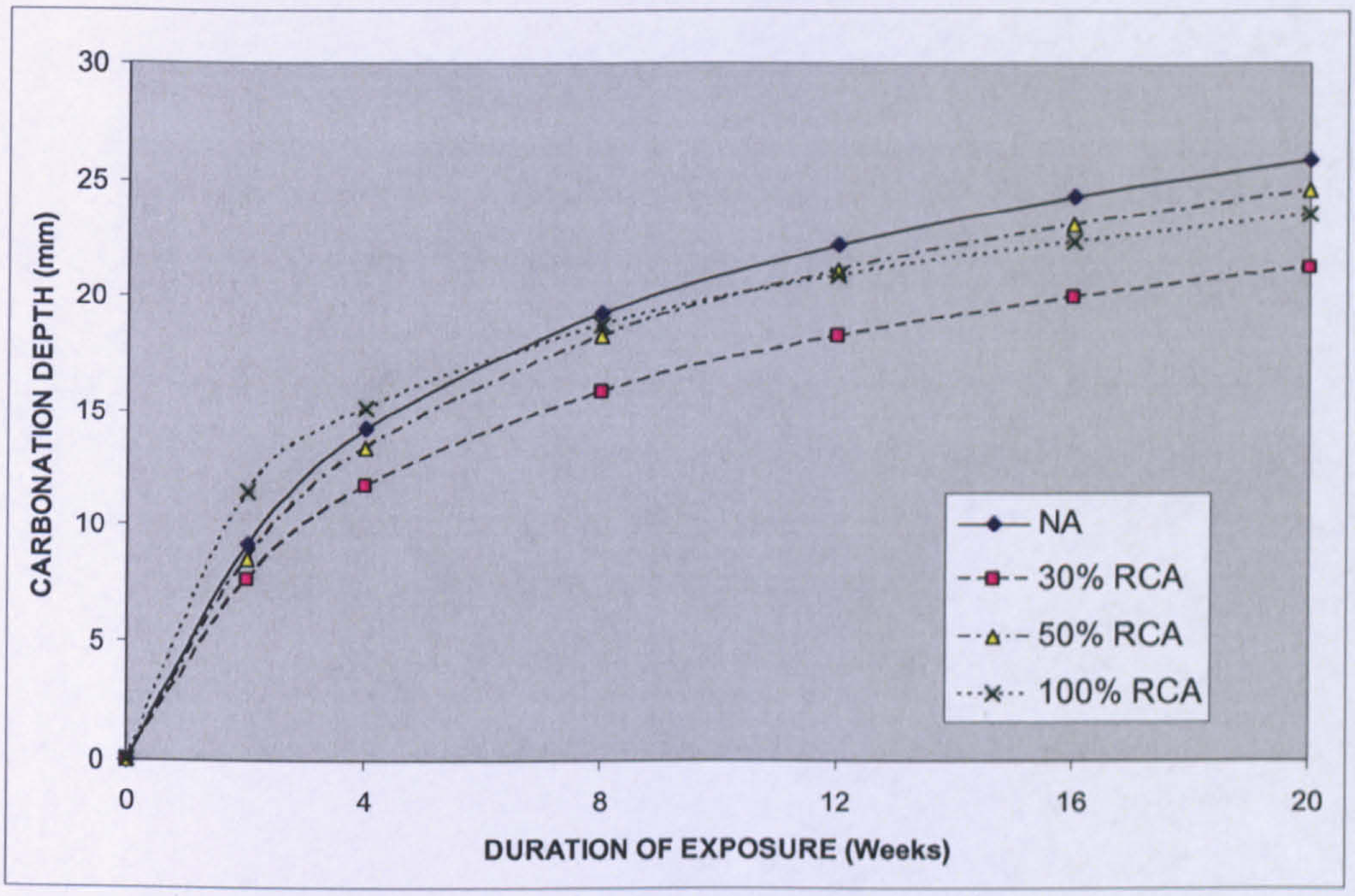


Figure 7.12 Effect RCA on the carbonation depth of GEN 3 PFA concrete.

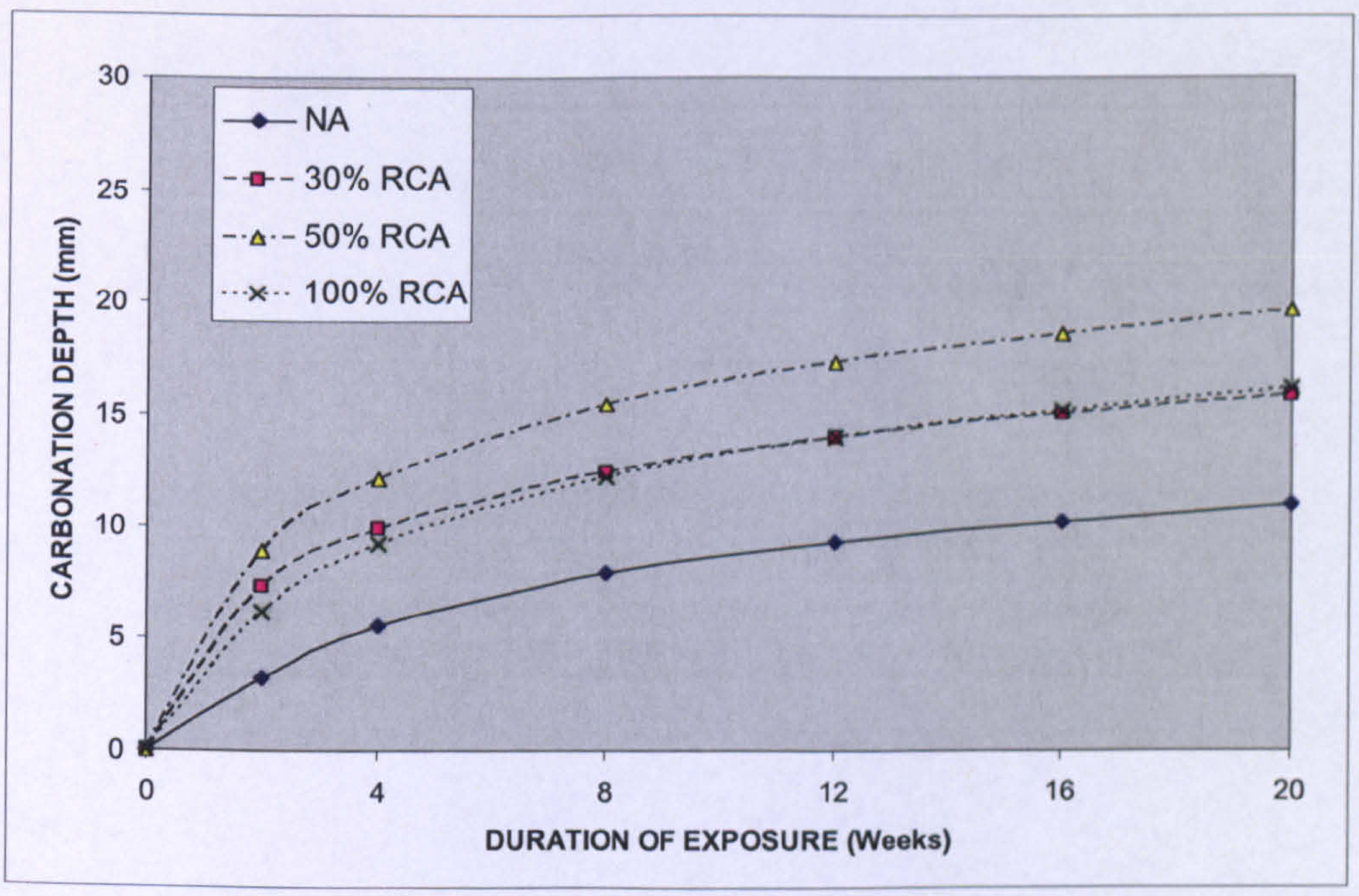


Figure 7.13 Effect RCA on the carbonation depth of RC 30 PFA concrete.

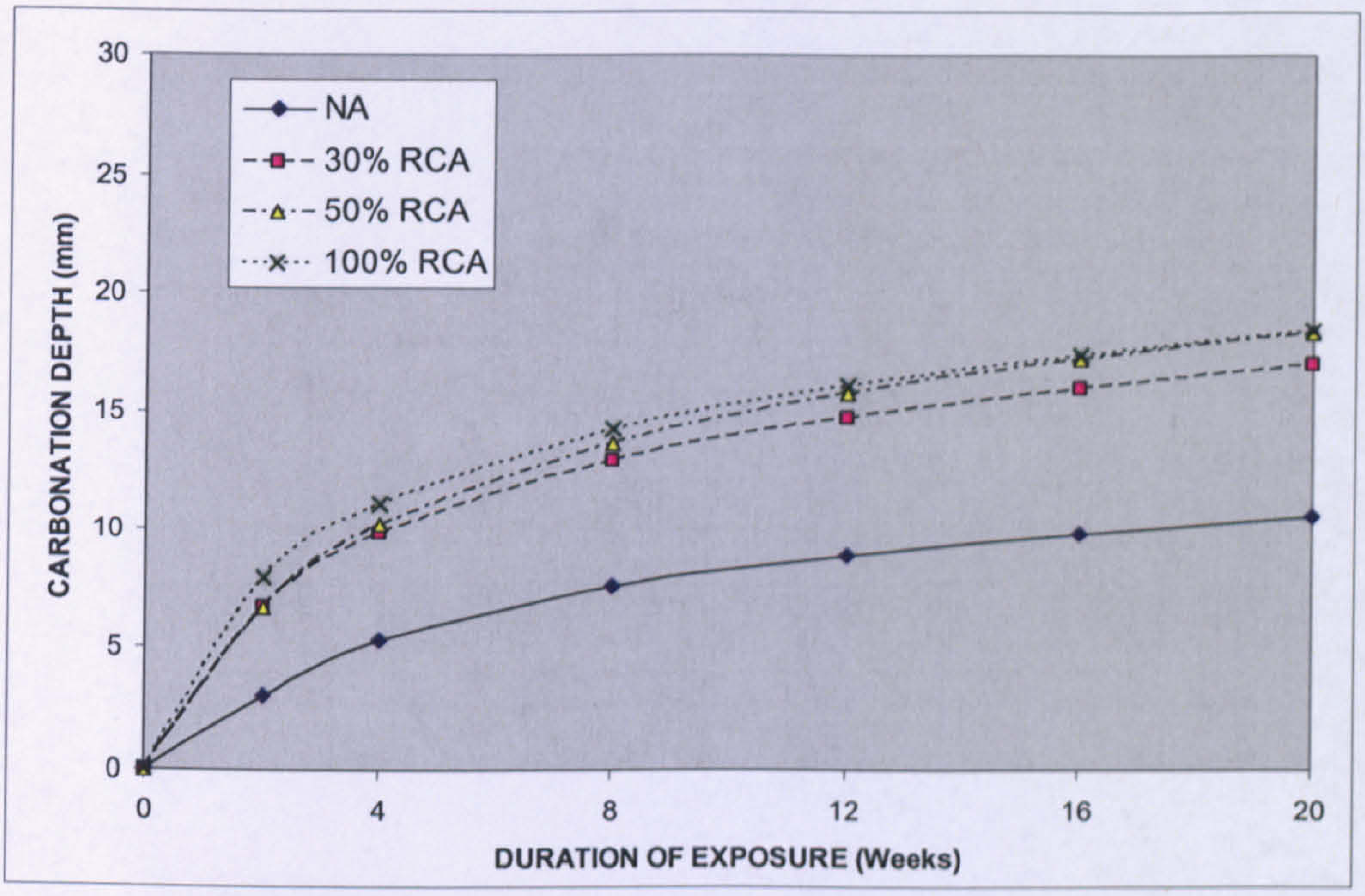


Figure 7.14 Effect RCA on the carbonation depth of RC 35 PFA concrete.

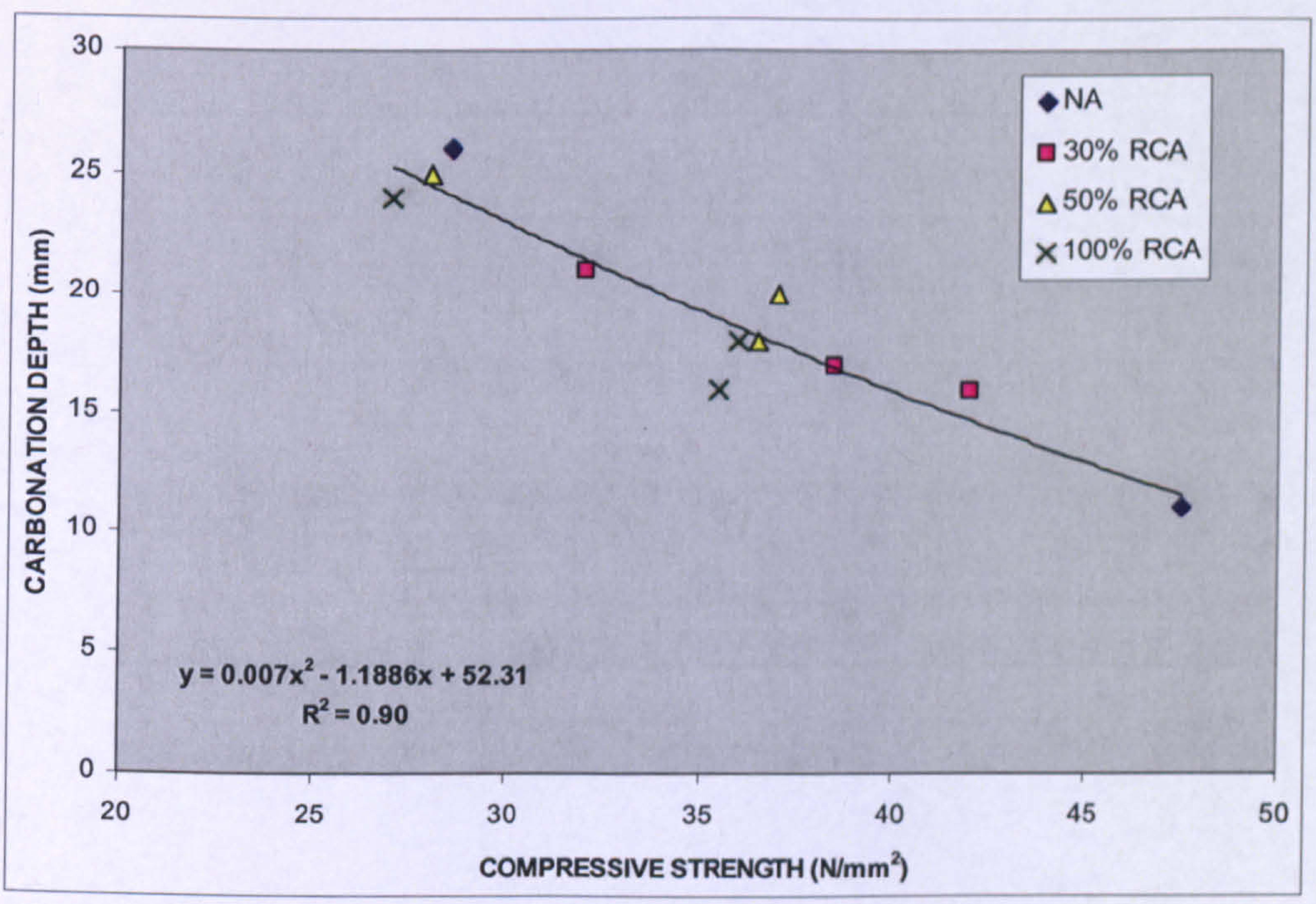


Figure 7.15 20 weeks carbonation depth vs. 28 day cube compressive strength of PFA concrete with various RCA contents.

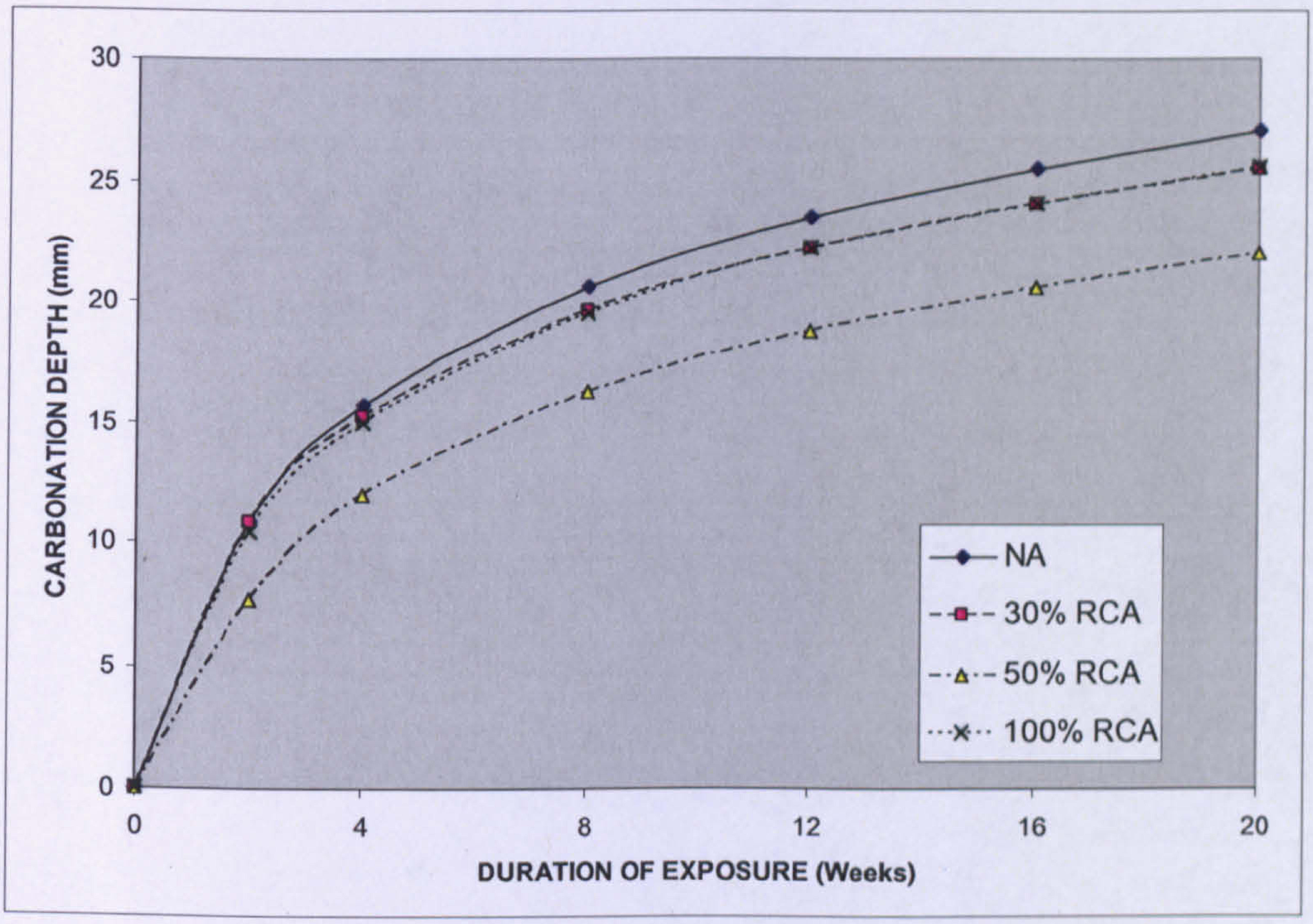


Figure 7.16 Effect RCA on the carbonation depth of RC 30 SF concrete.

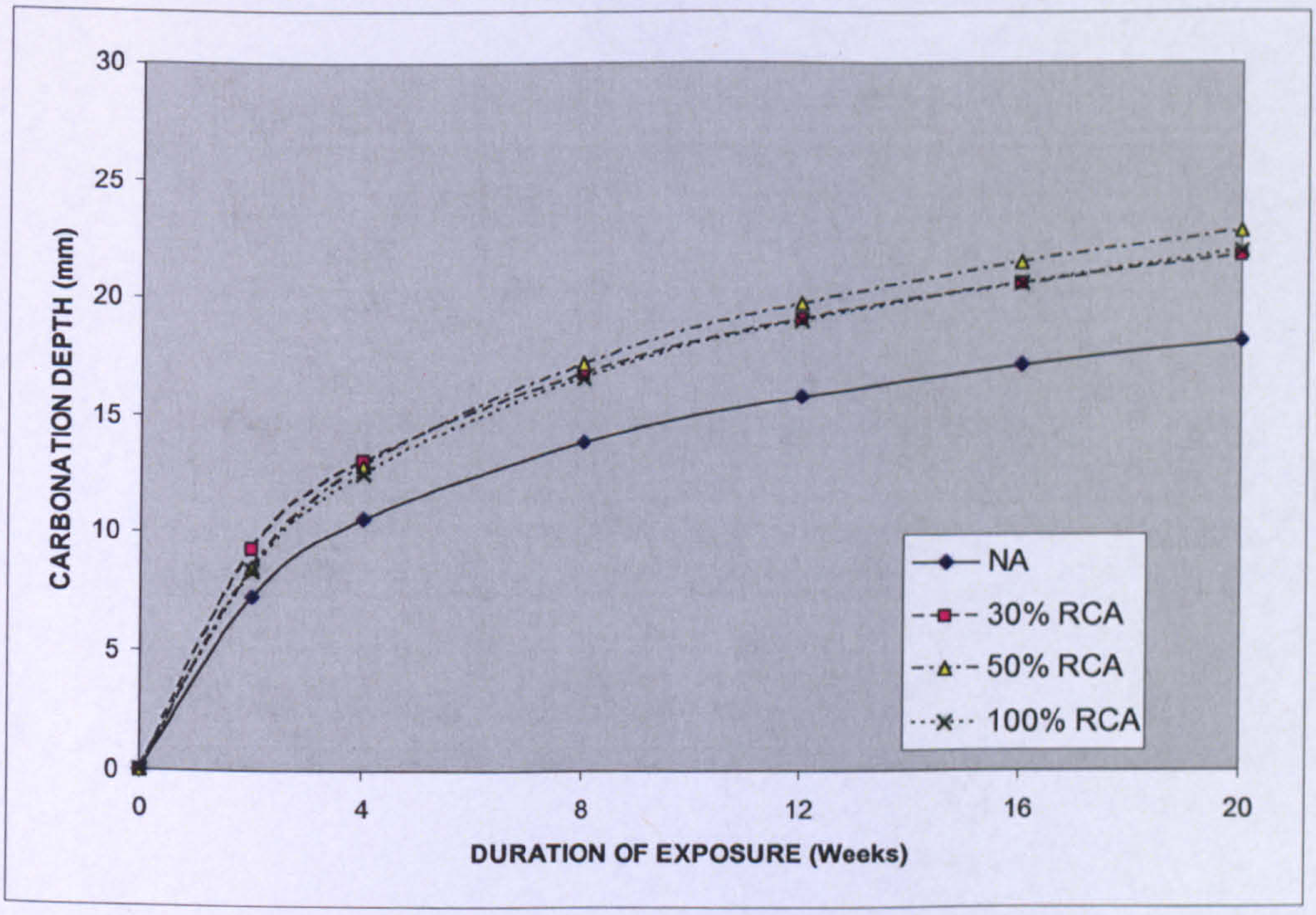


Figure 7.17 Effect RCA on the carbonation depth of RC 40 SF concrete.

RC 35 – The 30, 50 and 100% RCA concretes had similar carbonation depths after 20 weeks of exposure (22 – 23 mm). NA concrete had a lower carbonation depth of 18 mm.

Figure 7.18 shows the carbonation depth results of the SF mixes at 20 weeks in relation to their 28 day cube compressive strengths. It was found that there exists a strong correlation between the compressive strength of the SF concrete and its corresponding carbonation resistance regardless of its RCA content (R^2 = 0.80). It shows that similarly to PC and PFA concrete, the carbonation resistance of the SF concrete increases with the increase of the strength of concrete and is not affected by the amount of RCA used.

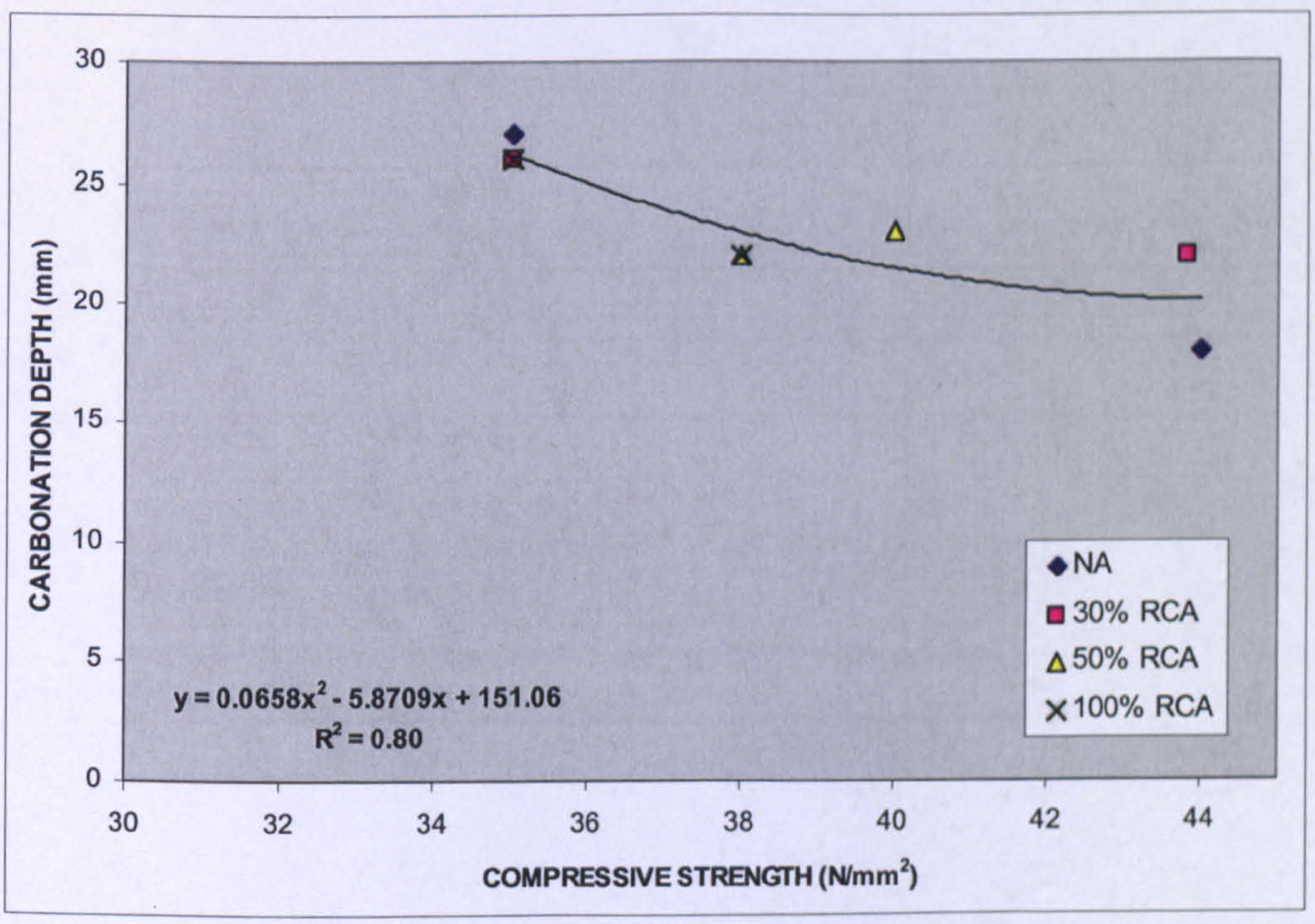


Figure 7.18 20 weeks carbonation depth vs. 28 day cube compressive strength of SF concrete with various RCA contents.

7.4.2 Binary cement concrete performance

7.4.2.1 PC/PFA

Figure 7.19 compares the relationship between the carbonation depths of the PC and PFA mixes after 20 weeks of exposure and their corresponding cube compressive strengths at 28 days. It can be seen from the results that at a specified strength, the corresponding carbonation depth in the PC mixes is lower when compared to the PFA mixes. The use of PFA results in an increase of the depth of carbonation of NA and RCA mixes. Similar findings were reported in a similar study [109]. The carbonation depth of PFA concrete, with a cube compressive strength ranging between 20 to 50 N/mm^2, was found to be up to 6 mm higher when compared to a corresponding PC concrete after 20 weeks of exposure. The calcium hydroxide formed during the hydration of cement is susceptible to reaction with CO_2 from the atmosphere. The ability of concrete to resist carbonation is related to the volume of calcium hydroxide available in concrete. The volume of calcium hydroxide available in concrete made with PFA is lower than in PC concrete, hence the lower carbonation resistance of the PFA concrete. However, this disadvantage can be offset by the low permeability of the PFA concrete as the lower the permeability, the greater the resistance to inward diffusion of carbonation into the concrete. Thus, the carbonation of the PFA concrete may proceed at a slower rate in reality. In fact, the carbonation test used in the study subjects the concrete to the equivalent of 20 years of carbonation in a period of 20 weeks and this testing method does not take in consideration the fact that PFA concrete over time can develop a cement paste with a denser structure than PC concrete which can play a big role in slowing down the carbonation of the concrete.

7.4.2.2 PC/SF

Figure 7.19 compares the relationships between the carbonation depths at 20 weeks of PC mixes and PFA mixes and their corresponding cube compressive strengths at 28 days with that of SF mixes. It was found that at a specified strength, the carbonation depths in the PC and PFA mixes are lower when compared to their corresponding SF mixes. The carbonation depth of SF concrete, with a cube compressive strength ranging between 30 to 50 N/mm^2, was found to be higher by up to 17 and 11 mm when compared to a corresponding PC and PFA concrete respectively after 20 weeks of exposure. This is attributed to the low volume of calcium hydroxide available in concrete made with SF compared to the PC and PFA concretes and the slightly higher permeability of the cement paste of the SF mixes due to their high w/c ratio.

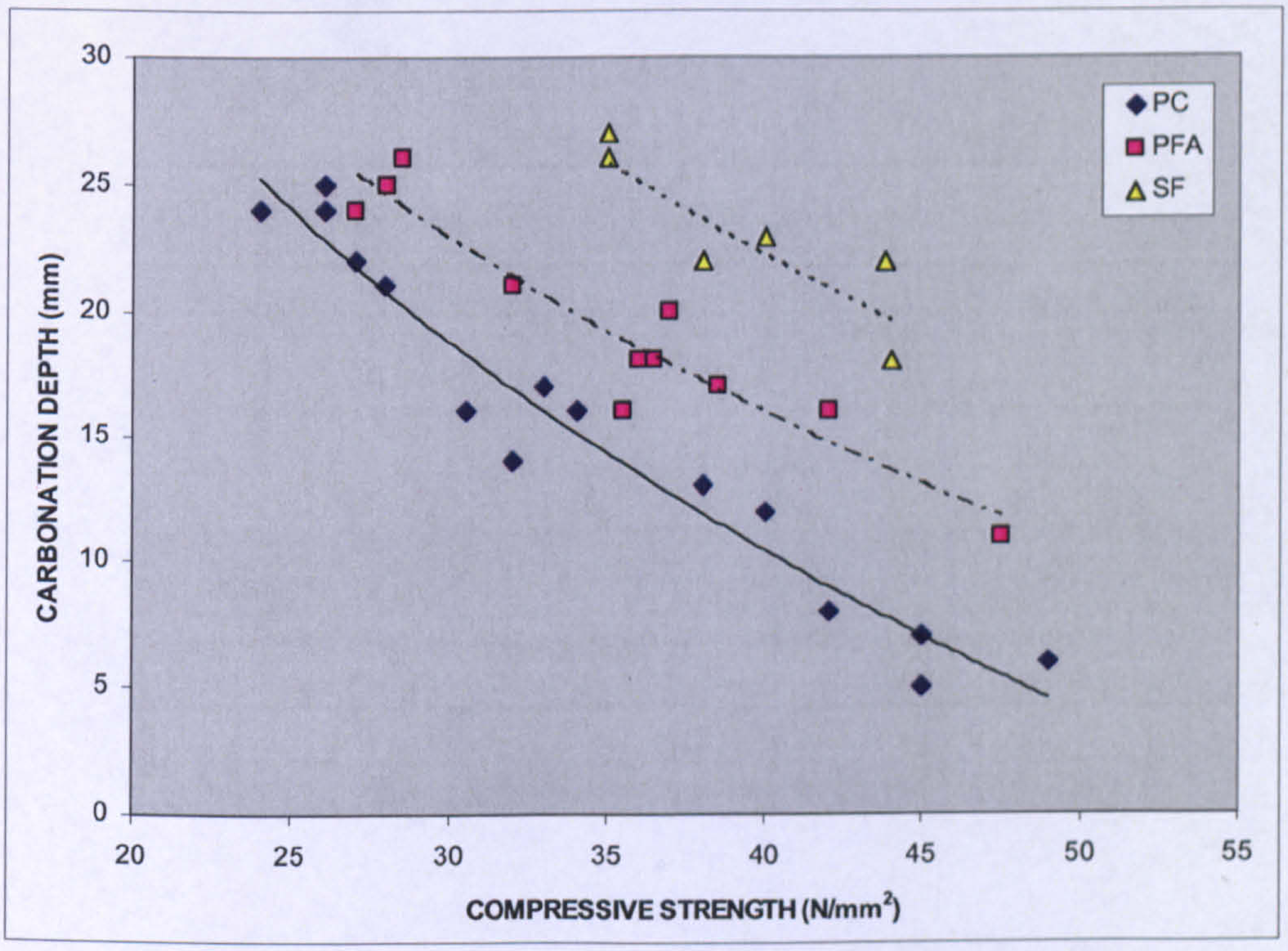


Figure 7.19 20 weeks carbonation depths vs. 28 day cube compressive strength of PC, PFA and SF concretes.

7.5 CHLORIDE INGRESS

In this study, a 1 mol Sodium Chloride solution (58.4g NaCl/l of distilled water) was ponded for 42 days on the top face of 150 mm specimens. The total chloride contents of dust samples recovered by drilling the top face from each specimen were thereafter measured. Each sample represented a different depth band; the intervals used were 0 – 5 mm, 5 – 10 mm, 10 – 15 mm and 15 – 20 mm. The 0 – 5 mm results were discarded, this is because of the unreliable readings obtained from this band.

7.5.1 Effect of RCA

7.5.1.1 PC mixes

RC 30 – Figure 7.20 shows the chloride contents measured at different depths of the NA and RCA RC 30 mixes. The results show that the 30% RCA concrete had similar or slightly lower chloride contents when compared to the NA concrete. The chloride content increased when 50% of the NA content was replaced with RCA, the chloride content on average doubled in the 10 – 15 and 15 – 20 mm samples when compared to NA concrete. Using 100% RCA resulted in higher chloride contents, especially in the 5 – 10 and 10 – 15 mm samples, however at the 15 – 20 mm depth band; the chloride content was only 46% higher than the NA concrete. The highest chloride content measured at 15 – 20 mm depth band was from the 50% RCA sample (2.35%).

RC 35 – Figure 7.21 shows the chloride contents measured at different depths of the NA and RCA RC 35 mixes. At the 5 – 10 mm depth band, the chloride contents of the NA, 30 and 50% RCA mixes were approximately the same, whilst the chloride content of the 100% RCA mix was lower by 34%. At the 10 – 15 mm depth band, the chloride content increased with an increase in the RCA content, the increase was by up to 52%. At the 15 – 20 mm depth band, the chloride contents of the NA, 50 and 100% RCA concretes were approximately the same (0.351 – 0.397%), the 30% RCA concrete on the other hand had a lower chloride content (0.232%).

RC 40 – Figure 7.22 shows the chloride contents measured at different depths of the NA and RCA RC 40 mixes. Using up to 30% RCA had no effect on the chloride content of the concrete except at the 5 – 10mm depth band where it increased by 36%. Using 50 and 100% RCA had a similar effect on the chloride content of the concrete, increasing the chloride content by 45% on average at the 5 – 10 mm and 10 – 15 mm depth bands and doubling it at the 15 – 20 mm depth band. The highest chloride content measured at 15 – 20 mm depth band was from the 100% RCA sample (0.364%).

Overall, it was found that the using up to 30% RCA had no effect on the chloride ingress, however using high contents of RCA (50 and 100%) resulted in the increase of chloride ion content in the concrete. The main reason behind this is the increase in the permeability of concrete when RCA is used. After omitting a couple of unusual results, a correlation was found between the chloride concentrations in the 15 – 20 mm depth band and the permeability of the PC concrete (R^2 = 0.80). Figure 7.23 shows the chloride content results in the 15 – 20 mm depth band of the PC mixes in relation to their corresponding ISA – 10 results at 28 days. The results demonstrate that a higher initial surface absorption is in general associated with a faster ingress of chlorides.

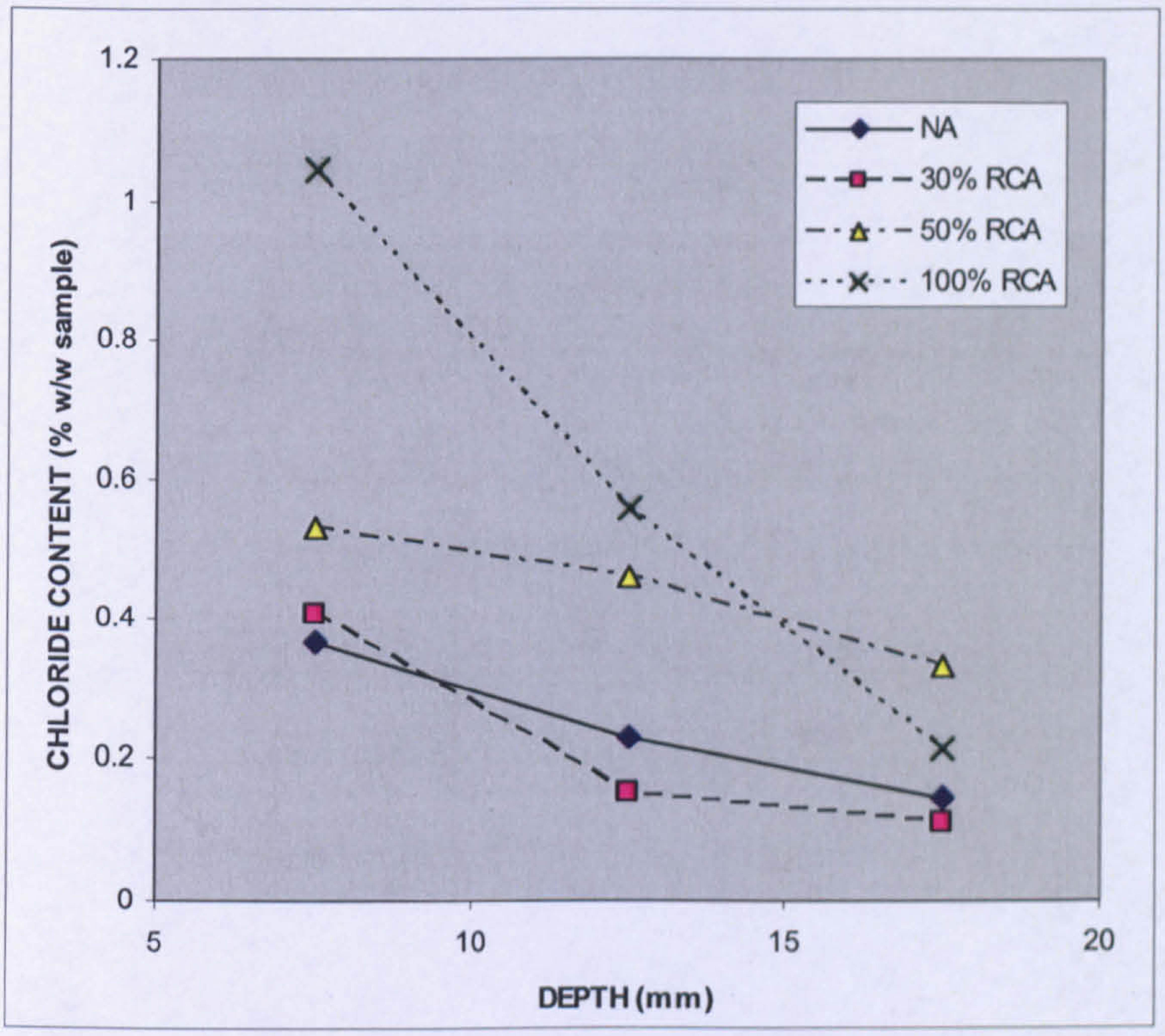


Figure 7.20 Profiles of Chloride content per mass of cement for RC 30 PC concrete

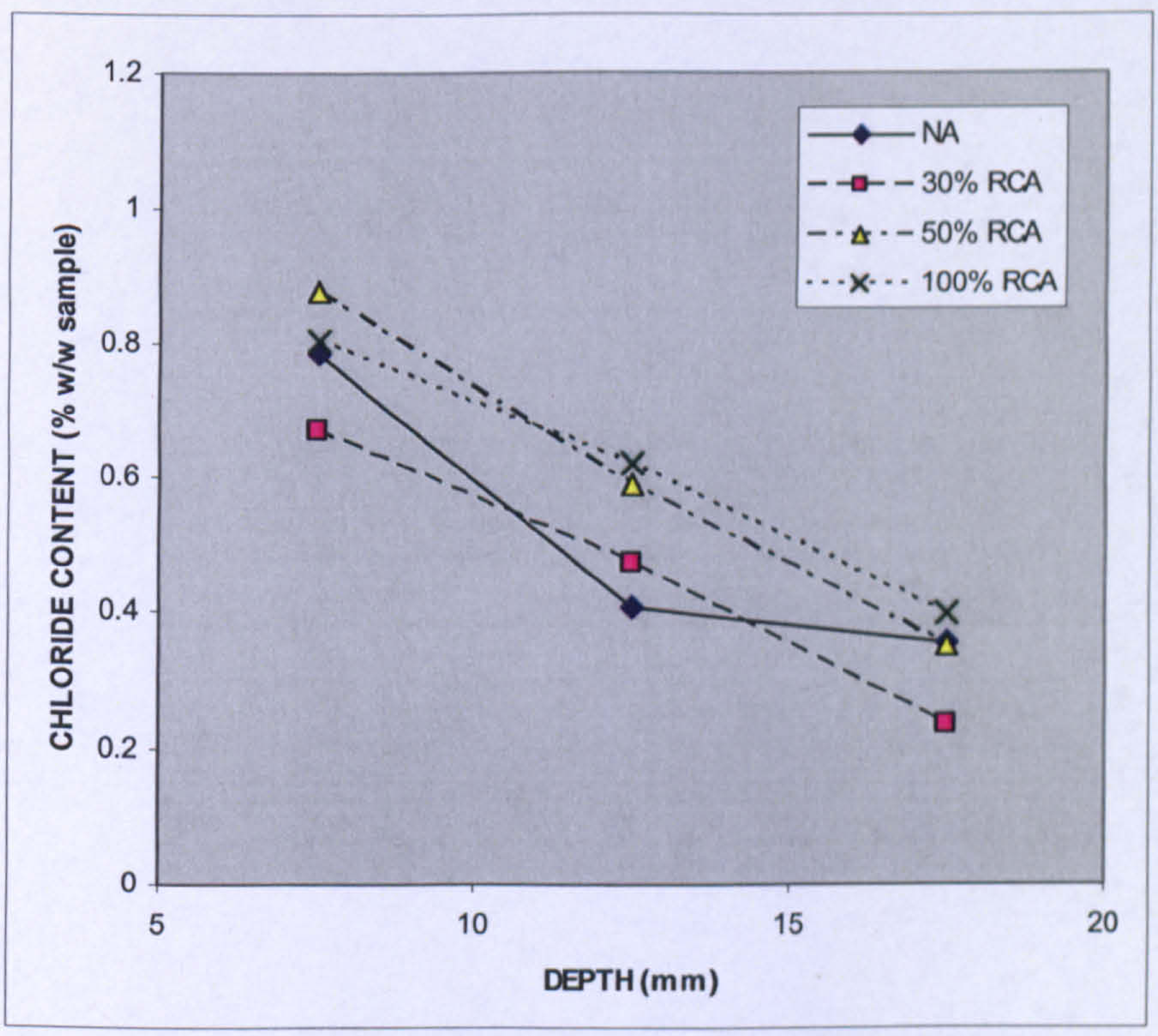


Figure 7.21 Profiles of Chloride content per mass of cement for RC 35 PC concrete

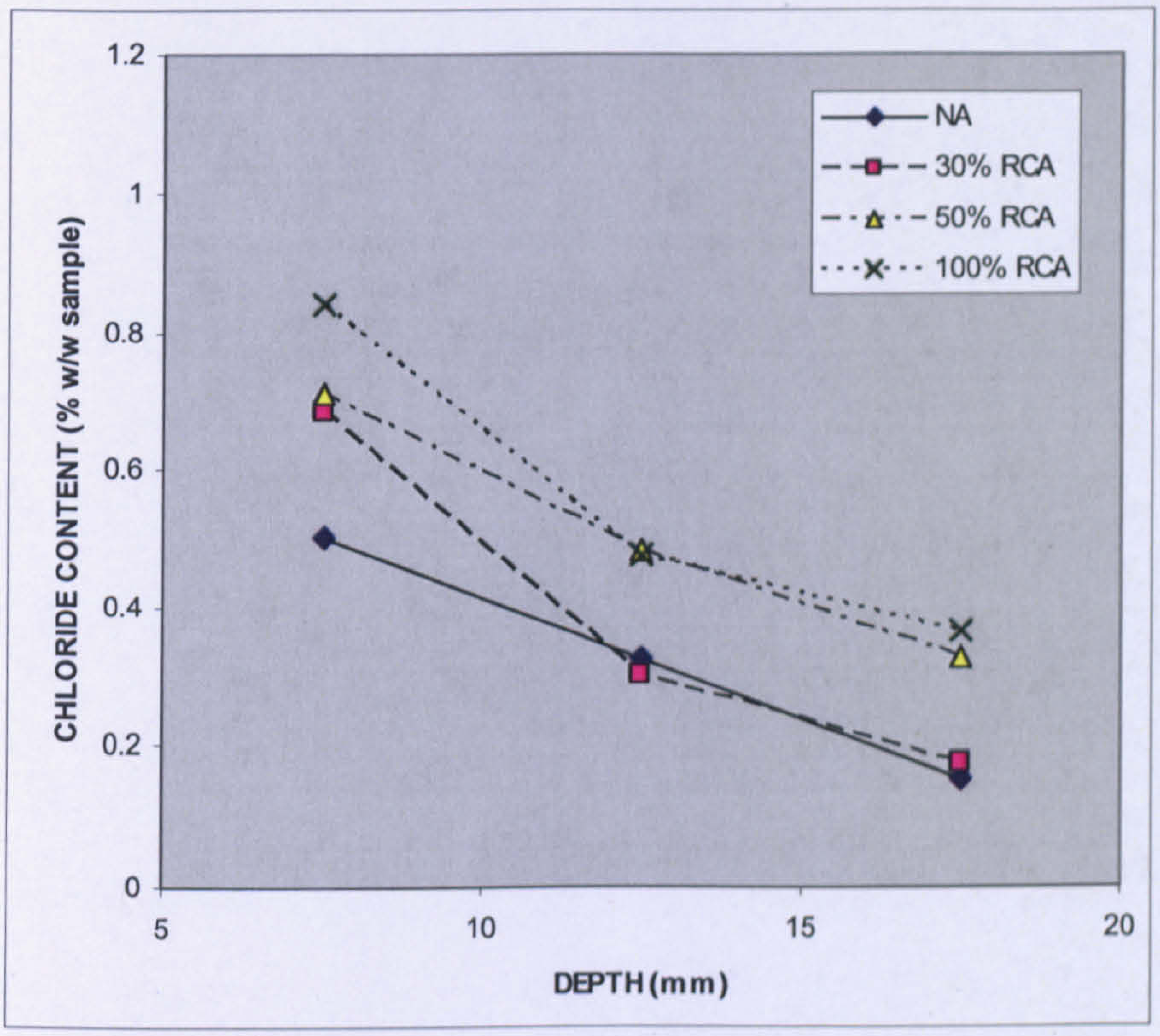


Figure 7.22 Profiles of Chloride content per mass of cement for RC 40 PC concrete.

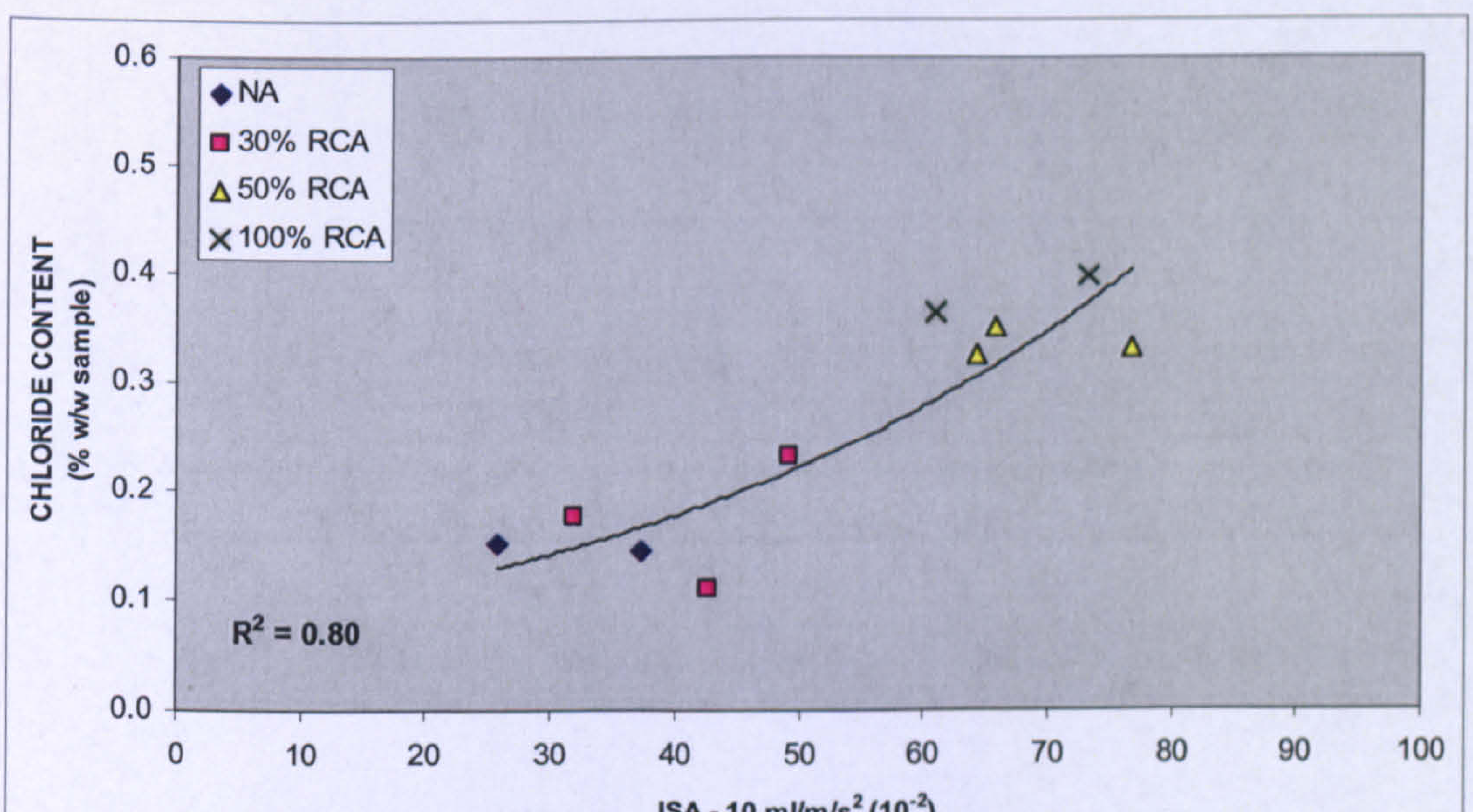


Figure 7.23 Chloride content in the 15 – 20 mm depth band vs. initial surface absorption of water at 28 days of PC mixes.

7.5.1.2 PFA mixes

RC 30 – Figure 7.24 shows the chloride contents measured at different depth bands of the NA and RCA RC 30 mixes. The results show that the NA and 30% RCA concrete samples had approximately similar chloride contents. At the 5 – 10 mm depth band the chloride content of the NA and RCA mixes were approximately the same. At the 10 – 15 mm and 15 – 20 mm depth bands, the chloride content increased with an increase of the RCA's use. At the 15 – 20 mm depth band, the use of 50 and 100% RCA increased the chloride content by 75 and 125% respectively when compared to NA concrete. The highest chloride content measured at 15 – 20 mm depth band was from the 100% RCA sample (0.256%).

RC 35 – Figure 7.25 shows the chloride contents measured at different depth bands of the NA and RCA RC 35 mixes. The results show that the NA and 30% RCA concrete samples had approximately similar chloride contents. The chloride contents of the 50% RCA concrete were higher on average by 32% when compared to the NA concrete except at the 15 – 20 mm depth band, where the chloride contents were approximately the same. Using 100% RCA increased significantly the chloride content in concrete in all the depth bands; the chloride content of the 100% RCA at the 15 – 20 mm depth band was more than double that of the NA concrete. The highest chloride content measured at 15 – 20 mm depth band was from the 100% RCA sample (0.554%).

Overall it was found that using 30% of RCA had no effect on the chloride ingress of PFA concrete. Beyond this limit, increasing the RCA content increased the chloride concentration in the concrete, the effect of using 50% RCA was however less pronounced than 100% RCA. As for the PC mixes, a correlation was found between the chloride concentrations and the permeability of the majority of the PFA mixes. The results demonstrate that a higher initial surface absorption is in general associated with a faster ingress of chlorides. Figure 7.26 shows the chloride content results in the 15 – 20 mm depth band of the PFA mixes in relation to their corresponding ISA – 10 results at 28 days.

7.5.1.3 SF mixes

RC 30 – Figure 7.27 shows the chloride contents measured at different depth bands of the NA and RCA RC 30 mixes. At the 5 – 10 mm depth band the chloride content of the 30 and 50% RCA mixes was higher by 60% on average than the NA mix, whilst the chloride content of the 100% RCA mix was twice as high compared to the NA mix. At the 10 – 15 mm depth band, the chloride contents of the 30, 50 and 100% RCA mixes were higher than the NA mix by 55, 25 and 85% respectively. At the 15 – 20 mm depth bands, the NA, 30% and 50% RCA concrete had approximately similar chloride contents whilst the chloride content of the 100% RCA was 33% higher. The highest chloride content measured at 15 – 20 mm depth band was from the 100% RCA sample (0.451%).

RC 35 – Figure 7.28 shows the chloride contents measured at different depth bands of the NA and RCA RC 35 mixes. All the mixes had approximately the same chloride contents regardless of the amount of RCA used and depth band. The highest chloride content measured at 15 – 20 mm depth band was from the NA sample (0.182%).

Overall no clear effect from the use of RCA on the ingress of chloride could be established. For the low strength concrete (RC 30), the use of RCA resulted in an increase of chloride concentration in the 5 – 10 and 10 – 15 mm depth bands, however at the 15 – 20 mm depth band, the RCA had no effect on the chloride concentration except when 100% RCA was used. For the concrete with a higher strength (RC 35), the use of RCA had no major effect on the chloride concentrations at all the different depth bands. No clear correlation was found between the chloride concentrations and the permeability of the SF mixes.

7.5.2 Binary cement concrete performance

7.5.2.1 PC/PFA

To assess the effect of PFA on the chloride ingress of concrete, the relationship between the chloride concentrations at the 15 – 20 mm depth band and the permeability of the PC and PFA concretes were compared in Figure 7.29. It was found that a for PC and PFA concrete with the same near surface absorption, the chloride content at the 15 – 20 mm depth band would be approximately the same.

The study in the first section of this chapter of the effect of using PFA on the permeability of RCA concrete has shown that the use of PFA decreases the initial surface absorption of RCA concrete when the RCA content is higher than 50%, thus it can be deduced that when comparing equal strength PC and PFA mixes, the PFA mix due to its low permeability, especially when high contents of RCA are used, will be less prone to the ingress of chlorides thus having a reduced rate of reinforcement corrosion. These findings are in agreement with those from previous studies [105, 106, 108, 109].

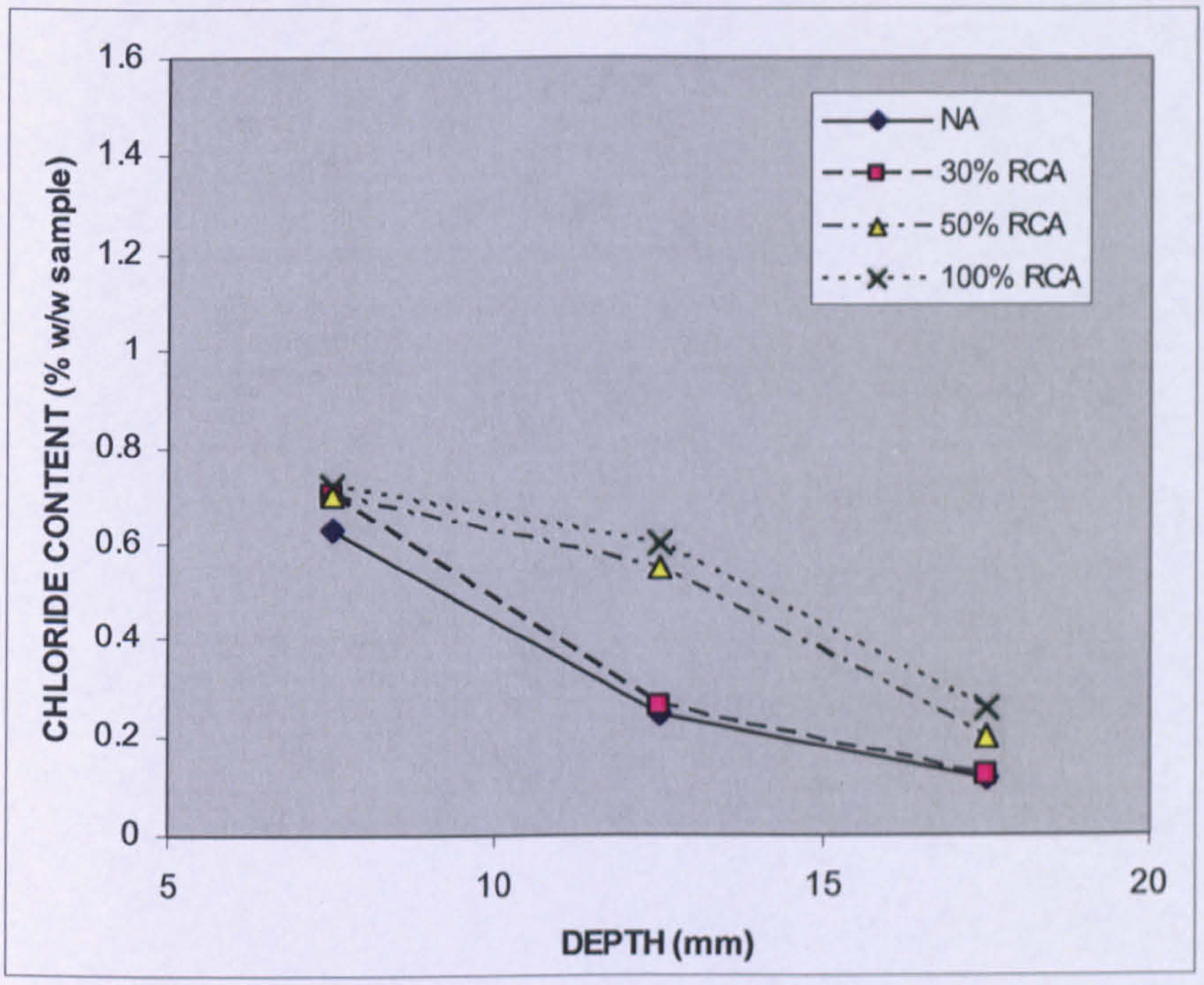


Figure 7.24 Profiles of Chloride content per mass of cement for RC 30 PFA concrete.

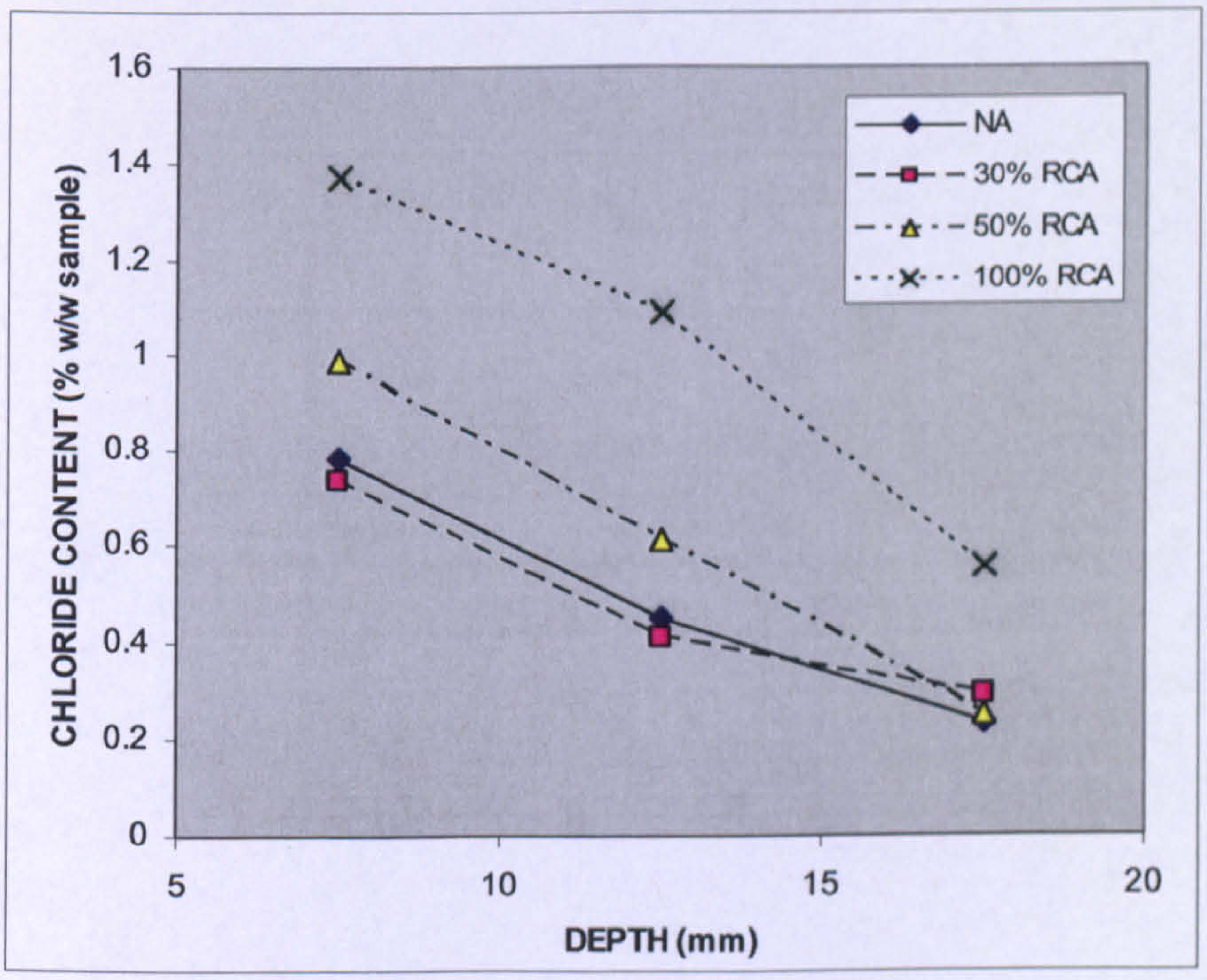


Figure 7.25 Profiles of Chloride content per mass of cement for RC 35 PFA concrete.

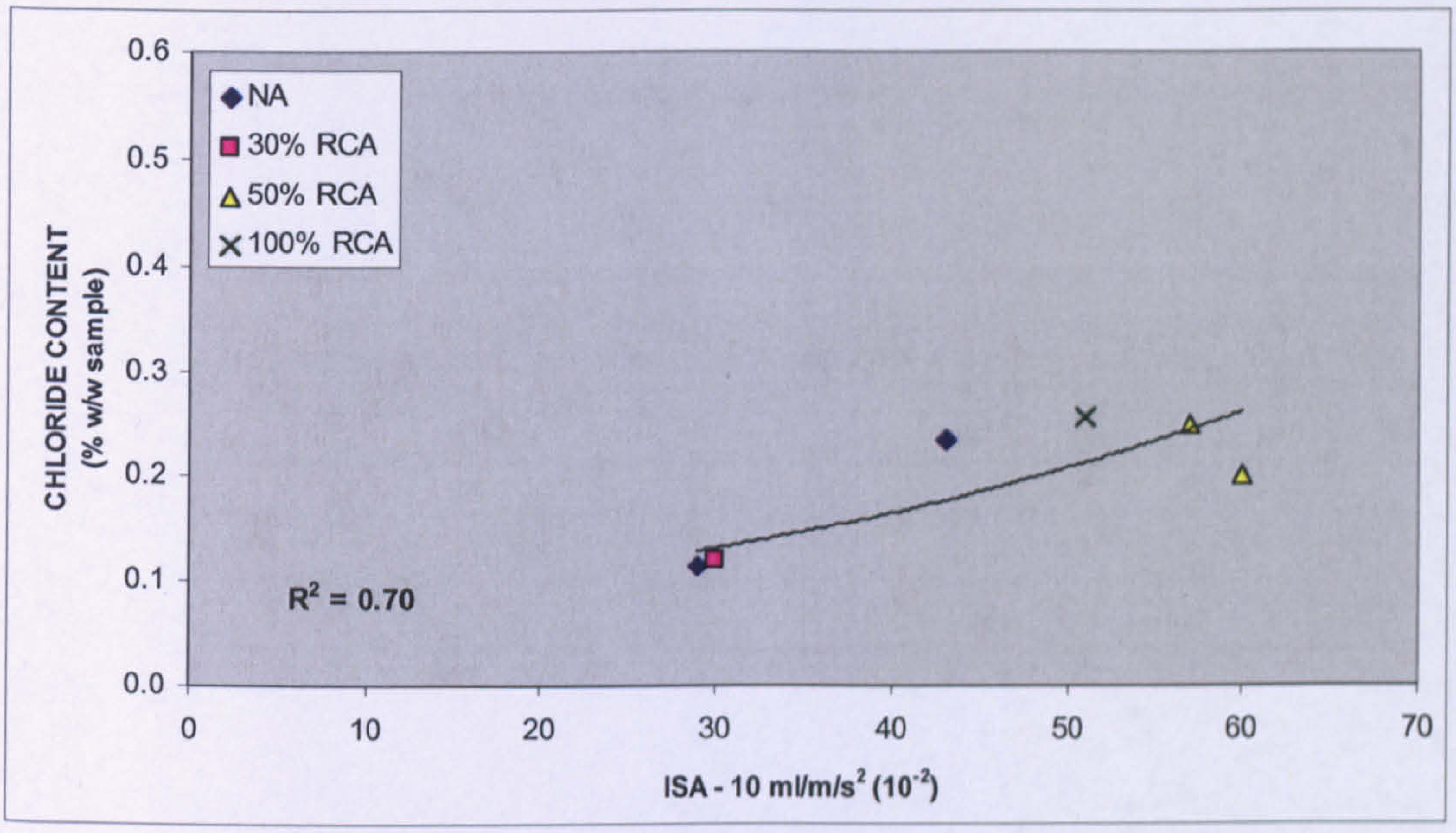


Figure 7.26 Chloride content in the 15 – 20 mm depth band vs. initial surface absorption of water at 28 days of PFA mixes.

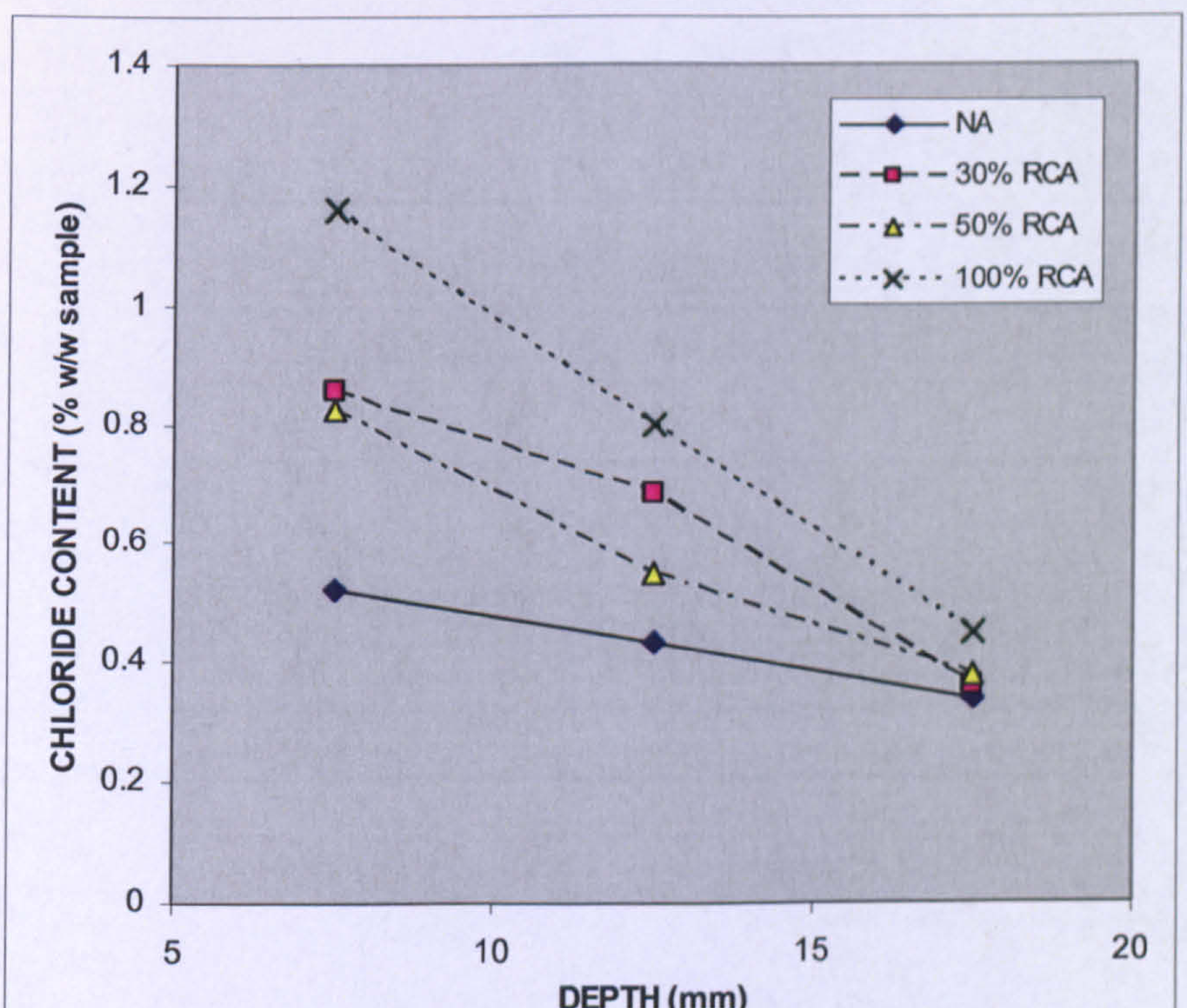


Figure 7.27 Profiles of Chloride content per mass of cement for RC 30 SF concrete

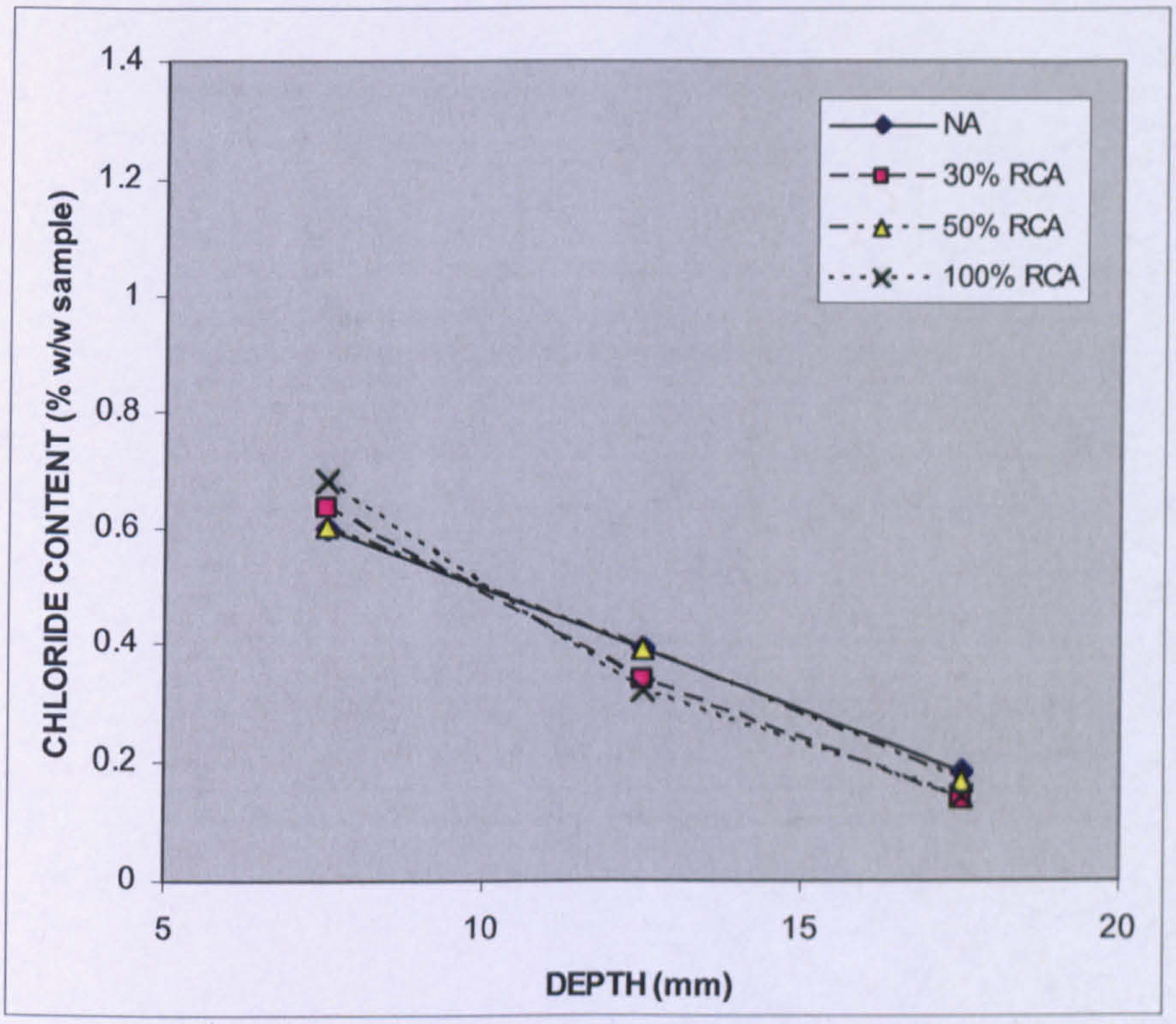


Figure 7.28 Profiles of Chloride content per mass of cement for RC 40 SF concrete

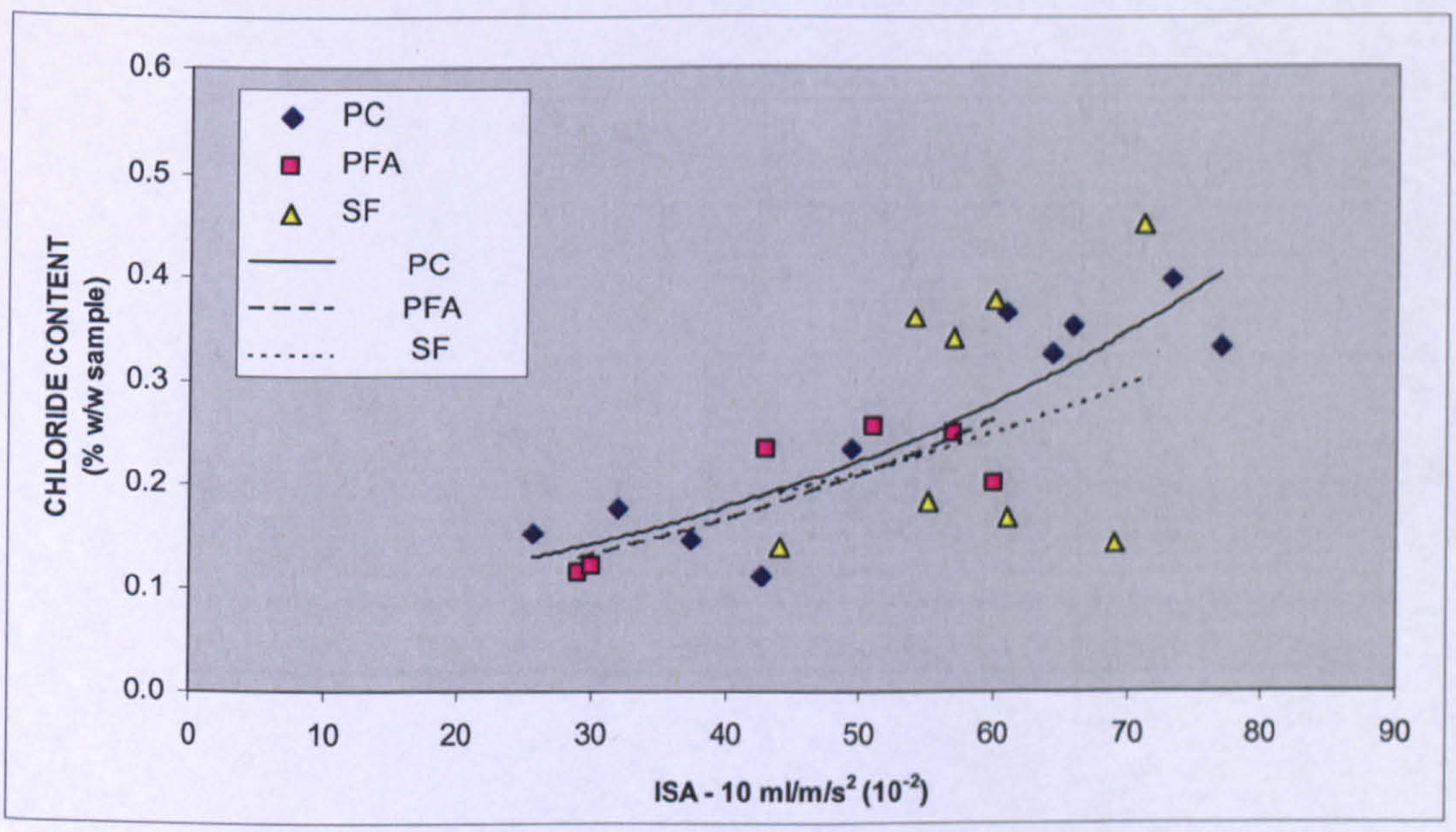


Figure 7.29 Chloride content in the 15 – 20 mm depth band vs. initial surface absorption of water at 28 days of PC, PFA and SF mixes.

The test used in this study yields the value of total chlorides (free and bound chlorides), however the threat to the durability of the concrete comes mainly from the presence of free chlorides. PFA due to its considerable alumina content is beneficial with regards to chloride binding, as aluminates are effective at binding chlorides, this advantage can further reduce the rate of corrosion of reinforcement in PFA concrete when compared to PC concrete.

7.5.2.2 PC/SF

A simple comparison of the chloride concentrations at the 15 – 20 mm depth band of the PC mixes with their corresponding SF mixes shows that for the low strength concrete (RC 30); the chloride concentrations in the SF mixes were higher than in the PC mixes. For the high strength concrete (RC 35); the chloride concentrations of the SF NA and 30% RCA mixes were higher, whilst the chloride concentrations of the SF 50 and 100% RCA mixes were lower when compared to their corresponding PC mixes. The variations in the chloride concentration results of the SF mixes may be due to experimental errors. The chloride concentrations obtained at the 15 – 20 mm depth band of the SF mixes were correlated with their corresponding ISA – 10 results in Figure 7.29. The results show that for PC and SF concretes, with the same near surface absorption rate, the chloride ingress in the SF concrete will be similar or slightly higher compared to the PC concrete.

The study in the first section of this chapter of the effect of using SF on the permeability of RCA concrete has shown that the initial surface absorption of SF concrete, when up to 30% of RCA was used, was higher compared to the PC concrete. However, when higher contents of RCA were used, the initial surface absorption of

SF concrete was slightly lower than the PC concrete. Thus it can be deduced that when comparing equal strength PC and SF mixes, when up to 30% of RCA is used in the mix, the SF concrete will have a slightly lower resistance to chloride ingress due to its higher permeability when compared to the PC concrete. On the other hand, when the RCA content used is 50% or higher, the SF concrete will have a similar or slightly higher resistance to chloride ingress compared to PC concrete potentially resulting in a reduction of the rate of corrosion of reinforcement.

7.6 SULPHATE ATTACK

Prism specimens (75×75×300 mm) with stainless steel DEMEC points, fixed on each of the 4 faces of the specimen, were used to monitor the change in length of concrete exposed a 0.3g/l Sulphate (Na_2SO_4) solution at 20°C.

7.6.1 Effect of RCA

7.6.1.1 PC mixes

GEN 1 – Figures 7.30 and 7.31 show the expansion measurements over time for GEN 1 mixes, with different RCA proportions, air and water cured respectively. The expansion was found to increase as the RCA content in the mix increased. The use of 50 and 100% RCA increased the expansion of concrete by 31 and 63% respectively on average for both the standard water and air curing conditions.

GEN 3 – Figure 7.32 gives the expansion over time measured for air cured GEN 3 mixes using different RCA proportions. The expansion was found to increase as the RCA content in the mix increased. The use of 30, 50 and 100% RCA increased the expansion of concrete by 9, 20 and 53% respectively.

Overall, using up to 30% RCA had no effect on the expansion due to sulphates of the concrete. Beyond this limit, the use of RCA increased the expansion of the concrete specimens. These findings are in line with those of previous studies [22]. This is mainly due to the high permeability of RCA mixes and their high cement content. This increase however is very small, the maximum increase was found to be 38.5 × 10^{-6} in the 100% RCA air cured GEN 1 mix. Water curing reduced the expansion of the GEN 1 mixes by 45% on average when compared to air curing, which shows the importance of a proper curing regime in reducing expansion due to sulphate attack.

7.6.1.2 PFA mixes

GEN 1 – Figures 7.33 and 7.34 show the expansion measurements over time for GEN 1 mixes, with different RCA proportions, air and water cured respectively. The expansion was found to increase as the RCA content in the mix increased. The use of 50 and 100% RCA increased the expansion of air cured concrete by 58 and 74% respectively. The use of 50 and 100% RCA increased the expansion of water cured concrete by 6 and 15% respectively.

GEN 3 – Figure 7.35 shows the expansion over time measured for air cured GEN 3 mixes using different RCA proportions. The expansion was found to increase as the RCA content in the mix increased. The use of 30, 50 and 100% RCA increased the expansion of concrete by 24, 29 and 93% respectively.

Overall, the use of RCA increased the expansion of the concrete specimens. This is mainly due to the high permeability of RCA mixes and their high cement content. However this increase is very small; the maximum increase was found to be 40.6 ×

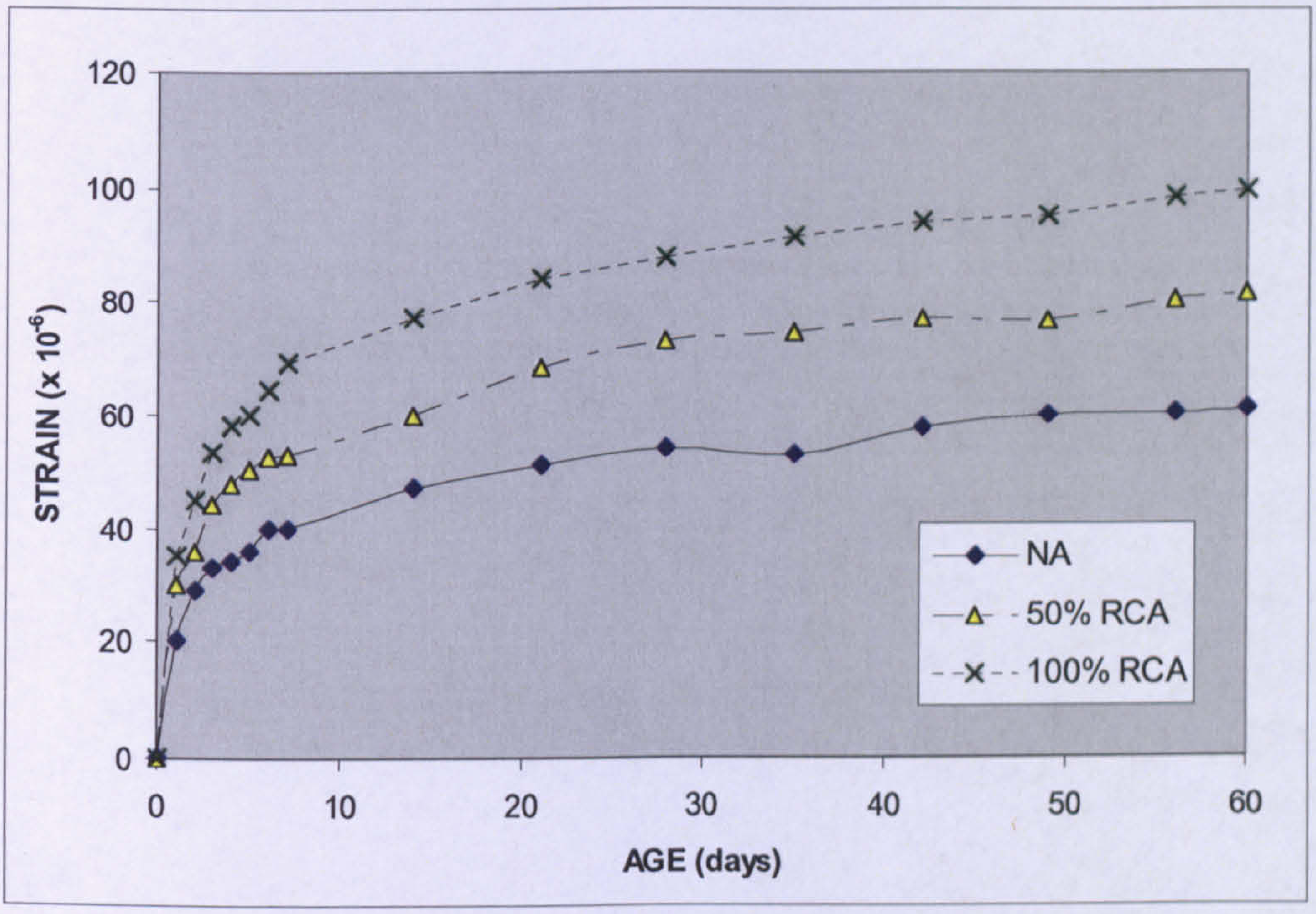


Figure 7.30 Comparison of swelling expansion due to sulphate attack of air cured PC GEN 1 mixes.

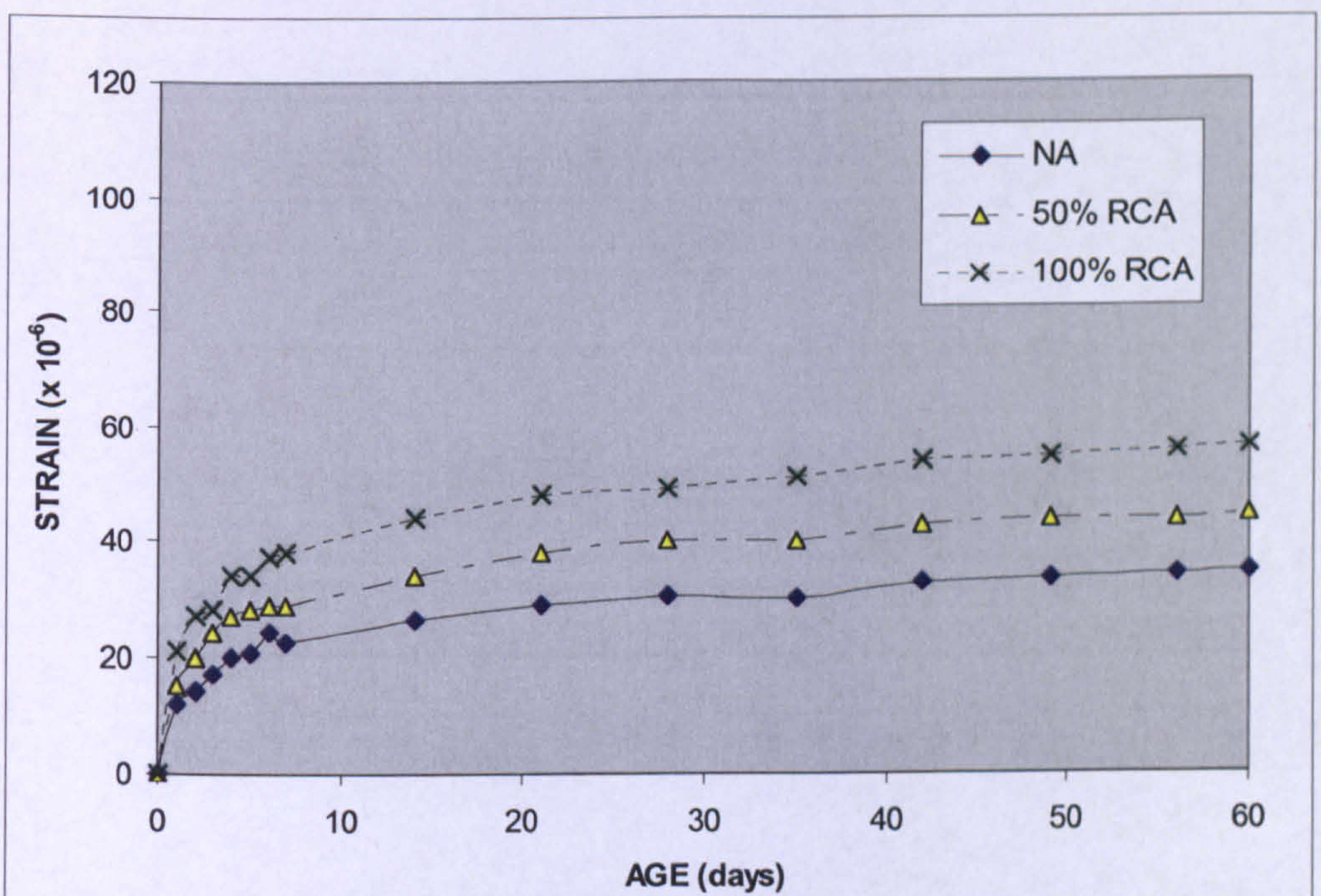


Figure 7.31 Comparison of swelling expansion due to sulphate attack of water cured PC GEN 1 mixes.

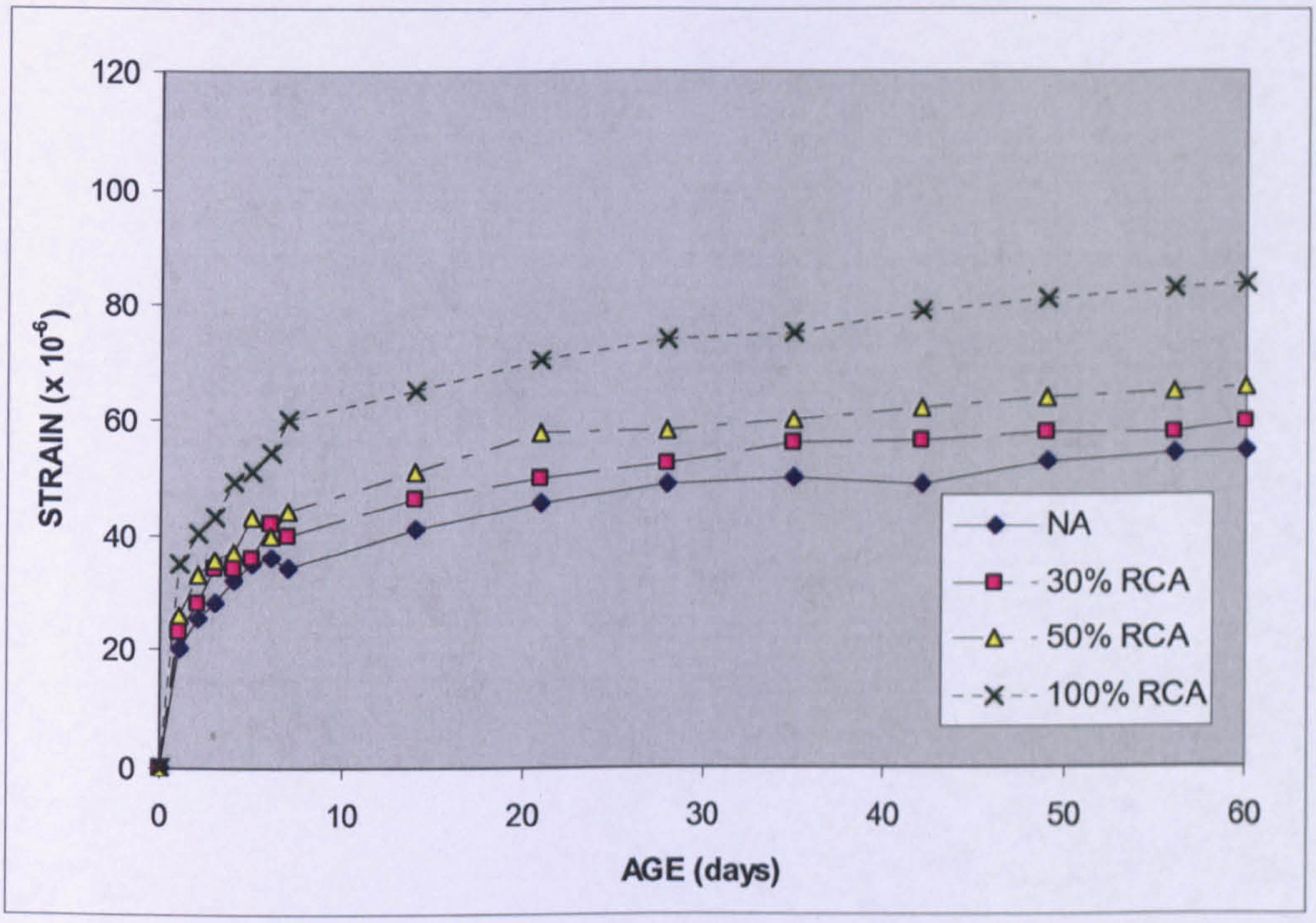


Figure 7.32 Comparison of swelling expansion due to sulphate attack of air cured PC GEN 3 mixes.

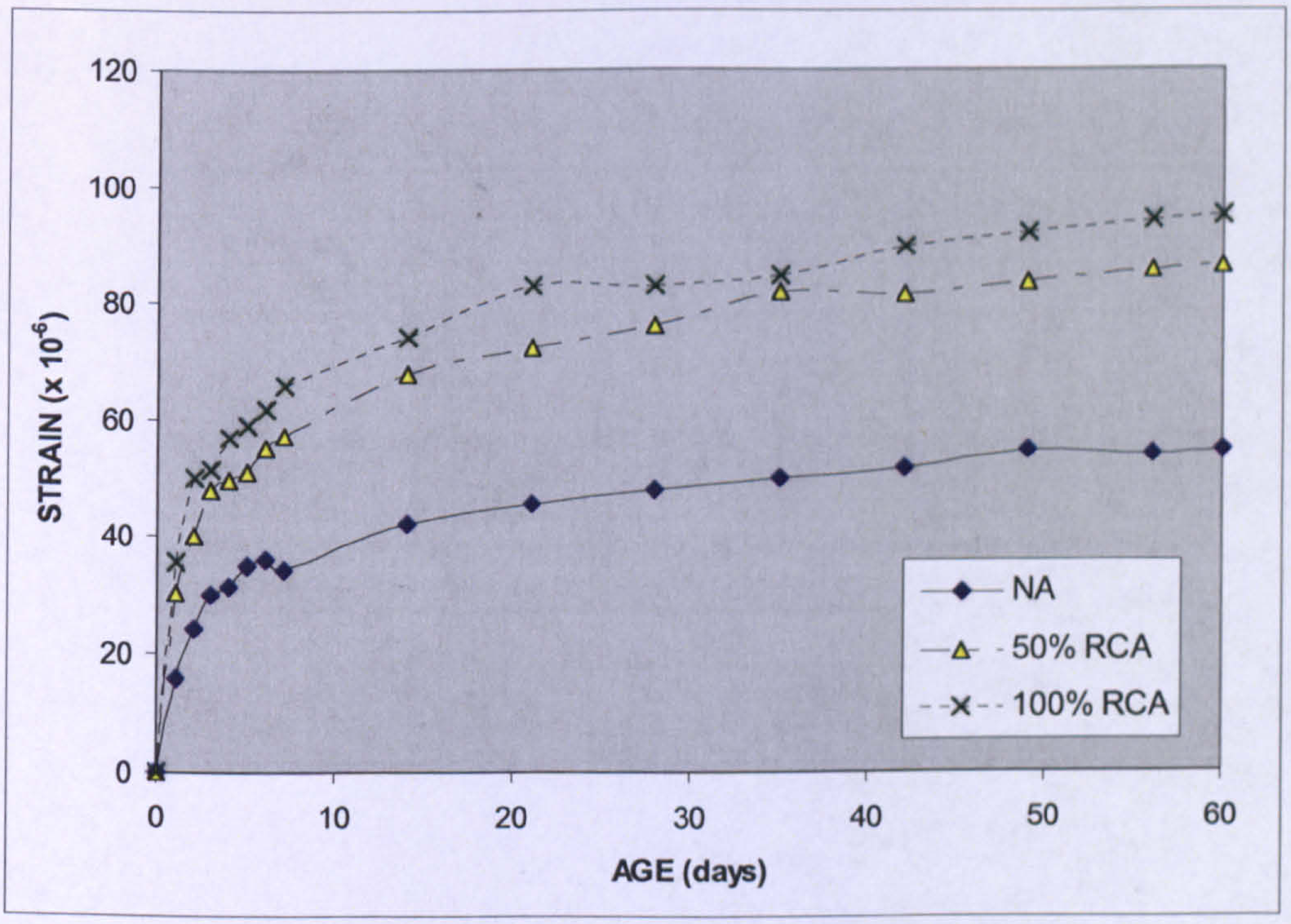


Figure 7.33 Comparison of swelling expansion due to sulphate attack of air cured PFA GEN 1 mixes.

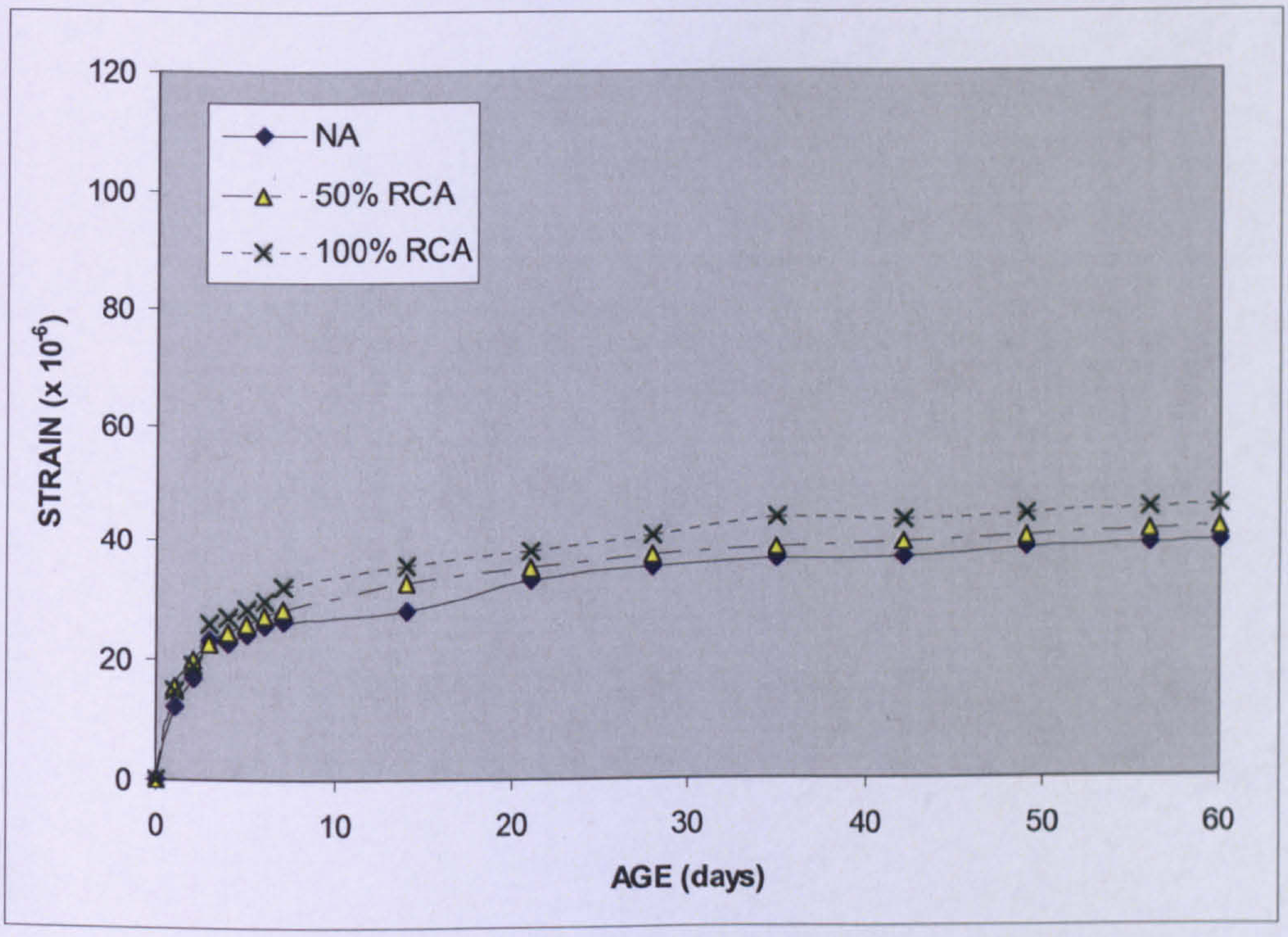


Figure 7.34 Comparison of swelling expansion due to sulphate attack of water cured PFA GEN 1 mixes.

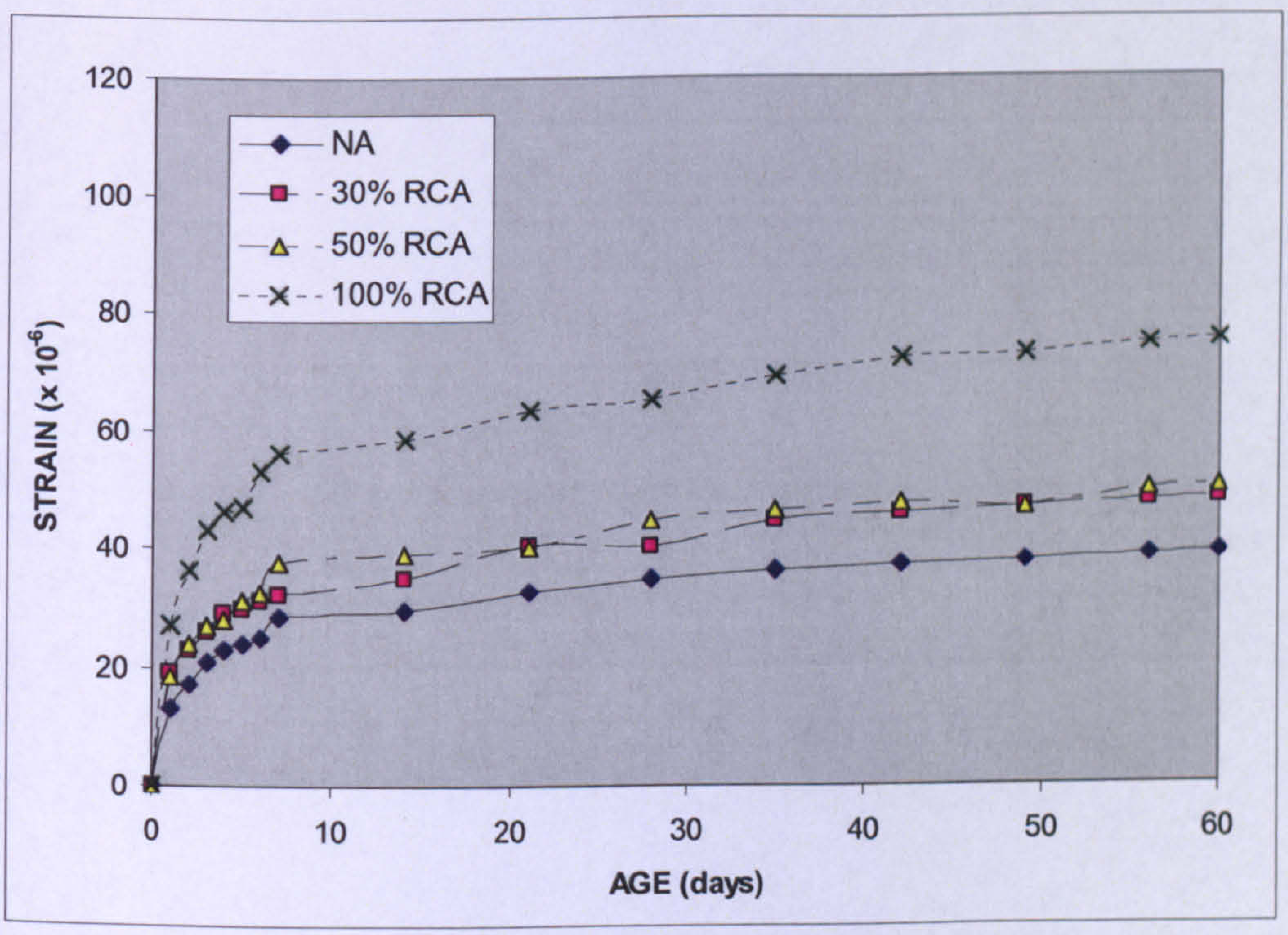


Figure 7.35 Comparison of swelling expansion due to sulphate attack of air cured PFA GEN 3 mixes.

10^{-6} in the 100% RCA air cured GEN 1 mix. Water curing reduced the expansion of the 30% RCA mix by 25% when compared to air curing. For the 50 and 100% RCA mixes, the reduction was by 50%. This shows the importance of a proper curing regime in reducing expansion due to sulphate attack.

7.6.2 Binary cement concrete performance

7.6.2.1 PC/PFA

GEN 1 – Figures 7.36 and 7.37 compare the expansions measured at 60 days of PC GEN1 mixes with different RCA proportions, air and water cured respectively with their corresponding PFA mixes. In general, the use of PFA had a minor effect on the expansions values.

GEN 3 – Figure 7.38 compares the expansions measured at 60 days for the air cured PC GEN 3 mixes with corresponding PFA mixes. The use of PFA had a more significant effect on the GEN 3 mixes when compared to the GEN 1 mixes. The use of PFA reduced the expansion values of the concrete by 10 to 29%.

Overall, the use of PFA slightly reduced the expansion of concrete due to sulphate attack. This is mainly due to the lower permeability of the PFA concrete and the reduced amount of Portland cement in the mix and thus of calcium hydroxide among the hydration products which react with sulphate ions resulting in concrete expansion. The influence of PFA up to 60 days is very small, the maximum decrease in expansion measured in PFA concrete was found to be 15.7×10^{-6} for the air cured NA and 50% RCA GEN 3 mix. The influence of using PFA is expected to be greater at later age, as the pozzolanic reaction continues over time. For the effect of the PFA to

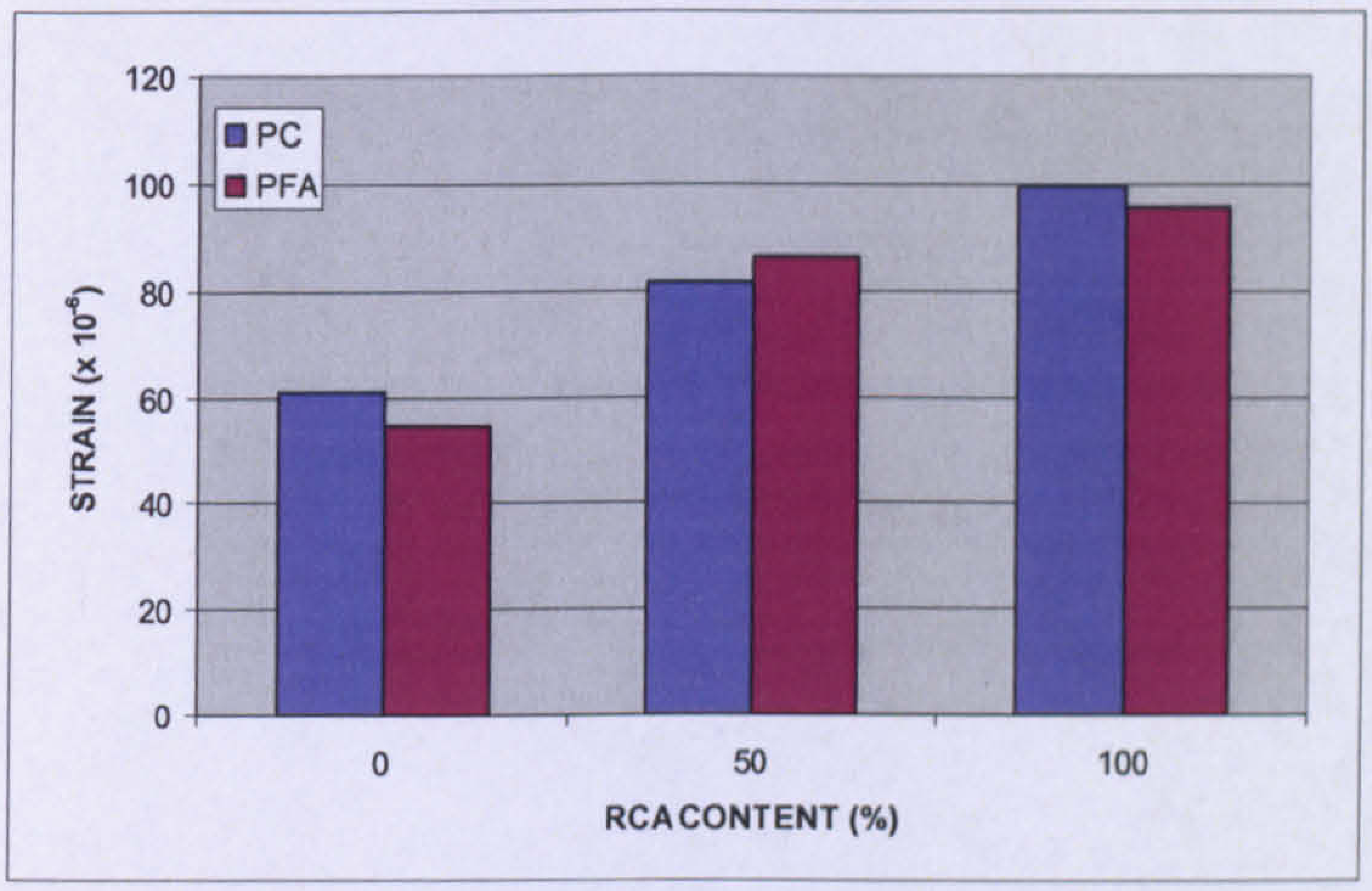


Figure 7.36 Comparison of swelling expansion due to sulphate attack of air cured PC and PFA GEN 1 mixes at 60 days.

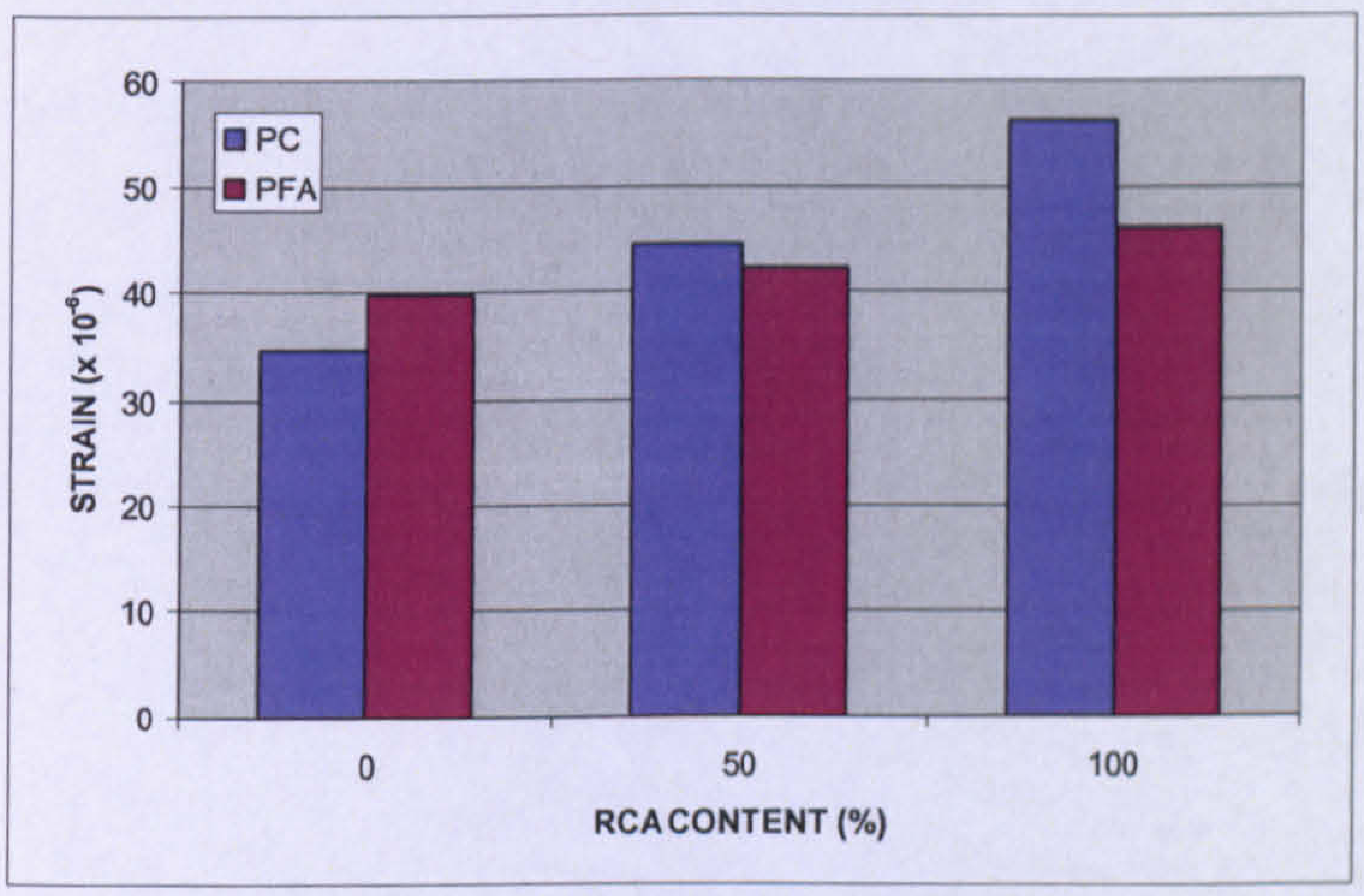


Figure 7.37 Comparison of swelling expansion due to sulphate attack of water cured PC and PFA GEN 1 mixes at 60 days.

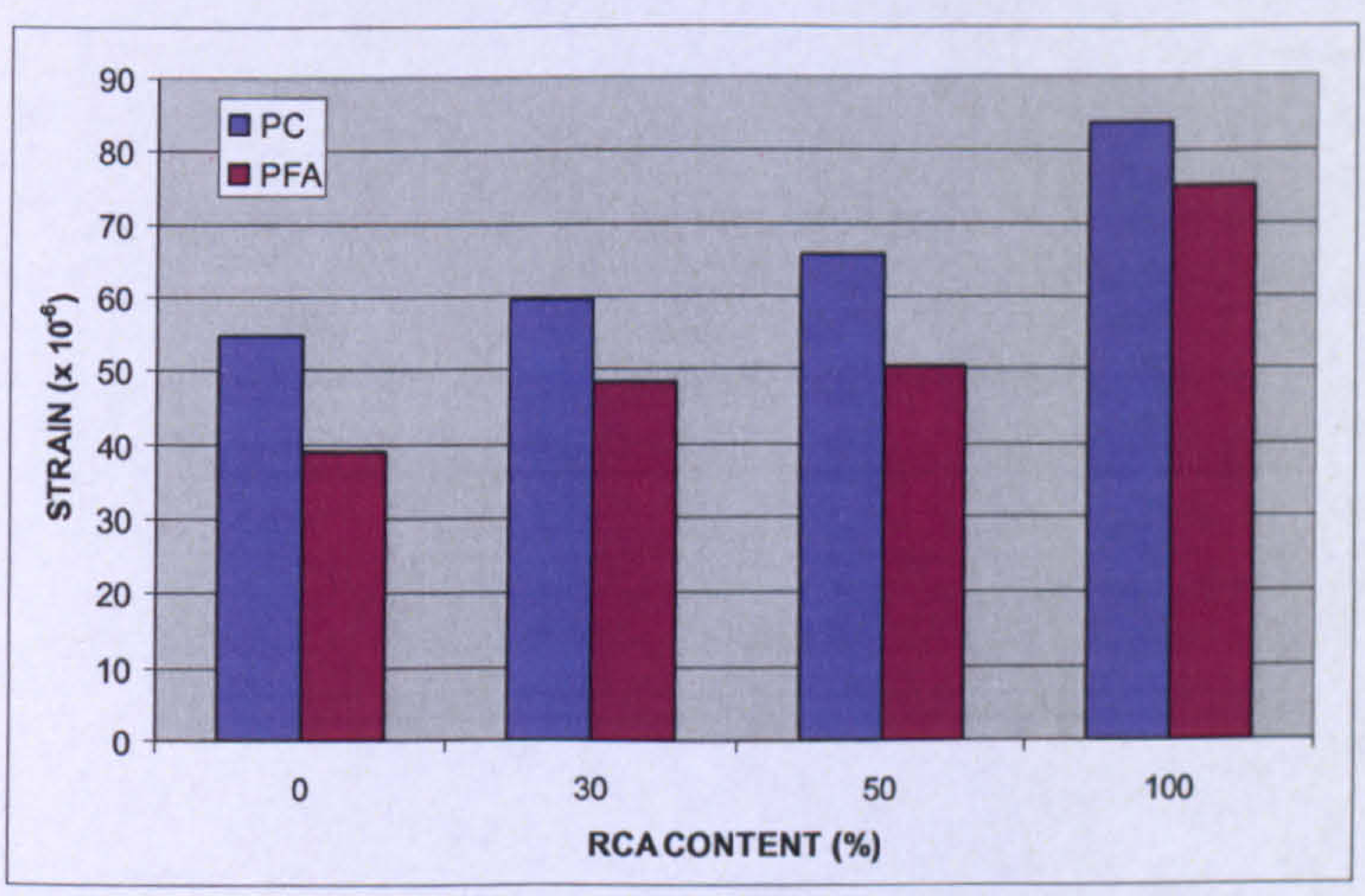


Figure 7.38 Comparison of swelling expansion due to sulphate attack of air cured PC and PFA GEN 3 mixes at 60 days.

be maximised, it is essential that the concrete is sufficiently cured prior to exposure to the sulphate environment.

7.7 PRACTICAL IMPLICATIONS

The initial surface absorption of the concrete is a very important property as the service life of a concrete structure will depend on the rate at which harmful ions and molecules move into the concrete. The initial surface absorption is mainly influenced by the type of constituents used in the concrete; the initial surface absorption of concrete was found to increase when more than 30% of the NA content of concrete was replaced by RCA.

When using up to 30% RCA, the permeability of equal strength PC and PFA concretes was similarly lower when compared to their corresponding SF concrete. However when higher RCA contents (50 and 100% RCA) were used, equal strength PC and SF concretes were found to have similarly higher initial surface absorption values when compared to their corresponding PFA concrete. Therefore when high contents of RCA are used in concrete it is recommended to use PFA to produce a concrete with a satisfactory initial surface absorption.

The carbonation of the concrete was unaffected by the use of RCA. The use of binary cements slightly increased the carbonation rate of concrete; however this may have been influenced by the accelerated test method chosen for the study.

Using up to 30% RCA had no effect on the chloride concentrations of PC and PFA concrete at the 15 – 20 mm depth band. Increasing the RCA content beyond this limit resulted in the increase of chloride ion content in the concrete. For the SF concrete, the use of RCA had no significant effect on the chloride concentrations at the 15 – 20 mm depth band. PFA and SF partially because of the improvement they bring to the permeability of RCA concrete make it less prone to the ingress of chlorides.

The results of the study showed that a relatively small increase in the expansion of concrete due to sulphates occurs with the increase of RCA content in concrete. The PFA concretes had lower expansions due to sulphates when compared to their corresponding PC concrete regardless of the RCA content.

Overall, the study has clearly shown that RCA affects most of the durability properties of concrete. Binary cements when used can greatly reduce the effects of RCA on the durability of concrete and thus contribute to the improvement of the durability performance of RCA concrete. It is therefore highly recommended to use binary cements (PC/PFA and PC/SF) especially when high quantities of RCA are used.

The prolonged curing of the PFA and SF mixes is essential to reap all the benefits of using binary cements. It is also essential to improve the workability of SF concrete by using a superplasticizer; this is in order to achieve the full compaction of the SF concrete which improves considerably its durability.

The effect of RCA on the durability of concrete should be taken into consideration in the structural design of concrete structures, in order to specify a suitable cover to reinforcement capable of resisting the chemical attacks emanating from the environment over the service life of the structure. Depending on the environment the structure is exposed to, RCA concrete may require a slightly higher cover to reinforcement when compared to NA concrete.

7.8 CONCLUDING REMARKS

- The use of up to 30% of RCA had no effect on the initial surface absorption of PC, PFA and SF concretes, however beyond this limit the initial surface absorption of the concrete increased with an increase in the RCA content. The ISA – 10 results for the 50 and 100% RCA mixes were on average 100% higher when compared to their corresponding NA mixes for the PC concrete, compared to 50% for the PFA concrete. For SF concrete, using 50 and 100% RCA increased the ISA – 10 results by 9 and 22% respectively. Overall, the near surface absorption of the SF concrete was the least affected by the use of high RCA contents followed by PFA and PC concretes respectively.

- Comparing the ISA results of the different mixes showed that for the NA and 30% RCA concrete, the PC mixes had lower ISA results than PFA and SF mixes in that order. However for the 50 and 100% RCA concretes, the ISA results of the PFA concrete were, up to 20%, lower compared to the PC and SF concretes which had approximately the same ISA.

- Overall, it was found that the use of RCA does not affect the carbonation of the PC, PFA and SF concretes. A strong correlation was found between the compressive strength and carbonation resistance of the PC, PFA and SF concretes regardless of the RCA content. The carbonation resistance of the NA and RCA concretes was found to increase with the increase in the strength of the concrete.

- However, comparing the relationship between the compressive strength of the concrete and its carbonation resistance of PC concrete with the PFA and SF concrete showed that for a given strength, the resistance to carbonation was found decreasing in the following sequence: PC; PFA; SF regardless of the amount of RCA used in the mix.

- Using up to 30% RCA had no effect on the chloride concentrations of PC and PFA concretes at the 15 – 20 mm depth band. Increasing the RCA content beyond this limit resulted in the increase of chloride ion content in the concrete. For the SF concrete, the use of RCA had no significant effect on the chloride concentrations at the 15 – 20 mm depth band.

- PFA and SF partially because of the improvement they bring to the permeability of RCA concrete make it less prone to the ingress of chlorides thus reducing the rate of corrosion of the reinforcement in concrete.

- The use of RCA increased the expansion due to sulphate attack on the concrete. However this increase was very small. The expansion due to sulphate attack of water cured concretes was lower than air cured concretes.

- The use of PFA slightly reduced the expansion of concrete due to sulphate attack. This is mainly due to the lower permeability and the reduced amount calcium hydroxide among the hydration products of the PFA concrete.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

8.1 SUMMARY OF MAIN FINDINGS

Practical implications and conclusions drawn from the various phases of the study are presented at the end of the relevant chapters. This Chapter presents the findings of the study in relation to the objectives of the research programme. The prime objective of the research is to examine the suitability of recycled concrete aggregates (RCA) for use in concrete produced using binary cements. In particular

1. Study the production procedure of RCA and their characteristics

Concrete debris obtained from demolished concrete structures can be used to produce clean and properly graded RCA suitable for use in concrete production in accordance with EN 12620.

The attached cement paste had a great effect on the properties of RCA; the RCA was found to be rougher, more porous and less angular than NA. The RCA also had a higher water absorption, a lower density and a relatively poor mechanical performance when compared to NA.

2. Study the effect of RCA on the fresh properties of binary cement designated concrete mixes

The incomplete saturation of the RCA particles resulted in an increase of the free water content of the RCA mixes while the round shape of the RCA particles improved the workability of concrete, this was behind the high initial slumps of some of the PC and PFA RCA mixes. The use of RCA had no influence on the slump values of the SF mixes.

The use of PFA decreased the water demand of the mixes, due to its contribution to improving the workability of the concrete. SF, on the other hand, increases the water demand of the mixes as a result of its fineness.

The PFA and SF mixes had slightly lower compacting factor values than the corresponding PC mixes. This may be due to the improved cohesiveness of these mixes when compared to the PC mixes. The PFA mixes, due to their high cementitious content had the same workability as the PC mixes. On the other hand, the SF mixes were slightly more difficult to handle and compact compared to the PC and PFA mixes confirming the importance of using a superplasticizer in SF concrete.

The high water content of the RCA mixes was behind the segregation and bleeding of some PC mixes. The use of PFA and SF in RCA concrete improved the cohesiveness of the mixes and eliminated the occurrence of bleeding.

3. Study the effect of RCA on the engineering properties of binary cement designated concrete mixes

All the NA and RCA designated mixes reached their specified strength at 28 days showing the validity of the method used to take account of the effects of RCA on the compressive strength, which simply entail adjusting the water/cement ratio of the mix. The same modification factors were used for the PC and PFA concretes. A series of trial tests showed that the use of RCA had a different effect on the strength of the SF concrete when compared to the PC and PFA concretes, hence the different modification factors used for the SF mixes.

The use of RCA in the PFA mixes speeded up the rate of strength development of the PFA mixes. For the PC and SF mixes, no evident effect of RCA on the rate of strength development was established.

The use of up to 30% RCA content did not affect the cube and cylinder compressive strengths relationship of the PC mixes. However beyond this limit the cylinder – cube strength ratio gradually increased with an increase in the RCA content. For the PFA and SF mixes, the cube and cylinder strength relationship was not affected by the use of RCA as much as the PC mixes. The average cylinder – cube ratios of the PC, PFA and SF mixes regardless of the RCA content and age were 81, 80 and 81% respectively, which is in agreement with the cylinder – cube ratio used for designated mixes in EN 206 – 1 and BS 8500 (≈ 80%).

The use of RCA and binary cements was not found to affect the flexural – compressive strength relationship of concrete. The relationship was only affected by the strength of the concrete; the flexural – compressive strength ratio was found to decrease as the compressive strength of the concrete increased.

The increase of the RCA content in the PC, PFA and SF concretes resulted in the reduction of their modulus of elasticity. The 30 and 50% RCA contents reduced the modulus of elasticity of all mixes regardless of the type of cement used by up to 14 and 22% respectively. The 100% RCA content resulted in the reduction of the modulus of elasticity by up to 40% for both the PC and PFA mixes and 29% for the SF mixes.

The use of PFA improved slightly the modulus of elasticity of low w/c ratio mixes whilst it had no effect on the high w/c ratio mixes. SF does not appear to have any major effect on the modulus of elasticity of concrete; the modulus of elasticity of the majority of PC mixes and their corresponding SF mixes were within the same range.

Using up to 30% RCA has no effect on the shrinkage of PC concrete, beyond this limit the gradual increase of the RCA content resulted in a gradual increase in the shrinkage values of concrete. For the PFA and SF concretes, the shrinkage values increased with the increase in the RCA content. The use of PFA and SF reduced the shrinkage values of all mixes regardless of the RCA content when compared their corresponding PC mixes.

The use of RCA had no effect on the swelling of the PC mixes from the use of RCA while it increased the swelling of the PFA mixes. For the SF mixes, the use of RCA resulted in a slight decrease of swelling deformation. The swelling deformation values were found increasing in the following sequence: PC; PFA; SF.

4. Study the effect of RCA on the durability properties of binary cement designated concrete mixes

The use of up to 30% RCA had no effect on the initial surface absorption of PC, PFA and SF concretes, however beyond this limit the initial surface absorption of the concretes increased with an increase in the RCA content. Overall, the ISA values of the SF mixes were the least affected by the use of high RCA contents followed by the PFA and PC mixes respectively.

Comparing the ISA results of the different mixes showed that for the NA and 30% RCA concrete, the permeability was found decreasing in the following order; SF, PFA, PC. However for the 50 and 100% RCA concrete, the PFA concrete had the lowest ISA results, by up to 20%, when compared to the PC and SF concretes which had approximately the same ISA.

It was found that the use of RCA does not affect the carbonation of PC, PFA and SF concretes. A strong correlation was found between the 28 day cube compressive strength of the concrete and the carbonation depth regardless of the RCA content. However, when binary cements are used, for a given strength, the resistance to carbonation was found decreasing in the following sequence: PC; PFA; SF regardless of the amount of RCA in the mix.

Using up to 30% RCA had no effect on the chloride concentrations of PC and PFA concretes at the 15 - 20 mm depth band. Increasing the RCA content beyond this limit resulted in the increase of the chloride ion content in the concrete. For the SF concrete, the use of RCA had no significant effect on the chloride concentrations at the 15 - 20 mm depth band. PFA and SF partially because of the improvement they bring to the permeability of RCA concrete (50 and 100% RCA) make it less prone to the ingress of chlorides.

The use of RCA increased the expansion of concrete due to sulphate attack. However this increase was very insignificant. Water curing reduced the expansion due to sulphate attack of concrete when compared to air curing. The use of PFA slightly reduced the expansion of concrete due to sulphate attack when compared to concrete made solely of PC.

5. The practical implications for the use of RCA in binary cement concrete.

The findings from this study present the industry with new technical information and advice on the use of RCA in concrete using binary cements, namely PC/PFA and PC/SF. The findings provide an incentive for the construction industry to confidently maximise the use of RCA and binary cements in a variety of concrete applications.

A mix design method that takes into account the effect of RCA on the strength of concrete was used successfully in the study to produce equal strength NA and RCA mixes. This method consists of adjusting the water/cement ratio of the RCA mixes (50 and 100% RCA content). The study has shown that RCA, when used with binary cements, is suitable for the production of a wide range of designated mixes without major detrimental effect to the fresh, engineering and durability performance of the concrete. The study has shown that binary cements composed of Portland cement and industrial by - products namely Pulverised Fuel Ash and Silica Fume can improve the properties of RCA concrete especially when high contents of RCA are used. Furthermore, the use of binary cements, in addition to improving the properties of RCA concrete, adds additional environmental and economical benefits to those derived from the use of RCA.

8.2 RECOMMENDATIONS FOR FURTHER STUDY

Whilst the study has proved the suitability of using RCA without it having a major effect on the majority of the properties of conventional and binary cement concretes, it has also highlighted the need for a more detailed and specialized study on the effect of RCA on certain properties of concrete. Hence further research on the following fields is recommended:

- The loss of workability in RCA binary cement concrete: Achieving the required workability all the time is essential to increase the use of RCA in concrete, this research can look into the effect of the moisture content of RCA on the loss of workability and the effect of using admixtures on the workability of RCA binary cement concrete.

- Pozzolanic additions are widely used to produce high strength concrete; information is required on the effect of RCA on the fresh, engineering and durability properties of high strength binary cement concrete ($> 50\ N/mm^2$).

- If RCA is to be used in structural members, it is essential to study the effect of RCA on the bond strength between different types of reinforcement and binary cement concrete as well as the effect of RCA on the strength development of binary cement concrete as this may influence the formwork striking times.

- Our study showed that binary cement RCA concrete mainly due to its improved permeability can help reduce the effects of the chemical attacks that emanate from its environment, however further studies need to be done on the effect of RCA on the corrosion rate of steel reinforcement in binary cement concrete subject to carbonation, chloride and sulphate attack.

- Long term studies on the effect of RCA on the durability of binary cement concrete exposed to various outdoor conditions should also be undertaken to verify the findings obtained from the accelerated laboratory testing procedures used.

- Finally, to promote the use of RCA and binary cements in concrete, a variety of demonstration and real projects covering a wide range of concrete applications should be undertaken. This will definitely dispel any doubt regarding the suitability of using RCA in concrete and showcase the great environmental benefits that can be achieved when using these materials.

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APPENDIX A

ENGINEERING RESULTS

1. COMPRESSIVE STRENGTH DEVELOPMENT

1.1 Cube and cylinder strength relationship

1.1.1 PC mixes

Table A.1 Cube and cylinder compressive strengths of PC mixes at 28 days.

RCA Content (%)	Cube strength $f_{c,cu}$ (N/mm^2)	Cylinder strength $f_{c,cyl}$ (N/mm^2)	$f_{c,cu}/f_{c,cyl}$ ratio (%)	Average ratio (%)
0	4.8	12.3	39	79
	11.9	15.5	77	
	15.5	24.4	64	
	25.3	24.4	104	
	20.7	25.8	80	
	23.0	25.8	89	
	20.9	24.2	86	
	21.4	30.7	70	
	24.4	30.7	80	
	24.7	30.7	80	
	25.4	32.1	79	
	25.5	32.1	79	
	28.3	32.2	88	
	31.5	38.7	81	
	31.6	38.7	82	
	27.9	29.0	96	
	33.5	49.5	68	
30	5.2	10.1	51	79
	10.9	19.4	56	
	16.5	19.4	85	
	23.5	25.8	91	
	28.7	34.2	84	
	28.3	34.2	83	
	25.0	32.7	76	
	27.5	31.1	88	
	23.4	31.1	75	
	25.6	27.9	92	
	39.0	45.8	85	

Table A.1 (cont.) Cube and cylinder compressive strengths of PC mixes at 28 days.

RCA Content (%)	Cube strength $f_{c,cu}$ (N/mm^2)	Cylinder strength $f_{c,cyl}$ (N/mm^2)	$f_{c,cu}/f_{c,cyl}$ ratio (%)	Average ratio (%)
50	14.3	16.1	88	83
	19.0	16.1	118	
	7.3	9.8	74	
	6.8	9.8	69	
	20.3	25.2	81	
	24.7	25.2	98	
	23.5	27.0	87	
	24.2	34.2	71	
	26.5	34.2	78	
	28.3	34.2	83	
	28.2	35.2	80	
	31.4	35.2	89	
	29.6	40.9	72	
	30.6	42.7	72	
100	13.0	15.0	86	86
	13.5	15.0	90	
	18.3	25.6	72	
	26.2	25.6	102	
	21.6	29.2	74	
	33.9	30.4	111	
	30.6	35.1	87	
	29.4	35.1	84	
	31.3	38.0	82	
	34.8	45.9	76	
Average $f_{c,cu}/f_{c,cyl}$			**81%**	

Table A.2 Cube and cylinder compressive strengths of PC mixes at 56 days.

RCA Content (%)	Cube strength $f_{c,cu}$ (N/mm^2)	Cylinder strength $f_{c,cyl}$ (N/mm^2)	$f_{c,cu}/f_{c,cyl}$ ratio (%)	Average ratio (%)
0	6.3	12.4	51	77
	13.9	17	82	
	14.0	17	82	
	22.3	27.5	81	
	20.6	27.5	75	
	26.9	34.3	78	
	25.0	34.3	73	
	28.2	34.3	82	
	26.6	32.3	82	
	34.3	40.2	85	
30	6.0	10.6	57	79
	19.8	21.4	92	
	19.6	21.4	92	
	27.3	35.6	77	
	27.4	35.5	77	
	34.2	43.9	78	
50	17.8	18.7	95	81
	19.2	18.7	103	
	8.4	11.1	75	
	8.4	11.1	75	
	21.6	27.4	79	
	22.7	27.4	83	
	25.3	38.5	66	
	26.8	35.6	75	
	27.7	35.6	78	
100	15.0	17.5	85	85
	25.4	27	94	
	25.6	27	95	
	22.1	29.7	74	
	23.1	29.7	78	
	31.4	34.5	91	
	34.2	44	78	
Average $f_{c,cu}/f_{c,cyl}$			**80%**	

1.1.2 PFA mixes

Table A.3 Cube and cylinder compressive strengths of PFA mixes at 28 days.

RCA Content (%)	Cube strength $f_{c,cu}$ (N/mm^2)	Cylinder strength $f_{c,cyl}$ (N/mm^2)	$f_{c,cu}/f_{c,cyl}$ ratio (%)	Average ratio (%)
0	12.1	14.5	83	79
	12.5	14.5	86	
	8.1	13.7	59	
	9.1	13.7	67	
	18.4	26.5	70	
	16.9	26.5	64	
	27.1	28.4	95	
	29.7	35.6	83	
	28.7	35.6	81	
	36.1	34.8	104	
	29.4	38.6	76	
	28.5	38.6	74	
	38.0	48.4	79	
	37.2	47.3	79	
30	23.6	28.2	84	80
	22.6	28.2	80	
	31.3	31.8	98	
	26.5	36.7	72	
	29.8	36.7	81	
	30.5	42.6	72	
	35.6	43.4	82	
	35.7	43.4	82	
	35.9	43.4	83	
	25.0	38.5	65	
50	14.4	16.1	90	83
	15.8	28.8	55	
	24.9	27.5	91	
	33.9	37.1	91	
	26.5	39.0	68	
	34.7	39.0	89	
	33.3	39.0	85	
	34.5	36.6	94	
100	13.7	16.9	81	84
	24.4	29.3	83	
	25.8	29.3	88	
	28.9	35.7	81	
	32.7	36.6	89	
	32.4	36.6	89	
	30.8	41.5	74	
Average $f_{c,cu}/f_{c,cyl}$			**81%**	

Table A.4 Cube and cylinder compressive strengths of PFA mixes at 56 days.

RCA Content (%)	Cube strength $f_{c,cu}$ (N/mm^2)	Cylinder strength $f_{c,cyl}$ (N/mm^2)	$f_{c,cu}/f_{c,cyl}$ ratio (%)	Average ratio (%)
	17.0	19.5	61	
	17.4	19.5	71	
0	25.7	33.1	78	81
	35.2	44.1	80	
	34.7	48.4	72	
	31.3	47.7	66	
	39.2	47.7	82	
30	39.7	56.9	70	76
	47.7	58	82	
	45.5	59.1	77	
	47.8	59.1	81	
	16.3	18.9	86	
	21.1	32.6	65	
	22.5	32.6	69	
50	25.6	37	69	76
	28.5	42.3	67	
	33.9	34.3	99	
	37.9	50	76	
	38.2	50	76	
	16.6	19.5	85	
	16.3	19.5	84	
100	25.7	33.6	77	83
	27.1	33.6	81	
	34.7	39.9	87	
Average $f_{c,cu}/f_{c,cyl}$			**78%**	

1.1.3 SF mixes

Table A.5 Cube and cylinder compressive strengths of SF mixes at 28 days.

RCA Content (%)	Cube strength $f_{c,cu}$ (N/mm^2)	Cylinder strength $f_{c,cyl}$ (N/mm^2)	$f_{c,cu}/f_{c,cyl}$ ratio (%)	Average ratio (%)
0	21.1	26	81	83
	29.0	37.5	77	
	31.4	37.7	83	
	32.1	37.7	85	
	39.0	44	89	
30	25.0	27.4	91	85
	22.8	27.4	83	
	35.3	43.8	80	
50	35.3	43	82	76
	32.5	43	76	
	31.2	43.9	71	
	33.5	43.9	76	
	30.0	40.3	74	
100	26.9	28.1	96	89
	28.0	28.1	100	
	27.4	35.2	78	
	31.3	38.2	82	
Average $f_{c,cu}/f_{c,cyl}$			**83%**	

Table A.6 Cube and cylinder compressive strengths of SF mixes at 56 days.

RCA Content (%)	Cube strength $f_{c,cu}$ (N/mm^2)	Cylinder strength $f_{c,cyl}$ (N/mm^2)	$f_{c,cu}/f_{c,cyl}$ ratio (%)	Average ratio (%)
0	24.8	31.1	80	77
	33.7	43.6	77	
	29.9	41.4	72	
	33.4	41.4	81	
30	27.3	34.9	78	78
	27.5	34.9	79	
50	36.8	44.3	83	82
	37.9	44.3	85	
	37.0	45	82	
	35.3	45	79	
100	29.2	32	91	78
	23.1	32	72	
	30.8	40	77	
	29.7	41.5	72	
Average $f_{c,cu}/f_{c,cyl}$			**79%**	

2. FLEXURAL STRENGTH

2.1 Cube and flexural strength relationship

2.1.1 PC mixes

Table A.7 Cube compressive strengths with corresponding flexural strengths of PC mixes at 28 days.

RCA Content (%)	Cube strength $f_{c,cu}$ (N/mm^2)	Flexural strength f_{flex} (N/mm^2)	$f_{c,cu}/f_{flex}$ ratio (%)	Average ratio (%)
0	12.3	3.2	26	17
	12.3	3.0	24	
	24.4	3.7	15	
	25.8	3.8	15	
	24.2	4.1	17	
	30.7	4.7	15	
	32.1	4.3	13	
	32.2	4.5	14	
	38.7	4.8	12	
	29.0	5.1	18	
	49.5	5.9	12	
30	19.4	3.6	18	16
	25.8	4.1	16	
	34.2	4.5	13	
	32.7	4.9	15	
	31.1	5.4	17	
	27.9	4.7	17	
	45.8	6.0	13	
	38.0	5.7	15	
50	16.1	3.8	24	17
	9.8	2.9	29	
	25.2	4.1	16	
	27.0	4.2	16	
	34.2	4.7	14	
	34.2	4.5	13	
	35.2	4.9	14	
	42.7	5.1	12	
100	15.0	2.9	19	15
	25.6	4.5	18	
	29.2	3.9	13	
	30.4	5.1	17	
	35.1	4.7	13	
	38.0	5.7	15	
	45.9	5.9	13	
Average $f_{c,cu}/f_{flex}$			**16%**	

Table A.8 Cube compressive strengths with corresponding flexural strengths of PC mixes at 56 days.

RCA Content (%)	Cube strength $f_{c,cu}$ (N/mm^2)	Flexural strength f_{flex} (N/mm^2)	$f_{c,cu}/f_{flex}$ ratio (%)	Average ratio (%)
0	12.4	2.7	22	18
	12.4	3.0	24	
	17.0	5.0	18	
	27.5	5.4	16	
	34.3	4.4	13	
	32.3	5.3	13	
30	21.4	4.3	20	16
	35.6	4.4	12	
	35.5	5.4	15	
50	18.7	3.5	19	18
	11.1	3.1	28	
	27.4	3.9	14	
	38.5	5.2	14	
	35.6	5.3	15	
100	17.5	3.7	21	17
	27.1	4.7	17	
	29.7	4.1	14	
	34.5	4.8	14	
Average $f_{c,cu}/f_{flex}$			**17%**	

2.1.2 PFA mixes

Table A.9 Cube compressive strengths with corresponding flexural strengths of PFA mixes at 28 days.

RCA Content (%)	Cube strength $f_{c,cu}$ (N/mm²)	Flexural strength f_{flex} (N/mm²)	$f_{c,cu}/f_{flex}$ ratio (%)	Average ratio (%)
0	14.5	2.6	18	17
	10.6	2.6	25	
	10.6	2.6	24	
	13.7	2.8	21	
	26.5	4.6	17	
	28.4	4.0	14	
	35.6	5.1	14	
	34.8	5.5	16	
	38.6	4.7	12	
	47.3	5.9	13	
30	12.3	2.5	20	15
	12.3	2.6	21	
	28.2	3.8	14	
	31.8	4.2	13	
	36.7	4.1	11	
	42.6	5.2	12	
	43.4	5.2	12	
	38.5	5.4	14	
50	16.1	3.5	22	17
	28.8	3.8	13	
	27.5	4.2	15	
	37.1	5.9	16	
	39.0	4.6	12	
	39.0	4.7	12	
100	16.9	3.4	20	14
	29.3	4.3	15	
	35.7	4.8	13	
	36.6	4.9	13	
	36.6	5.3	15	
	41.5	4.0	10	
Average $f_{c,cu}/f_{flex}$			**16%**	

Table A.10 Cube compressive strengths with corresponding flexural strengths of PFA mixes at 56 days.

RCA Content (%)	Cube strength $f_{c,cu}$ (N/mm^2)	Flexural strength f_{flex} (N/mm^2)	$f_{c,cu}/f_{flex}$ ratio (%)	Average ratio (%)
0	19.5	3.5	18	18
	12.0	2.7	23	
	12.0	2.7	23	
	16.4	3.8	23	
	33.1	5.2	16	
	44.1	5.4	12	
	48.4	5.8	12	
30	14.3	2.8	20	15
	14.3	2.8	19	
	47.7	7.0	15	
	50.0	7.1	14	
	59.1	6.2	11	
50	18.9	3.9	20	16
	32.6	5.3	16	
	50.0	5.6	11	
100	19.5	4.4	23	17
	33.6	4.7	14	
	39.9	5.6	14	
Average $f_{c,cu}/f_{flex}$			**17%**	

2.1.3 SF mixes

Table A.11 Cube compressive strengths with corresponding flexural strengths of SF mixes at 28 days.

RCA Content (%)	Cube strength $f_{c,cu}$ (N/mm^2)	Flexural strength f_{flex} (N/mm^2)	$f_{c,cu}/f_{flex}$ ratio (%)	Average ratio (%)
0	17.0	4.2	25	18
	11.1	2.5	22	
	11.1	2.1	19	
	26.0	4.4	17	
	37.5	5.8	15	
	37.7	5.3	14	
	44.0	5.7	13	
30	27.4	4.5	16	14
	38.1	4.8	12	
	43.7	4.8	11	
	43.9	7.0	16	
50	43.0	5.1	12	12
	43.9	5.7	13	
	40.3	4.8	12	
100	28.1	5.0	18	15
	35.2	6.2	18	
	38.3	4.0	10	
Average $f_{c,cu}/f_{flex}$			**16%**	

Table A.12 Cube compressive strengths with corresponding flexural strengths of SF mixes at 56 days.

RCA Content (%)	Cube strength $f_{c,cu}$ (N/mm^2)	Flexural strength f_{flex} (N/mm^2)	$f_{c,cu}/f_{flex}$ ratio (%)	Average ratio (%)
	4.0	21.8	19	
	3.0	13.8	22	
0	5.7	31.1	18	17
	4.4	43.6	10	
	6.3	41.4	15	
	34.9	4.9	14	
30	51.1	6.1	12	12
	46.0	4.9	11	
50	44.3	5.3	12	13
	45	5.9	13	
100	32.0	4.9	15	15
	41.5	6.5	16	
Average $f_{c,cu}/f_{flex}$			**15%**	

3. MODULUS OF ELASTICTY

3.1 Cube and modulus of elasticity relationship

3.1.1 PC Mixes

Table A.13 Cube compressive strengths with corresponding modulus of elasticity of PC mixes at 28 days.

RCA Content (%)	Cube strength (N/mm^2)	Modulus of elasticity (N/mm^2)
0	12.3	17.0
	15.5	16.0
	24.4	19.0
	24.2	18.0
	30.7	19.0
	32.2	18.5
	38.7	20.0
	29.0	19.0
	49.5	18.5
30	19.4	15.5
	25.8	16.5
	34.2	16.5
	32.7	15.5
	31.1	14.0
	27.9	14.5
	45.8	17.0
50	16.1	15.5
	9.8	12.0
	25.2	13.0
	27.0	16.0
	34.2	14.0
	34.2	15.5
	35.2	15.0
	40.9	14.0
	42.7	16.5
100	25.6	11.5
	29.2	12.0
	35.1	12.0
	38.0	12.5
	45.9	15.5

Table A.14 Cube compressive strengths with corresponding modulus of elasticity of PC mixes at 56 days.

RCA Content (%)	Cube strength (N/mm^2)	Modulus of elasticity (N/mm^2)
0	17.0	16.5
	27.5	19.5
	34.3	20.0
	32.3	16.5
	40.2	21.0
30	21.4	16.0
	35.6	18.0
	35.5	18.0
50	18.7	16.0
	27.4	13.5
	38.5	16.5
	35.6	16.5
100	11.5	17.5
	12.0	27.1
	13.5	29.7
	13.0	34.5

Table A.15 Cube compressive strengths with corresponding modulus of elasticity of PFA mixes at 28 days.

RCA Content (%)	Cube strength (N/mm^2)	Modulus of elasticity (N/mm^2)
0	14.5	16.5
	13.7	14.5
	26.5	20.5
	28.4	16.5
	35.6	22.0
	38.6	20.5
	47.3	20.0
30	12.3	15.0
	28.2	17.0
	31.8	20.0
	36.7	17.5
	43.4	20.0
	38.5	16.0
50	16.1	13.5
	27.5	14.5
	37.1	15.5
	39.0	16.5
	39.0	16.5
	36.6	18.5
100	16.9	10.0
	29.3	13.5
	44.0	16.0
	35.7	12.5
	36.6	13.5
	36.7	14.0

Table A.16 Cube compressive strengths with corresponding modulus of elasticity of PFA mixes at 56 days.

RCA Content (%)	Cube strength (N/mm^2)	Modulus of elasticity (N/mm^2)
0	19.5	19.5
	12.0	18.5
	33.1	22.0
	44.1	23.5
	48.4	23.0
30	14.3	14.5
	47.7	20.5
	50.0	22.0
	59.1	21.0
50	18.9	17.0
	32.6	16.0
	42.3	19.5
100	19.5	12.0
	33.6	16.0
	39.9	13.5

Table A.17 Cube compressive strengths with corresponding modulus of elasticity of SF mixes at 28 days.

RCA Content (%)	Cube strength (N/mm^2)	Modulus of elasticity (N/mm^2)
0	37.5	17.5
	37.5	17.5
	37.7	20.0
	37.7	19.0
	44.0	19.0
30	27.4	16.5
	27.4	16.5
	43.9	20.0
50	43.0	15.5
	43.9	17.0
	43.9	17.0
100	28.1	12.5
	28.1	12.5
	35.2	15.0
	35.2	15.0
	38.3	13.0

Table A.18 Cube compressive strengths with corresponding modulus of elasticity of SF mixes at 56 days.

RCA Content (%)	Cube strength (N/mm^2)	Modulus of elasticity (N/mm^2)
0	31.1	18.0
	31.1	18.0
	43.6	20.0
	43.6	18.5
	41.4	19.0
	41.4	19.0
30	34.9	15.5
	34.9	15.5
50	28.0	15.0
	44.3	17.5
	44.3	17.5
	45.0	18.0
	45.0	17.0
100	32.0	14.5
	32.0	14.5
	40.0	12.5
	41.5	15.0

APPENDIX B

DURABILITY RESULTS

1. INITIAL SURFACE ABSORPTION

1.1 PC mixes

Table B.1 ISA – 30 results of PC designated mixes at 28 days.

Designated mix	ISA -30 ($\times10^{-2}$ ml/m^2/sec) Coarse RCA content, % 0	30	50	100
GEN 1	46	77	78	84
GEN3	29	37	63	63
RC 30	25	30	53	59
RC 35	21	31	47	36
RC 40	17	22	46	35

Table B.2 ISA – 60 results of PC designated mixes at 28 days.

Designated mix	ISA -60 ($\times10^{-2}$ ml/m^2/sec) Coarse RCA content, % 0	30	50	100
GEN 1	34	56	60	64
GEN3	23	28	49	46
RC 30	19	23	41	43
RC 35	17	24	37	24
RC 40	14	17	37	23

1.2 PFA mixes

Table B.3 ISA – 30 results of PFA designated mixes at 28 days.

Designated mix	ISA -30 ($\times10^{-2}$ ml/m^2/sec) Coarse RCA content, %			
	0	**30**	**50**	**100**
GEN 1	51	61	58	67
GEN3	34	30	37	41
RC 30	26	25	30	29
RC 35	25	18	26	30

Table B.4 ISA – 60 results of PFA designated mixes at 28 days.

Designated mix	ISA -60 ($\times10^{-2}$ ml/m^2/sec) Coarse RCA content, %			
	0	**30**	**50**	**100**
GEN 1	38	46	44	50
GEN3	23	23	29	30
RC 30	17	18	24	22
RC 35	17	13	21	23

1.3 SF mixes

Table B.5 ISA – 30 results of SF designated mixes at 28 days.

Designated mix	ISA -30 ($\times 10^{-2}$ ml/m^2/sec)			
	Coarse RCA content, %			
	0	30	50	100
RC 30	35	32	41	45
RC 35	35	38	35	40

Table B.6 ISA – 60 results of SF designated mixes at 28 days.

Designated mix	ISA -60 ($\times 10^{-2}$ ml/m^2/sec)			
	Coarse RCA content, %			
	0	30	50	100
RC 30	26	24	29	32
RC 35	25	26	25	29