USE OF RECYCLED AND SECONDARY AGGREGATES IN CONCRETE: DEFORMATION PROPERTIES

by

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ABSTRACT

The characteristics of recycled and secondary aggregates: coarse recycled concrete aggregate (RCA), fine glass cullet aggregate (GCA) and fine copper slag aggregate (CSA), and their effects on concrete deformation properties: elastic modulus, creep and shrinkage, have been studied. A novel *Analytical Systemisation* method was developed for the analysis and evaluation of the results sourced from 713 studies, undertaken by 960 authors from 537 institutions in 46 countries during 1972–2017, forming a data matrix having over 400,000 data points. Aggregate physical properties were found to be affected by the crushing process, more so for RCA than GCA and CSA. It was found that RCA reduces the resistance of concrete to deformation, whilst GCA and CSA result in no change or an improvement. The change in the deformation was shown to be affected by aggregate content, concrete strength and other factors. Most of the existing models were found not to consider the aggregate effect in estimating the deformation of concrete. Three new empirical models, essentially based on aggregate stiffness in the form of aggregate absorption, aggregate content and its ratio to cement content, have been developed for estimating the deformation of concrete made with aggregate suitable for use in structural concrete.

This thesis is dedicated to

Mrs. Dhir

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

A/C	Aggregate/cement ratio
A_C	Cross-sectional area of the member
ANN	Artificial neural networks
α_c	Cement-dependent coefficient
α_{agg}	Proportion of aggregate
α_{RH}	Coefficient depending on the ambient environment
$\beta_{A/C}$	Coefficient relevant to the aggregate/cement ratio
β_{agg}	Coefficient relevant to the aggregate factor
β_{as}	Coefficient to describe the development of autogenous shrinkage
β_c	Coefficient to describe the development of creep
β_{ca}	Coefficient relevant to the coarse aggregate
β_{ds}	Coefficient to describe the development of drying shrinkage
β_{fa}	Coefficient relevant to the fine aggregate
β_H	Coefficient depending on the relative humidity
$\beta(f_{cm})$	Coefficient relevant to the concrete strength
$\beta(t_0)$	Coefficient for the effect of concrete age
CDEW	Construction, demolition and excavation waste
CDRA	Construction and demolition recycled aggregates
CS	Copper slag
CSA	Copper slag aggregate
CRT	Cathode ray tubes
D	Aggregate upper sieve size
d	Aggregate lower sieve size
E_C	Elastic modulus of concrete
EU	European Union
Eq	Equation
ε_{ca}	Autogenous shrinkage strain
ε_{cc}	Creep strain
ε_{cd}	Drying shrinkage strain
$\varepsilon_{cd,0}$	Basic drying shrinkage strain

ε_{ci}	Initial elastic strain
FA	Fly ash
f_c'	Specified cylinder strength
f_{ck}	Characteristic compressive cylinder strength
f_{cm}	Mean compressive cylinder strength
f_{cu}	Mean compressive cube strength
GC	Glass cullet
GCA	Glass cullet aggregate
GGBS	Ground granulated blast furnace slag
h_0	Notional size of the member
J	Compliance
LCD	Liquid crystal displays
LS	Limestone powder
MAPE	Mean absolute percentage error
MBE	Mean bias error
MRA	Mixed recycled aggregate
NA	Natural aggregate
n.d.	No date
φ	Creep coefficient
φ_0	Notional creep coefficient
φ_{RH}	Relative humidity factor
PC	Portland cement
PSD	Particle size distribution
R^2	Coefficient of determination
R^2_{adj}	Adjusted coefficient of determination
RA	Recycled aggregate
RCA	Recycled concrete aggregate
RH	Relative humidity
RMA	Recycled masonry aggregate
RMSE	Root mean square error
RSA	Recycled and secondary aggregate
SF	Silica fume
SSD	Saturated surface dry

σ_c	Stress in compression
t	Age of concrete at the moment considered
t_s	Age of the concrete at the beginning of drying (when curing ceased)
t_0	Age of concrete at loading
u	Perimeter of the member in contact with the atmosphere
w_{agg}	Water absorption of aggregate
W/C	Water/cement ratio
w_{ca}	Water absorption of coarse aggregate
w_{fa}	Water absorption of fine aggregate
WLS	Weighted least squares

LIST OF PUBLICATIONS

1. Lye C Q, Dhir R K, Mangabhai R and Koh S K, 2015. Use of copper slag and washed copper slag as sand in concrete: a state-of-the-art review Institution of Civil Engineers Journal, Magazine of Concrete Research 67 (12), 665-679.

2. Lye C Q, Dhir R K and Ghataora G S, 2015. Carbonation resistance of fly ash concrete. Institution of Civil Engineers Journal, Magazine of Concrete Research 67 (21), 1150-1178.

3. Lye C Q, Dhir R K and Ghataora G S, 2016. Carbonation resistance of GGBS concrete. Institution of Civil Engineers Journal, Magazine of Concrete Research 68 (18), 936-969.

4. Lye C Q, Dhir R K and Ghataora G S, 2016. Elastic modulus of concrete made with recycled aggregates. Proceedings of Institution of Civil Engineers, Structures and Buildings 169(5), 314-339.

5. Lye C Q, Dhir R K, Ghataora G S and Li H, 2016. Creep strain of recycled aggregate concrete. Construction and Building Materials 102, 244-259

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Sand, gravel and rock, which are used as aggregates in construction, take thousands of years to form. These naturally occurring resources represent a significant proportion of the total building materials used in the construction industry as low-cost inert aggregate fill material in concrete, geotechnical and road pavement applications. Globally, the annual aggregate production is estimated to be about 50 billion tonnes and is projected to grow at a rate of 5% yearly (Dhir et al., 2016). The increase is not unexpected, as three-fifths of the world still seeks to bring its infrastructure standard on par with that of the developed countries.

Considering concrete, the most consumed human-made material on earth, its annual production rate was reported in 2009 to be approximately 25 billion tonnes worldwide (World Business Council for Sustainable Development, 2009). As aggregates typically occupy about 70% of the volume or 75% of the weight of concrete, this would suggest that nearly 19 billion tonnes of aggregate, or one-third of the global aggregate production, are consumed in concrete production alone. A direct engineering solution to minimise the consumption of natural aggregate is to develop the use of recycled and secondary aggregates (RSA). However, these materials have not been widely accepted in practice and their adoption is slow. For example, at a regional level, the use of RSA amongst the European nations remained relatively stagnant at about 8%

of 3.5 billion tonnes produced in 2008 to 7% of 3.8 billion tonnes produced in 2014 (Figure 1.1). This is devastating as 'recycled aggregate' and 'manufactured aggregate' for use in concrete were introduced by the European Committee for Standardization in 2002 (EN 12620, 2008). Perhaps the pertinent question to answer should be why the construction industry is still sceptical about using RSA in concrete applications.

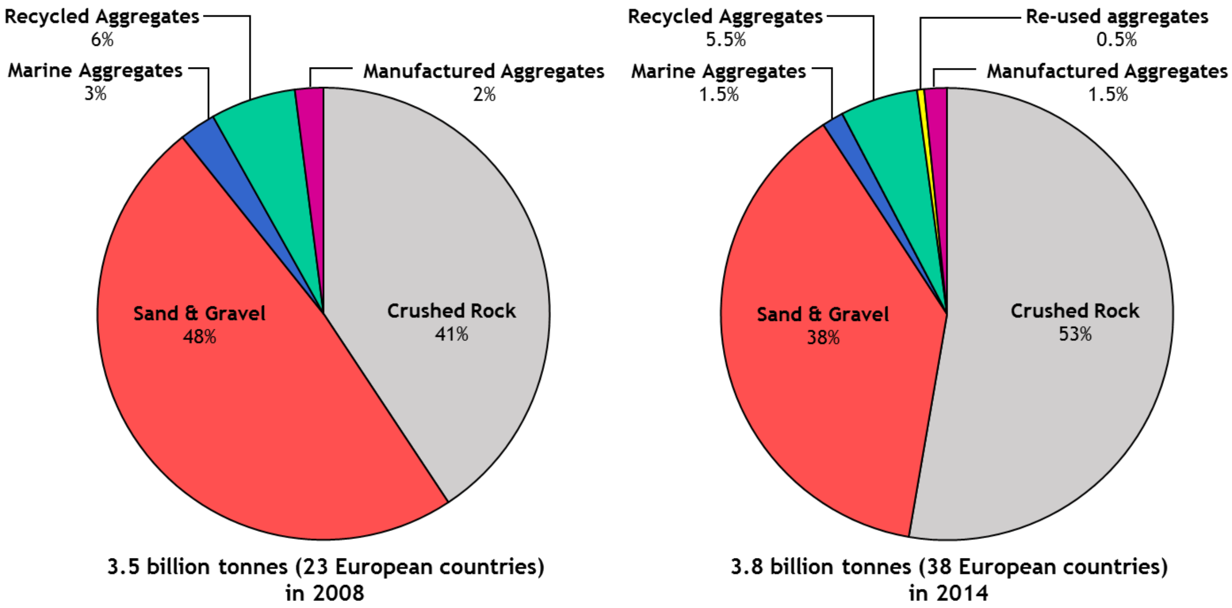


Figure 1.1 Total aggregate production in European countries in 2008 and 2014 (UEPG, 2016)

Dhir (2015) reported that over 6000 research papers related to RSA have been published globally during the past 40 years. Thus, it would appear that the construction industry has not been fully benefiting from the findings arising from the research accumulated over the years. Indeed, there should have been a call for a change in approach and attitude in the direction of research to more proactively encourage the use of sustainable materials in the construction industry.

1.2 RECYCLED AND SECONDARY AGGREGATES

As the name suggests, RSA consists of two major components: (i) recycled aggregates, arising from construction, demolition and excavation waste (CDEW), such as concrete and masonry bricks, and (ii) secondary aggregates, by-products resulting from an industrial process or granular material that have not been previously used as aggregates, such as incinerator bottom ash and granulated blast furnace slag.

In this study, three different types of RSA, namely coarse recycled concrete aggregate (RCA), fine glass cullet aggregate (GCA) and fine copper slag aggregate (CSA), were selected as the research subject. A description of these materials, as well as their production and recovery rate, is given next.

1.2.1 Recycled Aggregates

Recycled aggregate (RA) is the generic term that describes the processed aggregate arising from CDEW. Depending on its main composition, RA can be categorised into four different types (Silva et al., 2014):

(i) Recycled concrete aggregate (RCA): derived from crushed concrete made with natural aggregates

(ii) Recycled masonry aggregate (RMA): derived from masonry rubble, including ceramic bricks and sand–lime bricks

(iii) Mixed recycled aggregates (MRA): composed of a mixture of RCA and RMA

(iv) Construction and demolition recycled aggregates (CDRA): unsorted or unprocessed CDEW with high contaminants of foreign materials such as glass, plastics and woods

The global data for RA generated from construction, demolition and excavation activities are not well documented, as the definitions, classifications and measurement methods of the waste vary across countries, though typically, RA accounts for 80% of demolition waste (BRE, 2006). Notwithstanding this, the data for CDEW generated and its recovery rate in regions with high construction activities, such as China, Europe, the United States and India, together with a few other countries, reported during 2011–2015 are shown in Figure 1.2. This shows that only 38% of the total 2.5 billion tonnes of CDEW generated was recovered. The recovery rate in Japan, Singapore and the Netherlands (highest in the EU) was more than 95%, whilst that of China, South Africa and Greece (lowest in the EU) was less than 20%.

1.2.2 Glass Cullet

Glass cullet (GC), which is a processed waste glass, can be sourced within glass manufacturing plants as rejects and from recycling plants as post-consumer glass. GC is normally used as part of the raw materials in making new glass, as every 10% of GC addition reduces by 2.5% to 3.0% the energy consumption required for melting virgin raw materials (Scalet et al., 2015). This is known as closed-loop recycling, and it is practiced worldwide. Depending on the glass type and application, the amounts of GC used in re-melting can vary from 20% to 95% (De Jong et al., 2011).

Within the glass industry, the production of container glass such as bottles, jars and flagons, for use in the packaging industry, is the major sector. During the period of 2011 to 2015, the consumption of container glass in Europe, the United States and a

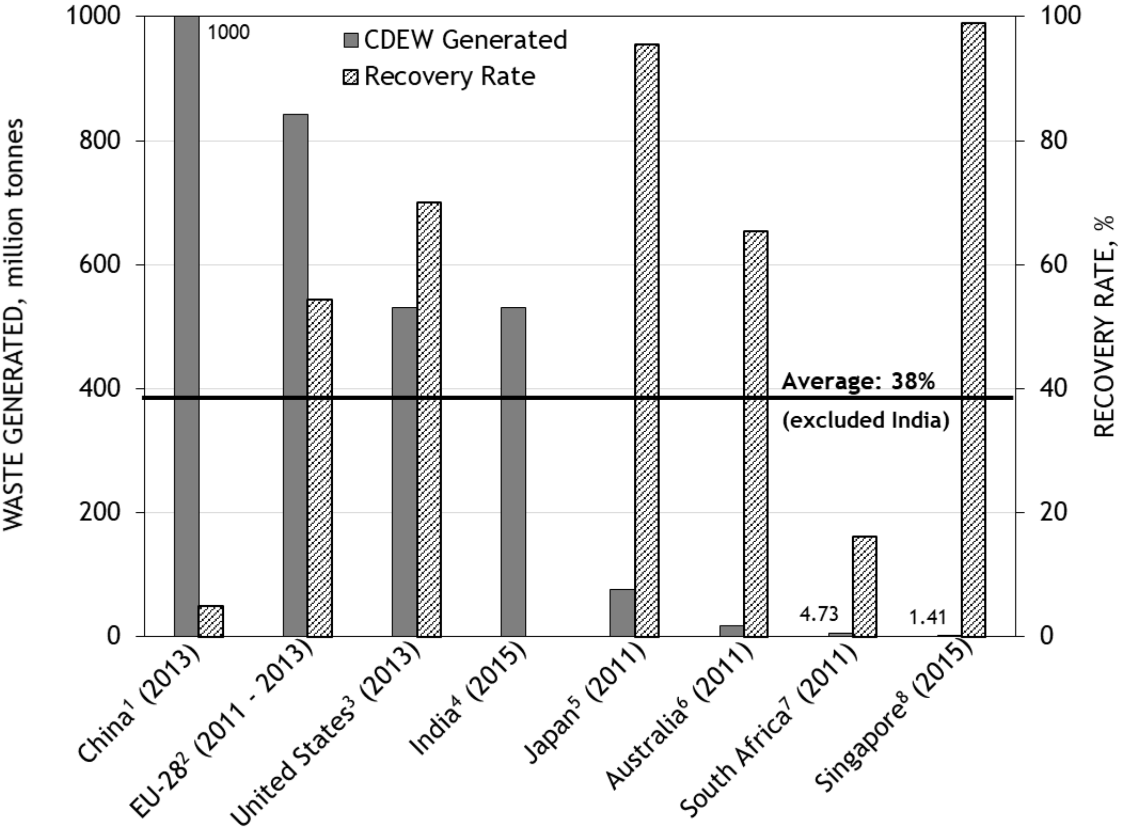


Figure 1.2 Generation and recovery rate of CDEW

Data taken from: [1] Duan H and Li J (2016), based on a report from National Development and Reform Commission of China; [2] European Commission (2015); [3] US EPA (2015) for waste generation, CDRA (2014) for recycling rate; [4] Ministry of Environment and Forest (2016), no reliable recovery rate is available; [5] MLIT (2014); [6] Department of the Environment and Energy (2013); [7] DEA (2012); [8] NEA (2015).

few countries in other continents was 29.4 million tonnes (Figure 1.3). On average, the recovery rate of container glass was 56%. The relatively high glass recovery rate in Europe is perhaps due to the implementation of the EU directive on packaging and packaging waste (94/62/EC), which has set a minimum target of 60% recycling rate for the member states, though a few countries, such as Hungary and Malta, have a rate of less than 40% (FEVE, 2015).

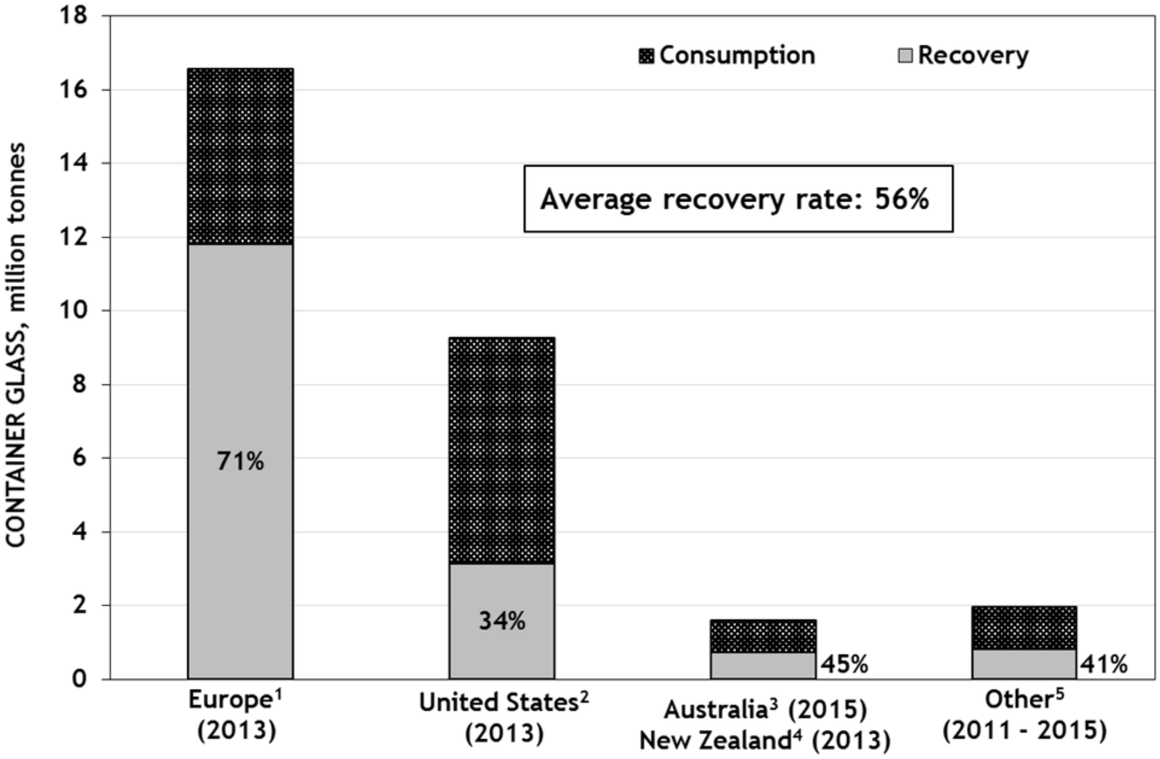


Figure 1.3 Consumption and recovery rate of container glass

Data taken from [1] Based on FEVE (2015), Consumption is defined as local production + imports – exports; [2] US EPA (2015), Content in municipal solid waste; [3] APC (2015), Local production + imports; [4] Glass Packaging Forum (2014), Total consumption; [5] Brazil: CEMPRE (2013), Local production; [5] Singapore: NEA (2016), Content in solid waste; [5] South Africa: GreenCape (2015), Local production + imports – exports.

There is no doubt that closed-loop recycling for GC is the best sustainability solution. However, such practice is often restricted by several issues such as the presence of non-glass material components, commingling of different glass types, colour contamination and imbalance of supply and demand (Vieitez et al., 2011). Thus, the development of alternative markets for GC, which can be based on its physical properties, chemical properties and properties at elevated temperature (Dhir and Dyer, 2003), is deemed necessary in dealing with this valuable resource.

1.2.3 Copper Slag

Copper slag (CS) is a by-product resulting from smelting, converting and fire-refining processes during the production of copper. For every tonne of copper produced about 2.2 tonnes of CS is generated (Gorai et al., 2003). In 2014, Asia accounted for nearly 60% of the global CS production of 40 million tonnes (Figure 1.4). This was followed by Europe and America, with almost similar shares of 18% of the CS produced.

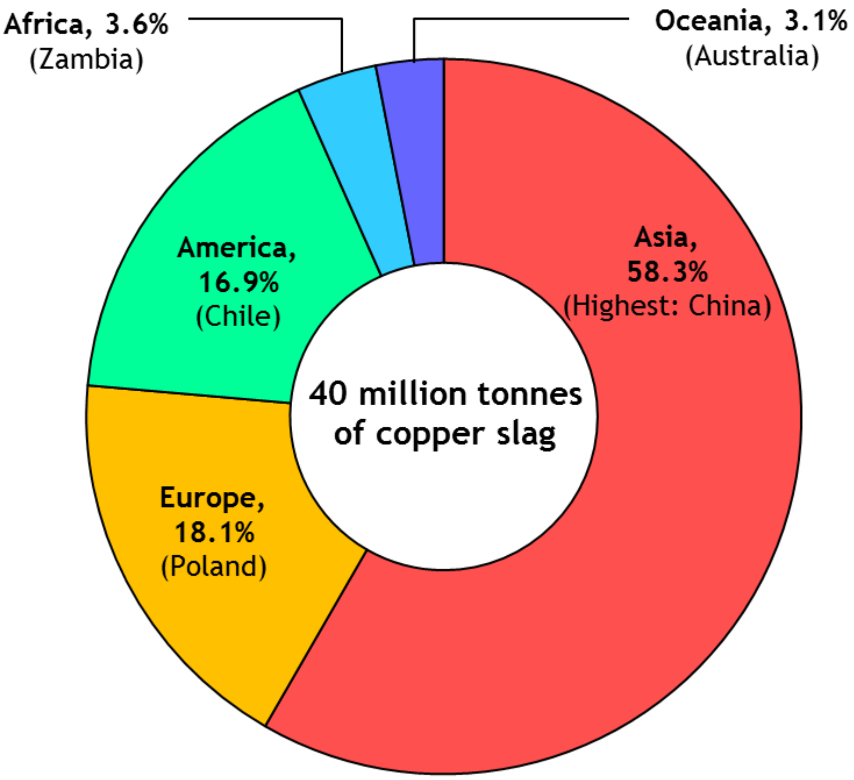


Figure 1.4 Global copper slag production in 2014 (Dhir et al., 2016)

The recovery rate of CS is not available. In general, though, CS containing more than 1% copper is treated for copper recovery, whilst CS with less than 1% copper is sent for other industrial applications or disposed of (Dhir et al., 2016). The slag can appear in two forms through (i) the slow air-cooling process, in which it solidifies into a large bulky crystalline material, and (ii) rapid cooling by water quenching processes, in which it forms as a sand-like granular amorphous material (Dhir et al., 2016). The latter can be used as an abrasive for blasting to remove rust, paint and marine growth on ships. The spent slag, after treatment, can be used as a sand in concrete, which is particularly common in the construction industry in Singapore (BCA, 2012).

1.3 DEFORMATION OF CONCRETE

After strength, the deformation of concrete is important in structural design as it affects the deflection of structural members, as well as the overall integrity of structures. During its service life, concrete experiences various forms of volume changes due to hydration chemistry, loading, time and ambient conditions. Figure 1.5 shows some of the dominant types of deformation strain that occur in concrete at different stages, under normal circumstances. Each of the strain types is described next.

Plastic Shrinkage

After placing, while concrete is still in a plastic stage, the internal water of the concrete tends to move upwards to its surface, which is known as bleeding. At the same time, the water on the surface of the concrete evaporates. Insufficient curing can cause the rate of evaporation to be higher than that of bleeding; thus the surface of the concrete experiences a net loss of water, resulting in a reduction in volume. Such contraction is restrained by the underlying main body of concrete, and it can lead to the formation of plastic shrinkage cracks due to the built-up tensile stresses.

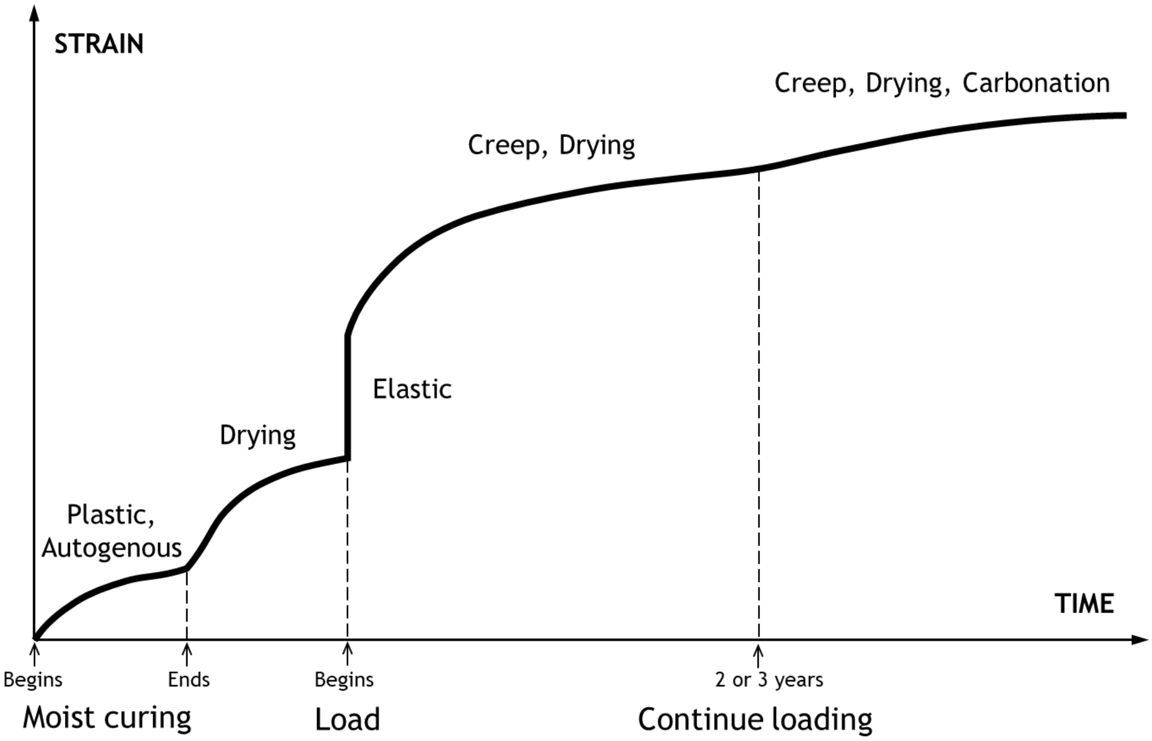


Figure 1.5 Dominant types of deformation strain that occur in concrete (Illustration not to scale)

Autogenous Shrinkage

During the hydration of cement, concrete undergoes autogenous shrinkage, which does not involve moisture exchange with the surrounding environment, temperature variations or influences of external forces (Tazawa, 1999). This volume change associates with two closely related mechanisms, namely chemical shrinkage and self-desiccation (Lamond and Pielert, 2006). The former is due to the volume of the hydration products being less than the sum of that of the unhydrated cement and water. The latter is a result of the consumption of water from capillary pores during the cement hydration process. Autogenous shrinkage is more significant in concrete with a low water/cement ratio (Neville, 1995).

Drying Shrinkage

Water can exist in concrete in three forms: (i) hydrated water, chemically bound to the hydration products; (ii) gel water, physically adsorbed onto the surface of the hydration products and the interlayer between them; and (iii) free water, present in the capillary pores (ACI, 2005; De Schutter, 2013). When moist curing ceases, the withdrawal of water, mostly the free water, from the cement paste system to the surrounding environment causes drying shrinkage in hardened concrete.

Carbonation Shrinkage

Carbonation of concrete is commonly associated with the corrosion of steel reinforcement due to the reduction of the pH in concrete, but it can also cause a shrinkage in concrete. Carbonation takes place in concrete when carbon dioxide combines with water to form carbonic acid, which reacts with calcium hydroxide, $Ca(OH)_2$, in the hydrated cement paste to form calcium carbonate. The dissolution of $Ca(OH)_2$ crystals in stressed regions is probably the cause of shrinkage during the carbonation process (Domone and Illston, 2010). Carbonation and the induced shrinkage are normally a slow process, their rates depend on the concrete design and exposure conditions.

Elastic Strain

When a load is applied to concrete, it deforms instantaneously, and its stress–strain response is quasi-linear. In design practice, however, it is assumed that the stress–strain relationship is linear at low load levels (Lamond and Pielert, 2006). Thus, the deformation at this stage is considered to be elastic. This elastic deformation is expressed as the modulus of elasticity, which is determined from the slope of the line connecting two specified points on a stress–strain curve after several loading–unloading cycles as specified in the standards. The upper point is a stress at 40% ASTM C469 (2014), or one-third of the strength of concrete as specified in BS EN 12390-13 (2013). Correspondingly, the lower point is a stress at 50 µ longitudinal strain, or at least either 0.5 MPa or 10% of the strength of concrete.

Creep

Under a sustained load, concrete undergoes an increase in strain with time, and this phenomenon is known as creep. It is different to elastic strain, which occurs at the time of application of load. There are three stages of creep, namely, primary creep, in which the creep increases at a decreasing rate; secondary creep, in which the creep rate is steady; and tertiary creep, which may occur if there is an increase in stress (Neville et al., 1983). Concrete normally experiences the first two creep stages. Depending on the ambient humidity of the surroundings, concrete can exhibit two types of creep. *Basic creep* occurs when there is no moisture movement to the surrounding environment, whilst *drying creep* is an additional deformation not accounted for by shrinkage under drying conditions (Neville et al., 1983).

Overall, deformation in concrete takes place in hydrated cement paste, which is a porous and weak component. Aggregate, on the other hand, restrains the deformation and provides dimensional stability to concrete. Like natural aggregate, RSA can also provide different degrees of restraining effect, depending on its physical properties, particularly the stiffness. Thus, it is important to establish how the deformation properties of concrete may change when RSA is used.

1.4 AIM AND OBJECTIVES

The main aim of this research is to study the effects of using RSA on the deformation properties of concrete and to develop a simple, yet reliable and practical, model for use in structural concrete design, for each of the deformation properties investigated.

The selected RSA in this study are coarse recycled concrete aggregates (RCA), fine glass cullet aggregate (GCA) and fine copper slag aggregate (CSA), representing the main spread of sustainable construction materials that are potentially suitable for use in structural concrete. Three deformation properties of concrete, which are normally used in structural designs, are studied, namely load-dependent and elastic deformation expressed as modulus of elasticity, load- and time-dependent deformation expressed as creep; and load-independent deformation with time, expressed as shrinkage.

The approach adopted is novel and different to the norm, named the *Analytical Systemisation* method. Experimental results sourced globally from published literature, which was, in effect, perceived to play the role of a quasi-virtual global laboratory, were used in this study. The methodology adopted captures the variability in concrete, which is more representative of real conditions and the tests normally deployed in the research. Indeed, a similar approach is commonly adopted in the medical field and government policy making machinery, but it has not been used in research in the field of civil engineering in general and in concrete research in particular.

The following objectives have been set to achieve the main aim of this study:

- Conduct a near-exhaustive search of the global experimental results in the relevant subject areas, published in the English medium.
- Design clearly structured and well-defined procedures to handle the large volume of data.
- Undertake critical analysis and evaluation of the material characteristics and the deformation properties of concrete made with RSA.
- Seek peer review, by the experts in the field, to further improve the work undertaken and establish standing of the work within the peer community with the comments received.
- Through progressive and timely publishing of the work in reputable and prestigious journals, seek to disseminate the research findings into the public domain.
- Develop a practical, yet simple, model for estimating elastic modulus, creep and shrinkage of concrete made with RSA, as well as NA.

- Direct the work such that the emerging models, possibly with some modifications, can work for concrete made with any form of aggregate that is suitable for making structural concrete.

1.5 LAYOUT OF THESIS

The thesis consists of nine chapters, as described below.

Chapter 1 provides the background information of the three chosen RSAs, namely, coarse RCA, fine GCA and fine CSA. The various types of deformation experienced by a concrete during its service life are also discussed.

Chapter 2 gives the details of the research method adopted, named the *Analytical Systemisation* method.

Chapter 3 presents the definition and physical characteristics of RSA, and compares them with NA.

Chapters 4 to 6 present the analysed experimental data for elastic modulus, creep and shrinkage, respectively, of concrete made with RSA as a replacement for NA.

Chapter 7 discusses the existing models for the estimation of the deformation properties of concrete adopted by various countries or developed by individual researchers. Additionally, three models are chosen to assess their accuracy and error measures in estimating the deformation of concrete made with RSA, as well as NA.

Chapter 8 presents three new empirical models for estimating separately the elastic modulus, creep and shrinkage of concrete, which are designed to work with concrete made with a wide range of aggregates, such as natural, recycled and secondary aggregates, or a mixture thereof.

Chapter 9 presents the conclusions and practical implications emerging from this research and provides recommendations for further study.

CHAPTER 2

METHODOLOGY

2.1 INTRODUCTION

This chapter describes the methodology used in this work, which is different to the commonly adopted experimental approach in most doctoral research projects in the field of concrete technology. Such an approach, although important and equitable, is not the only method to undertake in experimental research to understand a phenomenon or mechanism, or to attempt to bring a resolution to a problem. Indeed, at some point, the need of a study is no longer best served by adding yet more experimental data produced from a further series of laboratory tests, but rather by the analysis of the data that have already been produced globally from a large number of studies undertaken over the years. To undertake research for this study, a dedicated *Analytical Systematisation* methodology was developed, the main parts of which are described below.

There has been an estimated 6000 papers published on the subject of recycled and secondary aggregates (RSA) during the past 40 years (Dhir, 2015). However, much of the data remain fragmented and under-valued, to the extent that progress in the use of RSA in practice has been unacceptably slow, and the materials continue to suffer from poor perception; consequently construction is still lacking sustainability. Taking the scenario in Europe, for instance, the production of RSA is less than one-tenth of the total 3.8 billion tonnes of aggregate generated in 2014 (UEPG, 2016).

The aforementioned example points to the need for a different and novel approach to research using globally produced data as opposed to just those arising from a single test programme with a limited scope undertaken over a short period of time. The *Analytical Systemisation* method, on the other hand, through a clearly structured approach in the analysis and evaluation of global data, provides a much wider scope to conduct this timely research on the deformation properties of concrete made with RSA and to study how the use of such materials can be adopted within the existing design codes.

In addition, this method makes it possible to propose meaningful and easy-to-use models for estimating the elastic modulus, creep and shrinkage of concrete made with a wider range of aggregates manufactured from natural, recycled and secondary materials.

2.2 ANALYTICAL SYSTEMISATION

The *Analytical Systemisation* method essentially consists of four main tasks, which may, as a simplified analogy illustrated in Figure 2.1, be represented by the shape of a sand-filled hourglass. The wide top of the hourglass represents where the project starts broadly by extensively sourcing globally published data on the subject of coarse recycled concrete aggregate (RCA), fine glass cullet aggregate (GCA) and fine copper slag aggregate (CSA) and their use in construction applications. The upper neck of the hourglass narrows, and so does the focus of the study, wherein the sourced data are carefully vetted and sorted in building a complete data matrix. Thereafter, the lower

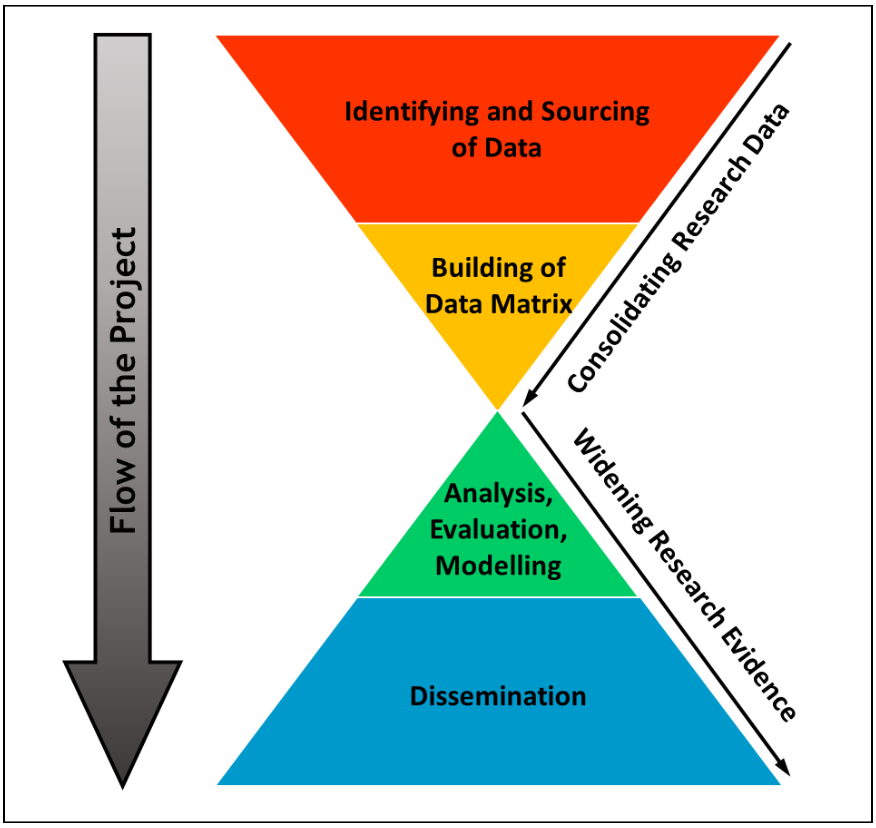


Figure 2.1 Outline of the flow of the project using the analogy of an hourglass

neck of the hourglass broadens out, where the findings are effectively viewed as by a wide-angle lens through comprehensive analysis and evaluation of the collective data, followed by modelling work. The wide bottom of the hourglass is taken to represent, as an integral part of the study, the dissemination of the research output into the public domain, for its eventual use, it is hoped, in practice.

An additional perceived potential strength of the *Analytical Systemisation* method is in its ability to focus clearly on what is known, thereby avoiding repetitive research, whilst conserving research resources, as well as its ability to identify knowledge gaps and thus provide clear directions for the research needed in the future.

2.2.1 Identifying and Sourcing of the Data

This is the first, and in effect the most important, step of the methodology. It aims to bring together the global data into one base; and thus for the study to be effective and capable of inspiring peer confidence, the search for data sources must be exhaustive and wide-reaching.

This is achieved by using a detailed list of relevant keywords, together with planned search engines, and in combinations to maximise the search capacity at each stage. In this search, in this case, journal papers were given a priority, whilst the search included conference papers, as well as technical reports from established organisations. Apart from this, the references provided in each sourced publication were also used to further widen the search. In the event that the identified publications were not available from the Internet, the inter-library loan services provided by the University's library were used. The entire search was judged to be exhaustive when the search results became insignificant for the time spent. That said, for practical reasons, the search was confined to the English medium, though in future, with greater maturity, and on an ongoing basis, data published in other dominant languages in the field, such as Japanese and Spanish, can be included.

In total, over 4000 publications were sourced, providing a wide coverage on the use of RCA, GCA and CSA as natural aggregate replacements in various construction applications, mainly concrete, geotechnical, road pavement and ceramics applications, as well as the relevant case studies and associated environmental assessments. As the focus of this study was on the deformation of concrete containing RSA, a total of

713 publications relevant to elastic modulus, creep and shrinkage of RSA concrete, as well as the physical characteristics of RSA, were used. As for the rest of the publications, though not referred to herein, they are saved for future use, after the completion of this study, for continuous personal development. Owing to the nature of the project, 18 standards and specifications and 58 supplementary references have also been included in the present study. The nature of the data used in this study and cited herein is summarised in Table 2.1

It is evident from Table 2.1 that, on a global scale, the majority of the research centres around RCA; this is followed by GCA and CSA. Although different in number, the nature of the background information of the sourced publications for these three materials showed some commonalities. Overall, the data have been published by 960 researchers, from about 537 institution and established organisations across 46 countries, over a period of 45 years. A few points of interest emerging from Table 2.1 are stated below.

- Although the work was first published around the 1970s, the real research interest in RCA, GCA and CSA in the subject area of this study started to pick up in the mid-1990s, and thereafter the rate of publications showed a steady growth. In all three cases, the peak of the publication rate occurred between the early and the mid-2010s. Thus, the data have relevance to the current period.

- A significant proportion of the work (more than half) has been carried out in Asia, followed by Europe. However, the United States was the champion in the areas of

Table 2.1 Background information of the publications used in this study

PARAMETER	COVERAGE	HIGHEST FREQUENCY
Recycled Concrete Aggregate (404)*		
Year	1977 – 2017	2013 (54)*; 2014 (43); 2011/2012 (31)
Countries	46 (55% Asia; 30% Europe)	USA (40); Spain (38); China (32)
Authors	453 Authors	J. De Brito (25); C. S. Poon (25); R.K. Dhir /S.C. Kou (22)
Institutions/ Organisations	282	The Hong Kong Polytechnic University (63); Technical University of Lisbon (55); University of Dundee (35)
Publication Types	Journal papers (68%); Conference papers (26%); Report (5%); Others (1%)	Construction and Building Materials (62); Journal of Materials in Civil Engineering (18); Magazine of Concrete Research/ Materials and Structures (16)
Glass Cullet (176)		
Year	1972 - 2017	2015 (24); 2014 (22); 2013 (19)
Countries	31 (55% Asia; 29% Europe)	USA (25); Hong Kong (21); UK (18)
Authors	241 Authors	C.S. Poon (19); T.C. Ling (16); A. Tagnit-Hamou/ H.Y. Wang (9)
Institutions/ Organisations	141	The Hong Kong Polytechnic University (51); University of Dundee (22); National Kaohsiung University of Applied Sciences (19)
Publication Types	Journal papers (84%); Conference papers (8%); Reports (3%); Others (5%)	Construction and Building Materials (33); Cement and Concrete Composites (18); Cement and Concrete Research (9)
Copper Slag (133)		
Year	1980 - 2016	2015 (28); 2014 (20); 2013 (18)
Countries	18 (61 % Asia; 22% Europe)	India (78); Singapore (11); Japan (9)
Authors	266 Authors	K.S. Al-Jabri (6); M.Shoya (5); V.F. Havanagi (4)
Institutions/ Organisations	114	Central Road Research Institute (21); Sultan Qaboos University (18); Hachinohe Institute of Technology (16)
Publication Types	Journal papers (74%); Conference paper (20%); Report (5%); Others (1%)	Construction and Building Materials (8); International Journal of Engineering Research & Technology (4); International Journal of Research in Engineering and Technology (4)

* Number in the parenthesis is the number of publications.

both RCA and GCA, whilst India was dominant in the case of CSA. Overall, Canada, Hong Kong, Japan, Portugal, the United Kingdom and the United States are considered active in the research field.

- R.K. Dhir from the University of Dundee and C.S. Poon from the Hong Kong Polytechnic University were the only researchers to make significant contributions to the work in the areas of both RCA and GCA. Other notable researchers and institutions/organisations include J. de Brito from the Technical University of Lisbon (for RCA), the National Kaohsiung University of Applied Sciences (GCA) and the Central Road Research Institute (CSA).

- More than two-thirds of the publication types were peer-reviewed journal papers, with *Construction and Building Materials,* published by Elsevier, having the highest number for all three materials.

2.2.2 Building the Data Matrix

The development of the data matrix is the second main step of the *Analytical Systematisation* method. It can perhaps best be described as similar to laying the foundation of a building. The analysis and evaluation of the data directly rely on the nature and sensitivity of the data considered and how they are assembled together, i.e., the quality of a matrix determines the extent to which the data can be analysed. This work requires a keen attention to detail and a deep mind to ensure the functionality of the data matrix. There are two distinct stages to this work:

(i) Initial Sorting

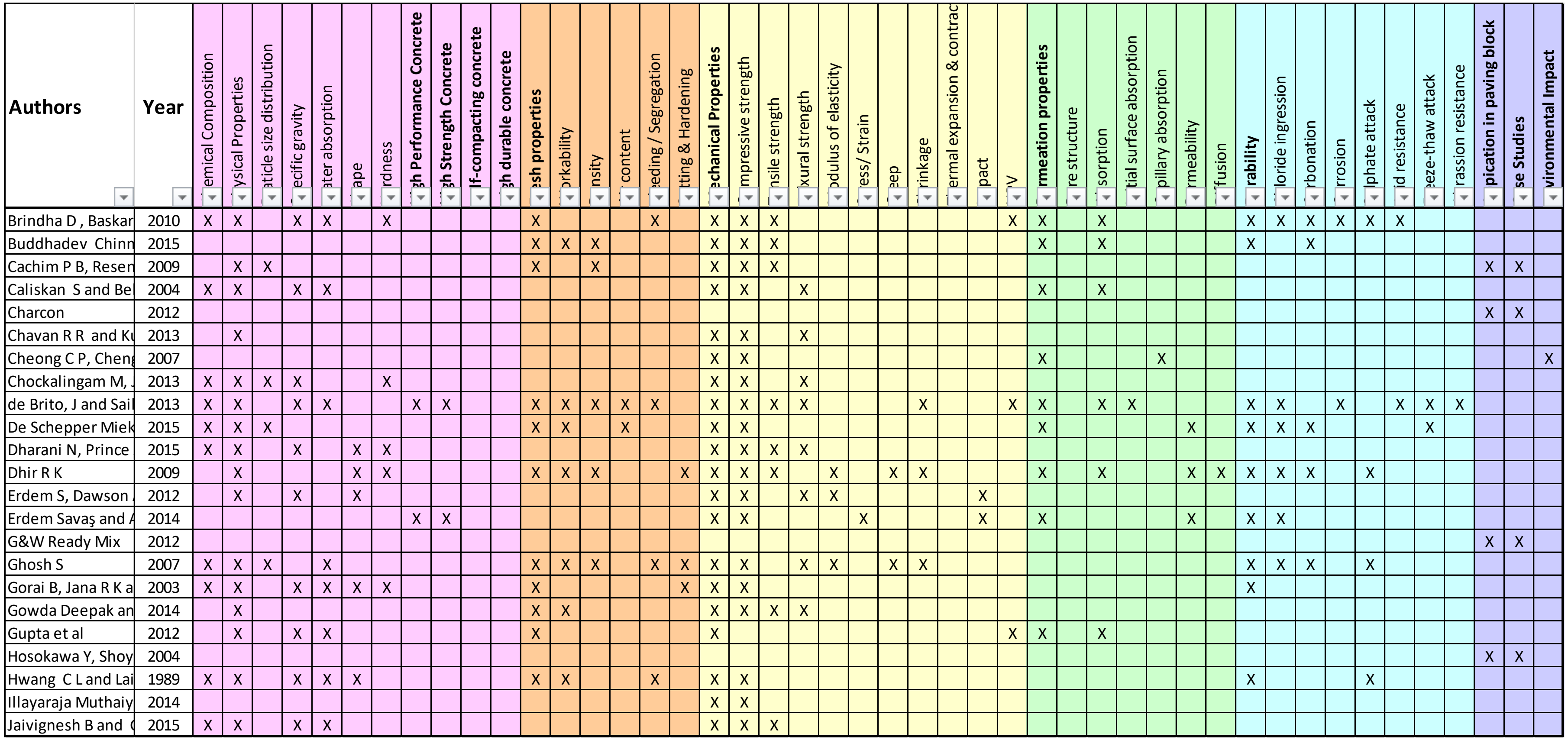
After compilation of the sourced publications, a preliminary list of main headings (e.g., Fresh Concrete Properties, Hardened Properties and Durability) and subheadings (e.g., Consistence, Density and Strength) is created to allow the content of the publications to be sorted in a precise manner, with the use of Excel. The headings may change as the work progresses. Each publication is vetted and carefully allocated to a specific heading. An example of initial sorting for CSA publications is shown in Figure 2.2.

(ii) Data Parking and Mining

The next step deals with the information from the publications, which is located within the initially formed specific headings. The data in the publications, presented in a qualitative and descriptive form in text and/or a quantitative data form in tables and figures, are extracted to form the data matrix. The extracted data covered specific subject areas, for example, nature of the publication, material characteristics, concrete types and mix design, preparation methods, curing conditions, and fresh and hardened concrete properties. Based on a rough estimation, the data matrix built in this study consisted of more than 400,000 data points. An example of one data matrix built to study the shrinkage of RCA concrete is shown in Figure 2.3.

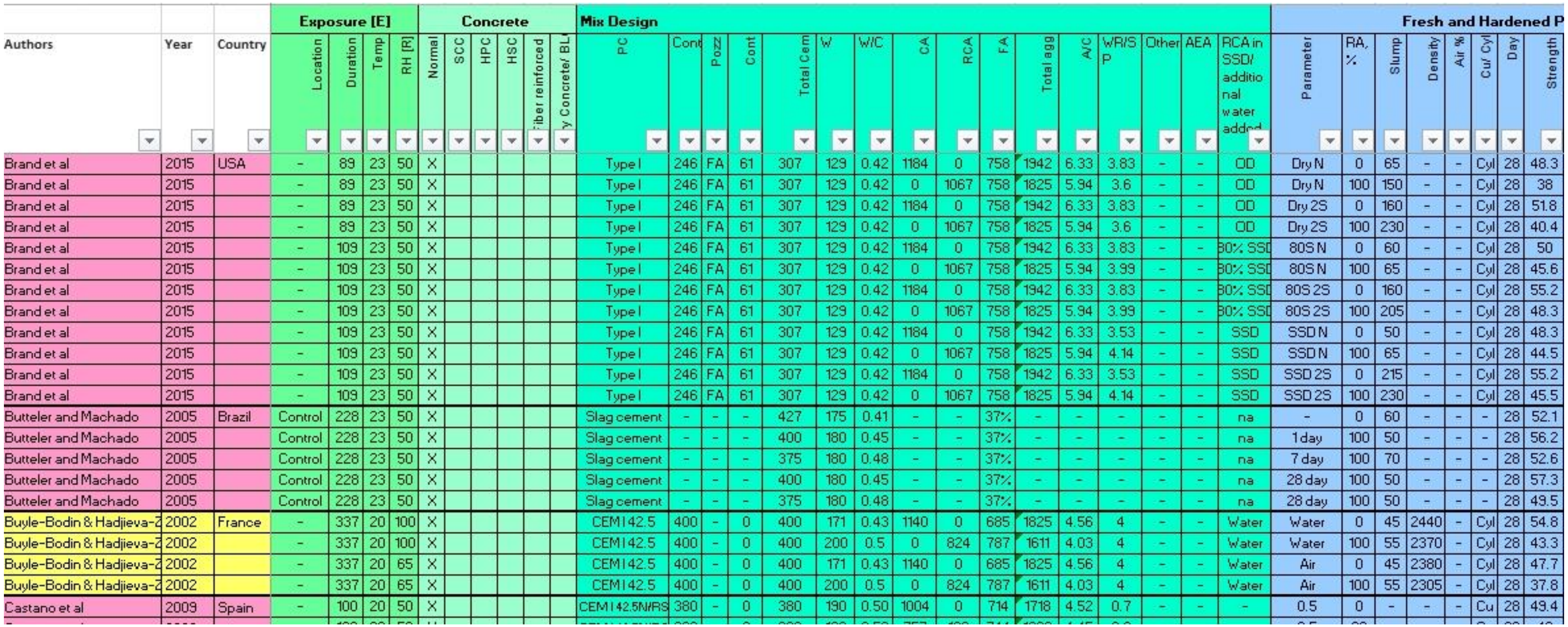
2.2.3 Analysis, Evaluation and Modelling

This work involves assessment and interpretation of the experimental results that have been embedded, in a systematic manner, within the data matrix. This task can usually be quite demanding and challenging, owing to the inevitable variability present within



Authors	Year	emical Composition	ysical Properties	aticle size distribution	ecific gravity	ater absorption	ape	rdness	gh Performance Concrete	gh Strength Concrete	lf-compacting concrete	gh durable concrete	esh properties	orkability	nsity	content	eding / Segregation	tting & Hardening	echanical Properties	mpressive strength	nsile strength	xural strength	odulus of elasticity	ess/ Strain	eep	rinkage	ermal expansion & contrac	pact	V	rmeation properties	re structure	sorption	tial surface absorption	pillary absorption	rmeability	fusion	rability	loride ingression	rbonation	rrosion	lphate attack	id resistance	eze-thaw attack	rassion resistance	pication in paving block	se Studies	vironmental Impact
Brindha D , Baskar	2010	X	X		X	X		X					X				X		X	X	X								X	X		X					X	X	X	X	X	X					
Buddhadev Chinn	2015												X	X	X				X	X	X									X		X					X		X								
Cachim P B, Resen	2009		X	X									X		X				X	X	X																								X	X	
Caliskan S and Be	2004	X	X		X	X													X	X		X								X		X															
Charcon	2012																																												X	X	
Chavan R R and Ku	2013		X																X	X		X																									
Cheong C P, Cheng	2007																		X	X										X				X													X
Chockalingam M, J	2013	X	X	X	X			X											X	X		X																									
de Brito, J and Sail	2013	X	X		X	X			X	X			X	X	X	X	X		X	X	X	X				X			X	X		X	X				X	X		X		X	X	X			
De Schepper Miek	2015	X	X	X									X	X		X			X	X										X					X		X	X	X				X				
Dharani N, Prince	2015	X	X		X		X	X											X	X	X	X																									
Dhir R K	2009		X				X	X					X	X	X			X	X	X	X		X		X	X				X		X			X	X	X	X	X		X						
Erdem S, Dawson	2012		X		X		X												X	X		X	X					X																			
Erdem Savaş and A	2014								X	X									X	X				X				X		X					X		X	X									
G&W Ready Mix	2012																																												X	X	
Ghosh S	2007	X	X	X		X							X	X	X		X	X	X	X		X	X		X	X											X	X	X		X						
Gorai B, Jana R K a	2003	X	X		X	X	X	X					X					X	X	X																	X										
Gowda Deepak an	2014		X										X	X					X	X	X	X																									
Gupta et al	2012		X		X	X							X						X										X	X		X															
Hosokawa Y, Shoy	2004																																												X	X	
Hwang C L and Lai	1989	X	X		X	X	X						X	X			X		X	X																	X				X						
Illayaraja Muthaiy	2014																		X	X																											
Jaivignesh B and	2015	X	X		X	X													X	X	X																										

Figure 2.2 A screen capture of the initial sorting for CSA publications (note: not all data were shown)



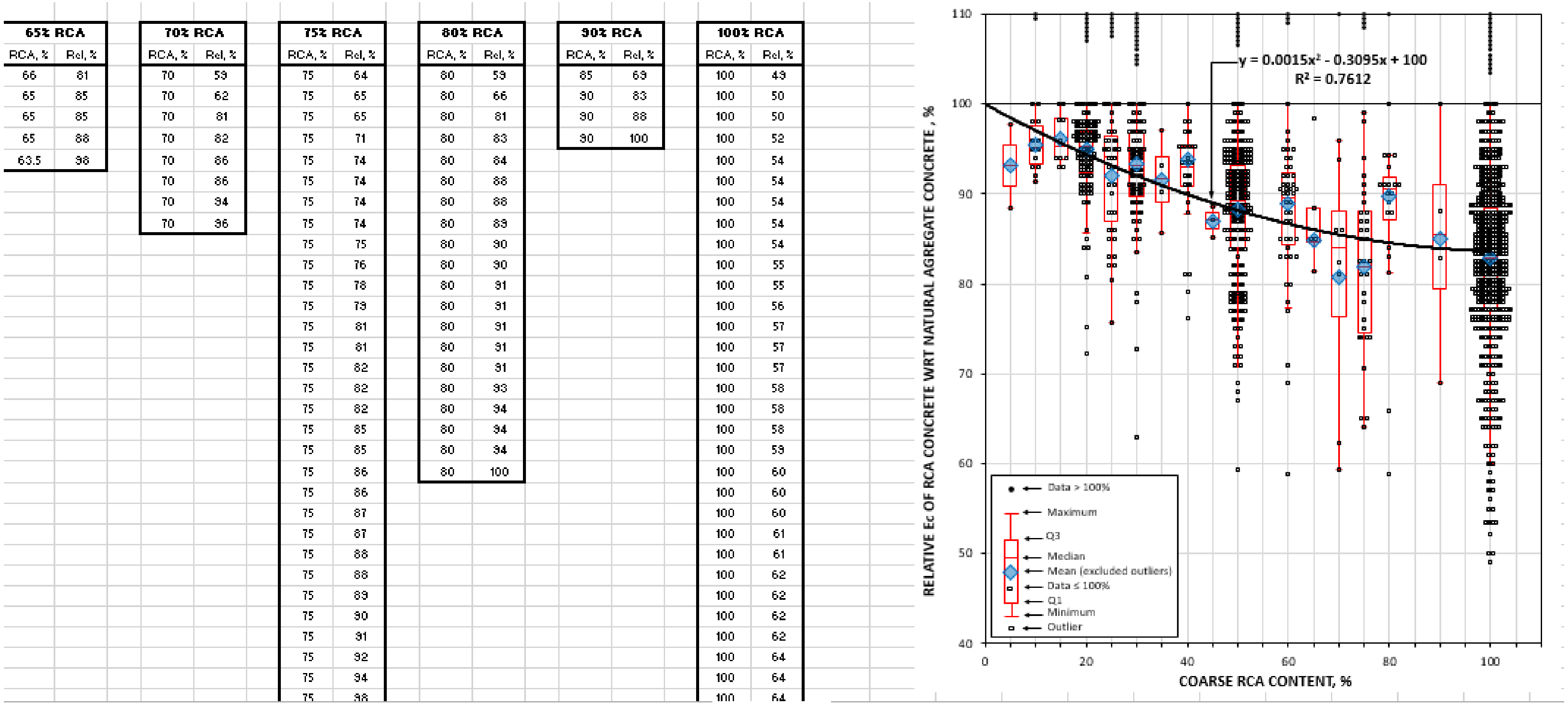
			Exposure [E]				Concrete						Mix Design																Fresh and Hardened P							
Authors	Year	Country	Location	Duration	Temp	RH [R]	Normal	SCC	HPC	HSC	iber reinforced	y Concrete/ BL	PC	Cont	Pozz	Cont	Total Cem	W	W/C	CA	RCA	FA	Total agg	A/C	WR/SP	Other	AEA	RCA in SSD/ additional water add	Parameter	RA, %	Slump	Density	Air %	Cu/ Cyl	Day	Strength
Brand et al	2015	USA	-	89	23	50	X						Type I	246	FA	61	307	129	0.42	1184	0	758	1942	6.33	3.83	-	-	OD	Dry N	0	65	-	-	Cyl	28	48.3
Brand et al	2015		-	89	23	50	X						Type I	246	FA	61	307	129	0.42	0	1067	758	1825	5.94	3.6	-	-	OD	Dry N	100	150	-	-	Cyl	28	38
Brand et al	2015		-	89	23	50	X						Type I	246	FA	61	307	129	0.42	1184	0	758	1942	6.33	3.83	-	-	OD	Dry 2S	0	160	-	-	Cyl	28	51.8
Brand et al	2015		-	89	23	50	X						Type I	246	FA	61	307	129	0.42	0	1067	758	1825	5.94	3.6	-	-	OD	Dry 2S	100	230	-	-	Cyl	28	40.4
Brand et al	2015		-	109	23	50	X						Type I	246	FA	61	307	129	0.42	1184	0	758	1942	6.33	3.83	-	-	0% SS	80S N	0	60	-	-	Cyl	28	50
Brand et al	2015		-	109	23	50	X						Type I	246	FA	61	307	129	0.42	0	1067	758	1825	5.94	3.99	-	-	0% SS	80S N	100	65	-	-	Cyl	28	45.6
Brand et al	2015		-	109	23	50	X						Type I	246	FA	61	307	129	0.42	1184	0	758	1942	6.33	3.83	-	-	0% SS	80S 2S	0	160	-	-	Cyl	28	55.2
Brand et al	2015		-	109	23	50	X						Type I	246	FA	61	307	129	0.42	0	1067	758	1825	5.94	3.99	-	-	0% SS	80S 2S	100	205	-	-	Cyl	28	48.3
Brand et al	2015		-	109	23	50	X						Type I	246	FA	61	307	129	0.42	1184	0	758	1942	6.33	3.53	-	-	SSD	SSD N	0	50	-	-	Cyl	28	48.3
Brand et al	2015		-	109	23	50	X						Type I	246	FA	61	307	129	0.42	0	1067	758	1825	5.94	4.14	-	-	SSD	SSD N	100	65	-	-	Cyl	28	44.5
Brand et al	2015		-	109	23	50	X						Type I	246	FA	61	307	129	0.42	1184	0	758	1942	6.33	3.53	-	-	SSD	SSD 2S	0	215	-	-	Cyl	28	55.2
Brand et al	2015		-	109	23	50	X						Type I	246	FA	61	307	129	0.42	0	1067	758	1825	5.94	4.14	-	-	SSD	SSD 2S	100	230	-	-	Cyl	28	45.5
Butteler and Machado	2005	Brazil	Control	228	23	50	X						Slag cement	-	-	-	427	175	0.41	-	-	37%	-	-	-	-	-	na	-	0	60	-	-	-	28	52.1
Butteler and Machado	2005		Control	228	23	50	X						Slag cement	-	-	-	400	180	0.45	-	-	37%	-	-	-	-	-	na	1 day	100	50	-	-	-	28	56.2
Butteler and Machado	2005		Control	228	23	50	X						Slag cement	-	-	-	375	180	0.48	-	-	37%	-	-	-	-	-	na	7 day	100	70	-	-	-	28	52.6
Butteler and Machado	2005		Control	228	23	50	X						Slag cement	-	-	-	400	180	0.45	-	-	37%	-	-	-	-	-	na	28 day	100	50	-	-	-	28	57.3
Butteler and Machado	2005		Control	228	23	50	X						Slag cement	-	-	-	375	180	0.48	-	-	37%	-	-	-	-	-	na	28 day	100	50	-	-	-	28	49.5
Buyle-Bodin & Hadjieva-Z	2002	France	-	337	20	100	X						CEM I 42.5	400	-	0	400	171	0.43	1140	0	685	1825	4.56	4	-	-	Water	Water	0	45	2440	-	Cyl	28	54.8
Buyle-Bodin & Hadjieva-Z	2002		-	337	20	100	X						CEM I 42.5	400	-	0	400	200	0.5	0	824	787	1611	4.03	4	-	-	Water	Water	100	55	2370	-	Cyl	28	43.3
Buyle-Bodin & Hadjieva-Z	2002		-	337	20	65	X						CEM I 42.5	400	-	0	400	171	0.43	1140	0	685	1825	4.56	4	-	-	Water	Air	0	45	2380	-	Cyl	28	47.7
Buyle-Bodin & Hadjieva-Z	2002		-	337	20	65	X						CEM I 42.5	400	-	0	400	200	0.5	0	824	787	1611	4.03	4	-	-	Water	Air	100	55	2305	-	Cyl	28	37.8
Castano et al	2009	Spain	-	100	20	50	X						CEM I 42.5N/RS	380	-	0	380	190	0.50	1004	0	714	1718	4.52	0.7	-	-	-	0.5	0	-	-	-	Cu	28	49.4

Figure 2.3 A screen capture of data matrix created for the shrinkage of RCA concrete (note: not all data were shown)

the tests, as well as the occasional conflicting findings across the studies, which in a worst case scenario could hide the real trends, which otherwise would be visible. Although there was no exact solution to address these issues, handling the data with a degree of sensitivity and independent judgement, coupled with a fair knowledge of concrete science and technology, proved to be helpful in dealing with such situations.

Integrating data across studies could also be difficult, especially when the number of studies is large and the magnitudes of the measured values are very different. However, this issue can be overcome by converting the data into relative values, that is, comparing the value of RSA concrete with respect to that of the reference concrete, i.e., natural aggregate (NA) concrete. In addition, current standards and specifications, mainly those of Europe and the United States, were also referred to, whenever necessary, to ensure compliance of the research outcome.

Figure 2.4 shows an example of a piece of work undertaken in the analysis and evaluation process, which was created for Chapter 5 for the effects of RCA as a natural coarse aggregate replacement on the elastic modulus of concrete. A total of 1368 data points were considered in this exercise, in which the results were expressed in a relative form. Box-and-whiskers plots were adopted to visualise the distribution of the data and identify potential outliers. Additionally, data with relative values greater than 100% (indicating that the stiffness of RCA is higher than that of NA) were considered outliers, owing to the presence of a significant amount of adhered cement paste on RCA, which was porous and weak. Polynomial regression was also used to obtain the overall trend line to reveal the underlying relationships in the collective data.



65% RCA		70% RCA		75% RCA		80% RCA		90% RCA		100% RCA	
RCA, %	Rel, %	RCA, %	Rel, %	RCA, %	Rel, %	RCA, %	Rel, %	RCA, %	Rel, %	RCA, %	Rel, %
66	81	70	59	75	64	80	59	85	69	100	49
65	85	70	62	75	65	80	66	90	83	100	50
65	85	70	81	75	65	80	81	90	88	100	50
65	88	70	82	75	71	80	83	90	100	100	52
63.5	98	70	86	75	74	80	84			100	54
		70	86	75	74	80	88			100	54
		70	94	75	74	80	88			100	54
		70	96	75	74	80	89			100	54
				75	75	80	90			100	54
				75	76	80	90			100	55
				75	78	80	91			100	55
				75	79	80	91			100	56
				75	81	80	91			100	57
				75	81	80	91			100	57
				75	82	80	91			100	57
				75	82	80	93			100	58
				75	82	80	94			100	58
				75	85	80	94			100	58
				75	85	80	94			100	59
				75	86	80	100			100	60
				75	86					100	60
				75	87					100	60
				75	87					100	61
				75	88					100	61
				75	88					100	62
				75	89					100	62
				75	90					100	62
				75	91					100	62
				75	92					100	64
				75	94					100	64
				75	98					100	64

Figure 2.4 A screen capture of analysis and evaluation showing the effects of RCA as a NA replacement on the modulus elastic of concrete (note: not all data were shown)

Sometimes, during the analysis and evaluation process, new findings may emerge, which cannot be ascertained or explained by any individual study within the group of studies being analysed. An example of this is presented in Figure 2.5, based on Dhir et al. (2016), for the effects of CSA on the consistence of concrete. This shows that the use of CSA gives a greater increase in consistence in concrete with low specified consistence (S1 and S2 classes of BS EN 206, 2013) than in concrete with high specified consistence (S3 and S4 classes).

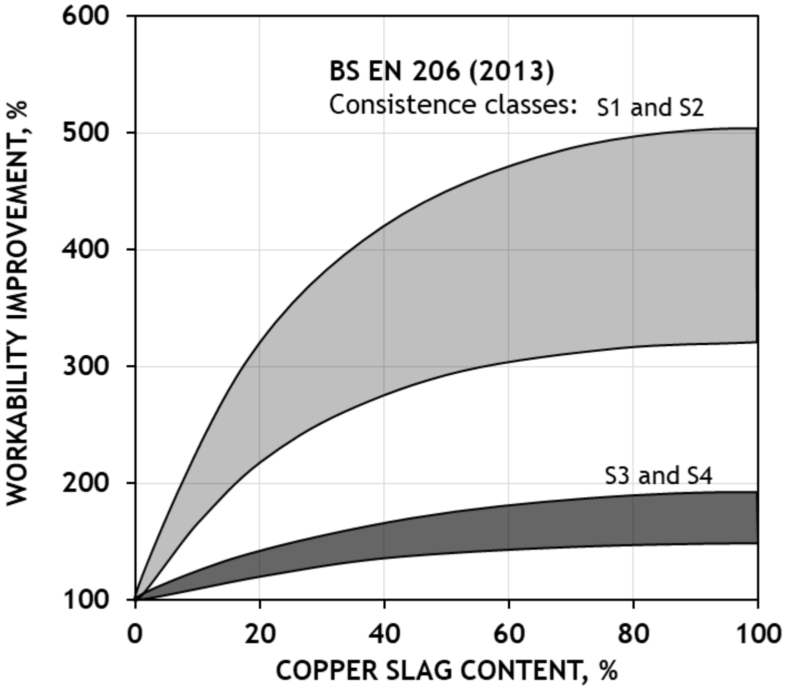


Figure 2.5 Influence of CSA on the improvement of concrete for different consistence classes (Dhir et al., 2016)

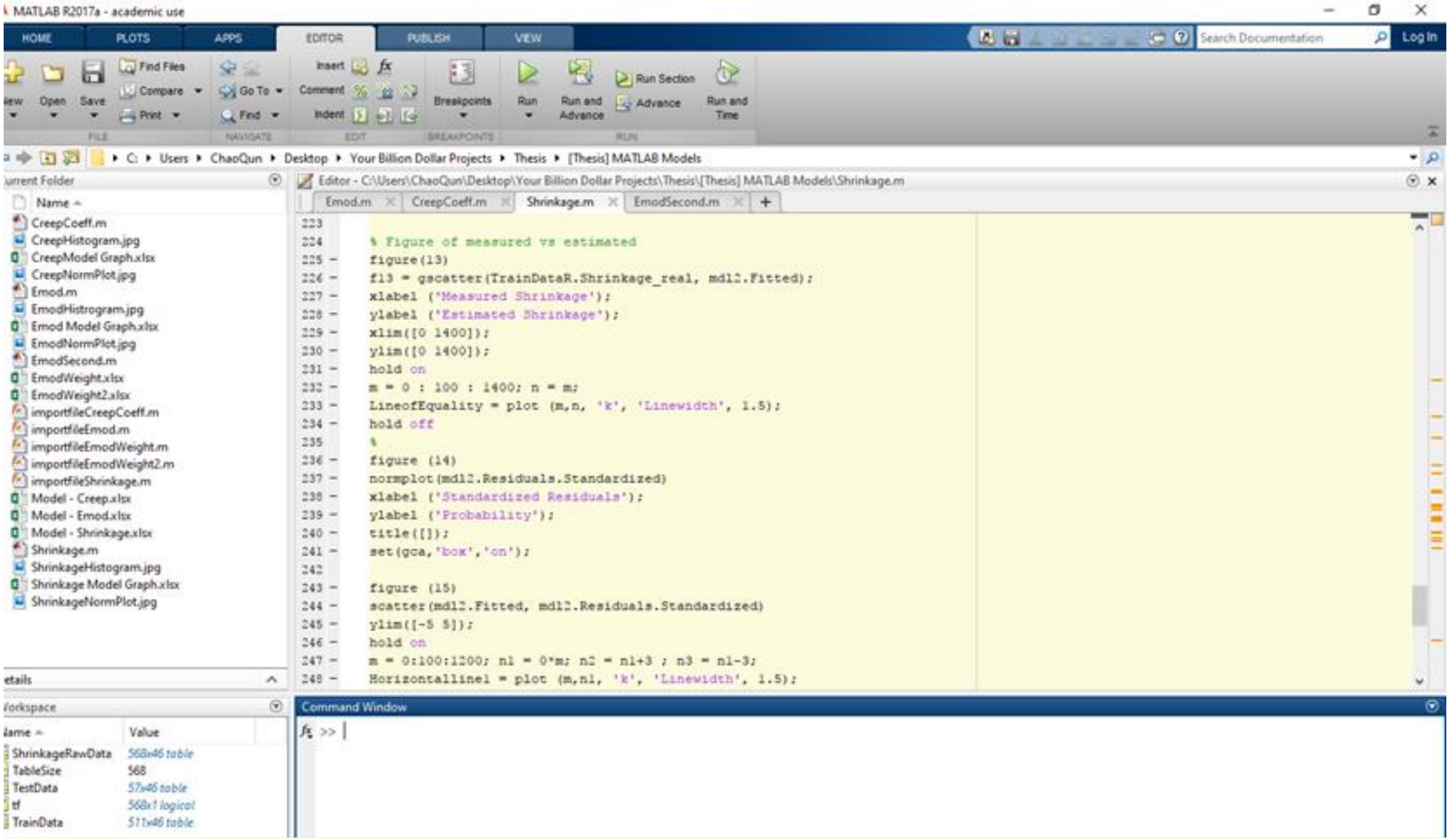
The final aim of the methodology adopted, which coincided with the natural outcome of the study, was to explore the possibility of using the large volume of deformation data to develop models for the elastic modulus, creep and shrinkage of concrete that can be used to work with any aggregate within all three types, that is, natural, recycled and manufactured, covered by BS EN 12620:2002+A1 (2008). Figure 2.6 shows a screen capture of the MATLAB interface with the program codes written for modelling work on the shrinkage of concrete.

2.3 PEER-REVIEW FEEDBACK AND DISSEMINATION

As part of the plan of the project, the decision was taken at the outset, in consultation with the supervisors, to seek both to benefit from peer-review comments and use them to improve the research undertaken, and to disseminate the output of the research by publishing it, as far as possible, in premier journals. This aspect of the research methodology proved to be most effective, both in improving the quality of research taken and in achieving three publications in the *Proceedings of the Institution of Civil Engineers: Structures and Buildings*, three papers in the ICE *Magazine of Concrete Research* and one publication in the Elsevier *Construction and Building Materials*. As the work was published in an easy-to-digest manner, it is hoped that the findings originating from this research can reach a wider audience and also be a useful source of information for researchers and practitioners.

2.4 CONCLUSIONS

This chapter explains the research methodology developed in the form of the *Analytical Systemisation* method for use in the study undertaken. It consists of four main stages, as described next.



```
% Figure of measured vs estimated
figure(13)
f13 = gscatter(TrainDataR.Shrinkage_real, mdl2.Fitted);
xlabel ('Measured Shrinkage');
ylabel ('Estimated Shrinkage');
xlim([0 1400]);
ylim([0 1400]);
hold on
m = 0 : 100 : 1400; n = m;
LineofEquality = plot (m,n, 'k', 'Linewidth', 1.5);
hold off
%
figure (14)
normplot(mdl2.Residuals.Standardized)
xlabel ('Standardized Residuals');
ylabel ('Probability');
title([]);
set(gca,'box','on');

figure (15)
scatter(mdl2.Fitted, mdl2.Residuals.Standardized)
ylim([-5 5]);
hold on
m = 0:100:1200; n1 = 0*m; n2 = n1+3 ; n3 = n1-3;
Horizontalline1 = plot (m,n1, 'k', 'Linewidth', 1.5);
```

```
>> 
```

lame	Value
ShrinkageRawData	568x46 table
TableSize	568
TestData	57x46 table
tf	568x1 logical
TrainData	511x46 table

Figure 2.6 A screen capture of written codes in the MATLAB interface for modelling work on the shrinkage of concrete

Stage 1 involved sourcing of global data, published in English, on the subject of the use of coarse recycled concrete aggregate (RCA), fine glass cullet aggregate (GCA) and fine copper slag aggregate (CSA) in concrete construction applications. The work relevant to the characteristics of these materials and deformation properties of concrete made with them was undertaken using data sourced from 713 publications, produced by 960 researchers working in 537 institutions across 46 countries worldwide over a period of 45 years.

Stage 2 began with sorting of the sourced publications into different categories, and this was followed by extracting data from each publication and assigning the data to specific subject areas in an orderly manner. This process resulted in a strong data matrix with more than 400,000 data points.

Stage 3 involved the analysis and evaluation of the experimental results assembled in the data matrix. Standards and specifications were referred to throughout the course of work. The findings and the data matrix facilitated the development of elastic modulus, creep and shrinkage models.

Stage 4 was designed to obtain peer-review feedback from experts in the field by continually publishing the work in reputable journals as the project progressed. The second purpose of publishing papers was to disseminate the output of the research to a wider audience.

CHAPTER 3

CLASSIFICATION AND CHARACTERISTICS OF RSA

3.1 INTRODUCTION

Aggregates occupy about 75% of the total volume of concrete and therefore it is important to understand the characteristics of aggregates and their potential influence on both the fresh and the hardened properties of concrete and, where appropriate, its durability. Indeed, to produce concrete of good quality, the aggregates used must be adequately clean and possess physical and chemical characteristics in compliance with the existing standards for use in concrete. In the main, they should have suitable shape, surface texture and grading to make a stable concrete mix and should be of low porosity with low-absorption material that is sufficiently strong to produce concrete with adequate strength, load-dependent and load-independent deformation, and durability properties.

The latest edition of European standard for aggregates used in concrete applications, implemented in the United Kingdom as BS EN 12620:2002+A1 (2008) *Aggregates for Concrete*, specifies the requirements of natural, recycled and manufactured aggregates in terms of their geometrical, physical, chemical and durability properties. Although the standard does not cover all types of recycled and secondary aggregates (RSA) (see Section 3.2 for details), it can still be used as a guide for the compliance of RSA with the requirements specified for natural aggregates (NA).

This chapter discusses the classifications of RSA used in this study, coarse recycled concrete aggregate (RCA), fine glass cullet aggregate (GCA) and fine copper slag aggregate (CSA), and examines the important characteristics of these materials that may influence aggregate packing, aggregate–cement paste bond, concrete mix design and the deformation properties of concrete. The chemical properties of these materials, albeit important, are beyond the scope of this study, although the relevant information can be found in Dhir et al. (2018a) for GCA and Dhir et al. (2016) for CSA.

3.2 CLASSIFICATION OF AGGREGATE

Based on material characteristics, there are several ways to classify aggregates into distinct groups having potentially similar engineering behaviour. A good example of this can be seen in the field of geotechnics, in which soil classification systems, such as those given in ASTM D2487 (2011) in the United States and BS EN ISO 14688-1:2002+A1 (2013) in the United Kingdom, are used to describe a soil by its engineering properties. Although such a system is not available in the field of concrete, aggregates used in concrete are normally classified based on their (i) source of origin, (ii) size, such as coarse or fine, and (iii) density, such as normal, light or heavy weight.

Based on BS EN 12620:2002+A1 (2008), three main sources have been identified to describe the origin of aggregate, as given in Table 3.1. The descriptions ‘recycled aggregate’ and ‘manufactured aggregate’ fit well for RCA derived from construction and demolished waste, CSA generated during the pyrometallurgical process of copper production and GCA processed from waste glass.

Table 3.1 Definitions of aggregate types given in BS EN 12620:2002+A1 (2008)

TYPE	DEFINITION
Natural aggregate	“Aggregate from mineral sources which has been subjected to nothing more than mechanical processing”
Recycled aggregate	“Aggregate resulting from the processing of inorganic material previously used in construction”
Manufactured aggregate	“Aggregate of mineral origin resulting from an industrial process involving thermal or other modification”

Under each classification of RSA, a further distinction on the exact source of the materials can also be made. This is important because, under the same aggregate type, there can be variations in the materials in terms of their physical and chemical properties. For example, RCA is essentially a natural aggregate, but coated with cement paste, as it is commonly used at present, and the material can be divided according to the type of the parent rock, such as basalt, limestone or granite. Indeed, the process of removing adhered cement paste is already being attempted and the practice of classifying recycled aggregate based on its parent aggregate can be perceived as attainable. Though information on the parent rock type of coarse RCA is not easily available in practice, as soon as efforts to produce clean recycled aggregate are commercialised, it should be possible to brand the material in such a system as, for example, granite RCA.

In the case of GCA, the material can easily be further classified based on its chemical composition, such as soda-lime GCA, borosilicate GCA or lead GCA, which are some examples of the common types of waste glass, in which the volume of soda-lime glass is abundant (Dhir et al., 2018a).

For CSA, the material can be categorised depending on the cooling method used during copper production. Air-cooled CSA obtained from a slow air-cooling process normally appears in a rock-like form, whilst quenched CSA resulting from a water quenching process is in a sand-like form. The latter is commonly used in blast cleaning applications, and after proper treatment the material, which is known as spent CSA (or washed CSA in certain countries), can be recycled back to the construction industry as fine aggregate.

Detailed information on the production of these materials can be found in three publications dealing with sustainable construction materials: Dhir et al. (2016) for CSA, Dhir et al. (2018a) for GCA and Dhir et al. (2018b) for RCA, of which the candidate is one of the authors.

3.3 PARTICLE SHAPE AND SURFACE TEXTURE

The particle shape and surface texture of aggregate are two basic properties that are, at present, not normally within the control of aggregate manufacturers. These attributes can affect the fresh and hardened properties of concrete. For example, particle shape affects the aggregate packing, formation of air voids and mix flow, and surface texture affects the mix flow and aggregate–cement paste bond strength.

Table 3.2 summarises the descriptions of the particle shape and surface texture of coarse RCA, fine GCA and fine CSA, which are normally based on visual examination, as there are no standard methods to measure particle shape and surface texture of aggregates, other than indirect methods such as BS EN 933-3 (2012) and BS EN 933-4 (2008), which can be used to determine the flakiness index and shape index of coarse aggregates, respectively.

Table 3.2 Particle shape and texture of coarse RCA, fine GCA and fine CSA

PROPERTY	DESCRIPTION	COARSE RCA	FINE GCA	FINE CSA
Particle Shape	Angular	✓✓✓	✓✓✓	✓✓✓
	Irregular	-	✓	✓✓✓
	Multifaceted	-	-	✓
	Equidimensional	✓✓	-	-
	Flaky/ Elongated	✓	-	-
	Rounded	✓	-	-
Surface Texture	Glassy	-	-	✓✓✓
	Smooth	-	✓✓✓	✓✓
	Rough	✓✓✓	-	✓
	Porous	✓✓✓	-	-

Note: ✓✓✓ Most commonly reported; ✓✓ commonly reported; ✓ not so commonly reported.

Data of RCA taken from Barbudo et al. (2013), Butler et al. (2013b), Cadersa and Ramchuriter (2014), Chidiroglou et al. (2008), Dam et al. (2012), Dhir and Paine (2007), Dhir et al. (1999), Domingo et al. (2010), Hendrik et al. (1998), Ho et al. (2013), Limbachiya et al. (2000), Rao et al. (2010), Ravindrarajah (1996), Sucic and Lofty (2016), Surya et al. (2015), Verian et al. (2013),
Data of GCA taken from Mirzahosseini and Riding (2014), Mirzahosseini and Riding (2015), Lee at al. (2013), Turgut (2013), Wang and Huang (2010), Limbachiya (2009), De Castro and De Brito (2013), Ling and Poon (2011a, 2011b), Tan and Du (2013), Chisolm, 2011.
Data of CSA taken from Ambily et al. (2015), Anudeep et al. (2015), Arivalagan (2013), Baragano and Rey (1980), Brindha and Sureshkumar (2010), Douglas et al. (1985), Hwang and Laiw (1989), JPL Industries (1997), Kang et al. (2013), Lavanya et al. (2012, 2013), Potana (2005), Salleh et al. (2014), Wu et al. (2010a, 2010b).

Coarse RCA, fine GCA and fine CSA are all considered to have an angular shape, although the particle shape of CSA can also be irregular. Compared with natural gravel and river sand, which are normally rounded, the angularity of these materials can provide a better particle interlocking effect, which is important to many mechanical properties of concrete. However, at the same time, angular aggregates demand higher water or cement paste content for a given consistence, owing to their higher inter-aggregate friction.

The shape of coarse RCA can be affected by the type of crushing process. Thus, it is not surprising that coarse RCA samples could appear in equidimensional, rounded or flaky/elongated (Table 3.2). Whilst an equidimensional or rounded shape of RCA is the result of secondary crushing (Dhir and Paine, 2007; Barbudo et al., 2013), flakiness/elongation might suggest that the material has not been properly processed.

As for the surface texture, GCA is usually described as smooth, whilst CSA is between glassy and smooth (Table 3.2). The smooth texture of an aggregate is known to improve the consistence of fresh concrete. In the case of CSA, it has been shown that the improvement in consistence due to the use of CSA can offer a potential reduction in water content, leading to an increase in concrete strength (Lye et al., 2015). On the other hand, the smooth surface of GCA does not seem to improve the consistency of concrete, probably because of its angularity, which results in an interlocking effect (Dhir et al., 2018a). Notwithstanding this, the smooth surface of an aggregate can result in weaker aggregate–cement paste bonding in concrete; this effect, however, has not been studied thoroughly for concrete made with GCA and CSA.

On the other hand, owing to the attached cement paste, coarse RCA has a rough and porous surface. The cement paste residue can affect the fresh and hardened properties of concrete, as it is weak and highly absorptive. Therefore, the surface saturation condition of RCA and the content of mixing water need to be carefully considered. Notwithstanding this, a study undertaken by Lye et al. (2015) showed that the use of coarse RCA in conjunction with fine CSA could maintain the consistence and compressive strength of concrete without having to increase its cement content. The use of these two materials together in manufacturing concrete can further improve the sustainability aspect of construction.

3.4 PARTICLE SIZE AND DISTRIBUTION

3.4.1 Particle Size

Aggregates used in concrete have been commonly separated into two main categories as coarse aggregates and fine aggregates. Depending on the standard used, this separation is determined from the particles passing through or retained on a sieve of either, for example, 4.75-mm size as specified in ASTM C33 (2016) or 4-mm size as in BS EN 12620:2002+A1 (2008).

Only quenched CSA and spent CSA are produced in a fine-grained size (Dhir et al., 2016), which can be readily used as fine aggregate. Other materials (RCA, GCA and air-cooled CSA) appear in a form that requires crushing and screening to achieve suitable aggregate size.

RCA can be processed into coarse and fine aggregates, but only the former is likely to be specified for use in structural concrete, whilst the latter is less appealing because of its high water absorption (generally more than 8%), which can have a detrimental effect on many properties of concrete.

Because the original form of most consumer glass is flat, its use as a coarse aggregate is unsuitable, as it would take the form of an extremely elongated and flaky particle (CCANZ, 2011; Dhir et al., 2018a). Thus, this material is more suitable for use as a fine aggregate.

Additionally, it should be mentioned that the sum of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3) of both CSA and GCA is greater than 70%, meeting the requirement specified in ASTM C618 (2015) for Class F fly ash. Thus, when finely ground to a powder form, these materials can be used as cementitious materials, as they exhibit pozzolanic behaviour. The effects of using ground GC and CS as a Portland cement replacement on the properties of concrete have been analysed and evaluated by Dhir et al. (2018a) and Dhir et al. (2016), respectively.

3.4.2 Particle Size Distribution: RCA as Coarse Aggregate

Particle size distribution (PSD), also known as grading, describes the distribution of different-sized particles present in a material, expressed in the form of percentage by mass of particles passing a certain range of sieve size. The PSD of the aggregate in concrete affects particle packing and air voids, which are the two important factors that have a profound influence on the fresh properties (particularly consistence) and hardened properties of concrete. Well-graded aggregates ensure maximum particle packing and full compaction.

In this section, the PSD data of coarse RCA, fine GCA and fine CSA used in studies related to concrete research are investigated, which can give an overall impression of the range of aggregate sizes that have been present in studies commonly undertaken in the field of concrete technology.

Figure 3.1 shows the PSD of coarse RCA used in 36 studies for its effect on the elastic modulus of concrete reported from 1985 to 2015. For comparison, the grading requirements of (i) BS EN 12620:2002+A1 (2008) for the G_c90/15 category, with two different sets of designated upper (*D*) and lower (*d*) aggregate sizes, and (ii) BS 882 (1992) for 20- to 5-mm aggregate are also shown.

It should be mentioned that, unlike the British Standard BS 882 (1992), in which the grading limits of three specified sieve sizes for graded coarse aggregate were given, the grading limits in BS EN 12620:2002+A1 (2008) are more flexible in the sense that they allow for different combinations of *D* and *d* within an allowable range of sieve sizes. Additionally, the grading limits given in BS EN 12620:2002+A1 (2008) are wider, which can accommodate higher variation in aggregate grading (Figure 3.1).

It is shown that coarse RCA is commonly crushed to a nominal maximum size of 20 mm (Figure 3.1). Most of the grading of RCA (shaded in grey) complies with the limits

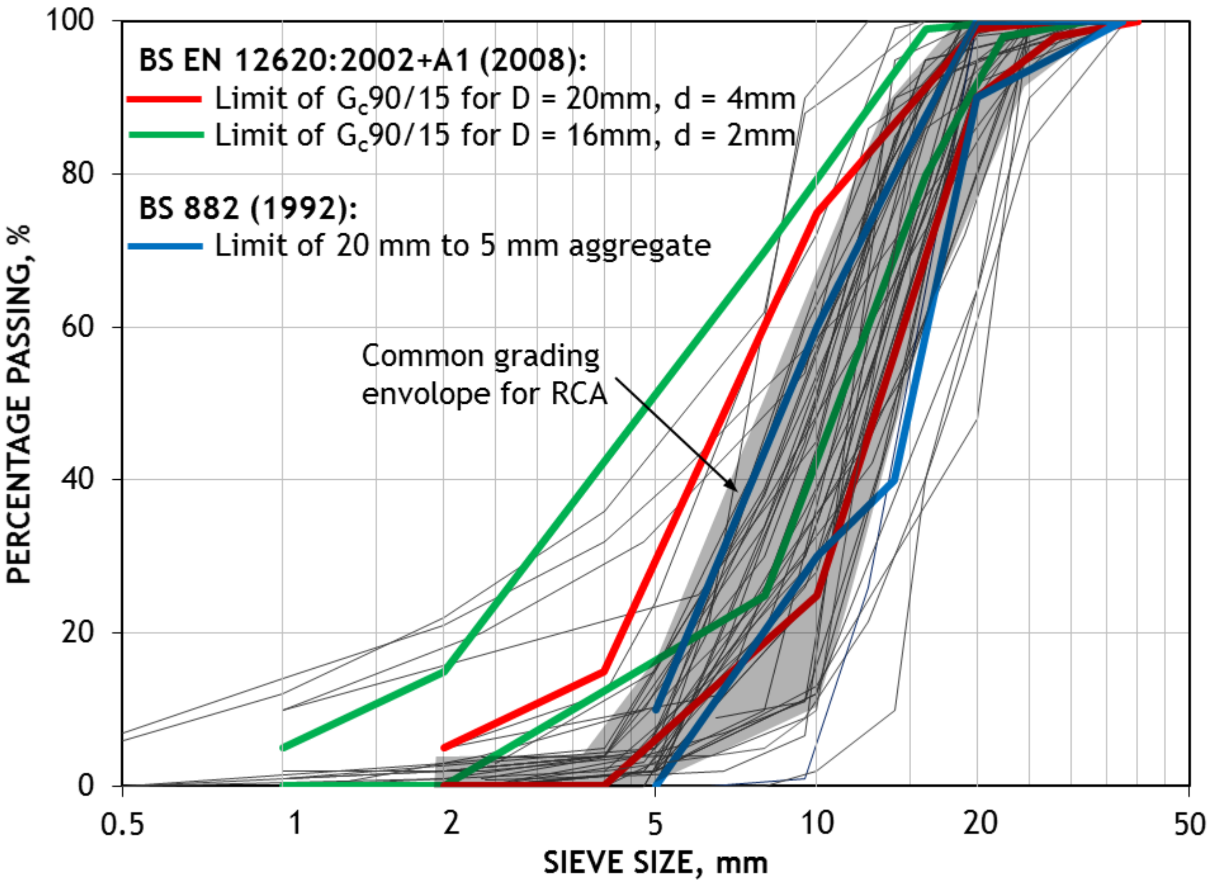


Figure 3.1 Particle size distribution of coarse recycled concrete aggregate

Data taken from Ahmad et al. (1986), Ahmed and Vidyaadhara (2013), Barbudo et al. (2013), Beltran et al. (2014b), Brand et al., (2013a), Butler et al. (2013b), Casuccio et al. (2008), Corinaldesi and Moriconi (2009a, 2009b), Deshpande et al. (2009), Dhir et al. (1999), Eckert and Oliveira (2017), Ekolu et al. (2012), Folino and Xargay (2014), Gonzalez-Fonteboa et al. (2011a), Ho et al. (2013), Inoue et al. (2012), James et al. (2011), Jimenez et al. (2013), Kiuchi (2001), Kiuchi and Horiuchi (2003), Koulouris et al. (2012a), Limbachiya et al. (2012a), Lo et al. (2013), López-Gayarre et al. (2011), Manzi et al. (2011), Park (1999), Pepe et al. (2014), Rao et al. (2011a), Ravindrarajah and Tam (1985), Safiuddin et al. (2011), Somna et al. (2012a), Tangchirapat et al. (2010), Vieira et al. (2011), Wardeh et al. (2015), Yang et al. (2008a), Yun (2010).

for $G_c90/15$ for *D* = 20 mm and *d* = 4 mm, although the passing of particles less than 10 mm tends to fall below the limits. This suggests that the proportion of coarse fraction in the RCA samples tended to be high. Notwithstanding this, provided that the aggregate is processed properly, there should be no issue with RCA being crushed to the required grading. This can be achieved with the use of primary and secondary crushers to reduce the concrete debris or waste to an appropriate size and the use of screens at various stages of the crushing process to detect oversized aggregate (Dhir and Paine, 2007).

3.4.3 Particle Size Distribution: GCA as Fine Aggregate

The particle size distribution of 95 GCA samples used in 53 studies is shown in Figure 3.2. The grading limits of fine aggregate proposed by Dhir et al. (2005a), instead of those given in the standard, are shown for comparison purpose. This is because the proposed combined grading ranges are more useful in describing the particle size distribution of fine aggregate (Dhir et al., 2016). The proposed grading limits contain three grading ranges for fine aggregate, these being coarse, medium and fine, which were developed based on a combination of the requirements given in BS 882 (1992) and BS EN 12620 (2002).

Figure 3.2 shows that most of the grading of GCA (shaded in grey) falls within the coarse range and the lower side of the medium range. In only a few cases the grading of GCA lies within the fine range. It can also be seen from Figure 3.2 that a small number of GCA samples contain coarse particles and fall below the proposed combined limits. These materials should not be used in making concrete, as optimum particle packing is unlikely to be achieved and may show some undesirable effects, such as bleeding in fresh concrete and the presence of excessive voids in hardened concrete, with consequent effects on the long-term performance of the concrete due to the lack of sufficient fines.

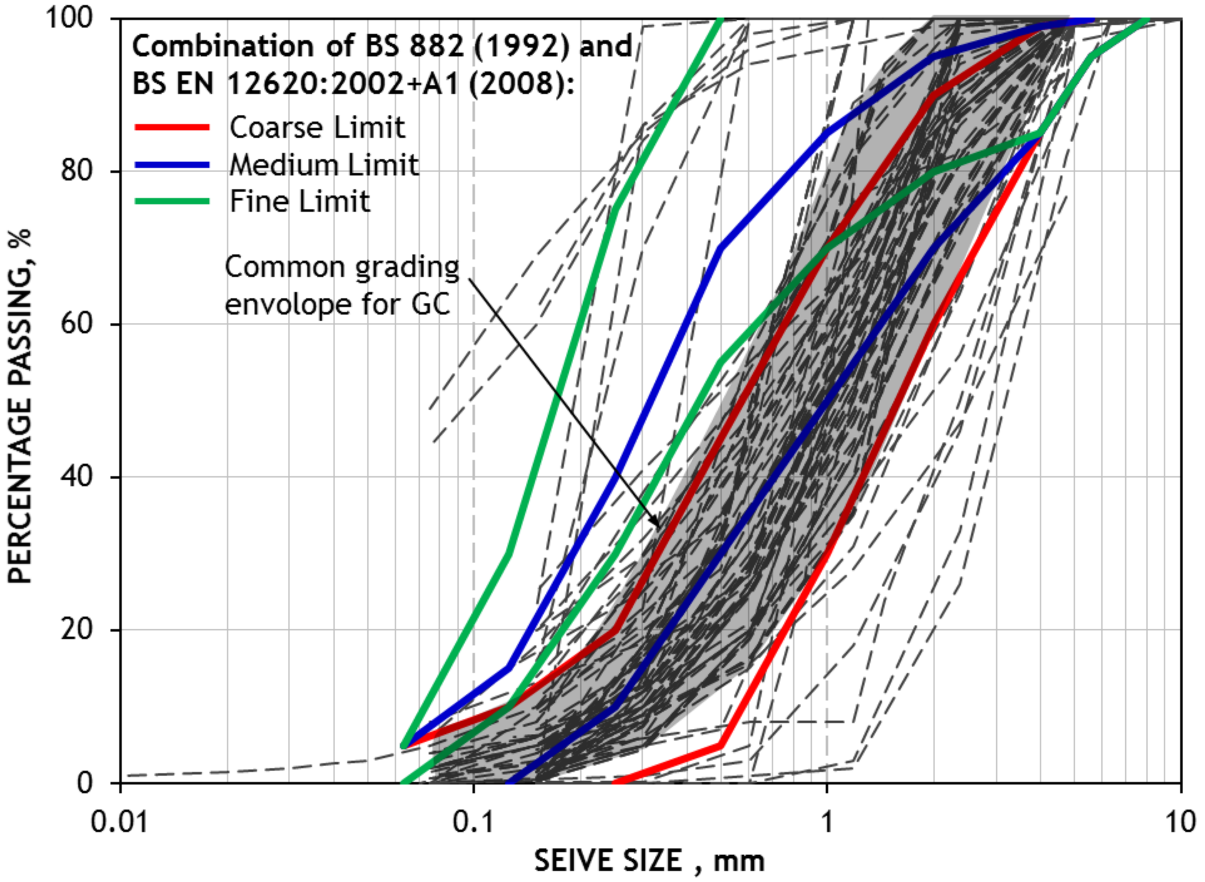


Figure 3.2 Particle size distribution of glass cullet as fine aggregate

Data taken from Abdallah and Fan (2014), Abendeh et al. (2015a), Abendeh et al. (2015b), Aghabaglou et al (2015), Berry et al. (2011), Borhan and Bailey (2014), Byars et al. (2004), Dhir et al. (2005a), Dhir et al. (2009), Disfani et al. (2012), Du and Tan (2014), Guo et al. (2015), Hui and Sun (2011), Isler (2012), Ismail and Al-Hashmi (2009), Kou and Poon (2009b), Lam et al. (2007), Lee (2011), Lee et al. (2008), Lee et al. (2011), Lee et al. (2013), Lim (2014), Limbachiya et al. (2012c), Ling and Poon (2014a, 2014c), Ling and Poon (2011a), Ling and Poon (2012a), Ling and Poon (2013), Ling and Poon (2012b), Ling et al (2011), Ling et al. (2012), Miranda et al (2014), Oliveira et al (2008, 2013), Penacho et al. (2014), Poon and Chan (2007b), Poutos et al. (2008), Rajabipour (2012), Romero et al. (2013), Saccani and Bignozzi (2010), Soyer et al. (2010), Su and Chen (2002), Taha and Nounu (2008, 2009), Turgut (2008a, 2008b), Turgut (2013), Turgut and Yahlizade (2009), Wang (2009a, 2009b), Wang and Huang (2010), Wang et al. (2014), Yuksel et al. (2013), Zhao et al. (2013a, 2013b).

Overall, it would be fair to argue the case that the PSD of fine GCA used in concrete research has mostly tended to be in the coarse range, although the material can be crushed into any size fraction (Figure 3.2). Furthermore, the data also show little change over time in the crushing and processing of GCA as a fine aggregate, suggesting that the material has always been used in the coarse sand zone. However, it would be in the interest of the industry to push the PSD of fine GCA towards the medium zone, where maximum particle packing is more likely to be achieved.

3.4.4 Particle Size Distribution: CSA as Fine Aggregate

Figure 3.3 shows the particle size distribution of air-cooled CSA, quenched CSA and spent CSA, together with the same proposed grading limits used in Figure 3.2. As unprocessed air-cooled CSA appears in a rock-like form, Figure 3.3 shows that the material could be processed into different gradings as required. However, compared with natural rock, the crushing of air-cooled CSA may consume more energy because of its high hardness value of 6.0–7.0 Mohs (Dhir et al., 2016). Thus, this material is not commonly used as fine aggregate.

The PSDs of quenched CSA and spent CSA are in two distinct zones (Figure 3.3). The grading envelope of quenched CSA is within the medium–coarse grading range, whilst that of spent CSA is within the fine–medium grading range, showing, as to be expected, that the latter material is finer than the former. This is because spent CSA has been previously used as a grit-blast for cleaning surfaces and thus its particle size is reduced in the process. In general, quenched CSA and spent CSA tend to appear in the size fraction zone that is suitable for use as fine aggregate in concrete, and normally without the need of further crushing.

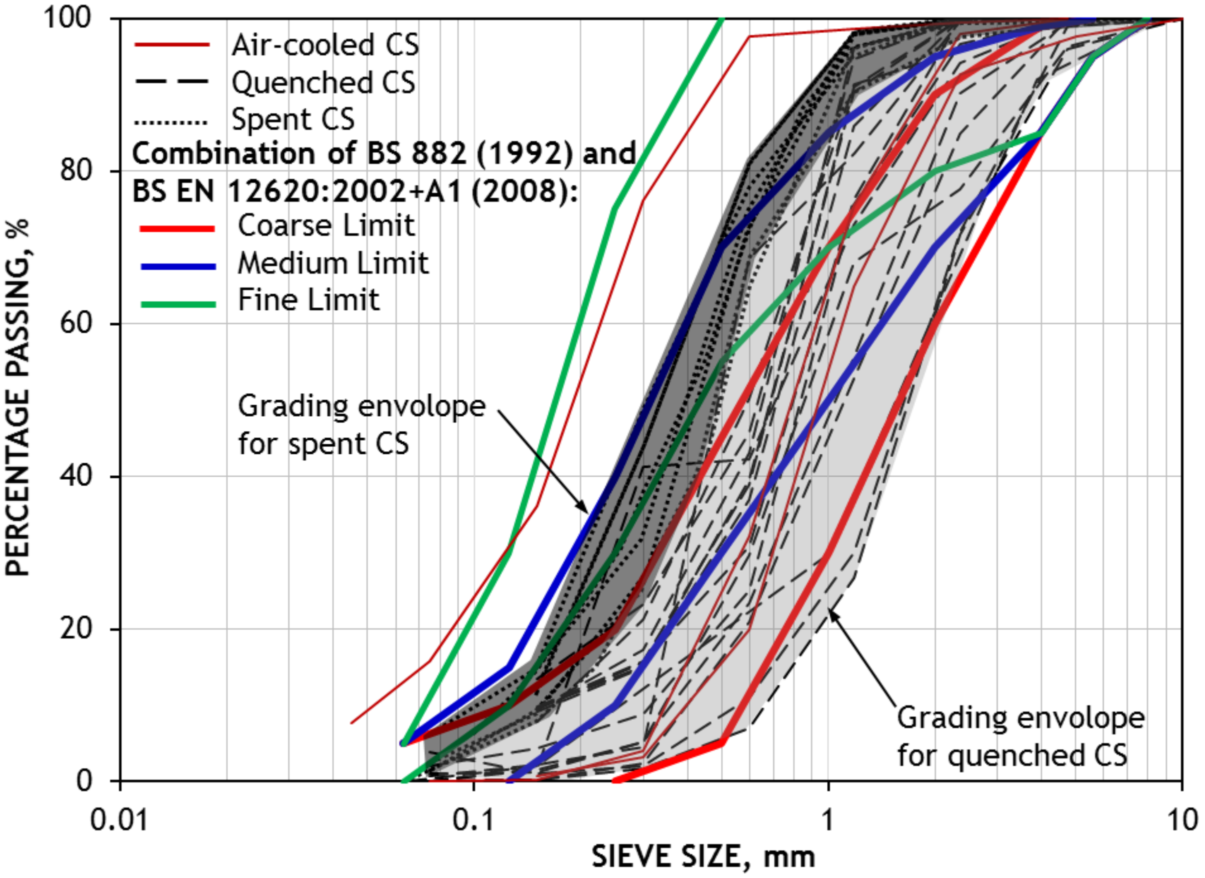


Figure 3.3 Particle size distribution of copper slag as fine aggregate

Data taken from Al-Jabri (2011), Al-Sayed and Mandany (1992), Ambily et al. (2015), Arivalagan (2013), Baragano and Rey (1980), Boakye (2014), Brindha and Nagan (2010), De Schepper et al. (2015), Gupta et al. (2012a); Hassan and Al-Jabri (2011), Koh and Lye (2012), Meenakashi and Ilangovan (2011), Ping (2011), Priyanka and Thahira (2013), Remade Scotland (2001), Resende et al. (2008), Selvanambi et al. (2011), Shoya et al. (1997, 1999), Tokuhashi et al. (2001), Wee et al. (1996), Tam (2001).

3.5 SPECIFIC GRAVITY

In the field of concrete, there are several ways to describe the relationship between the mass and the volume of an aggregate (Alexander and Mindess, 2005), such as (i) bulk density, which is the density of a solid in bulk form with inter-particle voids included, (ii) apparent density, which is the density of a solid particle with its closed pores included, and (iii) relative density, which is the apparent density of a material divided by that of water at 1000 kg/m^3. Among these, relative density, commonly known as specific gravity, is an important parameter in the design of a concrete mix.

Figure 3.4 shows the specific gravity of coarse RCA, fine GCA (of soda-lime, lead and aluminosilicate types) and fine CSA (of air-cooled, quenched and spent types). Additionally, for comparison purpose, the specific gravity value range for natural gravel and sand (2.6–2.7) that is commonly reported in the literature is shown in the green band.

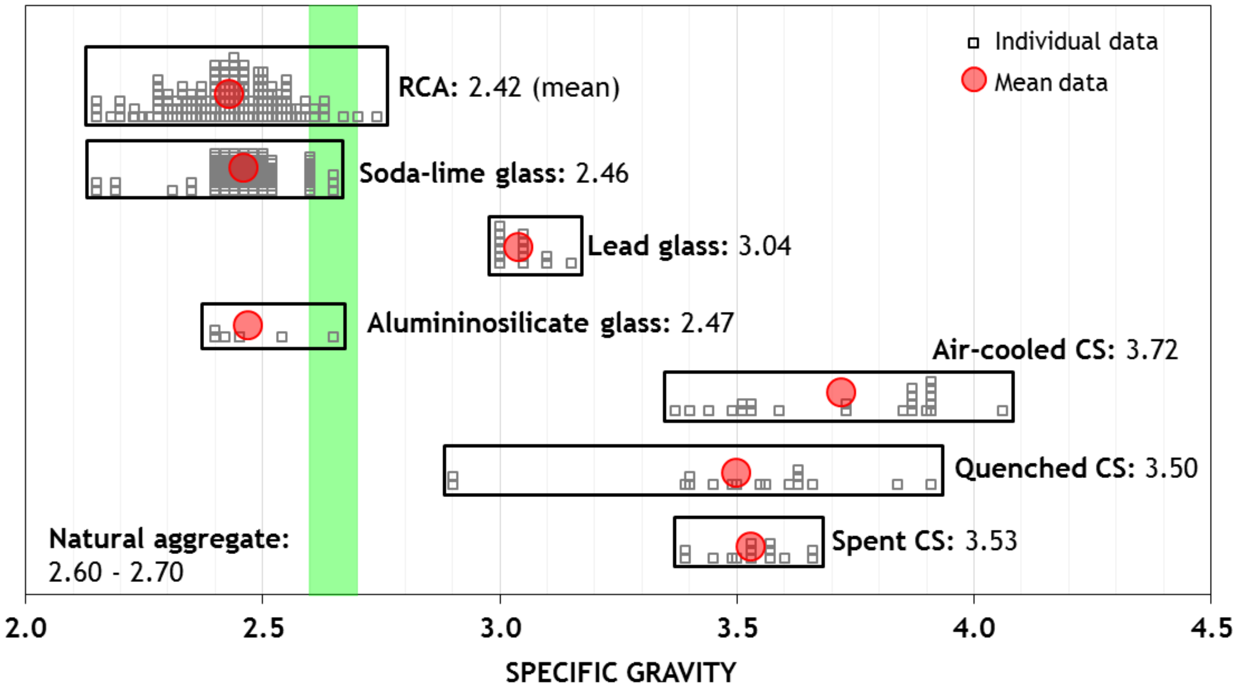


Figure 3.4 Specific gravity of recycled and secondary aggregates

Data of RCA taken from Ahmad et al. (1996), Ahmed and Vidyadhara (2013), Arezoumandi et al. (2015), Berndt (2004, 2009), Bhikshma and Manipal (2012), Brand et al. (2013a, 2013b), Bretschneider and Ruhl (1998), Cadersa and Ramchiriter (2014), Casuccio et al. (2008), Cervantes et al. (2007), Chen et al. (2003a, 2003b), Choi and Yun (2012, 2013), Corinaldesi (2009a, 2010, 2011), de Juan and Gutierrez (2004), de Oliveira and Vazquez (1996), Dilbas et al. (2014), Duan and Poon (2014), Duan et al. (2013), Fahmy et al. (2011), Fathifazl and Razaqpur (2013), Fathifazl et al. (2009a, 2009b, 2009c), Go et al. (2007), Grubl et al. (1999), Guo et al. (2014), Haque et al. (2014), Huda and Shahria Alam (2014, 2015), Imamoto et al. (2004), James et al. (2011), Kang et al. (2014), Khayat and Sadati (2014), Kim et al. (2012), Kikuchi et al. (1998), Knaack and Kurama (2011, 2013b, 2015a), Kou and Poon (2009a), Kumutha and Vijai (2010), Limbachiya et al. (2012b), Lo et al. (2013), Malesev et al. (2010), Mathew et al. (2013), Motwani et al. (2013), Padmini et al. (2009), Park and Sim (2005), Paul and van Zijl (2012, 2013a), Poon et al. (2009a, 2009b), Prasad and Kumar (2007), Purushothaman et al. (2014), Qasrawi and Marie (2013), Rahal (2007), Rao et al. (2011a, 2011b), Ravindrarajah (1996, 2012), Ravindrarajah and Tam (1985), Ravindrarajah et al. (1987), Safiuddin et al. (2011), Sakata and Ayano (2000), Sagoe-Crentsil et al. (2002), Salehlamein et al. (2015), Salem and Burdette (1998), Salem et al. (2001), Sarhat and Sherwood (2013), Sato et al. (2007), Schulz (1986), Sheen et al. (2013), Sivakumar et al. (2014), Soares et al. (2014) Somna et al. (2012a, 2012b), Song et al. (2015); Surya et al. (2013), Suryawanshi et al. (2015), Tangchirapat et al. (2010), Teranishi et al. (1998), Tia et al. (2009), Ujike (2000), Uygunoglu et al. (2014), Verian et al. (2013), Vyas and Bhatt (2013), Yanagi et al. (1998); Yang et al. (2008a), Yoda and Shintani (2014), Yun (2010), Zega and Di Maio (2006, 2011).

Data of GCA taken from Abendeh et al. (2015a, 2015b), Aghabaglou et al. (2015), Al-Akhras (2012), Almesfer et al. (2014), Al-Saffar (2013), Altaf et al. (2013), Aly et al. (2012), Anagnostopoulos et al. (2009), Bajad et al. (2012a, 2012b), Bhat and Rao (2014), Calmon et al. (2014), Cassar and Camilleri (2012), Chaïd et al. (2015), Chen and Wong (2015), Chen et al. (2006), Corinaldesi et al. (2005), De Castro and De Brito (2013), Dhir et al. (2005a), Disfani et al. (2012), Du and Tan (2014), Dumitru et al. (2010, 2013), Georgiadis et al. (2007), Huang et al. (2015), Hui and Sun (2011), Idir et al. (2009, 2010a, 2010b, 2011), Ismail and Al-Hashmi (2009), Jain and Neithalath (2010), Jang et al. (2015), Jangid and Saoji (2014), Kamali and Ghahremaninezhad (2015, 2016), Kim and Soh (2001), Kim et al. (2014, 2015), Klevbo (1998), Kou and Poon (2009b), Kou and Xing (2012), Laldji et al. (2004), Lam et al. (2007), Lee (2011), Lee and Lee (2016), Lee et al. (2013), Limbachiya (2009), Lin et al. (2009), Ling and Poon (2011b, 2012a, 2012b, 2014a, 2014b, 2014c), Ling et al. (2012), Liu (2011), Ling et al. (2011), Maier and Durham (2012), Malik et al. (2013, 2014), Maschio et al. (2013), Matos and Sousa-Coutinho (2012, 2016a, 2016b), Matos et al. (2015), Metwally (2007), Mirzahosseini and Riding (2014, 2015), Mitra et al. (2016), Narayana and Mailar (2015), Nassar and Soroushian (2011, 2012a, 2012b, 2013), Neithalath (2008), Neithalath and Schwarz (2009), Niang et al. (2015), Nunes et al. (2013), Omran and Tagnit-Hamou (2016), Ozkan and Yuksel (2008), Oliveira et al. (2008), Priscilla and Naik (2014), Parghi and Alam (2016), Park and Lee (2004), Park et al. (2004), Polley (1996), Polley et al. (1998), Poon and Chan (2007b), Proshin et al. (2005), Rajabipour et al. (2012), Romero et al. (2013), Salehuddin (2013), Schwarz and Neithalath (2008), Schwarz et al. (2007, 2008), Seju et al. (2015), Serpa et al. (2015), Shafaatian et al. (2013), Shao and Lehoux (2001), Shao et al. (2000), Sharif et al. (2014), Sharifi et al. (2015), Shayan and Xu (2006), Shi and Wu (2005), Shi et al. (2005), Siad et al. (2016), Singh et al. (2014), Su and Chen (2002), Soyer et al. (2010), Tejaswi et al. (2015), Tuncan et al. (2001), Tagnit-Hamou et al. (2015), Tagnit-Hamou and Bengougam (2012), Taha and Nounu (2008, 2009), Tang et al. (2005), Tognonvi et al. (2015), Turgut (2008a, 2008b, 2013), Turgut and Yahlizade (2009), Wattanapornprom and Stimanaithum (2015), Wright et al. (2014), Yilmaz and Degirmenci (2010), Wang (2009a, 2011), Wang and Chen (2010), Wang and Huang (2010), Wang and Hou (2011), Wang et al. (2009, 2014, 2016), Zhao et al. (2013a, 2013b).

Data of CSA taken from Afshoon and Sharifi (2014), Al-Jabri et al. (2002, 2006, 2009a, 2009b, 2011), Al-Sayed and Mandany (1992), Amarnaath et al. (2015), Anjana et al. (2015), Anudeep et al. (2015), Ayano and Sakata (2000), Behnood (2005), Boakye (2014), Boakye et al. (2013), Brindha and Nagan (2010), Brindha and Sureshkumar (2010), Cachim et al. (2009), Caliskan and Behnood (2004), Chew and Bharati (2009), Das et al. (1983), Dharani et al. (2015), Erdem et al. (2012), Ghosh (2007), Goi et al. (2003), Gowda and Balakrishna (2014), Havanagi et al. (2006, 2007, 2009), Hosokawa et al. (2004), Hwang and Laiw (1989), Jaivignesh and Gandhimathi (2015), Kang et al. (2013), Kayathri et al. (2014), Khan et al. (2015), Khanzadi and Behnood (2009), Kharade et al. (2013), Kitazume et al. (1998), Kumar

(2012), Lakshmanan et al. (2014), Lavanya et al. (2012, 2013), Lee (2008), Leema and Suganya (2015), Lim and Chu (2006), Madany et al. (1991), Madheswaran et al. (2014), Madhu and Venkataratnam (2015), Mahendran and Arunachelam (2015), Mahmood and Hashmi (2014), Meenakashi and Ilangovan (2011), Mithun and Narasimhan (2016), Mithun et al. (2015a, 2015b), Naganur and Chethan (2014), Najimi et al. (2011), Nazer et al. (2012, 2013), Patil (2015), Patel et al. (2011), Patnaik et al. (2015), Ping (2011), Priyanka and Thahira (2013), Pundhir et al. (2005), Resende et al. (2008), Sabarishri et al. (2015), Sakthieswaran and Ganesan (2013, 2014), Salleh et al. (2014), Saravana et al. (2005), Saxena (2015a, 2015b), Shabbeer et al. (2012), Shahu et al. (2012), Shams (2013), Sharifi and Kaafi (2013), Sharma et al. (2013a, 2013b), Shoya et al. (2003), Singh et al. (2014), Sudarvizhi and Ilangovan (2012), Suresh and Kishore (2013), Suresh et al. (2013), Sureshkumar et al. (2013), Sushma et al. (2015), Tam (2001), Tamil et al. (2014), Tiwari and Bhattacharya (2013), Ueno et al. (2005), Vamsi and Kishore (2013), Vamsi et al. (2013), Velumani and Nirmalkumar (2014), Viji (2014), Vimarsh et al. (2014), Wee et al. (1996), Wu et al. (2010a, 2010b), Yogendra (2008), Zain et al. (2004).

As shown in Figure 3.4, the specific gravity of individual coarse RCA samples varies in the range of 2.15–2.74, with the vast majority of the results being lower than the common specific gravity range of natural aggregate. On average, the specific gravity of coarse RCA is 2.42. The lower specific gravity of coarse RCA is to be expected, as the material is coated with cement paste residue, which is porous.

The specific gravity of GCA varies depending on its chemical composition. It can be seen from Figure 3.4 that the specific gravities of soda-lime glass (containing >20% $Na_2O + K_2O$) and aluminosilicate glass (≈16% Al_2O_3) are very similar, with an average value of 2.46 (with a range of 2.15–2.65) and 2.54 (with a range of 2.42–2.80), respectively. Both soda-lime and aluminosilicate GCA are lighter than natural aggregate, with the former, which is commonly commercially available, being the lighter of the two.

Owing to its high atomic mass, lead glass (contains >20% PbO), which is used for cathode ray tubes in television and computer screens, has the highest specific gravity, with a range of 2.99–3.15 and average of 3.04 (Figure 3.4). Treating lead glass with nitric acid to remove its lead content, however, does not result in a significant change in its specific gravity (Ling and Poon, 2012a; Ling and Poon, 2012b).

The specific gravity of CSA is controlled by the cooling process and its total iron content, expressed as ferrous (III) oxide (Fe_2O_3) (Dhir et al., 2016). Figure 3.4 shows that the average specific gravity of air-cooled CSA is higher than that of quenched CSA, i.e., 3.72 (with a range of 3.37–4.06) compared with 3.50 (with a range of 2.90–3.91). Spent CSA normally originates from quenched CS, and as to be expected, its specific gravity is close to that of quenched CSA, with a range of 3.39–3.66 and average value of 3.53.

The relatively higher specific gravity of air-cooled CSA is due to the slow air-cooling process, which gives the material a closed and dense structure, whilst the lower specific gravity value of quenched CSA is due to the quenching process, which tends to produce a less dense structure. Additionally, the higher specific gravity of air-cooled CSA compared to quenched CSA can be due to its higher total iron content. On average, the total iron content of air-cooled CSA is 61%, whilst that of quenched CSA is 40% (Dhir et al., 2016). Overall, all forms of CSA are heavier than natural aggregate.

In general, Figure 3.4 shows that the specific gravity of coarse RCA, GCA and CSA is different to that of natural aggregate, with coarse RCA, soda-lime GCA and aluminosilicate GCA having lower specific gravity, whilst lead glass GCA and all forms of CSA have higher specific gravity. This difference should be taken into consideration in designing concrete mixes, to maintain the volume-related properties such as yield, as well as to avoid possible segregation in the fresh concrete.

3.6 WATER ABSORPTION

The water absorption of an aggregate is largely a function of its porosity, which allows water to be absorbed. It is another important aggregate property used in concrete design to determine the amount of mixing water required. Highly absorptive aggregate is normally an undesirable material in any mix, because of its low physical properties. It can also result in a more variable concrete mix in both the fresh and the hardened states, in particular in consistence, strength and durability.

Figure 3.5 shows the water absorption of the selected RSA in this study, together with the commonly reported value range of 0.7–2.8% for the corresponding reference natural counterparts (shown in the green band). In general, the materials can be divided into two distinct groups: one is GCA and CSA with a near-zero water-absorption capacity, which is lower than that of natural aggregate, and the other is coarse RCA with a highly fluctuating water-absorption value that is mostly higher than that of natural aggregate (Figure 3.5).

As glass is an impermeable material, its maximum water absorption value has been reported in numerous studies to be less than 0.5%, with many results being 0% or close to it (Figure 3.5). For CSA, although the water absorption values are very low

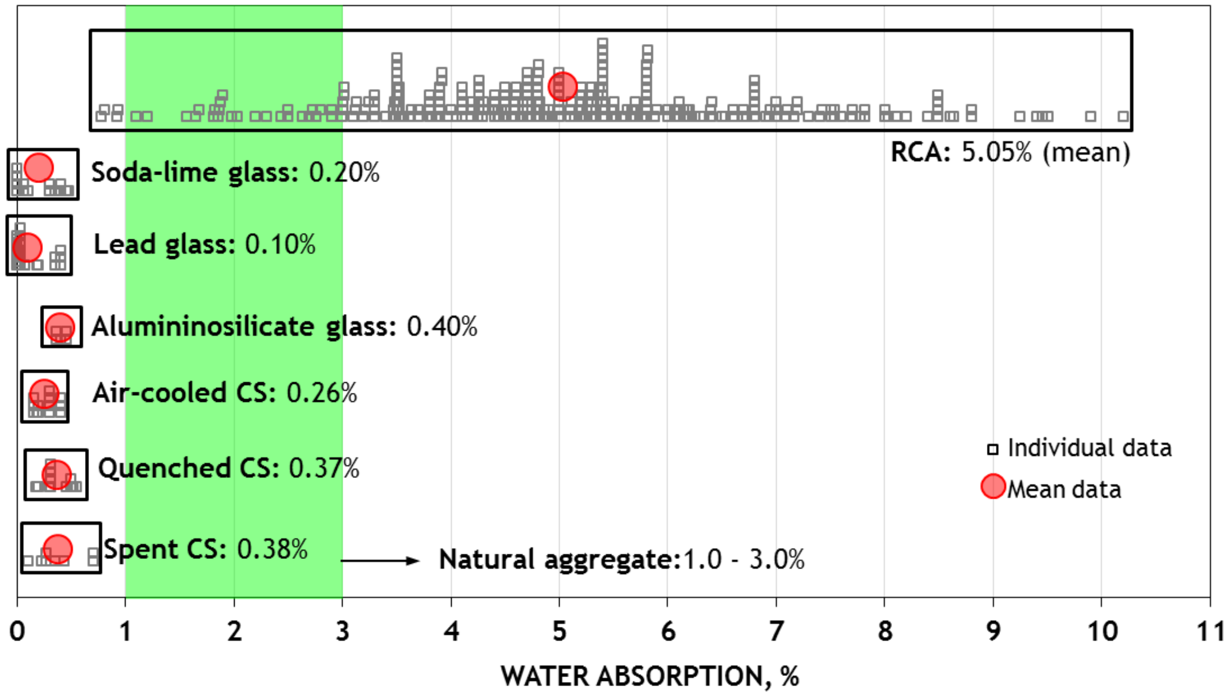


Figure 3.5 Water absorption of recycled and secondary aggregates

Data of RCA taken from Ahmad et al. (1996), Ahmed and Vidyadhara (2013), Akbarnezhad et al. (2011), Arezoumandi et al. (2015), Beltran et al. (2014b), Berndt (2004, 2009); Brand et al. (2013a, 2013b), Bravo et al. (2015), Bretschneider and Ruhl (1998), Butler et al. (2013a, 2013b), Cadersa and Ramchiriter (2014), Castano et al. (2009), Casuccio et al. (2008), Cervantes et al. (2007), Chen (2013), Chen et al. (2003a, 2003b, 2014), Choi ad Yun (2012, 2013), Collery et al. (2015), Corinaldesi (2010, 2011), Corinaldesi and Moriconi (2009a), Corinaldesi et al. (2011), Cui et al. (2015), de Juan and Gutierrez (2004), de Oliveira and Vazquez (1996), de Oliveira et al. (2004), Deshpande et al. (2009), Dhir and Paine (2007), Dhir et al. (1999), Dilbas et al. (2014), Dillmann (1998), Domingo-Cabo et al. (2009, 2010), Duan and Poon (2014), Duan et al. (2013), Etxeberria et al. (2006, 2007b), Fahmy et al. (2011), Fan et al. (2014), Fathifazl and Razaqpur (2013), Fathifazl et al. (2009a, 2009b, 2009c), Ferreira et al. (2011), Folino and Xargay (2014), Fonseca et al. (2011), Frondistou-Yannas (1977), Garcia-Navarro et al. (2010), Geng et al. (2014), Go et al. (2007), Gomes and de Brito (2007, 2009), Gomes et al. (2014), Gomez-Soberon (2002b, 2003), Gomez-Soberon et al. (2001, 2002), Gonzalez-Corominas and Etxeberria (2014), Gonzalez-Fonteboa and Martinez-Abella (2004, 2005, 2008), Gonzalez-Fonteboa et al. (2011a, 2011b), Grubl et al. (1999), Guardian et al. (2014), Guo et al. (2014), Haitao and Shizhu (2015), Haque et al. (2014), Henry et al. (2011), Ho et al. (2013), Huda and Shahria Alam (2014, 2015), Imamoto et al. (2004), Ishiyama et al. (2010), Ismail and Ramli (2014), James et al. (2011), Jimenez et al. (2013), Kang et al. (2014), Kenai et al. (2002, 2005), Kencanawati et al. (2013), Kerkhoff and Siebel (2001), Khayat and Sadati (2014), Kim et al. (2012), Kiuchi (2001), Kiuchi and Horiuchi (2003), Kikuchi et al. (1998), Knaack and Kurama (2011, 2013b, 2015a), Knights (1999), Konin and Kouadio (2012), Kou and Poon (2008, 2009a, 2010, 2013, 2015), Kou et al. (2004a, 2004b, 2007, 2008, 2012), Limbachiya et al. (2000, 2012a, 2012b), Liu et al. (2011), Lo et al. (2013), López-Gayarre et al. (2011), Manzi et al. (2011, 2013a), Maruyama et al. (2004), Mathew et al. (2013), Mendes et al. (2004), Morohashi et al. (2007), Motwani et al. (2013), Nishigori and Sakai (2012), Oliveira et al. (2013), Padmini et al. (2009), Paine and Dhir (2010), Paine et al. (2009), Park (1999), Park and Sim (2005), Paul and van Zijl (2012), Pedro et al. (2014a, 2014b), Poon et al. (2009a, 2009b), Prasad and Kumar (2007), Purushothaman et al. (2014), Qasrawi and Marie (2013), Rahal (2007), Rao et al. (2011a, 2011b), Ravindrarajah (1996, 2012), Ravindrarajah and Tam (1985), Ravindrarajah et al. (1987), Safiuddin et al. (2011), Sagoe-Crentsil et al. (2002), Sakata and Ayano (2000), Salehlamein et al. (2015), Salem and Burdette (2001), Salem et al. (2003), Sarhat and Sherwood (2013), Sato et al. (2007), Soares et al. (2014), Somna et al. (2012a, 2012b), Song et al. (2015), Surya et al. (2013), Suryawanshi et al. (2015), Tam et al. (2007b), Tangchirapat et al. (2010), Teranishi et al. (1998), Thomas et al. (2013, 2014a), Tia et al. (2009), Tsujino et al. (2007), Ueno et al. (2013), Ujike (2000), Verian et al. (2013), Vieira et al. (2011), Wang et al. (2013a, 2013b), Wardeh et al. (2015), Xiao et al. (2006b), Yang et al. (2008a, 2010), Yin et al. (2010), Yoda and Shintani (2014), Yun (2010), Zega and Di Maio (2011).

Data of GCA taken from Abendeh et al. (2015a, 2015b), Aghabaglou et al. (2015), Chen and Wong (2015), Chen et al. (2006), Corinaldesi et al. (2005), De Castro and De Brito (2013), Dhir et al. (2005a, 2005b), Du and Tan (2014), Dumitru et al. (2010), Huang et al. (2015), Hui and Sun (2011), Kim and Soh (2001), Kim et al. (2014), Kou and Poon (2009b), Lam et al. (2007), Lee (2011), Lee et al. (2013), Ling and Poon (2011b, 2012a, 2012b, 2014a, 2014c), Ling et al. (2012), Liu (2009, 2011), Maier and Derham (2012), Maschio et al. (2013), Nassar and Soroushian (2012), Omran and Tagnit-Hamou (2016), Park and Lee (2004), Park et al. (2004), Polley et al. (1998), Poon and Chan (2007b), Rajabipour et al. (2012), Serpa et al. (2015), Su and Chen (2002), Taha and Nounu (2008, 2009), Tuncan et al. (2001), Turgut and Yahlizade (2009), Wang (2009a), Wang and Chen (2010), Wang and Huang (2010), Wang et al. (2014, 2015), Wright et al. (2013), Zhao et al. (2013a, 2013b).

Data of CSA taken from Al-Sayed and Mandany (1992), Ambily et al. (2015), Arivalagan (2013), Brindha and Nagan (2010, 2011), Gupta et al. (2012a, 2012b), Ghosh (2007), Hassan and Al-Jabri (2011), Koh and Lye (2012), Kumar and Mahesh (2015), Madany et al. (1991), Nataraja et al. (2014), Ping (2011), Poozvizhi and Kathirvel (2015), Rajaselvi and Beatrice (2015), Resende et al. (2008), Sathya and Shanmugavalli (2014), Shoya et al. (1997, 1999, 2003), Siva et al. (2014), Srinivas and Muranal (2015), Tam (2001), Tixier (2000), Tokuhashi et al. (2001).

(0.10–0.65%), air-cooled CSA tends to have slightly lower value than quenched CSA (Figure 3.5). This is due to air-cooled CSA having a dense and crystalline structure, whilst quenched CSA has a porous texture (Dhir et al., 2016). As spent CSA is essentially quenched CSA that was previously used as a grit-blast material, its water absorption is not too dissimilar to that of quenched CSA (Figure 3.5).

Owing to the presence of adhered cement paste, which is of a porous nature, the water absorption of coarse RCA is generally higher than that of natural aggregate (Figure 3.5). On average, the water absorption of coarse RCA is 5.05%, but the individual data are rather inconsistent and vary across a very wide range, fluctuating between a minimum value of 0.80% and a maximum value of 10.2%. This high variability in water absorption reflects the quality of the crushing and screening effort made to produce coarse RCA. Inadequate processing of the material can result in a high content of cement paste adhered to the RCA, and the material may also contain other porous foreign contaminants such as masonry bricks. There is little to suggest that the machinery and technology used in processing coarse RCA have improved greatly over the years. Indeed, several methods have been developed that are capable of removing the adhered cement paste in coarse RCA, such as microwave-assisted beneficiation (Ong et al., 2010) and the use of an acidic solution (Tam et al., 2007a). However, these methods have not been developed for use in real practice.

Given that the porosity of the aggregate contributes to the total porosity of concrete, the use of near-zero water-absorptive (very low porosity) materials, such as GCA and CSA, as fine aggregates has been shown to enhance the performance of concrete in terms of its permeability and durability (Dhir et al., 2018a; Dhir et al., 2016). The high water absorption of coarse RCA is undesirable and it needs to be controlled by adopting a more effective technology to remove the adhered cement paste.

3.7 MODULUS OF ELASTICITY AND HARDNESS

As aggregates provide restraint to the volume changes in concrete, both load-dependent and load-independent, their modulus of elasticity (or stiffness) has a profound influence on the deformation properties of concrete. The hardness of the aggregate, which measures resistance to indentation, may also be a good indirect indication of its ability to resist the volume changes that concrete may experience during its service life.

Information on the modulus of elasticity of coarse RCA is not available. This is to be expected, as the modulus of elasticity of NA is directly referred to that of core samples drilled from larger pieces of parent rock, which is not possible in the case of RCA. Notwithstanding this, owing to the presence of adhered cement paste, which has a lower stiffness than natural materials, it can be safely assumed that the modulus of elasticity of RCA would be lower than that of NA.

Table 3.3 lists the modulus of elasticity and hardness (which is measured from the scratch test) of different types of GC and CS as well as natural sand. The modulus of elasticity of glass is affected by its chemical composition, which determines the bond strength between atoms and the connectivity of the atomic structure (Le Bourhis, 2008). The presence of an alkali such as sodium oxide (Na_2O) or potassium oxide (K_2O) decreases the connectivity of the glass structure, thus decreasing its modulus of elasticity. On the other hand, network formers such as aluminium oxide (Al_2O_3), boron trioxide (B_2O_3) and calcium oxide (CaO) participate in the glass network to increase its modulus of elasticity (De Jong et al., 2011).

Among the glasses listed in Table 3.3, aluminosilicate glass has the highest modulus of elasticity, whilst lead glass has the lowest. The modulus of elasticity values of all the glass types, nevertheless, are within or slightly above the modulus of elasticity range for natural sand. It can also be noted from Table 3.3 that the hardness of the glasses

Table 3.3 Modulus of elasticity and hardness of glass and copper slag

MATERIAL	**MODULUS OF ELASTICITY, GPa**	**HARDNESS, Mohs**
(a) Glass		
• Soda-lime	70 – 74	5.0 – 7.0
• Aluminosilicate	83 – 91	
• Lead	58 – 65	
• Borosilicate	64 - 89	
(b) Copper slag		
• Air-cooled	n.a.	6.0 – 7.0
• Quenched	n.a.	6.0 – 7.0
(c) Natural sand		
• Quartz/Quartzite	55 - 85	5.5 – 7.0

Data of glass taken from Le Bourhis (2008), De Jong et al. (2011).
Data of copper slag taken from Arivalagan (2013), Gaud et al. (2013), Jebitta and Sofia (2015), Poovizhi and Kathirvel (2015), Singh and Bath (2015), Singh et al. (2014), Song (2013), Sureshkumar et al. (2013).
Data of natural sand taken from Neville et al. (1983); Kogel et al. (2006).

is in the range of 5.0–7.0 Mohs, which is comparable to that of natural sand (5.5–7.0 Mohs).

The hardness of CS is not affected by its cooling process (Table 3.3). Both air-cooled and quenched CS have the same hardness range of 6.0–7.0 Mohs, which falls within the upper limit of the hardness range of natural sand.

In general, all things being equal, the use of coarse RCA as a coarse aggregate is likely to reduce the resistance of concrete to deformation, whilst the use of GCA and

CSA as fine aggregates can result in similar or better deformation properties of concrete compared to fine NA.

3.8 CONCLUSIONS

This chapter discusses the physical properties of recycled and secondary aggregates used in this study, namely, coarse recycled concrete aggregate (RCA), fine glass cullet aggregate (GCA) and fine copper slag aggregate (CSA), and compares their physical characteristics with those of natural aggregates normally used in concrete production. The chemical properties of these materials, though important, are outside the scope of this study.

Based on the definition given in BS EN 12620:2002+A1 (2008), because RCA is produced from construction and demolition waste, and excavation materials, it is covered by the *recycled aggregate* category in the standard. On the other hand, both GCA and CSA, derived from copper production and waste glass, respectively, come under the category of *manufactured aggregate*. Further distinction of RSA can be made based on the source of base materials.

The physical properties of coarse RCA are affected by the presence and amount of adhered cement paste residue, governed by the crushing process. In general, RCA is angular and has a rough and porous surface. Although it can be crushed into any required grading, the proportion of the coarse fraction tends to be high. The adhered cement paste, which is of a porous nature, makes the material more absorptive and lighter than natural aggregate. The water absorption of RCA can vary over a wide range from 0.80% to 10.2%, though the reported data have mostly shown it to be within the 4%–6% range, with an average of 5.1%. The specific gravity of RCA is normally in the range of 2.15–2.74 (mostly 2.3–2.5), with an average of 2.42. Although the modulus of elasticity of RCA cannot be measured, given that the material is coated with cement paste, it is likely that the modulus of elasticity of RCA would be lower than that of natural aggregate.

In the granular form, fine GCA is angular and smooth. Most GCA originates from soda-lime glass, which is the major commercial glass. The material is not suitable for use as a coarse aggregate because the particles are flaky and elongated. Although there is no issue with the processed material's compliance with the particle size distribution requirements as set out in BS EN 12620:2002+A1 (2008), it tends to be slightly on the coarse side. As glass is essentially an impermeable material, the water absorption of GCA can be considered to be zero in practice. The specific gravity of GCA of the soda-lime and aluminosilicate types tends to have an average value close to 2.5 (with a range 2.15–2.80), which is slightly lighter than that of fine natural aggregate. On the other hand, lead glass GCA is heavier than fine natural aggregate, having an average value of 3.14 (with a range of 3.0–3.2). The modulus of elasticity of GCA is in the range of 58–91 GPa with 5.0–7.0 Mohs hardness, which are comparable to those of fine natural aggregate.

Similar to GCA, CSA is also angular, but with a glassy and smooth surface texture. There are three distinct types of CSA in use: air-cooled, quenched and spent (or washed). Air-cooled CSA can be used as a coarse or fine aggregate, but quenched CSA and spent CSA are in a ready-to-use form as a fine aggregate. The grading of quenched CSA is mostly within the medium–coarse range, and it is coarser than spent CSA, which is within the fine–medium range. Compared to fine natural aggregate, CSA has lower water absorption, normally in the range of 0.10%–0.65%, with air-cooled CSA tending to have a slightly lower average value at 0.26% than quenched and spent CSA at 0.37% and 0.38%, respectively. The average specific gravity of air-cooled CSA is higher than that of quenched CSA, i.e., 3.72 (with a range of 3.37–4.06) compared with 3.50 (with a range of 2.90–3.91); and all CSA is heavier than fine natural aggregate. The material can be considered to have similar or slightly higher hardness compared to fine natural aggregate, i.e., 6.0–7.0 Mohs hardness compared to 5.5–7.0 Mohs hardness.

CHAPTER 4

ELASTIC DEFORMATION

4.1 INTRODUCTION

This chapter investigates the elastic deformation, in the form of the modulus of elasticity (Ec), of concrete made with (i) coarse recycled concrete aggregate (RCA) as a coarse natural aggregate replacement and (ii) fine glass cullet aggregate (GCA) and fine copper slag aggregate (CSA) as fine natural aggregate replacements.

In the context of concrete, the modulus of elasticity, based on the secant slope, is considered to describe its instantaneous deformation when subjected to a compressive load. The modulus of elasticity of concrete is an important property, as it is used in estimating the deflection and buckling of a structural member in designing buildings. However, as in practice the compressive strength of concrete is commonly used to estimate most of its mechanical properties, including the deformation properties, much of the research and development work surrounding the use of sustainable construction materials in concrete has tended to concentrate on the compressive strength only. Consequently, research on the effect of using recycled and secondary aggregate (RSA) on the elastic modulus of concrete has not been carried out to the same extent as on compressive strength.

In addition, whilst BS EN 12620:2002+A1 (2008) recognises recycled and secondary aggregates for use in concrete, and BS EN 206 (2013) allows the use of RSA in structural-grade concrete, there are some caveats to it, such as in Eurocode 2 (2004), which does not recognise RSA in estimating the E_C of concrete. Indeed, such a relationship is yet to be established.

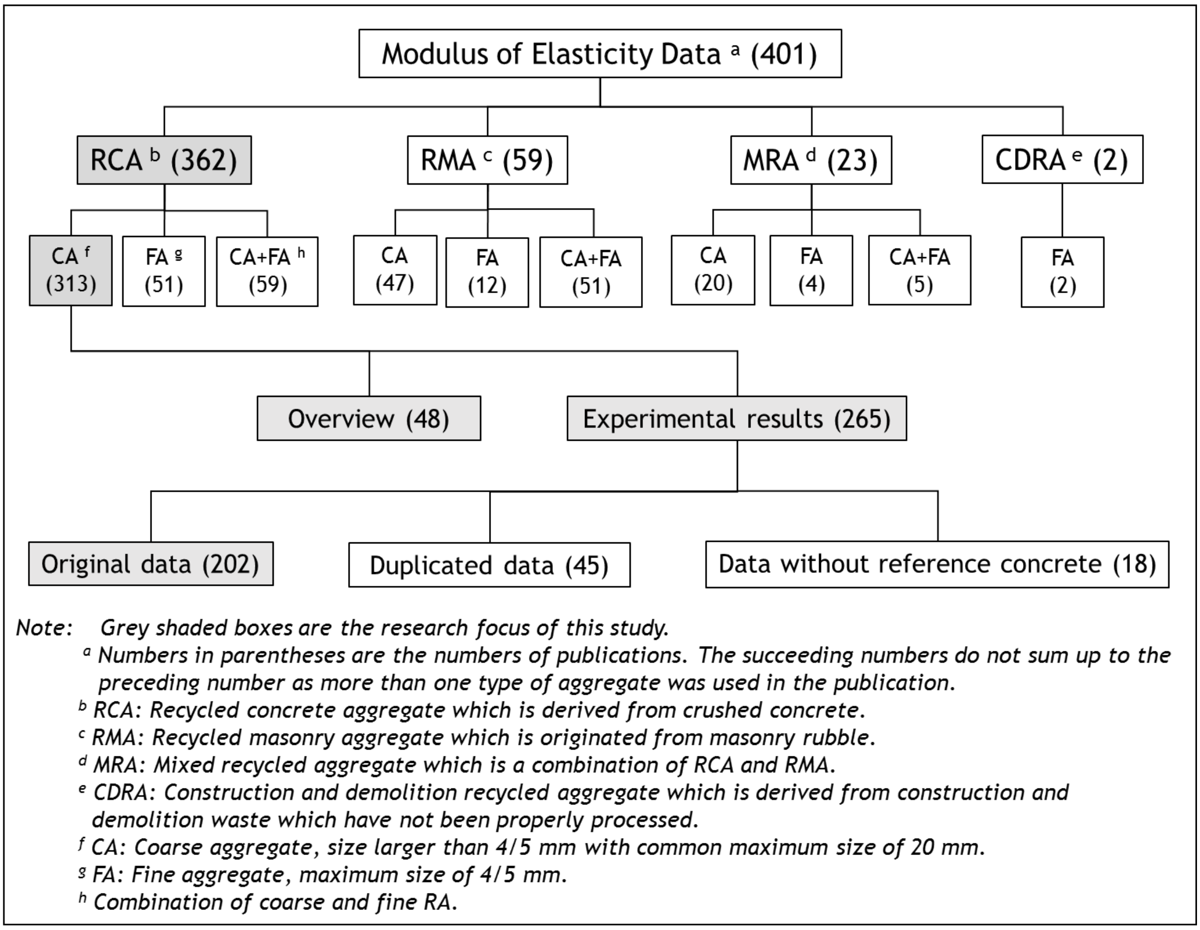
In this chapter, the elastic modulus of RSA concrete has been analysed extensively to assess its performance in comparison with natural aggregate concrete. To align with Eurocode 2 (2004), only concrete with characteristic cube strength of 15 to 105 MPa (or mean cylinder strength of 20 to 98 MPa) has been considered to be within the scope of this study.

4.2. COARSE RCA CONCRETE

4.2.1 Distribution of Data

Based on the established database, Figure 4.1 shows that the modulus of elasticity of RCA concrete is the most researched subject, accounting for about 80% of the total sources of data. Three other types of recycled aggregates (Silva et al., 2014), accounting for about 20% of the total, are in the early stage of development and are outside the scope of this study. For each type of material, the data have been further separated into coarse aggregate (for size larger than 4/5 mm), fine aggregate (for size smaller than 4/5 mm) or a mix of the two (Figure 4.1). The data for RCA concrete were classified into the following two groups:

(i) Publications of an overview nature, which present previous research on the E_C of coarse RCA concrete, including codes of practice and specifications. This information is discussed in Section 4.2.2.



Note: Grey shaded boxes are the research focus of this study.

[a] Numbers in parentheses are the numbers of publications. The succeeding numbers do not sum up to the preceding number as more than one type of aggregate was used in the publication.

[b] RCA: Recycled concrete aggregate which is derived from crushed concrete.

[c] RMA: Recycled masonry aggregate which is originated from masonry rubble.

[d] MRA: Mixed recycled aggregate which is a combination of RCA and RMA.

[e] CDRA: Construction and demolition recycled aggregate which is derived from construction and demolition waste which have not been properly processed.

[f] CA: Coarse aggregate, size larger than 4/5 mm with common maximum size of 20 mm.

[g] FA: Fine aggregate, maximum size of 4/5 mm.

[h] Combination of coarse and fine RA.

Figure 4.1 Distribution of data for elastic modulus of RA concrete

(ii) Publications with experimental results, in which the E_C data were obtained from dedicated laboratory studies and analysed by the researchers themselves. These results are further separated into three groups:

- Original data: experimental results for both coarse RCA and corresponding reference NA concrete.
- Duplicated data: the same results reported in more than one publication. These were considered only once to avoid exaggeration of the same view.

- Data without reference concrete: the corresponding reference NA concrete data were not available for comparison with the RCA concrete data.

Overall, the sourced experimental data covered a period of 41 years, 1977–2017, with the first journal publication by S. Frondistou-Yannas from the United States. The subject began to attract interest in the mid-1990s, and an increase in publishing was observed. The sourced data used in this study originated from 42 countries, and almost half were from Asia, as shown in Figure 4.2. However, the top 10 countries contributing to this knowledge were Spain, the United States, China, India, Japan, the United Kingdom, Canada, Hong Kong, Portugal and Australia. As most of these countries are known for their high-quality research, this can be taken as a sign of confidence in the sourced data for this study.

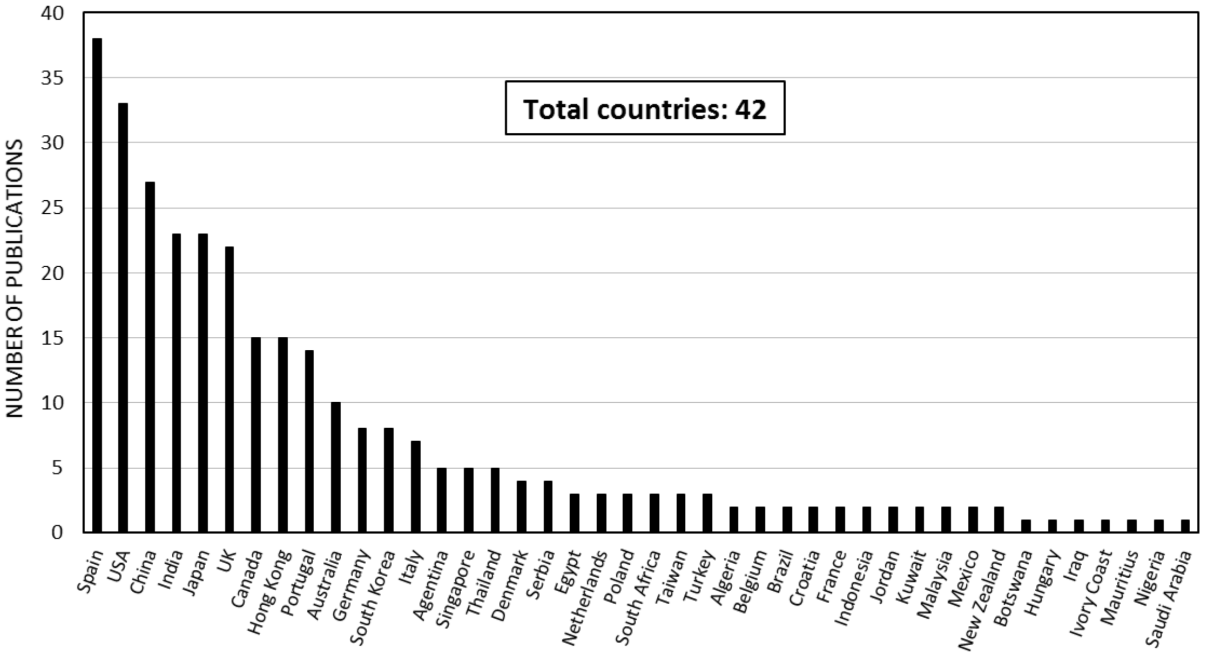


Figure 4. 2 Distribution of country of publication

4.2.2 Overview on Elastic Modulus of Coarse RCA Concrete

The E_C data for the overview of research on the use of coarse RCA in concrete were separated into two main groups: individual researchers (Table 4.1) and established organisations, the majority of which were from Europe and the United States (Table 4.2). In Table 4.2, the information is given in the form of (i) the E_C of coarse RCA concrete relative to NA concrete or (ii) a multiplying factor for the E_C of coarse RCA concrete. In general, the main messages emerging from the two groups are broadly the same.

It can be seen from Table 4.2 that only one report suggested that a 20% coarse RCA content replacement does not affect E_C (Task Force of Standing Committee of Concrete of Spain, 2004), and others reported no change, in the form of a multiplying factor of 1.0 (prENV 1992-1-1, n.d., Belgium Specifications, n.d., RILEM TC 121-DRG, 1994, Holland Specification, n.d., TNO Report, 1991, EHE-08, 2010).

However, at full replacement of coarse NA with coarse RCA, E_C is reported to be reduced by 6% to 40%, with an average of about 30%. As to be expected, and as in the case of strength, for a given water/cement ratio, the E_C of coarse RCA concrete has been reported as less than that of NA concrete (CCAA, 2008; Sagoe-Crentsil and Brown, 1998; Anderson et al., 2009).

In contrast to the average reduction of 30% reported above, a multiplying factor of 0.80 has been suggested for 100% RCA concrete with a minimum dry density of 2000 kg/m^3, maximum water absorption of 9% and maximum concrete strength of 60 MPa (Belgium

Table 4.1 Overview on the E_C of RCA concrete provided by individual researchers

REFERENCE	NO. OF REF. CITED	EFFECT ON E_C OF COARSE RCA CONCRETE
(a) Book Chapter		
Agrela et al. (2013)	3	Reduces by 20% at 100% RCA.
De Brito and Saikia (2013)	29	Reduces with increasing content with a range of 4 to 60% at 100% RCA.
Marinkovic et al. (2012)	4	Reduces by up to 45% (content not given).
(b) Journal		
Ajdukiewicz (2005)	n.c.[a]	Reduces by 15 – 30% (content not given).
Balazs et al. (2008)	4	Reduces by 18 and 20% at 50% and 100% content, respectively.
Bahera et al. (2014)	18	Unclear as the size of RCA is not clearly stated.
De Brito and Alves (2010)	4	Decreases as content increases.
De Brito and Robles (2010)	4	Decreases as content increases.
Evangelista & de Brito (2014)	6	Reduces by 15 – 40% (content not given).
Franklin & Gumede (2014)	4	Reduces by 15 – 70% (content not given).
Kisku et al. (2017)	4	Unaffected up to 30%, reduces by 13% at 50% RCA and 25% at 100% RCA.
Kukadia et al (2014)	5	Reduces by 15 – 45% at 100% RCA.
Li (2008a)	1	Reduces with increasing content with 45% at 100% RCA.
Li (2009b)	1	Unclear as results presented without specific discussion.
McNeil and Kang (2013)	3	Reduces by 20 – 40% (content not given).
Rao et al. (2007)	3	Reduces by 50 – 70% (content not given).
Safiuddin et al (2013)	7	Reduces by 10 – 45% (content not given).
Silva et al. (2016a)	7	Unaffected up to 30% but reduces by 20 – 40% at 100% RCA.
Xiao et al. (2006a)	2	Reduces by 15 – 45% (content not given).
Xiao et al. (2012b)	4	Reduces with increasing content with up to 45% at 100% RCA.

REF, references; n.c., no citations are given.

Table 4.2 Overview on the E_c of RCA concrete provided by established organisations

COUNTRY	REFERENCE	NUMBER OF REF. CITED	COARSE RCA, %		REMARKS
			20	100	
(a) Relative Ec of Coarse RCA Concrete with Respect to NA Concrete					
Australia	CCAA (2008)	n.c.	n.a.	n.a.	At equal w/c, RCA concrete has lower E_c than NA concrete.
	CSIRO by Sagoe-Crentsil and Brown (1998)	n.c.	n.a.	≤ 40% lower	n.a.
France	RILEM TC 37-DRC by Nixon (1978)	1	n.a.	n.a.	At equal w/c, RCA concrete has lower E_c than NA concrete.
	RILEM TC 37-DRC by Hansen (1986, 1992)	12	n.a.	≤ 40% lower	n.a.
	RILEM TC 217-PRE by Vazquez (2013)	5	n.a.	n.a.	E_c decreases as RCA increases
The Netherlands	Rijkswaterstaat by Geradu & Hendriks (1985)	3	n.a.	≤ 15% lower	n.a.
New Zealand	CCANZ by Chisolm (2011)	n.c.	n.a.	6 - 33% lower	n.a.
Spain	Task Force of Standing Committee of Concrete of Spain (2004)	n.c.	No change	20 - 40% lower	n.a.
Switzerland	OT 70085 (2006)*	n.c.	n.a.	20% lower	n.a.
USA	ACI Committee 555 (2001)	1	n.a.	10 - 33% lower	For 0.45 - 0.79 w/c ratio
	WSDOT by Anderson et al (2009)	1	n.a.	20 - 40% lower	At equal w/c ratio
	INDOT by Burke et al (1992)	2	n.a.	≤ 33% lower	n.a.
	MDOT by Dam et al (2011)	1	n.a.	10 - 33% lower	n.a.
	CP Tech Cen by Dam et al (2012)	1	n.a.	≤ 30% lower	n.a.
	PCA (2002)	1	n.a.	35% lower	n.a.
	US Army Corps of Engineers (2004)	n.c.	n.a.	35% lower	n.a.
(b) Multiplying Factor for Coarse RCA Concrete					
Belgium	Belgium Specification (n.d.)**	n.c.	n.a.	0.80	RCA with > 2100 kg/m^3 dry density, < 9% WA and max. str. of 37 MPa.
Netherlands	TNO Report (1991) ***	n.c.	1.00	0.95	For 20 - 30 MPa concrete.
			1.00	0.80	For 30 - 50 MPa concrete.
Spain	EHE-08 (2010)	n.c.	1.00	0.80	n.a.
France	RILEM TC 121-DRG (1994)	n.c.	n.a.	0.80	RCA with ≥ 2000 kg/m^3 dry density, ≤ 10% WA and max. str. of 60 MPa.
			n.a.	1.00	RCA with ≥ 2400 kg/m^3 dry density, ≤ 3% WA and no strength limit.

REF, reference; n.c., no citations are given; n.d.,no date; str, strength; WA, Water absorption

As reported in: * de Brito and Saikia (2013), ** Vyncke and Rousseau (1994), *** de Vries (1996)

Specifications, n.d., RILEM TC 121-DRG, 1994). However, a multiplying factor of 0.95 has been suggested for 100% RCA concrete with 20 to 30 MPa strength (TNO Report, 1991).

Overall, there are two shortcomings that can be noted in Table 4.2:

(i) The numbers of references cited in the reports produced by the established organisation group are very small, being no more than five in general, and at worst not even one in most cases. Without substantial visible background information, it is difficult to inspire engineers to specify coarse RCA as a replacement for the familiar NA for use in structural concrete.

(ii) The available data are limited to 20% and/or 100% coarse RCA content, and do not provide a clear indication of the effects on E_C at any other replacement level.

4.2.3 Coarse RCA Effect

Although the E_C test itself is simple, the variables used in the test are found to vary, in terms of aggregate properties, test method, specimen type and curing conditions (Table 4.3). To minimise this effect, the best possible method considered in this study is to analyse the data in relative terms, by comparing the E_C of RCA concrete to that of the corresponding NA concrete. This allows one to analyse the full spectrum of data in a concise manner that is easier to comprehend than presenting the actual measured values, as illustrated in Figure 4.3.

Table 4.3 Variations in the elastic modulus test for coarse RCA concrete

	PARAMETER	VARIABLE	NUMBER OF STUDIES
1. COARSE RCA PROPERTIES	Specific Gravity	< 2.4	18
		2.40 - 2.49	59
		2.50 - 2.70	36
		Not given	173
	Water Absorption, %	< 3	27
		3 - 5.9	142
		6 - 10	52
		Not given	65
	Aggregate Grading [a]	Similar	45
		Different	58
		Not given	183
	Parent Aggregate [a]	Similar	50
		Different	2
		Not given	234
	Moisture State When in Use	SSD [b]	89
		Air dry	9
		Oven dry	4
		Not given but water added	55
		Not given	129
2. TEST METHOD	Standard	ASTM C469 (USA)	38
		BS 1881-121 (UK)	20
		LNEC E397 (Portugal)	7
		UNE 83-316 (Spain)	7
		DIN 1048 (Germany)	6
		JIS A 1149 (Japan)	5
		IS 516 (India)	3
		UNI 6556 (Italy)	3
		AS 1012 (Australia)	3
		Others	12
		Not given	98

	PARAMETER	VARIABLE	NUMBER OF STUDIES
3. SPECIMEN TYPES	Shape and Dimension, mm	**Cylinder (Ø x *h*) [c]**	**133**
		• 75 x 150	4
		• 100 x 200	43
		• 100 x 250	1
		• 100 x 300	1
		• 120 x 240	1
		• 120 x 360	1
		• 150 x 250	1
		• 150 x 300	60
		• 160 x 320	2
		• Not given	19
		Prism (*l* x *w* x *h*) [d]	**11**
		• 100 x 100 x 300	4
		• 100 x 100 x 400	3
		• 150 x 150 x 300	2
		• Not given	2
		Not given	**58**
4. CURING CONDITIONS	Exposure	Moist	141
		Air	5
		Not given	56
	Duration, days	≤ 14	23
		15 - 30	112
		> 30	8
		Not given	59
	Temperature, °C	20 - 25	58
		25 - 30	16
		40	1
		Not given	127
	Humidity, R.H. %	90 - 100	125
		50 - 70	5
		Not given	72

[a] In comparison with the corresponding coarse natural aggregate.

[b] SSD = Saturated surface dry; [c] Ø x *h* = diameter x height; [d] *l* x *w* x *h* = length x width x height

Figure 4.3 shows the relative E_C of concrete containing coarse RCA in relation to that of the corresponding NA concrete. It should be mentioned that, in most cases, the water/cement ratio of RCA concrete is the same as that of NA concrete. To avoid overlap, each data point was slightly displaced in the vertical and/or horizontal direction. A box-and-whiskers plot was created at each coarse RCA content, based on the most widely used Tukey method, to visualise the distribution of the data, as well as to detect outliers. The whiskers are connected to the points that are no greater than 1.5 times the interquartile range (value of Quartile 3 minus value of Quartile 1), and any data that are beyond the endpoints of the whiskers are considered outliers. In the regression analysis, the following data have not been considered for reasons as explained:

- Statistically, 45 outliers determined using the box-and-whiskers plots, representing about 3% of the total data. Nearly half of the outliers were data for concrete made with 100% coarse RCA.

- Theoretically, 59 data points that showed an E_C of coarse RCA concrete higher than that of the corresponding NA concrete (value >100% in Figure 4.3), accounting for 4.5% of the total data. This is because the adhered cement paste on RCA is porous and weak, and as such, all other things being equal, the use of RCA could not result in an increase in the E_C of concrete. In fact, strictly speaking, the data showing no change in E_C when NA is replaced by RCA (value at 100% in Figure 4.3) are incorrect for this reason. However, it is assumed that coarse RCA at its best does not adversely affect the E_C of concrete; therefore these data have not been excluded.

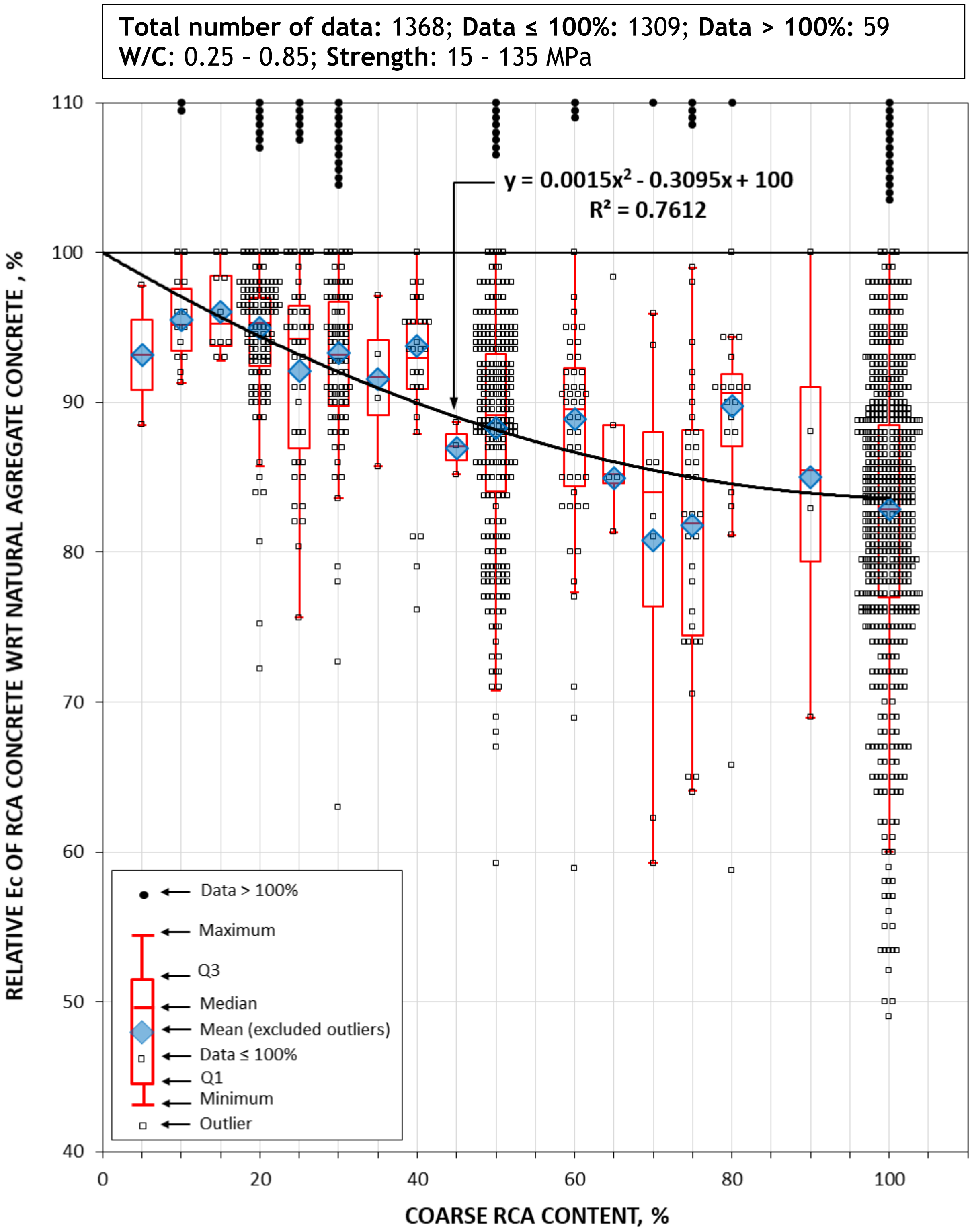


Figure 4.3 Relative elastic modulus of coarse RCA concrete with respect to corresponding reference NA concrete

Data taken from Adam et al. (2016), Ahmad et al. (1996), Ahmed and Vidyadhara (2013), Ajdukiewicz and Kliszczewicz (2002, 2007), Akbarnezhad et al.(2011), Arezoumandi et al. (2015), Arundeb et al. (2011), Barbudo et al. (2013), Beltran et al. (2014b), Brand et al. (2013a, 2013b), Bravo et al. (2015), Bretschneider and Ruhl (1998), Butler et al. (2013a, 2013b), Cadersa and Ramchiriter (2014), Castano et al. (2009), Casuccio et al. (2008), Cervantes et al. (2007), Chen (2013), Chen et al. (2003a, 2003b, 2014), Choi and Yun (2012, 2013), Collery et al. (2015), Corinaldesi (2010, 2011), Corinaldesi et al. (2011), Cui et al. (2015), Dapena et al. (2011), de Juan and Gutierrez (2004), de Oliveira and Vazquez (1996), de Oliveira et al.(2004), de Pauw et al. (1998), Deshpande et al. (2009), Dhir and Paine (2004, 2007), Dhir et al. (1999, 2004a), Dilbas et al. (2014), Dillmann (1998), Domingo-Cabo et al. (2009, 2010), Dosho (2007), Duan and Poon (2014), Duan et al. (2013), Eguchi et al. (2007), Ekolu et al. (2012), Etxeberria et al. (2006, 2007a, 2007b), Fahmy et al. (2011, 2012), Fan et al. (2014), Fathifazl and Razaqpur (2013), Fathifazl et al. (2009a, 2009b, 2009c), Ferreira et al. (2011), Folino and Xargay (2014), Fonseca et al. (2011), Frondistou-Yannas (1977), Garcia Navarro et al. (2010), Geng et al. (2015, 2016), Gesoglu et al. (2015), Go et al. (2007), Gomes and de Brito (2007, 2009), Gomes et al. (2014), Gomez-Soberon (2002b, 2003), Gomez- Soberon et al. (2001, 2002), Gonzalez-Corominas and Etxeberria (2014, 2016a, 2016b), Gonzalez-Fonteboa and Martinez-Abella (2004, 2005, 2008), Gonzalez-Fonteboa et al. (2011a, 2011b), Gonzalez-Taboada et al. (2017), Grubl et al. (1999), Guardian et al. (2014), Guo et al. (2014), Haitao and Shizhu (2015), Hansen and Boegh (1985), Haque et al. (2014), Henry et al. (2011), Ho et al. (2013), Huda and Shahria Alam (2014, 2015), Ignjatovic et al. (2013), Imamoto et al. (2004), Inoue et al. (2012), Ishiyama et al. (2010), Ismail and Ramli (2014), James et al. (2011), Kang et al. (2014), Kenai et al. (2002, 2005), Kencanawati et al. (2013), Kerkhoff and Siebel (2001), Khayat and Sadati (2014), Kheder and Al-Windawi (2005), Kikuchi et al. (1998), Kim et al. (2012), Kiuchi (2001), Kiuchi and Horiuchi (2003), Knaack and Kurama (2011, 2012, 2013a, 2013b, 2015a), Knights (1999), Konin and Kouadio (2012), Kou and Poon (2008, 2013, 2015), Kou et al. (2004a, 2004b, 2007, 2008, 2012), Koulouris et al. (2004), Kumutha and Vijai (2010), Laneyrie et al. (2016), Laserna and Montero (2016), Li et al. (2012), Limbachiya (2004, 2010), Limbachiya et al. (1998, 2000, 2004, 2012a, 2012b), Liu et al. (2011, 2016), Lo et al. (2013), López-Gayarre et al. (2009, 2011), Malesev et al. (2010), Manzi et al. (2011, 2013a, 2013b), Maruyama et al. (2004), Mathew et al. (2013), Meinhold et al. (2001), Mellman et al. (1999), Mendes et al. (2004), Mohamad et al. (2014), Motwani et al. (2013), Nishigori and Sakai (2012), Obla et al. (2007), Omary et al. (2016), Ong et al. (2010), Padmini et al. (2009), Paine et al. (2009), Park (1999), Paul and van Zijl (2012, 2013a), Pecur et al. (2015), Pedro et al. (2014a, 2014b), Pepe et al. (2014), Pickel et al. (2014), Poon and Kou (2004, 2010), Poon et al. (2006), Prasad and Kumar (2007), Purushothaman et al. (2014), Qasrawi (2014), Qasrawi and Marie (2013), Rahal (2007), Rao and Madhavi (2013), Rao et al. (2010, 2011a, 2011b), Rasheeduzzafar and Khan (1984), Ravindrarajah (1996, 2012), Ravindrarajah and Tam (1985), Ravindrarajah et al. (1987), Razaqpur et al. (2010), Roos (1998), Safiuddin et al. (2011), Sakata and Ayano (2000), Salehlamein et al. (2015), Salem and Burdette (2001), Sale0, m et al. (2003), Sarhat and Sherwood (2013), Sato et al. (2007), Schulz (1986), Seara-Paz et al. (2016), Silva et al. (2016b), Sheen et al. (2013), Sivakumar et al. (2014), Soares et al. (2014), Somna et al. (2012a, 2012b), Surya et al. (2013), Suryawanshi et al. (2015), Tam et al. (2007b, 2013), Tangchirapat et al. (2008, 2010, 2013), Teranishi et al. (1998), Thomas et al. (2013, 2014a, 2014b, 2016), Tsujino et al. (2007), Ueno et al. (2013), Ujike (2000), Uygunoglu et al. (2014), Verian et al. (2013), Vieira et al. (2011), Vyas and Bhatt (2013), Wagih et al. (2013), Waleed and Canisius (2007), Wang et al. (2013b), Wardeh et al. (2015), Xiao et al. (2005, 2006b, 2015), Yang and Lee (2017), Yang et al. (2008a, 2008b, 2010, 2012), Yin et al. (2010), Yun (2010), Zega and Di Maio (2006, 2009, 2011), Zhou and Chen (2017).

Overall, a polynomial regression was performed based on the mean value at each coarse RCA content, and a correlation of 0.7612 was obtained. As shown in Figure 4.3, the trend line suggests that the E_C of concrete decreases at a decreasing rate as coarse RCA content is increased, giving an average reduction of 16% when coarse NA is fully replaced by coarse RCA and a reduction of 5% and 12% at 20% and 50% coarse RCA content, respectively.

Compared with the information provided by the established organisations (Table 4.2), the average reduction of 16% in E_C at 100% RCA content found in this study (Figure 4.3) is considerably close to the multiplying factor of 0.80 suggested by:

- the Code on Structural Concrete (EHE-08) of the Spanish Ministry of Development in 2010;
- the specification proposed by RILEM Technical Committee 121 in 1994;
- recommendations from pilot projects undertaken in the Netherlands (year unknown), as reported by de Vries (1996);
- recommendations from a working group initiated by the Ministry of the Environment and Infrastructure in Belgium (year unknown), as reported by Vyncke and Rousseau (1994).

The finding of a 16% reduction at 100% coarse RCA content is also within the range of 6% to 40% reported by various organisations in Australia, New Zealand, Europe and the United States, during 1986–2012 (Table 4.2). However, there is a disagreement at 20% coarse RCA content. As opposed to the suggestion that there is no change in E_C when 20% RCA is used (Table 4.2), the results in Figure 4.3 show an average reduction of 5%, with individual values possibly as high as 15%.

Given that Figure 4.3 is established based on a large data population sourced from the work undertaken in 42 countries over a period of 40 years, it is likely to present a more representative and realistic case in assessing the effect of coarse RCA on the E_C of concrete.

4.2.4 Strength Grade Effect

To make the analysis closer to practice, the data used in developing Figure 4.3 were divided into six strength groups based on the measured compressive cube strength of reference NA concrete, covering a broad range of strengths, 20–130 MPa, as shown in Figure 4.4. The procedure adopted in developing this figure is described next:

(i) The mean compressive cube strength, instead of individual test specimen results, was used in the analysis of the data. The strengths of concrete measured using 100- and 150-mm cubes were taken as identical, as per BS 8500-1:2006+A1 (2012). When the shape of the specimen was not known, recorded strength was treated as cube strength.

(ii) Cylinder strengths were converted into cube strengths using a correction factor of 1.25 given in BS EN 12504-1 (2009), as:

$$Correction\ Factor = \frac{2.5}{1.5 + {}^{1}/_{\lambda}}$$

where,

λ is the length/diameter of the cylinder specimen, which was assumed as 2.

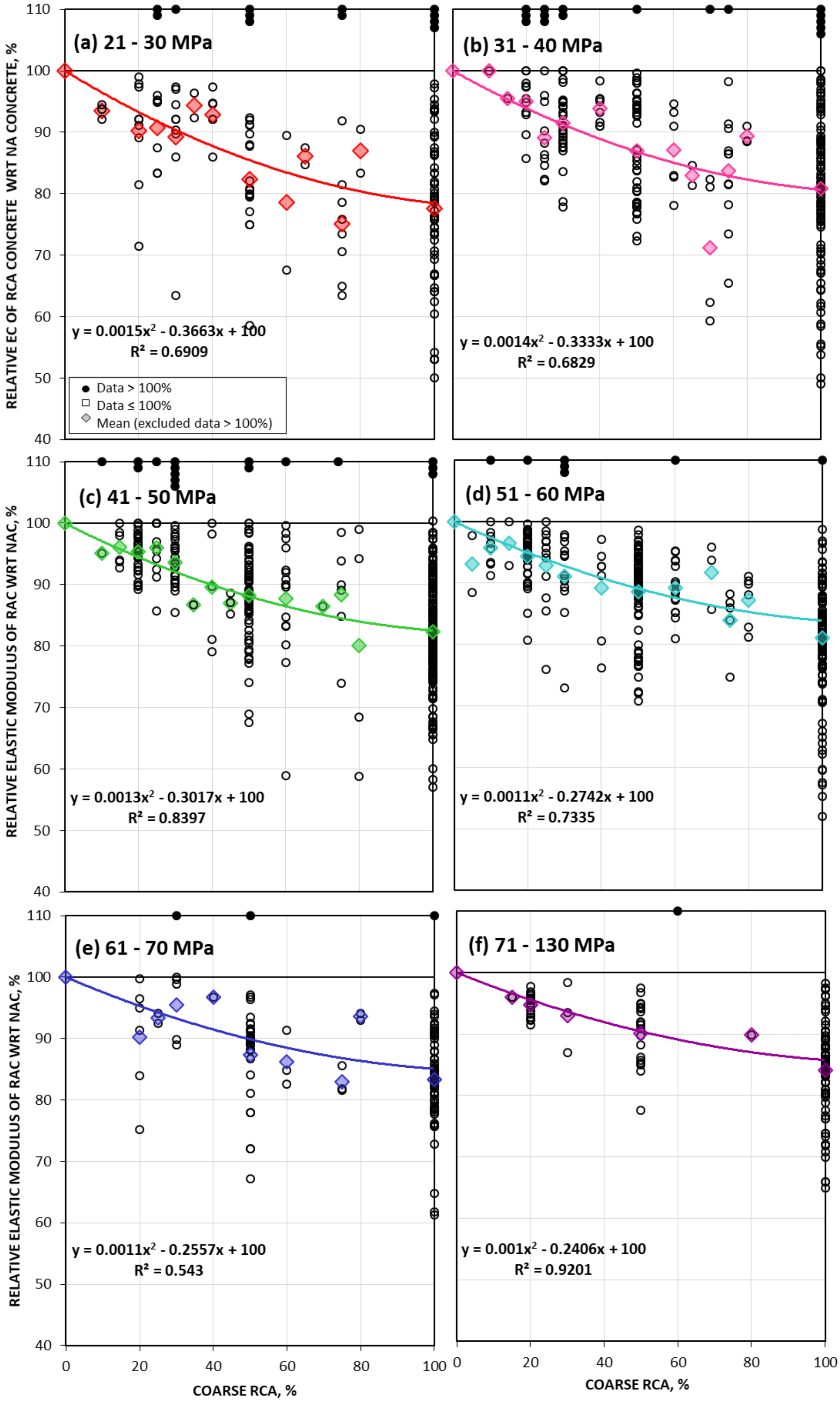


Figure 4.4 Relative Ec of coarse RCA concrete with respect to corresponding reference NA concrete at different strength grades

(iii) Data showing that the E_C of coarse RCA concrete was higher than that of reference NA concrete (that is >100% in relative terms) were considered unrealistic and excluded in determining the mean results at each coarse RCA content.

Figure 4.4 shows that the shapes of the trend lines, for each strength range, are very similar, exhibiting generally good correlation, ranging from 0.5430 [Figure 4.4(e)] to 0.9201 [Figure 4.4 (f)]. Collectively, the data suggest that, at a given coarse RCA content, as the compressive strength of the concrete increases, the reduction in the relative value of E_C decreases.

For use in practice, the trend lines in Figure 4.4 were reconstructed and assembled as Figure 4.5, showing a family of curves for a concrete cube strength grade range of 20–130 MPa, in increments of 10 MPa. In general, the results show that, at 100% coarse RCA content, the reduction in E_C can be as high as 22% for the lowest grade of concrete (20 MPa), and as low as 13% for the highest grade of concrete (130 MPa). This finding is opposite to the suggestion made in the pilot projects and research undertaken in the Netherlands (as reported by De Vries, 1996), as given in Table 4.2. This suggestion cannot be right for the following two reasons:

(i) In designing a concrete mix, as the concrete strength increases, the coarse aggregate volume decreases; in consequence, the aggregate effect on the properties of the concrete is decreased. Thus, when coarse RCA is used, there is a proportionately smaller influence of its adhered cement paste, resulting in a relatively smaller reduction in the E_C of concrete at higher strength.

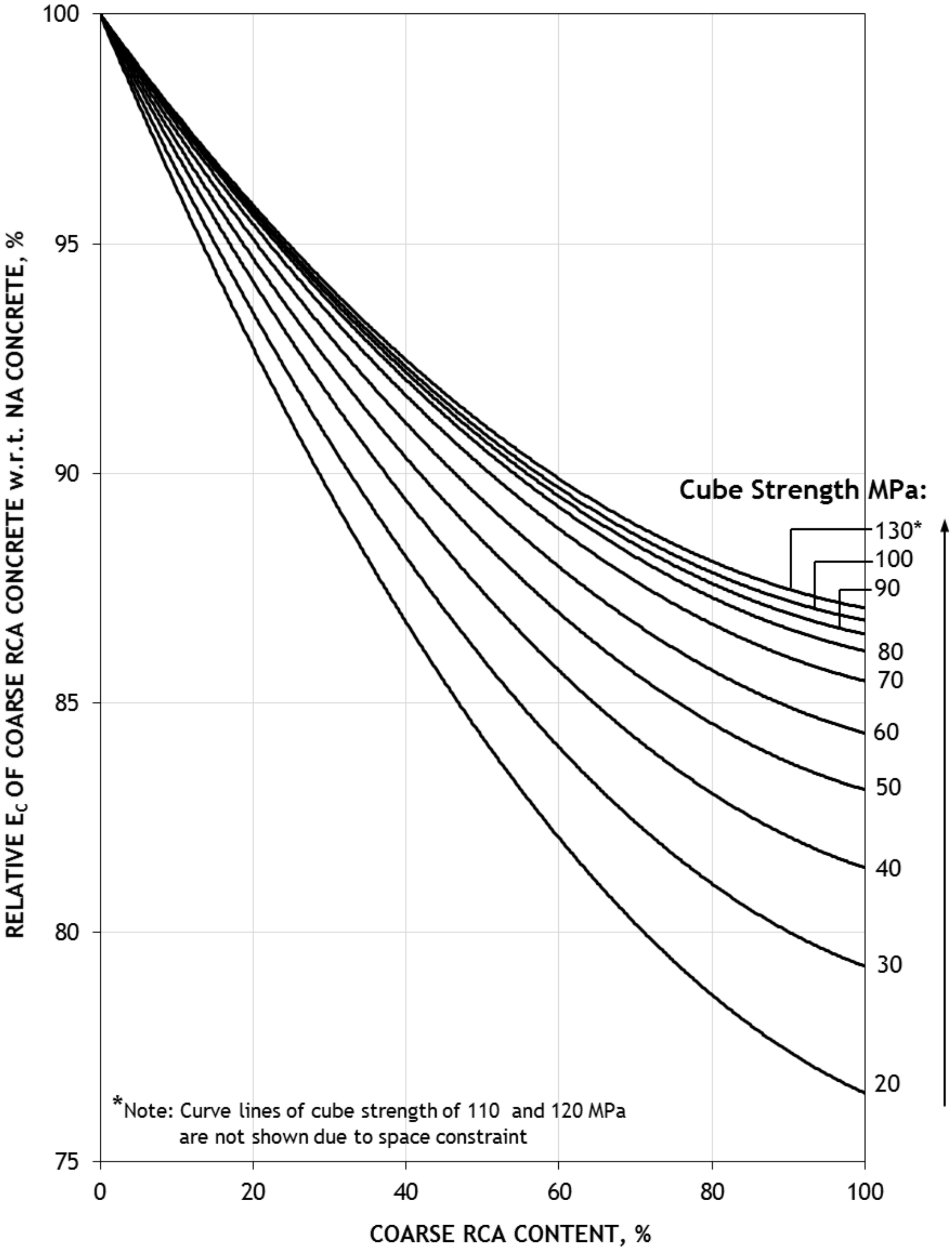


Figure 4.5 Effects of coarse RCA on the elastic modulus of concrete at different strength grade

(ii) High-strength concrete demands the use of high-quality coarse aggregate. Thus, the quality of the coarse RCA used in the production of high-strength concrete is expected to be better than that in low-strength concrete. As a result, the reduction in E_C in the former concrete should be smaller.

4.2.5 Elastic Modulus and Compressive Strength Relationship

The structural design codes such as Eurocode 2 (2004) and ACI 318 (2014) associate the E_C of concrete with its compressive strength. Additionally, Eurocode 2 (2004) suggests multiplying factors for concrete made with basalt, quartzite, limestone and sandstone. Thus, it is important to know how the elastic modulus–compressive strength relationship of concrete changes when coarse RCA is used as an NA replacement.

To visualise this in a graphical form, the compressive cube strength of concrete was plotted against its corresponding E_C, measured at 28 days, for both the reference NA concrete and the coarse RCA concrete. The data were divided into six groups with 20% coarse RCA content, as shown in Figure 4.6. Similar to the analysis in Section 4.2.5, cube strength was used throughout, and the same cylinder-to-cube strength conversion method was adopted. For comparison purposes, the E_C values of concrete made with basalt, quartzite, limestone and sandstone, given in Eurocode 2 (2004), are also shown in Figure 4.6.

In developing the trend line for each individual group, a small amount of data (about 3% from the total over 2000 data points) was not considered because of its having (i) extremely high or low E_C values at a given strength (shown as triangle markers in

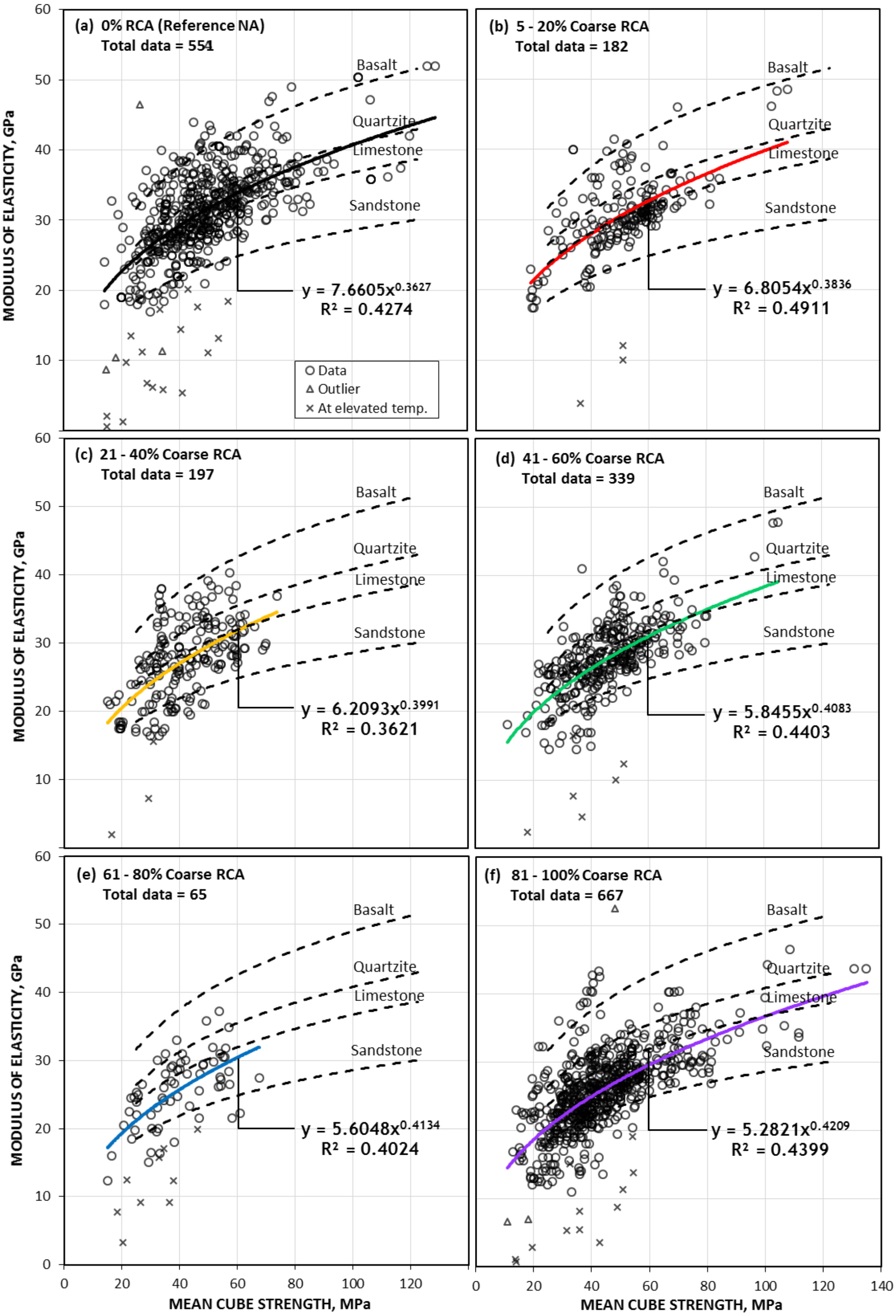


Figure 4.6 Relationship between elastic modulus and compressive strength of coarse RCA concrete

Figure 4.6), which could not be justified, or (ii) low E_C values for concrete after exposure to elevated temperature (shown as cross markers).

It can be seen from Figure 4.6 that specimens with 30 to 60 MPa compressive strength were mostly tested regardless of the coarse RCA content used, and concrete containing 81% to 100% coarse RCA had the highest number of data. It should be mentioned that for reference NA concrete, a specific trend line for each rock type could not be distinguished, as the information on the type of natural aggregate used had not always been reported. Thus, it is suggested that the trend line for NA concrete [Figure 4.6 (a)] roughly represents the natural aggregate normally used in making concrete. Overall, the trend line for NA concrete falls between sandstone and limestone for strength smaller than 60 MPa but between limestone and quartzite for strength greater than 60 MPa.

For RCA concrete, Figure 4.6 shows that, as the coarse RCA content increases, whilst the E_C of concrete reduces at a given strength, the trend lines progressively move from between quartzite and limestone concrete towards limestone and sandstone concrete. The trend lines of NA and RCA concrete were replotted collectively for ease of comparison and use in Figure 4.7 (a).

As the trend lines of NA concrete obtained in this study are not parallel to those of Eurocode 2 (2004) [Figure 4.7 (a)], there is a question of creditability regarding the E_C–compressive strength relationships given in Eurocode 2 (2004) for different types of NA. Notwithstanding this, if the findings in Figure 4.7 (a) were to comply with Eurocode

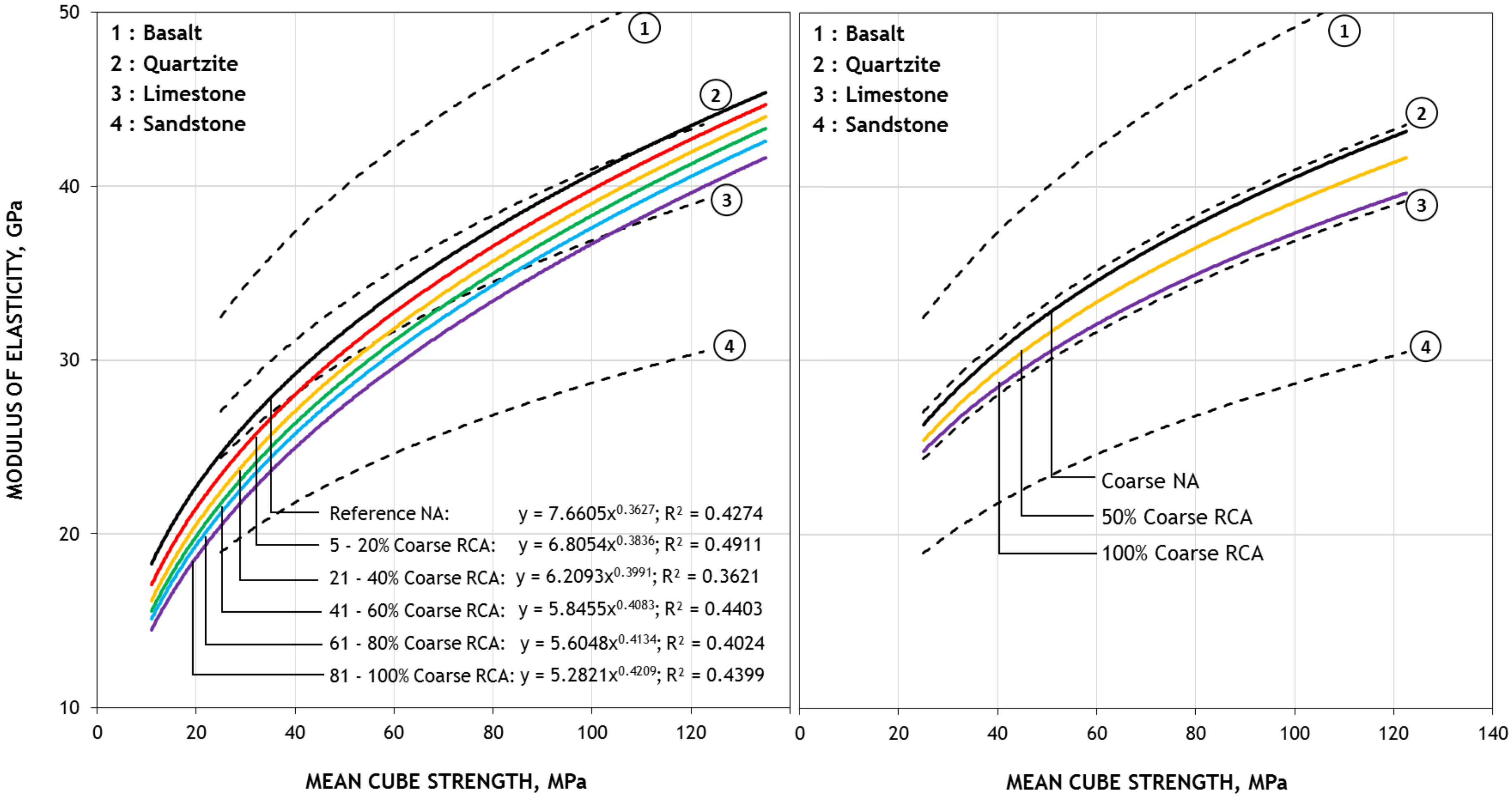


Figure 4.7 Relationship between elastic modulus and compressive strength for RCA concrete: compilation from Figure 4.6 (left), proposed (right)

2 (2004), the E_C–compressive strength relationships for concrete made with NA and RCA would take the form shown in Figure 4.7 (b).

4.3. FINE GCA AND FINE CSA CONCRETE

This section deals with the effects of using fine glass cullet aggregate (GCA) and fine copper slag aggregate (CSA) as fine natural aggregates on the E_C of concrete. As the two materials share some commonalities in terms of particle shape, water absorption and hardness properties (see Chapter 3), if concrete mixes were designed properly, these two fine aggregates should affect the E_C of concrete in similar manners.

A preliminary assessment conducted on the available information for the overview (Rashad, 2014; Rashad, 2015; Tam, 2001; Dhir, 2009) regarding the influence of fine GCA and fine CSA on E_C summarised below does not suggest a definitive conclusion in this regard. This is because the coverage of the subject was scarce and based on only a few supporting documents. In two separate sources, but which originated from the same researcher, the use of fine GCA derived from soda-lime glass decreases the E_C of concrete as the content increases (Rashad, 2014); on the other hand, the E_C of concrete made with fine GCA derived from cathode ray tubes (CRT) and liquid crystal displays (LCD) could be similar to or higher or lower than that of NA concrete (Rashad, 2015). However, the magnitude of the changes in all these cases has not been clearly indicated. For fine CSA, the E_C of concrete may remain essentially unchanged with inclusion of up to 30% content (Tam, 2001), or may even increase owing to the higher hardness of fine GCA compared to fine NA (Dhir, 2009).

Owing to the brevity of the narrative description, the information provided in the overview is not helpful in developing the use of these two fine aggregates in structural applications, suggesting that a rigorous assessment is required for better understanding of their effects on the elastic modulus of concrete.

The E_C data used in this study for fine GCA and fine CSA concretes covered a period of nearly 40 years, although much of it was for recent work. For GCA, the research was predominantly conducted in Asia but the United Kingdom has the highest contribution. For CSA, most of the work was from India. Overall, although the data population of these two materials is not as large as that of coarse RCA concrete, an analysis and evaluation of the effects of these two materials is needed to provide a rational basis for future development.

Before proceeding to the analyses of results, it should be mentioned that the experimental variations in the E_C tests for fine GCA concrete and fine CSA concrete, in terms of the material properties, test methods, specimen types and curing conditions, generally were similar to those observed for coarse RCA concrete (Table 4.3).

4.3.1 Fine Natural Aggregate Replacement

The relative E_C values of fine GCA and fine CSA concretes with respect to the corresponding fine NA concrete are shown in Figure 4.8. In most cases, the water/cement ratio of fine GCA and fine CSA concretes is the same as that of NA concrete. The box-and-whiskers plots (as previously described in Section 4.2.3) were

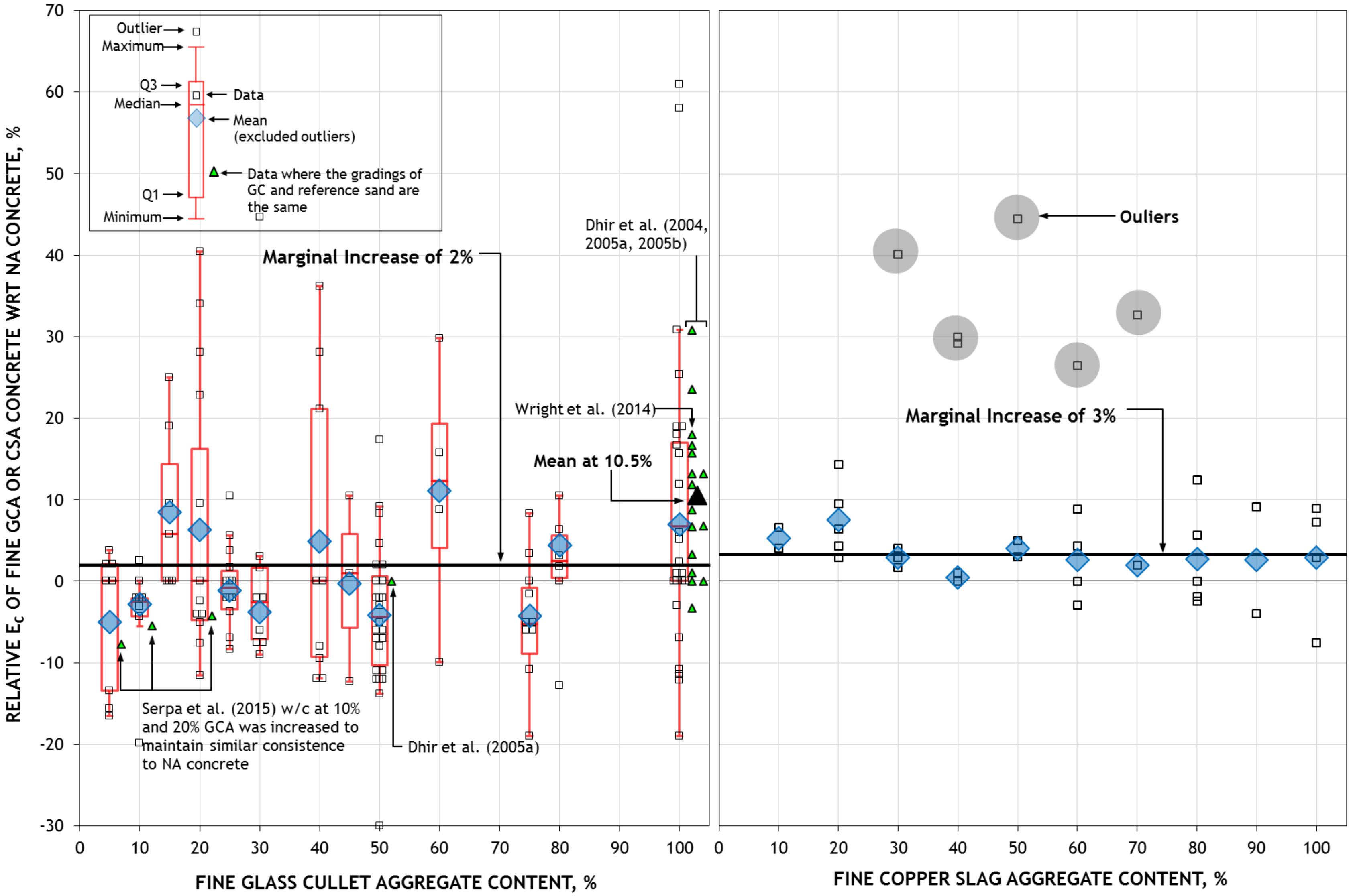


Figure 4.8 Relative E_C of fine GCA (left) and fine CSA (right) concrete with respect to fine NA concrete

Data of fine GCA taken from Abdallah and Fan (2014); Ali and Al-Tersawy (2012); Al-Sibahy and Edwards (2012); Dhir et al. (2004e, 2005a, 2005b); Du and Tan (2014); Dumitru et al. (2010); Ganiron (2013); Guo et al. (2015); Hui and Sun (2011); Jia et al. (2015); Kulkarni et al. (2015); Limbachiya (2009); Ling and Poon (2012b); Mavroulidou et al. (2011); Noruziaan and Buskell (2010); Roskos et al. (2015); Samarin (1980); Serpa et al. (2015); Shehata et al. (1996); Taha and Nounu (2008); Tan and Du (2013); Tang et al. (2005); Wang (2009a); Wright et al. (2014); Zhao et al. (2013a, 2013b)
Data of fine CSA taken from Jebitta et al (2015); Mavroulidou (2016); Mavroulicdou and Liya (2015); Mithun and Narasimhan (2016); Patil (2015); Patil et al. (2016); Sambhaji and Autade (2016).

constructed only for fine GCA at each fine NA replacement level to identify outliers from the data, and not for fine CSA as its data population was small. However, a few data for the latter are treated as outliers, shaded in grey in the Figure 4.8, owing to their significant deviation from most of the data.

It appears that the spread of data for fine GCA concrete is greater than that for fine CSA concrete. The possible explanation for this is that glass cullet needs to be crushed and sieved to the size of fine aggregate prior to its use; thus, its particle size and distribution can vary greatly depending on the quality of the processing. On the other hand, for fine CSA, the material used in making concrete is most likely derived from quenched and spent copper slag, whose size is similar to that of fine natural aggregate. Thus, comparatively, the particle size and distribution of fine CSA is likely to show less variation than that of fine GCA.

Overall, Figure 4.8 shows that, regardless of fine NA replacement level, the mean relative data of fine GCA concrete mostly fluctuate within the range of −10% to +10% and that of fine CSA concrete is within the range of 0% to 10%. On average, the use of fine GCA and fine CSA results in a marginal increase of 2% and 3%, respectively, in the elastic modulus of concrete. These average results, however, do reflect the difference in hardness between the two materials, that is, the use of fine CSA (6–7 Mohs hardness) shows a slightly higher increase in E_C than fine GCA (5–7 Mohs).

It should be mentioned that the particle size distribution of fine GCA and fine CSA has not been kept the same as that of the corresponding fine NA in all the tests, apart from a few studies fine GCA concrete (shown in green triangle markers in Figure 4.8). In this case, the slightly lower relative values at 10% and 20% fine GCA contents were the result of using a higher water/cement ratio in the fine GCA mixes compared to the reference mix to maintain the consistence. On the other hand, at 100% fine GCA content, an average increase of 10.5% in E_C is shown. This increase is likely to be due to (i) greater particle interlocking attributed to the angular shape of GCA and (ii) the higher hardness of GCA, compared to fine NA.

As the hardness of fine CSA is slightly greater than that of fine GCA, it is postulated that if the same occurs in fine CSA concrete, the increase in E_C could be at least or higher than 10.5% when fine NA is fully replaced by fine CSA.

4.3.2 Elastic Modulus and Compressive Strength Relationship

Given the importance of the relationship between the E_C and the compressive strength of concrete as seen in structural design codes, this relationship for fine GCA and fine CSA concretes is plotted in Figure 4.9 (a), using the same method previously described in Section 4.2.6 for coarse RCA. However, unlike in the case of coarse RCA concrete, the trend lines of fine GCA and CSA concretes are not separated based on their fine

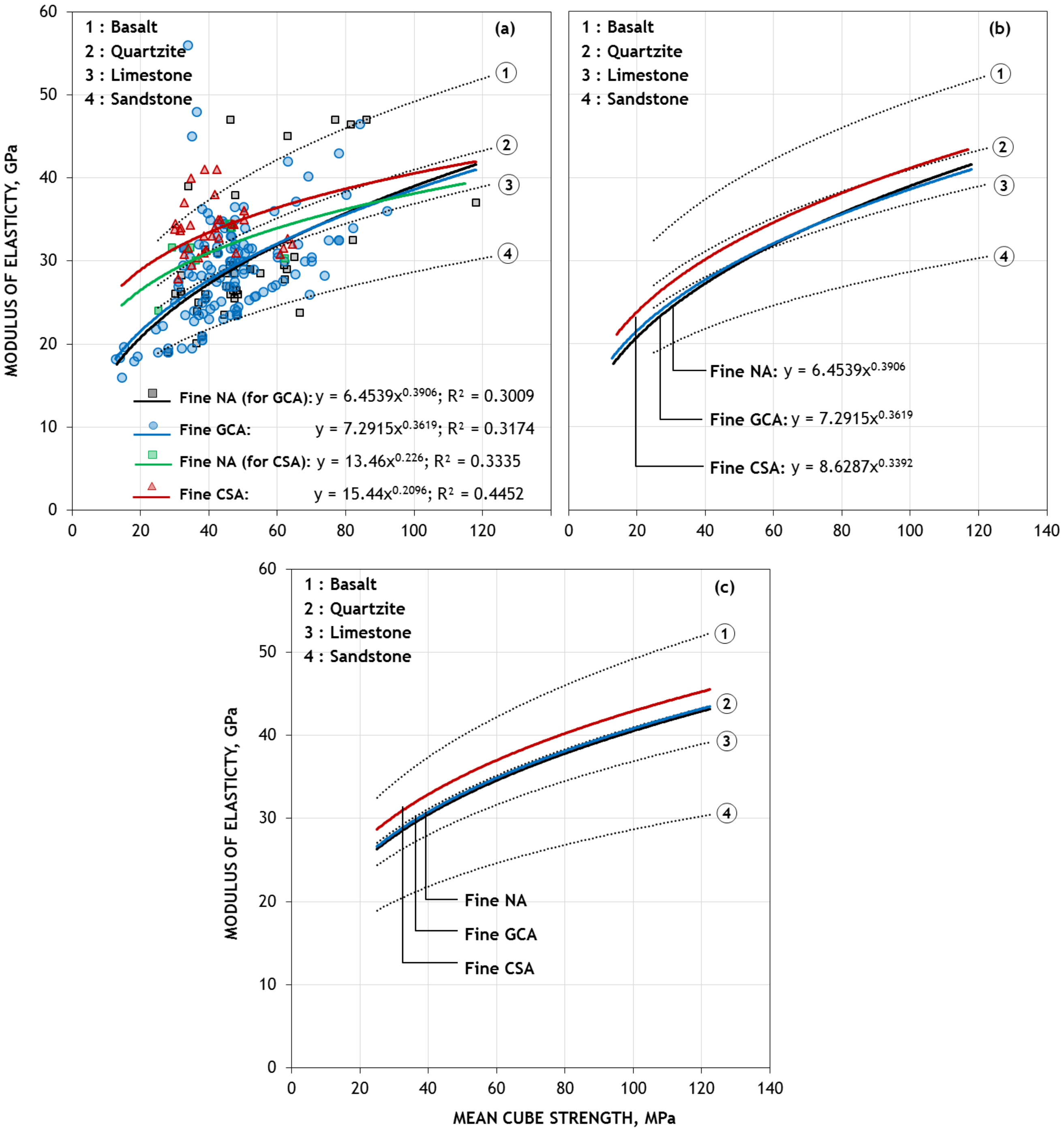


Figure 4.9 Elastic modulus-compressive strength relationship for fine GCA and fine CSA concrete: (a) compilation from Figure 4.8, (b) normalised and (c) proposed

NA replacement level, because of the small data populations for these materials, as can be seen in Figure 4.8. The trend lines obtained from Eurocode 2 (2004) for four natural aggregates are shown in Figure 4.9 for comparison.

Figure 4.9 shows that the two trend lines of the NA concrete corresponding to the fine GCA and fine CSA concretes are not the same. However, the trend line of fine GCA concrete is very similar to that of fine NA concrete, suggesting that its use as a replacement for fine NA does not significantly change the E_C–compressive strength relationship. For fine CSA concrete, it is evident that for a given compressive strength, the E_C of the resultant concrete is higher than that of the fine NA concrete.

To compare the E_C–compressive strength relationships of fine GCA and fine CSA concretes, the trend line of the fine CSA concrete was normalised in form to that of fine GCA concrete [Figure 4.9 (b)], but still maintaining the similar gap distance from fine NA concrete. This shows that, for a given compressive strength, the use of fine CSA is likely to result in a slightly higher E_C than fine NA concrete, whilst the use of fine GCA is not likely to result in a significant change in E_C.

It should be noted that the trend lines of the fine NA, fine GCA and fine CSA concretes shown in Figure 4.9 (b) are not of a form similar to those in Eurocode 2 (2004). This disparity cannot be assigned to the use of fine GCA and fine CSA, as fine NA concrete also exhibited a similar trend. As engineers are more inclined to follow the relationships given in the structural design code, to put the knowledge into practice, the trend lines obtained were normalised so that their shapes are in line with those given in Eurocode 2 (2004) [Figure 4.9 (c)].

4.4 CONCLUSIONS

This chapter deals with the effects of using coarse recycled concrete aggregate (RCA), fine glass cullet aggregate (GCA) and fine copper slag aggregate (CSA) as natural aggregate replacements on the elastic modulus of concrete.

First, an assessment was made based on the overview obtained from technical reports from the established organisations and literature of a review nature prepared by individual researchers. It was revealed that the use of coarse RCA reduces the elastic modulus of concrete, and the level of reduction can be affected by the content and properties of the RCA (density and water absorption), as well as the strength of the concrete. As for fine GCA and fine CSA, no definitive conclusions can be drawn owing to the limited information. Overall, the main drawback seen in the overview-based literature is that the number of references used is small, with no more than 10 in most cases, and the information provided therein tends to be narrative in nature.

Based on the analysis and evaluation of the data obtained from over 300 publications, it was found that, as the coarse RCA content increases, the elastic modulus of the concrete decreases at a decreasing rate, giving an average of 16% reduction when NA is fully replaced by RCA. This level of reduction is within the range of 6%–40% reported by various organisations. However, in contrast to the view that there is no change in elastic modulus at 20% RCA content, as suggested by some organisations, this study shows that the use of 20% RCA can result in an average reduction of 5%, which can possibly increase up to 15%.

It was also found that the relative reduction in elastic modulus of RCA concrete with respect to NA concrete decreases as the concrete strength increases, showing an average 22% reduction in the lowest strength concrete (20 MPa) and a 13% reduction in the highest strength concrete (130 MPa). Comparing the relationships between elastic modulus and compressive strength of concrete obtained in this study with those of Eurocode 2 (2004) for different rock types, namely basalt, quartzite, limestone and sandstone, it was shown that the trend line of NA concrete is within that of quartzite and sandstone concrete; on the other hand, that of RCA concrete moves towards that of sandstone concrete as RCA content increases.

In the study of the effects of fine GCA and CSA on the elastic modulus of concrete, although their relative results with respect to the corresponding NA concrete fluctuate, it was found that, on average, the use of fine GCA results in a marginal increase of 2% (fluctuating within the range of −10% to +10%); and fine CSA also results in a marginal increase of 3% (0% to 10% range). The results suggest that fine CSA can result in a slightly higher elastic modulus of concrete compared to fine GCA. For a given strength, the elastic modulus–compressive strength trend line of fine GCA concrete is very similar to that of fine NA concrete, whilst that of fine CSA is higher than that of fine NA concrete.

CHAPTER 5

CREEP DEFORMATION

5.1 INTRODUCTION

This chapter examines the creep deformation of concrete when coarse natural aggregate (NA) is replaced by coarse recycled concrete aggregate (RCA) or, as a separate study, fine NA is replaced by fine glass cullet aggregate (GCA) or fine copper slag aggregate (CSA).

Although measured as strain in the tests according to ASTM C512 (2015) and BS ISO 1920-9 (2009), the creep deformation of concrete can be expressed in several forms:

(i) **creep strain**—strain that develops with time under a sustained load;

(ii) **specific creep**—creep strain per unit stress applied;

(iii) **creep coefficient**—the ratio of creep strain to elastic strain;

(iv) **compliance**—the total load-induced strain (sum of elastic strain and creep strain) per unit stress applied (ACI 209, 2008).

This time- and load-dependent deformation of concrete can affect the serviceability of structural concrete; for example, it can cause an increase in deflection of a structural member, a reduction in pre-stressing force in pre-stressed concrete and a redistribution of stresses from concrete to the steel reinforcement in a structural column under compression (fib, 2009). Thus, structural engineers are required to have an accurate assessment of the creep deformation of concrete at the design stage.

It is generally accepted that the creep phenomenon takes place in hardened cement paste and that aggregates do not undergo creep (Neville et al, 1983). In addition to its content in a mix, the physical properties of aggregate such as the modulus of elasticity (or hardness) can affect the creep deformation of concrete. Indeed, concrete mixes of the same composition made with different aggregates may exhibit different creep values and this is most likely to be the case when coarse RCA is used as a replacement for coarse NA. However, the stiffness of the aggregate has not been considered in estimating the creep deformation of concrete and this can be seen from the many established creep prediction models, such as those given in ACI 209(2008) and Eurocode 2 (2004) (Chapter 7).

5.2 COARSE RCA CONCRETE

Owing to both the time required for and the high cost of the test, studies on the creep deformation of concrete containing recycled aggregates (RA) are relatively few compared to studies of elastic deformation (Chapter 4) and shrinkage deformation (Chapter 6). Amongst the four RA types (as defined in Chapter 1) and their possible uses as coarse, fine or a mixture of both coarse and fine aggregates, coarse RCA remains the most popular research subject. The research relevant to RCA has been carried out since the 1980s and mostly in the European countries.

In this section, the information and experimental data on the creep of coarse RCA concrete are assessed, including an overview on the use of coarse RCA produced by individual researchers and established organisations, an analysis of the creep deformation of coarse RCA concrete with respect to the corresponding NA concrete, and consideration of other factors affecting creep deformation of coarse RCA, in relation to NA.

5.2.1 Overview of Creep of Coarse RCA Concrete

Similar to the approach adopted in Chapter 4, Section 4.2.2, the studies providing an overview of the effects of coarse RCA on the creep deformation of concrete were separated into two groups: (i) individual researchers and (ii) established organisations. The reviews published by the individual researchers were brief and of a cursory nature, and were written as a small part of a larger publication, with few citations, except for one published by Silva et al. (2015a). Overall, all of these researchers tended to suggest a notional figure or range for the increase in creep of concrete that occurred with the use of coarse RCA, varying from, for example, greater than 20% or 40% and less than 40% or 50% to ranges of 20%–40%, 20%–60% or 40%–80% increase (Agrela et al., 2013; De Brito and Saikia, 2013; Balaz et al., 2008; Safiuddin et al., 2013; Silva et al., 2015a; Xiao et al., 2012b; Xiao et al., 2014). The stand-alone publication by Silva et al. (2015a) concluded that the published data suggest that the use of 100% RCA content can, depending on its quality, result in an increase of 20%–90% in creep strain and 10%–65% in the creep coefficient of concrete.

Table 5.1 presents an overview provided by established organisations from Australia, New Zealand, the United States, and a few countries in Europe, again mostly as parts of overarching projects undertaken. The information provided was in the form of (a) a

Table 5.1 Overview on the creep of RCA concrete

COUNTRY	REFERENCE	NUMBER OF REF. CITED	COARSE RCA, %		REMARKS
			20	100	
(a) Relative Creep of Coarse RCA Concrete with Respect to NA Concrete					
Australia	CSIRO by Sagoe-Crentsil and Brown (1998)	n.c.	n.a.	up to 40	n.a.
France	RILEM TC 37-DRC by Hansen (1986, 1992)	4	n.a.	20 - 60	n.a.
	RILEM TC 217-PRE by Vazquez (2013)	3	n.a.	n.a.	Creep is increased.
New Zealand	CCANZ by Chisolm (2011)	n.c.	n.a.	30 – 60	n.a.
Spain	Task Force of Standing Committee of Concrete of Spain (2004)	n.c.	0	20 – 60	n.a.
Switzerland	OT 70085 (2006) [1]	n.c.	n.a.	30 – 40	n.a.
USA	ACI Committee 555 (2001)	n.c.	n.a.	30 – 60	n.a.
	ECCO (1999)	n.c.	n.a.	40 – 80	n.a.
	NRMCA BY Obla et al. (2007)	1	n.a.	30 - 60	n.a.
	PCA (2002)	n.c	n.a.	n.a.	At equal w/c, creep of RCA concrete is higher
	US Army Corps of Engineers (2004)	n.c.	n.a.	n.a.	At equal w/c, creep of RCA concrete is higher
	WSDOT by Anderson et al. (2009)	n.c.	n.a.	20 - 40	n.a.
(b) Multiplying Factor for Coarse RCA Concrete					
Belgium	prENV 1992-1-1 (n.d.) [2]	n.c.	n.a.	1.00	RCA with > 2100 kg/m^3 dry density, < 9% WA and max. str of 37 MPa
Belgium	Belgium Specification (n.d.) [3]	n.c.	1.00	1.25	n.a.
France	RILEM TC 121-DRG (1994)	n.c.	1.00	n.a.	RCA with ≥ 2400 kg/m^3 dry density, ≤ 3% WA and no strength limit
			n.a.	1.00	RCA with ≥ 2000 kg/m^3 dry density, ≤ 10% WA and max. str. of 60 MPa
Holland	Holland Specification (n.d.) [3]	n.c.	1.00	1.25 – 1.45	n.a.
The Netherlands	TNO Report (1991) [4]	n.c.	1.00	1.45	For 20 - 30 MPa concrete
			1.00	1.25	For 30 - 50 MPa concrete
Spain	EHE-08 (2010)	n.c.	1.00	1.25	n.a.

Note: REF., Reference; n.c.: no citations are given; n.d.: no date; str, strength; WA: Water Absorption
As reported by **1** As reported by de Brito and Saikia (2013); **2** Vyncke and Rousseau (1994); **3** Task Force of Standing Committee of Concrete of Spain (2004); **4** Reported by de Vries (1996)

relative increase in the creep of RCA concrete with respect to NA concrete or (b) a multiplying factor greater than 1.00 for coarse RCA concrete. Most of these overviews do not indicate the citations that were used, and where the relevant information was available, the number of citations was less than 5.

The main points arising from Table 5.1 are given below:

- At 20% coarse RCA, there is no change in creep of concrete, indicated as 0% in relative creep terms and as 1.00 when a multiplying factor was given (Task Force of Standing Committee of Concrete of Spain, 2004; RILEM TC 121-DRG, 1994; EHE-08; 2010; de Vries, 1996).

- At 100% coarse RCA, the change in creep of concrete varies widely. In relative terms, the creep of RCA concrete can increase by 20% to 80% but mostly in the region of 30% to 60%; whilst in multiplying factor terms, the creep of RCA concrete needs to be multiplied by 1.25 or 1.45 (read as 25% and 45% increase, respectively). In contrast, a draft European pre-standard, prENV 1992-1-1 (as reported by Vyncke and Rousseau, 1994), and RILEM recommendation (RILEM TC 121-DRG, 1994) suggest a multiplying factor of 1.00 (read as no change in creep) for 100% RCA concrete made with (a) a minimum dry aggregate density of 2000 kg/m^3 and a maximum water absorption of 10% and (b) a maximum concrete strength of 60 MPa.

5.2.2 Coarse RCA as NA Replacement

About half of the creep data population obtained for this study was determined in accordance with the ASTM C512 (2015) method (Lye et al., 2016a). The test methods used for the other half of the data were not clearly presented, though based on the experimental setups and procedures used, it would appear that they were, by and large, similar to that described in ASTM C512 method. The commonly used experimental variables are as follows:

- Specimen type: cylinder with height-to-diameter ratio of 2 to 3
- Number of creep specimens: 2 to 5
- Load: no more than 40% of the compressive strength of concrete
- Exposure conditions: 20°C–25°C temperature and 50%–65%RH ambient humidity
- Test duration: up to 6 months

Given that the creep of concrete can be expressed in various forms (as described in Section 5.1), the best possible way to synchronise all the RCA concrete creep data is to convert them into relative terms with respect to the corresponding NA concrete. Figure 5.1 shows that the relative data generally exhibit a high fluctuation at each RCA content, which shows a variation can be as large as from −60% to +70% at 50% RCA content and from −40% to +170% at 100% RCA content.

A closer examination of the data, however, reveals that a small group of data points, which are individually marked with a number in the figure, have been excluded from further analysis, for reasons of inadequacy in experimental design, conflicting with technical knowledge or inconsistency of data (Table 5.2). In fact, these omissions can

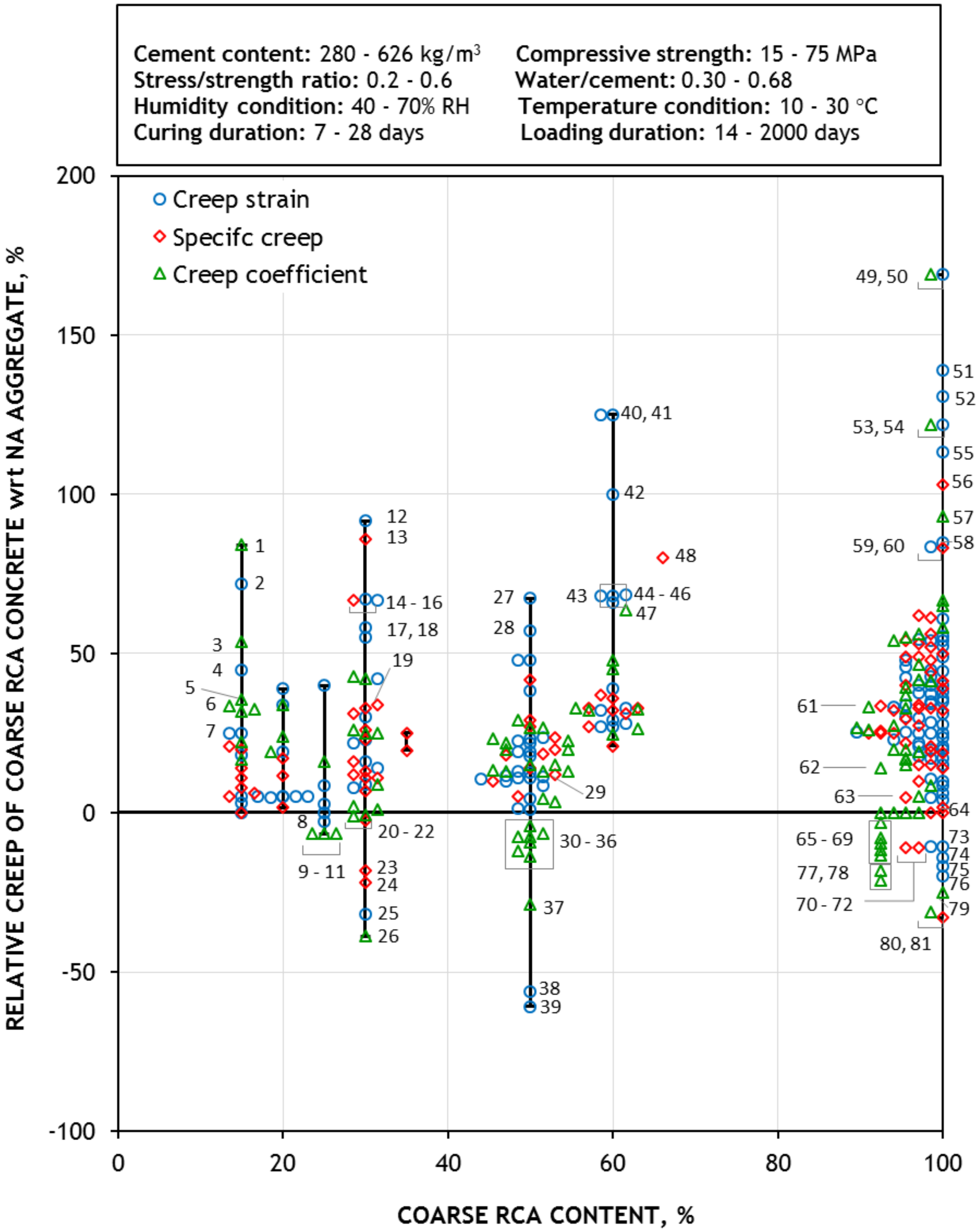


Figure 5.1 Relative creep of coarse RCA concrete with respect to corresponding reference NA concrete

Data taken from Ajdukiewicz (2005); Ajdukiewicz and Kliszczewicz (2002); Castano et al. (2009); Collery et al. (2015); de Pauw et al. (1998); Domingo et al. (2010); Fan et al. (2014); Fathifazl and Razaqur

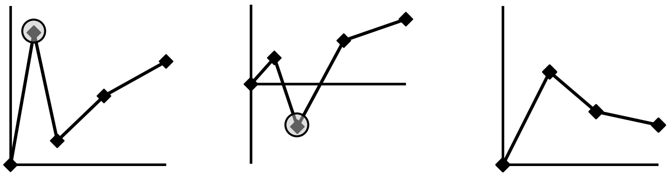
(2013); Fathifazl et al. (2008); Fathifazl et al. (2011); Fraaij et al. (2002); Ghuraiz et al. (2011); Gomez-Soberon (2002a); Gomez-Soberon (2002b); Gomez-Soberon (2003); Gomez-Soberon et al. (2002); Henschen et al. (2012); Ho et al. (2014); Hoffmann and Leemann (2007); Hoffmann et al. (2012); Immelman and de Villiers (2013); Kerhoff and Siebel (2001); Kimura et al. (2004); Kishore and Bairagi (2007); Knaack and Kumara (2013b, 2015b); Kou and Poon (2012); Kou et al. (2007); Limbachiya (2010); Limbachiya et al. (2000); Limachiya et al. (2004); Manzi et al. (2011); Ng et al. (2006); Parekh and Modhera (2011); Paul and van Zijl (2013a); Paul and van Zijl (2013b); Pietersen et al. (2002); Ravindrarajah and Tam (1985); Ravindrarajah and Tam (1987); Razaqpour et al. (2010); Reinhardt and Kummel (1999); Roos (1998); Sakata and Ayano (2000); Sato et al. (2007); Schulz (1986); Seara-Paz et al. (2016); Sryh and Forth (2016); Tam and Tam (2007); Tam et al. (2007c); Teramoto et al. (2011); Tsujino et al. (2007); Tsujino et al. (2006); Waleed and Canisius (2007); Yang et al. (2008a).

be prevented if the work done complies with standard procedures and good laboratory control is strictly adhered to.

The data were then replotted in Figure 5.2, and only 2% of the data therein are identified as outliers using box-and-whiskers plots. In most cases, the water/cement ratio of RCA concrete is similar to that of NA concrete. Overall, a polynomial trend line with a correlation of 0.8415 was obtained based on the average data at each RCA content. The trend line suggests that the creep of RCA concrete in comparison to NA concrete increases at a decreasing rate as its content increases. For convenience, the increase in creep at each coarse RCA content is tabulated within Figure 5.2.

Comparing with the information given by the established organisations (Table 5.1), it would appear that it has been incorrectly suggested by some that the creep of concrete remains unchanged when 20% coarse RCA is used. As can be seen from Figure 5.2, the use of 20% RCA can result in, on average, an increase of 12% in creep with a 95% confidence interval of 3%–23%. In addition, the commonly suggested range of 30%–60% increase in creep deformation at 100% coarse RCA appears to be slightly overstated, as the results in Figure 5.2 show an average increase of 32% with a 95%

Table 5.2 Reasons for removing data in Figure 5.1

REASONS FOR DATA EXCLUSION	POINTS
(a) Inadequacy in Experimental Design	
Concrete with strength less than 25 MPa, which is not likely to be used as structural concrete.	13, 19, 22, 29, 63, 64, 82, 85 – 88.
Applied load/ strength ratio is 0.1, although within the recommended of ≤ 0.4 given in the ASTM C512 (2015), it is considered to be too low in reality.	51, 52, 58.
Uncontrolled exposure conditions with high fluctuation in relative humidity or temperature.	12, 14–18, 27, 28, 30 – 42, 44–46, 48, 55, 56, 59, 60, 65–69, 77, 78, 80.
(b) Conflicting with Technical Knowledge	
Negative values indicating that coarse RCA concrete deforms less than NA concrete, which is not possible due to the presence of adhered paste in coarse RCA.	8–11, 23, 24, 70–76, 79, 81.
(c) Inconsistency of Data	
Anomalous data from the same set of results or erratic results where the relative value changes irregularly, for example: 	1–7, 20, 21, 25, 26, 43, 47, 57, 58, 61, 62, 83.
High relative creep values for which the data could not be justified due to lack of information.	49, 50, 53, 54.

confidence interval of 22%–42%. On the other hand, the suggested multiplying factor of 1.25 or 1.45 for RCA concrete can be considered to be in line with the findings in this study.

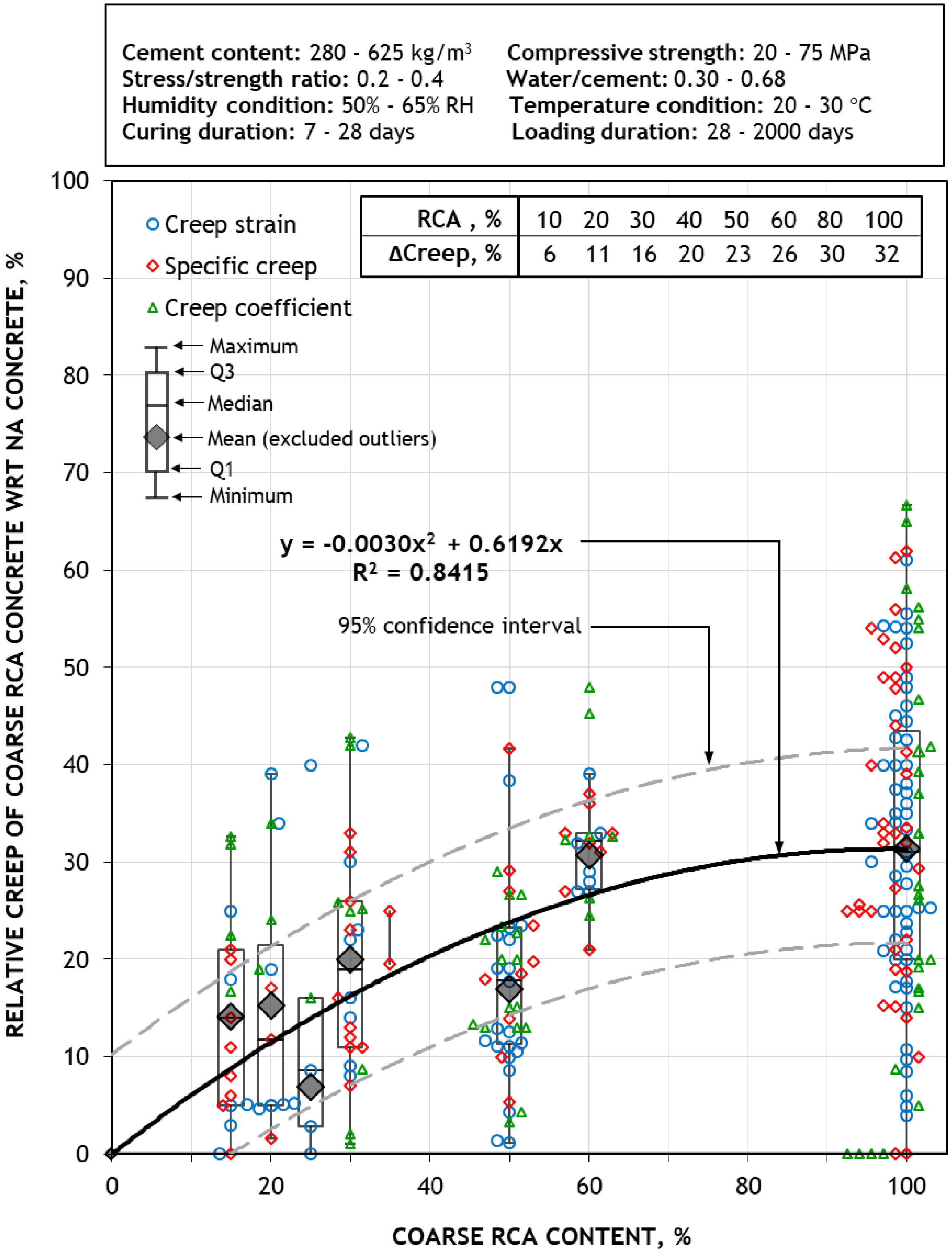


Figure 5.2 Relative change in creep of coarse RCA concrete with respect to corresponding reference NA concrete (after removal of inappropriate data)

5.2.3 Effect of Porosity of RCA Concrete

The increase in creep of concrete due to the use of coarse RCA can be attributed to the presence of adhered cement paste, which is of a porous nature, thereby increasing the porosity of the concrete. The relationship between creep and porosity of concrete has been developed using concrete mixes containing up to 100% coarse RCA, having a water/cement ratio of 0.50–0.55. The specimens were tested under sealed conditions (for basic creep) and unsealed conditions (for drying creep). The specific creep of all the concrete specimens was plotted against the corresponding porosity, measured at 28 days (Figure 5.3).

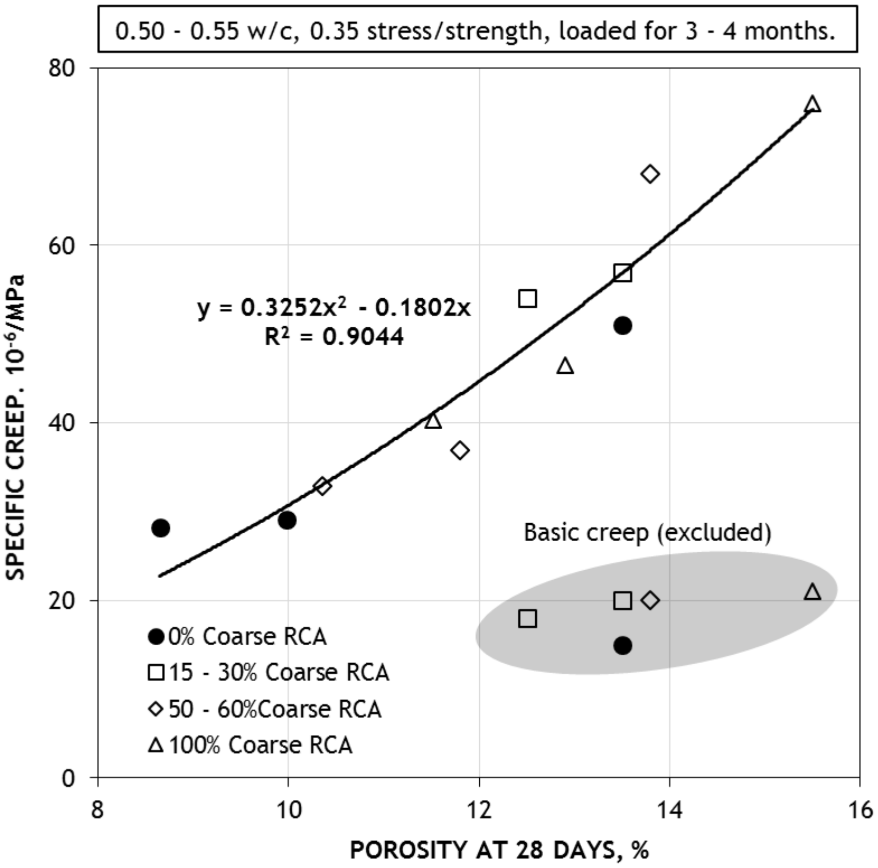


Figure 5.3 Relationship between the specific creep and porosity of RCA concrete

Data taken from Kou (2006) and Gomez-Soberon (2003)

Figure 5.3 shows a strong relationship between creep and porosity of concrete, regardless of the coarse RCA content used, and this relationship is more significant in unsealed specimens compared to sealed specimens (shaded in grey in the figure). Ignoring the data from the sealed specimens, the results suggest that as the porosity of RCA concrete increases, its creep coefficient increases at a slightly increasing rate.

Apart from the porosity of the aggregate, the porosity of concrete is also a function of the moist curing duration. Sufficient curing ensures that proper cement hydration takes place, resulting in a denser cement paste structure. Figure 5.4 shows the influence of moist curing duration on creep, in the form of the ratio of creep of concrete cured for 28 to 173 days to that of concrete cured for 7 days.

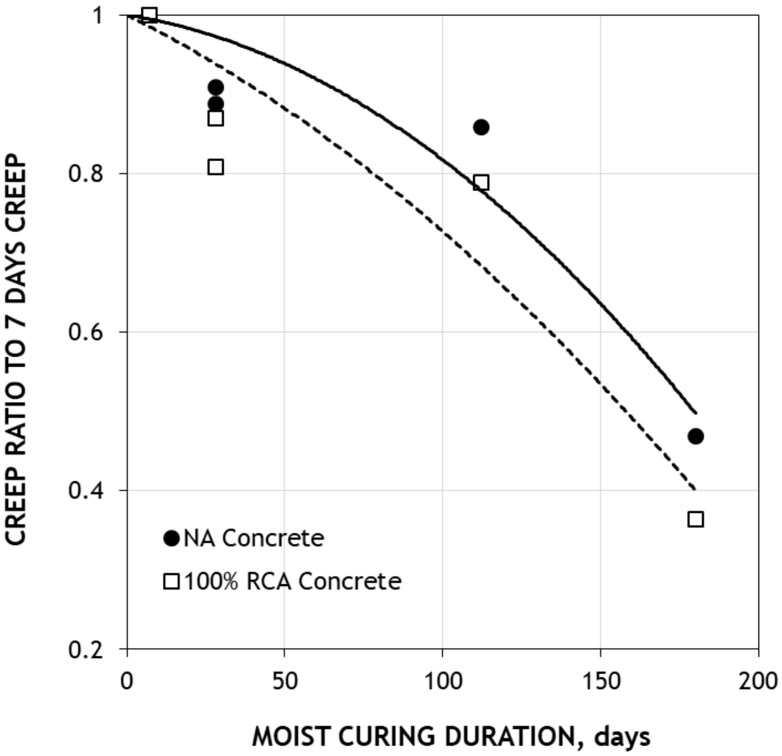


Figure 5.4 Effect of moist curing duration on creep of coarse RCA concrete

Data taken from Knaack, (2013), Sato et al. (2007)

Figure 5.4 shows that the creep ratio decreases as curing duration increases for both NA and 100% RCA concrete. At a given curing duration, the creep ratio of RCA concrete is lower than that of NA concrete, suggesting that the creep of RCA concrete is more sensitive than that of NA concrete to moist curing duration. Indirectly, this emphasises the importance of curing, particularly for RCA concrete, to ensure proper development of concrete properties.

5.2.4 Effect of Concrete Strength

The effect of coarse RCA on creep of concrete was further evaluated based on its compressive strength, as compressive strength is normally used to correlate with other hardened properties. To begin with, the results in Figure 5.2 were used, but by separating them into three strength groups, based on the strength of NA concrete, namely 25–40, 41–50 and 51–70 MPa, as shown in Figure 5.3 (a)–(c). These strength groups were selected such that each has a reasonable data population size. Cube strength was used throughout and the same procedure as discussed in Chapter 4, Section 4.2.5, was used for the conversion of cylinder to cube strength.

It can be seen from Figure 5.3 (a)–(c) that, whilst the relative creep value increases as coarse RCA content increases, for a given coarse RCA content, the increase becomes smaller when the strength becomes higher. This finding is in line with the creep multiplying factor suggested from pilot projects and research work undertaken in the Netherlands (de Vries, 1996) (see Table 5.1). This can possibly be explained as the aggregate content effect, which has been described previously in Section 4.2.5. As the

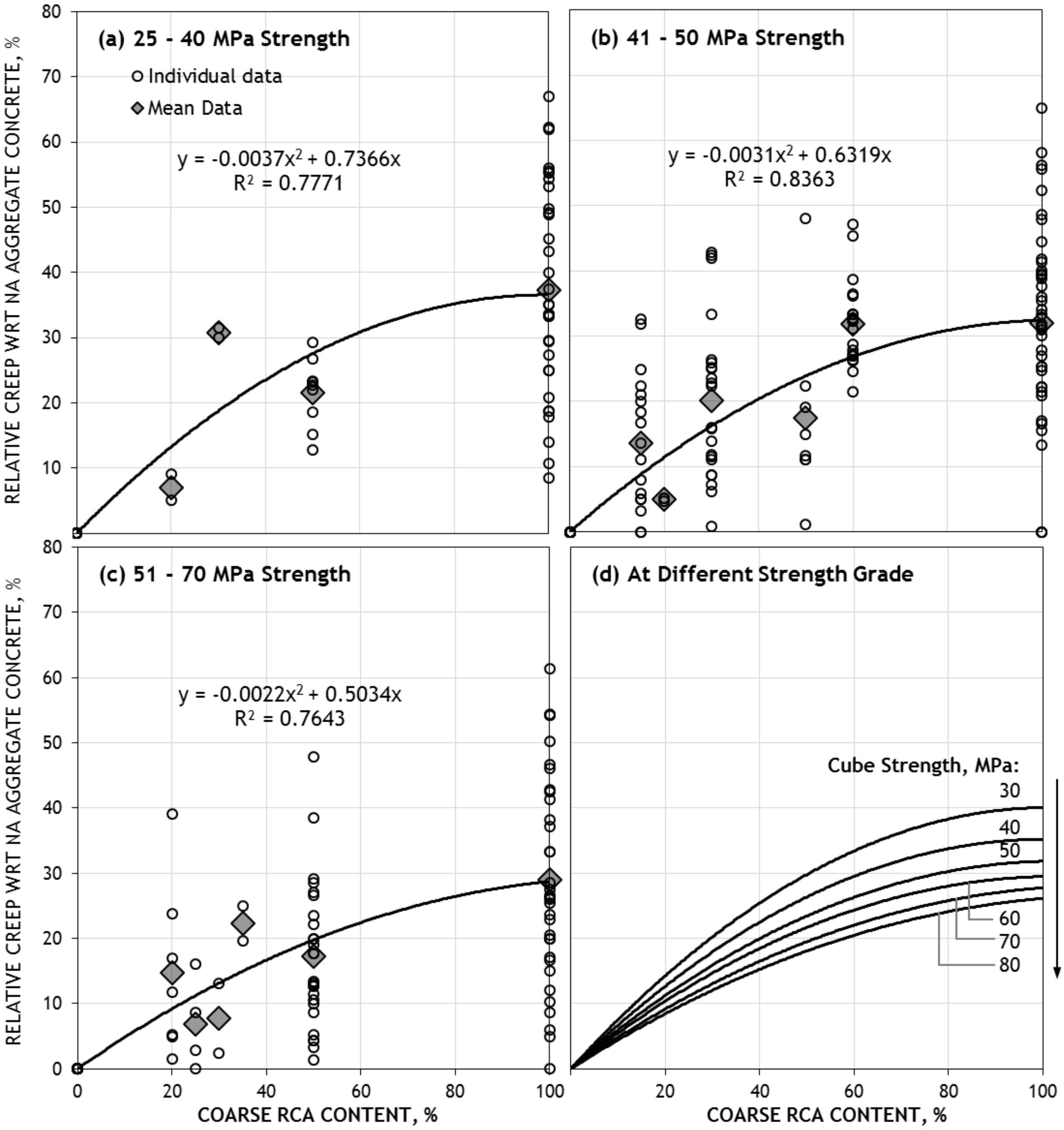


Figure 5.5 Relative creep of coarse RCA concrete with respect to NA concrete at (a) 25 – 40 MPa, (b) 41 – 50 MPa, (c) 51- 70 MPa and (d) different strength grade

design strength of the concrete increases, the coarse aggregate content per unit volume decreases owing to the increase in cement content. In the case of coarse RCA, the influence of the adhered cement paste present in the RCA is proportionately reduced and in return gives rise to a relatively smaller increase in the creep deformation of concrete. To put these findings into practice, a family of strength curves ranging from 30 to 80 MPa, covering the normally used structural concrete grade, is proposed, as shown in Figure 5.3 (d).

5.2.5 Effect of Fly Ash

Owning to the spherical shape of fly ash, its use in conjunction with RCA can be expected to improve the consistence of fresh concrete, as well as the creep resistance of concrete, as discussed below.

Figure 5.4 shows the creep of concrete made with 0%–100% coarse RCA and 0%–35% fly ash, used as (i) a Portland cement (PC) replacement and (ii) a PC addition, measured in accordance with ASTM C512 method. The results show that the creep of concrete increases as the coarse RCA content increases, for all specimens made with or without fly ash. However, for a given RCA content, when fly ash is used as a PC replacement at 25% and 35%, the creep strain of the RCA concrete is reduced by 12% and 18%, respectively, compared to RCA concrete made without fly ash. However, when fly ash is used as a PC addition at 25% and 35%, the creep strain is reduced by 20% and 25%, respectively.

The results in Figure 5.6 also suggest that, to achieve a creep strain similar to or lower than that of NA concrete, coarse RCA can be used up to 75% with 25% fly ash as PC

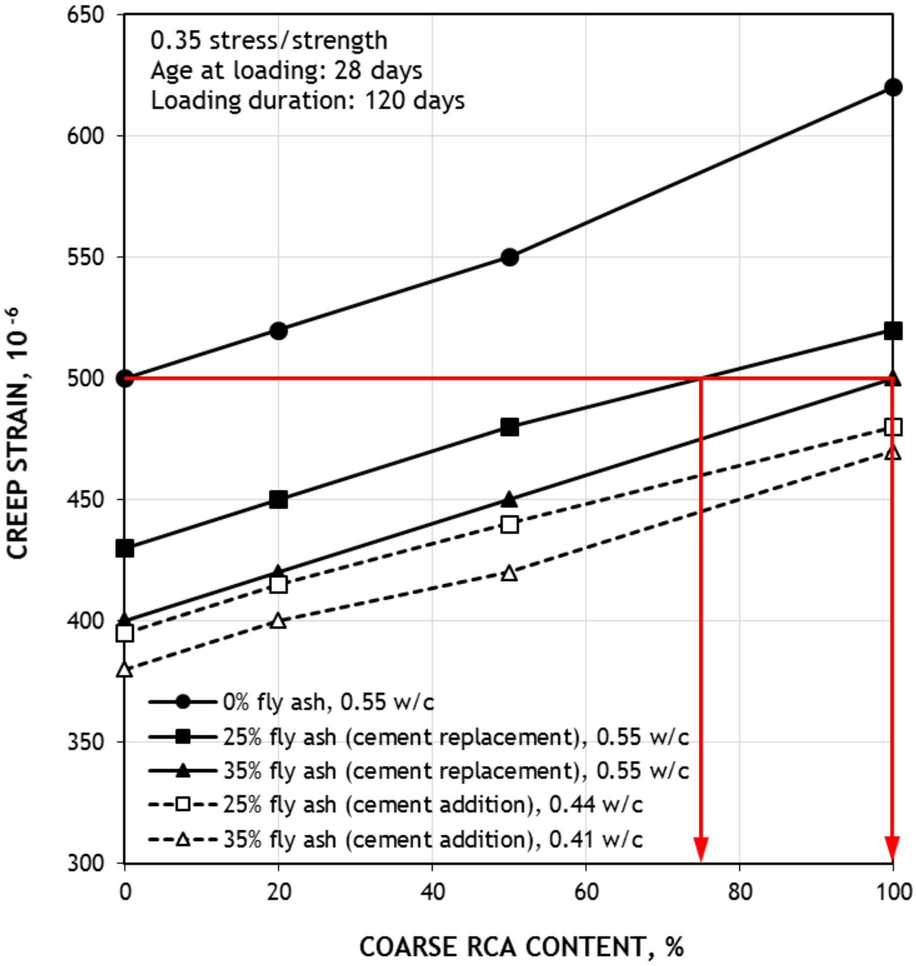


Figure 5.6 Creep strain of concrete containing coarse RCA and fly ash stored at a controlled temperature of 23 °C (based on Kou and Poon, 2002)

replacement, or up to 100% content with 35% fly ash as PC replacement. On the other hand, the use of fly ash as a cement addition at 25% and 35% contents can reduce the creep of RCA concrete to below that of NA concrete made with 100% PC.

5.3 FINE GCA AND FINE CSA CONCRETE

Although a considerable amount of research has been conducted on using fine GCA and fine CSA in concrete, as recently reported by Dhir et al. (2018a) and Dhir et al.

(2016), respectively, the database in the area of creep for these two materials is still small and calls for rigorous experimental investigations.

Notwithstanding this, an initial assessment was made, based on Neville et al. (1983), by comparing creep of concrete made with different types of aggregates, with a wide range of modulus of elasticity, 10–110 GPa. This suggested that creep of concrete is not significantly influenced by the modulus of elasticity of the aggregate when its value is greater than 70 GPa.

Referring to Chapter 3, Section 3.7 '*Modulus of Elasticity and Hardness'*, it is shown that both the moduli of GCA of various types and fine NA of quartz are in the region of 60 to 80 GPa. Thus, in general, it can be safely assumed that the use of fine GCA (regardless of its type) should not adversely affect the creep resistance of concrete, in comparison to the corresponding concrete made with fine NA.

Although the modulus of elasticity of CSA is lacking, given that the material tends to have a higher hardness value than GCA (6–7 Mohs hardness compared to 5-7 Mohs hardness of GCA), fine CSA concrete is likely to provide similar or slightly higher creep resistance compared to fine GCA concrete.

Overall, although further studies are needed to validate the real effects of fine GCA and fine CSA on creep deformation of concrete, at this preliminary stage, if good concrete practice is adhered to, it can be safely assumed that, for a given condition, the creep of concrete decreases in the following order: fine NA > fine GCA > fine CSA.

5.4 CONCLUSIONS

This chapter investigates the creep deformation of concrete when the natural aggregate (NA) is separately replaced by coarse recycled concrete aggregate (RCA), fine glass cullet aggregate (GCA) and fine copper slag aggregate (CSA).

The study shows that the creep of concrete made with coarse RCA, in relation to the corresponding NA concrete, increases at a decreasing rate as the coarse RCA content increases. On average, the creep of concrete can increase by 32% (with a 95% confidence interval of 22%–42%) when NA is fully replaced by RCA. This level of increase indicates that the increasing range of 30%–60%, suggested by the established organisations, is overstated. In contrast to the 'no change' at 20% coarse RCA content suggested by some established organisations, the findings of this study show that there is an average increase of 12% at this level of RCA use in concrete, and this cannot be ignored.

The use of RCA increases the porosity of concrete, as well as the creep deformation. Compared with coarse NA concrete, the creep of coarse RCA concrete is more sensitive to moist curing duration. It was shown that the relative increase in creep of coarse RCA concrete decreases as concrete strength increases. A family of strength curves ranging from 30 to 80 MPa was developed, showing that the increase in creep due to the use of RCA decreases as the strength of the concrete increases. Although further developmental work is still needed, the use of fly ash as a Portland cement replacement or cement addition was found to improve the resistance of RCA concrete to creep deformation.

For fine GCA concrete and fine CSA concrete, their creep is under-researched and requires an in-depth study. Notwithstanding this, an initial assessment based on the modulus of elasticity of the aggregate suggests that fine GCA can be used as a replacement for fine NA without compromising the creep resistance of the concrete. Given that the hardness of fine CSA tends to be higher than that of fine GCA, its use as a fine NA is likely to result in similar or slightly lower creep compared to that of fine GCA.

CHAPTER 6

SHRINKAGE DEFORMATION

6.1 INTRODUCTION

Like creep, shrinkage of concrete is also a time-dependent property, but the deformation takes place without the application of load. The influence of shrinkage on structural concrete is similar to that of creep, as described in Chapter 5, that is, it can cause an increase in deflections, loss of pre-stress and redistribution of stresses.

The structural interest of shrinkage of concrete also arises from the fact that it is the common cause of crack formation in concrete. If unrestrained, concrete is free to move, and shrinkage can take place without affecting structural performance. However, the movement in structural concrete is normally restricted by different forms of external and internal restraint, such as steel reinforcement and adjacent members, leading to the development of tensile stress. Cracking occurs when the net tensile strain exceeds the tensile strain capacity of the concrete.

Cracks in concrete facilitate the transportation of fluids into the concrete, which can, in some cases, result in corrosion of steel reinforcement, which can be particularly critical in pre-stressed members, and serviceability failure of the structure.

In most cases, shrinkage of concrete is inevitable, and thus it is an important parameter in structural design, and this makes it particularly important that it is properly understood. As one of the primary functions of aggregate in concrete is to resist deformation, the use of recycled and secondary aggregates (RSA) in place of natural aggregates (NA) will affect the shrinkage properties of concrete owing to the change in the overall stiffness of the aggregate. However, in estimating the shrinkage strain of concrete, major standards and specifications, such as ACI 209·2R (2008) and Eurocode 2 (2004), do not consider the properties of aggregates in their models, which should be addressed to produce a more accurate estimation.

It should be mentioned that, although often reported as drying shrinkage in the studies, the shrinkage data sourced for this project are in a form that can be taken only as the total measured shrinkage. Given that the standard test methods do not normally differentiate drying shrinkage from other types of shrinkage, such as autogenous and carbonation shrinkage, the terminology ‘shrinkage’ used in this study is taken to imply total shrinkage.

6.2 COARSE RCA CONCRETE

6.2.1 Overview of Shrinkage of Coarse RCA Concrete

Similar to Chapter 4, Section 4.2.1 (for elastic deformation), and Chapter 5, Section 5.2.1 (creep deformation), the overview of research relating to the effects of coarse recycled concrete aggregate (RCA) on the shrinkage deformation of concrete are separated into two distinct groups: (i) those produced by established organisations and (ii) those produced by individual researchers.

Table 6.1 summarises the overviews undertaken by various established organisations from Australia, New Zealand, Europe and the United States, from 1978 to 2012. The overall findings of the work undertaken by the established organisations and individual researchers are similar, and to avoid repetition, the work of the established organisations is discussed in this chapter. However, the information provided in the individual overviews can be found in Angrela et al. (2013), Ajdukiewicz (2005), Balazs et al. (2008), Behera et al. (2014), de Brito and Alves (2010), de Brito and Robles (2008, 2010), de Brito and Saikia (2013), Dhir et al. (2004c, 2005a, 2005b), Hendriks and Henrichsen (1996), Kisku et al. (2017), Kukadia et al. (2014), Li (2008), Marinkovic et al. (2012), Poon and Chan (2007a), Ramachandran (1981), Rao et al. (2007), Safiuddin et al. (2013), Silva et al. (2015b), Vazquez (2013) and Xiao et al. (2012b, 2013, 2014).

Table 6.1 (a) shows that only the Task Force of the Standing Committee of Concrete of Spain (2004) concluded that the use of up to 20% RCA does not significantly affect the shrinkage of concrete. This is similar to other established organisations that have recommended the use of a multiplying factor of 1.0 at 20% RCA content, as reported by prENV 1992-1-1 (n.d.), Belgium Specifications (n.d.), RILEM TC 121-DRG (1994), Holland Specification (n.d.), TNO Report (1991) and EHE-08 (2010) in Table 6.1 (b).

At 100% coarse RCA content, an increase in shrinkage of 20%–50% has been commonly reported, though a few studies have suggested a lower as well as a higher figure [Table 6.1 (a)]. On the other hand, some organisations have proposed the use of a multiplying factor of about 1.50 for RCA concrete with dry density more than

Table 6.1 Overview on the shrinkage of coarse RCA concrete

COUNTRY	REFERENCE	NO. OF REF. CITED	Coarse RCA, %		REMARKS
			20	100	
(a) Relative Increase in Shrinkage of Coarse RCA with Respect to NA Concrete					
Australia	CCAA (2008)	n.c.	n.a.	n.a.	Shrinkage is increased.
	CSIRO by Sagoe-Crentsil and Brown (1998)	n.c.	n.a.	Up to 30%	At equivalent strength to NA concrete.
France	RILEM TC 37-DRC by Nixon (1978)	1	n.a.	10 - 30	-
	RILEM TC 37-DRC by Hansen (1986, 1992)	4	n.a.	50%	-
New Zealand	CCANZ by Chisolm (2011)	n.c.	n.a.	20 – 50%	-
Spain	Task Force of Standing Committee of Concrete of Spain (2004)	3	Similar/ Slightly higher*	40%	* RCA of controlled quality.
Switzerland	OT 70085 (2006) [1]	n.a.	n.a.	10%	-
USA	ACI Committee 555 (2001)	1	n.a.	20 – 50%	-
	CP Tech Center by Dam et al. (2012)	1	n.a.	20 – 50%	-
	ECCO (1999)	n.c.	n.a.	40 – 80%	-
	INDOT by Burke et al. (1992)	1	n.a.	40%	-
	MDOT by Dam et al. (2011)	1	n.a.	20 – 50%	-
	PCA (2002)	1	n.a.	n.a.	At equal w/c, shrinkage of RCA is higher
	US Army Corps of Engineers (2004)	n.c.	n.a.	n.a.	At equal w/c, shrinkage of RCA is higher
	WSDOT by Anderson et al. (2009)	1	n.a.	n.a.	Shrinkage of RCA concrete is higher.
(b) Multiplying factor for Coarse RCA Concrete					
Belgium	prENV 1992-1-1 (n.d.) [2]	n.c.	n.a.	1.50	RCA with > 2100 kg/m^3 dry density, < 9% WA and max. str. of 37 MPa.
	Belgium Specification (n.d.) [3]	n.c.	1.00	1.50	n.a.
France	RILEM TC 121-DRG (1994)	n.a.	1.0	n.a.	RCA with ≥ 2400 kg/m^3 dry density, ≤ 3% WA and no strength limit.
			n.a.	1.50	RCA with ≥ 2000 kg/m^3 dry density, ≤ 10% WA and max. str. of 60 MPa.
Holland	Holland Specification (n.d.) [3]	n.c.	1.00	1.35 – 1.55	n.a.
The Netherlands	TNO Report (1991) [4]	n.a.	1.0	1.35	For 20 - 30 MPa concrete
			1.0	1.55	For 30 - 50 MPa concrete
Spain	EHE-08 (2010)	n.a.	1.0	1.50	n.a.

Note: REF., Reference; n.c., no citations are given; n.d., No date; str, strength; WA, Water absorption
As reported by **1** de Brito and Saikia (2013); **2** Vyncke and Rousseau (1994); **3** Task Force of Standing Committee of Concrete of Spain (2004); **4** de Vries (1999).

2000 kg/m^3 and water absorption up to 9%, and concrete strength up to 60 MPa [Table 6.1 (b)]; though it was proposed that the multiplying factor can be varied depending on the strength of the concrete, with a factor of 1.55 for strength above 30 MPa and 1.35 for strength below 30 MPa (TNO Report, 1991).

6.2.2 Influence of Coarse RCA Content

The shrinkage data obtained in this study were taken from specimens that were mostly moist cured for up to 1 month, and thereafter stored in a 20°C–30°C and 40%–60% RH environment. Figure 6.1 shows the relative shrinkage of coarse RCA concrete with respect to the corresponding NA concrete, mainly stored in a drying environment for 2 weeks to 6 months. The water/cement ratio of RCA concrete and NA concrete is similar in most cases.

In developing Figure 6.1, a small number of data values were not considered for different reasons, as follows:

- They were outliers, as identified from box-and-whiskers plots (see Section 4.2.3 for the construction method).
- The relative value exceeded 200%, which could not be justified.
- The relative value was less than 0%, which suggested that coarse RCA concrete shrinks less than NA concrete. This again could not be justified as the stiffness of coarse RCA is lower than that of NA owing to the presence of adhered paste.

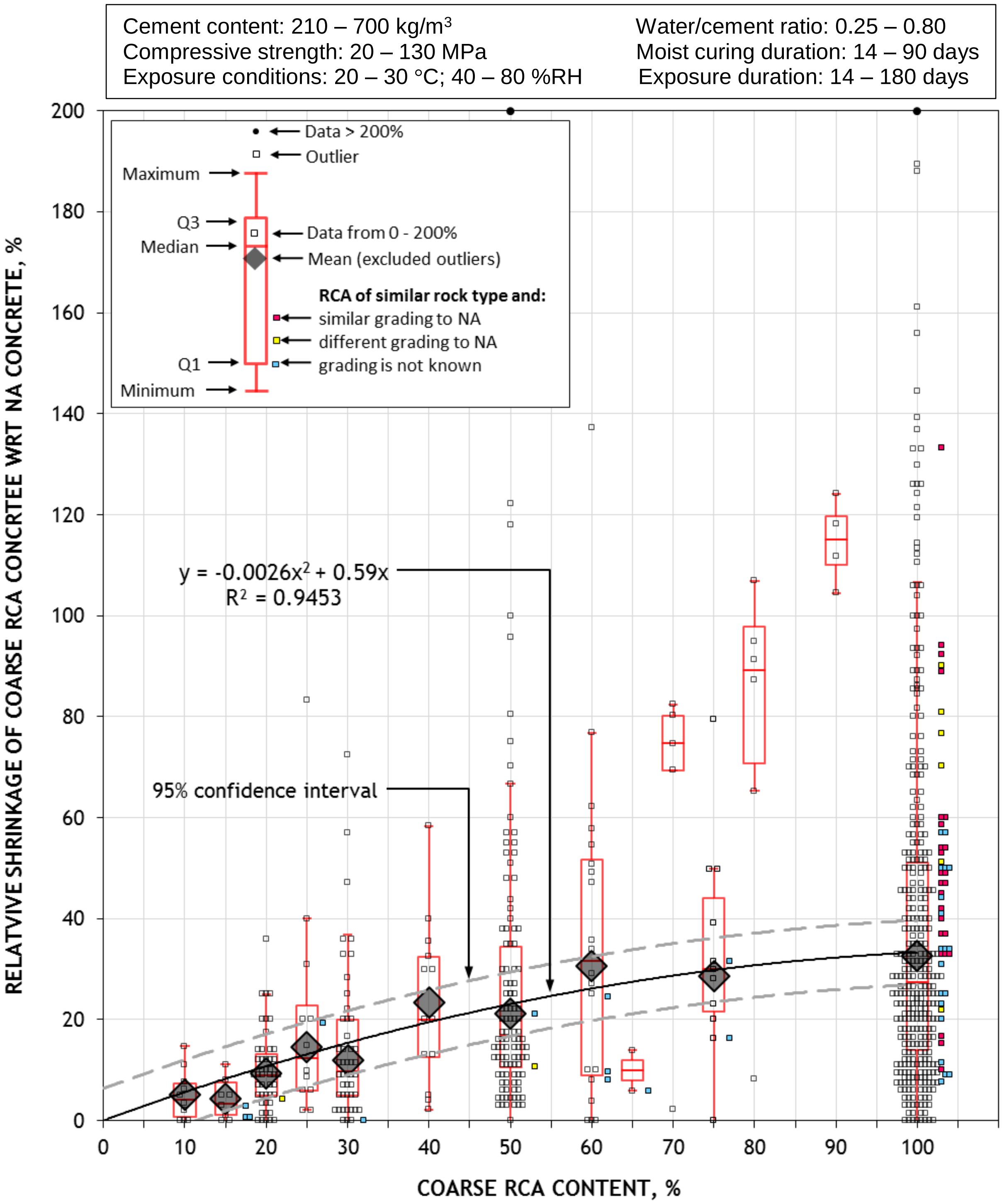


Figure 6.1 Relative shrinkage of coarse RCA concrete with respect to corresponding reference NA concrete

Data taken from Ajdukiewicz and Kliszczewicz (2002), Amorim et al. (2012), Andal et al. (2016), Babu et al. (2014), Badr (2015), Beltran et al. (2014a, 2014b), Brand et al. (2015), Buttler and Machado (2005), Buyle-Bodin and Hadjieva-Zaharieva (2002), Castano et al. (2009), Cervantes et al. (2007), Collery et al. (2015), Corinaldesi (2010), Corinaldesi and Moriconi (2007, 2009a, 2010, 2012), Costabile (2001), Cui et al. (2015), de Brito et al. (2016), de Juan and Gutierrez (2004), de Pauw et al. (1998), Deshpande et al. (2009), Dhir and Paine (2007, 2010), Dhir et al. (2004a, 2004d), Dillman (1998), Domingo et al. (2010), Duan and Poon (2014), Eckert and Oliveira (2017), Eguchi et al. (2007), Fan et al. (2014), Fathifazl et al. (2011), Ferreira et al. (2011), Fraaij et al. (2002), Fumoto and Yamada (2003), Gesoglu et al. (2015), Go et al. (2007), Gomes et al. (2014), Gomez-Soberon (2002a, 2002c), Guo et al. (2011, 2013), Haitao and Shizhu (2015), Hansen and Boegh (1985), Henry et al. (2011), Ho et al. (2013), Imamoto (2008), Ismail and Ramli (2014), Kameyama et al. (2014), Khayat and Sadati (2014), Kikuchi et al. (1994, 1998), Kim and Goulias (2014), Kimura et al. (2004), Kishore and Bairagi (2007), Kiuchi (2001), Kiuchi and Horiuchi (2003), Knaack and Kurama (2013b, 2015b), Kou and Poon (2010, 2012, 2015), Kou et al. (2004a, 2008, 2011, 2012, 2014), Koulouris et al. (2004), Kwan et al. (2012), Lederle and Hiller (2013), Limbachiya et al. (2000, 2012a, 2012b), Lotfy and Al-Fayez (2015), Malesev et al. (2010), Manzi et al. (2013a), Matar and El Dalati (2011), Matias et al. (2014), Mazzotti et al. (2013), Meinhold et al. (2001), Moriconi and Corinaldesi (2006), Morohashi et al. (2007), Ng et al. (2006), Nishigori amd Sakai (2012), Obla et al. (2007), Park (1999), Park and Sim (2006), Paul and Van Zijl (2013b), Pedro et al. (2014a, 2014b), Pietersen et al. (2002), Pimienta et al. (1998), Poon et al. (2006), Ravindrarajah (1996), Razaqpur et al. (2010), Ridzuan et al. (2001), Sagoe-Crentsil et al. (1998, 2001a), Sakata and Ayano (2000), Santos et al. (2002), Sato et al. (2007), Schulz (1986), Seara-Paz et al. (2016), Shaikh and Nguyen (2013), Shayan and Xu (2003), Soares et al. (2014), Sryh and Forth (2016), Sucic and Lotfy (2016), Surya et al. (2015), Tam and Tam (2007), Tam et al. (2007c), Tavakoli and Soroushian (1996), Teramoto et al. (2011), Teranishi et al. (1998), Ueno et al. (2013), Van Acker (1998), Verian et al. (2013), Waleed and Canisius (2007), Wang et al. (2013b), Whiting et al. (1998), Xiao et al. (2015), Yamato et al. (1998), Yanagibashi et al. (2002), Yang et al. (2008a, 2008b), Zhu and Wu (2010), Zhu et al. (2013).

- The data for coarse RCA contents of 60%, 70%, 80% and 90% were ignored as there were no more than five values for each level. Additionally, the corresponding mean values tended to deviate grossly from the main body of the results.

Overall, based on the mean values at different coarse RCA replacement levels, a polynomial regression was performed, giving a correlation of 0.9453. It can be seen from Figure 6.1 that the relative shrinkage value increases at a decreasing rate with increasing coarse RCA content, giving an average of 33% increase in shrinkage when NA is fully replaced by coarse RCA. The average increase in shrinkage obtained in this study was within the range of 30%–50% commonly reported by the established organisations for concrete made with 100% RCA (Table 6.1). However, the findings in this study show that the use of 20% RCA results in an average 10% increase in shrinkage (with a 95% confidence level of 4%–17%), whilst some organisations considered there to be no change at this level of NA replacement.

In addition, Figure 6.1 shows the data for concrete made with RCA having the same rock type as the corresponding NA concrete and (i) similar grading (red square markers) or (ii) different grading (yellow square markers) or (iii) when the grading of one or both aggregates is not known (blue square markers). Although the data of the first group are expected to be more reliable than those of the other two, the results suggest otherwise, as the variability in relative shrinkage at 100% RCA for the first group (10%–133% range with mean of 50%) is higher than that in the second group (21%–89% range with mean of 65%) and third group (8%–57% range with mean of 32%).

6.2.3 Influence of Relative Humidity

The major part of the shrinkage strain of concrete results from the drying process, with its magnitude particularly affected by the relative humidity. Indeed, many structural design codes consider relative humidity as one of the parameters in estimating the shrinkage of concrete (Chapter 7).

With the reference to Eurocode 2 (2004), the shrinkage data of concrete used in Figure 6.1 are divided into four categories, 20%–40%, 41%–60%, 61%–80% and 81%–95% RH, and under each category the relative shrinkage value is shown plotted against coarse RCA content. No specimens were measured at 20%–40% and >95% RH. Overall, the polynomial trend lines, based on the mean value of each coarse RCA

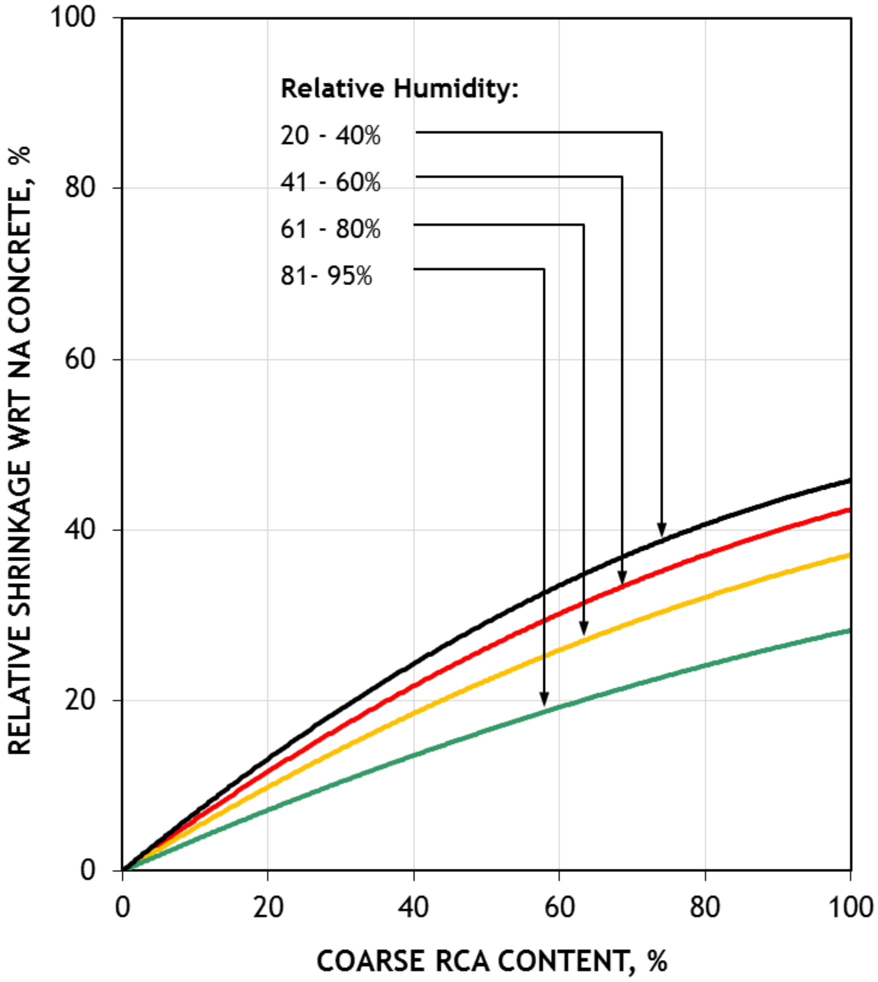


Figure 6.2 Influence of ambient humidity on the relative shrinkage of RCA concrete

content, were obtained, giving a correlation value over 0.9 in each case. Figure 6.2 shows the trend lines, together with a proposed trend line for 20%–40% RH.

For a given coarse RCA content, the magnitude of the shrinkage value decreases as the relative humidity increases, and Figure 6.2 can be used for estimating the effects of coarse RCA on the shrinkage deformation of structural concrete subjected to different humidity conditions, such as low indoor humidity in air-conditioned offices and high humidity in foundation footings and basement units.

6.2.4 Influence of Strength Grade

As compressive strength is generally considered to be closely related to the other hardened properties of concrete, its effect on the shrinkage of concrete is assessed in this study. Using the shrinkage data in Figure 6.1, and the corresponding strength data gained from the same source, six strength groups ranging from 20 to 130 MPa were created, based on the measured strength of NA concrete, as shown in Figure 6.3. All the strength data were standardised to cube strength as described in Section 4.2.5.

As to be expected, the rates of change in shrinkage of RCA concrete relative to NA concrete, for each individual strength group, are very similar, but at a given coarse RCA content, the relative change decreases as concrete strength increases (Figure 6.3). This observation is similar to that seen for elastic deformation in Figure 4.4 in Chapter 4 and for creep deformation in Figure 5.3 in Chapter 5. The common factor is that RCA content (and with it the adhered cement content), and accordingly its influence on concrete performance, decreases with increasing strength.

For convenience of use in practice, based on Figure 6.3, a family of empirical relationships between relative shrinkage and coarse RCA content was developed for different strength grades, ranging from 20 to 130 MPa, as shown in Figure 6.4.

It should, however, be noted that these proposed relationships are opposite to the multiplying factors for coarse RCA concrete given in an earlier research undertaken in the Netherlands by de Vries (1996) (Table 6.1). Given the width and depth, as well as the size, of the data population used in this work, in a properly designed concrete, the

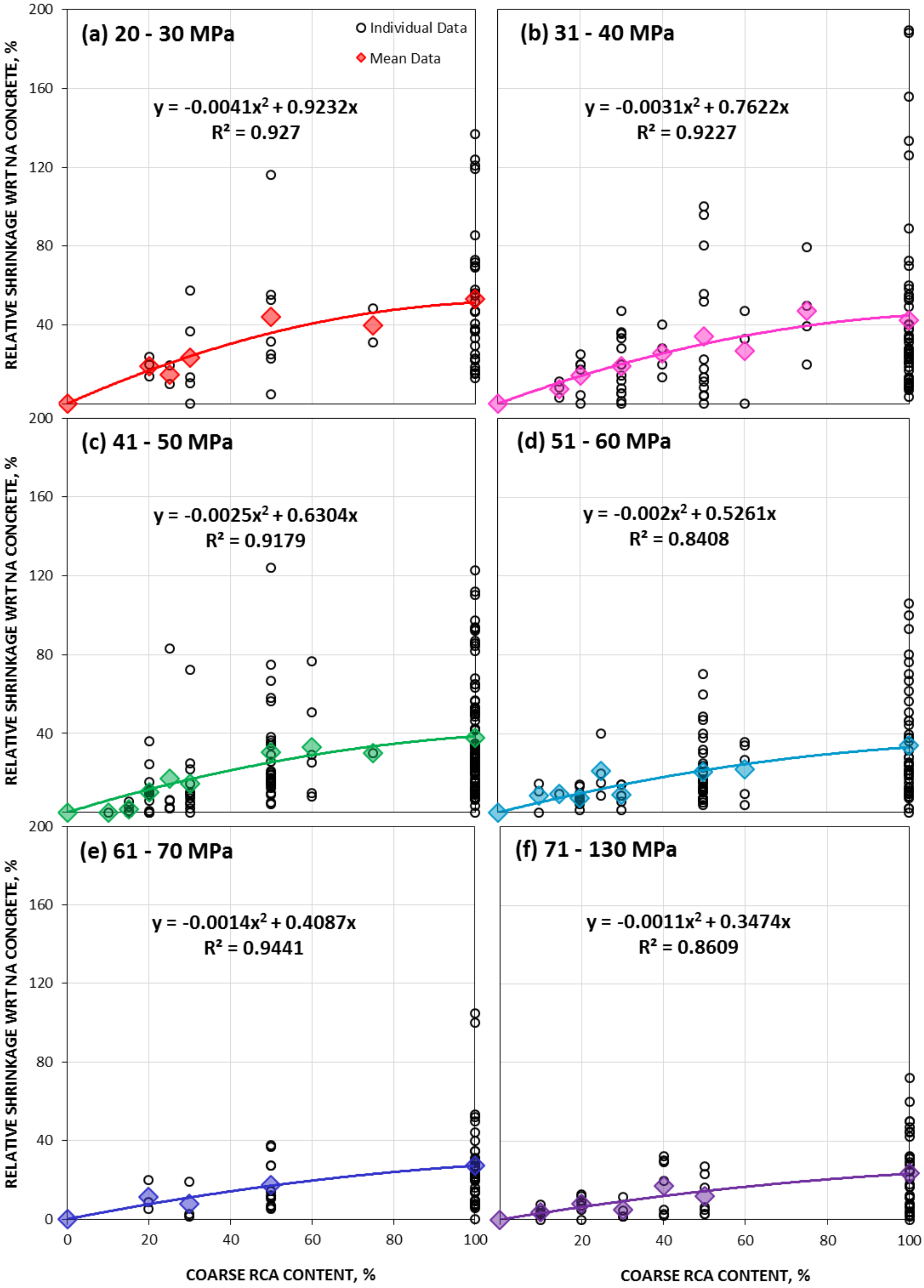


Figure 6. 3 Relative of shrinkage of coarse RCA concrete with respect to corresponding reference NA concrete at different strength groups

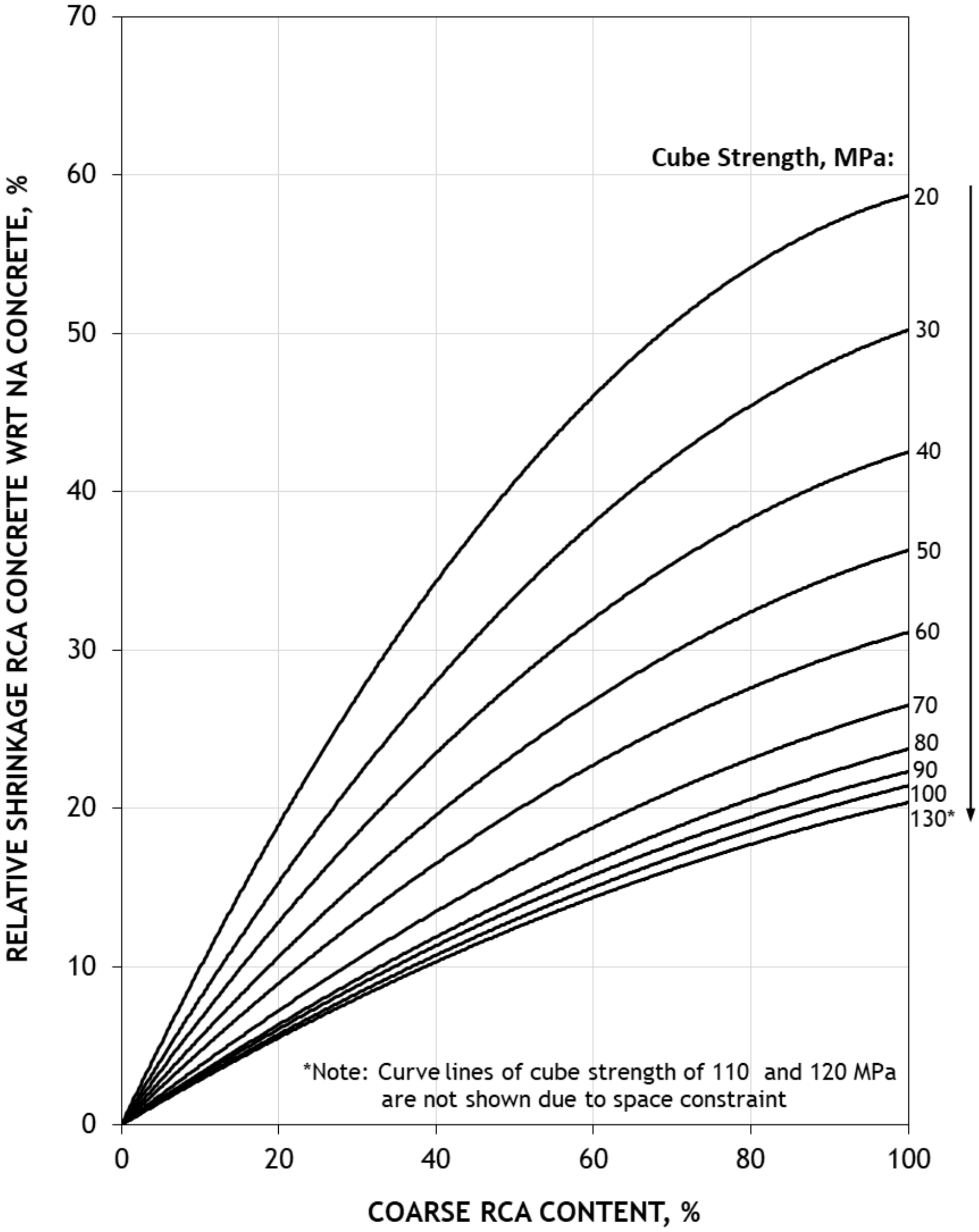


Figure 6.4 Proposed relative shrinkage of coarse RCA concrete with respect to NA concrete at different strength grade

shrinkage properties of RCA concrete in relation to NA concrete are more likely to reflect the findings shown in Figure 6.4.

6.3 FINE GCA AND FINE CSA CONCRETE

The effects of fine glass cullet aggregate (GCA) and copper slag aggregate (CSA) as fine NA replacements on the shrinkage deformation of concrete are examined together in this section. The overview of these two materials on shrinkage is limited, and therefore can only be briefly summarised.

For fine GCA concrete, Cement Concrete & Aggregates Australia (2008) have suggested that its shrinkage values are marginally lower than those of NA concrete. However, no clarifications on the magnitude of reduction or the rate of influence of GCA content have been made. The information provided by Rashad (2014) for fine GCA derived from soda-lime glass, and by Rashad (2015) for cathode ray tube (CRT) and liquid crystal display (LCD) glasses, suggests that the inclusion of fine GCA generally tends to reduce the shrinkage deformation of concrete.

For fine CSA concrete, Dhir (2009) has suggested that the use of fine CSA can lower the shrinkage strain of concrete, owing to the higher stiffness of the material compared to most natural sands aggregates. Tam (2001) has also observed that the shrinkage deformation of concrete remains essentially unchanged with the use of fine CSA, up to 30%.

6.3.1 Fine GCA and Fine CSA

The experimental variation in the shrinkage strains of fine GCA concrete and fine CSA concrete, in terms of the test procedure, i.e., moist curing of the specimens and its duration prior to the test and exposure conditions where the test specimens are stored, is by and large similar to that in the coarse RCA concrete shrinkage studies that have been published in the Proceedings of the Institution of Civil Engineers, *Structures and Buildings* (Lye et al., 2016d). In general, the shrinkage data for these two materials were taken from test specimens that were stored under conditions of 20°C–30°C temperature and 50%–60% RH for up to 5 months.

The shrinkage data population for concrete made with fine GCA and fine CSA is different. For ease of comparison between the two, the shrinkage results are expressed in terms relative to the corresponding NA concrete, as shown in Figure 6.5. In most cases, the water/cement ratio of fine GCA and CSA concrete is the same as that of NA concrete.

For fine GCA concrete, in developing this figure, the following types of data were disregarded for various reasons:

- shrinkage results obtained from mixes with water/cement ratio greater than 1.0, which are considered not commonly used in practice (shown in grey square markers);
- outliers identified from the box-and-whiskers plots;
- the mean values for the 15%, 40%, 45%, 60%, 70% and 80% fine GCA levels, as each of them was calculated from fewer than five data values, although they tend to show that the shrinkage of fine GCA concrete is smaller than that of the corresponding reference NA concrete.

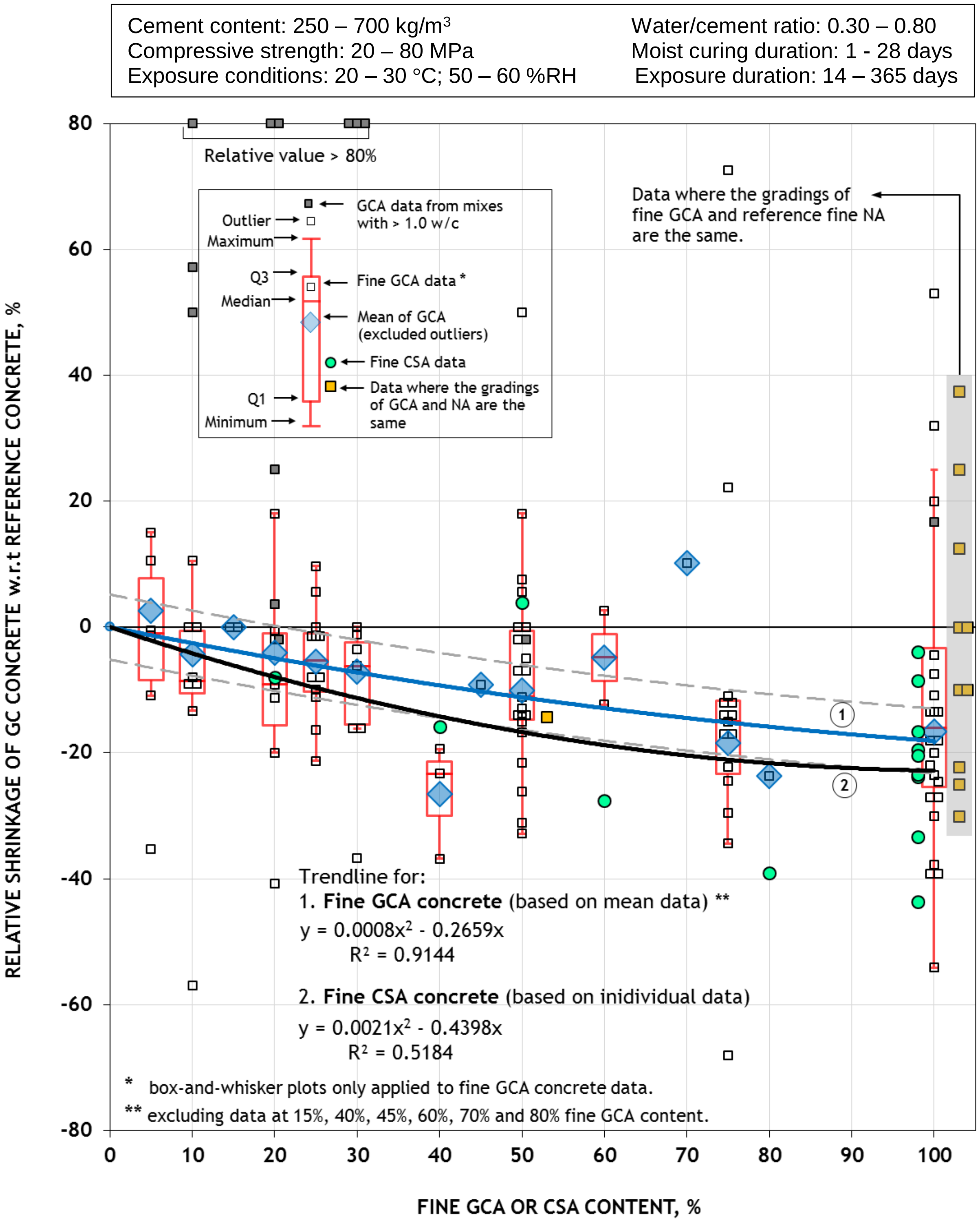


Figure 6.5 Relative shrinkage of fine GCA and fine CSA concrete with respect to corresponding reference NA concrete

Fine GCA concrete data taken from Boniface (2006); De Castro and De Brito (2013); Dhir et al. (2005a); Du and Tan (2014); Dumitru et al. (2010); Huang et al. (2015); Hui and Sun (2011); Limbachiya (2009); Ling and Poon (2011a, 2011b, 2012a, 2012b, 2013); Ling et al. (2011); Oliveira et al. (2013, 2015); Penacho et al. (2014); Phillips et al. (1972); Poon and Ling (2010); Sagoe-Crentsil et al. (2001b);

Sharif et al. (2014); Shayan (2002), Shayan and Xu (2006); Tan and Du (2013); Wang and Chen (2008, 2010); Wang and Huang (2010); Wang et al. (2014); Wright et al. (2014); Zhao et al. (2013a, 2013b). **Fine CSA concrete data taken from** Ayano and Sakata (2000); Hwang and Laiw (1989); Kumar (2012); Shoya et al. (1999); Zhang et al. (2013).

A polynomial regression was performed on the mean value for each fine GCA content and a correlation of 0.9144 was obtained. It can be seen that the shrinkage deformation of concrete decreases at a decreasing rate as the fine GCA content increases, giving an average reduction of 16% when NA is 100% replaced by fine GCA. Similar to the observation seen in Figure 6.1 for RCA, the results in Figure 6.5 again reveal that even with tight material control, by keeping the particle size distribution of fine GCA and NA the same (shown in orange square markers), the data still tend to vary considerably, showing a range of -30% to +37.5% relative shrinkage at 100% GCA concrete. This reinforces the need of having a large data population to properly understand the actual effect of the material on the shrinkage of concrete.

For fine CSA concrete, the polynomial regression was obtained based on individual data (green circle markers). Although some irregularity is present in the data, a moderately good coefficient of 0.5184 was obtained (Figure 6.5). The trend line suggests that the shrinkage deformation of concrete decreases at a decreasing rate as fine CSA content increases, giving a reduction of about 24% at 100% fine CSA.

Comparing the trend lines of fine GCA concrete and fine CSA concrete, for a given fine NA replacement level, the use of fine CSA tends to result in a larger shrinkage reduction than the use of fine GCA, suggesting that concrete containing the former material has better shrinkage deformation resistance. This is coherent with the observation made in the case of elastic deformation (Figure 4.8), which is likely to be due to the fact that fine CSA has a higher hardness value (6–7 Mohs) than fine GCA (5–7 Mohs).

6.3.2 Strength Grade of Concrete

To examine the influence of compressive strength on the shrinkage deformation of fine GCA concrete and fine CSA concrete, the data used in Figure 6.5 were separated into four strength groups from 30 to 70 MPa with 10-MPa increments, based on the measured strength of reference NA concrete. All the strength data were standardised to cube strength as described in Section 4.2.5.

In the case of fine GCA concrete, the trend line for each strength group suggests that the shrinkage decreases with increasing fine GCA content, but as a whole, the reduction does not show a clear order. Notwithstanding this, an empirical relationship for the shrinkage of fine GCA concrete relative to NA concrete at strength grades from 30 to 70 MPa was developed (Lye et al, 2017d). Figure 6.6 suggests that as the compressive strength of concrete increases, the relative increase in shrinkage decreases owing to the decreasing content of fine GCA in the concrete. This suggestion is based on the fact that the volume of fine aggregate decreases with increasing designed strength of concrete, and as a result, the deformation resistance provided by fine GCA becomes less pronounced.

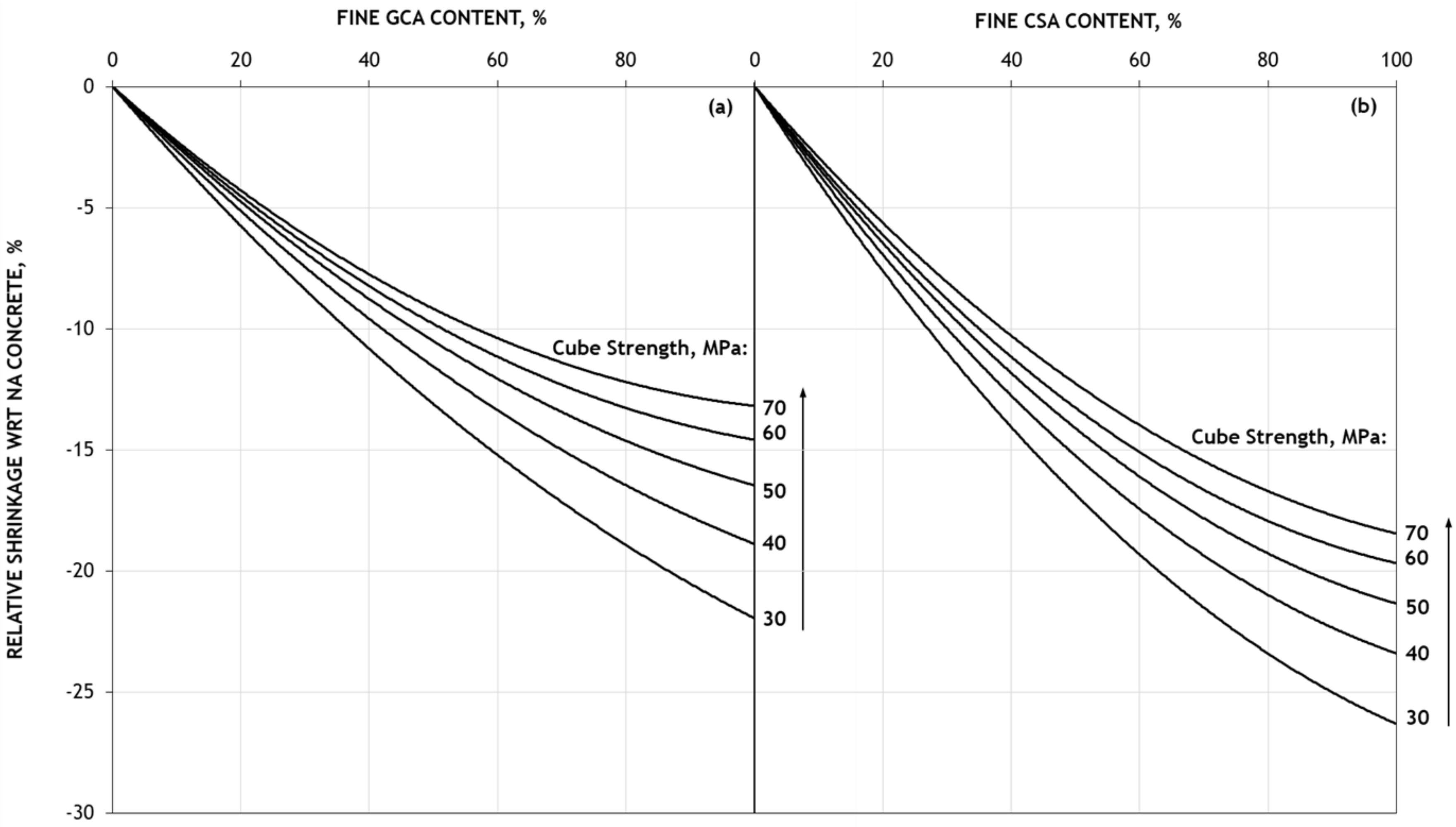


Figure 6.6 Proposed relative shrinkage of (a) fine GCA concrete and (b) fine CSA concrete with respect to NA concrete at different strength grade

In the case of fine CSA concrete, owing to its small data size, the corresponding trend lines for different strength grades were developed based on those of fine GCA concrete in Figure 6.6 (a) and its relationship with fine GCA concrete in Figure 6.5.

6.4 CONCLUSIONS

This chapter has investigated the influence of coarse recycled concrete aggregate (RCA), fine glass cullet aggregate (GCA) and fine copper slag aggregate (CSA) on the shrinkage deformation of concrete.

The use of coarse RCA in place of coarse NA increases the shrinkage of concrete, but this increase in shrinkage, relative to NA concrete, occurs at a decreasing rate as the coarse RCA content is increased, giving an average of 33% increase when NA is fully replaced by coarse RCA.

The increase in shrinkage with the use of RCA varies with the relative humidity of the environment and the designed strength of the concrete. On average, the relative increase in shrinkage at 100% RCA concrete decreases (i) from 45% to 28% as the ambient humidity rises from the 20%–40% RH range to 81%–95% RH and (ii) from 58% to 20% as the designed strength of the concrete moves up from 20 to 130 MPa, making it a more important factor than the effect of relative humidity. The empirical relationships between shrinkage and coarse RCA content for ambient humidity in the range of 20%–95% and designed strength in the range of 20–130 MPa have been developed.

Interestingly, the study of RCA use also established that shrinkage of concrete is an extremely sensitive property and as such can result in a high level of variation in the results, within a single study (up to 100%) and/or a small group of studies, even when the main factors are carefully and rigorously controlled. Though discouraging, this provided an additional boost to the confidence in the Analytical Systemisation method that examines a large globally sourced data matrix.

The use of both fine GCA and fine CSA was found to decrease the shrinkage of concrete compared to concrete made with normal sand, up to 100%. Both materials show that the reduction in the shrinkage of concrete, relative to fine NA concrete, decreases at a decreasing rate, as the GCA or CSA content increases. However, owing to the slightly higher stiffness of CSA compared to GCA, for a given fine NA replacement, the relative reduction in shrinkage of CSA concrete is greater than that of GCA concrete. On average, at 100% fine NA replacement, the reduction in shrinkage is about 24% for fine CSA concrete and 16% for fine GCA concrete. An empirical relationship between the reduction of shrinkage in concrete and the use of fine GCA or fine CSA at different strength grades was developed, with both showing that the relative value of reduction in shrinkage decreases as the design strength of the concrete increases from 30 to 70 MPa.

As with the very high variability in shrinkage arising from the use of coarse RCA, the use of fine GCA and CSA, though to a lesser extent, was found to give rise to high variability as well, again confirming the merits of using the Analytical Systemisation method to study the behaviour of concrete based on a globally sourced data matrix.

CHAPTER 7

ESTIMATION OF DEFORMATION OF CONCRETE USING EXISTING MODELS

7.1 INTRODUCTION

The deformation properties of concrete, in the form of load-dependent and load-independent, such as elastic, creep and shrinkage, are normally estimated using design codes, for example, in structural design, routine appraisal and safety assessment applications. Over the years, various models for estimating the deformation of concrete, especially its creep and shrinkage strains, have been developed. Amongst them, perhaps the most noteworthy are those developed by the ACI 209R-92 (2008) in the United States, the *fib* Model Code 2010 by *fib* (2013) in Europe and the B4 model by Bazant et al. (2015) from Northwestern University in Evanston, Illinois, USA. These models have significant influence on the development of design standards and codes; for example, the creep and shrinkage models in Eurocode 2 (2004) are based on the *fib* models (Holowaty, 2015).

The complexity and accuracy of the models can differ, however; some are highly sophisticated and require large amounts of input data, whilst others are relatively simple yet still practical. Given that these models are mostly empirical, and most likely have been developed based on the data obtained from natural aggregate concrete, their applicability in estimating the deformation properties of concrete made with recycled and secondary aggregate (RSA) can be questionable, as the characteristics of these materials are generally different to those of natural aggregate, which would accordingly affect the properties of the concrete (see Chapters 4 to 6).

This chapter has two goals: first, to analyse the parameters used in the aforementioned models as well as a few other models adopted in different countries, and second, to compare the experimental values obtained in this study with the estimated values, using the models in ACI 209R-92 (2008), Eurocode 2 (2004) and B4 (2015). The first two models were chosen as they represent the scenarios adopted in the United States and Europe, respectively, whilst the last model was chosen as it is more complex, requiring more parameters than the first two.

7.2 ERROR MEASURES

Before proceeding further, a brief description is provided of the error measures used to evaluate the accuracy of the models considered for use in estimating the deformation properties of concrete made with recycled and secondary aggregate, as well their counterpart, the natural aggregate.

In principle, the error measures describe the difference between a measured value (actual) and an estimated value, and this difference can be expressed in an absolute form as well as a relative form. These error measures are widely used in the economic and meteorology fields for model evaluation. There are a number of error measures that have been proposed, and each of them has its own advantages and limitations, and no single measure can be considered better than the others. Thus, the performance of models is normally assessed using more than one error measure, where the error measures chosen are relevant to the type of data, as well as the application of the models.

In this study, the selected models, ACI 209-2R (2008), Eurocode 2 (2004) and B4 (2015), are assessed using the following three error measures: mean bias error (MBE), root mean square error (RMSE), and mean absolute percentage error (MAPE). A brief discussion of each of these error measure is given in Table 7.1.

Table 7.1 Description of the error measures used in this study

FORMULA	RANGE	INTERPRETATION
$MBE = \frac{\sum_{i=1}^{n}(E_i - M_i)}{n}$	-∞ to +∞	Positive values suggest over-estimation; negative values suggest underestimation.
$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(E_i - M_i)^2}{n}}$	0 to +∞	Higher values suggest greater significant of error.
$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left\lvert\frac{E_i - M_i}{M_i}\right\rvert \times 100\%$	0 to +∞	< 10% means very good estimation*; < 20% means good estimation; < 30% means reasonable estimation; > 30% means inaccurate estimation.

E = estimated value; M = measured value, n = sample size

* Based on Lewis (1982)

Mean Bias Error

This is the simplest measure of the three chosen for this study, and is calculated by determining the average of the difference between the actual results and the estimated values obtained using a model. A zero value of MBE is the desired outcome, as a positive value implies an overestimation, whilst a negative value, an underestimation. Thus, MBE allows a quick detection of the biasness of a model. However, the limitation of MBE is that positive and negative errors cancel each other, and thereby a poor model can finish up having a small MBE value, giving rise to a misleading assessment of the estimation ability of the model.

Root Mean Square Error

The RMSE is similar in function to the standard deviation, but it deals with the deviation from the measured value, whilst the latter deals with the deviation from the mean value. The RMSE is due to randomness or an important estimation variable being overlooked in the model. Thus, this error is useful to describe the accuracy of a model, with a lower value suggesting good estimation. However, as the calculation of this error involves a square term, the presence of outliers has a significant effect on the interpretation of RMSE.

Mean Absolute Percentage Error

The MAPE describes the error in a relative form, and with respect to the measured value, without indicating the positive or negative sign. As it gives the relative size of the total estimation error, the MAPE is easy to interpret and appreciate and is commonly used by both academics and practitioners. However, this error is sensitive to the magnitude of the measured value, as a very small value can result in an extremely high MAPE value, or a zero measured value can result in infinity.

7.3 ELASTIC DEFORMATION OF RSA CONCRETE

7.3.1 Elastic Deformation Models

The modulus of elasticity of concrete is commonly known to be between that of its constituent aggregate and hydrated cement paste (Neville, 1995). However, it is also affected by several other factors, such as aggregate particle packing, the volume of the aggregate and the properties of the interfacial transition zones. Consequently, to build models with all these difficult-to-measure parameters can be too complex for use in practice to estimate the modulus of elasticity of concrete.

The models for estimating the modulus of elasticity of concrete found in the literature have normally been developed using an empirical approach based on static elastic modulus tests. Table 7.2 summarises the empirical models and the parameters considered in their estimation of the modulus of elasticity of concrete, as given in the structural design codes of Australia, Hong Kong, Europe, South Africa and the United States, as well as those proposed by established organisations and individual researchers. In general, these models are expressed in a simple power function, in the form:

$$Modulus\ of\ Elasticity\ =\ k \cdot x \cdot (strength)^{a}$$

where

k is a constant, ***x*** is a variable and ***a*** is a fractional exponent.

As can be seen from Table 7.2, the compressive strength of concrete is a common variable used in the estimation of the modulus of elasticity. This is to be expected, as compressive strength is the easiest and most commonly measured and used property

Table 7.2 Parameters used in estimating elastic modulus of concrete

REFERENCE	COUNTRY	PARAMETER			MODEL*
		Concrete Strength	Density of Concrete	Rock Type	
(a) Organisations/ Design Codes					
ACI 209-2R (2008)	USA	✓	✓	-	$E_c = 0.043 w_c^{1.5}\sqrt{f_{cm}}$
ACI 318 (2014)	USA	✓	✓	-	$E_c = 0.043 w_c^{1.5}\sqrt{f_c'}$
AS 3600 (2009) **	Australia	✓	✓	-	$E_c = 0.024 \times w_c^{1.5}\sqrt{f_{cm} + 0.12}$
Eurocode 2 (2004)	Europe	✓	-	✓	$E_c = 22000[(f_{cm}/10)]^{0.3}$
fib (2013) for MC 2010	Europe	✓	-	✓	$E_c = 21500\alpha_E[(f_{cm}/10)]^{1/3}$
HKBD (2013)	Hong Kong	✓	-	-	$E_c = 3.46\sqrt{f_{cu}} + 3.21$
SABS (2000)	South Africa	✓	✓	-	(Not available as value provided in a table form)
(b) Individual Researchers					
B4 (2015)	USA	✓	-	-	$E_c = 4734\sqrt{f_{cm}}$
GL-2000 (2004)***	Canada	✓	-	-	$E_c = 4300\sqrt{f_{cm}} + 3500$

* All units in MPa except for Hong Kong and South Africa, which are in GPa, ** this applies to concrete with strength > 40 MPa. For concrete with strength ≤ 40 MPa, the model is the same to that of ACI 209-2R (2008). *** Based on ACI 209-2R (2008). Note: E_C = Modulus of elasticity; f_{cm} = Mean compressive cylinder strength; f_c'= Specified cylinder strength; f_{cu} = Mean compressive cube strength; α_E = Aggregate factor

of hardened concrete. Additionally, strength relates to the compactness of a concrete mixture, in which aggregate can be an influencing factor (de Larrad, 1999). There is then the question of which form of compressive strength is adopted in a model. Apart from the building design codes in Hong Kong (HKBD, 2013) and the United States (ACI 318, 2014), the compressive strength used in all other models is the mean strength of cylinder specimens measured at 28 days. In HKBD (2013), the model is applicable for both the mean and the characteristic cube compressive strengths. However, in ACI 318 (2014), the specified (characteristic) cylinder compressive strength is used.

Other than the compressive strength, the density of concrete is also considered in ACI 209-2R (2008) and ACI 318 (2014) in the United States, AS 3600 (2009) in Australia and SABS (2000) in South Africa. Except for SABS (2000), in which a separate multiplying factor is given for concrete with a density in the range of 1400–2300 kg/m^3, an exponent of 1.5 is applied to the density of concrete in the models. The reason for using the density of concrete is probably associated with the aggregate effect for its volumetric proportion in concrete as well as its stiffness (normally, the density of aggregate is indirectly proportional to its stiffness).

On the other hand, in the Eurocode 2 (2004) and *fib* (2013) models in Europe, the modulus of elasticity of concrete is expressed as a function of compressive strength and, though limited to four, the type of aggregate used. This is perhaps based on the assumption that the modulus of elasticity of concrete is affected by the stiffness of its aggregate. In these two models, four different types of natural aggregate are considered, in a broadly based descending stiffness order, namely, basalt, quartzite, limestone and sandstone. As the equation given in these models is for concrete made with quartzite, for other aggregates the estimated elastic modulus is changed by a multiplying factor, such as 1.2 when basalt is used and 0.9 and 0.7 when limestone and sandstone are used, respectively. Given that the stiffness of RSA is different to that of natural aggregate (see Chapter 3, Section 3.7), perhaps a new model is needed for estimating the modulus of elasticity of concrete where RSA is used.

7.3.2 Comparison between Estimated and Measured E_C of Concrete

The models given in ACI 209-2R (2008), Eurocode 2 (2004) and B4 (2015), as explained in Section 7.1, were selected to assess their performance in estimating the elastic modulus of concrete made with coarse RCA, fine glass cullet aggregate (GCA) or fine copper slag aggregate (CSA), as well as coarse and fine natural aggregate (NA), by comparing the measured values (experimental results) with the estimated values. The elastic modulus data used herein were determined from laboratory cast specimens, and they are the same as those used in Chapter 4 in dealing with the effects of RSA on the elastic modulus of concrete. In preparing the data for the assessment, the following steps have been undertaken:

(i) Only concrete specimens tested at 28 days and with a minimum elastic modulus value of 27 GPa were considered. This minimum value was chosen based on Eurocode 2 (2004) for concrete with mean compressive cylinder strength of 20 MPa.

(ii) As all three models make use of cylinder strength, the cube strength of concrete was converted to cylinder strength by dividing it by a factor of 1.25, as discussed in Chapter 4, Section 4.2.5.

(iii) In estimating the elastic modulus using ACI 209-2R (2008), the density of the concrete is required. However, this information has not always been provided, and where available was mainly for concrete in the fresh state. Thus, the fresh concrete density has been mostly used in the estimation, with the assumption that the concrete is properly cured so that the difference in density between the fresh and the hardened states is insignificant.

(iv) In using Eurocode 2 (2004), the type of aggregate is required. Again, this information is not commonly reported. However, as shown in Figure 4.6 in Section 4.2.5, the relationship of compressive strength and elastic modulus of natural aggregate concrete obtained in this study is by and large close to that for the quartzite aggregate concrete. Thus, the elastic modulus of quartzite concrete is used throughout this work.

(v) Although data on the elastic modulus of concrete containing RSA are available for different concrete ages, to eliminate the possible influence of the maturity of the concrete, only the 28-day results are considered. The data were separated into four main categories for analysis, based on the RSA content, (a) 0%, i.e., without RSA, (b) 10% to 30%, (c) 40% to 80% and (d) 90% to 100%, primarily to achieve a reasonable sample size within each category. Additionally, as the stiffness of GCA and CSA are sufficiently close, the data for concrete made with either of these fine secondary aggregates were analysed together.

Figures 7.1 and 7.2 compare the measured and estimated elastic modulus values using the three selected models for concrete made with (a) coarse RCA and (b) fine GCA or fine CSA, respectively. It should be mentioned that most of the data with elastic modulus value below 27 GPa, though not shown in Figures 7.1 and 7.2, are above the line of equality, implying that the model is likely to overestimate concrete with a low elastic modulus.

In the case of coarse RCA concrete, the main points to emerge from Figure 7.1 are as follows:

(i) **ACI 209-2R (2008):** The data points for concrete made with 10%–30% and 40%–80% coarse RCA content are generally closer to the line of equality, compared to 0% and 90%–100% coarse RCA content.

(ii) **Eurocode 2 (2004):** The data points tend to be clustered slightly above the line of equality for concrete with measured elastic modulus values ranging from 27 to 35 GPa, regardless of the coarse RCA content. This is a clear sign of overestimation. However, the model tends to underestimate when the measured value is higher than 40 GPa.

(iii) **B4 (2015):** Though similar to Eurocode 2 (2004), which relies only on compressive

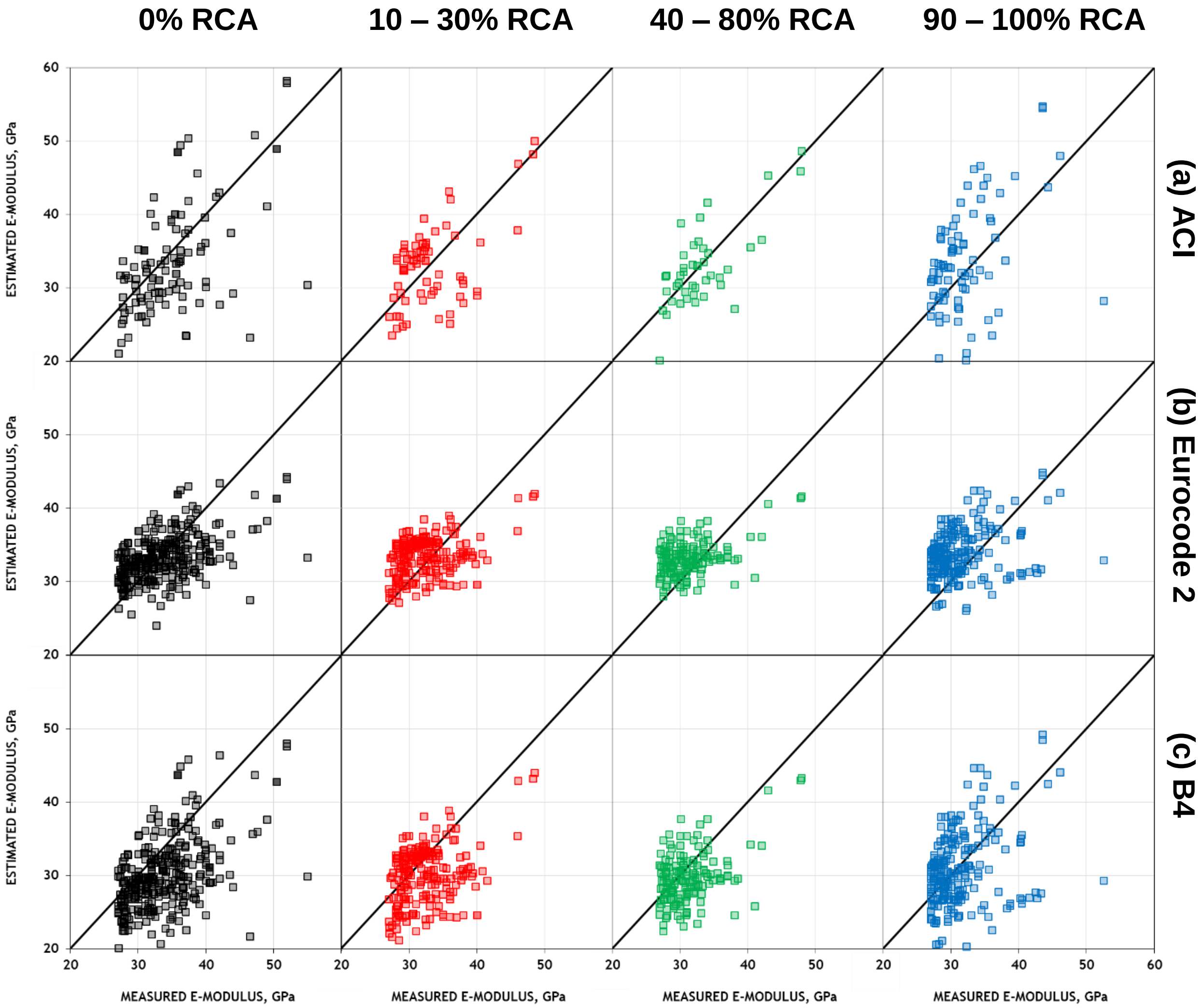


Figure 7.1 Comparison of elastic modulus of concrete made with coarse RCA between measured values and estimated values using (a) ACI 209-2R, 2008, (b) Eurocode 2, 2004 (c) B4, 2015.

strength in estimating the elastic modulus, the data points in Figure 7.1 are relatively scattered. The results also suggest that the model underestimates the elastic modulus of concrete, particularly for concrete made with natural aggregate.

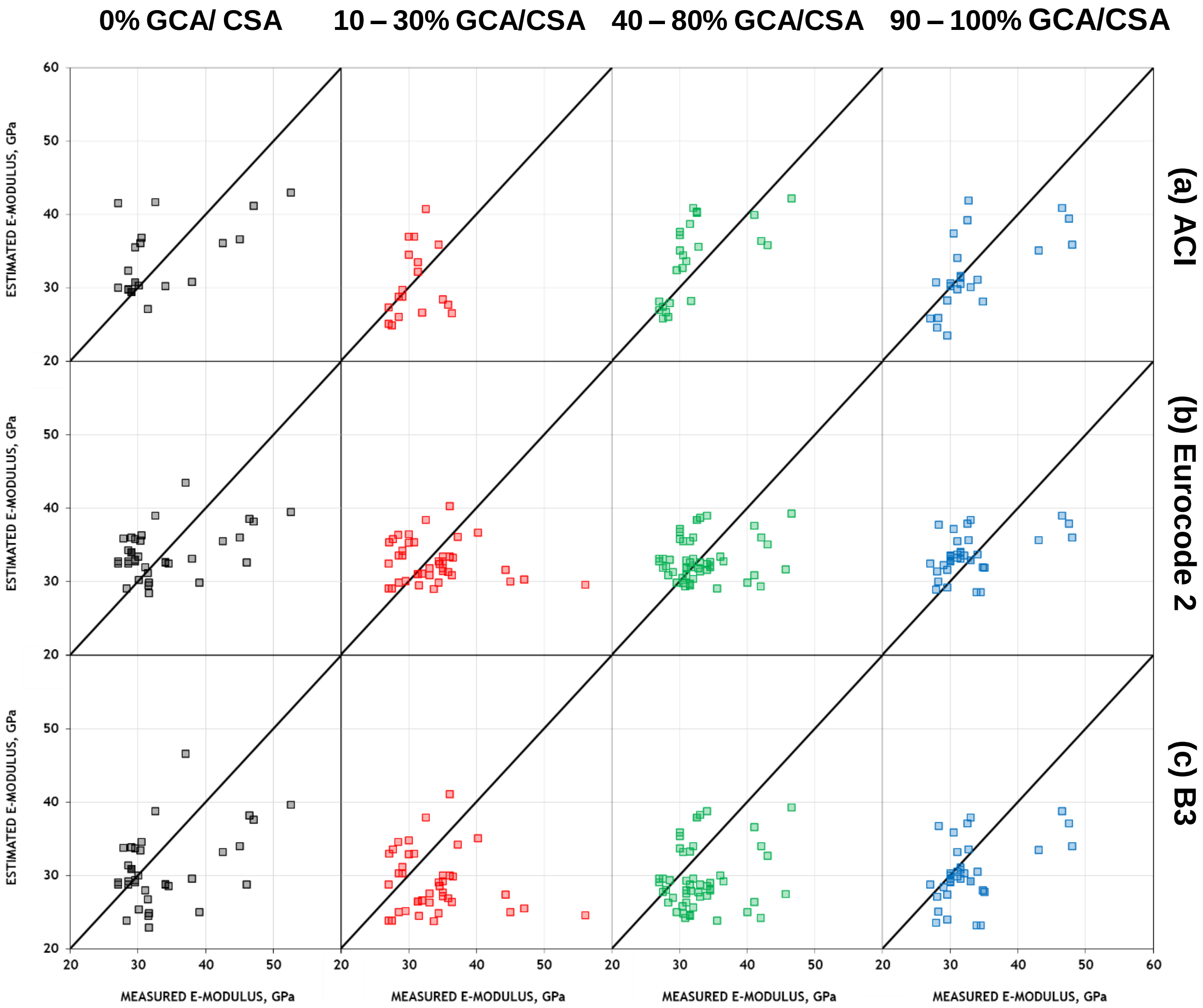


Figure 7.2 Comparison of elastic modulus of concrete made with fine GCA or fine CSA between measured values and estimated values using (a) ACI 209-2R, 2008, (b) Eurocode 2, 2004 (c) B4, 2015.

In the case of fine GCA and fine CSA concrete, the main points emerging from Figure 7.2 are as follows:

(i) **ACI 209-2R (2008):** The data points below 30 GPa are closer to the line of equality. However, as the modulus of elasticity increases, the data points tend to fall below the line of equality.

(ii) **Eurocode 2 (2004):** The distribution of the data points is similar to that of Figure 7.1 for concrete containing RCA, in that they tend to cluster below the value of 35 GPa and fall above the line of equality. The model underestimates the elastic modulus of concrete for the measured values above 40 GPa.

(iii) **B4 (2015):** The model does not fit well with the data and the results show a general tendency of underestimation.

The results of the error measures, namely MBE, RMSE and MAPE, for the three selected models in estimating the modulus of elasticity of concrete made with (a) coarse RCA and (b) fine GCA or fine CSA are given in Table 7.3. As the combined sample size of concrete made with either fine GCA or fine CSA is small, generally fewer than 50 data points at each replacement level, the results presented in Table 7.3 could, at best, be considered only as exploratory.

The following main points can be observed from Table 7.3:

(i) **MBE:** For coarse RCA concrete, as the RCA content increases, the MBE values progressively change from negative to positive for the ACI 209-2R (2008) and Eurocode 2 (2004) models, or from more negative to less negative for the B4 (2015) model. This clearly suggests that the three models have a tendency to overestimate the modulus of elasticity of concrete containing RCA. In addition, the result also implies that the estimated values obtained using Eurocode 2 (2004) require a correction factor for coarse RCA, like the ones suggested for basalt (1.2),

Table 7.3 Comparison of estimation for the modulus of elasticity of concrete made with (a) coarse RCA and (b) fine GCA or fine CSA

MODEL	RCA, %	DATA SIZE	MBE, GPa	RMSE, GPa	MAPE, %
(a) Coarse RCA					
ACI 209-2R (2008)	0	110	**-1.1**	6.7	13.9
	10 – 30	68	**-0.1**	5.0	12.8
	40 – 80	43	**-0.4**	3.9	5.9
	90 – 100	80	**+1.7**	6.7	16.0
Eurocode 2 (2004)	0	322	-0.4	4.4	9.8
	10 – 30	210	**+1.1**	4.0	10.7
	40 – 80	156	**+2.0**	4.0	10.6
	90 – 100	214	**+2.5**	5.2	13.9
B4 (2015)	0	322	**-3.6**	6.1	13.6
	10 – 30	210	**-2.2**	5.0	11.7
	40 – 80	156	**-1.5**	4.1	10.2
	90 – 100	214	**-0.5**	5.6	12.9
MODEL	**GCA/ CSA, %**	**DATA SIZE**	**MBE, GPa**	**RMSE, GPa**	**MAPE, %**
(b) Fine GCA or Fine CSA					
ACI 209-2R (2008)	0	23	**+0.4**	5.7	12.9
	10 – 30	18	**-0.3**	4.9	11.9
	40 – 80	24	**+1.6**	4.8	7.0
	90 – 100	23	**-1.4**	5.2	11.3
Eurocode 2 (2004)	0	37	**+0.5**	6.0	14.8
	10 – 30	41	**-1.8**	8.5	14.7
	40 – 80	52	**-0.2**	5.0	7.0
	90 – 100	35	**+0.8**	4.8	11.4
B4 (2015)	0	37	**-2.5**	6.7	15.0
	10 – 30	41	**-5.4**	10.5	20.1
	40 – 80	52	**-3.6**	6.8	10.2
	90 – 100	35	**-2.4**	5.5	11.6

limestone (0.9) and sandstone (0.7) relative to quartzite. On the other hand, for fine GCA and fine CSA concrete, no consistent trend can be observed as the replacement level increases. As most of the MBE values are negative, it is evident that the models may have underestimated the modulus of elasticity of concrete made with fine GCA and fine CSA. The underestimation is significant for the B4 (2000) model.

(ii) **RMSE:** The RMSE values of all three models are generally within the range of 4–7 GPa, as given in Table 7.3. For those relating to Eurocode 2 (2004), the estimation for concrete made with coarse RCA has the lowest RMSE value in most cases. The two high RMSE values of 8.5 and 10.5 GPa for concrete made with 10%–30% fine GCA or fine CSA in the Eurocode 2 (2004) and B4 (2015) models, respectively, are due to the extreme deviations caused by the outliers, as can be seen in Figure 7.2.

(iii) **MAPE:** In most cases, the MAPE values for concrete made with or without RSA are in the range of 10%–20%, indicating that the estimation accuracy of the selected models is good (Lewis, 1997). In a very few cases, the MAPE values of ACI 209-2R (2008) and Eurocode 2 (2004) are less than 10%, which is considered to be a very good estimation.

7.4 CREEP OF RSA CONCRETE

7.4.1 Creep Deformation Models

Owing to its heterogeneous nature, and the fact that many variables are involved in the determination of creep deformation of concrete, the methods of estimating creep strains can be complex, though a simple, yet reliable, approach would be more attractive and, it is hoped, useful in practice.

Most models proposed for estimating creep of concrete are of an empirical nature, and are not necessarily based on mechanisms of creep, but rather present a likely outcome for a given set of conditions. Thus, such models are, understandably, subjected to progressive refinement and calibration to improve their accuracy. This can be seen from the latest development of *fib*'s model, Model Code 2010 (*fib*, 2013), in which the new formulation of creep estimation is expressed as the sum of basic creep and drying creep, instead of treating it as total creep, as in the previous models.

Table 7.4 lists the creep estimation models from the design codes adopted in Australia, Hong Kong, Europe, South Africa and the United States, and a couple of those proposed by individual researchers, together with the parameters that are used in each model. The information is separated into five main categories, namely (i) creep type and methods, (ii) concrete mix design, (iii) concrete properties, (iv) member geometry and (v) curing and exposure conditions, as discussed next.

Table 7.4 Parameters used in estimating creep of concrete

		ACI 209-2R (2008)	AS 3600 (2009)	Eurocode 2 (2004)	fib (2013)	SABS (2000)	HKBD (2013)	B4 (2015)	GL2000 (2004)
Creep Type and Methods	Creep coefficient	✓	✓	✓	✓	✓	✓	-	✓
	Compliance	✓	-	-	-	-	-	✓	✓
	Mathematic equations	✓	✓	✓	✓	-	-	✓	✓
	Nomograms	-	-	✓	-	✓	✓	-	-
Concrete Mix Design	Cement content	-	-	-	-	-	✓	✓	-
	Cement type	✓	-	✓	✓	-	✓	✓	-
	Aggregate type	-	-	-	-	-	-	✓	-
	Admixture type and content (optional)	-	-	-	-	-	-	✓	-
	Water/cement ratio	-	-	-	-	-	✓	✓	-
	Aggregate/cement ratio	-	-	-	-	-	-	✓	-
	Fine aggregate/ total aggregates ratio	✓	-	-	-	-	-	✓	-
Concrete Properties	Consistence (Slump)	✓	-	-	-	-	-	-	-
	Air content	✓	-	-	-	-	-	-	-
	Compressive strength	-	✓	✓	✓	-	-	✓	-
	Modulus of elasticity	✓	-	-	-	-	-	✓	✓
Geom-etry	Shape of member	-	-	-	-	-	-	✓	-
	Dimensions of member	✓	✓	✓	✓	✓	✓	✓	✓
Curing and Exposure Conditions	Curing method	✓	-	-	-	-	-	-	-
	Curing temperature	-	-	✓	✓	-	-	✓	-
	Drying duration	-	-	-	-	-	-	✓	✓
	Relative humidity	✓	✓	✓	✓	✓	✓	✓	✓
	Exposed temperature	-	-	-	✓	-	-	✓	-
	Age at loading	✓	✓	✓	✓	✓	✓	✓	✓
	Loading duration	✓	✓	✓	✓	-	✓	✓	✓

(i) Creep Type and Methods

In all the models, apart from the B4 model (2015), creep is commonly estimated as a form of creep coefficient (**φ**), which is the ratio of creep strain (**ε_{cc}**), at any age (**t**) after loading at the age of (**t_0**), to initial elastic strain (**ε_{ci}**) at the age of 28 days. Thus, the creep strain of a concrete member at any age can be calculated for a given constant stress (**σ_c**) and elastic modulus (**E_c**), as follows:

$$\varphi(t,t_0) = \frac{\varepsilon_{cc}(t,t_0)}{\varepsilon_{ci}} = \frac{\varepsilon_{cc}(t,t_0)}{{}^{\sigma_c}/_{E_c}} \Longrightarrow \varepsilon_{cc}(t,t_0) = \varphi(t,t_0)\frac{\sigma_c}{E_c}$$

The creep coefficient in most models, ACI 209-2R (2008), AS 3600 (2009), Eurocode 2 (2004), *fib* (2013) and GL 2000 (2004), is a product of (a) the notional creep coefficient and (b) a series of coefficients that account for various factors affecting creep. However, the SABS (2000) and HKBD (2013) models consist of only the latter. In addition, the creep coefficient in the *fib* (2013) and GL 2000 (2004) models is separated into two components, i.e., basic creep and drying creep, representing different physical mechanisms. Basic creep occurs when concrete is loaded under conditions of no moisture movement with the ambient environment, whilst drying creep is an additional creep caused by the drying process (Neville et al., 1983).

As for B4 (2015), this model estimates the creep of concrete in a form of compliance (**J**), which is defined as the total strain caused by an applied stress. The compliance in this model consists of three terms, i.e., instantaneous compliance, compliance for basic creep and compliance for drying creep. Indeed, compliance is also presented in the ACI 209-2R (2008) and GL 2000 (2004) models, and is derived from the estimated creep coefficient and elastic modulus. The general form of compliance is as follows (Jirasek, 2015):

$$J(t,t_0) = \frac{1}{E_{cm}(t,t_0)} + \frac{\varphi(t,t_0)}{E_{cm}(t,t_0)}$$

Overall, two types of methods have been adopted in estimating the creep coefficient and the compliance of concrete. In most models, these values are estimated using a series of mathematical equations of varying complexity. However, the design codes in Hong Kong (HKBD, 2013) and South Africa (SABS, 2000) employ nomograms to determine the creep coefficient, which are based on the old CEB-FIP (1970) and Concrete Society (1978) models, respectively. On the other hand, both the computational and the nomogram methods are provided in the design code in Europe (Eurocode 2, 2004), in which it is advised that the latter may be used when great accuracy is not required.

(ii) Concrete Mix Design

The details of the concrete mix design of a structural member are normally not known to engineers during the designing stage. Thus, whilst the properties of the constituent materials and their contents have a direct influence on creep and they can be useful parameters in the estimation, their inclusion in the model has been considered less favourable. However, having said that, there is one exception, the cement type used, which is the most adopted concrete mix design parameter in the models listed in Table 7.4. In general, three broad groups of cement have been defined based on hydration reactivity, i.e., normal, rapid hardening and slow setting cements. This is not too surprising as the type of cement that is to be used in a concrete mix can be anticipated based on the design and the intended use of the structure. Conventionally, CEM I (BS EN 197-1, 2011) or Type I (ASTM C150, 2016) cement, which can be considered normal-setting cement, is used in most structural concrete. However, in thick slab elements, to minimise the thermal gradient between the concrete and the ambient environment, which otherwise can lead to thermal cracking or delayed ettringite formation, slow-setting cement, such as CEM III or Type IV cement, is likely to be used. In precast concrete, to facilitate and speed up the production cycle, rapid-hardening cement, such as CEM 52.5R or Type III, is the ideal candidate. It should be mentioned that, for a given applied stress and loading age, the creep of concrete is inversely proportional to the rate of hardening of the cement; the higher the rate, the more rigid the concrete, the lower the creep (Neville et al., 1983).

The next parameter of interest in designing concrete mixes in this case is the type of aggregate used. Though not generally acknowledged, the modulus of elasticity/hardness of aggregate relates to the degree of restraint it can provide against the deformation of the concrete (Jackson and Dhir, 1996). Notwithstanding this, in a recently established B4 (2015) model, developed by Bazant and his co-workers, the effect of aggregate type was introduced in estimating both creep and shrinkage deformation of concrete (see Section 7.5), whereby six natural aggregate types, of varying modulus of elasticity and particle density, were considered, namely diabase, quartzite, limestone, sandstone, granite and quartz diorite. The multiplying factors for these aggregates suggested by the authors are listed in Table 7.5. It is noted that, perhaps because of the large variations in the physical properties of these rock types, the multiplying factors do not seem to follow any particular order.

Table 7.5 Multiplying factors for different aggregate types given in the B4 model

AGGREGATE TYPE	MULTIPLYING FACTOR 1	MULTIPLYING FACTOR 2	ELASTIC MODULUS, GPa	PARTICLE DENSITY, g/cm^3
Diabase	0.60*	0.76*	70 – 90	2.8 – 3.0
Quartzite	0.59	0.71	50 – 90	2.5 – 2.8
Limestone	1.80	0.95	10 – 70	1.8 – 2.9
Sandstone	2.30	1.60	10 – 50	2.0 – 2.8
Granite	4.00	1.05	30 – 70	2.5 – 2.8
Quartz diorite	15.0*	2.20*	50 - 100	2.7 – 3.1
Unknown	1.00	1.00	-	-

*Noted as uncertain fitted parameters

Other parameters that have been included in the models listed in Table 7.4, such as admixture type and its content, water/cement ratio, aggregate/cement ratio and fine aggregate/total aggregate ratio, though they might be useful in improving the estimation, require prior information of the concrete mix design, which, as mentioned previously, is normally not available to the structural engineer at the design stage.

(iii) Concrete Properties

Because it has to be specified during the design stage, and because it is a most frequently measured property, compressive strength has been most commonly used in estimating creep deformation, as seen in AS 3600 (2009), Eurocode 2 (2004), *fib* (2013) and B4 (2015) models. The 28-day mean compressive cylinder strength has been used in all the aforementioned models, except for AS 3600 (2009), in which characteristic cylinder strength is used instead. In addition, it should be mentioned that a simplified version of model B4, developed by Bazant and his co-workers, is based solely on the compressive strength of concrete, to overcome the shortcomings of not knowing the composition of the concrete (Bazant et al., 2015).

The elastic modulus of concrete is perhaps the only hardened concrete property that is closely related to creep, as both deformations are load-dependent. This is used in the ACI 209-2R (2008), B4 (2015) and GL 2000 (2004) models in estimating the compliance of concrete in terms of total load-induced strain per unit stress. However, its use is associated with the elastic component and does not relate directly to the creep component in the estimation.

In addition, the ACI 209-2R (2008) model uses the consistence (workability) and air content of concrete in estimating the creep coefficient; all things being equal, a high value of either of these two parameters can lead to an increase in creep coefficient. The effect of air content is very clear; air voids do not resist load, thus their presence in concrete generally reduces the mechanical properties of the concrete. However, the effect of consistence on creep is not so straightforward, as this property can be affected by many factors. Some of these factors can be explained easily; for example, an increase in cement paste can increase the consistence owing to its lubricating effect, but it would at the same time increase the creep of the concrete, which will be further compounded because of the reduction in the aggregate content. However, the influence of admixture on creep has not been established, as it depends on the type and amount of admixture used, as well as the combined effect with the cement type (Hubler, 2015). Given that, in practice, a specified consistence of concrete can be achieved in several ways, this may pose a serious question regarding the reliability of the use of consistency as a parameter in the ACI model.

(iv) Member Geometry

The geometry of the member used in the estimation of creep, as seen in all the models in this chapter, involves the member dimension, except in the B4 (2015) model, which also considers member shape (Table 7.4). In all the models, the member dimension can be expressed in two different forms, namely volume/surface ratio or effective thickness. The former is used in ACI 209-2R (2008) and GL 2000 (2004), whilst the latter is used in the rest of the models. The effective thickness is generally defined as the ratio of the cross-sectional area of a member to its exposed semi-perimeter, which is equivalent to twice the volume/surface ratio (Neville et al., 1983).

The effect of member dimension on the creep of concrete is associated with the loss of internal moisture to the ambient environment. This is more relevant to the drying creep than to the basic creep. Indeed, in the models in which the estimation of creep is separated into basic creep and drying creep (*fib*, 2013; B4, 2015; GL 2000, 2004), the member dimension parameter is used only in the latter component. For a small specimen, its surface/volume ratio is large, thus a greater part of the concrete is subjected to drying whilst the creep phenomenon occurs, and a greater drying creep value is therefore expected (Neville et al., 1983).

The shape factor of the member in creep is closely related to the dimension of the member. Changing the shape of the member will result in a change in its dimension, and thus its volume/surface ratio or effective thickness. In the B4 (2015) model, a multiplying factor is assigned for members of different shapes, namely slab, cylinder, square prism, sphere and cube.

(v) Curing and Exposure Conditions

The curing conditions (temperature and relative humidity) affect the maturity of the concrete, and this can modify its creep response. The effects of moist curing and steam curing are considered in ACI 209-2R (2008). However, the B4 (2015), Eurocode 2 (2004) and *fib* (2013) models consider only the effect of curing temperature. This effect is possibly meant for precast elements, which are usually subjected to high curing temperatures.

Only the B4 (2015) and GL 2000 (2004) models allow for the influence of drying duration in estimating creep, i.e., the period between the age when moist curing ceases and the age at loading. In general, the longer the drying duration prior to the application of load, the lesser the creep of the concrete. However, longer drying duration should not be taken as a measure to reduce creep, as insufficient curing could have a negative effect on the other hardened properties of concrete.

In the preceding paragraphs, the discussion is about the environmental factors on the creep of concrete prior to the application of load. These factors, of course, will continue to affect creep after loading. All the models listed in Table 7.4 consider ambient relative humidity in their estimation, but in B4 (2015), Eurocode 2 (2004) and *fib* (2013), both ambient relative humidity and temperature are considered. In general, creep is likely to increase when concrete is exposed to an environment with lower relative humidity or higher temperature.

7.4.2 Comparison between Estimated and Measured Creep Coefficient of RSA Concrete

The ability to estimate the creep of RCA concrete is assessed in this section, applying the ACI 209-2R (2008), Eurocode 2 (2004) and B4 (2015) models. The experimental data on both GCA and CSA are minimal; therefore they could not be included in this assessment. In preparing the data for this work, where specific information required for the estimation was unavailable, the following commonly used values/properties were adopted (Lye et al., 2016c):

- Cement type: CEM I or Type I cement
- Fine/total aggregate ratio: 0.40
- Consistence (workability): 100 mm slump
- Age at loading: 28 days
- Curing conditions: 20°C temperature, 100% RH humidity
- Exposure conditions: 20°C temperature, 60% RH humidity
- Specimen: cylinder with 100 mm diameter × 300 mm height

The data for both coarse RCA concrete and the corresponding reference NA concrete were used in the assessment, but separated into four groups, namely: 0%, 10%–40%, 50%–80% and 90%–100% RCA content. The measured creep coefficient is plotted against its corresponding estimated value using the three aforementioned models individually, as shown in Figure 7.3, where the solid line represents the line of equality and a pair of dashed lines represent ±20% deviations from the line of equality.

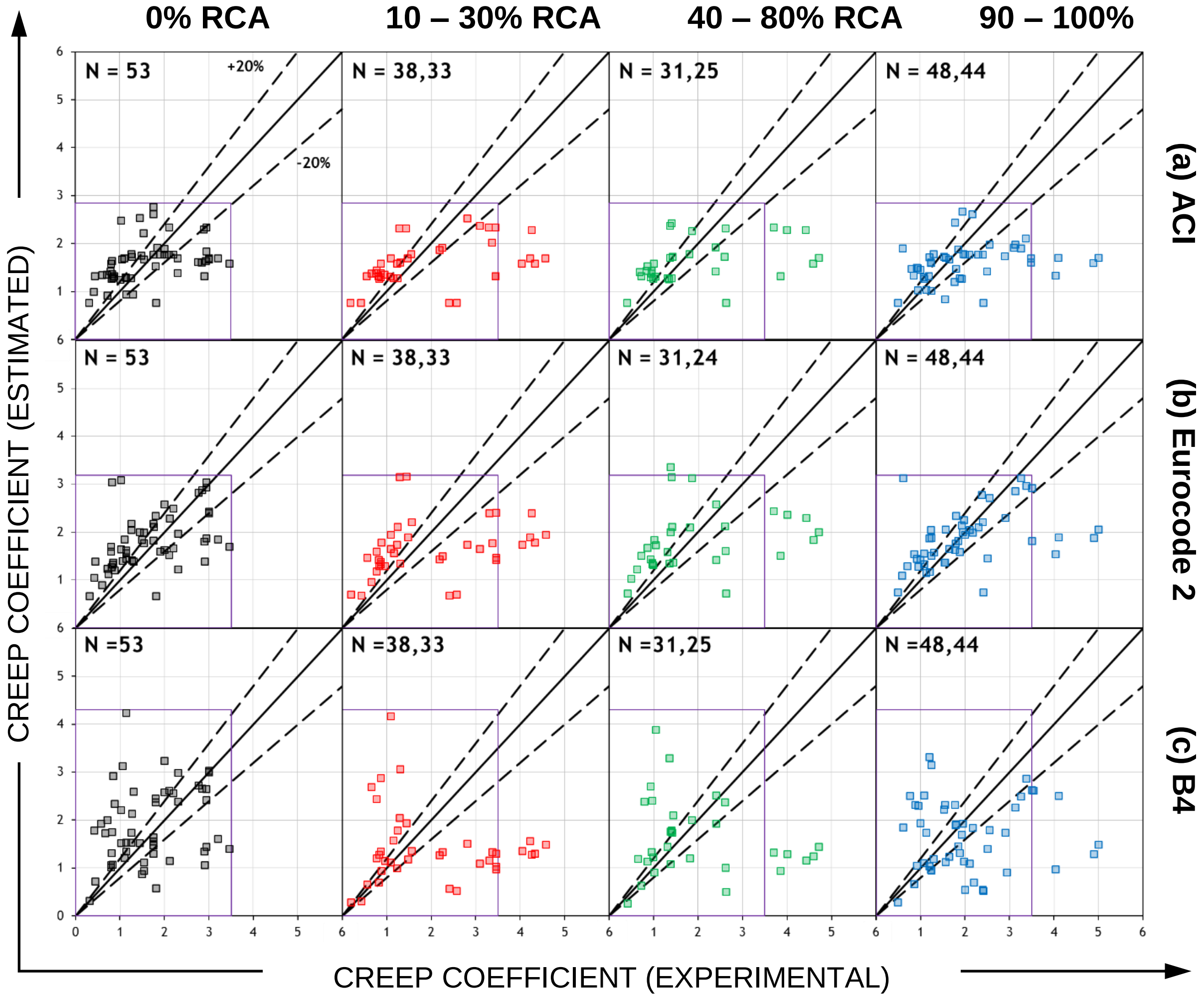


Figure 7.3 Comparison of creep coefficient of concrete made with coarse RSA between the measured values and estimated values using (a) ACI 209-2R, 2008, (b) Eurocode 2, 2004 (c) B4, 2015.

This analysis has been carried out for (a) all the data and (b) data with extreme results excluded. For the latter, in order not to compromise the size of the data, only those of the RCA concrete greater than the maximum measured or estimated creep coefficient of NA concrete (outside the box as shown in Figure 7.3) are treated as extreme results. These extreme results were noted to be from two specific studies (Gomez-Soberon, 2002a; Waleed and Canisius, 2007). The error measures of the models for the two groups of data are given in Tables 7.6 (a) and 7.6 (b). It should be noted here that the use of MAPE in this assessment is perhaps less effective, as it is sensitive to the errors made when the measured creep coefficient values are less than 1.

The main points emerging from Figure 7.3 and Table 7.6 (a) are summarised as follows:

(i) ACI 209-2R (2008) model: For NA concrete, the data are clustered around the line of equality, but mostly fall below the line of equality when the measured values are greater than 2. The same is observed in the case of RCA concrete, but the deviation of the data is more significant. The MBE of both the NA and the RCA concretes is negative, suggesting that the model tends to underestimate the creep of concrete. The RMSE value for NA concrete is 0.79, which is lower than that of RCA concrete, ranging from 1.13 to 1.24. The MAPE values for both the NA and the RCA concretes vary from 38% to 58%. Overall, the data distribution and error measures of ACI 209-2R (2008) suggest that the estimation of the creep coefficient of both RCA and NA concrete produces similarly large errors.

Table 7.6 Comparison of estimation for the creep coefficient of concrete made with coarse RCA using selected models

MODEL	RCA, %	DATA SIZE	MBE	RMSE	MAPE, %
(a) All the data					
ACI 209-2R (2008)	0	53	**-0.04**	0.79	48.7
	10 – 30	38	**-0.38**	1.24	57.8
	40 – 80	31	**-0.32**	1.20	45.2
	90 – 100	48	**-0.43**	1.13	38.9
Eurocode 2 (2004)	0	53	**0.15**	0.78	51.0
	10 – 30	38	**-0.32**	1.30	65.9
	40 – 80	31	**-0.13**	1.35	56.7
	90 – 100	48	**-0.15**	1.00	37.6
B4 (2015)	0	53	**0.28**	1.09	70.2
	10 – 30	38	**-0.55**	1.68	77.6
	40 – 80	31	**-0.33**	1.64	64.4
	90 – 100	48	**-0.37**	1.32	59.7
(b) Data without extreme results					
ACI 209-2R (2008)	0	53	**-0.04**	0.79	48.7
	10 – 30	33	**-0.06**	0.90	57.7
	40 – 80	25	**0.15**	0.66	43.2
	90 – 100	44	**-0.21**	0.77	35.8
Eurocode 2 (2004)	0	53	**0.15**	0.78	51.0
	10 – 30	33	**-0.01**	1.07	71.4
	40 – 80	25	**0.28**	0.80	54.6
	90 – 100	44	**0.08**	0.66	35.6
B4 (2015)	0	53	**0.28**	1.09	70.2
	10 – 30	32	**-0.13**	1.38	74.4
	40 – 80	25	**0.30**	1.08	62.9
	90 – 100	44	**-0.13**	1.03	56.1

(ii) Eurocode 2 (2004) model: The data distribution is similar to that of the ACI 209-2R (2008) model, except that the 90%–100% RCA concrete in this case has more data points falling within the ±20% deviation lines. The positive MBE value for NA concrete suggests that the model generally overestimates the creep of NA concrete; however, the opposite is shown for RCA concrete. The RMSE values for RCA concrete, ranging from 1.00 to 1.35, are higher than the RMSE value for NA concrete at 0.78. Notwithstanding this, the MAPE value for 90%–100% RCA concrete is the lowest (37.6%), whilst that of NA concrete and concrete made with other RCA content varies from 50% to 66%. Comparing the data distribution and error measures of the four groups of data, the estimation of concrete made with 90%–100% RCA is considered to be more accurate. However, the results also suggest the need for an accurate estimation for all the concrete, regardless of its RCA content.

(iii) B4 (2015) model: Compared with the previous two models, the data points of both the NA and the RCA concrete are generally more scattered, and the spread of the data tends to show a funnel-shaped pattern. The MBE values suggest that the model generally overestimates the creep of NA concrete but underestimates that of RCA concrete. The RMSE value for NA concrete is 1.09, which is lower than that of RCA concrete ranging from 1.32 to 1.68. The MAPE values for all the concretes are considerably high, varying between 59% and 78%. In general, the results suggest that the model is not able to accurately estimate the creep coefficient of either the NA or the RCA concrete.

Overall, it can be seen from Figure 7.3 that the data for RCA concrete are more scattered, and the corresponding error measures are larger, than those for the NA concrete. However, when the variability of the RCA concrete is kept the same as that of NA concrete, the error measures of RCA concrete show a considerable reduction [Table 7.6 (b)]. However, this does not suggest that the models are adequately suited to estimate the creep of RCA concrete, as well as that of NA concrete, and further refinement of these models is needed to improve their estimation accuracy. Among the three models, B4 (2015) is the least accurate.

7.5 SHRINKAGE OF RSA CONCRETE

7.5.1 Shrinkage Deformation Models

Shrinkage is another important deformation property used in designing structures, as when ignored it can lead to the development of cracks that can adversely affect the performance of structures. Thus, an accurate estimation of shrinkage is essential to ensure the long-term durability and serviceability of concrete structures.

This section deals with the same eight models studied previously in Section 7.4.1, of which six are from the design codes adopted in Australia, Hong Kong, Europe, South Africa and the United States, and two were proposed by individual researchers. The shrinkage type and estimation methods of these models are summarised in Table 7.7, together with the main factors used in estimating the shrinkage of concrete, namely: (i) concrete mix design, (ii) concrete properties, (iii) member geometry, (iv) curing and (v) exposure conditions. In general, though the mechanisms involved are different, these

Table 7.7 Parameters used in estimating the shrinkage of concrete

		ACI 209-92R (2008)	AS 3600 (2009)	Eurocode 2 (2004)	SABS (2000)	HKBD (2013)	fib (2013)	B4 (2015)	GL2000 (2004)
Shrinkage Type and Methods	Autogenous shrinkage	-	✓	✓	-	-	✓	✓	-
	Drying shrinkage	-	✓	✓	✓	✓	✓	✓	-
	Shrinkage	✓	-	-	-	-	-	-	✓
	Mathematical equations	✓	✓	✓	-	-	✓	✓	✓
	Monogram	-	-	-	✓	✓	-	-	-
Concrete Mix Design	Cement content	✓	-	-	-	✓	-	✓	-
	Cement type	-	-	✓	-	-	✓	✓	✓
	Water content	-	-	-	✓	✓	-	✓	-
	Water/cement ratio	-	-	-	-	✓	-	-	-
	Admixture types and content (optional)	-	-	-	-	-	-	✓	-
	Aggregate type	-	✓	-	-	✓	-	✓	-
	Aggregate/cement ratio	-	-	-	-	-	-	✓	-
	Sand/total aggregate ratio	✓	-	-	-	-	-	-	-
Concrete Properties	Slump	✓	-	-	-	-	-	-	-
	Air content	✓	-	-	-	-	-	-	-
	Compressive strength	-	✓	✓	-	-	✓	✓	✓
	Modulus of elasticity	-	-	-	-	-	-	✓	-
Member Geometry and Exposure Conditions	Shape of member	-	-	-	-	-	-	✓	-
	Dimension of member	✓	✓	✓	✓	✓	✓	✓	✓
	Curing method	✓	-	-	-	-	-	✓	-
	Curing duration	✓	-	-	-	-	-	-	-
	Curing temperature	-	-	-	-	-	-	✓	
	Ambient relative humidity	✓	✓	✓	✓	✓	✓	✓	✓
	Ambient temperature	-		-	-	-	✓	-	-
	Age at the beginning of drying	✓	✓	✓	-	✓	✓	✓	✓
	Age at the moment considered	✓	✓	✓	✓	✓	✓	✓	✓

factors are by and large similar to those used in estimating concrete creep (see Table 7.4).

Although the roles of these factors have been described in Section 7.4.1, some of the main points emerging from Table 7.7 are discussed in the following:

- Although, depending on concrete age and exposure conditions, the shrinkage of concrete can take place in different forms, such as plastic, autogenous, drying or carbonation, none of the models were developed to estimate all types of shrinkage. The Australian AS 3600 (2009), Eurocode 2 (2004), *fib* (2013) and B4 (2015) models estimate the autogenous and drying shrinkage of concrete as its total shrinkage, whilst the South African SABS (2000) and Hong Kong HKBD (2013) models estimate only the drying shrinkage of concrete. On the other hand, no distinction as to the type of shrinkage is made clear in the ACI 209-2R (2008) and GL 2000 (2004) models, though it is most likely that the total shrinkage is being estimated.

- The effect of aggregate type is considered in some of the models, namely B4 (2015), HKBD (2013) and AS 3600 (2009), in estimating the drying shrinkage of concrete. In B4 (2015), six aggregate types are considered, namely diabase, quartzite, limestone, sandstone, granite and quartz diorite. The HKBD (2013) model covers only crushed granitic aggregate. On the other hand, in AS 3600 (2009), instead of rock mineralogy, the effect of aggregate type is assigned based on the regional source of the aggregate, i.e., Sydney, Brisbane, Melbourne and other regions. Interestingly, as in dealing with elastic modulus and creep, in this case dealing with shrinkage, consideration of aggregate type at best is limited to the rock type and not its material properties. Overall, it would also appear that the models currently used in the standards and codes do not take into account the stiffness value of the aggregate in calculating the shrinkage of concrete.

- Although the shrinkage of concrete does not depend on its elastic modulus per se, amongst the models listed in Table 7.7, only B4 (2015) takes the elastic modulus of concrete into account in estimating the drying shrinkage of concrete.

7.5.2 Comparison between Estimated and Measured Shrinkage of RSA Concrete

The same three models, ACI 209-2R (2008), Eurocode 2 (2004) and B4 (2015), are used again to assess the accuracy in predicting the shrinkage of concrete made using RSA, as well as NA. The data used to test the validity of these models were taken from Chapter 6, using NA and RCA as separate materials, and the data for GCA and CSA were combined for the reason explained before in Chapter 6. Similar to creep (Section 7.4), not all the information required for this assessment was available, and some assumptions have been made (Lye et al., 2016d and Lye et al., 2017):

- Cement type: CEM I or Type I
- Fine/total aggregate ratio: 0.40
- Consistence (workability): 100 mm slump

- Curing conditions: 20°C temperature, 100% RH humidity
- Exposure conditions: 20°C temperature, 60% RH humidity
- Specimens: 100 × 100 × 400 mm prism for RCA concrete, 75 × 75 × 285 mm prism for GCA or CSA concrete

The measured and estimated shrinkage values for RCA concrete and GCA or CSA concrete, together with their corresponding NA concrete, are given in Figures 7.4 and 7.5, respectively. To be consistent, for the purpose of analysis, the data have been separated into four main categories throughout as explained earlier. These are 0%, 10%–30%, 40%–80% and 90%–100% RSA content. For ease of visualisation, in Figures 7.4 and 7.5, the lines of equality have been drawn as solid lines, each with a pair of ±20% deviation lines, drawn as dashes. The error measures in estimating the shrinkage of (a) RCA concrete and (b) GCA or CSA concrete are summarised in Table 7.8.

For RCA concrete, the following main points can be observed from Figure 7.4 and Table 7.8 (a):

Model ACI 209-2R (2008): The distributions of the data for concrete made with 0%, 10%–30% and 40%–80% RCA content are very similar, with almost half of the data points clustered within the ±20% deviation lines and a significant proportion of the remaining data points being above the +20% deviation line. However, the opposite is shown in the case of 90%–100% RCA concrete. It also appears that, for all concretes, the data points tend to fall beyond the −20% deviation line when the measured value

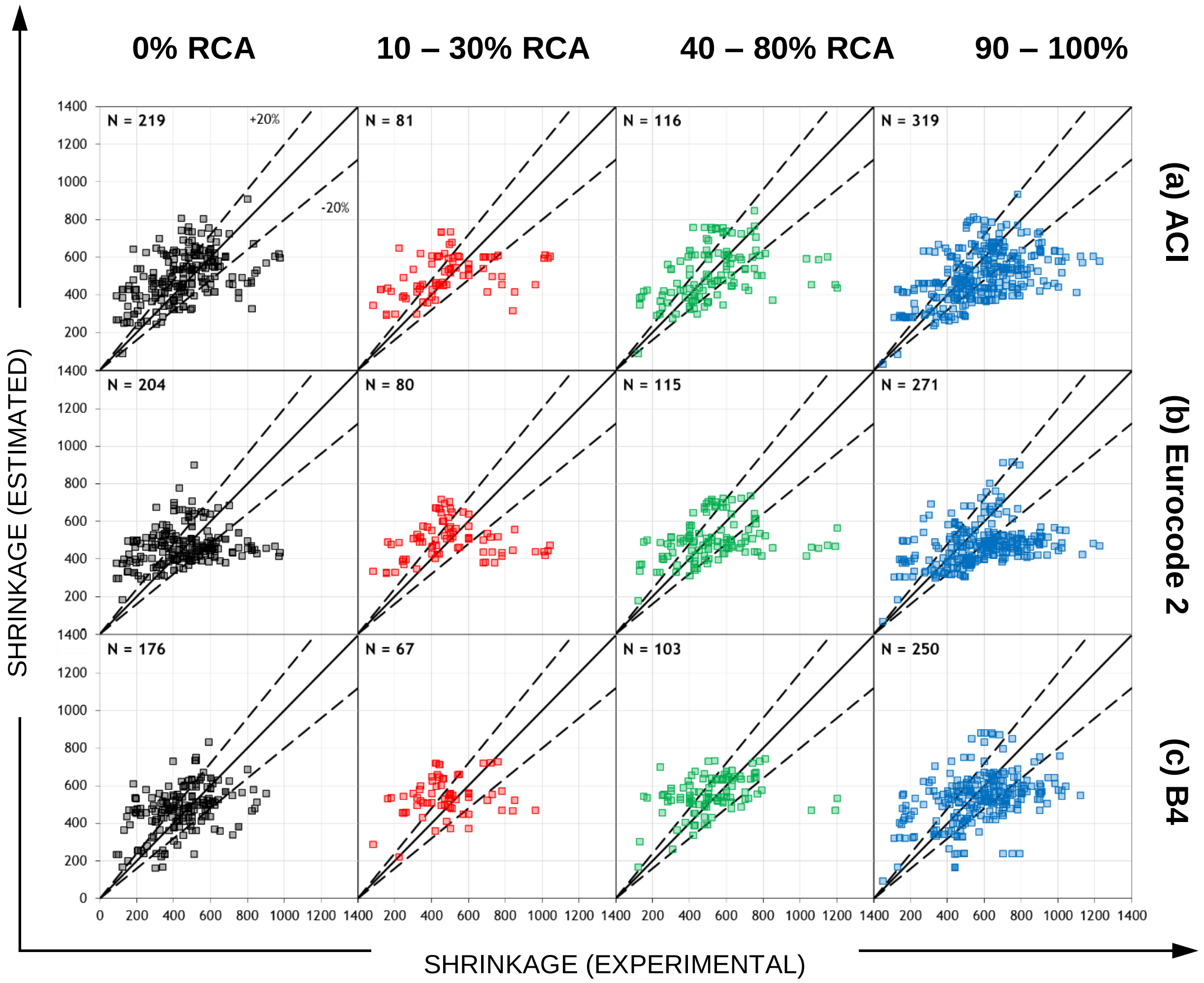


Figure 7.4 Comparison of shrinkage of concrete made with RCA between the measured values and estimated values using (a) ACI 209-2R, 2008, (b) Eurocode 2, 2004 (c) B4, 2015.

is greater than 800 µ. As the RCA content increases, the MBE values change progressively from negative (underestimating) to positive (overestimating). The RMSE values for NA and RCA concrete are about 170 and 200 µ respectively. The MAPE values for NA concrete and RCA concrete are close, varying within the region of 30%–40%. In summary, the error measures for both the NA and the RCA concrete are not too dissimilar, and are considerably high.

Table 7.7 Comparison of estimation for the shrinkage of concrete made with RSA using selected models

MODEL	**RSA, %**	**DATA SIZE**	**MBE, µ**	**RMSE, µ**	**MAPE, %**
(a) Coarse RCA					
ACI 209-2R (2008)	0	219	**+48.4**	173.3	41.4
	10 – 30	81	**+13.6**	201.2	42.8
	40 – 80	116	**-9.5**	206.5	33.6
	90 – 100	319	**-68.6**	200.5	30.8
Eurocode 2 (2004)	0	204	**+16.8**	185.9	43.9
	10 – 30	80	**+4.3**	228.5	43.6
	40 – 80	115	**-26.4**	214.5	35.7
	90 – 100	271	**-104.8**	228.6	35.1
B4 (2015)	0	176	**+31.0**	159.1	37.3
	10 – 30	67	**+63.1**	190.4	42.6
	40 – 80	103	**+32.6**	183.8	32.5
	90 – 100	250	**-44.0**	199.4	35.4
(b) Fine GCA or Fine CSA					
ACI 209-2R (2008)	0	46	**-89.3**	356.8	42.3
	10 – 30	36	**-32.8**	282.0	40.1
	40 – 80	44	**+49.8**	274.5	34.2
	90 – 100	37	**+113.4**	401.2	59.4
Eurocode 2 (2004)	0	43	**-194.8**	251.9	27.9
	10 – 30	30	**-197.7**	248.1	28.6
	40 – 80	42	**-142.3**	247.4	25.4
	90 – 100	36	**-119.8**	223.7	28.1
B4 (2015)	0	33	**+37.6**	252.0	27.2
	10 – 30	24	**-98.6**	259.9	34.1
	40 – 80	33	**+114.7**	273.9	38.1
	90 – 100	29	**+243.1**	345.9	52.2

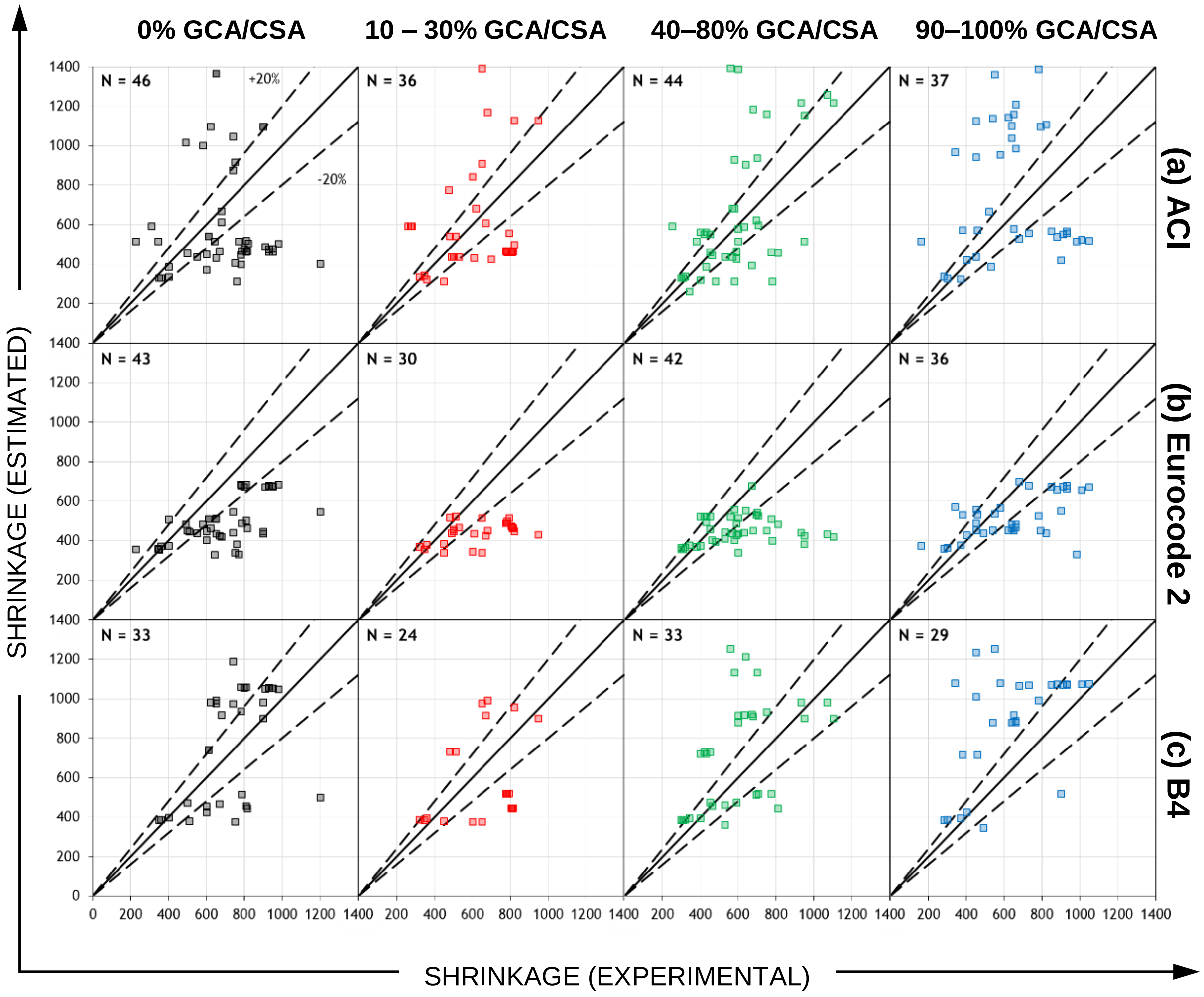


Figure 7.5 Comparison of shrinkage of concrete made with GCA/CSA between the measured values and estimated values using (a) ACI 209-2R, 2008, (b) Eurocode 2, 2004 (c) B4, 2015.

Eurocode 2 (2004): The distribution of the data is similar to that with the ACI 209-2R (2008) model. However, regardless of RCA content, the majority of the estimated values tend to congregate within the small range of 400–500 µ. The MBE error value changes progressively from a small positive value (overestimated) to a large negative value (underestimated) as the RCA content is increased. The NA concrete has an RMSE value at about 185 µ, which is slightly lower than that of RCA concrete (210–

230 µ). The MAPE values for NA and 10%–30% RCA concrete are nearly 44%, whilst those for 40%–80% and 90%–100% RCA concrete are about 35%. Overall, it appears that the model does not seem to accurately estimate the shrinkage of either NA or RCA concrete, especially when the measured value is greater than 800 µ.

B4 (2015): Compared to the previous two models, the data are generally clustered and closer to the line of equality. In addition, the data for NA and 90%–100% RCA concrete appear to be more evenly distributed along the line. However, for 10%–30% and 40%–80% RCA concrete, a considerable number of data points still fall above the +20% deviation line. The positive MBE values for NA and 10%–30% and 40%–80% RCA concretes suggest that the model tends to overestimate their shrinkage strain. On the other hand, the model works the opposite for 90%–100% RCA concrete. The RMSE value for NA concrete (159 µ) is slightly lower than that for RCA concrete (180–200 µ). However, the MAPE values for NA and RCA concretes are of similar orders, varying within 30%–45%. Although the error measures of B4 (2015) are smaller than those of the previous two models, the accuracy of the model is still considered unsatisfactory.

For GCA or CSA concrete, the main points to emerge from Figure 7.5 and Table 7.8 (b) are summarised next. It is important to point out that, as the samples of all the concretes are small, with no more than 50 data points in each, the findings should be treated as exploratory.

ACI 209-2R (2008): The data are scattered widely around the line of equality. This is particularly the case for the shrinkage results with a measured value greater than 700 µ, for which almost all the data are outside the ±20% deviation lines. It is found that the results that fall outside the +20% deviation line are from mortar specimens with about 3 months' test duration. As the GCA or CSA content increases, the MBE values progressively change from negative, being underestimated, to positive, being overestimated. Both the RMSE and the MAPE values for GCA or CSA concrete, as to be expected, are considerably high and in the range of 250–410 μ and 34%–60%, respectively. Given the high error measures, the ACI 209-2R (2008) model appears not to accurately estimate the shrinkage of concrete made with GCA or CSA.

Eurocode 2 (2004): Compared with ACI 209-2R (2008), the distribution of the data is more clustered, but there is a significant proportion of data showing deviation of more than −20%. As such, the MBE values for NA concrete and GCA or CSA concrete are all highly negative, suggesting that the model tends to underestimate the shrinkage of concrete made with NA, as well as GCA and CSA. The RMSE and MAPE values for NA concrete are not too dissimilar to those for GCA or CSA concrete, which are about 240 μ and 27%, respectively. Overall, it can be concluded that Eurocode 2 (2004) is not suitable for use to estimate the shrinkage of concrete made with GCA or CSA, because of the tendency to underestimate.

B4 (2015): The data are scattered, with two-thirds of the data points lying outside the ±20% deviation lines. Amongst the four categories of concrete, the spread of the data for 90%–100% GCA or CSA of concrete is the greatest. The MBE value changes from less positive to more positive as GCS or CSA content is increased, except for 10%–30% GCA or CSA concrete for which the value is negative. This suggests that the model tends to overestimate the shrinkage of concrete made with NA, as well as GCA or CSA. Both the RMSE and the MAPE values increase as GCA or CSA content is increased, resulting in a maximum increase of 35% and 90%, respectively, when the NA is fully replaced by GCA or CSA. Overall, the model is not fit to be used for concrete made with NA as well as GCA or CSA.

7.6 CONCLUSIONS

Two tasks are considered in this chapter. First, the elastic modulus, creep and shrinkage models given in the design codes adopted in Australia (AS 3600, 2009), Hong Kong (HKBD, 2013), Europe (Eurocode 2, 2004; *fib*, 2013), South Africa (SABS, 2000) and the United States (ACI 209-2R, 2008; ACI 318, 2014), as well as those proposed by individual researchers (B4, 2015; GL2000, 2004), are discussed. Second, the models from ACI 209-2R (2008), Eurocode 2 (2004) and B4 (2015) are selected to evaluate their accuracy in estimating the deformation of concrete made with RSA, as well as NA.

In the elastic modulus models, the equations are generally expressed as a simple power function, in which the compressive strength of concrete is the commonly used variable. Amongst the aforementioned models, only Eurocode 2 (2004) and *fib* (2013) consider the effect of aggregate type in the form of four main rock types, namely basalt, quartzite, limestone and sandstone. The density of concrete is used in the American, Australian and South African models.

The accuracy of the ACI 209-2R (2008) model in estimating the elastic modulus is inconsistent across concrete made with NA, RCA and GCA or CSA. The Eurocode 2 (2004) model can estimate the elastic modulus of NA and GCA or CSA concretes with an acceptable accuracy, but its estimation for RCA concrete tends to be high and has relatively large error values. The B4 (2015) model is generally not suitable for use in estimating the elastic modulus of either coarse RCA or fine GCA or CSA concrete, as the model tends to underestimate the values and has high error terms.

In estimating the creep of concrete, only the B4 (2015), *fib* (2013) and GL 2000 (2004) models separate the estimation into basic creep and drying creep components. The parameters used in each model are different, with dimension of concrete member, exposure to relative humidity, age at loading and loading duration being commonly used. The main omission in these models is that the aggregate effect has not been considered, except for the B4 (2015) model, in which the estimation involved the influences of aggregate type used and the aggregate/cement ratio.

The assessment of the ability of the three selected models in estimating the creep of RCA concrete may be considered as exploratory because of the small sample size and large variability in the data. Notwithstanding this, in general, the results show that the models tend to underestimate the creep of RCA concrete, but the opposite for NA concrete. The error terms of NA concrete are generally smaller than those of RCA concrete in each model.

In estimating the shrinkage of concrete, none of the models were developed to estimate all types of shrinkage. The SABS (2000) and HKBD (2013) models estimate only the drying shrinkage of concrete, whilst the other six models, namely AS 3600 (2009), Eurocode 2 (2004), *fib* (2013), B4 (2015), ACI 209-2R (2008) and GL 2000 (2004), estimate the total shrinkage, with the first four of these separating the total shrinkage into autogenous and drying shrinkage. The effects of aggregate type are considered in the B4 (2015), HKBD (2013) and AS 3600 (2009) models in estimating the drying shrinkage of concrete.

In general, the accuracy of the selected three models in estimating the shrinkage of RSA concrete as well as NA concrete is considerably poor, particularly for concrete made with GCA and CSA.

CHAPTER 8

MODELLING OF DEFORMATION OF CONCRETE

8.1 INTRODUCTION

It was shown in Chapter 7 that the errors are generally high in estimating the elastic, creep and shrinkage deformation of concrete made with recycled and secondary aggregate (RSA), as well as with natural aggregate (NA), using the three models, ACI 209-2R (2008) and Eurocode 2 (2004), which were selected because they are most commonly used in the United States and Europe, respectively, and beyond on a global scale, in designing structures, and B4 (2015), because of the prestige attached to the work done by Bazant and his team in this area.

The major discrepancy in the estimated values, particularly for time-dependent deformation, found with all of these models is considered to be due to the fact that the properties of the aggregates used, especially their stiffness, which can greatly affect the deformation properties of concrete, have not been considered properly. In some cases, although the rock type of the aggregate is considered (elastic modulus in Eurocode 2, 2004, and creep and shrinkage in B4, 2015), the approach adopted is less appropriate because of the high variation in aggregate characteristics, even within the same rock type.

This inaccurate estimation of the deformation of concrete can result in undesirable consequences, such as structural failures due to under-design or increased construction cost with negative environmental impact due to over-design and, as a result, unnecessarily high volume of cement used. Thus, models with better accuracy in estimating the deformation properties of concrete are required. This would indirectly improve the longevity of concrete structures, as well as improving their life cycle environmental impact.

This chapter presents three new empirical models for estimating separately the elastic, creep, and shrinkage deformation of concrete, which, as explained previously, are designed to work with concrete made with a wide range of aggregates, such as natural, recycled, secondary or a mixture thereof. For the proposed models to be of practical value and helpful in promoting the use of RSA in structural concrete, they have been designed to work around Eurocode 2 (2004), which is widely recognised and can evolve further with time.

All three models were developed in MATLAB version 2017a, using the built-in Statistics Toolbox and the global data that were sourced, analysed and evaluated previously in Chapter 4 (elastic modulus), Chapter 5 (creep) and Chapter 6 (shrinkage). In this chapter, the general concepts of the methodology adopted in the development of the models are first discussed, followed with the working details and equations of the developed models.

8.2 MODEL BUILDING PROCESS

As with developing any model to describe a phenomenon, it is important to consider the nature and relevance of the available knowledge on the subject. During this process, the information that emerges can help to guide how the model may possibly be developed, using either a theoretical or an empirical approach. The construction of a theoretical model requires understanding of the mechanisms and parameters that explicitly represent the processes involved. Indeed, in the case of the deformation properties of concrete, such as creep and shrinkage, the underlying mechanisms are yet to be established, so at present they are difficult, if not impossible, to address. Additionally, there are several uncertainties about the nature of the structural fabric of concrete, including micro-cracks and pores and their influence on concrete performance, which would further make the process of modelling difficult. Thus, it was concluded that at present theoretical models for estimating deformation properties of concrete accurately would not be possible. On the other hand, an empirical model, based on the evidence in the form of data collected from experimental studies, would be able to describe the deformation properties of concrete based on their relationship with various parameters. The advantage of an empirical approach is that it allows a complicated phenomenon to be expressed in a simplified, yet practical, manner. Such models are, mostly, in use in structural design codes.

Given that empirical models rely on experimental data, this study with sizeable data sourced globally (Chapter 2) and carefully characterised (Chapter 3), analysed and evaluated (Chapters 4 to 6) offered an ideal opportunity to look to this approach, as the preferred option, for developing meaningful models for predicting three main forms of deformation: modulus of elasticity, creep and shrinkage.

In general, modelling methods can be classified into two broad categories: machine learning and statistical analysis. The machine learning method that is commonly used in estimating the properties of concrete is artificial neural networks (ANN). The ANN method, however, is not suitable for this study, as the resulting model is not in an equation form, and therefore the model cannot be transferred to the structural design codes. Thus, in this study the statistical analysis method was used as the preferred option in developing all three deformation models, but for practical reasons, and to gain popularity in use, as well as to avoid reinventing the wheel, where possible this work was undertaken in a pragmatic manner, in conjunction with the latest version of Eurocode 2, dated 2004. The entire investigation was carried out in MATLAB version 2017a, relying on its built-in mathematical optimisation algorithms. The steps used in developing the models are outlined next.

Step 1: Organise the data. The data used in model building were the same as those used in Chapters 4 to 6. Criteria applied in selecting the data were, for example, that concrete was moist cured at room temperature and that its cylinder strength at 28 days was above 20 MPa, which is in compliance with Eurocode 2 (2004). The data were randomly split into two groups, using MATLAB, as (i) training data (90%) used to build the models and (ii) testing data (10%) used to evaluate the performance of the models developed.

Step 2: Identify potential variables. Examine the data (maximum, minimum and mean values) for each variable, and its distribution using histograms, to ensure that the data are not too skewed.

Step 3: Construct a nonlinear multivariate regression model. A step-wise approach was adopted in introducing a new variable at each stage and retaining those with a p-value less than 0.05. This procedure was terminated when all the variables had been tested. The adjusted coefficient of determination (R^2_{adj}) was monitored at each stage to ensure that the model was not overfitting.

Step 4: Examine the residuals graphs. If heteroscedasticity (funnel-shaped distribution) is present, transform the variables into logarithmic, power or reciprocal form and/or introduce a new variable and repeat Step 3.

Step 5: Remove unhealthy data. These are data that have a high leverage value or high Cook's distance value with an absolute value of ≥2 standardised residuals and outliers with an absolute value of ≥3 standardised residuals.

Step 6: Re-examine the residuals graphs for the presence of heteroscedasticity. If present, perform weighted least-squares (WLS) regression, whereby the weight of each data point is assigned using the inverse variance weighting method, in which the variances are obtained by forming approximate groups of replicate data based on the variable values. Examine the weighted residuals graph of the WLS regression model.

Step 7: Validate the model. Using the testing data, ensure its RMSE value and other error measures are close to that of the training data. If the difference is large, the model is considered unstable; repeat from Step 2.

Step 8: Finalise the model. Round the coefficients to the nearest whole number or to two decimal place.

8.3 PARAMETERS ADOPTED IN MODEL DEVELOPMENT

As the models developed in this study were designed with the hope that they would work in practice, the parameters that were originally used in Eurocode 2 (2004), whilst generally retained, were modified in some cases. New parameters were also introduced to better capture the deformation phenomenon. For example, (i) the water absorption of the aggregate was introduced to account for rock type with greater sensitivity in the modulus of elasticity model and as a new parameter in the creep and shrinkage models and (ii) the cement strength classes further elaborated the role of BS EN 197-1 (2011) most commonly used cementitious materials, such as fly ash, ground granulated blast furnace slag (GGBS), limestone and silica fume. In addition, new parameters that relate to the aggregate factor, in terms of aggregate size and proportion, were introduced into the models to improve their estimation accuracy. The parameters considered in developing all three models are discussed next.

(i) Aggregate Stiffness

Of the three deformation models, only the elastic modulus model in Eurocode 2 (2004) and creep and shrinkage models in B4 (2015) consider the rock type used. The rock type effect considered in these models, though it is a step in the right direction, has serious limitations; for example, it is not sensitive to many potentially significant variations within each of the - rock types. Additionally, as RSA are not covered in any of models relating to the design codes, such as Eurocode 2 (2004), it can be argued that they are acting as a barrier to specifying RSA in structural concrete applications.

To overcome such limitations and thereby encourage a more open approach to the use of all aggregates, the aggregate material effects, in terms of the two most important factors, aggregate stiffness and proportion in concrete, are considered in the construction of the new elastic modulus model. However, regarding stiffness, whilst its consideration makes scientific sense, such property has never been always quoted.

As the mechanical properties of concrete, including deformation properties, can be affected by the porosity of aggregate and, in turn, its density (specific gravity), it should be feasible to use the density of aggregate, which is more easily measured, in estimating the deformation properties of concrete. However, as the range of density of most of the materials suitable for use as aggregates in normal concrete is small (as shown in Figure 8.1), it would be better to use water absorption instead to represent aggregate stiffness in developing the models.

(ii) Aggregate Content

As RSA is more likely to be used as a partial NA replacement, instead of full NA replacement, in structural concrete, the restraint offered by two aggregates in resisting deformation would be proportional to their content in concrete. Therefore, the contents of different aggregates are adopted as one of the main parameters in estimating the elastic modulus of concrete. Additionally, a distinction is made between coarse and fine aggregates for their restraining effect on the deformation of concrete.

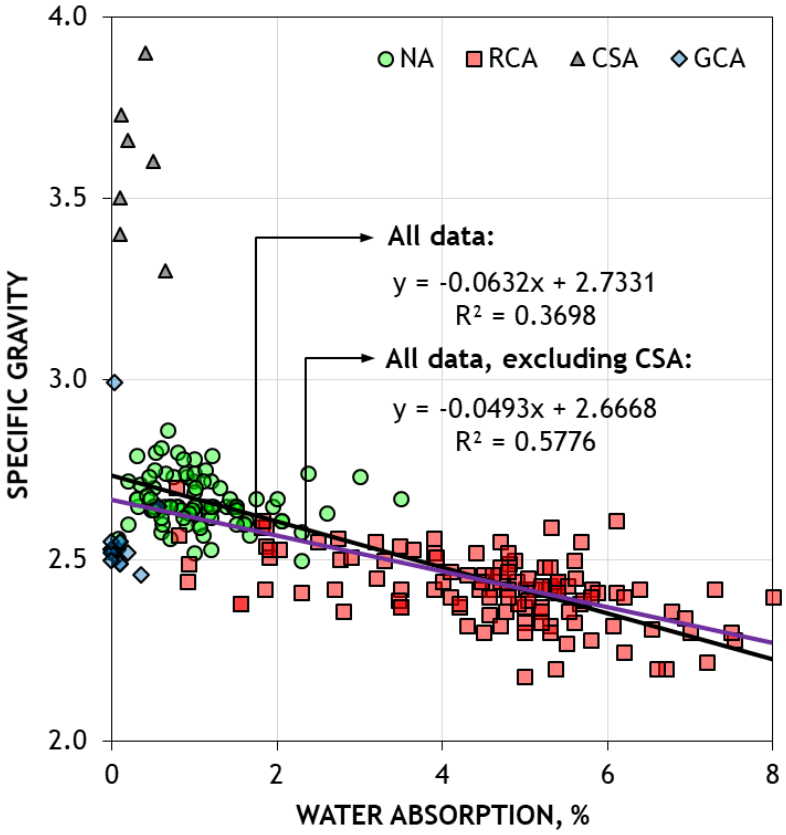


Figure 8.1 Relationship between water absorption and specific gravity of aggregate

(Data used are the same to those in Chapter 3, Sections 3.5 and 3.6)

(iii) Aggregate/Cement Ratio

As the deformation that takes place in cement paste is restrained by aggregates, their contents in a mix can affect the deformation of concrete. This combined opposite effect is perhaps best represented in terms of their proportions. This suggests that concrete with a higher aggregate/cement ratio will have a higher resistance to deformation.

(iv) Type of Cement

The deformation resistance of concrete can also be affected by the type of cement used during the hydration process. This is because different cements would achieve different 28-day strengths, with cements having a faster reaction rate developing a more hardened and rigid cement paste structure, and consequently a concrete with relatively higher resistance to deformation. Indeed, a cement factor is used in estimating creep and shrinkage in Eurocode 2 (2004). Examples of the cement types for different strength classes given in Eurocode 2 (2004) are listed in Table 8.1.

Table 8.1 Cement strength classes based on Eurocode 2 (2004)

CEMENT STRENGTH CLASSES	**CLASS S**	**CLASS N**	**CLASS R**
Cement Type as per Eurocode 2	• CEM 32.5 N	• CEM 32.5 R • CEM 42.5 N	• CEM 42.5 R • CEM 52.5 N • CEM 52.5 R
Cement Type as per this Study	• CEM 32.5N • CEM I 32.5N with ≤ 20% FA/GGBS /LS. • CEM I 32.5 R / CEM I 42.5 N with > 20% FA/GGBS/LS.	• CEM 32.5R • CEM 42.5 N • CEM I 32.5R/ CEM I 42.5 N with ≤ 20% FA/GGBS/LS. • CEM I 42.5R/ CEM I 52.5N/ CEM I 52.5R with > 20% FA/GGBS/LS.	• CEM 42.5R • CEM 52.5N • CEM 52.5R • CEM I 42.5R/ CEM I 52.5N/ CEM I 52.5R with ≤ 20% FA/GGBS/LS • CEM I 32.5R/ CEM I 42.5 N with 10% SF.

Note: FA: Fly ash, GGBS: Ground granulated blastfurnace slag, LS: Limestone, SF: Silica fume

The examples given do not implicitly refer to the use of CEM I (Portland cement) with the BS EN 197-1 (2011) materials in the family of common cements, such as fly ash (FA), ground granulated blast furnace slag (GGBS), limestone powder (LS) and silica fume (SF). Given that in lowering carbon dioxide emissions the role of BS EN 197-1

(2011) common cements is gaining importance, cement strength classes based on such cements are proposed in this study, within the strength classes S, N and R referred to in Eurocode 2 (2004). The concept of the proposed cement strength classes is that when ≤20% of FA, GGBS or LS is in composition with CEM I Portland cement, the strength class of the resulting cement would remain the same as that of CEM I Portland cement. When the content exceeds 20%, the strength class of the resulting cement would be one class lower than that of CEM I Portland cement (i.e., moving from R to N or N to S). On the other hand, when SF is used to replace 10% of CEM I Portland cement from strength Class N, the resulting cement will be considered as Class R, because of its higher rate of pozzolanic reactivity and pore-filling effect. This grouping of cements complying with BS EN 197-1 (2011).

8.4 ELASTIC MODULUS OF CONCRETE

8.4.1 The Model

The model for estimating the elastic modulus of concrete made with recycled and secondary aggregates, as well as natural aggregates, was developed using over 800 data points sourced from globally published literature and screened before use against a set of compliance requirements, such as a minimum 20-MPa cylinder strength, being moist cured, and being tested at 28 days. The selected parameters for developing the model are listed in Table 8.2, together with those of Eurocode 2 (2004) for comparison. It can be seen that a greater number of variables are used in the proposed model, compared to Eurocode 2 (2004), as well as the range of rock type and strength being widened.

Table 8.2 Comparison of parameters used in Eurocode 2 (2004) and the proposed model for elastic modulus

PARAMETER	EUROCODE 2 (2004) MODEL	PROPOSED MODEL
Rock type	Basalt, quartzite, limestone and sandstone	NA and RSA with water absorption values stated below.
Water absorption of aggregate	-	Coarse aggregate, up to 8.0% water absorption; Fine aggregate, up to 3.5% water absorption.
Proportions of aggregate used	-	✓
A/C ratio	-	3.0 to 8.5
Type of cement	-	Class S, N, R *
Compressive cylinder strength	20 to 98 MPa	20 to 105 MPa

✓ indicates that the parameter is considered in the model; * Refer to Table 8.1

The proposed model of elastic modulus, E_{cm}, consists of three components, as stated below:

$$E_{cm} = (\beta_{ca} + \beta_{fa}).\beta_{A/C}.\beta_{str} \tag{8.1}$$

where

β_{ca} *and* β_{fa} are coefficients relevant to the coarse and fine aggregates, respectively;

$\beta_{A/C}$ is a coefficient relevant to the total aggregate/cement ratio of concrete;

β_{str} is a coefficient relevant to the 28-day compressive cylinder strength.

For the coefficients relevant to coarse and fine aggregates, the corresponding Eqs. (8.2) and (8.3) consider the water absorption of the aggregates used, which marks a difference to Eurocode 2 (2004) where four natural rock types are considered. In the case in which two types of aggregate are used (for example, coarse NA is partially replaced by coarse RCA), the water absorption of the resulting aggregate is taken as a composite effect of the absorption of two materials and their proportions. This shows that the model has an ability to cope with concrete made with more than one type of aggregate, in any combination. For coarse aggregates, Eq. (8.2) is applicable for those with a maximum absorption value of 8.0%, though it is appreciated that the absorption of NA commonly used in practice is unlikely to exceed 3.5%, whilst that of RCA used for concrete is likely to be within the range of 4%–6%. For fine aggregates, Eq. (8.3) is applicable with water absorption not exceeding 3.5%, implying that fine recycled aggregates arising from construction and demolition are not considered in the proposed model, and in general the model should work with most fine NA and secondary aggregates coming mainly from metallurgical slag and glass families. These equations are given below:

$$\beta_{ca} = \begin{cases} 1.13 \times (0.91)^{w_{ca}}, & \text{for } \mathrm{w_{ca}} < 2.5\% \\ 0.95^{w_{ca}}, & \text{for } \mathrm{w_{ca}} \geq 2.5\% \end{cases} \tag{8.2}$$

$$\beta_{fa} = \begin{cases} 0.82^{\exp(w_{fa}/10)}, & \text{for } \mathrm{w_{fa}} < 1.0\% \\ 0.80^{\exp(w_{fa}/10)}, & \text{for } \mathrm{w_{fa}} \geq 1.0\% \end{cases} \tag{8.3}$$

where

w_{ca} and w_{fa} are the water absorption of coarse and fine aggregate, respectively, in %. If two types of coarse or fine aggregate are used, the water absorption of the total coarse or fine aggregate is calculated from Eq. (8.4):

$$w_{agg\_total} = \alpha_{agg1}.w_{agg1} + \alpha_{agg2}.w_{agg2} \tag{8.4}$$

where

α_{agg1} and α_{agg2} are the proportions of aggregate type 1 and aggregate type 2 to the total coarse or fine aggregate, respectively, in decimal;

w_{agg1} and w_{agg2} are the water absorption of aggregate type 1 and aggregate type 2, respectively, in %.

For the coefficient relevant to the aggregate/cement ratio, the equation is given by:

$$\beta_{A/C} = 1.04^{\log(A/C)} \tag{8.5}$$

where

A/C is the total aggregate/cement ratio of the concrete.

For the coefficient relevant to the compressive strength β_{str}, the effect of the type of cement used, as defined in Table 8.1, is taken into consideration, as given below:

$$\beta_{str} = \alpha_c.(f_{cm})^{0.22} \tag{8.6}$$

where

α_c is the cement-dependent coefficient, which is

= 7.8 for cement Class S, 8.2 for cement Class N, 8.6 for cement Class R

f_{cm}, is the 28-day compressive cylinder strength, in MPa.

8.4.2 Model Verification and Validation

Throughout the model building process, both graphical (mainly the residual plots) and numerical (statistics summary) methods were used to provide diagnostic insights of the model as well as to access its adequacy and accuracy. The standardised residual plot shown in Figure 8.2 (a) was one of the examples obtained during the process, wherein the presence of heteroscedasticity in the error (funnel-shaped distribution) was detected, which violated the assumption of constant variance. In this study, the heteroscedasticity problem was handled by performing the weighted least-squares (WLS) method, whereby the weights of the data were estimated based on the standard deviations of the elastic modulus of concrete.

The standardised residuals of the final model, using WLS and after removing unhealthy data, illustrated in Figure 8.2 (b) show that the spread of residuals has evened out, and the distribution of the residuals appears to be more homoscedastic (randomly scattered) and uncorrelated to the RSA content. Although it is shown that the residuals after the value of 38 GPa tend to be positive (estimated value < measured value), this does not appear to be of great concern as the weights of these data [Figure 8.2(c)] are less than 0.1, which has little influence in determining the coefficients of the model.

It should be mentioned that the standardised residuals plots of other parameters, such as water absorption of the aggregate, aggregate/cement ratio and compressive strength, were also found not to display any sign of heteroscedasticity (illustrations not shown to avoid repetition).

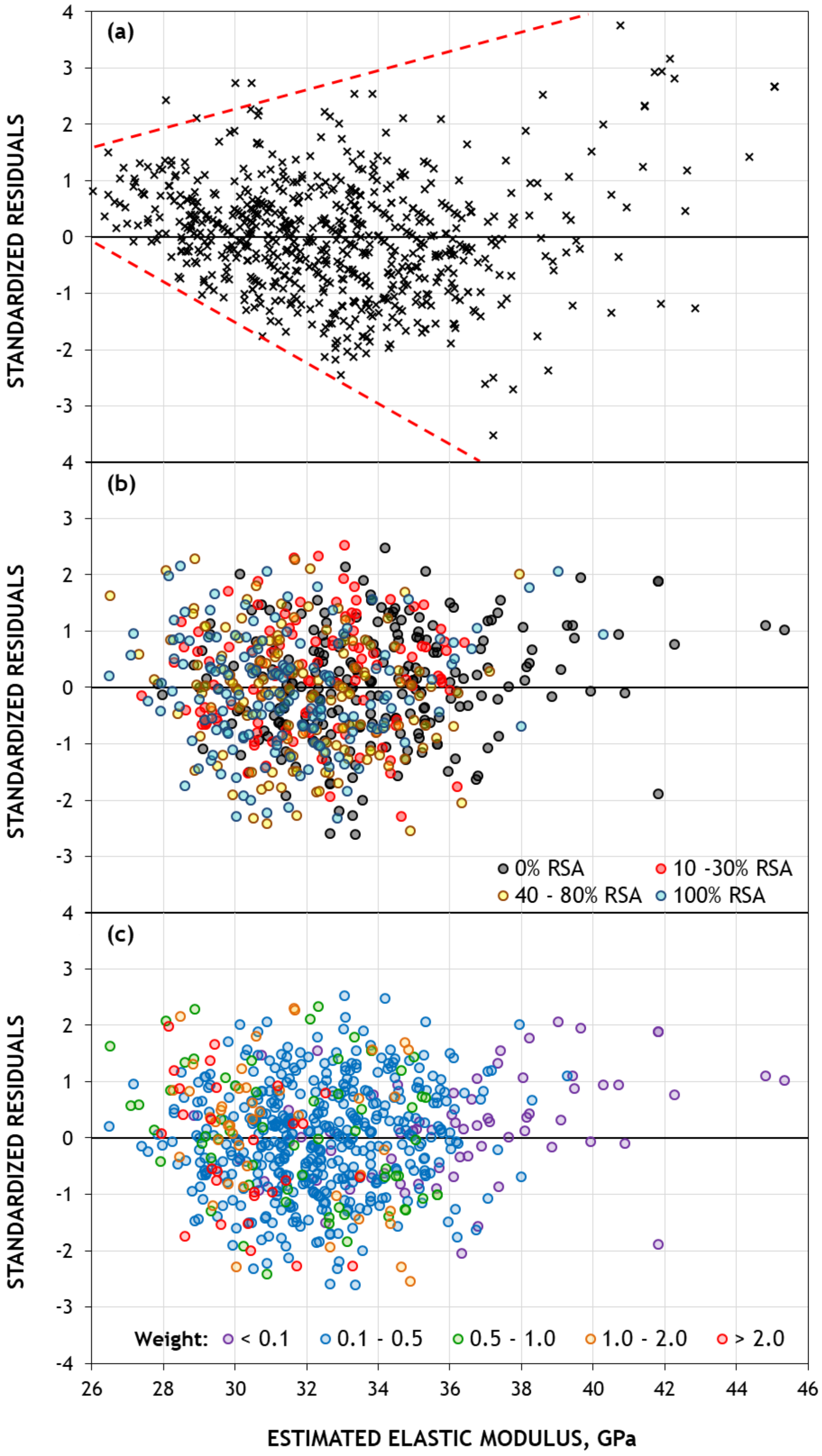


Figure 8.2 Standardised residuals against the estimated E_{cm} in (a) initial model, and (b) and (c) final model for different RSA content and weight of data, respectively

Apart from these, the reasonably symmetric shape of the histogram plot [Figure 8.3 (a)] and the straight line in the normal probability plot [Figure 8.3 (b)] of the standardised residuals suggest that the errors of the proposed model are normally distributed.

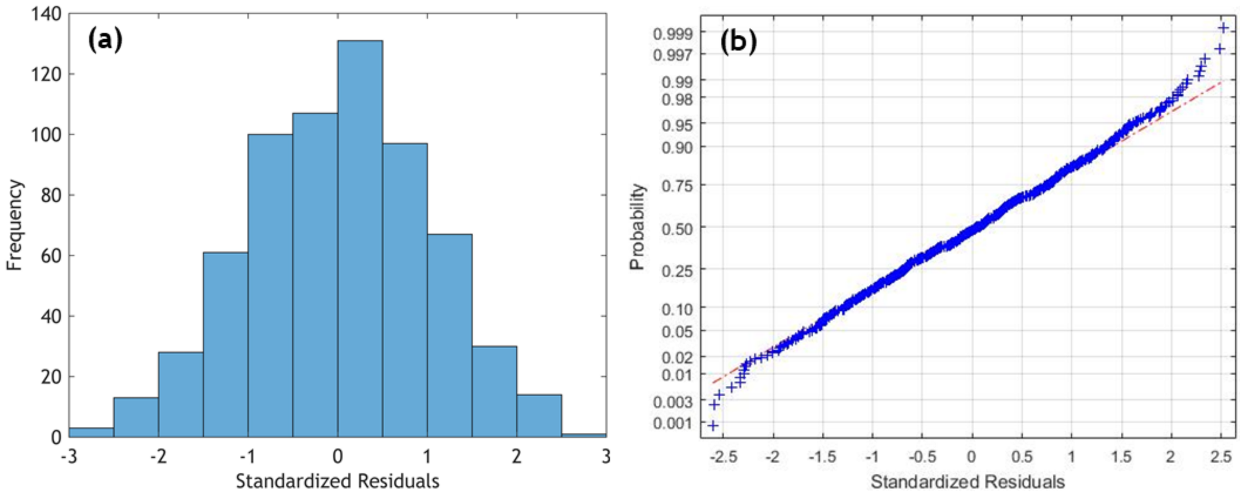


Figure 8.3 (a) Histogram and (b) Normal probability plot of standardised residuals of the proposed elastic modulus model

In addition, the measured vs estimated elastic modulus data were plotted [Figure 8.4 (a)], showing that all the data points, particularly within the normal working range of 25–40 GPa in structural designs, are close to the line of equality. Again, data that significantly deviate from the line of equality carry low weight [Figure 8.4 (b)]. Comparing Figure 8.3 (a) with Figure 7.1 (for concrete made with 0%–100% coarse RCA) and Figure 7.2 (for concrete made with 0%–100% fine GCA and CSA), it can be seen that, in this case, the proposed model has a higher estimation accuracy than that achieved with the Eurocode 2 (2004), ACI 209-2R (2008) and B4 (2015) models.

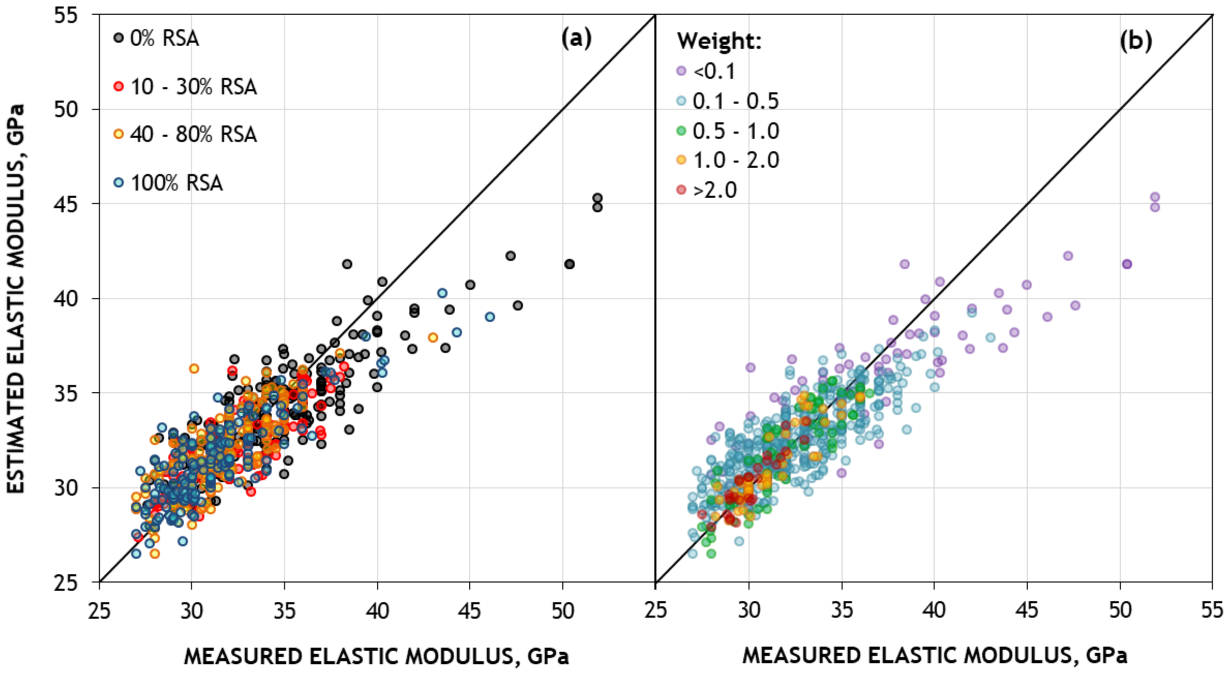


Figure 8.4 Measured elastic modulus versus estimated elastic modulus using the proposed model for (a) different RSA content and (b) weight of data

The statistics indicators and error measures calculated for the proposed model are given in Table 8.3, together with those for the Eurocode 2 (2004) model, which were previously reported in Chapter 7 in Table 7.3, for comparison. The R^2 and adjusted R^2 values of the model are both over 0.7 and close to each other, indicating that the model is reasonably good and not overfitting. The high f-statistic value and zero p-value of the model also suggest that the parameters used in the models are statistically significant. The proposed model was validated using the testing data, from which the error measures were found to be close to those of the training data. This suggests that the model is stable and not biased to the training data. Additionally, in comparison to the Eurocode 2 (2004) model, even though the two do not have the same population size, the proposed model gives low error measure values.

Table 8.3 Statics indicators and error measures of the proposed elastic modulus model

	PROPOSED MODEL		EUROCODE 2 (2004) MODEL	
	Training Data	Testing Data	All Data *	Testing Data **
Number of Data	730	81	1067	81
R-Squared	0.729	-	-	-
Adj. R-Squared	0.726	-	-	-
f-statistic	3.76×10^4	-	-	-
p-value	0	-	-	-
MBE, GPa	-0.7	+0.9	+2.2	+1.6
RMSE, GPa	1.94	2.29	5.00	3.57
MAPE, %	8.2	9.3	12.7	10.1

* The error measures were the average values reported in Table 7.3; ** Same as those used in the proposed model

8.5 CREEP OF CONCRETE

8.5.1 The Model

The proposed model is suitable for use in estimating the creep coefficient of concrete made with natural aggregate, recycled concrete aggregate, and any combination thereof. As for secondary aggregates such as those derived from the glass and slag families, although they have not been tested at present because of a lack of data, it is assumed that the proposed model is still applicable to these aggregates as the hardness of these materials is, by and large, similar to that of fine natural aggregate (see Chapter 3, Section 3.7).

Table 8.4 compares the parameters used in the Eurocode 2 (2004) model and the proposed model. This shows that the proposed model contains the parameters used

Table 8.4 Comparison of parameters used in Eurocode 2 (2004) and the proposed model for creep coefficient

PARAMETER	EUROCODE 2 (2004) MODEL	PROPOSED MODEL
Cement type	Class S, N, R	Class S, N, R*
Aggregate type	-	NA and RSA with water absorption stated below.
Water absorption of aggregate	-	Coarse aggregate, up to 8.0% water absorption; Fine aggregate, up to 3.5% water absorption.
Proportion of aggregate used	-	✓
Aggregate/cement ratio	-	3.0 – 7.0
Compressive cylinder strength	20 – 98 MPa	20 – 98 MPa
Dimensions of member	✓	✓
Temperature	✓	✓
Relative humidity	✓	✓
Age at loading	✓	✓
Loading duration	✓	✓

✓ indicates that the parameter is considered in the model; * Refer to Table 8.1

in Eurocode 2 (2004), with additional factors, aggregate type in terms of their proportions and water absorption, as well as the aggregate/cement ratio of concrete.

The equations of the proposed models are given in Eqs. (8.7) to (8.23). Apart from the equations for aggregate factors and aggregate/cement ratio, all other equations relevant to compressive strength, concrete age, ambient humidity and dimensions of the member were deliberately kept the same as those of Eurocode 2 (2004). However, some modifications were made to better represent the effects of compressive strength and ambient humidity, as well as in estimating the short-term creep more accurately.

In the proposed model, the creep coefficient of concrete, $\boldsymbol{\varphi(t,t_0)}$, subjected to 30%–40% of its compressive strength is given by:

$$\varphi(t,t_0) = \varphi_0.\beta_c\,(t,t_0) \tag{8.7}$$

where

$\boldsymbol{\varphi_0}$ is the notional creep coefficient [see Eq. (8.8)];

$\boldsymbol{\beta_c(t,t_0)}$ is a coefficient to describe the development of creep with time $\boldsymbol{t}$ after loading at $\boldsymbol{t_0}$ (see Eq. 8.19).

The notional creep coefficient, $\boldsymbol{\varphi_0}$**,** is affected by, aggregate factor, aggregate/ cement ratio, concrete strength, ambient relative humidity, and age at loading, which is expressed as:

$$\varphi_0 = \varphi_{RH}.\beta_{agg}.\beta_{A/C}.\beta(f_{cm}).\beta(t_0) \tag{8.8}$$

where

$\boldsymbol{\varphi_{RH}}$ is a relative humidity factor [see Eqs. (8.9) and (8.10)];

$\boldsymbol{\beta_{agg}}$ is the coefficient relevant to the aggregate factor [see Eq. (8.12)];

$\boldsymbol{\beta_{A/C}}$ is the coefficient relevant to the aggregate/cement ratio [see Eq. (8.13)];

$\boldsymbol{\beta(f_{cm})}$ is the coefficient relevant to the concrete strength [see Eq. (8.14)];

$\boldsymbol{\beta(t_0)}$ is the coefficient for the effect of concrete age at loading $\boldsymbol{t_0}$ [see Eq. (8.15)].

The ambient relative humidity factor, ***φ_{RH},*** is calculated as follows:

$$\varphi_{RH} = \begin{cases} \alpha_{RH}.\left[1+\dfrac{1-RH/100}{0.1\sqrt[3]{h_0}}\right], & \text{for } \mathrm{f_{cm}}\leq 35\mathrm{MPa} \qquad (8.9) \\ \alpha_{RH}.\left[1+\dfrac{1-RH/100}{0.1\sqrt[3]{h_0}}.\alpha_1\right].\alpha_2, & \text{for } \mathrm{f_{cm}}>35\mathrm{MPa} \qquad (8.10) \end{cases}$$

where

RH is the relative humidity of the ambient environment, in %;

α_1 and ***α_2*** are coefficients that affect the concrete strength [see Eq. (8.23)];

α_{RH} is the coefficient depending on the ambient environment, where

= 1.00 for <60 %RH and 0.88 for ≥60 %RH;

h_0 is the notional size of the member, in mm, as given in Eq. (8.11).

$$h_0 = {}^{2A_C}/_{u} \qquad (8.11)$$

where

A_c is the cross-sectional area of the member, in mm^2;

u is the perimeter of the member in contact with the atmosphere, in mm.

The coefficient relevant to the aggregate factor, ***β_{agg}***, is calculated as follows:

$$\beta_{agg} = 1.03^{[w_{ca}+\exp(w_{fa}/10)]} \qquad (8.12)$$

where

w_{ca} and ***w_{fa}*** are the water absorption of coarse aggregate and fine aggregate, respectively, in %. If two types of coarse or fine aggregate are used, the water absorption of the total coarse or fine aggregate may be calculated from Eq. (8.13):

$$w_{agg\_total} = \alpha_{agg1}.w_{agg1} + \alpha_{agg2}.w_{agg2} \tag{8.13}$$

where

$\boldsymbol{\alpha_{agg1}}$ and $\boldsymbol{\alpha_{agg2}}$ are the proportion of aggregate type 1 and aggregate type 2, respectively, to the total coarse or fine aggregate, in decimal;

$\boldsymbol{w_{agg1}}$ and $\boldsymbol{w_{agg2}}$ are the water absorption of aggregate type 1 and aggregate type 2, respectively, in %.

The coefficient relevant to the aggregate/cement ratio, $\boldsymbol{\beta_{A/C}}$, is given by:

$$\beta_{A/C} = 0.82^{\log(A/C)} \tag{8.14}$$

where

A/C is the total aggregate/cement ratio of concrete.

The coefficient relevant to the compressive strength of concrete, $\boldsymbol{\beta(f_{cm})}$, is given in Eq. (8.15), which is influenced by the type of cement used:

$$\beta(f_{cm}) = \alpha_c.\left(\frac{16.8}{\sqrt{f_{cm}}}\right) \tag{8.15}$$

where

$\boldsymbol{\alpha_c}$ is the cement-dependent coefficient, as given in Table 8.5;

$\boldsymbol{f_{cm}}$ is the 28-day compressive cylinder strength, in MPa.

Table 8.5 Cement dependent coefficients used in the creep coefficient model

EQUATION	COEFFICIENT	CLASS S*	CLASS N*	CLASS R*
8.15	α_c	1.2	1.2	2.4
8.17	α	-1.0	0	+1.0

* Refer to Table 8.1 for the cement types in each class

The concrete age coefficient, ***β(t₀)***, used in the Eq. (8.8), is given below:

$$\beta(t_0) = \frac{1}{(0.1 + {t_0}^{0.2})} \tag{8.16}$$

where

t_0 is the age of the concrete at loading, in days.

The age of concrete at loading, t_0, can be adjusted depending on the type of cement used, as well as the temperature to which the concrete is subjected (within the range of 0°C–80°C). However, it should be noted that the proposed model has been tested only for concrete made with RCA subjected to temperature in the range of 20°C–30°C. This adjustment is expressed as:

$$t_0 = t_{0,T}.\left[\frac{9}{2 + {t_{0,T}}^{1.2}} + 1\right]^{\alpha} \geq 0.5 \tag{8.17}$$

$$t_T = \sum_{i=1}^{n} e^{-(4000/[273+T(\Delta t_i)]-13.65)}.\Delta t_i \tag{8.18}$$

where

$t_{0,T}$ is the temperature-adjusted age of the concrete at loading, in days, according to Eq. (8.18);

α is a cement-dependent power term, as given in Table 8.5;

t_T is the temperature-adjusted concrete age, which replaces ***t*** in the corresponding equations;

$T(\Delta t_i)$ is the temperature during the time period ***Δt_i***, in °C;

Δt_i is the number of days during which a temperature *T* prevails.

The coefficient to describe the development of creep with time ***t*** after loading, ***$\beta_c(t,t_0)$***, used in Eq. (8.7), is calculated below:

$$\beta_c(t,t_0) = \begin{cases} 0.90\left[\dfrac{(t-t_0)}{\beta_H+(t-t_0)}\right]^{0.3}, \text{for t<180 days} & (8.19) \\ \left[\dfrac{(t-t_0)}{\beta_H+(t-t_0)}\right]^{0.3}, \quad \text{for t} \geq \text{180 days} & (8.20) \end{cases}$$

where

t is the age of the concrete at the moment considered, in days;

$t - t_0$ is the unadjusted duration of loading, in days;

β_H is a coefficient depending on the relative humidity (***RH*** in %) and the notional member size [***h_0*** from Eq. (8.11)], as given below:

$$\beta_H = \begin{cases} 1.5[1+(0.012RH)^{18}]h_0 + 250 \leq 1500, \quad \text{for } \mathrm{f_{cm}} \leq 35\mathrm{MPa} & (8.21) \\ 1.5[1+(0.012RH)^{18}]h_0 + 250\alpha_3 \leq 1500\alpha_3, \text{for } \mathrm{f_{cm}} > 35\mathrm{MPa} & (8.22) \end{cases}$$

where

α_1 *to* ***α_3*** are coefficients that affect the concrete strength, as given below:

$$\alpha_1 = \left[\frac{35}{f_{cm}}\right]^{0.7} \qquad \alpha_2 = \left[\frac{35}{f_{cm}}\right]^{0.2} \qquad \alpha_3 = \left[\frac{35}{f_{cm}}\right]^{0.5} \qquad (8.23)$$

8.5.2 Model Verification and Validation

The presence of outlier, leverage and influence points in the training data was assessed during the development of the model. No bad leverage points were detected, but approximately 4% of the data, which came from a single study, were identified as outlier and influence points.

As a routine process, the residuals plots of the model were checked during the development of the model. The constant variance assumption of the errors of the proposed model holds, as its standardised residuals plot does not display any clear pattern of heterogeneity (Figure 8.5). The same observations were also made in the standardised residuals plots for other parameters. The normality of the errors of the proposed model was checked, as presented in the form of histogram and normal probability plots as shown in Figure 8.6 (a) and (b), respectively. In general, both plots show an approximate symmetrical and straight-line pattern, although the lower tail in the normal probability plot departs from the fitted line (known as long-tailed in statistical terms). Given that the creep test itself is difficult to perform and tends to carry high measurement errors, the proposed model is considered acceptable within the confines of the data available and can be refined as further data become available.

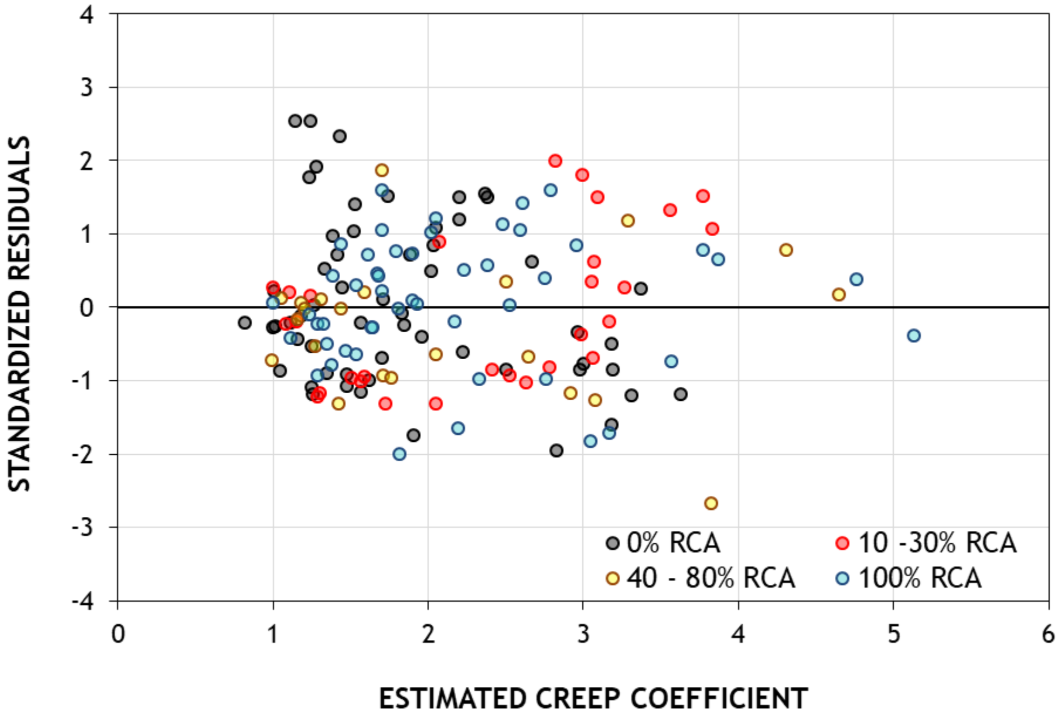


Figure 8.5 Standardised residuals against the estimated creep coefficient

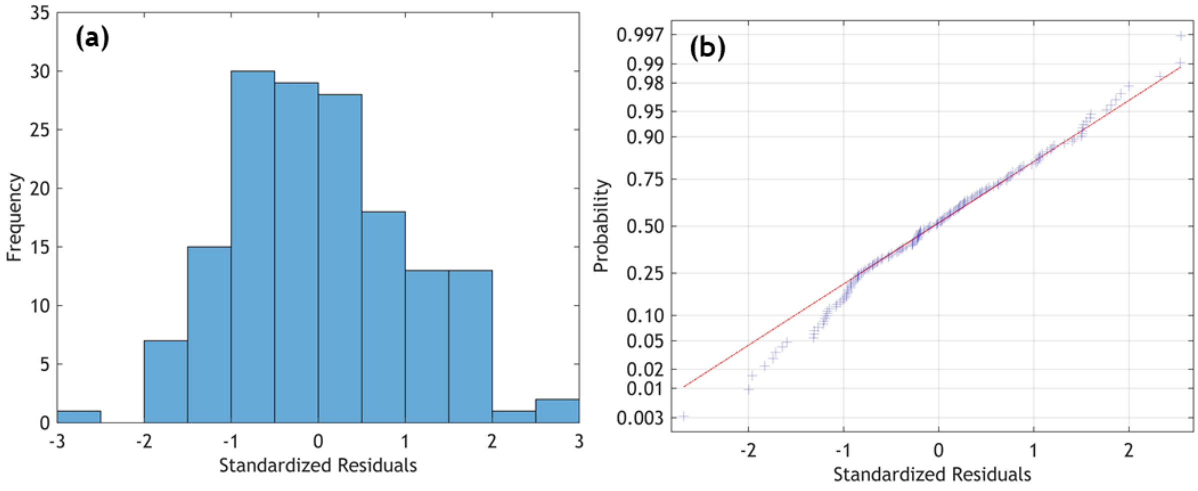


Figure 8.6 (a) Histogram and (b) Normal probability plot of standardised residuals of the proposed creep model

Figure 8.7 compares the measure creep coefficient of concrete to its corresponding estimated value using the proposed model. This shows that the data points are reasonably close to the line of equality, but those with measured value close to 1.5 or beyond 4 tend to fall above or below the line. Such observation does not present a great concern, as the data for these concrete mixes were recorded only up to 5 months. However, it should be mentioned that the proposed model allows for the estimation of short-term creep of concrete, for a period of less than 6 months.

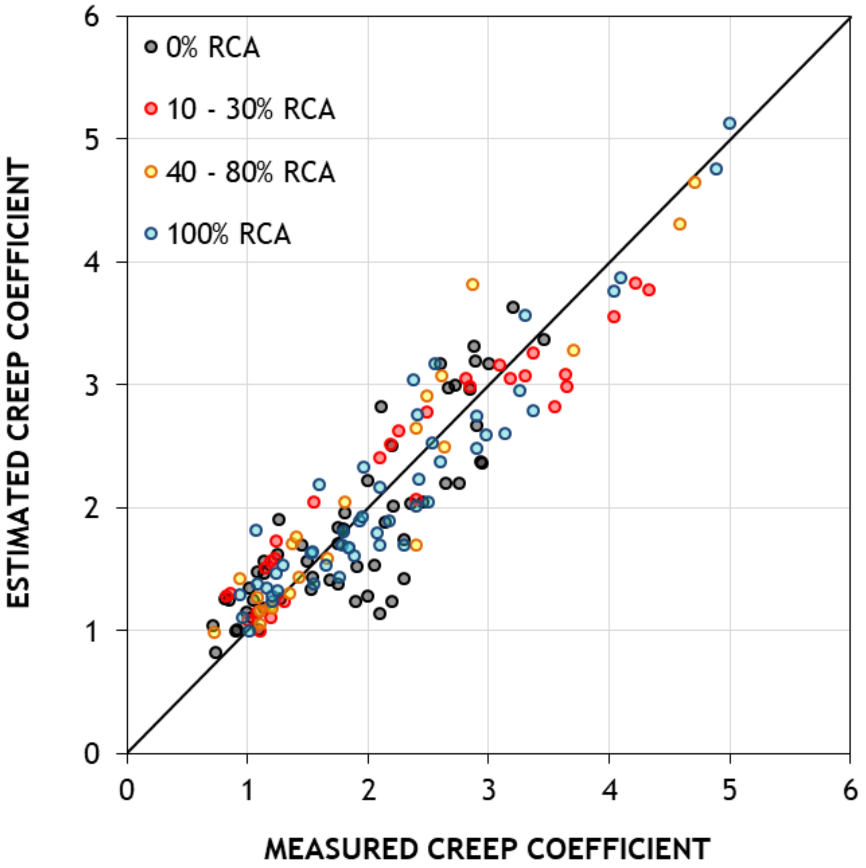


Figure 8.7 Measured creep coefficient versus estimated creep coefficient using the proposed creep model

Table 8.6 summarises the statistics indicators and error measures of the proposed model, as well as those of the Eurocode 2 (2004) model, which were previously reported in Table 7.6 of Chapter 7. The R^2 and adjusted R^2 values of the model are close to each other and both are over 0.8, suggesting that the model is not overfitting and has reasonably good estimation ability. The high f-statistic value and low p-value indicate that the parameters used have collectively significant influence on the model.

Table 8.6 Statics indicators and error measures of the proposed creep model

	PROPOSED MODEL		EUROCODE 2 (2004) MODEL	
	Training Data	Testing Data	All Data *	Testing Data **
Number of Data	153	17	170	17
R-Squared	0.851	-	-	-
Adj. R-Squared	0.845	-	-	-
f-statistic	801	-	-	-
p-value	2.19×10^{-115}	-	-	-
MBE, GPa	+0.09	-0.05	-0.13	+0.06
RMSE, GPa	0.378	0.383	1.221	0.585
MAPE, %	22.4	24.5	52.1	31.7

* The error measures were the average values reported in Table 7.6; ** Same as those used in the proposed model

The error measures of the testing data are close to those of the training data, suggesting that the model is valid and not biased towards the training data. The proposed model also shows higher creep estimation accuracy than the Eurocode 2 (2004) model.

8.6 SHRINKAGE OF CONCRETE

8.6.1 The Model

Stemming from the Eurocode 2 (2004) model, the proposed model was developed to estimate the total shrinkage of concrete made with natural, recycled and secondary aggregates, as well as the combination thereof. Although the total shrinkage consists of many forms that concrete experiences during its service life, in practice, only autogenous shrinkage and drying shrinkage are considered in structural design such as in Eurocode 2 (2004). This is adopted in the estimation of the total shrinkage of concrete in the proposed model.

The calculation of autogenous shrinkage is kept similar to that of Eurocode 2 (2004), as it is usually very small compared to drying shrinkage (Neville, 1995), and an examination of the small volume of data available did not justify exploring new avenues in this respect. As for the drying shrinkage, unlike Eurocode 2 (2004), the roles of aggregate stiffness in the form of its absorption and aggregate content in the form of the aggregate/cement ratio are considered together with modified factors for strength, age and relative humidity.

Table 8.7 compares the parameters used, as well as their range for the proposed model, compared to that of Eurocode 2 (2004).

In the proposed model, the total shrinkage strain of concrete, $\boldsymbol{\varepsilon}_{cs}$, is the sum of autogenous shrinkage and drying shrinkage, as given by:

Table 8.7 Comparison of parameters used in Eurocode 2 (2004) and the proposed model for shrinkage

PARAMETER	Eurocode 2 (2004) MODEL	PROPOSED MODEL
Cement type	Class S, N, R	Class S, N, R*
Aggregate type	-	NA and RSA with water absorption stated below.
Water absorption of aggregate	-	Coarse aggregate, up to 8.0% water absorption; Fine aggregate, up to 3.5% water absorption.
Aggregate/cement ratio	-	2.0 to 9.0
Compressive cylinder strength	20 - 98 MPa	20 - 98 MPa
Dimension of member	✓	✓
Ambient relative humidity	20 - 100 %RH	40 – 80 %RH
Age at the beginning of drying	✓	✓
Age at the moment considered	✓	✓

✓ indicates that the parameter is considered in the model; * Refer to Table 8.1

$$\varepsilon_{cs} = \varepsilon_{ca} + \varepsilon_{cd} \tag{8.24}$$

where

$\boldsymbol{\varepsilon_{ca}}$ is the autogenous shrinkage strain, in μ, as given in Eq. (8.25);

$\boldsymbol{\varepsilon_{cd}}$ is the drying shrinkage strain, in μ, as given in Eq. (8.28).

The autogenous shrinkage strain of concrete, $\boldsymbol{\varepsilon_{ca}}$, at age of concrete ***t*** is given by:

$$\varepsilon_{ca}(t) = \beta_{as}(t)\varepsilon_{ca}(\infty) \tag{8.25}$$

where

$\beta_{as}(t)$ is the time-dependent coefficient to describe the development of autogenous shrinkage, as given in Eq. (8.26);

$\varepsilon_{ca}(\infty)$ is the final value of autogenous shrinkage, as given in Eq. (8.27).

$$\beta_{as}(t) = 1 - e^{(-0.2t^{0.5})} \tag{8.26}$$

$$\varepsilon_{ca}(\infty) = 2.5(f_{ck} - 10) \tag{8.27}$$

where

t, is the age of concrete at the moment considered, in days;

f_{ck} is the characteristic compressive cylinder strength at 28 days, in MPa.

The drying shrinkage strain of concrete, **ε_{cd}**, at age of concrete **t** is given by:

$$\varepsilon_{cd}(t) = \beta_{ds}(t, t_s).k_h.\varepsilon_{cd,0} \tag{8.28}$$

where

$\beta_{ds}(t)$ is the time-dependent coefficient to describe the development of drying shrinkage, as given in Eqs. (8.29) to (8.32);

k_h is the coefficient depending on the notional size of the member, **h_0**;

$\varepsilon_{cd,0}$ is the basic drying shrinkage strain, as given in Eq. (8.34).

For the time-dependent coefficient **$\beta_{ds}(t)$** the equation was designed to consider the effect of moist curing duration and to allow for better estimation of short-term shrinkage. These are given by:

$$\beta_{ds}(t,t_s) = \begin{cases} \dfrac{\alpha_{c1}.(t-t_s)}{(t-t_s)+0.04\sqrt{h_0^3}}, \text{ for } t_s \leq 7\text{days, (t}_\text{s}\text{-t)<180 days} & (8.29) \\ \dfrac{1.08(t-t_s)}{(t-t_s)+0.04\sqrt{h_0^3}}, \text{ for } t_s > 7\text{days, (t}_\text{s}\text{-t)<180 days} & (8.30) \\ \dfrac{1.17(t-t_s)}{(t-t_s)+0.04\sqrt{h_0^3}}, \text{ for } t_s \leq 7\text{days, (t}_\text{s}\text{-t)}\geq\text{180 days} & (8.31) \\ \dfrac{(t-t_s)}{(t-t_s)+0.04\sqrt{h_0^3}}, \text{ for } t_s > 7\text{days, (t}_\text{s}\text{-t)}\geq\text{180 days} & (8.32) \end{cases}$$

where

α_c is the cement-dependent coefficient given in Table 8.9;

t is the age of the concrete at the moment considered, in days;

t_s is the age of the concrete at the beginning of drying (when curing ceased),in days;

h_0 is the notional size of the cross section of the member, in mm, where:

$$h_0 = {}^{2A_c}/_{u} \tag{8.33}$$

where

A_c is the cross-sectional area of the member, in mm^2;

u is the perimeter of that part of the cross section that is exposed to drying, in mm.

The values of coefficient **k_h** are given in Table 8.8. Linear interpolation may be used to find the value between two **h_o** values in the table.

Table 8.8 Values of **k_h** used in Eq. (8.28)

h_0	≤ 100	200	300	≥ 500
k_h	1.0	0.85	0.75	0.70

The basic shrinkage strain, $\varepsilon_{cd,0}$, is given by:

$$\varepsilon_{cd,0} = 0.85\left[(220 + 110.\alpha_{ds1}).\left[exp\left(-\alpha_{ds2}.\frac{f_{cm}}{f_{cm0}}\right)\right].\alpha_{c2}\right].(\beta_{ca} + \beta_{fa}).\beta_{A/C}.\beta_{RH} \quad (8.34)$$

where

α_{ds1}, α_{ds2} and α_{c2} are cement-dependent coefficients, as given in Table 8.9;

f_{cm} is the 28-day compressive cylinder strength, in MPa;

f_{cmo} is a constant value of 10 MPa;

β_{ca} and β_{fa} are coefficients relevant to the coarse aggregate and fine aggregate, respectively, given in Eqs. (8.37) to (8.40);

$\beta_{A/C}$ is a coefficient relevant to the aggregate/cement ratio, given in Eqs. (8.42) to (8.45);

β_{RH} is a coefficient relevant to the ambient humidity, given in Eq. (8.46).

Table 8.9 Cement dependent coefficients used in the proposed shrinkage model

EQUATION	COEFFICIENT	CLASS S*	CLASS N*	CLASS R*
8.29	α_{c1}	1.27	1.27	1.09
8.34	α_{ds1}	3	4	6
8.34	α_{ds2}	0.13	0.12	0.11
8.34	α_{c2}	0.64	0.60	0.56
8.42	α_{c3}	0.80	0.80	0.68
8.43	α_{c4}	0.72	0.72	0.65

The aggregate factor is separated for coarse aggregate and fine aggregate, as given in Eqs. (8.37) to (8.40). For coarse aggregate, Eqs. (8.37) and (8.38) are applicable for aggregates with a maximum water absorption value of 8.0%, whilst for fine aggregate, Eqs. (8.39) and (8.40) is applicable for aggregates with a maximum water absorption value of 3.5%.

These aggregate factor, for coarse and fine aggregate, is given by:

$$\beta_{ca} = \begin{cases} 1.02^{w_{ca}}, & \text{for } \mathrm{w_{ca}} < 2.0\% \quad (8.37) \\ 1.06^{w_{ca}}, & \text{for } \mathrm{w_{ca}} \geq 2.0\% \quad (8.38) \end{cases}$$

$$\beta_{fa} = \begin{cases} 1.05^{\exp(w_{fa}/10)}, & \text{for } \mathrm{w_{fa}} < 1.0\% \quad (8.39) \\ 1.23^{\exp(w_{fa}/10)}, & \text{for } \mathrm{w_{fa}} \geq 1.0\% \quad (8.40) \end{cases}$$

where

w_{ca} and ***w_{fa}*** are the water absorption of coarse aggregate and fine aggregate, respectively, in %. If two types of coarse or fine aggregate are used, the water absorption of the total coarse or fine aggregate may be calculated from Eq. (8.41):

$$w_{agg\_total} = \alpha_{agg1}.w_{agg1} + \alpha_{agg2}.w_{agg2} \quad (8.41)$$

where

α_{agg1} and ***α_{agg2}*** are the proportions of aggregate type 1 and aggregate type 2 to the total coarse or fine aggregate, respectively, in decimal;

w_{agg1} and ***w_{agg2}*** are the water absorption of aggregate type 1 and aggregate type 2, respectively, in %.

The aggregate/cement ratio coefficient, ***$\beta_{A/C}$,*** depends on the type of cement used and the compressive cylinder strength of the concrete, which can be calculated as follows:

$$\beta_{A/C} = \begin{cases} {\alpha_{c3}}^{\log(A/C)}, & \text{for A/C} < 5,\ \text{f}_{\text{cm}} \leq 35\text{MPa} \quad (8.42) \\ {\alpha_{C4}}^{\log(A/C)}, & \text{for A/C} \geq 5,\ \text{f}_{\text{cm}} \leq 35\text{MPa} \quad (8.43) \\ 0.78^{\log(A/C)}, & \text{for A/C} < 5,\ \text{f}_{\text{cm}} > 35\text{MPa} \quad (8.44) \\ 0.74^{\log(A/C)}, & \text{for A/C} \geq 5,\ \text{f}_{\text{cm}} > 35\text{MPa} \quad (8.45) \end{cases}$$

where

α_{c3} and ***α_{c4}*** are the cement-dependent coefficients, as given in Table 8.9;

A/C is the total aggregate/cement ratio of concrete.

The ambient humidity coefficient, ***β_{RH}***, can be calculated from Eq. (8.46).

$$\beta_{RH} = \left\{1.55\left[1 - \left(\frac{RH}{RH_0}\right)^3\right]\right\}^{\alpha_{RH}} \tag{8.46}$$

where

RH is the ambient relative humidity, in %;

RH_0 is a constant relative humidity value at 100%;

α_{RH} is a power term depending on the ambient relative humidity, where

= 0.6 for ≥60% RH and 1.0 for <60% RH.

8.6.2 Model Verification and Validation

In the development of the model, about 3% of the training data were identified as unhealthy and excluded owing to (i) having standardised residuals with absolute values higher than 3 or (ii) having high leverage or Cook's distance values combined with standardised residuals with absolute values higher than 2. The majority of the excluded data were of the former case.

The plot of standardised residuals vs the estimated shrinkage strains using the proposed model is shown in Figure 8.8. The randomly scattered pattern observed in the residuals plot suggests that the standardised residuals are uncorrelated with the estimated values, as well as the proportions of RSA in concrete. A similar pattern was observed in the standardised residuals plots for other parameters. Apart from these, the approximate symmetrical shape of the histogram [Figure 8.9 (a)] and approximate straight line in the normal probability plot [Figure 8.9 (b)] indicate that the residuals have a normal distribution.

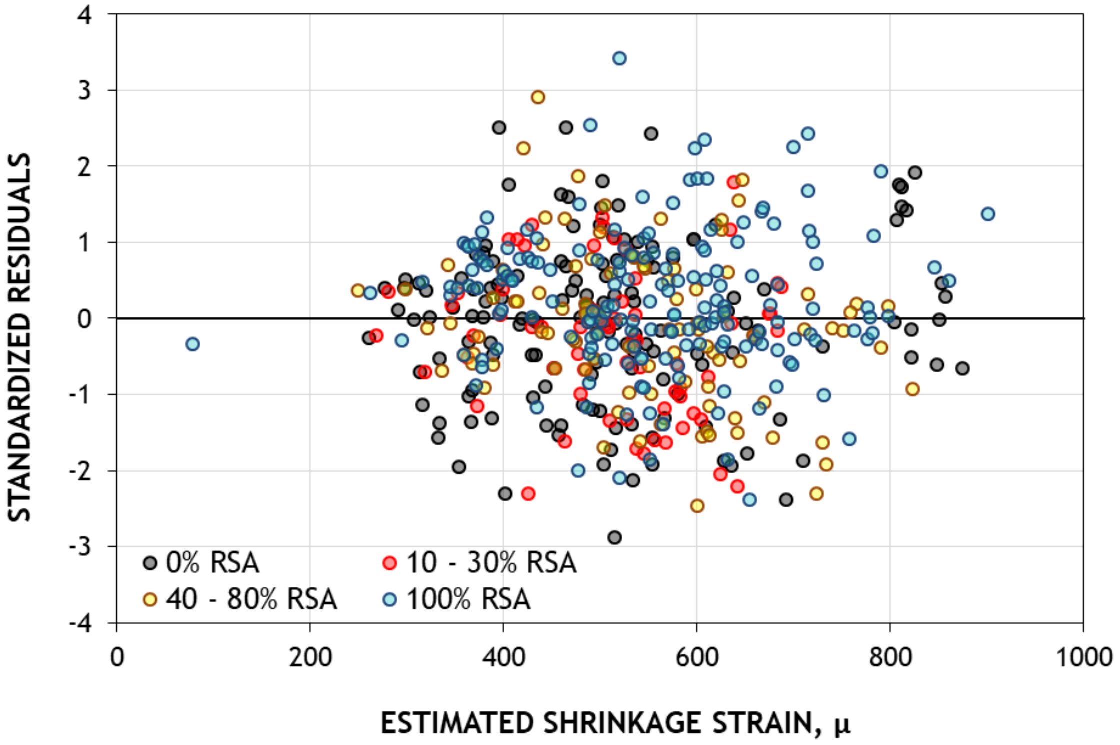


Figure 8.8 Standardised residuals versus estimated shrinkage

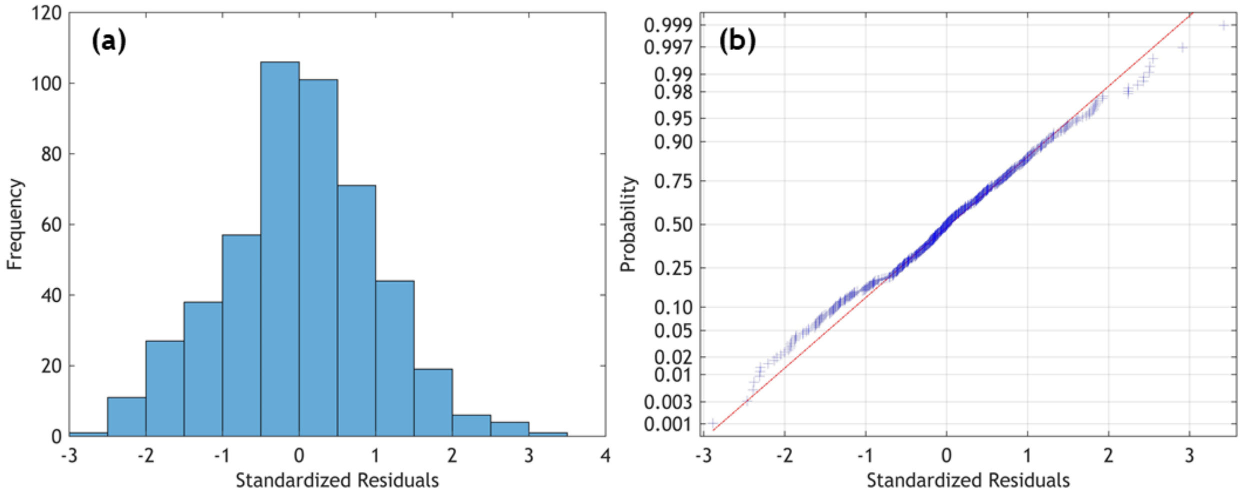


Figure 8.9 (a) Histogram and (b) Normal probability plot of standardised residuals of the proposed shrinkage model

Figure 8.10 shows the plot of measured shrinkage strains against the corresponding estimated shrinkage strains using the proposed model. In general, it can be seen that the data points are clustered around and close to the line of equality. It is noted that data with measured values less than 300 µ tend to be overestimated. As these data were obtained from concrete exposed to a short drying period (no more than 3 months), this does not appear to be of great concern regarding the accuracy of the model, although further improvement of the model in estimating short-term shrinkage strains is worthy of investigation.

The statistics indicators and error measures of the proposed model, as well as the Eurocode 2 (2004) model, are given in Table 8.9. The proposed model has reasonably good R^2 and adjusted R^2 values, which both are over 0.7. The high f-statistic value and zero p-value also indicate that the parameters used collectively have a significant

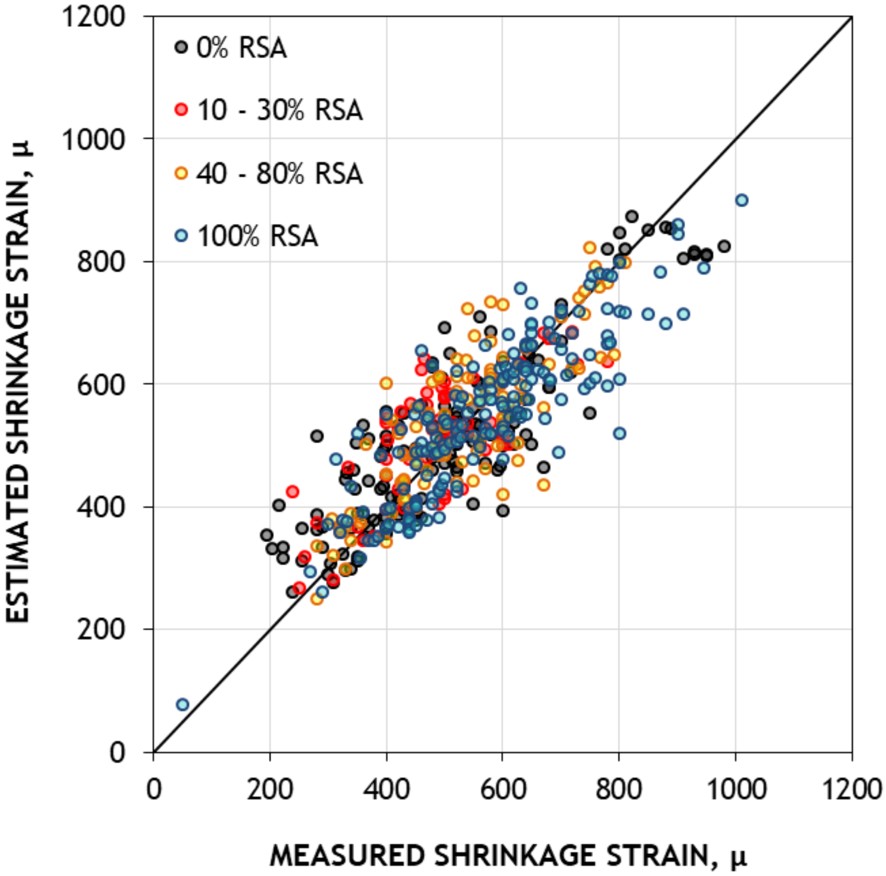


Figure 8.10 Measured shrinkage versus estimated shrinkage using the proposed shrinkage model

influence on the model. In addition, the error measures for the testing data are close to those of the training data, which confirms that the proposed model is valid. Table 8.9 also shows the error measures of Eurocode 2 (2004), obtained previously in Chapter 7, Section 7.5.2. In comparison, it is evident that the proposed model shows higher estimation accuracy than Eurocode 2 (2004), owing to its relatively low biasness (MBE) and error values (RMSE and MAPE) in the estimation.

Table 8.10 Statistics indicators and error measures of the proposed shrinkage model

	PROPOSED MODEL		EUROCODE 2 (2004) MODEL	
	Training Data	Testing Data	All Data *	Testing Data **
Number of Data	511	57	821	57
R-Squared	0.714	-	-	-
Adj. R-Squared	0.703	-	-	-
F-Statistic	1.11×10^3	-	-	-
p-Value	0	-	-	-
MBE, μ	+1.98	+14.6	-130.3	-77.9
RMSE, μ	83.2	117.3	231.5	152.6
MAPE, %	16.7	23.6	36.8	27.1

* The error measures were the average values reported in Table 7.7; ** Same as those used in the proposed model

8.7 CONCLUSIONS

This chapter deals with the model building process and presents three new empirical models developed for estimating the elastic modulus, creep coefficient and shrinkage strain of concrete potentially made with a wide range of aggregates alone or in combination, including natural, recycled and secondary aggregates. These proposed models were, for ease of use in practice, deliberately designed to work around Eurocode 2 (2004) and were developed in MATLAB version 2017a.

The key basic factors of the proposed models are the consideration of: (i) coarse and fine aggregates as separate material components; (ii) the type of aggregate used, incorporating natural, recycled and secondary aggregates, but essentially within the normal-weight aggregate range and used to produce normal-weight concrete as specified in BS EN 206 (2013); (iii) the aggregate stiffness effect expressed as water absorption and (iv) the aggregate volume effect expressed as aggregate/cement ratio. Additionally, the use of pozzolanic materials is made more explicit. Finally, and perhaps most importantly, the models developed in this study have a wider range of use compared to those of Eurocode 2 (2004).

It is shown that the proposed models have potentially good sensitivity to respond to changes, in terms of mix materials and proportions used, in structural concrete mixes, and can potentially work with a sufficiently high degree of accuracy. That said, it is recognised that the proposed models offer scope for further development when more data become available.

CHAPTER 9

CONCLUSIONS, PRACTICAL IMPLICATIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

9.1 CONCLUSIONS

This research studies the effects of using recycled and secondary aggregates (RSA) on the deformation properties of concrete. Three types of RSA were selected for this study, namely coarse recycled concrete aggregate (RCA), fine glass cullet aggregate (GCA) and fine copper slag aggregate (CSA), and together they provide the main spread of sustainable construction materials that are potentially suitable for use in structural concrete. Three areas of deformation of concrete, which are of structural importance, were considered, namely elastic modulus, creep and shrinkage.

A novel and original research approach, *Analytical Systemisation*, was developed and adopted in this study. This method started with an extensive search of the globally published data, followed by the building of a data matrix. The next step involved the analysis, evaluation and modelling work. Finally, as the study progressed, the output of the research was presented in the form of papers to reputable journals for peer-review comments and thereafter publication for wider dissemination.

Overall, the work presented in this study was based on a strong data matrix, consisting of more than 400,000 data points, sourced from 713 publications, produced by 960 researchers, from 537 institutions and established organisations across 46 countries, over a period of 45 years. In total, five papers directly relevant to this study were published. In addition, to complement the main study, two papers on the carbonation of concrete containing fly ash and ground granulated blast furnace slag (GGBS) were also published (Section 9.2).

The physical properties of coarse RCA, fine GCA and fine CSA could be affected by the crushing process, more so for RCA than GCA and CSA. There is no issue with these materials being processed with a particle size distribution conforming to the standards, but their gradings have been generally overlooked. Depending on the adhered cement paste content, the absorption and specific gravity of RCA can vary over a wide range, with average values of 5.1% and 2.42, respectively. The absorption of GCA and CSA is close to zero. The specific gravity of GCA, which can be affected by its chemical composition, is about 2.5; and that of CSA, which can be affected by its cooling process, is about 3.6. In terms of stiffness value, coarse RCA is likely to be lower than coarse natural aggregate (NA), whilst CSA is higher than GCA and both materials are higher than fine NA.

It is found that as the coarse RCA content increases, the elastic modulus of the concrete decreases at a decreasing rate, giving an average of 16% reduction when coarse RCA is used. This relative reduction in elastic modulus of RCA concrete decreases as the concrete strength increases. The use of fine GCA and fine CSA marginally increases the elastic modulus of concrete by 2% and 3%, respectively. Compared with NA concrete, the elastic modulus–compressive strength relationship of concrete made with these materials still holds. Although for a given strength, the elastic moduli of RCA concrete and CSA concrete are lower and higher, respectively, than that of NA concrete, they are similar to that of GCA concrete. The elastic modulus–compressive strength relationship of NA concrete shown in this study does not match that given in Eurocode 2 (2004) for different rock types. This is a cause for concern.

In comparison to NA concrete, the creep of RCA concrete increases at a decreasing rate as the replacement level increases, giving an average of 32% increase at 100% RCA content. The increase in creep due to the use of RCA decreases as the strength of the concrete increases. Compared to NA concrete, the creep of RCA concrete is more sensitive to moist curing duration. The use of fly ash as a Portland cement replacement or cement addition was found to improve the resistance of RCA concrete to creep deformation, although further developmental work is still needed. The effects of using fine GCA and fine CSA as a fine NA replacement on the creep of concrete are under-researched. Notwithstanding this, based on their stiffness property, it can be safely assumed that, for a given condition, the creep of concrete would decrease in the following order: fine NA > fine GCA > fine CSA.

The use of coarse RCA as an NA replacement increases the shrinkage of concrete at a decreasing rate as the RCA content increases. On average, the shrinkage of concrete can increase by 33% when 100% RCA is used. It is shown that the relative increase in shrinkage with the use of RCA decreases as (i) the ambient humidity rises or (ii) the designed strength of the concrete increases. The use of either fine GCA or fine CSA decreases the shrinkage of concrete compared to fine NA concrete, at a decreasing rate as their content increases. At full fine NA replacement, the average reduction in shrinkage is about 24% for fine CSA concrete and 16% for fine GCA concrete. Both fine GCA and fine CSA concretes show that the relative reduction in shrinkage decreases as the design strength of the concrete increases.

The existing models given in the design codes adopted in Australia, Hong Kong, Europe, South Africa and the United States, as well as two other models developed by individual researchers, have been discussed as regards estimating the deformation of concrete. The main omission in most of these models is the aggregate effect, in terms of its stiffness and content in concrete has not been properly considered. The Eurocode 2 (2004), *fib* (2013) and B4 (2015) models were selected to assess their estimation accuracy for concrete made with RSA, as well as NA. The results suggest that the errors in estimation for both RSA concrete and NA concrete using all three models are high, and further refinement and calibration of these models are required.

Three new empirical models were developed for estimating the elastic modulus, creep coefficient and shrinkage of concrete. The key factors used in these models are:

(i) coarse and fine aggregates as separate material components
(ii) aggregate types, used alone or in combination, including natural, recycled and secondary aggregates
(iii) water absorption of aggregate
(iv) aggregate/cement ratio
(v) clearer definition of the cement strength classes

9.2 PRACTICAL IMPLICATIONS

With the increasing emphasis on carbon footprint reduction within the construction industry, and provisions for the use of sustainable construction materials in the standards, RSA as well as pozzolanic materials are likely to continue to play a key role in addressing sustainability challenges. The work presented in this study, thus, clearly helps to build a clearer understanding of the effects of using RSA on the deformation properties of concrete. Additionally, the models developed help to estimate the deformation of concrete made with a wide range of aggregates, including RSA.

Referring back to the findings obtained, the use of coarse RCA reduces the resistance of concrete to deformation, and the use of either fine GCA or fine CSA results in no change or an improvement. Clearly, the reduction in the resistance to deformation of RCA concrete will inevitably limit its potential use in structural applications. On the other hand, fine GCA and fine CSA are unlikely to be treated as inferior in terms of their influence on the deformation of concrete, but attention is required in other areas, such as the alkali-silica reaction when GCA is used (Dhir et al., 2018a) and the setting time of concrete when CSA is used (Dhir et al., 2016). All these may act as a psychological obstacle in realising the potential for greater adoption of these materials.

To facilitate the use of RSA as a viable material, the concrete mix design for RSA needs to be considered carefully. In most cases, pozzolanic materials, such as fly ash and GGBS, are likely to be used as a Portland cement replacement in conjunction with RSA to ensure the other properties of concrete are not compromised by the use of

RSA (indeed, there is a real temptation in cement industries to maximise the use of pozzolanic materials, which are available in abundance).

This design option, although appealing, requires attention to the effects of pozzolanic materials on the carbonation resistance of concrete. A supplementary work undertaken by the author shows that both fly ash (Lye et al., 2015b) and GGBS (Lye et al., 2016a) increase the carbonation of concrete as their content increases; at a given content, the increase with the use of FA is higher than that of GGBS. The carbonation effects of these pozzolanic materials can be minimised by limiting their content in concrete, although this has to be weighed against various aspects such as durability, practicality and sustainability.

9.3 RECOMMENDATIONS FOR FURTHER RESEARCH

Outlined below are some of areas that can be effectively pursued to further strengthen the outcomes realised in this study:

1. Although the *Analytical Systemisation* method is mature enough to be used in the field of concrete research, it can be further enhanced by incorporating more statistical elements into the data analysis and evaluation.

2. The data matrix built from this research can be widened by exploring the data published in other dominant languages in the field, such as Japanese and Spanish.

3. The research area on the deformation properties of fine GCA and fine CSA concretes requires more attention as the relevant data are lacking.

4. Although the models developed in this study were based on an extensive data-matrix, these models can be refined by building an even bigger data population by selectively using other sources that have remained untouched in this study, such as non-English journals, unpublished sources such as those from standard organisations and higher education institution libraries and extending the choice of aggregate materials.

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