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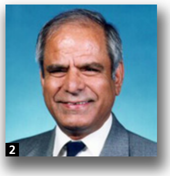


A global literature search, in the English medium, on the modulus of elasticity of concrete made with recycled aggregates revealed coarse recycled concrete aggregate (RCA) to be most widely reported, covering 284 publications from 42 countries since 1977 and yielding a 14 500 data matrix for systematic analysis, evaluation and synthesis. The modulus of elasticity of concrete was found to decrease at a decreasing rate with increasing coarse RCA content, giving an average 16% reduction at full natural aggregate replacement. This reduction was found to be dependent on concrete strength, becoming smaller with increasing strength. The relationship between modulus of elasticity and cube strength based on the literature data was compared with Eurocode 2, showing the modulus of elasticity of concrete made with normal aggregate falling from being just below quartzite rock at 100 MPa to limestone rock at 60 MPa concrete strength; for concrete made with 100% coarse RCA, the comparable rock types were found to be limestone and sandstone, respectively. An empirical method for estimating, in conjunction with Eurocode 2, the modulus of elasticity of concrete made with coarse RCA and sustainable measures to compensate for the reduction in the modulus of elasticity are proposed.

1. Introduction

1.1 Background

A great deal has been said about sustainability and, accordingly, the need to maximise the use of recycled and secondary materials. Indeed, the construction industry globally is expected to play a major role in driving this agenda. However, in the final analysis, the acceptance of these materials in practice will depend on real understanding of their performance so that they can be used effectively and appropriately, with confidence and without undue risk.

In the field of concrete construction, billions of tonnes of natural aggregates (NAs) are used per annum worldwide and it is claimed that a significant amount of these can be replaced by recycled aggregates (RAs) arising from construction demolition and excavation. However, in order to adopt the use of RA in concrete construction confidently, it is important that the performance of this material in concrete is well understood and engineers are sufficiently confident in specifying it routinely.

After strength, engineers need to know the deformation properties of concrete, both in the form of load-dependent properties such as the modulus of elasticity and creep and load-independent properties such as shrinkage. Adhered mortar on RA is accepted to lower the modulus of elasticity of concrete made from RAs when compared with corresponding concrete made with virgin NAs but, beyond this, there is no consensus and the information available in the published literature is generally fragmented and design engineers, as well as the standards, remain sceptical about adopting the use of RA in structural concrete. This has hindered progress in establishing the responsible use of RAs in concrete construction.

A series of systematic literature review projects is being undertaken by the authors in order to investigate the effect of RA on the deformation properties of concrete, including the modulus of elasticity, creep and shrinkage. This paper, one of three in the series, deals with the subject of the modulus of elasticity of concrete made with RAs.

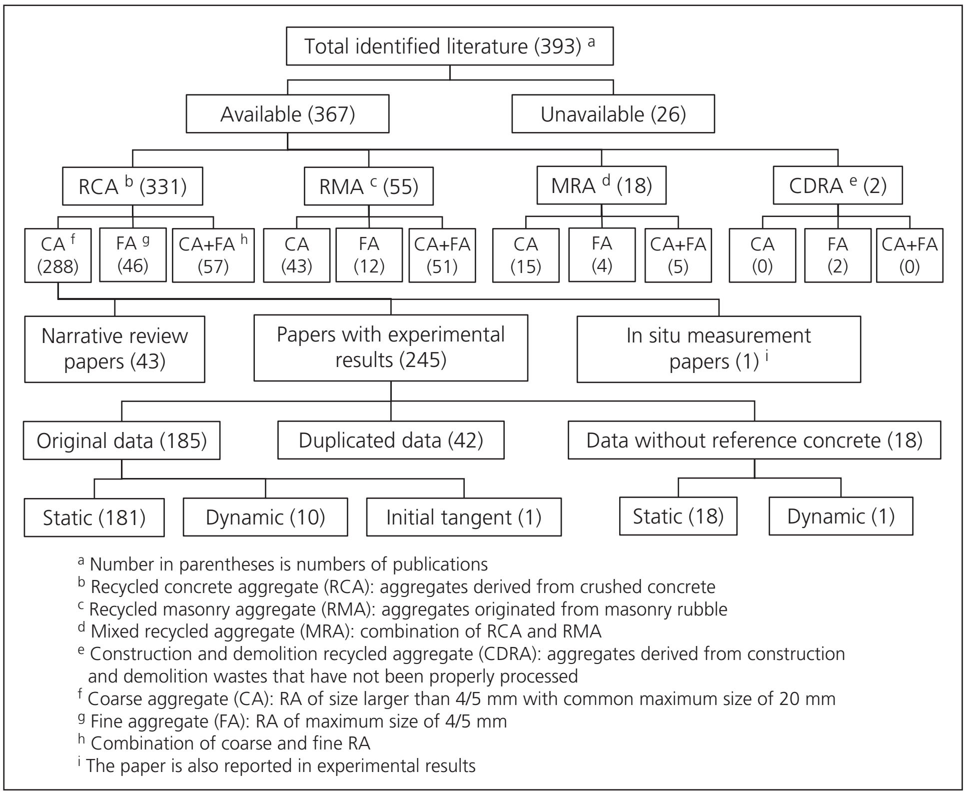

Figure 1. Distribution of publication data from the literature search

1.2 Aims and objectives

The main aim of this study is to systematically analyse, evaluate and synthesise globally published data on the modulus of elasticity of concrete made with RA in relation to that of concrete made with NA and thereby facilitate measures that could be taken to develop its use in practice. It should also help to establish what is known and avoid repetitive research and, instead, direct valuable resources to the information that is still needed.

2. Outline of approach adopted

A near-exhaustive global literature search, but limited to the English medium, was conducted using combinations of keywords defining and elaborating the subject area considered using many sources, such as the American Concrete Institute, American Society of Civil Engineers and Institution of Civil Engineers libraries and engineering village, Google, Google Scholar, Science Direct, Scopus, Springer Link, Taylor & Francis Online and Wiley Online Library.

The search yielded a total of 393 publications, grouped into various categories, as shown in Figure 1. Based on the main composition of RA used, the sourced literature was, in the first place, separated into four RA types (Silva *et al.*, 2014), as described in Figure 1. It can be seen that the use of recycled concrete aggregate (RCA) as NA replacement has been the subject of investigation of most (90%) and the coarse fraction size has been most commonly used.

Based on material resource availability and potential for use considerations, coarse RCA was selected as the main subject of this project and the relevant published literature was classified into the following three categories (Figure 1).

(*a*) Narrative review papers, which present previous research on the modulus of elasticity of concrete made with coarse RCA; these also include codes and proposed specifications.
(*b*) Papers with experimental results, in which test data were obtained from dedicated cast specimens, analysed, evaluated and discussed by the researchers of the studies themselves. A further breakdown was also made in which
  (i) the data available for the modulus of elasticity of RCA concrete and that of the corresponding reference NA concrete are original
  (ii) similar data are reported in more than one publication from the total identified literature
  (iii) the modulus of elasticity of RCA concrete is original but the corresponding information for reference NA concrete is not available.

Measurements of modulus of elasticity in terms of static, dynamic and initial tangent were also separated.

(*c*) Papers reporting in situ measurements – the data were obtained from specimens cored from actual concrete structures that had been in service for a period of time.

As the vast majority of the results present the static modulus of elasticity, this narrowed down the research focus of this project to the effect of using coarse RCA as NA replacement on the static modulus of elasticity of concrete. For this, the data used were sourced from 284 publications from review, experimental results and in situ measurement papers (Figure 1), covering over 39 years since 1977 (Figure 2) and originating from 42 countries (Figure 3). Only these 284 publications are listed as references used at the end of the paper.

3. Overview of the literature

From the 43 publications of a review nature, two groups were created based on the origin of the information

- group 1: established organisations, codes and proposed specifications (as listed in Table 1)
- group 2: individual researchers (Agrela *et al.*, 2013; Ajdukiewicz, 2005; Balazs *et al.*, 2008; Behera *et al.*, 2014; de Brito and Alves, 2010; de Brito and Robles, 2010; Dhir *et al.*, 2011; Franklin and Gumede, 2014; Kukadia *et al.*, 2014; Li, 2008a, 2008b; Marinkovic *et al.*, 2012; McNeil and Kang, 2013; Nixon, 1978; Park *et al.*, 2015; Poon *et al.*, 2003; Ramachandran, 1981; Rao *et al.*, 2007; Safiuddin *et al.* 2013; Safiuddin *et al.*, 2011; Xiao *et al.*, 2006a, 2012a, 2012b).

Given that the main observations of the two groups are broadly the same, only the suggested relative decrease and multiplying factor of modulus of elasticity of RCA concrete with respect to NA concrete from group 1 are compiled as an example in Table 1, which shows the following.

- In general, the use of RCA reduces the modulus of elasticity of RCA concrete as compared with NA concrete, with 100% RCA use giving a reduction of 6–40% (30% on average). At 20% RCA use, one publication suggests the modulus of elasticity remains similar to that of the NA concrete. As expected, at equal water/cement (w/c) ratios, RCA concrete has a lower modulus of elasticity than the corresponding reference NA concrete.
- A multiplying factor of 0·80 has been suggested for concrete made with 100% RCA with concrete strength in the range 37–60 MPa and 0·95 for concrete strength within the range 20–30 MPa. No multiplying factor is required for concrete made with 20% RCA content and, for high-quality RCA, a multiplying factor may also not be necessary for up to 100% RCA replacement of NA.
- Even though the data in the literature are, in the main, limited to 100% RCA replacement of NA, there is a suggestion that the reduction in modulus of elasticity of concrete containing RCA will be affected by the RCA content and RCA properties such as aggregate density and water absorption. Additionally, the literature suggests that the RCA performance relative to NA in concrete can be influenced by its w/c ratio and design strength.

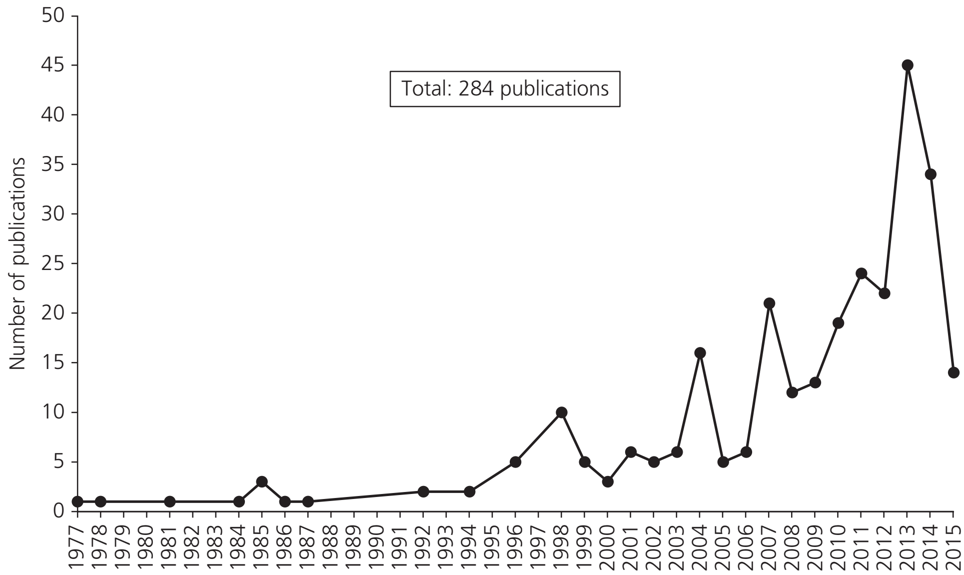

Figure 2. Distribution of publication per year

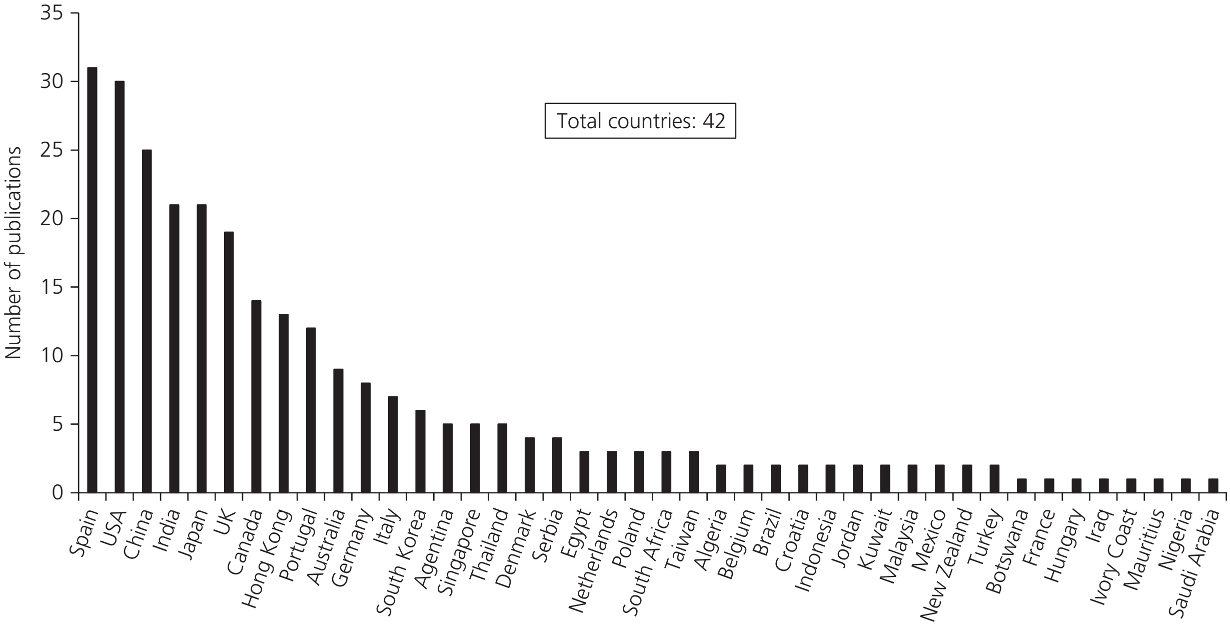

Figure 3. Distribution of country of publication (based on first author)

4. Systematic analysis and evaluation of published data

4.1 Variations in modulus of elasticity tests

Except for the publications with duplicate data, experimental variations in measuring the modulus of elasticity of the test concrete in the literature were categorised into four main groups under the headings of RCA properties, test method, specimen type and curing conditions, as summarised in Table 2 and described in the following.

4.1.1 RCA properties

Of the three basic aggregate properties (specific gravity/density, water absorption and grading), although used in designing concrete mixes, information on the specific gravity and density of RCA in the sourced literature for this study was found to be surprisingly lacking. The water absorption of RCA is reported to be in the range of 3·0–5·9%, which more or less reflects the amount of the adhered cement paste commonly remaining on RCA.

Given that the grading of the aggregates used can greatly influence the performance of concrete, the literature was first screened for aggregate grading in terms of RCA grading being (i) similar or different to the corresponding reference NA or (ii) information of RCA and/or NA was not provided. This showed that only a small number of studies (16%) used the same gradings of both RCA and NA, thus avoiding potential dissimilarity in aggregate packing between the resulting RCA and NA concrete. Surprisingly, 20% of the studies did not control the aggregate grading and 64% of studies were indifferent to providing grading data for the aggregates used.

As each NA type has its own properties, RCAs are not only affected by the amount of adhered cement paste but also their parent rock type. Thus, in comparing the performance of RCAs with NAs, the same origin material would be ideal for eliminating the effect of the base aggregate material factor. About 18% of the studies reported using NA and RCA having the same original rock base. Of the remaining vast majority of studies, this information was not provided while a few reported that the parent rock of RCA and NA was known to be different.

The moisture condition of the RCA used appears to vary, with about 32% reporting it to be in a saturated surface dry (SSD) state (including pre-saturation), 4% stating air-dry or oven-dry state, 19% not stating but reporting that additional water was added for compensation during mixing and the rest providing no information on moisture condition.

Thus, in dealing with analysis and evaluation of the data, the assumption was made that, ideally, the discrepancies noted above would have been minimal and not significant enough to affect the accuracy of comparison between the data of concrete made with RCA and the corresponding reference NA concrete.

4.1.2 Test method

Almost half of the sourced literature stated the standard test method used to determine the modulus of elasticity of

	Reference	Number of references used	Elastic modulus of RA concrete wrt NA concrete		Remarks
			20% RCA	100% RCA	
Relative performance					
Australia	CCAA (2008)	n.a.	n.a.	n.a.	At equal w/c, RCA concrete has lower elastic modulus than NA concrete
Australia	Sagoe-Crentsil and Brown (1998) (CSIRO)	n.a.	n.a.	≤ 40% lower	n.a.
New Zealand	Chisolm (2011) (CCANZ)	n.a.	n.a.	6–33% lower	n.a.
Netherlands	Gerardu and Hendriks (1985)(Rijkswaterstaat)	3	n.a.	≤ 15% lower	n.a.
Spain	TFSCCS (2004)	n.a.	No change	20–40% lower	n.a.
Switzerland	OT 70085 (2006) (reported by de Brito and Saikia (2013))	n.a.	n.a.	20% lower	n.a.
USA	ACI (2001)	1	n.a.	10–33% lower	For 0·45–0·79 w/c ratio
USA	Anderson *et al*. (2009) (WSDoT)	1	n.a.	20–40% lower	At equal w/c ratio
USA	Burke *et al*. (1992) (INDoT)	2	n.a.	≤ 33% lower	n.a.
USA	Dam *et al*. (2011) (MDoT)	1	n.a.	10–33% lower	n.a.
USA	Dam *et al*. (2012) (NCPTC)	1	n.a.	≤ 30% lower	n.a.
USA	PCA (2002)	1	n.a.	35% lower	n.a.
USA	USACE (2004)	n.a.	n.a.	35% lower	n.a.
n.a.	Hansen, 1985, 1992 (Rilem TC 37-DRC)	12	n.a.	≤ 40% lower	n.a.
n.a.	Vazquez, 2013 (Rilem TC 217-PRE)	5	n.a.	n.a.	Elastic modulus decreases as RCA increases
Multiplying factor on RCA concrete					
Belgium	Belgium (not dated) (reported by Vyncke and Rousseau (1994))	n.a.	n.a.	0·80	For RCA with >2100 kg/m^3 dry density, < 9% water absorption and max. strength of 37 MPa
Netherlands	CUR-VB (1994) (reported by de Vries (1996))	n.a.	1·00	0·95	For 20–30 MPa concrete
			1·00	0·80	For 30–50 MPa concrete
Spain	EHE-08 (2010)	n.a.	1·00	0·80	n.a.
n.a.	Rilem TC121 (1994), Hendriks and Henrichsen (1996)	n.a.	n.a.	0·80	For RCA with ≥2000 kg/m^3 dry density, ≤ 10% water absorption and max. strength of 60 MPa
			n.a.	1·00	For RCA with ≥2400 kg/m^3 dry density, ≤ 3% water absorption and no strength limit

n.a. = not applicable

Table 1. Relative decrease of elastic modulus and multiplying factor for RCA concrete with respect to NA concrete from various organisations and specifications

Parameter	Variable	Number of studies
RCA properties		
Specific gravity	< 2·3	10
	2·30–2·49	63
	2·50–2·69	36
	Not given	172
Density (SSD): kg/m^3	< 2400	11
	2400–2490	32
	≥ 2500	21
	Not given	218
Water absorption: %	< 3	27
	3–5·9	141
	6–10	50
	Not given	63
Grading	Similar	45
	Different	55
	Not given	181
Parent aggregate	Similar	50
	Different	2
	Not given	229
Moisture condition when in use	SSD	89
	Air dry	9
	Oven dry	4
	Not given but water added	52
	Not given	127
Test method		
	ASTM C 469 (USA)	36
	BS 1881:121 (UK)	19
	LNEC E397 (Portugal)	7
	DIN 1048 (Germany)	6
	UNE 83-316 (Spain)	6
	JIS A 1149 (Japan)	5
	IS 516 (India)	3
	UNI 6556 (Italy)	3
	Others	13
	Not given	98
Specimen type (shape and dimension: mm)		
	Cylinder (∅ × *h*)	131
	• 75 × 150	4
	• 100 × 200	42
	• 100 × 250	1
	• 100 × 300	1
	• 120 × 240	1
	• 120 × 360	1
	• 150 × 250	1
	• 150 × 300	59
	• 160 × 320	2
	• Not given	19
	Prism (*l* × *w* × *h*)	8
	• 100 × 100 × 300	3
	• 100 × 100 × 400	2
	• 150 × 150 × 300	2
	• Not given	1
	Not given	57

Table 2. Compilation of test parameters of modulus of elasticity of RCA concrete in the literature

Parameter	Variable	Number of studies
Curing conditions		
Exposure	Moist	138
	Air	3
	Not given	56
Duration: d	≤ 14	23
	15–30	110
	>30	8
	Not given	59
Temperature: °C	20–25	58
	25–30	14
	40	1
	Not given	125
RH: %	90–100	123
	50–80	4
	Not given	71

Table 2. Continued

concrete, with ASTM C 469 being more common than any other, followed by BS 1881:121. However, the remainder of publications, especially those from Spain, did not provide any information on the test procedure.

4.1.3 Specimen type

Cylinder specimens of various dimensions with height-to-diameter ratios of 2–3 were the most commonly used in determining the modulus of elasticity of the test concrete mixes, with a few studies using prisms.

4.1.4 Curing conditions

Moist curing with relative humidity (RH) of 90–100% and temperature 20–30°C for a duration of up to 30 d was the most commonly used in the reported studies. The effect of curing per se has not been the subject of study in the reported literature.

4.2 Effect of coarse RCA as NA replacement

Data on static modulus of elasticity reported in 181 out of 223 studies (excluding 42 duplicate papers) of the sourced literature are plotted in Figure 4. This contains 1311 sets of results with the modulus of elasticity of concrete made with RCA expressed in relative terms to concrete made with NA. Each data point in Figure 4 has been slightly displaced both horizontally and/or vertically in order to avoid overlapping more than one data point at the same location. To visualise distribution of the data, box-and-whisker plots were created at each RCA replacement level and the outliers thus determined. For the purpose of regression analysis, the following data were excluded.

- Cases where the modulus of elasticity of concrete made with RCA was higher than the corresponding concrete made with NA as, like-for-like with adhered cement paste,

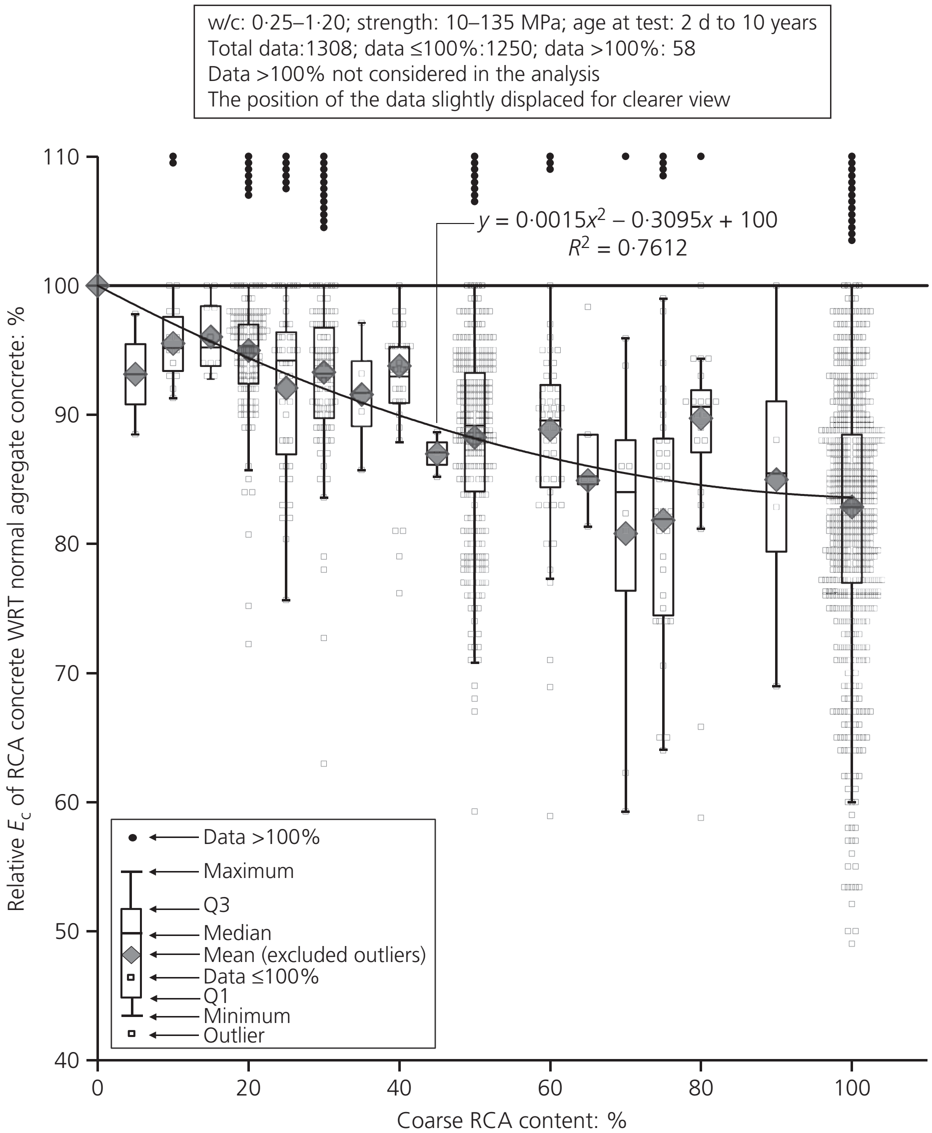

Figure 4. Relative change of modulus of elasticity of coarse RCA with respect to corresponding reference NA in concrete. Data taken from Ahmad *et al*. (1996), Ahmed and Vidyadhara (2013), Ajdukiewicz and Kliszczewicz (2002, 2007), Akbarnezhad *et al*. (2011), Arezoumandi *et al*. (2015), Arundeb *et al*. (2011), Barbudo *et al*. (2013), Beltran *et al*. (2014), 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*. (2010), 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), Go *et al*. (2007), Gomes and de Brito (2007, 2009), Gomes *et al*. (2014), Gomez-Soberon (2002, 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), 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

the former cannot give a higher value (i.e. >100%). This accounted for 4·4% of the total data population (i.e. 58 out of 1311 results).
- Outliers determined using the box-and-whisker plots; these amounted to 3·4% of the total data (i.e. 45 results).

A polynomial regression was obtained, giving the best correlation of 0·7612. Overall, and without reference to the RCA properties and concrete strength, this suggests that the modulus of elasticity of concrete made with RCA relative to NA decreases at a decreasing rate with increasing RCA content, reaching a maximum average reduction of 16% at 100% RCA replacement level, and the corresponding values for 20% and 50% RCA replacements being 5% and 12%, respectively.

This finding of 16% reduction in modulus of elasticity for 100% RCA concrete is close to the multiplying factor of 0·80 suggested within the restricted range of aggregate density and water absorption and concrete strength given by (see Table 1)

- the Code on Structural Concrete (EHE-08) of the Spanish Ministry of Development (MdF, 2010)
- recommendations from pilot projects and research work in the Netherlands (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)).
- specifications proposed by Rilem Technical Committee 121 (Rilem TC121, 1994).

As shown in Table 1, similar results are found in technical reports of various organisations and committees based in North America, Europe, Australia and New Zealand published over the period 1986–2012. However, in these cases the relative reduction of modulus of elasticity was generally in the range 20–40% for 100% RCA concrete.

However, at 20% RCA level, while Figure 4 shows a reduction of 5% in the modulus of elasticity of concrete, reports from Spain (Eguchi *et al.*, 2007; TFSCCS, 2004) and the Netherlands (de Vries, 1996) (Table 1) suggest no change in the modulus of elasticity of concrete at this replacement level. The fact that Figure 4 is based on a vast amount of results sourced from literature published over a period of 39 years and involving RCA characteristics and content and concrete mixes varying over a large range, the reduction in the modulus of elasticity of concrete with the use of RCA is likely to be more representative.

4.3 Effect of RCA on modulus of elasticity in different strength grades of concrete

In order to further analyse the data in Figure 4, the same data were categorised into six different strength groups based on the measured strength of NA concrete, ranging from 15 to 130 MPa, as shown in Figures 5(a)–5(f). In preparing Figure 5

- cylinder strength was converted into cube strength using a factor of 1·25 given in BS EN 12504-1 (BSI, 2009).
- where the specimen type was not indicated in the publications, cube strength was assumed
- data with relative modulus of elasticity values of RCA concrete higher than 100% were excluded in calculation of mean results.

Figures 5(a)–5(f) show that, while the form of the trendlines is essentially similar, collectively the trendlines show that the reduction in modulus of elasticity of RCA concrete relative to NA concrete becomes smaller with increasing concrete strength. To visualise this effect clearly and prepare it for use in practice, the data plotted in Figure 5 were regrouped into

(2003), Knaack and Kurama (2011, 2012, 2013a, 2013b, 2015), Knights (1999), Konin and Kouadio (2012), Kou and Poon (2008, 2013, 2015), Kou *et al*. (2004, 2007, 2008, 2012), Koulouris *et al*. (2004), Kumutha and Vijai (2010), Li *et al*. (2012), Limbachiya (2004, 2010), Limbachiya *et al*. (1998, 2000, 2004, 2012a, 2012b), Liu *et al*. (2011), 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), Ong *et al*. (2010), Padmini *et al*. (2009), Paine *et al*. (2009), Park (1999), Paul and van Zijl (2012, 2013), Pecur *et al*. (2015), Pedro *et al*. (2014), 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), Salem *et al*. (2003), 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), 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), 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 *et al*. (2008a, 2008b, 2010, 2012), Yin *et al*. (2010), Yun (2010), Zega and Di Maio (2006, 2009, 2011)

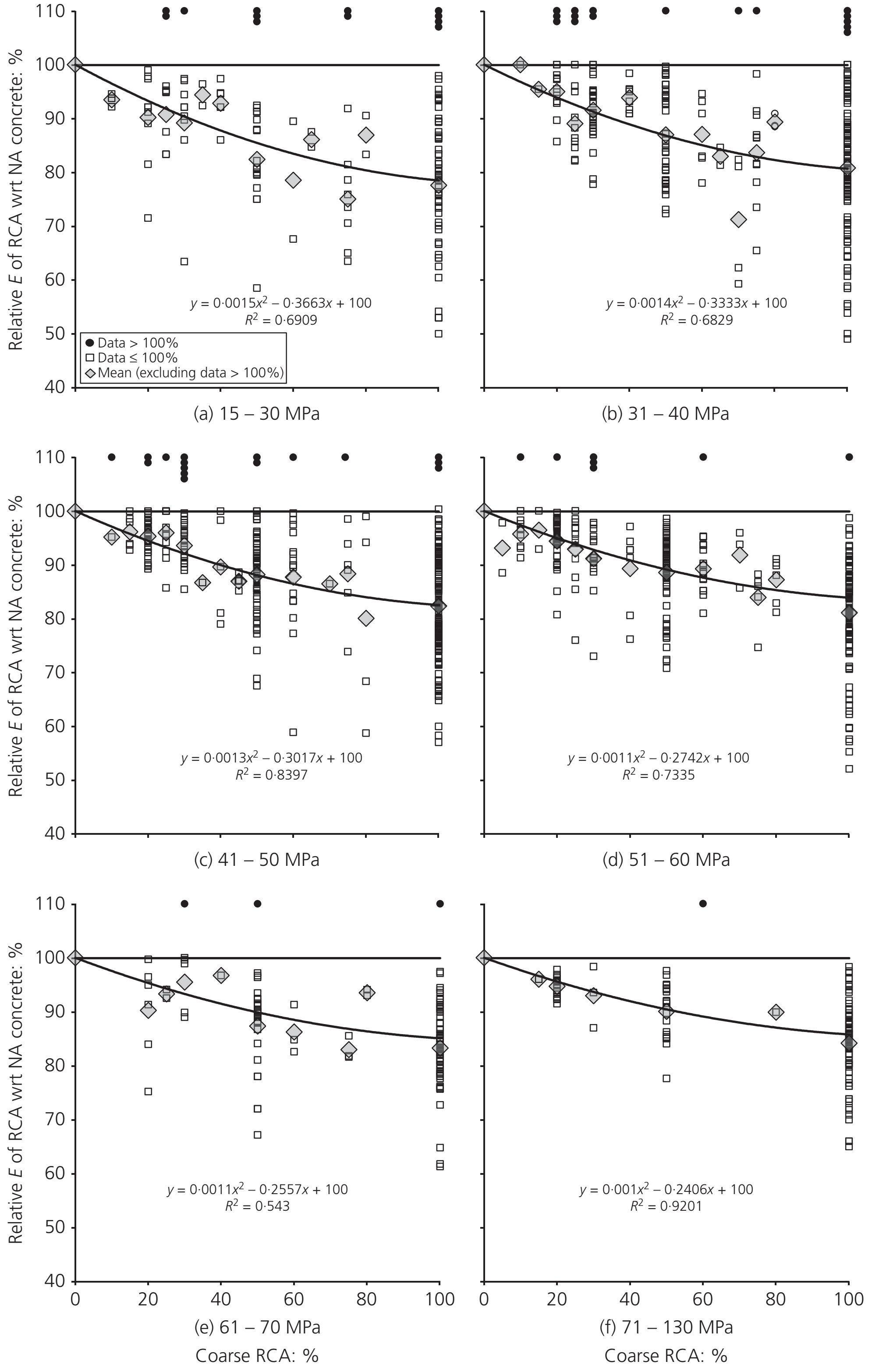

Figure 5. Relative change of modulus of elasticity of coarse RCA with respect to corresponding reference NA in concretes of different strength ranges

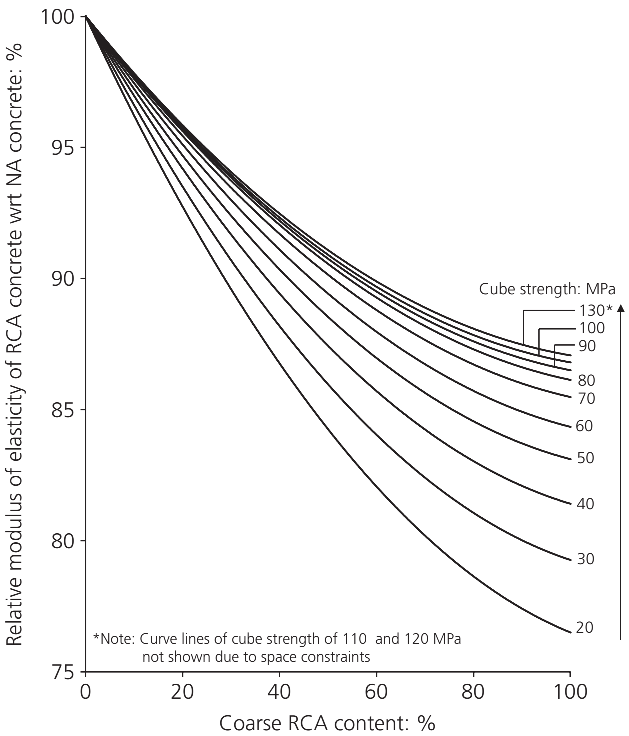

Figure 6. Compilation of relative elastic modulus of coarse RCA concrete with respect to NA concrete for different strength groups

strength increments of 10 MPa ranging from 20 MPa to 130 MPa and the family of curves thus produced is shown in Figure 6. This figure clearly shows the above-mentioned decreasing trend of modulus of elasticity of RCA concrete with increasing strength, albeit opposite to the suggestion made by de Vries (1996). This can be explained in terms of coarse aggregate volume decreasing with increasing concrete strength. In the case of RCA concrete, there is proportionately less adhered mortar, giving rise to a relatively smaller reduction in the modulus of elasticity of RCA concrete.

4.4 Relationship between modulus of elasticity and compressive strength

It is known that the modulus of elasticity of concrete increases with strength but, because RCA has relatively low stiffness compared with the corresponding NA, the increase in modulus of elasticity of RCA concrete would be lower than that in a corresponding reference NA concrete. In order to visualise this in graphical form, the published experimental data of modulus of elasticity for both NA concrete and RCA concrete are plotted against the corresponding cube strength in Figure 7.

The data used to produce Figure 7 were extracted from the sourced literature of 199 publications categorised in Figure 1 under the groupings of 'original data' (references as listed for Figure 4) and 'data without reference concrete' (Akhtar and Akhtar, 2014; Bhikshma and Manipal, 2012; Hossain and Sohji, 2004; Jimenez *et al*., 2013; Morohashi and Sakurada, 2007; Morohashi *et al*., 2007; Olanike, 2014; Paine and Dhir, 2010; Pecur *et al*., 2013; Radonjanin *et al*., 2013; Salem *et al*., 2001; Song *et al*., 2015; Tam and Tam, 2008; Tam *et al*., 2006, 2007a; Wang *et al*., 2013a; Wu *et al*., 2013; Yanagi *et al*., 1998), initially rendering a total data population of 2008, from which 54 results (2·7% of the total) were excluded for reasons such as

- the specimens were subjected to elevated temperature after moist curing for 28 d followed by a pre-conditioning period, resulting in low modulus of elasticity values
- very high or low modulus of elasticity values that could not be justified.

The cube strength data used in developing the plots in Figure 7 were either as given in the literature or were converted from the given cylinder strength using a multiplying factor of 1·25 as given in BS EN 12504-1 (BSI, 2009).

For comparison purposes, the modulus of elasticity of concretes made with different NAs (i.e. basalt, quartzite, limestone and sandstone) as obtained from Eurocode 2 (BSI, 2004) are also shown in Figure 7. Although some papers identified the nature of the rock type of the NAs used (commonly limestone and granite), this was not sufficient for use in any further analysis. Interestingly, however, the trendlines for NAs fall within the sandstone and limestone values when the strength was less than 60 MPa and between limestone and quartzite values for strength higher than 60 MPa.

To see the effect of RCA replacement level on the modulus of elasticity of concrete, the trendlines in Figures 7(a)–7(f) are plotted together in Figure 8. This shows that, as RCA content increases, the trendline moves towards to the values of concrete made with sandstone: at 100% RCA content and a cube strength of 35 MPa, the modulus of elasticity of RCA concrete would be similar to that of concrete made with coarse sandstone aggregate.

5. Estimation of modulus of elasticity of RCA concrete

The modulus of elasticity of RCA concrete for a given characteristic cube strength of 15–105 MPa and coarse RCA content of 0–100% can be estimated using Figure 9 in conjunction with Eurocode 2 (BSI, 2004), which is required to obtain the corresponding modulus of elasticity of NA concrete to start the process.

In developing Figure 9, the analysis of the published data used previously for Figures 5 and 6 was adopted in conjunction with the coefficient of variation of 12·5% given in ACI 301-05 (ACI, 2005) for fair construction quality control for calculating

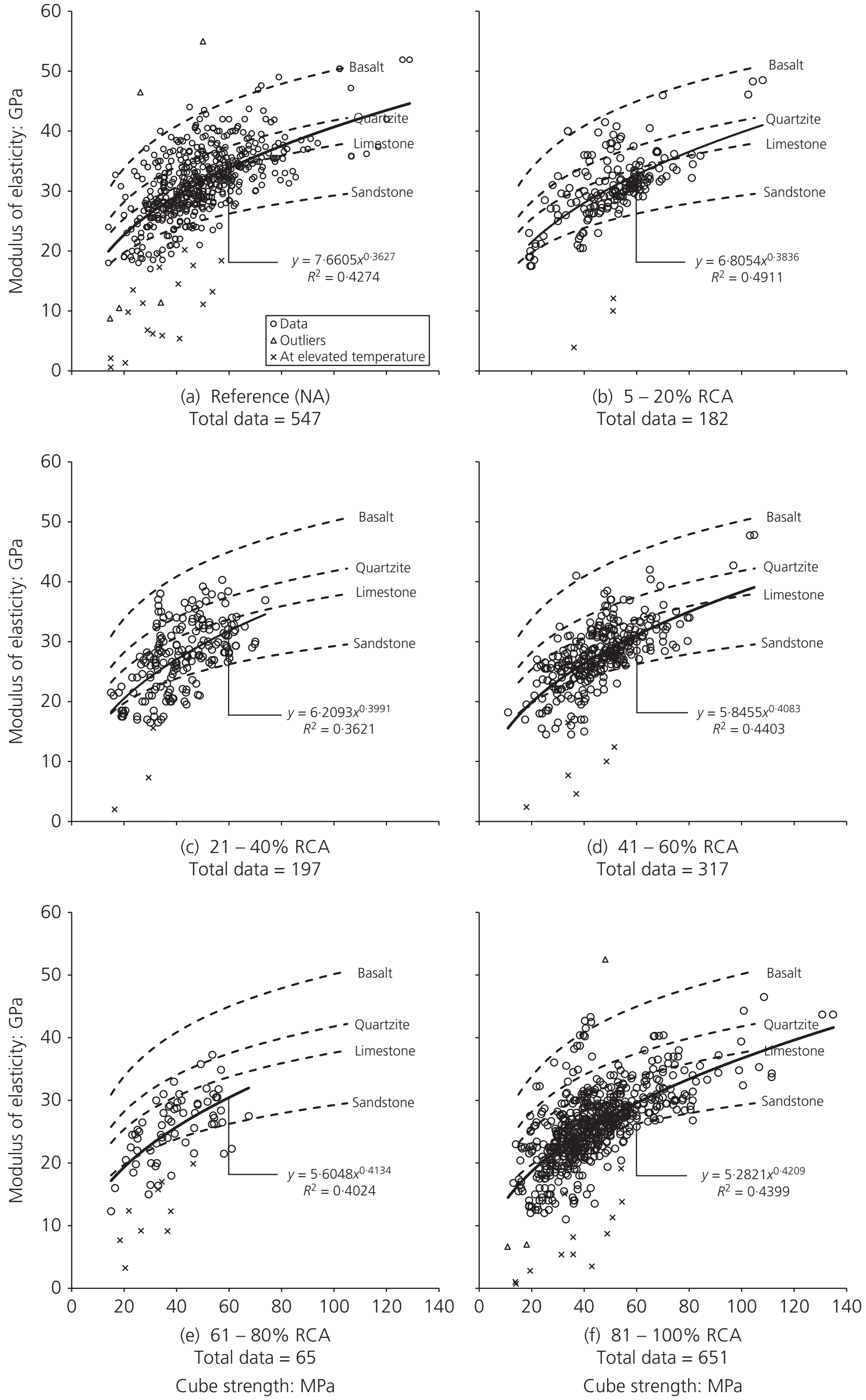

Figure 7. Modulus of elasticity and mean cube strength of RCA concrete for different RCA contents

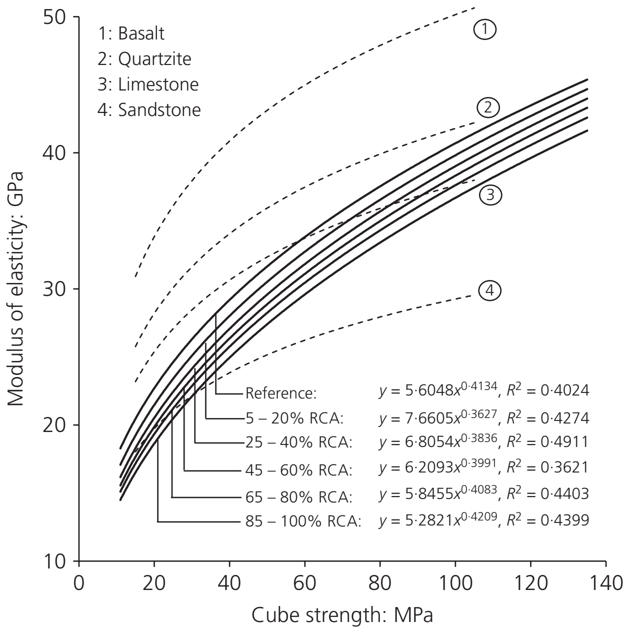

Figure 8. Compilation of modulus of elasticity and cube strength of concrete for different RCA contents

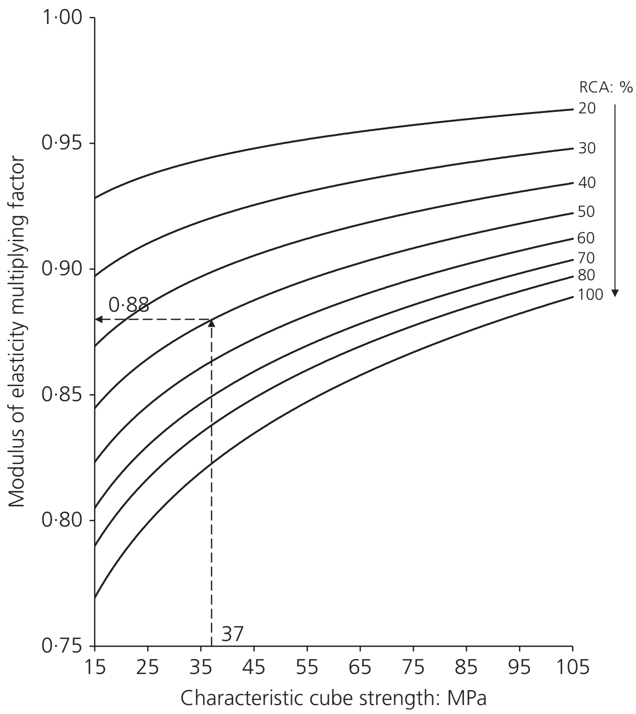

Figure 9. Proposed modulus of elasticity multiplying factors for RCA concretes of different characteristic cube strengths

the characteristic strengths of the measured strength data reported in the literature.

For ease of use of Figure 9 in practice, Table 3 gives conversion factors for estimating the modulus of elasticity of RCA concrete for a given characteristic cube strength in line with Eurocode 2 and coarse RCA content.

The following steps show how Figure 9 can be used to estimate the modulus of elasticity of RCA concrete.

- Step 1: Determine the modulus of elasticity of NA concrete. For example, according to Eurocode 2, concrete made with coarse basalt, quartzite, limestone or sandstone aggregate of designed characteristic cube strength of 37 MPa is estimated to have a modulus of elasticity of 42·9 GPa, 33·0 GPa, 29·7 GPa or 23·1 GPa, respectively.
- Step 2: Determine the multiplying factor required for RCA concrete. If 50% of the NA is replaced by RCA of a similar rock type for concrete with a characteristic cube strength of 37 MPa, Figure 9 suggests that a modulus of elasticity multiplying factor of 0·88 is required.
- Step 3: Estimate the modulus of elasticity of RCA concrete. By applying the multiplying factor to the modulus of elasticity of coarse natural basalt, quartzite, limestone or sandstone aggregate concrete, the estimated modulus of elasticity of corresponding to 50% RCA concrete is 37·8 GPa, 29·0 GPa, 26·1 GPa or 20·3 GPa, respectively.

6. Methods proposed to enhance the modulus of elasticity of RCA concrete

In order to enhance the modulus of elasticity of coarse RCA concrete and thereby improve its potential for specifying for use in structural concrete by engineers as a sustainable construction material, two simple and not so dissimilar methods involving mix adjustments of RCA concrete are proposed.

6.1 Cement paste reduction

For a given w/c ratio and workability, Dhir *et al.* (2006) showed that a reduction in cement content, by as much as 30%, could be realised by using water-reducing admixtures, leading to an increase in modulus of elasticity ranging from 8% to 17% (a mean of 12%). The fines content of the mix was maintained with the use of filler aggregate.

Using the previous examples discussed in Section 5, if the cement content of the concrete made with 50% RCA is reduced by 30%, the modulus of elasticity of the revised RCA concrete is almost similar to that of the corresponding reference NA concrete, as shown by

$$E_{R50} = 1{\cdot}12 \times 0{\cdot}88E_N = 0{\cdot}99E_N$$

where E_{R50} is the modulus of elasticity of concrete made with 50% RCA and 30% cement reduction and E_N is the modulus of elasticity of concrete made with NA.

RCA: %	Modulus of elasticity multiplying factor for RCA concrete													
	Characteristic cube strength: MPa													
	15	20	25	30	37	45	50	55	60	67	75	85	95	105
20	0·93	0·93	0·94	0·94	0·94	0·95	0·95	0·95	0·95	0·96	0·96	0·96	0·96	0·97
30	0·90	0·90	0·91	0·91	0·92	0·93	0·93	0·93	0·93	0·94	0·94	0·95	0·95	0·95
40	0·87	0·88	0·89	0·89	0·90	0·91	0·91	0·91	0·92	0·92	0·93	0·93	0·93	0·94
50	0·84	0·85	0·86	0·87	0·88	0·89	0·89	0·90	0·90	0·91	0·91	0·92	0·92	0·93
60	0·82	0·83	0·84	0·85	0·86	0·87	0·88	0·88	0·89	0·89	0·90	0·91	0·91	0·92
70	0·80	0·82	0·83	0·84	0·85	0·86	0·87	0·87	0·88	0·88	0·89	0·90	0·90	0·91
80	0·79	0·80	0·82	0·83	0·84	0·85	0·86	0·86	0·87	0·88	0·88	0·89	0·90	0·90
100	0·76	0·78	0·80	0·81	0·82	0·84	0·84	0·85	0·86	0·86	0·87	0·88	0·89	0·90

Table 3. Modulus of elasticity multiplying factors for RCA concretes with selected characteristic cube strengths, as shown in Figure 9

Concrete made with 100% NA		Concrete made with 50% coarse RCA	
		Method 1: cement paste reduction	Method 2: increase in design strength
Rock type	Modulus of elasticity: GPa[a]	Modulus of elasticity: GPa	Additional strength required: MPa
Basalt	42·9	42·3	13·0
Quartzite	33·0	32·5	10·0
Limestone	29·7	29·2	9·0
Sandstone	23·1	22·7	7·0

aAt characteristic cube strength of 37 MPa

Table 4. Modulus of elasticity and additional strength required of concrete made with 50% RCA from the proposed methods

The modulus of elasticity values for NA concrete made with different rock types and the corresponding 50% RCA concrete are given in Table 4. This 30% reduction of cement and water content in a mix is considered to be the maximum water reduction level that can be realised with water-reducing admixtures, suggesting that this method can only offer a maximum 50% RCA as NA replacement without compromising the modulus of elasticity of the concrete produced.

In revising the mix design of RCA concrete, high-range water-reducing admixtures such as polycarboxylate ether based superplasticisers can be considered. This is equally effective as a normal water-reducing admixture but a relatively low dose is required. The use of fly ash as filler would be preferable as its use can additionally offer some improvement in workability.

6.2 Increase in design strength

Another method to enhance the modulus of elasticity would be to increase the design strength of the RCA concrete. The additional strength required for matching the modulus of elasticity of RCA concrete with that of NA concrete, for designing concrete with up to100% RCA content and 20–45 GPa modulus of elasticity, is shown in Figure 10. This figure was produced from the previously used data in Figures 7 and 8 with measured strength data converted into characteristic strength by applying a coefficient of variation of 12·5% as used previously in developing Figure 9.

Following the previous example, to achieve a similar modulus of elasticity of 37 MPa characteristic cube strength concrete made with different NA rock types, when 50% of the aggregate is replaced with coarse RCA, Figure 10 shows that the strength of the RCA concrete needs to be increased by 7–13 MPa depending on the modulus of elasticity of NA concrete, as shown in Table 4.

This additional strength can be obtained by reducing the water content of the concrete by using a water-reducing admixture, thereby reducing the w/c ratio of the concrete and resulting in higher strength (Dhir *et al.*, 2004b, 2006), or by increasing the cement content to achieve the same effect. Of the two options, the former would be preferable on the grounds of sustainability as it uses less Portland cement. However, as the maximum water reduction is unlikely to be greater than 30%, the additional strength resulting from such an approach is also limiting and could be expected to limit the increase in strength

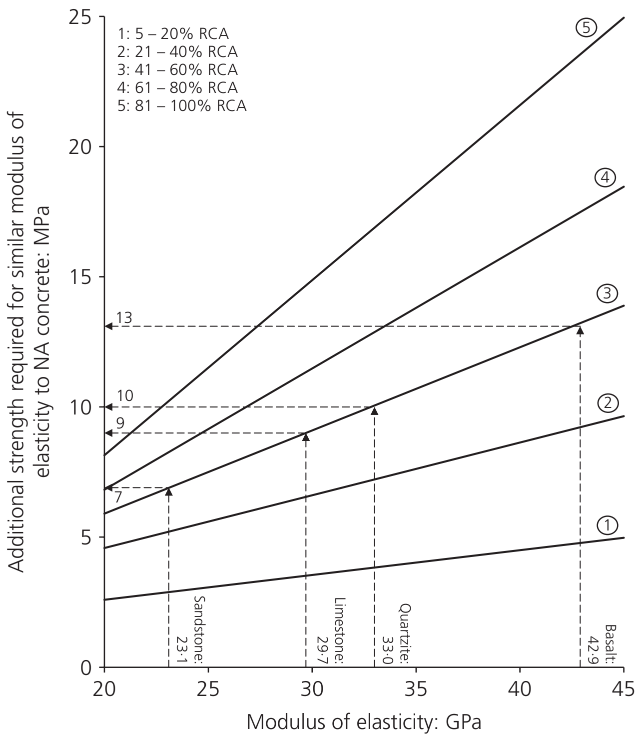

Figure 10. Additional strength required for concrete made with different coarse RCA contents to achieve similar modulus of elasticity to NA concrete

to a maximum of 10 MPa, depending on the properties of the constituent materials and mix design used. Thus, when higher additional strength is required due to an increase in RCA replacement level and the targeted modulus of elasticity, it can only be achieved through increasing the cement content of a mix.

Given the above, it would appear that, at present, the use of coarse RCA without having to increase cement content is likely to be limited to the maximum 50% replacement of NA as engineers endeavour to balance concrete performance requirements, the sustainability benefits that can be gained with the use of RAs and the extent to which concrete design can be manipulated.

7. Conclusions

Consolidation of 393 publications on the modulus of elasticity of concrete made with recycled aggregates identified from a near-exhaustive global literature search (limited to the English medium) revealed the following.

- The effect of coarse recycled concrete aggregate (RCA) on the static modulus of elasticity of concrete is most commonly reported, with 284 identified works published since 1977.
- Data on the modulus of elasticity of concretes made with fine RCA, mixtures of coarse and fine RCA, and other types and sizes of recycled aggregate (e.g. recycled masonry aggregate (RMA), mixed recycled aggregate (MRA) and construction and demolition recycled aggregate (CDRA)) have also been reported, but on a relatively very small scale.
- Technical reports produced by established organisations reveal that the use of coarse RCA in place of natural aggregate (NA) in concrete reduces its modulus of elasticity, with the level of reduction depending on RCA content and its properties, as well as mix design parameters such as w/c ratio and compressive strength.

Narrowing the focus to the effect of coarse RCA on the static modulus of elasticity of concrete, data from the 284 publications published since 1977 were systematically analysed, evaluated and synthesised. The main points to emerge from this analysis are as follows.

- The modulus of elasticity of RCA concrete relative to a corresponding reference NA concrete decreases at a decreasing rate with increasing RCA content, with a mean of 16% reduction at 100% RCA content, which is close to the modulus of elasticity multiplying factor of 0·80 suggested by some organisations. At 20% RCA content, rather than no change in modulus of elasticity suggested by some works, a slight reduction (5% on average) was calculated from the overall data population analysed.
- The reduction in modulus of elasticity of RCA concrete relative to NA concrete also decreases with an increase in the design strength of concrete, with a mean of 22% to 14% reduction at 100% RCA content in the lowest to highest strength groups, respectively.
- Plotting cube strength against modulus of elasticity and comparing it with values given in Eurocode 2 for concrete made with different NA rock types in decreasing aggregate stiffness order (namely basalt, quartzite, limestone and sandstone), the trendline of NA concrete for the published literature was found to be within the range of values for concrete made with quartzite and sandstone. The trendline of RCA concrete moved towards to concrete made with sandstone aggregate with increasing RCA content, and almost matched it at 100% RCA content for concrete strength up to 35 MPa.
- For a given characteristic cube strength and RCA content, the modulus of elasticity of RCA concrete can be estimated with the use of proposed multiplying factors developed from the published data in conjunction with a code of practice such as Eurocode 2.

Two simple and not so dissimilar methods involving mix adjustments of coarse RCA concrete have been proposed to enhance its modulus of elasticity, making it more appealing to specifying engineers for use in structural concrete.

- Achieving a reduction in cement paste, the water and cement contents of a mix can be reduced by the same proportion for a given w/c ratio. The workability and fines content can be maintained with the use of a water-reducing admixture and filler.
- Achieving an increase in strength by reducing the w/c ratio, it is recommended to reduce only the water content of a mix with the use of a water-reducing admixture, rather to increase its cement content. A method for estimating the additional strength required for RCA concrete at a given modulus of elasticity and RCA content has been proposed.

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