Elastic modulus of concrete made with recycled aggregates
Lye, Chao; Dhir, Ravindra; Ghataora, Gurmel

DOI:
10.1680/jstbu.15.00077
License:
None: All rights reserved

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (Harvard):

Link to publication on Research at Birmingham portal

Publisher Rights Statement:
Checked for eligibility: 29/01/2016. Copyright © ICE Publishing, all rights reserved.

General rights
Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

• Users may freely distribute the URL that is used to identify this publication.
• Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
• Users may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
• Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy
While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Download date: 14. Nov. 2022
Elastic modulus of concrete made with recycled aggregates
Lye, Dhir and Ghataora

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.
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.

![Figure 1. Distribution of publication data from the literature search](image-url)
Measurements of modulus of elasticity in terms of static, dynamic and initial tangent were also separated.

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.
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
<table>
<thead>
<tr>
<th>Reference</th>
<th>Number of references used</th>
<th>Elastic modulus of RA concrete wrt NA concrete</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Relative performance</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCAA (2008)</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>New Zealand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chisolm (2011) (CCANZ)</td>
<td>n.a.</td>
<td>n.a.</td>
<td>≤ 40% lower</td>
</tr>
<tr>
<td>Netherlands</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gerardu and Hendriks (1985)(Rijkswaterstaat)</td>
<td>3</td>
<td>n.a.</td>
<td>6–33% lower</td>
</tr>
<tr>
<td>Spain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Switzerland</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OT 70085 (2006) (reported by de Brito and Saikia (2013))</td>
<td>n.a.</td>
<td>n.a.</td>
<td>20% lower</td>
</tr>
<tr>
<td><strong>Multiplying factor on RCA concrete</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Belgium</td>
<td></td>
<td>0·80</td>
<td>For RCA with &gt;2100 kg/m³ dry density, &lt;9% water absorption and max. strength of 37 MPa</td>
</tr>
<tr>
<td>Belgium (not dated) (reported by Vyncke and Rousseau (1994))</td>
<td>n.a.</td>
<td>n.a.</td>
<td>For 0·45–0·79 w/c ratio</td>
</tr>
<tr>
<td>New Zealand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CUR-VB (1994) (reported by de Vries (1996))</td>
<td>1·00</td>
<td>0·95</td>
<td>For 20–30 MPa concrete</td>
</tr>
<tr>
<td>Spain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EHE-08 (2010)</td>
<td>1·00</td>
<td>0·80</td>
<td>For 30–50 MPa concrete</td>
</tr>
<tr>
<td>n.a.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rilem TC121 (1994), Hendriks and Henrichsen (1996)</td>
<td>n.a.</td>
<td>n.a.</td>
<td>For RCA with ≥2000 kg/m³ dry density, ≤10% water absorption and max. strength of 60 MPa</td>
</tr>
<tr>
<td>n.a.</td>
<td></td>
<td></td>
<td>For RCA with ≥2400 kg/m³ dry density, ≤3% water absorption and no strength limit</td>
</tr>
</tbody>
</table>

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
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,
y = 0.0015x^2 - 0.3095x + 100
\[ R^2 = 0.7612 \]

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

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

$$E_{R50} = 1\cdot12 \times 0\cdot88E_N = 0\cdot99E_N$$

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.
The modulus of elasticity values for NA concrete made with different rock types and the corresponding 50% RCA concrete values 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 to 100% 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.
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.

REFERENCES
ACI (American Concrete Institute) (2001) ACI 555-01: Removal and reuse of hardened concrete. American Concrete Institute, Farmington Hills, MI, USA.
ACI (2005) ACI 301-05: Specifications for structural concrete. American Concrete Institute, Farmington Hills, MI, USA.
Burke TT, Cohen MD and Scholer CF (1992) Synthesis Study on the Use of Concrete Recycled from Pavements and Building Structures and Buildings
Rubble in the Indiana Highway System. Purdue University and Indiana Department of Transportation JHRP (INDoT), West Lafayette, IN, USA, Report FHWA/IN/JHRP-92-15.


Cervantes V, Roesler J and Bordelon A (2007) Fracture and Drying Shrinkage Properties of Concrete Containing Recycled Concrete Aggregate. Department of Civil and Environmental Engineering, University of Illinois, Champaign, IL, USA, Technical Note 34.


Structures and Buildings

Dhir RK, Paine KA, de Brito J

Dhir RK, McCarthy MJ, Tittle PAJ and Zhou S

Dhir RK, Limbachiya MC and Leelawat T

Dhir RK and Paine K

Deshpande Y, Hiller JE and Shorkey CJ

de Vries P

de Pauw P, Thomas P, Vyncke J and Desmyter J


Fahmy W, Heneidy E, Ali E and Agwa I (2012) Performance of concrete containing crushed waste concrete exposed to...


Elastic modulus of concrete made with recycled aggregates
Lye, Dhir and Ghataora


Mohamad N, Samad AAA, Goh WL, Suffian S and Hizami MT (2014) The use of recycled aggregate in a development of


Structures and Buildings

Elastic modulus of concrete made with recycled aggregates

Lye, Dhir and Ghataora


Sarhat S and Sherwood E (2013) Residual mechanical response of recycled aggregate concrete after exposure to elevated...
Structures and Buildings

Elastic modulus of concrete made with recycled aggregates
Lye, Dhir and Ghatoora


WHAT DO YOU THINK?
To discuss this paper, please email up to 500 words to the editor at journals@ice.org.uk. Your contribution will be forwarded to the author(s) for a reply and, if considered appropriate by the editorial panel, will be published as discussion in a future issue of the journal.

Proceedings journals rely entirely on contributions sent in by civil engineering professionals, academics and students. Papers should be 2000–5000 words long (briefing papers should be 1000–2000 words long), with adequate illustrations and references. You can submit your paper online via www.icevirtuallibrary.com/content/journals, where you will also find detailed author guidelines.