Establishing rational use of recycled aggregates in concrete: a performance-related approach

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Leading on from the foundation research and development projects undertaken and published in several papers by the authors on the use of recycled and manufactured aggregates during the past 15 years, this paper describes the experimental work carried out to compare the strength, load-dependent and load-independent deformation characteristics of concrete made from 30 normal-weight, natural, recycled and manufactured aggregates. The main aim of this specific study was to explore the possibility for considering all normal-weight aggregates within the framework of BS EN 12620 under one umbrella and thereby removing the stigma commonly associated with the recycled and manufactured materials. This 3-year extensive research led to the development of a performance-related approach that rationalises the use of recycled aggregate in concrete and could lead to its greater use and contribution to the global sustainability agenda.

Notation
\( E_c \) elastic modulus of concrete
\( f_c \) compressive strength of concrete
\( f_{ct} \) tensile strength of concrete
\( f_{ct,fl} \) tensile flexural strength of concrete
\( f_{ct,sp} \) tensile splitting strength of concrete
\( h \) height of beam used in flexural test

Introduction

BS EN 12620 (BSI, 2008a) specifies the properties of aggregates and filler aggregates with an oven-dried particle density greater than 2000 kg/m\(^3\). Materials with a lower particle density are described as lightweight aggregates and are subject to appropriate caveats for use in concrete. Although BS EN 12620 specifies no upper limit on aggregate density, BS EN 206 (BSI, 2013a) classifies normal-weight aggregates to have oven-dry particle density ranging from 2000 kg/m\(^3\) to 3000 kg/m\(^3\). Consequently, aggregates with an oven-dried particle density between 2000 and 3000 kg/m\(^3\) may be classified as normal-weight aggregates.

The material permitted by BS EN 12620 as normal-weight aggregate can be obtained by processing of natural mineral resources, or from industrial by-products or construction demolition, and is also permitted to be a combination of these materials. BS EN 12620 describes these aggregates as follows

- natural aggregates are from mineral sources and subject to nothing more than mechanical processing
- manufactured aggregates are of mineral origin resulting from industrial process involving thermal or other modification
- recycled aggregates result from the processing of inorganic material previously used in construction.

Normal-weight natural aggregates are by far the most widely used in construction, whereas manufactured and recycled aggregates constitute less than 3% of all aggregate use worldwide (Dhir and Paine, 2010). However, provided that the aggregates are of suitable shape, size and texture, and meet requirements pertaining to the inclusion of harmful species, for example through limits on chlorides, sulfates and organic materials, they may be used in concrete.

Other than the requirement that aggregates are hard and stable, the engineering performance-related requirements for aggregates are rarely, if ever, considered for their use in concrete. This is because concrete producers state that they can easily cope with the effects such characteristics have on the strength, deformation and durability performance of concrete by making adjustments to mix proportions — in particular water-to-cement (w/c) ratio. Thus, possibly for this reason, BS EN 12620 makes no specific recommendations on the choice of a particular normal-weight natural aggregate for use in concrete.

In contrast, for normal-weight recycled aggregates BS EN 12620 does include specific requirements on the composition of the aggregates based on the crushed concrete (RC), crushed masonry (RB), unbound stone (RU), crushed asphalt (RA) and crushed glass...
(\(R_c\)) contents, in addition to determining the mass of floating and non-floating stony material. Given that requirements for shape, size and chemical content are identical to those of normal normal-weight aggregates, these categories must reflect differences in performance levels when used in concrete. Nevertheless, there is currently no methodology for use of these categories to assist with the appropriate selection of aggregates, nor is there any research to demonstrate whether recycled aggregates meeting a specific category provide a given level of performance when used in concrete.

Gonçalves and De Brito (2010) have attempted to use composition to classify aggregates and establish the requirements for use in concrete. However, their work was restricted to only three categories: (a) \(R_c > 90\%\), (b) \(R_b > 90\%\) and (c) all other recycled aggregates. Additionally, in the UK in particular, concrete made from material falling into the third category will vary significantly. Furthermore, because recycled aggregate may contain significant proportions of natural stone, it can often be a better-quality aggregate than that containing large proportions of \(R_c\). It is clear from substantial research on the use of recycled aggregates in concrete that the performance of concrete cannot be directly correlated with the composition of the aggregates used (Dhir et al., 2011; Xiao et al., 2006). Indeed, the characteristics of the aggregate used are much more important.

There are two further objections to the use of composition as an approach to classifying aggregates for use in concrete.

(a) Recycled aggregates of nominally similar composition can have entirely different properties depending on the original source of crushed concrete, stone, brick and other constituents from which they are derived.

(b) Owing to the much wider variability and composition of natural and manufactured aggregates, such an approach would be unwieldy when it is applied to such aggregates.

Consequently, users have to treat similar performing natural and manufactured aggregates in a completely different manner to how they approach the use of recycled aggregates.

Bearing this in mind, Paine and Dhir (2010) have developed an alternative to composition-based classification systems that is based on the performance-related properties of aggregates. Their research has shown that the effect of a given recycled aggregate on the strength, deformation characteristics and durability of concrete can be ascertained through the knowledge of the aggregate’s (a) Los Angeles (LA) coefficient, (b) particle density, (c) water absorption and (d) drying shrinkage value, as determined using standard European test methods. Consequently, recycled aggregates can be classified effectively in three classes suitable for different applications, as given in Table 1.

Although this approach has merit, it does not overcome the issue that a performance-related approach to the use of recycled aggregates is different to the methods currently used for other normal-weight aggregates. The danger of this is that, with such an approach, recycled aggregates will continue to be considered as distinct aggregates and not as one part of a single family of normal-weight aggregates. This is unacceptable for the wider interest of sustainability, which requires greater and wider use of recycled and manufactured aggregate resource and thereby minimising the use of natural resource.

The research described in this paper represents work undertaken to investigate whether a performance-related approach can be used or broadened to cover the use of the whole family of normal-weight coarse aggregates permitted by BS EN 12620 for use in concrete.

Materials and methodology

Aggregates

To determine the suitability of the performance-related approach to the wider family of normal-weight coarse aggregates, ten aggregates covering what may be considered to approximate the complete range of particle density, water absorption, LA coefficient and drying shrinkage that can be achieved by aggregates commonly used in the production of concrete were used. Furthermore, the aggregates chosen reflected the range of differences in shape, texture, porosity and flakiness of commonly used normal-weight aggregates. The particular aggregates were selected based on much broader studies of differences in natural aggregate quality (Dhir et al., 1971) and recycled aggregate properties (Dhir et al., 2008). The ten normal-weight aggregates comprised: five natural aggregates, four recycled aggregates and one manufactured aggregate. Their composition, properties and characteristics are presented in Tables 2 and 3.

The five natural aggregates are listed below

(a) Natural gravel; a naturally smooth and rounded granular material with a low water absorption and aggregate density of 2570 kg/m\(^3\), quarried from naturally occurring gravel pits.

(b) Four crushed rock aggregates that were of irregular/angular shape resulting from rock breaking, crushing, washing and screening:

(i) carboniferous limestone

(ii) dolomitic limestone

(iii) granite

(iv) basalt.

The four crushed rock aggregates represented both sedimentary and igneous rock formations.

The four recycled aggregates comprised three mixed recycled aggregates (RA) and a recycled concrete aggregate (RCA). The three RAs were selected as representative of RA available in the UK (Dhir et al., 2008). The physical properties of the RCA were in the middle of the range of typical commercially available RCA (Dhir et al., 1999).

The one manufactured aggregate, incinerator bottom ash aggre-
Table 1. Performance-related aggregate requirements for the three proposed classes of coarse RA and permissible forms of concrete based on exposure conditions (Paine and Dhir, 2010)

<table>
<thead>
<tr>
<th>Class</th>
<th>Minimum LA class</th>
<th>LA&lt;sub&gt;25&lt;/sub&gt;</th>
<th>Minimum density, SSD: kg/m&lt;sup&gt;3&lt;/sup&gt;</th>
<th>2500</th>
<th>Maximum water absorption: %</th>
<th>3</th>
<th>Max. drying shrinkage value: %</th>
<th>0.075</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>No risk of corrosion</td>
<td>XO</td>
<td>XC-1</td>
<td>XC-2</td>
<td>XC-3</td>
<td>XC-4</td>
<td>XD-1</td>
<td>XD-2</td>
</tr>
<tr>
<td></td>
<td>Freeze-thaw attack</td>
<td>XF-1</td>
<td>XF-2</td>
<td>XF-3</td>
<td>XF-4</td>
<td>DC-1</td>
<td>DC-2</td>
<td>–</td>
</tr>
<tr>
<td>B</td>
<td>Minimum LA class</td>
<td>LA&lt;sub&gt;40&lt;/sub&gt;</td>
<td>Minimum density, SSD: kg/m&lt;sup&gt;3&lt;/sup&gt;</td>
<td>2375</td>
<td>Maximum water absorption: %</td>
<td>4.5</td>
<td>Max. drying shrinkage value: %</td>
<td>0.075</td>
</tr>
<tr>
<td></td>
<td>No risk of corrosion</td>
<td>XO</td>
<td>XC-1</td>
<td>XC-2</td>
<td>XC-3</td>
<td>XC-4</td>
<td>XD-1</td>
<td>XD-2</td>
</tr>
<tr>
<td></td>
<td>Freeze-thaw attack</td>
<td>XF-1</td>
<td>XF-2</td>
<td>–</td>
<td>–</td>
<td>DC-1</td>
<td>DC-2</td>
<td>–</td>
</tr>
<tr>
<td>C</td>
<td>Minimum LA class</td>
<td>LA&lt;sub&gt;55&lt;/sub&gt;</td>
<td>Minimum density, SSD: kg/m&lt;sup&gt;3&lt;/sup&gt;</td>
<td>2150</td>
<td>Maximum water absorption: %</td>
<td>No limit</td>
<td>Max. drying shrinkage value: %</td>
<td>0.075</td>
</tr>
<tr>
<td></td>
<td>No risk of corrosion</td>
<td>XO</td>
<td>XC-1</td>
<td>XC-2</td>
<td>–</td>
<td>–</td>
<td>DC-1</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Corrosion induced by carbonation</td>
<td>XC-1</td>
<td>XC-2</td>
<td>–</td>
<td>–</td>
<td>DC-1</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Freeze-thaw attack</td>
<td>XF-1</td>
<td>XF-2</td>
<td>–</td>
<td>–</td>
<td>DC-1</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Sulfate attack</td>
<td>DC-1</td>
<td>DC-2</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

SSD = saturated surface dry density.

Table 2. Composition of the five coarse recycled and manufactured aggregates

<table>
<thead>
<tr>
<th>Type of aggregate</th>
<th>Constituent</th>
<th>RA1</th>
<th>RA2</th>
<th>RA3</th>
<th>RCA</th>
<th>IBAA</th>
</tr>
</thead>
<tbody>
<tr>
<td>R&lt;sub&gt;B&lt;/sub&gt; (clay masonry)</td>
<td>12.0</td>
<td>10.0</td>
<td>6.5</td>
<td>1.0</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>R&lt;sub&gt;C&lt;/sub&gt; (concrete)</td>
<td>37.0</td>
<td>35.0</td>
<td>23.0</td>
<td>34.0</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>R&lt;sub&gt;D&lt;/sub&gt; (stone)</td>
<td>51.0</td>
<td>54.0</td>
<td>67.0</td>
<td>63.0</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>R&lt;sub&gt;A&lt;/sub&gt; (asphalt)</td>
<td>0.0</td>
<td>0.5</td>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>R&lt;sub&gt;G&lt;/sub&gt; (glass)</td>
<td>0.0</td>
<td>0.0</td>
<td>1.1</td>
<td>0.0</td>
<td>77.0</td>
<td></td>
</tr>
<tr>
<td>X (clay, soil)</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>Fl (floating material)</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>

RA = recycled aggregate; RCA = recycled concrete aggregate.
<table>
<thead>
<tr>
<th>Standards</th>
<th>Natural gravel</th>
<th>Carboniferous limestone</th>
<th>Dolomitic limestone</th>
<th>Granite</th>
<th>Basalt</th>
<th>RA1</th>
<th>RA2</th>
<th>RA3</th>
<th>RCA</th>
<th>IBAA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flakiness index</td>
<td>BS EN 933-3</td>
<td>12</td>
<td>14</td>
<td>13</td>
<td>14</td>
<td>38</td>
<td></td>
<td>12</td>
<td>42</td>
<td>26</td>
</tr>
<tr>
<td>Shape (visual inspection)</td>
<td></td>
<td>Rounded</td>
<td>Irregular</td>
<td>Angular</td>
<td>Angular</td>
<td></td>
<td></td>
<td>Angular</td>
<td>Irregular</td>
<td>Angular</td>
</tr>
<tr>
<td>Texture (visual inspection)</td>
<td></td>
<td>Smooth</td>
<td>Rough</td>
<td>Rough</td>
<td>Rough</td>
<td></td>
<td></td>
<td>Rough</td>
<td>Rough</td>
<td>Rough</td>
</tr>
<tr>
<td>Density: kg/m³</td>
<td>BS EN 1097-6</td>
<td>2570</td>
<td>2680</td>
<td>2620</td>
<td>2610</td>
<td>2730</td>
<td></td>
<td>2400</td>
<td>2370</td>
<td>2430</td>
</tr>
<tr>
<td>(a) Oven dry</td>
<td>BS EN 1097-3</td>
<td>1520</td>
<td>1440</td>
<td>1430</td>
<td>1450</td>
<td>1460</td>
<td></td>
<td>1190</td>
<td>1250</td>
<td>1270</td>
</tr>
<tr>
<td>(b) Loose bulk</td>
<td>BS EN 1097-4</td>
<td>1610</td>
<td>1540</td>
<td>1520</td>
<td>1560</td>
<td>1560</td>
<td></td>
<td>1250</td>
<td>1390</td>
<td>1420</td>
</tr>
<tr>
<td>(c) Compacted bulk</td>
<td>BS EN 1097-6</td>
<td>1-0</td>
<td>0-8</td>
<td>2-0</td>
<td>0-7</td>
<td>1-5</td>
<td>4-4</td>
<td>2-9</td>
<td>3-5</td>
<td>3-0</td>
</tr>
<tr>
<td>Water absorption: %</td>
<td>BS EN 1097-6</td>
<td>0-03</td>
<td>0-03</td>
<td>0-03</td>
<td>0-016</td>
<td>0-031</td>
<td>0-065</td>
<td>0-055</td>
<td>0-06</td>
<td>0-054</td>
</tr>
<tr>
<td>LA coefficient: %</td>
<td>BS EN 1097-2</td>
<td>25</td>
<td>22</td>
<td>25</td>
<td>26</td>
<td>20</td>
<td>36</td>
<td>21</td>
<td>34</td>
<td>26</td>
</tr>
<tr>
<td>Micro-Deval coefficient: %</td>
<td>BS EN 1097-1</td>
<td>20</td>
<td>24</td>
<td>17</td>
<td>12</td>
<td>14</td>
<td>39</td>
<td>32</td>
<td>37</td>
<td>24</td>
</tr>
<tr>
<td>Drying shrinkage: %</td>
<td>BS EN 1367-4</td>
<td>0-03</td>
<td>0-03</td>
<td>0-03</td>
<td>0-016</td>
<td>0-031</td>
<td>0-065</td>
<td>0-055</td>
<td>0-06</td>
<td>0-054</td>
</tr>
<tr>
<td>Loss on ignition: %</td>
<td>BS EN 1744-1</td>
<td>3-5</td>
<td>42-2</td>
<td>49</td>
<td>0</td>
<td>0-5</td>
<td>5-0</td>
<td>7-6</td>
<td>9-0</td>
<td>7-2</td>
</tr>
<tr>
<td>Acid-soluble sulfates: %</td>
<td>BS EN 1744-1</td>
<td>0-1</td>
<td>ND</td>
<td>ND</td>
<td>0-1</td>
<td>ND</td>
<td>0-4</td>
<td>0-2</td>
<td>0-3</td>
<td>0-3</td>
</tr>
<tr>
<td>Acid-soluble chlorides: %</td>
<td>BS EN 1744-5</td>
<td>0-01</td>
<td>0-01</td>
<td>0-01</td>
<td>0-00</td>
<td>0-02</td>
<td>0-1</td>
<td>0-1</td>
<td>0-11</td>
<td>0-1</td>
</tr>
<tr>
<td>Water-soluble chlorides: %</td>
<td>BS EN 1744-1</td>
<td>0-00</td>
<td>0-00</td>
<td>0-00</td>
<td>0-00</td>
<td>0-00</td>
<td>0-01</td>
<td>0-09</td>
<td>0-01</td>
<td>0-01</td>
</tr>
</tbody>
</table>

Table 3. Properties and characteristics of the coarse aggregates used.
agate (IBAA), was chosen in order to have an aggregate with more extreme values of density, LA coefficient and drying shrinkage value than what is normally associated with normal-weight aggregates. IBAA is a by-product of the incineration of municipal solid waste (Paine et al., 2002).

Mix proportions
All ten aggregates were used to produce concretes with w/c ratios of 0.35, 0.50 and 0.70. In the case of natural aggregates these were used as the sole coarse aggregate. Recycled and manufactured aggregates were also used as the sole coarse aggregates; they are also in combination with natural aggregates (natural gravel and carboniferous limestone) at 25% and 50% by mass of all coarse aggregate. In total this led to 30 combinations of coarse aggregates. In all concretes, natural river sand was used as the fine aggregate and CEM I (42.5N) was used as the cement.

Mixes were proportioned for equal w/c ratio; the water content was adjusted to reflect the more angular shape of the crushed aggregates when compared with natural gravel. The aggregates were proportioned in accordance with the procedures described in Teychenne et al. (1988).

The engineering properties of concrete tested were: compressive strength (to BS EN 12390-3; BSI, 2009a), tensile splitting strength (to BS EN 12390-6; BSI, 2009b), flexural strength (to BS EN 12390-3; BSI, 2009a), static modulus of elasticity (to BS EN 1367-4 test for aggregates; BSI, 1988b), and basic/creep (to the method described by Dhir et al. (1986)).

Concrete properties

Compressive strength
The effect of aggregate type on the cube strength of concrete is shown in Table 4. The data in Table 4 represent the mean values of three cubes tested at each w/c ratio. It is clear that the aggregates have a large effect on the compressive strength of concrete, for example at a w/c ratio of 0.5 strengths from 24.0 to 57.5 N/mm² were obtained, depending on the aggregate used. This range of compressive strength is not surprising given the wide range of normal-weight aggregates used (Table 3). Similar findings have been reported by Zhou et al. (1999) and Limbachiya et al. (2004).

From the results, Figure 1 shows two relationships between w/c ratios and cube strength for two normal-weight aggregates, additionally showing the difference in w/c ratio required to achieve a cube strength of 40 N/mm² as obtained from interpolation of the data. For example, for concrete produced with RA1 a w/c ratio of 0.41 is required, whereas for concrete with natural gravel (NG) a w/c ratio of 0.57 is required. Evidently, this indicates the effect that aggregate type/properties can have on the compressive strength of concrete, and more importantly on the cement content required when mix proportioning. Similarly, in Table 4. Effect of aggregate type on 28-day cube strength of concretes

<table>
<thead>
<tr>
<th>Aggregate type</th>
<th>28-day cube strength: N/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>w/c = 0.35</td>
<td>w/c = 0.50</td>
</tr>
<tr>
<td>Natural gravel (NG)</td>
<td>64.5</td>
</tr>
<tr>
<td>Basalt</td>
<td>72.0</td>
</tr>
<tr>
<td>Carboniferous limestone</td>
<td>76.0</td>
</tr>
<tr>
<td>Dolomitic limestone</td>
<td>72.0</td>
</tr>
<tr>
<td>Granite</td>
<td>67.0</td>
</tr>
<tr>
<td>75% NG, 25% RA1</td>
<td>59.0</td>
</tr>
<tr>
<td>75% NG, 25% RA2</td>
<td>62.0</td>
</tr>
<tr>
<td>75% NG, 25% RA3</td>
<td>63.5</td>
</tr>
<tr>
<td>75% NG, 25% RCA</td>
<td>65.0</td>
</tr>
<tr>
<td>75% NG, 25% IBAA</td>
<td>51.5</td>
</tr>
<tr>
<td>50% NG, 50% RA1</td>
<td>55.0</td>
</tr>
<tr>
<td>50% NG, 50% RA2</td>
<td>58.0</td>
</tr>
<tr>
<td>50% NG, 50% RA3</td>
<td>60.5</td>
</tr>
<tr>
<td>50% NG, 50% RCA</td>
<td>63.5</td>
</tr>
<tr>
<td>50% NG, 50% IBAA</td>
<td>43.5</td>
</tr>
<tr>
<td>RA1</td>
<td>50.0</td>
</tr>
<tr>
<td>RA2</td>
<td>54.0</td>
</tr>
<tr>
<td>RA3</td>
<td>55.0</td>
</tr>
<tr>
<td>RCA</td>
<td>60.0</td>
</tr>
<tr>
<td>IBAA</td>
<td>36.5</td>
</tr>
</tbody>
</table>

Figure 2, four aggregate properties are plotted against compressive strength, indicating the relationships. As the quality of the aggregate changed, in terms of higher water absorption and lower density a clear reduction in compressive strength was observed. Similar findings have been reported by Dhir et al. (1999) and Limbachiya et al. (2004).

Tensile strength
All samples were tested at 28-day strength. Results from the flexural strength (ft,sp) and tensile splitting strength (fc,sp) tests were converted into axial tensile strength (fa) values in accordance with equations presented in Eurocode 2 (BS EN 1992-1-1; BSI, 2004) (Equation 1 and Equation 2). Equation 2 has been rearranged from that given in Eurocode 2, so the mean axial tensile strength values can be obtained. In this research the value obtained from Equation 1, axial tensile strength, is deemed to be a mean axial tensile strength value for comparison purposes. The mean axial tensile strengths of the two tests are illustrated in Figure 3. The mean axial strength is affected by the aggregate characteristics as it is clear that in general aggregates with higher LA coefficient, higher aggregate impact value, lower density and higher water absorption produce concretes that have lower tensile strength. The coefficient of determination, R², is useful as it gives a guideline of the inclination of the importance of the parameter on the tensile strength of concrete. The coefficient of determi-
nation is the ratio of the explained variation to the total variation and ranges from 0 \(< R^2 < 1\), and denotes the strength of the linear association between \(x\) and \(y\).

1. \( f_{ct} = 0.90 f_{ct,up} \)

2. \( f_{ct} = \left[ \frac{f_{ct,0}}{1 - 0.006 (h/1000)} \right] \)

Modulus of elasticity
Aggregates have the most significant effect on modulus of elasticity of all the constituents of concrete (Alexander, 1993). The modulus of elasticity of concrete \((E_c)\) is also affected by strength and age of the concrete; cylinders were loaded to a third of their compressive strength at the age of 28 and 90 d. The slope (steepness) of the hysteresis loop was used to calculate the modulus of elasticity for the concretes. All concretes assessed in this research have similar coarse aggregate volumetric contents (41–43\% of all the constituents for the concretes), therefore variation in modulus of elasticity values is dependent on the coarse aggregate characteristics.

Considering the nature of modulus of elasticity and the range of characteristics of normal-weight aggregates, an assortment of modulus of elasticity values was expected within this research. Figure 4 shows a correlation between elastic modulus and three aggregate properties. As the aggregate quality deteriorates (decrease in the aggregate density, increase in water absorption and LA coefficient), a reduction in the modulus of elasticity was observed at all three w/c ratios. These findings correspond with findings reported in the literature (Ajdukiewicz and Kliszczewicz, 2002; Berndt, 2009; Gonzalez-Fonteboa and Martinez-Abella, 2008).

Despite the poor correlation with aggregate characteristics, the equations in Eurocode 2 recognise that it is not possible to determine elastic modulus without some knowledge of the aggregate type. The current method has a basic equation (Equation 3) based on the cylinder strength of concrete \((f_c)\) for which the output should be reduced by 10\% and 30\% respectively when using limestone and sandstone, and should be increased by 20\% for basalt aggregates. Clearly, this indicates the effects that different aggregates have on the modulus of elasticity, which leads to the question: why are aggregate properties or aggregate categories as given in BS EN 12620 not used to estimate the modulus of elasticity of concrete?

3. \( E_c = 22 \left( \frac{f_c}{10} \right)^{0.3} \)

Creep
The creep behaviour of concrete is influenced by a number of mechanisms, of which the most important are associated with the hydrated cement paste and are independent of specimen size and shape. However, for a nominally identical hydrated cement paste (based on cement type, cement content and w/c ratio), researchers have reported that concrete containing lower-grade normal-weight aggregates (e.g. those with higher water absorption and lower particle density) creep more than concrete with higher-grade normal-weight aggregates (Gomez-Soberon et al., 2002; Hansen, 1992; Limbachiya et al., 1998).

The results presented in this research were for concretes loaded to 40\% of their 28-day cube compressive strength after 28 d of water curing. Figure 5 shows the creep strain and creep coefficients (defined as creep strain divided by the initial elastic strain). It is clear that as the replacement level of lower-grade aggregates increased, the concrete creep also increased. This was to be expected as the modulus of elasticity of aggregates contributes to the modulus of elasticity of the concrete, which helps restrain the cement paste from undergoing creep, indicating that in general
the higher the modulus of elasticity of concrete, the lower the creep strain. Dhir et al. (1999) have reported similar findings.

At the lower ends of the normal-weight aggregate range, IBAA gave the highest creep strain results within this research, a 21.5% increase in creep strain over that of NG concrete when used as the sole aggregate.

Shrinkage
Drying shrinkage of concrete is the shrinkage caused by evaporation of the internal water in hardened concrete. The aggregates in the concrete influence the shrinkage by restraining the cement paste. It is known that an increase in aggregate content will normally reduce shrinkage of the concrete, if the aggregates are stiffer than the cement paste and have a lower shrinkage value. According to BS EN 12620, aggregates for structural concrete shall, when required, not lead to a concrete shrinkage in excess of 0.075% when tested in accordance with BS EN 1367-4 using a prescribed concrete. Within this research, the concretes were tested according to the method described in BS EN 1367-4, but the mix proportions described earlier were used rather than the prescribed concrete proportions in BS EN 1367-4. The prisms

Figure 2. Effect of aggregate properties on the compressive strength of concrete for w/c ratios of 0.35, 0.50 and 0.7: (a) LA coefficient; (b) aggregate impact value; (c) water absorption; (d) aggregate density SSD
were subjected to wetting for 120 h and drying for 72 h, and the changes in length were expressed as a percentage of the initial length of the prism.

The results indicated that as the RA and IBAA content increased so too did the drying shrinkage of the concretes. These findings are similar to those reported by Dhir and Paine (2003). IBAA concrete (as the sole aggregate) had the highest drying shrinkage value.

**Applicability of Eurocode 2 equations**

Eurocode 2 provides methods, in the form of a set of equations, for determining the engineering properties of concrete from its 28-day compressive strength, by simple relationships that, with the exception of elastic modulus, are independent of concrete constituents or mix proportions. However, there has been concern that these relationships may not fully embrace all materials permitted by BS EN 12620 and BS EN 197-1 (Dhir et al., 2005). Thus, it is desirable to clarify whether these equations are

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![Graphs showing the effect of aggregate properties on the axial tensile strength of concrete for w/c ratios of 0.35, 0.50, and 0.7: (a) LA coefficient; (b) aggregate impact value; (c) aggregate density SSD; (d) water absorption.](image-url)

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**Figure 3. Effect of aggregate properties on the axial tensile strength of concrete for w/c ratios of 0.35, 0.50, and 0.7:**

(a) LA coefficient; (b) aggregate impact value; (c) aggregate density SSD; (d) water absorption
applicable to the wide range of normal-weight aggregates used in concrete and, where necessary, develop modifications to complement those in Eurocode 2.

To assess the effect of aggregates on the relationship between 28-day compressive strength and engineering properties, mean cube strengths obtained in this study were converted to characteristic or mean cylinder strengths, as appropriate, in accordance with the relationships given in Eurocode 2; these had been previously verified for recycled and manufactured aggregates (Paine et al., 2009). Figure 6 shows the relationships between compressive strength and Figure 6(a) splitting tensile strength, Figure 6(b) elastic modulus, Figure 6(c) drying shrinkage and Figure 6(d) creep, for all experimental data obtained. The appropriate Eurocode 2 relationships are also shown together with their 95% confidence limits. Additional data supplied from a parallel study by the BRE (2007) is also given.

For drying shrinkage, the values measured were compared to the nominal unrestrained drying shrinkage values given in Eurocode 2. An equation presented in Annex B of Eurocode 2 was used to determine a drying shrinkage value for 0% relative humidity with variation in compressive strength. A coefficient of variation of approximately 30% can be expected with Eurocode 2 estimated values which are illustrated in Figure 6(c) with error bars. Comparisons of the experimental and estimated values are discussed in more detail in the following section.

Based on these comparisons between estimated and experimental values, Table 5 indicates the applicability of the relevant Eurocode 2 equations for each aggregate. For the majority of aggregates, the Eurocode 2 equations have been shown to be appropriate and this is designated in Table 5 with a ‘yes’; however, as the modulus of elasticity has four design curves recommended within the Eurocode 2, the most appropriate design curve is named in Table 5. Also included in Table 5 are four aggregate properties representing the effect aggregate properties have on the applicability of Eurocode 2 equations to estimated engineering properties of normal-weight aggregate concretes based exclusively on compressive strength values.

Summarising the data presented in Table 5, it can be deduced that the Eurocode 2 design equations adequately estimated the compressive strength development, mean axial tensile strength, modulus of elasticity, creep coefficient (method one) and drying shrinkage for the majority of normal-weight concretes. However, as the range of normal-weight aggregate properties varies (WA value < 2.5% and AD > 2500 kg/m³), it is recommended that the modulus of elasticity be estimated with the 30% reduction to design equation (sandstone design curve), as other design curves could lead to overestimating the values. Similarly, caution is required when estimating the creep coefficient with the ‘basic equations for determining the creep coefficient’ presented in Annex B of Eurocode 2, as this could result in an underestimation value. It is recommended that creep coefficient of
Figure 5. Creep strain and creep coefficient of normal-weight aggregate concretes at different replacement levels: (a) 25%; (b) 50%; (c) 100%
normal-weight aggregate concretes be estimated by section 3.1.4 in Eurocode 2.

**Performance-related approach for normal-weight aggregates**

Previous research has demonstrated that, although the use of recycled aggregates in concrete leads in the most part to lower concrete performance than equivalent concrete mixes prepared with natural aggregates at the same w/c ratio, the loss in performance may be correlated to appropriate properties of the aggregate (LA coefficient, aggregate absorption, density and drying shrinkage) (Paine and Dhir, 2010). Furthermore it was shown that it was possible to separate the combinations of aggregate into classes that would perform to a given requirement provided suitable practical considerations were taken into account; for example, slight adjustments to the w/c ratio, as recommended elsewhere (Dhir et al., 1999). It was also suggested that there was a strong case for considering the use of all aggregates on a performance-related basis, but this was not proven (Paine and Dhir, 2010).

The results of the experimental work described in this paper have shown that there is indeed a strong correlation between LA coefficient, aggregate absorption, density and drying shrinkage and the key engineering properties of all normal-weight aggregate concretes. As a result it is possible to ascertain that these four

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**Figure 6.** Correlation between Eurocode 2 design equations and experimentally obtained values: (a) mean axial tensile strength; (b) static modulus of elasticity; (c) drying shrinkage; (d) creep

normal-weight aggregate concretes be estimated by section 3.1.4 in Eurocode 2.
aggregate properties together are effective in appropriately rank-
ing all normal-weight aggregates, not just recycled aggregates, in
terms of their effect on strength and deformation characteristics.

This suggests that there is a case for considering the use of all
normal-weight aggregates as part of a single family of aggregates
regardless of source and that any differences in performance can
be considered on a performance-related approach.

There are many means by which a performance-related approach
can be adopted in concrete design. As an example, one simple
approach, although not necessarily the most appropriate, is to use
it in the selection of mix proportions.

In order to establish mix proportioning charts, the following steps
were carried out.

\( (a) \) The \( w/c \) ratio required for concrete to achieve strengths of 30,
40 and 60 N/mm\(^2\) was interpolated, or extrapolated where
necessary, from strength plotted against \( w/c \) ratio curves,
assuming Abrams Law to hold true, for each aggregate
combination. For example, for limestone it was found that a
maximum \( w/c \) ratio of 0.75, 0.66 and 0.47 corresponds to
achievement of 30, 40 and 60 N/mm\(^2\) respectively, whereas
for RA3 the equivalent maximum \( w/c \) ratios were 0.61, 0.51
and 0.34. An example is given in Figure 7(a).

\( (b) \) The \( w/c \) ratios for each aggregate combination (for strength)
were then plotted against the corresponding aggregate
property (LA coefficient, aggregate absorption, density and
aggregate impact value) for each concrete–aggregate
combination at a given strength; and a linear regression was
determined for each relationship (see Figure 7(b) as an
example – \( w/c \) ratios required for a strength of 40 N/mm\(^2\)
concrete plotted against LA coefficient).

\( (c) \) The \( w/c \) ratios relating to the different characteristic
categories in BS EN 12620 were then obtained from the
linear equation relationship (e.g. in Figure 7(b), the \( w/c \) ratios
required for a strength of 40 N/mm\(^2\) concrete plotted against LA coefficient).

\( \left( \right. \) The \( w/c \) ratios were calculated for LA
coefficient, aggregate absorption and density for compressive
strengths of 30, 40 and 60 N/mm\(^2\).

### Table 5. Normal-weight aggregate concretes compared to
Eurocode 2 design equations

<table>
<thead>
<tr>
<th>Aggregate properties</th>
<th>Conformance to Eurocode 2 design equations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compressive strength development, ( f_c )</td>
</tr>
<tr>
<td>Natural gravel (NG)</td>
<td>Yes</td>
</tr>
<tr>
<td>Basalt</td>
<td>Yes</td>
</tr>
<tr>
<td>Carboniferous limestone</td>
<td>Yes</td>
</tr>
<tr>
<td>Dolomitic limestone</td>
<td>Yes</td>
</tr>
<tr>
<td>Granite</td>
<td>Yes</td>
</tr>
<tr>
<td>NG 75%, RA 1 25%</td>
<td>Yes</td>
</tr>
<tr>
<td>NG 50%, RA 1 50%</td>
<td>Yes</td>
</tr>
<tr>
<td>RA1</td>
<td>Yes</td>
</tr>
<tr>
<td>NG 75%, RA 2 25%</td>
<td>Yes</td>
</tr>
<tr>
<td>NG 50%, RA 2, 50%</td>
<td>Yes</td>
</tr>
<tr>
<td>RA2</td>
<td>Yes</td>
</tr>
<tr>
<td>NG 75%, RA 3, 25%</td>
<td>Yes</td>
</tr>
<tr>
<td>NG 50%, RA, 3, 50%</td>
<td>Yes</td>
</tr>
<tr>
<td>RA3</td>
<td>Yes</td>
</tr>
<tr>
<td>NG 75%, RCA, 25%</td>
<td>Yes</td>
</tr>
<tr>
<td>NG 50%, RCA, 50%</td>
<td>Yes</td>
</tr>
<tr>
<td>RCA</td>
<td>Yes</td>
</tr>
<tr>
<td>NG 75%, IBAA, 25%</td>
<td>Yes</td>
</tr>
<tr>
<td>NG 50%, IBAA, 50%</td>
<td>Yes</td>
</tr>
<tr>
<td>IBAA</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Note: Yes = values are applicable to Eurocode 2 design equation; No = values are not applicable Eurocode 2 design equation.
From the data obtained above, a family of strength plotted against w/c ratio curves was generated for LA coefficient, aggregate absorption and density as shown in Figure 8. For example, Figure 8(b) shows the variation in strength plotted against w/c ratio curves for aggregates of different LA coefficients.

The resulting mix proportioning charts, shown in Figure 8, allow calculation of a maximum w/c ratio to achieve a given strength based on knowledge of an aggregate’s water absorption, particle density and LA coefficient. As an example of how this mix design procedure can be used, imagine the need to estimate the w/c ratio to obtain a compressive strength of 45 N/mm² using natural gravel (with a known water absorption of 1% by mass, 0·25 0·35 0·45 0·55 0·65 0·75 0·85 0·95
Compressive strength: N/mm²
(a)

Figure 7. Development of mix proportioning charts: (a) relationship between compressive strength of concrete and w/c ratio for three normal-weight aggregates; (b) relationship between w/c ratio required to achieve a concrete strength of 40 N/mm² and the LA coefficient of the coarse aggregate used

(d) From the data obtained above, a family of strength plotted against w/c ratio curves was generated for LA coefficient, aggregate absorption and density as shown in Figure 8. For example, Figure 8(b) shows the variation in strength plotted against w/c ratio curves for aggregates of different LA coefficients.

Figure 8. Design strength plotted against w/c ratio curves based on: (a) density, (b) LA coefficient and (c) water absorption of aggregates
particle density of 2600 kg/m$^3$, and an LA coefficient of 25% by mass).

From Figure 8 it can be seen that aggregates with a water absorption of 1%, on average, need to have a w/c ratio less than or equal to 0.56 to achieve a strength of 45 N/mm$^2$; likewise for the values of particle density and LA coefficient, on average w/c ratios less than or equal to 0.53 and 0.60 are required respectively. As 0.53 is the lowest of these values, this is the appropriate design value – which can for practical purposes be taken as 0.50.

Independent tests (Dhir et al., 2001) using an aggregate with these properties at a w/c ratio of 0.50 gave a compressive strength of 47 N/mm$^2$ – confirming the suitability of the approach.

A further outcome of this approach is that, while it clearly shows that all normal-weight aggregates are part of a single family, those aggregates with lower performance characteristics (high LA coefficient, high water absorption and low density) need lower w/c ratios to achieve a given strength than better-performing aggregates. As the required strength becomes higher, it becomes increasingly difficult to use lower-performing aggregates, either because the w/c ratio becomes so low that achievement of a reasonable consistency would be difficult to achieve even with admixtures, the cement content required is so high that cost or other aspects of mix design start to govern requirements, or optimum use of cement is not being made. As a result it becomes clear that certain aggregates are not suitable for high-strength concrete, and limits on choice and use of aggregates can be made through use of performance-related criteria. Likewise, some of the higher-performing aggregates can be deemed to be unsuitable for low-strength concretes because when used at w/c ratios that deliver appropriate consistence and finishability they yield concrete that is higher strength than it needs to be. Consequently, it is to be recommended that concrete producers implement minimum and maximum aggregate properties (LA coefficient, aggregate absorption, density and drying shrinkage) for given concrete strength classes.

Conclusions

The research reported in this paper has shown that all normal-weight aggregates, regardless of origin, are part of a broad family that may be treated in a similar way with respect to predicting the performance of concrete. Recycled aggregates are part of this single family, and they are not a distinct subset that requires more detailed understanding and knowledge than natural aggregates – as is currently the situation in most design codes and standards.

Specifically the following points have been shown.

(a) The Eurocode 2 design equations are applicable for the majority of normal-weight concretes subject to the caveats in Table 5.

(b) Aggregate properties can be incorporated into concrete mix proportioning charts to enable the prediction of effects on the compressive strength of concrete and on other performance aspects.

Subsequently, an approach has been proposed that bases the selection of aggregates on performance-related characteristics that relate the properties of aggregates to concrete performance across the whole range of normal-weight aggregate quality, independent of constituents and source. The methodology is based on an understanding that knowledge of four key aggregate properties (LA coefficient, particle density, water absorption and drying shrinkage value) are sufficient to assess the appropriate use of aggregates for most normal concrete operations.

In the authors’ opinion the implementation of a system based on performance-related characteristics is a rational approach and will be essential in eliminating the undue concerns associated with non-natural aggregates; this will lead to the greater use of recycled and manufactured aggregates and their contribution to the global sustainability agenda.

Given the ever-increasing importance of using alternatives to natural aggregates, it is recommended that further work, similar to that reported here, be undertaken so that the proposed performance-related approach be strengthened for its adoption in practice and perhaps be extended to lightweight and heavyweight aggregates. Further consideration of aspects of permeability and durability of concrete is also required.

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