DEFORMATION PROPERTIES OF CONCRETE MADE WITH RECYCLE AGGREGATES

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ABSTRACT. The characteristics of coarse recycled concrete aggregate (RCA), and their effects on concrete deformation properties: elastic modulus, creep and shrinkage, have been studied. A novel *analytical systemisation* method was developed for the analysis and evaluation of the results sourced from 713 studies, undertaken by 960 authors from 537 institutions in 46 countries during 1972–2017, forming a data matrix having over 400,000 data points. The physical properties of RCA were found to be affected by the crushing process. It was found that RCA reduces the resistance of concrete to deformation, due to the presence of the adhered cement paste. The change in the deformation was shown to be affected by aggregate content, concrete strength and other factors. Most of the existing models were found not to consider the aggregate effect in estimating the deformation of concrete. Three new empirical models, essentially based on aggregate stiffness in the form of aggregate absorption, aggregate content and its ratio to cement content, have been developed for estimating the deformation of concrete made with aggregate suitable for use in structural concrete.

Keywords: Recycled concrete aggregate, Deformation, Elastic modulus, Creep, Shrinkage

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INTRODUCTION

Globally, the annual aggregate production is estimated to be about 50 billion tonnes and is projected to grow at a rate of 5% yearly. As aggregates typically occupy about 70% of the volume or 75% of the weight of concrete, this would suggest that nearly 19 billion tonnes of aggregate, or one-third of the global aggregate production, are consumed in concrete production alone. A direct engineering solution to minimise the consumption of natural aggregate (NA) is to develop the use of recycled aggregates, such as recycled concrete aggregate (RCA), which is derived from concrete debris. However, these materials have not been widely accepted in practice and their adoption is slow.

After strength, the deformation of concrete is important in structural design as it affects the deflection of structural members, as well as the overall integrity of structures. During its service life, concrete experiences various forms of volume changes due to hydration chemistry, loading, time and ambient conditions. The deformation properties of concrete, in the form of load-dependent such as elastic and creep, and load independent such as shrinkage, are normally estimated using design codes, for example, in structural design, routine appraisal and safety assessment applications.

This paper presents the effects of using RCA on the deformation properties, namely, elastic, creep and shrinkage deformation, of concrete and three simple, yet reliable and practical models for use in structural concrete design, for each of the deformation properties investigated. A novel and original research approach, *analytical systemisation* method, as described in [1 - 5], has been adopted throughout the study.

CHARACTERISTICS OF RCA

The physical characteristics of aggregate have profound influence on aggregate packing, aggregate–cement paste bond, concrete mix design and stiffness of the mix, all which can affect the deformation properties of concrete. Table 1 compares some of the important physical characteristics of RCA to those NA.

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

Table 1 Characteristics of natural aggregate and recycled concrete aggregate [5]

PROPERTY	AGGREGATE TYPES	
	Natural Aggregate	Recycled Concrete Aggregate
Particle Shape	-	Angular
Surface Texture	-	Rough, porous
Grading	-	Tends to have particles > 10mm
Specific Gravity	2.6 – 2.7	2.42
Water Absorption	1 – 3%	5.1%
Hardness	-	Less stiff than NA

EFFECT OF RCA ON DEFORMATION

Three areas of deformation of concrete, which are of structural importance, are considered, namely elastic modulus, creep and shrinkage. Figure 1 shows the effect of RCA on the deformation of concrete, which was based on a strong data matrix, consisting of more than 400,000 data points, sourced from 713 publications, produced by 960 researchers, from 537 institutions and established organisations across 46 countries, over a period of 45 years. The main points emerged for each deformation property are given below:

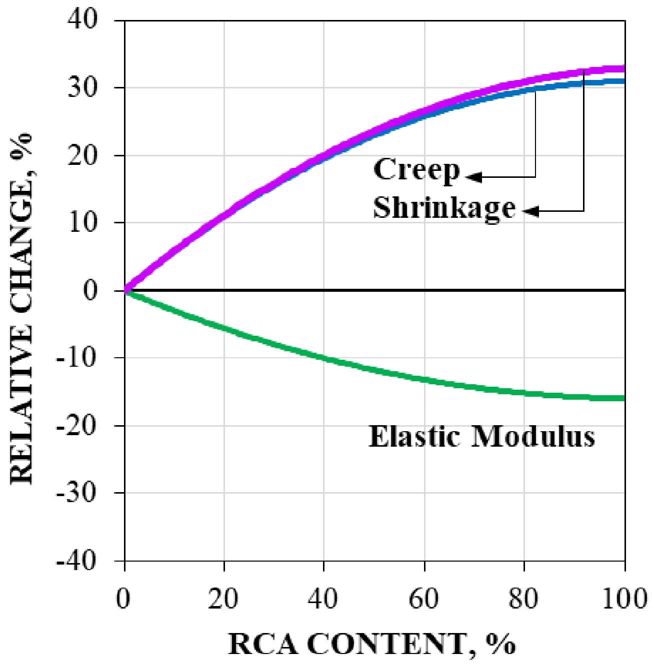

Figure 1 Deformation properties of concrete made with coarse RCA

Elastic Modulus

The elastic modulus of the concrete decreases at a decreasing rate, as the coarse RCA content, increases, giving an average of 16% reduction when NA is fully replaced by RCA. This level of reduction is within the range of 6%–40% reported by various organisations [6]. However, in contrast to the view that there is no change in elastic modulus at 20% RCA content, as suggested by some organisations, this study shows that the use of 20% RCA can result in an average reduction of 5%, which can possibly increase up to 15%.

It was also found that the relative reduction in elastic modulus of RCA concrete with respect to NA concrete decreases as the concrete strength increases, showing an average 22% reduction in the lowest strength concrete (20 MPa) and a 13% reduction in the highest strength concrete (130 MPa) [6]. Comparing the relationships between elastic modulus and compressive strength of concrete obtained in this study with those of Eurocode 2 (2004) for different rock types, namely basalt, quartzite, limestone and sandstone, it was shown that the trend line of NA concrete is within that of quartzite and sandstone concrete; on the other hand, that of RCA concrete moves towards that of sandstone concrete as RCA content increases.

Creep

The creep of concrete made with coarse RCA, in relation to the corresponding NA concrete, increases at a decreasing rate as the coarse RCA content increases. On average, the creep of concrete can increase by 32% when NA is fully replaced by RCA. This level of increase indicates that the increasing range of 30%–60%, suggested by the established organisations, is overstated [7]. In contrast to the 'no change' at 20% coarse RCA content suggested by some established organisations, the findings of this study show that there is an average increase of 12% at this level of RCA use in concrete, and this cannot be ignored.

The use of RCA increases the porosity of concrete, as well as the creep deformation. Compared with coarse NA concrete, the creep of coarse RCA concrete is more sensitive to moist curing duration. It was shown that the relative increase in creep of coarse RCA concrete decreases as concrete strength increases [7].

Shrinkage

The use of coarse RCA in place of coarse NA increases the shrinkage of concrete, but this increase in shrinkage, relative to NA concrete, occurs at a decreasing rate as the coarse RCA content is increased, giving an average of 33% increase when NA is fully replaced by RCA. The increase in shrinkage with the use of RCA varies with the relative humidity of the environment and the designed strength of the concrete [8]. On average, the relative increase in shrinkage at 100% RCA concrete decreases (i) from 45% to 28% as the ambient humidity rises from the 20%–40% RH range to 81%–95% RH and (ii) from 58% to 20% as the designed strength of the concrete moves up from 20 to 130 MPa, making it a more important factor than the effect of relative humidity [8].

ESTIMATION OF DEFORMATION OF CONCRETE

Over the years, various models for estimating the deformation of concrete, especially its creep and shrinkage strains, have been developed. These models are mostly empirical, and most likely have been developed based on the data obtained from natural aggregate concrete, their applicability in estimating the deformation properties of concrete made with recycled and secondary aggregate (RSA) can be questionable, as the characteristics of these materials are generally different to those of natural aggregate, which would accordingly affect the properties of the concrete.

The elastic modulus, creep and shrinkage models given in design codes adopted in Europe (Eurocode 2, 2004) [9] and the United States (ACI 209-2R, 2008) [10], as well as those proposed by individual researchers (B4, 2015) [11] have been assessed by comparing the experimental values to estimated values for both concrete made with NA and RCA. An example of this for the elastic modulus of concrete is given in Figure 2.

In general, the major discrepancy in the estimated values, particularly for time-dependent deformation (creep and shrinkage), found with all of these models is that the properties of the aggregates used, especially their stiffness, which can greatly affect the deformation properties of concrete, have not been considered properly. In some cases, although the rock type of the aggregate is considered (elastic modulus in Eurocode 2, 2004, and creep and shrinkage in B4, 2015), the approach adopted is less appropriate because of the high variation in aggregate characteristics, even within the same rock type. As such, the accuracy of the selected three models in estimating the deformation of RCA concrete as well as NA concrete has been shown to be not satisfactory, and further refinement and calibration of these models are required.

PROPOSED MODELS FOR DEFORMATION OF CONCRETE

Three new empirical models developed for estimating the elastic modulus, creep coefficient and shrinkage strain of concrete potentially made with a wide range of aggregates alone or in combination, including natural, recycled and secondary aggregates (such as fine glass cullet aggregate and fine copper slag aggregate). These proposed models were, for ease of use in practice, deliberately designed to work around Eurocode 2 (2004) and were developed in MATLAB version 2017a.

The key basic factors of the proposed models are the consideration of:

(i) coarse and fine aggregates as separate material components;
(ii) the type of aggregate used, incorporating natural, recycled and secondary aggregates, but essentially within the normal-weight aggregate range and used to produce normal-weight concrete as specified in BS EN 206 (2016) [12];
(iii) the aggregate stiffness effect expressed as water absorption;
(iv) the aggregate volume effect expressed as aggregate/cement ratio;
(v) the use of pozzolanic materials is made more explicit. Finally, and perhaps most importantly, the models developed in this study have a wider range of use compared to those of Eurocode 2 (2004).

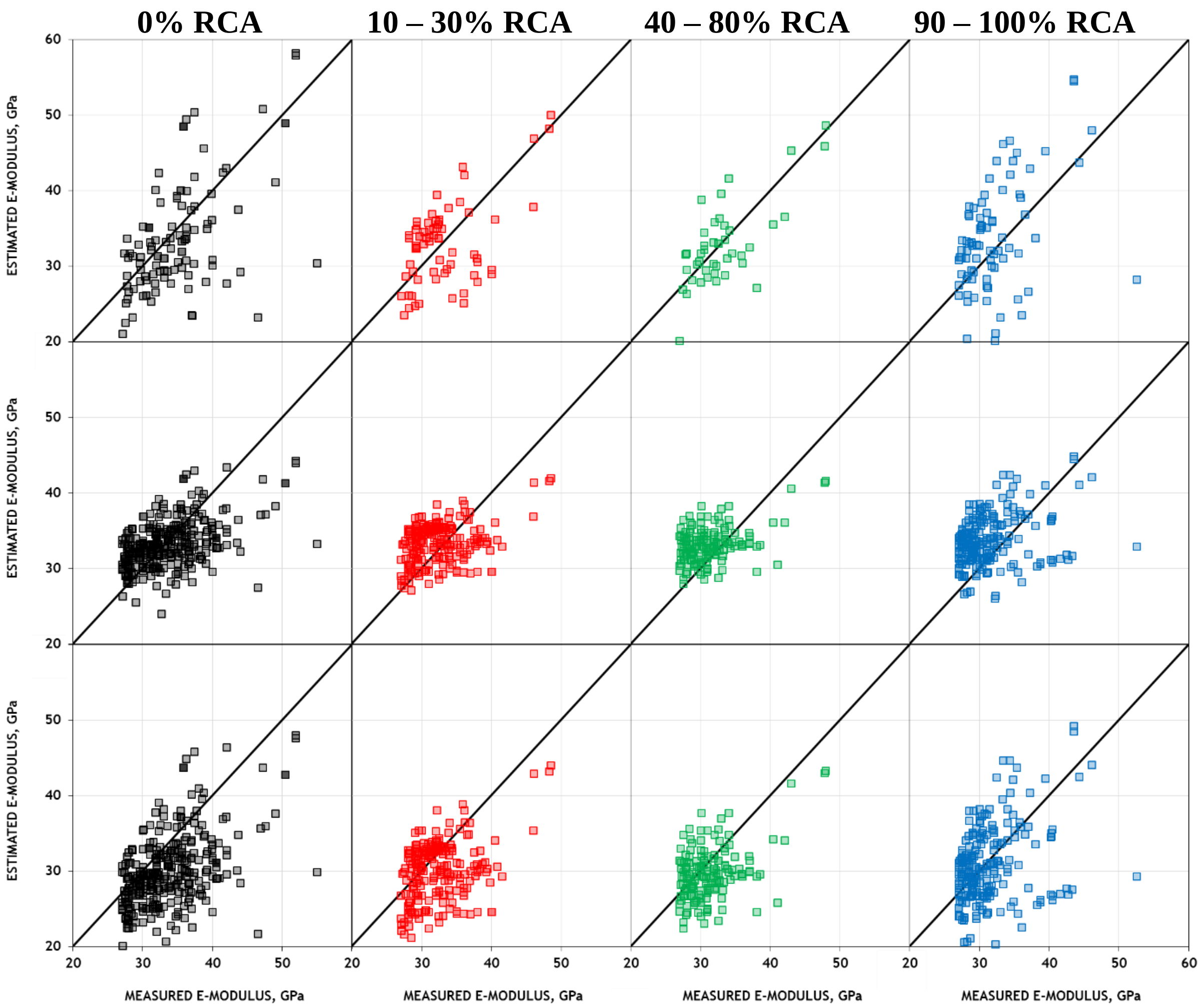

Figure 2 Comparison of elastic modulus of concrete made with coarse RCA between measured values and estimated values using
(a) ACI 209-2R, 2008, (b) Eurocode 2, 2004 (c) B4, 2015.

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

CONCLUSIONS

- The physical characteristics of coarse RCA are mostly affected by the content of adhered cement paste, which is depending on the quality of the crushing process.

- As the coarse RCA content increases, (i) the elastic modulus of the concrete decreases at a decreasing rate, giving an average of 16% reduction when 100% coarse RCA is used, (ii) the creep and shrinkage of the concrete increases at a decreasing rate as the replacement level increases, giving an average of 32% and 33% increase, respectively, when 100% coarse RCA is used.

- The main omission in most of the models in the design codes is the aggregate effect, in terms of its stiffness and content in concrete has not been properly considered.

- Three new empirical models were developed for estimating the elastic modulus, creep coefficient and shrinkage of concrete, which are suitable for use for structural concrete made with natural aggregates, recycled and secondary aggregates or the combination thereof.

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