USE OF RECYCLED CONCRETE AGGREGATES IN SUSTAINABLE STRUCTURAL CONCRETE APPLICATIONS

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Abstract

The increasing difficulty in securing natural coarse and fine aggregates for the production of concrete coupled with the environmental issues and social costs of unlimited extraction of natural aggregates makes the usage of recycled aggregate concrete (RCA) in the construction industry of prime importance. However the full use of the material can be justified only through structural applications. Engineers are reluctant to use RCA in structural applications due to lack of design information. A brief review of the recent literature on Recycled Aggregate Concrete (RCA) used as a structural material is reported in this paper. It is found that the most of the research studies conducted up to now are mostly based on material properties rather than investigation of the RCA and its performance as a structural material. Major issues and problems associated with RCA concrete compared to normal concrete are identified in the paper.

Keywords: Sustainable Buildings, Green Concrete, Recycled Aggregates, Structural Design, Design Codes

1. Introduction

Concrete is the most used construction material on earth. As the majority of the volume of a concrete mix is composed of aggregate, it is becoming increasing difficult to secure natural coarse and fine aggregates for the production of concrete and this is compounded by the social and environmental impacts associated with unlimited extraction of natural materials. At the same time, disposal of construction and demolition waste (CDW) is another environmental problem, particularly for countries with higher demographic but smaller surface areas. According to the Department of Sustainability (report prepared by Hyder Consulting, 2011), a total of 19.0 million tonnes of CDW was generated in Australia (2008-09), 80% of which is constituted of concrete materials, yet at present only about half of this material is being recycled. It is interesting to note that in some European countries, almost all CDW is recycled (European Recycling Society, 2011). With aging infrastructure and buildings, the volume of CDW is expected to rise worldwide. It is for this reason that the re-use of hardened concrete from CDW as aggregate, that is, "recycled concrete aggregate" (RCA) is an important initiative gaining significant momentum.

The idea of incorporating RCA in new concrete is not new, it has been around for a number of years. Significant research has been undertaken as regards the general performance of RCA in concrete and its mechanical properties compared to concrete made with virgin aggregates (Eg. Xiao et al., 2004; Tang, 2007; Evangelista and de Brito, 2007; Mater and Dalati, 2012; Xiao and Li, 2005). It is generally accepted in the literature that the use of RCA can affect mainly the water demand, permeability and shrinkage properties of the parent concrete. However it is also generally reported that when limited to a replacement proportion of 20-30%, recycled aggregate can be used in most applications, without causing any noticeable difference in strength or workability. In fact the Standards Australia HB155 (2002) "Guide to the use of recycled concrete and masonry materials" allows up to 30% of good quality Class 1A RCA material in concrete up to 40MPa. American Concrete Institute committee 555 presents a guide on removal and reuse of handed concrete (ACI 555R-01, 2001) in which no limits are presented for percentage of RCA as a replacement of natural aggregates. However, it provides a limit on allowable amounts of deleterious impurities in recycled aggregates intended for use for making new concrete. It cautions on reductions of strength properties in generally and requiring mandatory trials mixtures made with RCA. In practice, the usage of RCA in concrete has been mostly limited to non-structural applications such as pavements, earthworks and road construction. It is believed that the primary reasons for the limited use of RCA in higher grade structural concretes is due to perceptions regarding its quality as well as a lack of research, knowledge and experience, particularly with respect to structural applications. Australian building codes and standards do not provide guidance on the use of RCA concrete as a structural material, thus engineers are not equipped to comfortably specify recycled aggregates as a construction material alternative.

Recent literature indicates there is a growing interest in establishing the feasibility of integrating RCA in the production of new concrete with properties acceptable for use in structural concrete and even pre-stressed elements (Comes and de Brito, 2009; Matar and El Dalati, 2012). The engineering properties of concrete containing RCA depend on the quality, strength and the proportion of the RCA material itself. It has been shown that with a more rigorous mix selection, desired concrete properties including good durability can be achieved (Liu and Lei, 2012; Evangelista and de Brito, 2007). Further, it is noted that there has been a great advancement in recycling techniques to produce RCA with quality that is close to natural aggregate. The key message is that RCA may perform differently to virgin products with respect to mechanical and structural properties, but if concrete technology allows these properties to be better understood and if appropriate design guidelines can be developed, the use of RCA in concrete will increase and extend more comfortably to structural concrete.

This paper presents a brief review of the recent literature regarding the engineering properties of RCA concrete. Section 2 presents research findings on the mechanical properties of RCA concrete, including compressive strength, flexural strength, modulus of elasticity and Poisson's ratio. The use of recycled aggregate concrete in pre-stressing applications is discussed in Section 3. A brief literature review on the effects of recycled concrete aggregate on the early age properties and bond performance of the concrete, two parameters paramount in consideration of post-tensioned applications, is also presented.

2. Mechanical Properties of Recycled Aggregates Concrete

Significant research has been conducted on the influence of recycled concrete aggregate (RCA) on the mechanical properties of the resultant concrete. Results as given by recent literature are summarised in the next subsection.

2.1 Compressive strength

The influence of RCA on the compressive strength of the concrete has been thoroughly studied (Xiao et al., 2004; Tang, 2007; Li, 2004; Jin et al., 2008, Evangelista and de Brito, 2007; Mater and Dalati, 2012). The studies generally found that the concrete compressive strength decreases with the increase of RCA content (Figure 1). This is mainly due to the adherence of old mortar to the surface of the RCA, which results in a higher water absorption compared to natural aggregates. However, it was generally reported that no systematic reduction in strength was observed if the RCA content is less than 30%.

Due to the higher water absorption of the RCA, more water is generally needed to improve workability of the concrete to match the control concrete made with natural aggregate. The increase in water/cement ratio was found to generally result in decrease the compressive strength of the recycled aggregate concrete as indicated in Figure 2 (Li, 2004). However, the inverse was observed when the percentage of the recycled concrete aggregate is 50%. The water absorption capability of the recycled concrete aggregates was also found to affect the compressive strength (Yang et al., 2008). It was found that the compressive strength decreases with the increase of the RCA content which has a higher water absorption capability. Clearly, the optimum mix in regards to the use of the recycled aggregate depends on water/cement ratio, quality and volume of recycled aggregates used.

Research has also been undertaken to investigate the effects of supplementary cementitous material additions on the performance of the recycled aggregates concrete (Corinaldesi and Moriconi, 2009; Parekh and Modhera, 2012). It was found that the compressive strength (and workability) of RCA concrete can be significantly improved by adding fly ash or silica fume to the mixture.

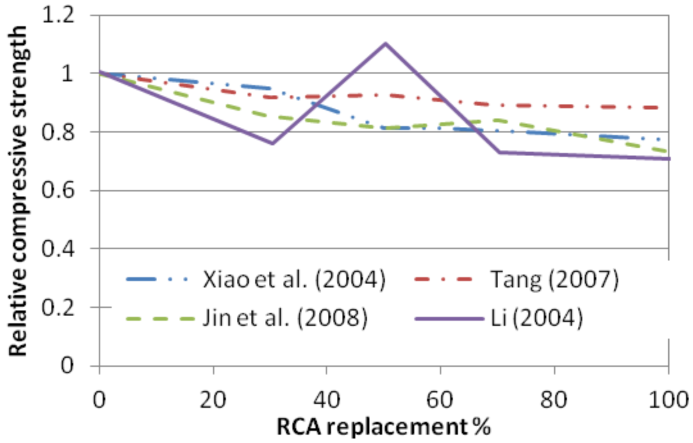

Figure 1: Effects of RCA replacement on compressive strength

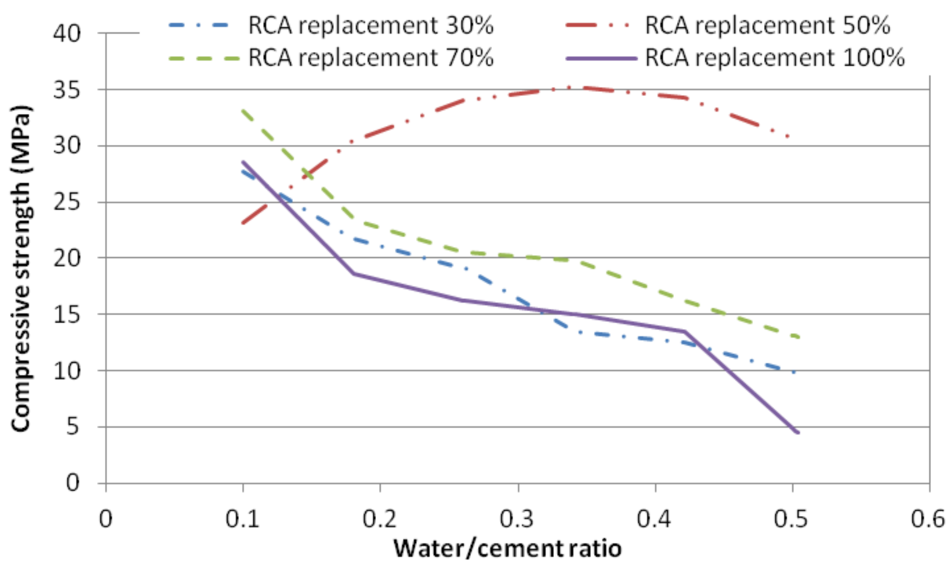

Figure 2: Effects of water/cement ratio on compressive strength

2.2 Splitting and flexural tensile strength

Studies on the influence of RCA on the splitting and tensile strength reveal that an increase in RCA content causes a decrease in splitting and flexural tensile strength of the concrete (Cheng, 2005; Ge and Zeng, 2004; Xiao and Li, 2005). RCA content was found to have less significant effects on flexural strength compared to concrete made with virgin aggregates (Xiao and Li, 2005; Yang et al., 2011).). It was observed that failure could be initiated not only from the interfaces between RCA and the cement past as normally observed in conventional concrete, but also from the RCA itself (Xiao et al., 2008; Corinaldesi and Moriconi, 2009). The addition of supplementary cementitious materials such as fly ash and silica fume was found to be less effective in increasing the tensile strength of concrete compared to its capability to improve the compressive strength of RCA concrete. (Corinaldesi and Moriconi, 2009).

The splitting and flexural tensile strength properties of the concrete were shown to be indirectly related to the increasing water absorption value of the RCA (Yang et al., 2008) - the higher the water absorption value, the lower the splitting and flexural tensile strengths.

While this structural aspect requires due consideration, it is noted that the increase in water demand can often be partially or fully offset by the appropriate use of water reducing admixtures in practice.

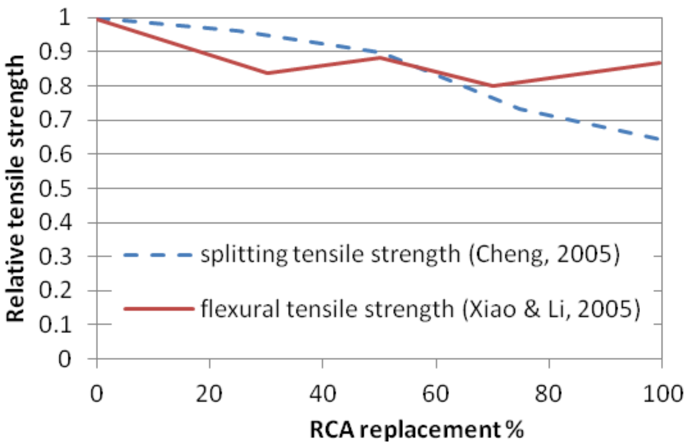

Figure 3: Effects of RCA replacement on splitting tensile and flexural tensile strength

2.3 Modulus of elasticity and Poisson's ratio

Studies on the effects of RCA content on the modulus of elasticity show that the values of modulus of elasticity of recycled aggregate concrete is generally lower than that of conventional concrete (Xiao, 2007; Rao, 2005; Katz, 2003). The lower values of the modulus of elasticity are caused by a large amount of old mortar that is often attached to the aggregates in RCA. The old mortar has a lower modulus of elasticity compared to the cement paste used in the new mix. It was found that modulus of elasticity values generally ranges between 50 and 70% of conventional concrete depending on water/cement ratio and RCA replacement.

Values of Poisson's ratio were found to vary between 0.15 and 0.23 (Hu et al, 2009; Li, 2007). These values are similar to that of conventional concrete made with natural aggregates.

3. The Use of Recycled Aggregate Concrete in Pre-Stressing Application

A literature review has revealed that no investigations appear to have been carried out in the field of RCA in post-tensioned concrete elements in Australia or elsewhere in the world. This poses a major limitation as post-tensioned concrete with high-strength steel strands is the preferred method used for constructing slab elements in buildings in Australia and around the world. There are many advantages associated with the use of post-tensioning including, reduced volume of concrete, significant reductions in the amount of reinforcements, thinner and lighter structural members, reduced deflections and cracking, flexible column spacing, enhanced structural form, and improved durability. Other important factors that make post-tensioned technology an attractive option to the building industry are cost and constructional efficiencies. Most significantly, it is these advantages that also render post tensioned construction a highly sustainable construction option. In a paper by Jenkins, Baweja and Portella on Optimising Building Design for Sustainability (Jenkins, Baweja and Portella, 2011), it is demonstrated that post-tensioned concrete can result in structures with lower embodied energy than cast in-situ concrete designs. In an investigation by Gupta and Watry (Gupta and Watry, 2012), it was shown how post-tensioned concrete can minimise overall material usage, cost and environmental impact.

Given the need for increased utilisation of RCA in concrete and the popularity and sustainable benefits offered by post-tensioned concrete. It would seem logical to consider these two concepts together. But RCA in post-tensioned concrete may exhibit different early age and bonding properties with prestressing strands. Simply relying on compressive strength of the material and extrapolating models and equations meant for ordinary concrete using natural aggregate may lead to unsafe designs. Therefore, there is a need for more research in this area, to gain some understanding of the structural behaviour and properties of RCA in post-tensioned applications.

3.1 Early age properties

Significant research has been carried out to investigate compressive strength properties of recycled aggregate concrete and other mechanical properties as discussed in Section 2 of this paper, but relatively limited information is available relating to early age properties of recycled aggregate concrete. The findings of two research investigations are presented here.

Al-Mufti and Fried (2012) reported that normal and recycled aggregate concretes displayed a similar pattern of strength increase at an early age but the differences appear at later ages (Al-Mufti and Fried, 2012). Generally, ss with conventional concrete, compressive strength of concrete made with RCA decreases as the water/cement ratio is increased (Figure 4). Comparisons between compressive strength of concretes made with natural aggregates and RCA shows that during the first few hours after mixing similar values were obtained for both concretes. This might be due to the higher water absorbency associated with recycled concrete aggregate resulting in a stiffer concrete than conventional concrete at this stage. However, beyond 2 days the difference in strength varies with age for the two concretes, with a higher strength development for normal concrete than RCA concrete. The heat development rate was found to be very similar due to the similarity in the hydration development of cement paste in the two concretes, which is due to the fact that the same cement type (OPC) and water/cement ratio are used in both concretes.

Further, as demonstrated in Figure 5, experimental studies by Liu and Lei found that the proportion of RCA replacement had a more significant effect on early age compressive strengths compared to 28-days strength (Liu and Lei, 2012).

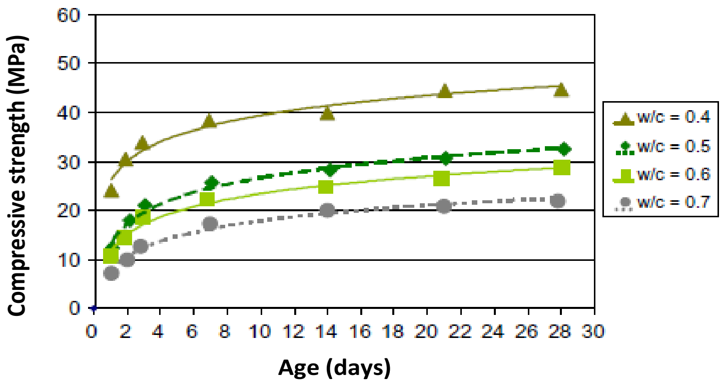

Figure 4: Effects of water/cement ratio on early age compressive strength (Al Mufti and

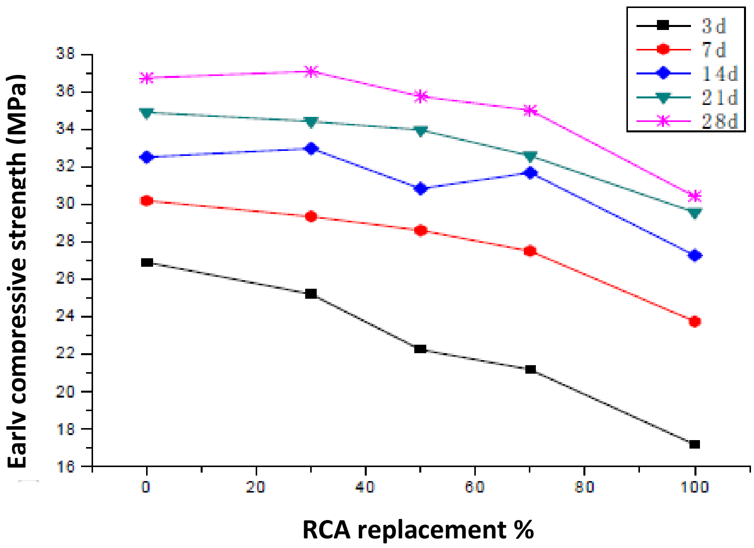

Figure 5: Effects of RCA replacement on early age compressive strength (Liu and Lei, 2012)

3.2 Bond strength

Only a small number of studies on bond performance of reinforced RCA concrete has been reported. Bond strength properties of RCA concrete at early ages which are relevant to prestressing and precast applications are not investigated adequately at all. Nonetheless, what is published indicates that the inclusion of recycled aggregate into a concrete mix has a very small effect on bond performance. Ajdukiewicz and Kliszczewicz (2002) used the pull-out method recommended by RILEM (1970) to test bond strength of reinforcement in RCA concrete cubic specimens at 28 days. Six groups of specimens (R5–R9 and R11) with different aggregates gained from crushed structures were tested. A 20% reduction in bond strength is reported when RCA (coarse and fine) is used entirely when compared to virgin aggregates. The reduction is only 8% if only fine RCA is used. Figure 6 reports comparisons of the rounds and ribbed bars according to Ajdukiewicz and Kliszczewicz (2002), where, $\tau_{0.01}$ denotes the stress recorded at initial slip 0.01 mm, τ_b stress recorded at failure by slipping. In the figure comparable mixes with virgin aggregates are denoted by .1 (e.g., R11.1 and 5.1r) and subscripts "r" stands for ribbed bars. The slip of the bar is denoted by (Δ) in all these series. A mean 28-day strength about 60 MPa was assumed.

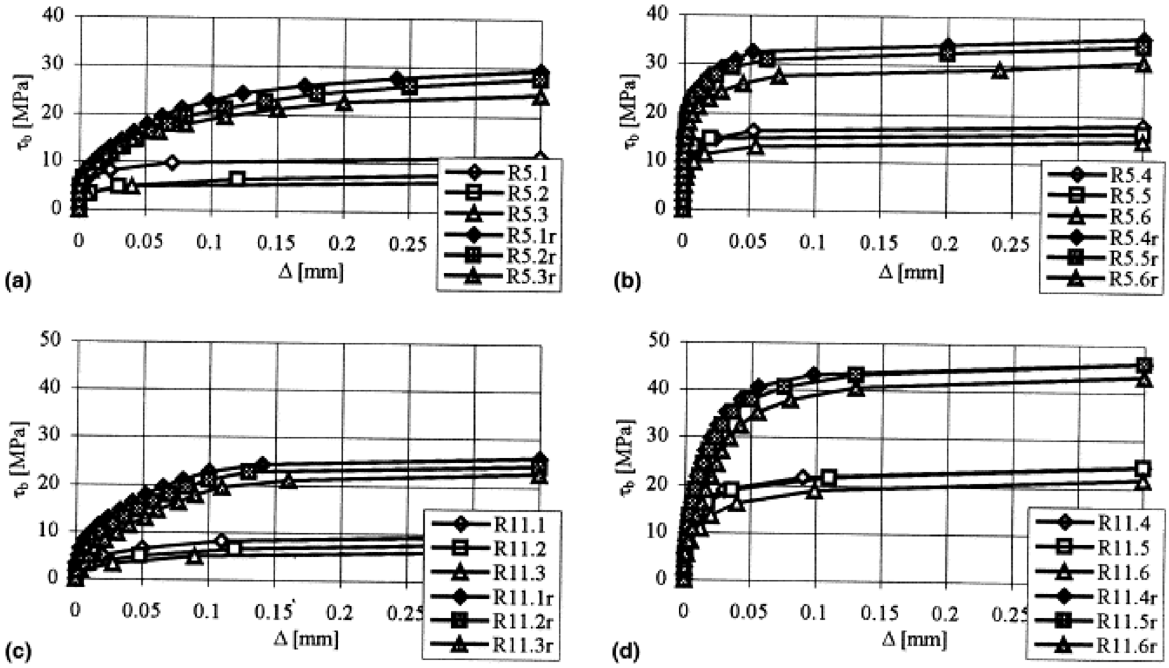

Figure 6: Comparisons of bond stresses τ0.01 and τb for round and ribbed (r) bars: (a), (b) group R5 of series of concrete with granite aggregates; (c), (d) group R11 of series of concrete with basalt aggregates.

Xiao and Falkner (2007) and Huang and Wang (2011) have equally found based on experimental evidence that concrete strength rather than aggregate contents govern bond strength properties. Xiao and Falkner (2007) tested 36 pullout specimens in order to investigate the bond behaviour between RCA concrete and steel rebars. Three RCA replacement percentages (i.e., 0%, 50% and 100%) and two types of steel rebar (i.e., plain and deformed) were considered in their study. It is equally found that under equivalent mix proportions (i.e., the mix proportions are the same, except for different RCA replacement percentages), the bond strength between the RCA concrete and the plain rebar decreases with an increase of the RCA replacement percentage, whereas the bond strength between the RAC and the deformed rebar has no obvious relation irrespective of the RCA replacement percentage. Based on their tests results Xiao and Falkner (2007) recommend a development length for rebars similar to ordinary concrete with the conditions of having similar compressive strength of concrete. The tests are, however, based on direct pullout specimen only.

Fathifazl et al. (2012) reported the results of an experimental study of bond performance of deformed steel bars in concrete produced with coarse RCA. Twelve beam-end specimens were prepared and tested according to ASTM A944-99 standard. A typical beam-end specimen with support reactions are presented in Figure 7. The test variables comprised mix proportioning method, bar size, and aggregate type. The distinctive feature of the study is the new mix proportioning method for RCA concrete that results in the strength to elastic modulus ratio (f'_c/E_c) similar to a conventional concrete having the same amount of total mortar and coarse aggregate. Hence the mortar and aggregate phases in RCA are treated as part of the total mortar and total aggregate volume of RCA concrete, respectively. The results showed that the bond strength between the reinforcing steel bars and the RCA concrete proportioned by the new method is comparable to their bond strength with regular concrete but 18% to 33% higher than their strength with RCA.

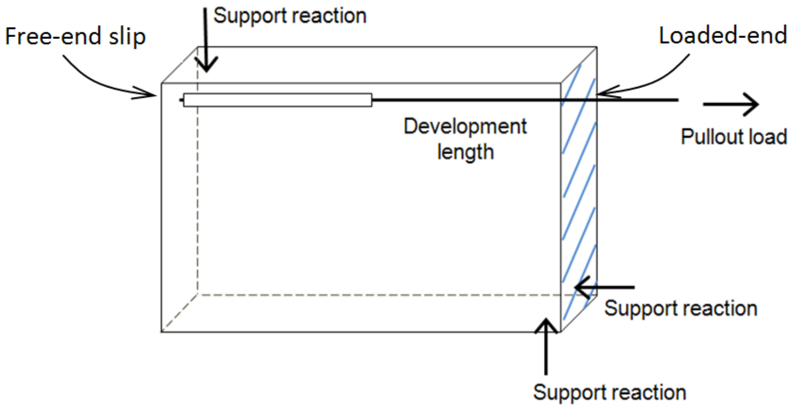

Figure 7: A typical beam-end specimen indicating support reactions

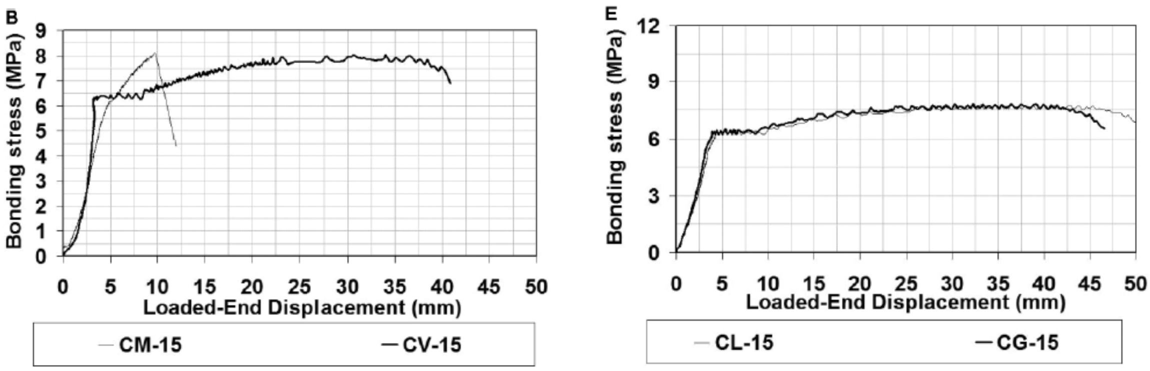

Figure 8: Effect of aggregate type on bond stress variation with loaded-end deformations of different mixes (Fathifazl et al. (2012)

One of the key questions regarding the inclusion of RCA in new concrete and its effects on bond has been discussed by Fathifazl et al. (2012). Figure 8 which illustrates the effect of aggregate type on the bond stress and bar-loaded end displacement relationship for beam end specimens is presented. In the figure, notations CL and CG represent natural aggregates and CM and CV represent RCA of different sources. In each case, the bond behaviour of two mixes are compared, the difference between the mixes being their coarse aggregate type. The authors conclude that the type of aggregate has negligible effect on the bond properties of RCA concrete conforms to the current state of knowledge. This is reflected by the design codes which do not recognise aggregate type as one of the parameters that directly affect the bond strength of natural aggregate concrete.

4. Concluding Remarks

This paper has presented a review of the literature covering the engineering properties of concrete made with recycled concrete aggregate. It is concluded that new concrete made with up to 30% of RCA as a partial replacement of the natural aggregate component compares favourably with concrete made entirely with natural aggregate. The results of experimental investigations generally demonstrate that the strength properties of the concrete made with recycled concrete aggregate is somewhat reduced. With the declining availability of natural aggregates suitable for use in concrete and the increased pressure on landfills, the use of recycled concrete aggregate in concrete mixes at high percentages in the aggregate blend may become a lot more common in structural applications. However, this can only be possible with more technical information to support its use, particularly in structural concrete and post-tensioned applications.

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