Performance of Recycled Aggregate Concrete and Structural Members: Particle Packing Method of Mix Design Approach

Abstract

The use of waste concrete generated from construction and demolition (C&D) waste is a sustainable approach to the rapidly depleting natural resources, which will not only reduce the huge dependency of concrete industries on the non-renewable resources but also reduce solid waste management issues.

The scope of the study is limited to the use of recycled coarse aggregate (RCA), which is yielded by crushing the waste concrete in C&D debris. Recycled aggregate concrete (RAC) is prepared by partial or complete substitution of natural coarse aggregate (NCA) with RCA. The performance of fresh and hardened RAC is adversely affected owing to the inferior properties of RCA (mainly due to the presence of adhered mortar layer, microcracks and old interfacial transition zone (ITZ)). In this context, Particle Packing Method (PPM) of mix design approach is proposed, which is based on the idea of void minimisation by enhancing the packing density of the aggregate mixture of different sizes. The material inferiority is minimized by using PPM mix design and Two Stage Mixing Approach (TSMA) and based on the improved short-term macro-mechanical properties (compressive strength, tensile strength and modulus of elasticity) the 100% use of RCA is suggested.

The three-point bending (TPB) test is performed using three different sizes of single edge notched beam. The fracture energy is evaluated by using the load-CMOD curve obtained from the TPB test. In this process, the curtailment of load-CMOD curve is suggested at 2% of the depth of the beam. The fracture energy and fracture toughness parameters of RAC is inferior to NAC. However, the PPM mix design approach improves the fracture properties of concrete in comparison to the conventional mix design approach and the fracture properties of PPM mix designed RAC is comparable to that of NAC prepared using conventional mix design method.

The microstructural characteristics are analysed using thermogravimetric analysis (TGA), nanoindentation technique, image analysis of back-scattered electrons (BSE) images and X-ray microtomographic (XRT) images. The influence different types of aggregate and mix design approach on degree of hydration (α) is investigated using the TGA test of hydration products from the 7, 28 and 90 days cured samples. A method is proposed by combining two earlier methods to estimate α from the recorded chemically bound water. Irrespective of the aggregate type α values of PPM mix designed concrete are estimated to be lower than the concrete mix proportioned using conventional method. For a particular type of concrete the compressive strength parameter is observed to be directly proportional to α at different age, whereas this relationship was not substantiated for concrete with different aggregate type and design mix approach. The Nanoindentation technique and image analysis of BSE images indicate thicker ITZ of RAC than natural aggregate concrete (NAC). Moreover, higher voids and unhydrated cement content is observed in RAC from the BSE images. The image analysis of XRT images suggests higher void content in RAC specimens. However, the PPM mix designed concrete exhibits lower void content at the meso level. An expression is proposed to predict the compressive strength of concrete from its microstructural characteristics and its correlation with the experimental results is substantiated.

A systematic analysis of the influence of RCA and PPM mix design method on life cycle assessment (LCA) of concrete as compared to those concrete prepared using NCA and conventional mix design method is conducted. Considering the Indian scenario a LCA based on cradle-to-gate theory is conducted and the environmental impacts are measured using CML baseline method with the help of SimaPro and Ecoinvent 3.1 database. The primary data regarding the preparation of NCA and RCA are collected from the respective production facilities. Owing to the use of lesser cement content the advantages of PPM mix design is observed for each impact category. Moreover, the combination of RCA and PPM mix design approach exhibits minimum environmental impacts due to the lower cement consumption, transport distance and energy consumption. Transport activities are the second largest contributor in each category of environmental impacts after cement. From the sensitivity analysis the maximum collection distance of C&D waste is optimized for different supply distance of processed RCA to obtain comparable environmental impact with natural aggregate concrete prepared using conventional mix design method in Indian context. The maximum possible supply distance of RCA is determined for different impact categories with specific collection distance of C&D waste.

The performance of reinforced RAC structural members (beam, column and slab) are studied with the 100% use of RCA. For this, the concrete is prepared using PPM and TSMA due to the improved macro-mechanical properties, fracture behaviour, microstructural characteristics and lesser environmental impacts. The flexure behaviour of RAC beams is observed to be similar to conventional concrete beams, whereas a reduction of 14% is recorded in shear strength of RAC beams. Expressions are proposed to predict the ultimate strength and diagonal cracking strength of RAC beams with and without transverse reinforcement, respectively by operating the database prepared by compiling the existing and present test results of RAC beams. A reduction of 18% is recorded in the axial load of RAC columns with respect the NAC columns irrespective of the tie spacing. An increment of 3% is observed in axial load carrying capacity of both NAC and RAC columns due to the closely spaced lateral ties. Moreover, the existing expressions in ACI 318 (2008) and NZS 3101 (2006) overestimate the axial load carrying capacity of RAC columns. The experimental investigation indicates that, the punching shear strength of RAC slabs is 4.8% lower, whereas the ultimate deflection is 8.2% higher than the NAC slabs. The initial cracking load and strain energy absorption by RAC slabs are respectively 12.5% and 6% lower than NAC slabs. BS 8110-2 (1985), Eurocode 2 (2004), and JSCE (2007) uniformly and conservatively predict the punching shear capacity of RAC slabs. The Critical Shear Crack Theory exhibits conservative predictions of the punching shear capacity of RAC slabs for higher values of $\psi d/(d_{g0} + d_g)$, whereas more unconservative predictions are observed for lower $\psi d/(d_{g0} + d_g)$ values.

Keywords: *Recycled Coarse Aggregate, Recycled Aggregate Concrete, Particle Packing Method, Fracture Analysis, Thermogravimetric analysis, Nanoindentation, Back-scattered Electrons, X-ray Microtomography, Life Cycle Assessment, Beam, Column, Slab.*