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Shear performance of recycled aggregate concrete beams: An insight for design aspects

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HIGHLIGHTS

- Particle Packing Method of mix design approach is used to prepare both NAC and RAC.
- The diagonal tension cracking strength (v_c) of RAC beams is 14% lower than NAC beams.
- The experimental results of RAC beams were collected to form a database.
- Examining the applicability of available expressions to predict v_c is examined.
- Expression is derived using the database to predict v_c.

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ABSTRACT

The shear failure of reinforced concrete beam is a brittle type of failure and can be dangerous if it is not properly designed. The inherent inferior quality of recycled coarse aggregate (RCA) makes the recycled aggregate concrete (RAC) beams even more vulnerable in shear resistance. This persuades the structural designers to account each of the contributing components in the shear resistance mechanisms seriously, especially that of concrete. In this regard, an experimental investigation was carried out on fourteen beams to examine the shear performance of RAC beams in the absence and presence of transverse reinforcement. Six numbers of beams without transverse reinforcement were tested to examine the contribution of RAC in shear resistance mechanisms and eight beams with shear reinforcement were tested to verify the applicability of the prevailing shear design provisions for RAC beams. The inferior mechanical properties of the RAC are improved satisfactorily by implementing the Particle Packing Method of mix design approach along with the established Two Stage Mixing Approach. However, even with the improved mechanical properties of RAC, the poor performance of RAC beams in shear could not be avoided and a drop of 14% was recorded in the ultimate shear strength of RAC beams without stirrups. A database is prepared by compiling the reported test results of RAC beams with and without transverse reinforcement. An alternative equation is proposed to predict the diagonal tension cracking strength of RAC beams, by using the database of RAC beams without transverse reinforcement and it exhibits a better correlation with the experimental results. Further, in the shear resistance mechanisms of RAC beams the effectiveness of stirrups is studied using the database of RAC beams without and with transverse reinforcement.

1. Introduction

Construction industry consumes a huge quantity of non-renewable natural resources; especially in the form of aggregates. The unavoidable social demand of industrialization and urbanization aggravates this situation. Apart from the rapid depletion of the natural resources, construction work is also associated with generating an enormous amount of waste products, mostly construction and demolition (C&D) wastes. This leads to shift our focus in the direction of alternative construction practices which are sustainable in nature. In this context, the reuse of old concrete from C&D waste as a source of aggregate is a potential alternative to natural aggregate (NA) in concrete construction. But, prior to the confident use of recycled coarse aggregate (RCA) in the construction

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sector, the behaviour of recycled aggregate concrete (RAC) in structural elements must be analysed thoroughly.

The problem in hand, involved several researchers across the globe to study the performance of RAC. There is evidence of comprehensive research on the short term and long term mechanical properties of RAC. The complete replacement of natural coarse aggregate (NCA) with recycled coarse aggregate (RCA) is not suggested by the researchers, due to the degradation of mechanical properties of RAC [1–4]. In the available literature the shear behaviour of RAC beams was studied at different substitution level of RCA. Sogo et al. [5] and Sato et al. [6] investigated the shear behaviour of RAC beams without transverse reinforcement at different tensile reinforcement content (2.39%, 4.03%, and 4.22%) and by completely substituting the NAC with RCA. The crack pattern and failure mode of RAC beams were very similar to the conventional beams as per their observations. However, a reduction of 10%–20% was recorded for the RAC beams. González-Fonteboa and Martínez-Abella [7] conducted the shear test of reinforced RAC beams consisting of 50% of RCA and overall longitudinal reinforcement content of 2.98%. The ultimate load and deflection of RAC beams exhibited no significant difference as compared to the conventional concrete beam, although premature cracking and horizontal splitting tension cracks along the tension reinforcement was witnessed. More importantly, they concluded that, the existing shear design provisions for RC beams can be readily used for RAC beams without any modification. In this context, Ji et al. [8] notified that, because of the conservative approach of the existing codes except Eurocode 2, the shear design of RAC beams needs no further revision. Further, González-Fonteboa and Martínez-Abella [9] observed that, the addition of 8% silica fume has no significant improvement in the performance of RAC beams in shear. The experiment carried out by Etxeberria et al. [10,11] on RC beams containing 25%, 50% and 100% of RCA suggests that, the reduction in cracking load is unavoidable with the incorporation of RCA. Further, the use of the prevailing design standards was recommended for RAC beams with 25% replacement ratio and mentioned that, further research is needed on the shear performance of RAC beams at higher replacement ratio of RCA [11]. Fathifazl et al. [12,13] reported that, the Equivalent Mortar Volume (EMV) mix proportioning method helped in enhancing the shear strength of RAC beams as compared to the conventional mix design approach. However, the RAC beams prepared using EMV method also exhibited lower shear strength than the NAC beams and in this regard, the less effective aggregate interlocking mechanism plays an important role in lowering the shear strength of RAC beams. The existing shear design provisions for conventional concrete beams in Canadian standards, ACI-318 and Eurocode 2 also suffice the reliable design of RAC beams owing to their inherent conservative approach. Choi et al. [14] studied the effect of RCA (at 30%, 50% and 100% replacement ratio) on the shear performance of RC beams at different longitudinal reinforcement content (0.53%, 0.81% and 1.61%) and concurrently investigated with different shear span to depth ratio (1.5, 2.5 and 3.25). The tested beam specimens exhibited a shear tension mode of failure for both NAC and RAC beams and the ultimate shear strength of RAC beams was recorded to be lower than that of NAC beams. In addition to this, the reduction in shear strength with the increase in shear span to depth ratio was more significant in RAC beams. Again, Choi et al. [14] confirmed that, for RAC beams the existing design standards are efficient to provide sufficient shear strength because of their conservative nature. Kim et al. [15] studied the effect of the size of RAC beams on shear behaviour at 50% and 100% use of RCA. The experimental results showed that, the shear force of RAC beams increased with the depth of the beams, whereas the shear stress decreased with the same. In addition to this, the existing design standards were suggested for the design of RAC beams, since the authors experienced similar behaviour of RAC beams up to 600 mm depth. However, the authors mentioned that, the good quality of RCA used in the study could be the possible reason for such satisfactory performance of RAC beams. Arezoumandi et al. [16] performed the experimental investigation on RAC beams by complete replacement of NCA at longitudinal reinforcement ratio of 1.27%, 2.03% and 2.73% and observed that, the crack pattern and load–deflection relationship were identical to the NAC beams. The results of the tested beams were within the acceptable range of 95% confidence interval of the existing shear test database of the conventional concrete beams. In addition to this, Arezoumandi et al. [17] also performed the tests to study the effect of replacement level on shear strength of RAC beams. From the experiments, no significant difference was observed in shear resistance of RAC beams at 50% replacement level, whereas at 100% replacement level 11% drop in shear strength was recorded. Moreover, Arezoumandi et al. [16] suggested for further experimental investigation to increase the database of RAC beams. The experimental investigation executed by Knaack and Kurama [18] revealed that, the performance of RC beams was unaffected by the incorporation of RCA. Though the use of existing design standards for conventional beams was suggested for RAC beams, Knaack and Kurama advocated for further investigations using various quality of RCA prior to its assured use [18]. Sadati et al. [19] observed a reduction of 16% in shear strength of RAC beams at 50% replacement of RCA and reported that, apart from AASHTO LRFD and CSA, the ACI – 318, JSCE, fracture mechanics approaches and modified compression field theory (MCFT) conservatively predicts the shear strength of RAC beams. Katkhuda and Shatarat [20] treated the RCA chemically, in order to acquire better quality of RCA with less quantity of adhered mortar. The performance of shear critical beams were studied for different shear span to depth ratio (2 and 3) using 50% and 100% chemically treated RCA. The performance of RAC beams was improved by using treated RCA than that of untreated RCA. Ignjatović et al. [21] studied the shear performance of RAC beams reinforced without transverse reinforcement as well as with transverse reinforcement. The experiment conducted at two different replacement ratio (50% and 100%) revealed no significant difference in crack pattern and failure mode. Again, only marginal variation was observed in service load deflection. The overall study concluded that, because of the inherent conservative approach of the prevailing design standards, RAC beam design needs no further modification. Rahal and Alrefaei [22] verified the shear strength of RAC beams at 5%, 10%, 16%, 23%, 35%, 50%, 75% and 100% substitution of RCA and observed 13% - 18% reduction in shear strength of RAC beams beyond 15% replacement of NCA. In addition to this, the relevance of the use of compressive strength of RAC to predict the shear strength was checked and recommended to apply a reduction factor (λ_r) of 20%, while predicting the shear strength of RAC beams. Rahal and Alrefaei [22] heve recommended for further experimental investigation on shear behaviour of RAC beams prior to the exemption of any restriction on replacement lvel of RCA.

2. Research significance

The comprehensive study on the shear behaviour of RAC beams indicates its inferior ability to withstand shear resistance in comparison to conventional concrete beams. The reported results on the shear performance of RAC beams by the researchers can be categorised on the basis of the replacement ratio of RCA. In this context, at 25%, 30%, 50%, 63.5% and 100% replacement ratio the experimental investigations were carried out by prior researchers. The literature confirms that, there is no need for any further revision of the available design specifications for NAC beams up to the