Construction and Building Materials 174 (2018) 210–223

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Flexural performance and tension-stiffening evaluation of reinforced concrete beam incorporating recycled aggregate and fly ash

Sushree Sunayana *, Sudhirkumar V. Barai

Department of Civil Engineering, Indian Institute of Technology, Kharagpur 721302, India

HIGHLIGHTS

- Flexure performance of reinforced concrete beams using fly ash and recycled aggregates.
- Particle packing method of mix design is used for proportioning of concrete.
- Tensile stress-strain curves are derived for cracked concrete beams.
- Effect of tension stiffening is highlighted in the numerical study.

ARTICLE INFO

Article history:
Received 11 December 2017
Received in revised form 28 March 2018
Accepted 8 April 2018

Keywords:
Recycled aggregate concrete beam
Fly ash
Particle packing method
Moment carrying capacity
Mid-span deflection
Tension-stiffening

ABSTRACT

This paper presents the effect of fly ash in recycled aggregate concrete (RAC with 100% recycled coarse aggregates) on the flexural performance of reinforced concrete (RC) beam. Particle packing method (PPM) of mixture proportioning is used in a novel way for the flexure study. This method by principle accounts for the excess adhered mortar present on the outer surface of recycled coarse aggregates (RCA) while calculating maximum packing density and consequently minimize the requirement of fresh mortar. The parameters such as materials (aggregate type and fly ash), mix design method and reinforcement percentages are considered for evaluation of moment carrying capacity, deflection, and failure pattern. Based on experimental results, the constitutive relation for cracked RAC and natural aggregate concrete (NAC) is evaluated numerically showing tension stiffening effect. The results conclude mostly comparable moment carrying capacity of RAC incorporating fly ash beams and NAC beams at ultimate limit state. The maximum mid-span deflection has been observed to be higher, but the variation is not substantial at service load due to the effect of fly ash and PPM in RAC. The reduced tension-stiffening effect, as observed from the derived stress–strain relation of cracked concrete justifies the higher mid-span deflection in RAC. The applicability of existing code provisions for NAC beam is assessed for RAC with fly ash beams. The results suggest the potential application of 100% recycled coarse aggregates and up to 30% fly ash in a reinforced concrete beam without compromising its flexure performance.

1. Introduction

Waste disposal is the foremost concern for the development of a sustainable environment. In particular, rapid urbanization results in enormous quantities of construction and demolition wastes, which affect the environment adversely. In addition, concrete construction industries are facing severe challenges due to limited natural aggregate resources as well. Hence, recycled aggregates can become a useful alternative constituent for concrete thus converting wastes into wealth. Effect of recycled coarse aggregates (RCA) on the material level performance of concrete had been studied previously regarding fresh and hardened properties [1–13]. It was reported that complete replacement of natural coarse aggregates (NCA) by RCA causes a reduction up to about 30% in compressive strength (CS), 24% in split tensile strength (STS) and 45% in modulus of elasticity. The deviation in the property of recycled aggregate that makes a difference on resulting performance of concrete is primarily attributed to adhered mortar content present on the aggregate surface. Duan and Poon [14] studied the effect of quality and quantity of old adhered mortar on RCA surface for varying sources of recycled aggregates and low strength to high strength concrete.

* Corresponding author.
E-mail addresses: sushree111@gmail.com (S. Sunayana), skbarai@civil.iitkgp.ernet.in (S.V. Barai).

https://doi.org/10.1016/j.conbuildmat.2018.04.072
0950-0618/

Use of pozzolanic materials, modifications in mix design and mixing method had also been studied in the past to overcome the adverse impact of RCA on concrete. The effect of fly ash on the performance of RAC is reported in few studies in this domain [15–21]. A combination of 50% fly ash and 50% RCA can produce economic concrete (40% cost savings) compromising 50% strength [17]. Required workability and CS were achieved by 40% fly ash replacement in long-term [18]. The positive effect of ground fly ash on CS of concrete was reported up to 35% or lower fly ash replacement depending on water to binder ratio (w/b) [19]. On the contrary, it was also observed that fly ash addition in RAC affect the strength of concrete adversely, but improves durability concerning chloride-resistance, drying shrinkage and creep properties [21]. Partial substitution of cement with fly ash can as well reduce the carbon footprint of concrete on the environment.

Mixture proportioning for conventional concrete was modified by quantifying the residual mortar present on RCA surface using equivalent mortar volume method, which restricted the use of RCA up to 20% [22]. In a previous study by the authors [23], complete replacement of natural coarse aggregates by RCA has been suggested. In that study, the authors have implemented particle packing method (PPM) and triple mixing method with slight modification in RAC incorporating fly ash. The experiments depicted that, up to 30% fly ash replacement in recycled aggregate (100%) can produce concrete with comparable compressive strength (variation of 5%), flexural strength (about 10% difference) and modulus of elasticity (13% deviation). However, a significant decrease (maximum up to about 28%) was reported in the split tensile strength of RAC with fly ash concrete.

In addition to material level studies using RCA and fly ash, few research studies have analyzed the behaviour of structural elements comprising 100% RCA. RAC beams showed a reduction of about 3.5% in load carrying capacity for longitudinal reinforcement ratio of 0.90% and 1.60%, but deflection was found to be 1.18 to 2 times higher [24]. Similar moment carrying capacity, greater deflection and wider cracks in RAC was observed as compared to the NAC beams using three different longitudinal reinforcement ratios (0.59%, 1.06%, and 1.65%) [25]. Equivalent and even superior flexure behaviour was reported in RAC beams using equivalent mortar volume method of mix design [26]. The use of available analytical models and code provisions for NAC beams was recommended for RAC beams in spite of higher deflection up to 30% RCA replacement [27,28]. No significant difference was observed in the moment carrying capacity and service load deflection for both NAC and RAC reinforced concrete (RC) beam at constant reinforcement percentage, water-cement ratio and compressive strength of concrete [29]. Closer crack spacing, lower cracking moment, and reduced stiffness after cracking were reported for RAC beams with a complete substitution of RCA [30]. Reduction in bond splitting tensile strength between steel and concrete was observed by Kim et al. [31]. Long-term behaviour (380 days) of RAC beams were studied by Choi and Yun [32]. They observed 20% lower flexural strength, variation in neutral axis depth due to weak aggregate-mortar interface and lower instant to long-term deflection ratio. However, the authors feel that studies on performance evaluation of structural elements using 100% RCA and fly ash have not been intensively investigated. Also, the tension-stiffening aspect of cracked concrete that affects flexure behaviour of a reinforced concrete structural element has not been addressed for RAC beams.

Regardless of the positive economic and environmental impact, use of recycled coarse aggregates and fly ash in concrete construction practice is limited due to lack of research. Hence, this paper focuses on the flexure performance of fly ash incorporated reinforced RAC beam highlighting the tension-stiffening behaviour of cracked concrete.

2. Research significance

The bond between concrete and steel in RC beams make the behaviour different as compared to plain concrete. Therefore, the simplified material stress–strain formulations cannot be directly applied to predict the flexure behaviour of a reinforced concrete beam. Hence, this work performs a comprehensive study on the flexure performance (moment carrying capacity, failure pattern, crack spacing, mid-span deflection) of reinforced concrete beam incorporating 100% RAC with 20% and 30% fly ash. Particle packing method of mix design is adopted for the concrete. A comparative study of different code provisions (available for NAC) and previous literature (for 100% RAC) has been carried out. The tensile stress–strain relation for cracked concrete is derived from the experimental moment–curvature curve for NAC and RAC incorporating fly ash beams. Tension stiffening aspect is established in case of RAC beams.

3. Experimental program

The experimental plan comprises (i) PPM mix proportioning, (ii) material characterization, (iii) reinforcement detailing of test beams, (iv) properties of reinforcing steel and (v) loading conditions and test details.

3.1. Particle packing method of mix design

In the particle packing method, aggregates are packed in such a way that smaller size aggregates are filled up between the larger ones to minimize the voids and thereby to maximize the packing density. The remaining voids are filled with fresh mortar. Moreover, in case of RAC, the presence of adhered mortar on the RCA surface also contributes for filling the voids; consequently reducing the extent of fresh binders required. The experimental methodology for mix design is adopted from a separate study [20]. In the present work, packing density (PD) was calculated experimentally for different trial proportions based on coarse aggregate sizes. Further details of the experimental trials can be referred from a previous study by the authors [23]. The final proportion corresponding to maximum PD was obtained. Considering this PD, remaining voids and quantity of paste required to fill those voids were found out. In addition, cement can be substituted partly with any other finer (larger surface area) cementitious material to increase the packing density of the paste [33]. Hence, partial replacement of cement with fly ash used in this study is expected to increase the PD in concrete.

3.2. Materials and mix proportion

Processed RCA was procured from a recycling plant in India. The physical properties of the coarse aggregates were determined as per IS:2386 (Part3) [34]. Lower specific gravity (2.29–2.54) and higher water absorption (3%-5%) were observed in RCA as compared to NCA (specific gravity 2.8–2.9 and water absorption within 1.5%). Locally available river sand conforming to zone II specification of BIS (IS: 383–1970) [35] was used as fine aggregates. Ordinary Portland cement (OPC) of 53 grade and class F fly ash were used to produce concrete.

Table 1 shows the proportions of aggregates and cementitious materials used in this study. Concrete with natural aggregates without fly ash and superplasticizer (referred as NAC) was considered as the control mix. 20% of total cementitious materials replaced by fly ash in RAC is indicated as FA20RAC, and 30% fly ash replacement is abbreviated as FA30RAC in the presence of