Construction and Building Materials 156 (2017) 376–386

Contents lists available at ScienceDirect

Construction and Building Materials

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

Recycled aggregate concrete incorporating fly ash: Comparative study on particle packing and conventional method

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HIGHLIGHTS

- Systematic study of particle packing method (PPM) mix design for 100% recycled aggregate concrete with fly ash.
- Theoretical and experimental packing density were calculated and compared.
- Effect of replacement of cement with cementitious material finer than it to increase packing of paste.
- Effect of compressive strength on split tensile to compressive strength ratio for RAC with fly ash.
- Comparison of PPM with conventional mix design method in terms of strength and modulus of elasticity.

ARTICLE INFO

Article history:
Received 20 July 2017
Received in revised form 23 August 2017
Accepted 23 August 2017

Keywords:
Particle packing method
Fly ash
Recycled aggregate concrete
Compressive strength
Tensile strength
Modulus of elasticity

ABSTRACT

In the present study, particle packing method (PPM) of mix proportioning is applied in a novel way for recycled aggregate concrete (RAC) incorporating fly ash as a partial replacement of cement. Lesser fresh mortar content was achieved by PPM which resolves the major concern of excess adhered mortar in RAC. Theoretical packing density (PD) obtained using compaction-interaction packing model was compared with experimental PD. 18% and 28% reduction in cement content was observed for RAC with 20% and 30% fly ash replacement respectively due to PPM mix proportions as compared to conventional method at water-binder ratio of 0.45. Compressive strength, flexural strength and modulus of elasticity of RAC with fly ash showed comparable results with natural aggregate concrete in PPM. The rate of long term compressive strength gain was about 11%–20% and 30% in RAC and natural aggregate concrete (NAC) respectively. Split tensile strength and modulus of elasticity in RAC was comparable in both the conventional as well as PPM methods. Flexural strength was improved in RAC incorporating fly ash mix due to PPM. Statistical analysis showed better tensile strength for RAC as compared to NAC up to the characteristic compressive strength of 25 MPa. Poor tensile behaviour was reported for high strength recycled aggregate concrete. The results suggest that, the particle packing method can be used in RAC with fully replaced recycled aggregates incorporating fly ash (up to 30% replacement) for sustainable construction practices.

1. Introduction

Construction and demolished wastes (C&DW) are generated due to rapid infrastructure development, renovation of existing structures or demolition in the process of socio-economic development of a country. About 850 and 530 million tonnes of C&DW are generated per annum in the European Union and India respectively [1,2] with very low utilization rate; posing a serious concern on sustainability in construction practices. Previous research studies [3–5] reported higher water absorption and porosity of recycled coarse aggregates (RCA) due to adhered mortar content. In addition, industrial by-products such as fly ash can be substituted for cement in the context of waste utilization with positive economical and environmental impact [6].

There is no specific generally accepted mix design method for RAC like conventional concrete. On the basis of recycled coarse aggregates simply replacing natural aggregates in the concrete, direct weight replacement and direct volume replacement methods were used in earlier investigations available. The equivalent mortar volume method of mix design [7] showed some advantages in terms of basic properties of concrete by minimizing fresh paste content, but restricts the replacement level of RCA up to 20%. No

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http://dx.doi.org/10.1016/j.conbuildmat.2017.08.132
0950-0618/

Nomenclature

The following notations are used in this paper

a_{ij}	Factor which describes the loosening effect caused by the particles in size class j on the packing density of the particles in size class i
b_{ij}	Factor which describes the wall effect caused by the particles in size class j on the packing density of the particles in size class i
β_i	Virtual packing density of size class i
β_j	Virtual packing density of size class j
β_{ti}	Calculated virtual packing density of a mixture when size class i is dominant
c_a	Compaction-interaction constant within the loosening effect a_{ij}
c_b	Compaction-interaction constant within the wall effect b_{ij}
d_i	Diameter of size class i. For largest diameter, i = 1
d_j	Diameter of size class j
d_c	Transition diameter in CIPM
i	integer denoting the dominant size class in a mixture
j	integer denoting a size class in a mixture
n	total number of size-class present
r_j	Volume fraction of size class *j*
$w_{0,a}$	Maximum range of loosening effect
$w_{0,b}$	Maximum range of wall effect
w_a	Constant denoting the maximum range of loosening effect
w_b	Constant denoting the maximum range of wall effect

study that allows for fully replaced recycled aggregate incorporating fly ash with satisfactory performance is found in earlier studies. On the other hand, the particle packing method (PPM) of mix design to achieve maximum packing density (PD) was used for conventional concrete with positive effects on workability [8] and high performance concrete [9]. Apart from normal mixing method, other mixing techniques such as two stage mixing approach [10] and triple mixing method [11] were also used for RAC and RAC with mineral admixture respectively to improve its properties by modifying microstructure of concrete.

The effect of recycled aggregates on the behaviour of concrete in terms of strength was observed in previous studies using conventional mix design methods. Reduction in compressive strength (CS) of RAC was up to 30% at 100% replacement of natural aggregate [12–16]. The decrease in split tensile strength (STS) was up to 24% [17] and modulus of elasticity was up to 45% at 100% replacement level [17–20]. The influence of fly ash on performance of RAC designed with conventional method was observed in limited studies as mentioned below. There was a reduction in CS, STS, and static modulus of elasticity, but improvement in resistance to chloride ion penetration, drying shrinkage and creep of the RAC with fly ash [21]. Pulverized fly ash at 30% compensated the reduction in compressive strength of concrete containing recycled aggregate at long-term [22]. Use of 100% RCA and recycled fine aggregates (RFA) with the fly ash addition, as replacement of fine aggregates, enhanced CS, STS, carbonation and chloride ion penetration and reduced stiffness in comparison to NAC [23]. Replacement of Portland cement by 20%–35% high fineness fly ash in RAC resulted in equivalent or higher CS than NAC. The use of RFA resulted in decrease of CS at 28-day, but increase at 90-day. STS was not affected by fly ash. Lower modulus of elasticity (E) was reported for RAC with or without fly ash [24]. Use of ground fly ash up to 35% by weight of cement increased the CS for water binder ratio (w/b) of 0.45 and up to 20% part replacement increased the CS at w/b of 0.55 and 0.65 [25]. Addition of super plasticizer along with 20% fly ash compensated around 10% reduction in CS and improved workability [26]. Enhanced workability, reduced water absorption of RCA and higher long-term (56 days and 91 days) CS was reported in 40% fly ash incorporated RAC [27]. Effects of High-volume fly ash replacement (40%, 50% and 60%) on RAC showed reduction in CS with increase of fly ash and RCA replacement percentage. 50% fly ash and 50% RCA resulted in compromising 50% strength and 40% cost savings [28].

Based on previous studies, it is evident that the behaviour of fly ash on the performance of RAC is not very clear from the limited studies available in this domain. The effect of mix design method that can enable replacement of 100% RCA and fly ash maintaining satisfactory performance of concrete in terms of strength is hardly observed in earlier studies. Therefore, in the present study, particle packing method (PPM) of mix proportioning is adopted for recycled aggregate concrete incorporating fly ash. Natural coarse aggregate (NCA) was fully replaced by recycled coarse aggregates (RCA). Full replacement of natural aggregates was considered to check the effect of solely recycled aggregates (0% natural aggregates) and partially substituted supplementary cementitious material (fly ash) on performance of new sustainable concrete. Concrete with only natural aggregates without the addition of fly ash was used as control concrete. The performance of concrete was evaluated in terms of compressive strength, split tensile strength, flexure strength and modulus of elasticity.

2. PPM as an alternative mix design method

Packing density (PD) is defined as the ratio of the solid volume to the total volume and can be maximized by adopting a continuous particle size range of less than 4.75 mm–20 mm coarse aggregates. Voids between larger particles are filled up by smaller ones to attain minimum voids in a concrete mix. Total paste required to fill the voids between aggregates will be reduced due to minimization of the voids. So, it is supposed to be beneficial in improving performance of RAC where excess adhered mortar content is the major reason for inferior properties of RAC. One of the methods to achieve maximum PD with a particular particle size distribution is the use of optimization curve i.e. Fuller curve [29] or Andersen curve [30].

Another method considers analytical particle packing models. Different analytical models such as Modified Toufar model [31], Dewar model [32], De Larrard Linear Packing Model [33] and Compressible Packing Model [34] are available for optimization of aggregates (>125 μm) to achieve maximum PD. The way of pouring, particle shape, density and applied compaction energy are considered as the basic parameters affecting packing of the larger aggregates. These mathematical models consider the geometrical shape of larger particles, but not the packing of finer particles (cement or fillers) which behaves differently due to larger surface area. It was reported that, replacing cement partially with comparatively finer materials (higher surface area to volume ratio), increases packing density of total paste content by filling voids between cement particles [35]. In such conditions, in addition to simple geometrical interaction as in case of aggregates, surface related Vanderwaal forces and electrostatic charges also become