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Recycled aggregate concrete: Particle Packing Method (PPM) of mix design approach

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HIGHLIGHTS

- Systematic application Particle Packing Method and Indian codes of practice for mix design of recycled aggregate concrete.
- Overcoming the inferiority of recycled aggregate concrete using Particle Packing Method.
- Comparative studies of experimental results with existing literature and codes.
- Statistical analysis of results using single factor ANOVA test.

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ABSTRACT

A sustainable and eco-friendly approach is essential for the construction industry, as it is one of the major sectors responsible for the depletion of the natural resources and the generation of greenhouse gases. In this context, the recycled aggregate (RA) is an effective alternative to natural aggregate. But, the use of RA has not gained popularity yet, because of the inferior quality of RA and yielded recycled aggregate concrete (RAC) using RA. The proposed Particle Packing Method (PPM) of design mix is executed along with the established Two Stage Mixing Approach (TSMA) to produce RAC by completely replacing the natural coarse aggregate. The synergistic effect of PPM design mix and TSMA on fresh and hardened stage performance of RAC were studied. In this context, a comparative analysis showed encouraging results for the PPM design mix as compared to the IS: 10262 (2009) method of mix design approach.

1. Introduction

The rapid growth in population and economy in India leads to the unavoidable process of industrialization and urbanization. It requires a huge amount of construction work and also produces large quantities of construction and demolition (C&D) wastes. According to Ministry of Environment and Forests (MoEF) India generates nearly 530 million tonnes of C&D waste annually [1]. Globally, this figure goes up to 1.5 billion tonnes per annum [2]. This C&D debris consists of very high percentage of waste concrete. In this ambitious goal of economic and infrastructure development, the much needed attention towards the environment has been neglected globally. A balance must be maintained between development of the society and maintaining the integrity of the environment. So, effective use of environment friendly materials, sustainable materials, especially recycled materials should be encouraged. In order to promote this idea, a synergistic effort among various government departments, research groups, designers, construction engineers and certifying authorities is required.

The reuse of old concrete as a source of aggregate is a reliable alternative to natural aggregate (NA) mined from nature for concrete construction. The aggregate yielded by the crushing of C&D debris is known as recycled aggregate (RA). The RA can be in the form of crushed concrete, crushed brick or broken glass pieces. However, the scope of the present study is limited to the use of crushed concrete as a source of aggregate to produce concrete. In this context, demolished building, rejected precast concrete member, concrete road beds, unused concrete in ready mix concrete

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plant and tested specimens from different laboratories are the sources of waste concrete. The RA can be grouped as recycled coarse aggregate (RCA) and recycled fine aggregate (RFA). Natural aggregate and adhered hardened mortar are the constituents of RA. The adhered mortar layer and its quantity are the main reasons for RA having inferior physical and mechanical properties as compared to NA [3–12].

The concrete in which NA is replaced partially or fully by RA is known as recycled aggregate concrete (RAC). The performance of fresh and hardened RAC properties has been studied by different researchers. RAC has lower workability than conventional concrete as the water absorption capacity of RA is on the higher side due to its porous structure [3,6,12–25]. The compressive strength of RAC is primarily influenced by replacement ratio of natural aggregate and w/c ratio. Apart from these, some other factors like type of parent aggregate, age and exposure condition of parent concrete, number of crushing stages, physical and mechanical properties of RA, and amount of adhering mortar in RCA also affect the compressive strength of RAC. Again, the concrete prepared using RCA consists of two interfacial transition zone (ITZ), which is known to be the weakest link in concrete [26,27]. So, in microstructure level also RAC is inferior to natural aggregate concrete (NAC). The reduction in compressive strength of RAC is not very significant when the replacement of RCA is up to 30% [4,26,28,29]. Studies also reported that the reduction in compressive strength of RAC is up to 30% at 100% replacement of natural aggregate [4,13,24,29–31]. The split tensile strength of RAC decreases as the replacement ratio increases and reduction can be up to 10% at different replacement percentage [4,16,32,33]. Rao et al. [34] found that the reduction can be up to 24%, at 100% replacement level. However, replacement ratio has little influence on the flexural tensile strength of RAC [4,26,29,34]. But, in some literature, it has been mentioned that the flexural tensile strength is reduced up to 10% with the increase in RCA replacement up to 100% [4,16,25,32,33]. Modulus of elasticity is the most affected mechanical property of RAC. Its value for RAC was found to be 50% - 70% of conventional concrete [4,32,34]. The increased amount of mortar content in RAC with respect to conventional concrete is the primary reason for having lower modulus of elasticity of RAC [21]. There is a substantial decrease in modulus of elasticity with increase in degree of substitution of RCA and markedly up to 45% reduction at 100% replacement level [16,20,32–35].

The fresh and hardened stage performance of RAC can be improved by reducing the old mortar content adhered to the RA. So, at the material level many researchers have employed different methods such as, freeze-thaw method, mechanical grinding and ultrasonic treatment method, thermal treatment method and chemical treatment method to disintegrate the mortar layer and obtain cleaner RCA [5,36–40]. The techniques approached by different researchers to improve the performance of RAC are incorporation of mineral admixture, using different mix design methods and modifying the mixing process. The mineral admixtures act as filler material and fill up the pores present in the ITZ. The secondary hydration products of the pozzolanic reaction of these mineral admixtures fill up the open pores and capillary spaces and enhance the compactness of the concrete matrix. The addition of mineral admixtures to RAC improves the workability in fresh stage [41]. The compressive strength of RAC can be enhanced by using silica fume or meta kaolin [42]. The incorporation of nano silica helps in improving the mechanical properties of RAC and also enhances the ITZ and matrix quality by minimising the voids [43–46]. However, the addition of these mineral admixtures are not prudent. Whereas, the use of inexpensive mineral admixtures like fly ash or GGBS as partial replacement of cement reduces the compressive strength of RAC [42,47,48]. However, as reported by some researchers the addition of fly ash with cement increases the compressive strength [47,49]. The use of fly ash does not have any significant effect on modulus of elasticity of RAC [50]. The mineral admixtures (GGBS, flyash) are very effective in improving the durability performance of RAC also [41,47,49].

Direct Weight Replacement (DWR) Method, Equivalent Mortar Replacement (EMR) Method, and Direct Volume Replacement (DVR) Method are three different aggregate replacement methods employed by different researchers. In DWR method, the total weight of coarse aggregate (natural coarse aggregate along with RCA), cement, and water content is kept constant for any replacement ratio. In order to produce same volumetric yields the fine aggregate amount is reduced. Fathifazl et al. [51] proposed the EMR method and treated RCA as a two phase material rather than a single coarse aggregate. In EMR method the total volume of mortar; i.e. residual mortar along with the fresh mortar content in RAC remains same as the fresh mortar content of target natural aggregate concrete. The direct volume replacement (DVR) method considers RCA as a single phase coarse aggregate. In this method the volume of replacing RCA is same as the volume of NCA. The amount of fine aggregate, cement and water are unaffected as the total volume of coarse aggregate remains constant. Knaack and Kurama [52] compared these methods based on workability, compressive strength, and modulus of elasticity of RAC and concluded that DVR method provides better workability condition as compared to DWR and EMR methods of mix design. In EMR method workability reduces significantly and replacement ratio more than 20% needs changes in mix proportions and high dose of water reducing admixture. However, the compressive strength is not influenced significantly by any of these mix design methods at any replacement ratio.

The modified mixing approaches, such as Double Mixing Method (DM), Two Stage Mixing Approach (TSMA), and Triple Mixing Method (TM) have been employed to enhance the performance of RAC [26,53–55]. Basically, in each of these mixing approaches water is added at two different stages. However, the amount of water involved in each stage as well as the mixing period of each step of these mixing processes are not same. The Double Mixing Method employed by Otsuki et al. [53], half of the water is added to the dry mix of coarse and fine aggregate. This method helps in improving the ITZ quality, strength and durability of RAC. Similarly, in TSMA water is added at two stages of the mixing process, as recommended by Tam et al. [26,54]. The TSMA helps in developing a stronger ITZ by effectively filling the voids and cracks present in RCA. The compressive strength of RAC is increased up to 21% and TSMA is also effective in enhancing the durability of RAC. The TSMA helps in developing a stronger ITZ by effectively filling the voids and cracks present in RCA. The compressive strength of RAC is increased up to 21% and TSMA is also effective in enhancing durability. Kong et al. [55] developed the triple mixing method (TM) to improve the ITZ. In this method mineral admixture, cement and mixture of water and superplasticizer are added at three different phases. The TM contributes significantly in improving workability, compressive strength and flexural strength in comparison to double mixing method [56].

Different authors have employed various techniques and methods in the material processing stage, mix design stage, mixing stage and even in curing stage to improve the performance parameters of RAC. However, in the knowledge of the authors the Particle Packing Method (PPM) has not been applied to the mix design of RAC. The simplicity and effectiveness of PPM is the motivation to implement the same in this work to produce RAC.

2. Research significance

The literature available on the performance of RAC indicates to the fact that, the poor performance of RAC both in fresh stage and