Comparative Study on Properties of Recycled Aggregate Concrete Using Recycled Aggregates Coated with Different Pozzolanic Materials

Popat Kumbhar*, Hemant Lohar, Sagar Sanap, Rohit Rajratan, Abhishek Shingade

Department of Civil Engineering, K. E. Society's, Rajarambapu Institute of Technology, Rajaramnagar (Islampur), Dist. Sangli, MS, India, 415

Research Article

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***For Correspondence:**
Popat Kumbhar, Department of Civil Engineering, K. E. Society's, Rajarambapu Institute of Technology, Rajaramnagar (Islampur), Dist. Sangli, MS, India, 415

E-mail: popat.kumbhar@ritindia.edu

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ABSTRACT

Recycled Aggregates (RA) are the aggregates obtained from reprocessing materials, which were earlier used in constructions. The use of RA contributes to reducing waste and energy consumption and achieving sustainability. Several investigators have attempted to develop concretes using RA; however, the concrete so produced exhibited poor performance concerning workability and strength properties. The poor performance is found to be mainly due to high porosity and water absorption properties occurred due to the presence of sticked mortar to the RA surface. This fact necessitated proper treatment of RA so that the Recycled Aggregate Concrete (RAC) could enhance its performance. In this paper, M20 grade RAC has been developed using 'RA' without and with coating of different pozzolanic materials *viz*., Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), Microsilica (MS), Ultrafine Slag (US) and other ingredients *viz*., cement, crushed sand, water and chemical admixture. Results of the experimentation show that the average workability (slump) and strengths of RAC produced using 'RA' coated with different pozzolanic materials increased by 102% and 17.27% respectively when compared to the RAC produced using RA without coatings. The RAC with RA coated using GGBS has shown higher strength (31.80 MPa) amongst the others. Further, the workability and strengths of normal concrete are found to be more by 108% and 19.38% respectively when compared to normal concrete. The study concludes that, RA coated with pozzolanic materials can be considered as an alternative to NA for producing the concretes as they satisfy the required workability and strength properties.

Keywords: Recycled aggregate; Recycled aggregate concrete; Sustainability; Pozzolanic materials; Ultrafine slag

INTRODUCTION

The RA are the aggregates which are produced from the recycling of clean concrete waste in which very low content of other building waste exists. In India, every year the 'Construction and Demolition (C&D)' waste gets produced to the tune of 700 million tonnes. Further, natural disasters like earthquakes, hurricanes, and other similar natural disasters may also continue to contribute to the generation of excessive amounts of concrete waste. Additionally, the increased urbanization growth rate has resulted in the development of huge quantities of 'C&D' waste. However, to protect the environment and make use of available natural resources effectively it becomes essential to recycle and reuse the generated 'C&D' waste for producing Recycled Aggregates (RA). The studies have indicated that using 'C&D' waste for producing new concrete would have significant environmental and economic impacts. Also, the replacement of Natural Aggregates (NA) by RA would result in reducing CO_2 emission by about 15-20% and thus it would be possible to conserve the world's major share of the limestone resources. The present situation in the construction industry is such that it has to face the basic challenges of fulfilling the housing and huge infrastructural needs. Further, there are concerns about the high requirements of energy and the emissions of greenhouse gases due to the manufacturing of cement and similar products.

The process of recycling aggregates from concrete waste is comparatively simple and involves various stages such as breaking, removing, and crushing the waste available concrete waste into a material of the required quality and size. Such RA can be used for producing RAC of lower grades. Many experimental works have been carried out to utilize RA for making RAC using Ordinary Portland Cement (OPC) as a bonding material. However, studies have revealed that the use of RA in making concrete results into the overall poor performance of concrete mainly because of the existence of old mortar remains on the exterior surface of RA. The existence of such residual sticked mortar to the exterior surface of RA significantly affects the characteristics of RA *viz*., density, porosity, and water absorption. RA generally has a lower density when compared to NA because of the less dense sticked mortar on RA as opposed to the rocks from which NA are obtained. NA typically possess low water absorption capacity because of their low porosity, while RA have adhered mortar with higher porosity that permits the mortar to hold in its pores.

Existing methods for pre-treating recycled aggregates

The pre-treatments to RA can help in enhancing its qualities. A number of techniques are used for treating the RA to enhance their properties such as density, porosity, water absorption, etc. which in turn contributes in enhancing the performance of RAC. The improvement in the properties of RA is possible to be achieved by pre-treating them using the techniques which may involve: (i) chemical and/or mechanical method of removing the mortar or (ii) retaining of the mortar and its strengthening. The techniques that used for treating the RA categorized under mortar removal approach include: (a) Thermal treatment technique, (b) mechanical treatment, (c) water cleaning, (d) chemical treatment and (e) thermal mechanical treatment. The most commonly used techniques for treating the RA categorized under mortar retention approach include: (a) Polymer treatment, (b) calcium carbonate bio deposition, (c) carbonation, (d) activation using sodium silicate solutions, and (e) usage of Pozzolanic materials. The mortar retention techniques. The mortar removal techniques adopted for treating the RA are reported to be costlier and inconvenient while mortar retention and strengthening techniques are considered to be time consuming but are more convenient for application.

Literature review

The researches carried out by several investigators to experimentally study the characteristics of 'RA and RAC' are published in many journals and are briefly discussed in the following section.

Katrina and Thomos (2013) have reviewed the literature with regard to RA, properties of RA that affects the properties of RAC and also large-scale effect on structural members. From the review study, the authors have arrived at some findings with respect properties of RAC that include: (i) Replacing of NA in concrete with RA contributes in reducing the compressive strength, however, gives comparable split tensile strength; (ii) modulus of rupture of 'RAC' is slightly lesser than the conventional concrete, likely to be caused due to the weakening of ITZ from residual mortar; and (iii) the modulus of elasticity reduces than expected because of the more ductile aggregates. Based on the review study, authors conclude that use of RAC produced using RA is likely a feasible option for structural purposes [1].

Hongru have carried out experimental work of providing treatment to 'RA' on the surface using the slurries containing nanomaterials and compared the characteristics of 'RA' before and after the surface treatment is applied. Also, the investigators have examined the effects of applying the surface treatment using nanomaterials with respect to the micro structure and macro properties of 'RAC'. Results of experimentation showed that both the slurries of nanomaterials improved the new interfacial transition zone (ITZ) in between old and new mortars. Study concluded that, the properties of both 'RA' and RAC get enhanced due to the use of nanomaterials for surface treatment of 'RA' [2].

Fernando performed experimental study to reduce porosity of 'RA' by providing the coating of cement in a lab granulator. The 'RA' was coated with a cement film of 0.16–0.23 mm thickness. The testing of 'RA' was done for determine porosity and freeze-thaw resistance. The results of the study showed enhancement in the properties *viz*., porosity and resistance against freezing-thawing. The researchers conclude that, the coating of RA causes improvement in its properties due to the formation of dense cement matrix at ITZ which indicates reduction in 'porosity' and increase in the 'strength' of 'RA'[3-5].

Tianyu have rigorously carried out a literature review dealing with the mechanical properties of RAC produced using RA so as to give comprehensive understanding about the behaviour of 'RAC'. The authors have also presented the effects of providing surface treatment to aggregate, moisture state of aggregate, and mixing of concrete on the behaviour of 'RAC'.

Jiangang experimentally studied the characteristics of both 'RA and RAC' by treating the 'RA' using different treatment methods to study the effect on the various properties (*viz*., dynamic elastic modulus, compression strength, drying shrinkage rate, and coefficient of chloride ion penetration) of 'RA and RAC'. Results of the study indicated improvement in the mechanical properties and also the resistance to drying shrinkage of 'RAC' when 'RA' are treated with 'carbonation method'. Also, the 'slurry wrapping method' improved RAC's resistance to the penetration of chloride ion. Study proposes optimisation methods for 'RA and RAC' based on the improved properties of 'RA and RAC' by use of carbonation and slurry wrapping treatment [6-8].

Natt have carried out a review study related to the treatment techniques that are chemical-dependent investigated by different researchers. From the study, authors have presented the analysed sources of literature which addresses about the use of techniques that would improve the quality and the also the effects of this such techniques on the characteristics of ITZ and 'RAC'.

Wimal and Lim performed experimental study to investigate the influence of higher temperatures (25°C–800°C) on the properties of 'RAC' *viz*., microstructure performances, physical and residual mechanical. The study was carried out on 'RAC' by strengthening through the coupling effect of basalt fibers and 'RA' treated using pozzolana slurry. The results of study indicated that, a significant improvement occurs in residual properties of strengthened (modified) RAC produced by using combination of utilization of BF and pozzolanic slurry treated 'RA' [9-10].

Mamatha performed optimization study on carbonated 'RA' for preparing pavement quality concrete for roads. The optimization parameters considered for the study included different types of material (cement, fly ash, and silica fume) using the concentrations varying between 20%−60%, exposure durations ranging between 4–12 h, and different sized 'RA' (10 mm and 20 mm) while the properties *viz*., dry density, absorption, porosity and toughness were considered for optimization process. Results of the study indicates that, soaking the 'RA' using the slurry of any cementitious material having concentration of 40% and exposure time of six (6) hours contributes in improving performance of both 'RA' and PQC produced using treated 'RA'[11-13].

Soheil have carried out an experimental work to reinforce the ITZ and matrix of 'RA' using a mixture of pulverized coal bottom ash and poly carboxylate-water solution. The results of the study recommend that, the bottom ash slurry when adequately dispersed contributes in enhancement of the performance of 'RAC'. The coating of well dispersed bottom ash slurry strengthens both the ITZ bulk matrix. Further, the slurry causes the decrease in the porosity and unhydrated clinker content with an increase in the indicate that Calcium-Silicate-Hydrate (C-S-H) near ITZ. Researchers concluded that, use of well dispersed mixture of coal bottom ash slurry with poly carboxylate-water solution for coating the 'RA' causes significant increment in tensile, compressive strength and also fracture toughness (~12%).

MATERIALS AND METHODS

Experimental program

The experimental work carried out for providing treatment to the 'RA' and to produce 'RAC' using the treated 'RA' is presented in the following sections.

Materials: The various materials used for producing 'RAC' are explained in the following section. Now we explain these two laws in a generalized way in terms of vectors.

Cement: A 53-grade ordinary Portland cement (OPC, brand name 'Bangur') having 3.15 specific gravity, conforming to IS:269-2015 has been used as shown in Figure 1.

Figure 1. Cement bag (OPC, 53 grade).

Figure 2. Fine aggregate (CS).

Fine aggregate: The Crushed Sand (CS) procured from local manufacturing plant (Vijay Stone Crusher, Islampur) conforming to IS:383-2016. The sand belongs to zone I and its other properties are given in Table 1.

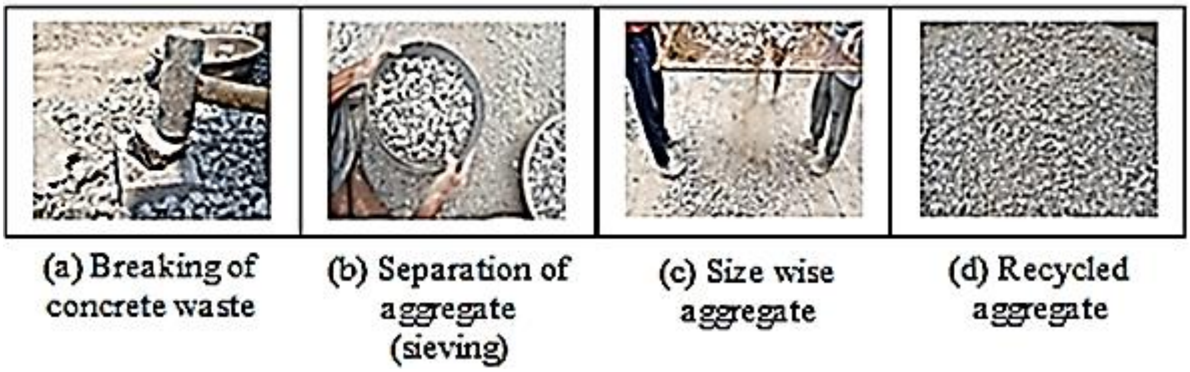
Coarse aggregates: The coarse aggregates of two types *viz*., NA and 'RA' are used for making the concretes.

Natural Aggregates (NA): The NA (crushed stone aggregates) of 10 mm and 20 mm size obtained from local stone crushing plant are used as shown in Figure 3.

Figure 3. Natural aggregates.

Recycled Aggregates (RA): The 'RA' (size: 10 mm and 20 mm) are obtained from laboratory concrete waste available in the form of damaged concrete cube specimens after performing destructive testing under compression testing machine. The process followed in obtaining the RA from damaged concrete cube specimen involved various operations (i) breaking of concrete cube specimen by swing hammer, (ii) separation of aggregate by sieving, and (iii) sorting of aggregates (sieve analysis). Figures 4a-4d shows the sequence of operation in obtaining the RA.

Figure 4. Operations in obtaining recycled aggregates. (a): A breaking of concrete waste. (b): Separation of aggregate (sieving). (c): Size wise aggregate. (d): Recycled aggregate.



The aggregate properties as determined by following the guidelines given in IS:2386(Part-3)-1963 are tabulated in as shown in Table 1.

Table 1. Fine and coarse aggregate properties.

Type of property	Fine aggregate	Coarse aggregate	
	CS	NA	RA
Specific gravity	2.8	2.9	2.68
Water absorption (%)	2.5	1.2	4.86
Moisture content (%)	0.4	0.2	0.4

Pozzolanic materials: The pozzolanic materials *viz*., Fly Ash (FA), Ground Granulated Blast furnace Slag (GGBS), Microsilica (MS) and Ultrafine Slag (US) procured from different suppliers have been used for making their slurries to provide coatings to the RA. The specific gravity of FA, GGBS, MS and US are found to be 2.17, 2.9, 2.2 and 2.9 respectively.

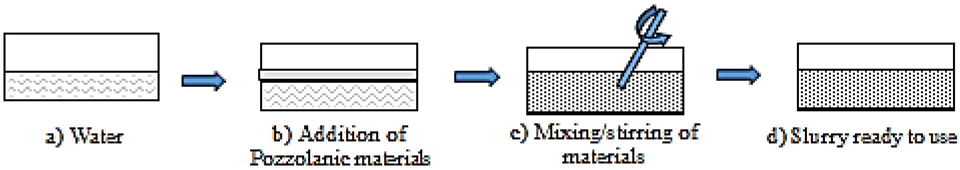
Chemical admixture: A Poly Carboxylate Ether (PCE) type chemical admixture (Fosroc Auramix 300) with specific gravity of 1.10 has been used for improving workability of concrete mixes (IS:9103-1999).

Water: Use of portable water has been done for preparing all the concrete mixes [14-16].

Treatment (coating) to Recycled Aggregate (RA)

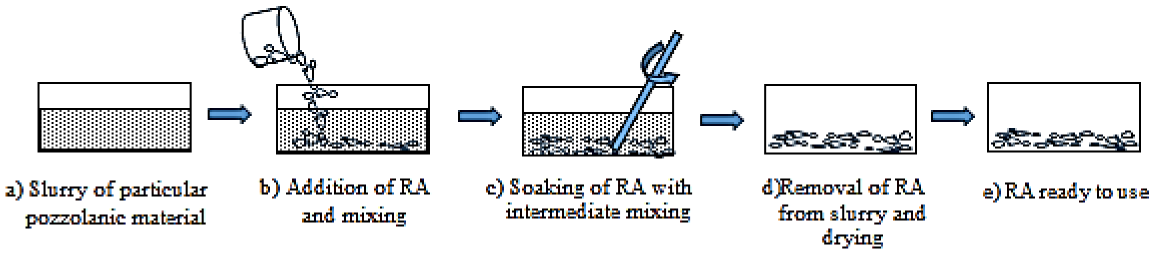
The RA obtained after processing provied with coatings of different Pozzolanic materials *viz*., FA, GGBS, MS and US by immersing them into the slurry prepared by using water and individual Pozzolanic material. For making slurry, a 40% quantity of each Pozzolanic material by weight of RA was mixed with a quantity of water taken twice the weight of RA. The mixture of Pozzolanic material and water was stirred continuously for a duration of 2 minutes by using mixing rod. The slurry making procedure is as shown in Figure 5.

Figure 5. Stages in the preparation of slurry.



The RA were immersed in the container consisting slurries prepared using different Pozzolanic materials for soaking purpose. The process of soaking was performed on RA using each pozzolanic material. The soaking process lasted for 4 hours, with intermediate mixing done after every 30 minutes interval. After allowing for soaking, the RA were removed from the container and kept for drying under the shed for 4 days. After drying, the testing of RA was performed to determine various properties. The entire process of providing treatment to RA using coating of each pozzolanic material is indicated by a flow chart shown in Figure 6.

Figure 6. Treatment of RA by coating method.



Properties of coated Recycled Aggregates (RA): RA obtained by coating with each pozzolanic material as per the process explained in earlier section were tested for determining various properties *viz*., specific gravity, water absorption, and moisture content following the guidelines given in IS:2386-1963. The properties of coated RA obtained by following standard procedure are given in Table 2.

Table 2. Properties of coated recycled aggregates.

Properties	Cement coated RA	Micro-silica coated RA	Fly ash coated RA	GGBFS coated RA	Ultrafine slag coated RA
Specific gravity	2.72	2.7	2.7	2.71	2.7

Water absorption (%)	2.72	3.02	3.13	3.16	3.08
Moisture content (%)	0.5	0.56	0.42	0.53	0.45

Mix design of M20 grade concrete and preparation of trial mixes: The mix design of a M20 grade concrete is performed considering the properties of NA, RA, and RA coated with different pozzolanic materials following the guidelines of IS:10262-2019. The concrete mixes are designed by maintaining same water to cement ratio (W/C), and superplasticizer content (@0.8% by weight of cement). The quantities of concrete ingredients obtained through mix design process (for 1 m^3 concrete volume) are finalized after incorporating the changes required for the field adjustment. The finalized quantities of concrete ingredients required for preparing concrete mixes using NA, RA, and RA coated with different pozzolanic materials are given in Table 3.

Table 3. Quantities of concrete ingredients and mix proportion.

Aggregate type used for mix	Cement, kg	Water, kg	Fine aggregate, kg	Coarse aggregate, kg	
				Size, 20 mm	Size,10 mm
i) NA	316	187.87	800.43	754.5	503
ii) RA without coating	316	227.52	800.43	672.89	448.59
iii) RA coated with C	316	201.62	800.43	698.95	465.96
iv) RA coated with FA	316	207.22	800.43	690.33	460.22
v) RA coated with MS	316	204.26	800.43	692.1	461.4
vi) RA coated with US	316	206.27	800.43	690.9	460.6
vii) RA coated with GGBS	316	206.39	800.43	693.46	462.3

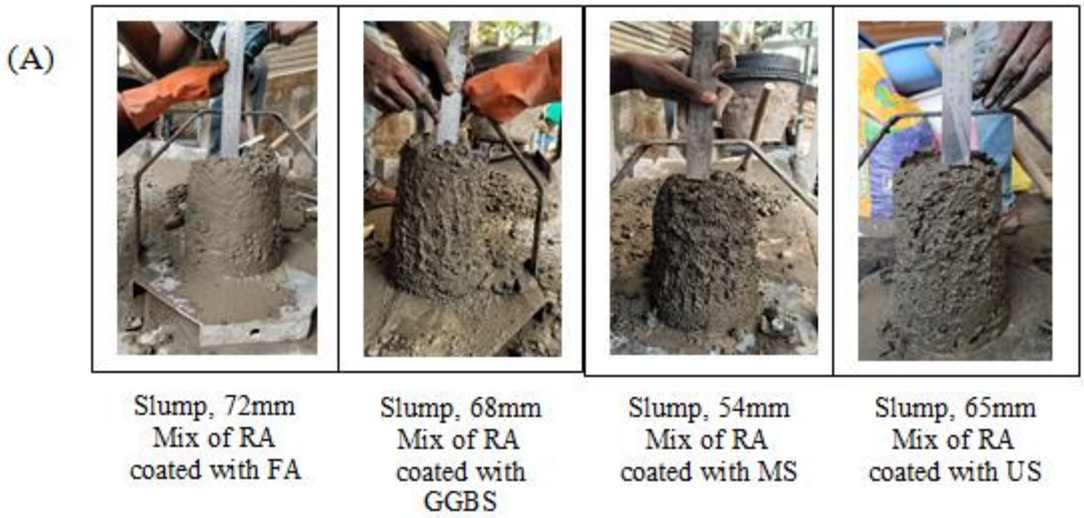
Preparation of concrete mixes: The concrete mixes were prepared by using each type of aggregate adopting finalized quantities of concrete ingredients (Table 3). All the concrete mixes were prepared following the procedure outlined in IS:516-1959. The stepwise process is explained in the following section.

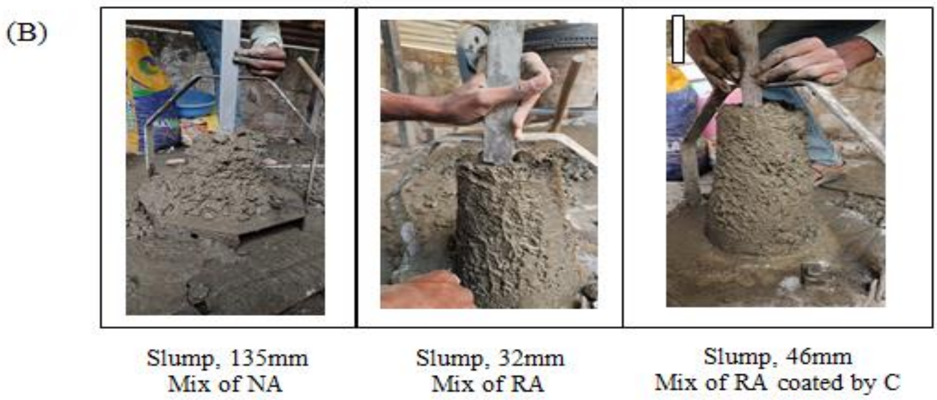
Batching of materials: In this stage, the required quantities of materials were measured by weigh batching using weighing balance of 20 kg capacity having 5 gm as least count [17, 18].

Mixing of materials: The measured quantities of all the ingredients of concrete were dumped in a 'drum' type concrete mixer for obtaining homogeneous concrete mix. The drum of the mixer was rotated for a duration of 2 mins so as to achieve dry mixing of the materials. The water addition was done in two steps. In the first step, 75% water of the total water quantity was added to the mix and the mixing was carried out for a duration of 2 min. The remaining quantity of water (25%) was then mixed with 0.8% (by weight of cement) superplasticizer. The water with superplasticizer was mixed thoroughly by stirrer and then added to wet concrete mix in the drum of mixer for get fluidizing effect to the concrete mix and then the drum was rotated for a period of 2 mins to get homogeneous concrete mix. The wet concrete mix was then removed from the drum mixer and collected in the metal tray.

Workability (slump) measurement of fresh concrete: The workability of fresh or wet concrete was measured by 'slump cone test' as per the guidelines provided in IS:1199-2018. The slump cone and the base plate of the test apparatus was cleaned and the inner side was coated with oil to avoid the sticking of concrete. The slump cone mould was firmly fixed with the base plate by fixing clamps and then the concrete was poured in the mould in three equal layers. Each layer was tamped 25 times by 16 mm diameter rod. The top layer was finished using trowel and mould (slump cone) was slowly lifted vertically up by holding handles of the mould after releasing clamps. The concrete allowed to subside under its own weight and after allowing the concrete to subside, its depth (slump) was recorded using steel scale to an accuracy of 0.5 mm. The slump tests performed on the concrete mixes produced using NA, RA and RA coated with different materials are shown in Figure 7.

Figure 7. Slump tests on concrete mixes prepared using different coarse aggregates. (A): Slump tests on concrete mixes produced using NA, RA and RA coated with cement. (B): Slump tests on concrete mixes produced using RA coated with materials.



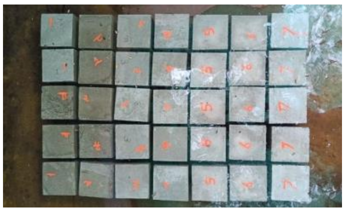


Casting of cube specimens: The casting of the cube specimen was performed by following the standard procedure given in IS:516-1959. The concrete cube moulds of 150 mm size were initially cleaned with a cloth and the inside surfaces coated with oil. The pouring of concrete in the mould was done using the 'scoop'. The mould was filled in three equal layers with each layer tamped for 35 times using 16 mm diameter rod. After the last layer was tamped, it was levelled by trowel (Figure 8). The concrete filled cube moulds were then stored under the shed for 24 hours and covered with wet gunny bags. After 24 hours, the concrete cubes were demolded and provided with designations or nomenclatures as per the contents of aggregate types and pozzolanic material used. After providing the nomenclatures, the concrete cube specimens were taken for curing process as shown in Figure 8.

Figure 8. Casted concrete cube specimens.

Curing of cube specimens: The concrete cube specimens were immersed in a water tank consisting clean water and kept there for 28 days period for gaining strength as shown in Figure 9.

Figure 9. Curing of specimens.



Testing: After curing all the concrete cubes for 28 days curing period they were removed from the water tank and taken for testing their compressive strength under compression testing machine (capacity, 200T). Each concrete cube specimen was wiped out using dry cloth and then placed in the machine such that their smooth faces get contacted with the jaws of the machine. The machine was then started and the application of load was maintained with a rate of 140 $kg/cm^2/min$ till the crushing of the concrete takes place. The maximum failure load was recorded. The compressive strength of each concrete cube specimen was calculated by dividing the maximum failure load by area of one face of concrete specimen. Thus, the average compressive strength of three cube specimens was determined and reported.

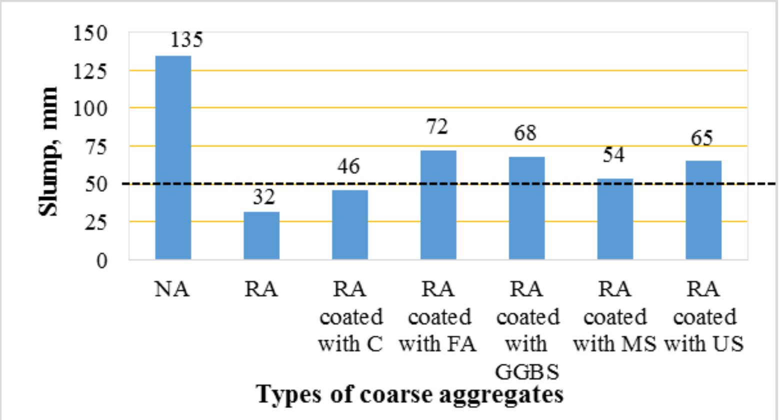
RESULTS AND DISCUSSION

The results of the workability and strength properties of 'RAC' produced by using 'RA' without and with coatings of cement and pozzolanic materials (*viz*., FA, GGBS, MS and US) are determined. The workability and strength results are also compared with the concrete produced using NA and uncoated 'RA'. The results obtained for all the types of 'RAC' for the workability and strength properties are presented and discussed in the following section.

Workability (slump) results: The workability of the fresh concrete produced by using different types of coarse aggregates (i.e. NA, 'RA' and coated 'RA') has been measured by slump cone test method and the variations in the slump values of RAC produced are graphically represented in the Figure 10 as shown below.

From Figure 10 it is seen that the slump of RAC produced using uncoated RA as well as RA coated with cement is the lowest (avg. slump 39 mm) and it does not satisfy the design requirement. However, the RAC produced using RA coated with all the pozzolanic materials (i.e. excluding RA with cement coating) satisfies the design requirement of workability (i.e. slump, 50 mm) and is found to be more by an average value of 102% (i.e. more than twice) when compared with the RA without coating. Further, it is observed that slump values of RAC produced using NA are more by 108% when compared with the slump values of RAC produced using RA coated with all the pozzolanic materials

Figure 10. Variation in slump of RAC for different types of coarse aggregates.

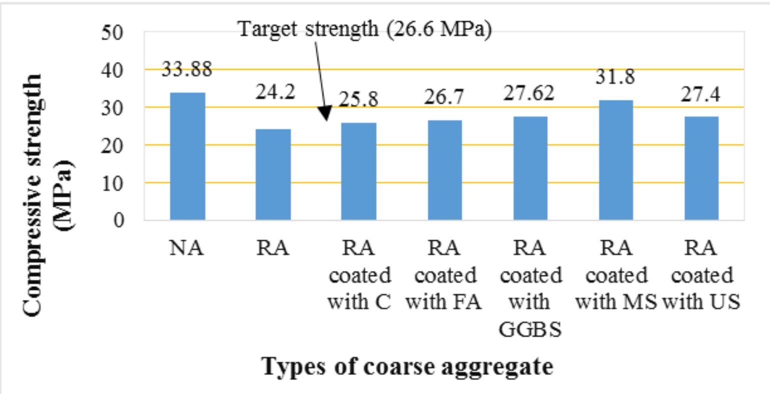


Compressive strength results

The average compressive strength of the concrete cubes produced by using different types of aggregates and its variation in the strength of RAC produced using different types of aggregates is graphically indicated in Figure 11.

From Figure 11 it is seen that the strength of RAC produced using RA without any coating as well as RA coated with cement is the lowest (avg. strength, 25 MPa) and it does not satisfy the design requirement (i.e. target strength, 26.6 MPa). However, the RAC produced using RA coated with all the pozzolanic materials (i.e. excluding RA coated with cement) satisfies the design requirement of strength and is found to be more by an average value of 17.27% when compared with RA without coating. Further, it is observed that strength of RAC produced using NA are more by 19.38% when compared with the strength of RAC produced using RA coated with all the pozzolanic materials.

Figure 11. Variation in strength of RAC for different types of coarse aggregates.



CONCLUSIONS

From the experimental work of determining properties of RAC produced using NA, RA and RA coated with different Pozzolanic materials, the following conclusions are drawn.

1. A RAC of M20 grade produced by using RA coated with different Pozzolanic materials *viz*., FA, GGBS, MS and US have shown satisfactory results for the workability (slump, 50 mm) and compressive strength (26.6 MPa) requirements. The RAC produced using cement coated RA did not achieve the required workability and strength properties as per the design requirements. However, the RAC produced using RA coated with all the Pozzolanic materials under consideration have satisfied the workability (slump) requirements.

Further, the compressive strength of RAC produced using RA coated using GGBS is found to be more by 16.74% when compared over RAC produced using RA coated with other pozzolanic materials.

2. The average workability (slump) and compressive strength values obtained for RAC produced using RA coated with different Pozzolanic materials are found to be more by 102% and 17.27% respectively when compared over the corresponding values obtained for RAC produced using uncoated RA. Further, the average workability and strength values of concrete produced using NA are found to be more by 108% and 19.38% respectively when compared over the corresponding workability and strength values of RAC produced using RA coated with different pozzolanic materials under consideration.
3. The RA can be considered as an alternative to the NA for producing the concretes, however, it becomes essential to provide prior surface treatment in the form of coating so as to improve their properties and hence the properties of RAC.

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