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Characteristics of sustainable concrete incorporating recycled coarse aggregates and colloidal nano-silica

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Abstract. The present study addresses about the development of sustainable concrete utilizing recycled coarse aggregates manufactured form waste concrete and colloidal Nano-Silica. Experimental investigations are carried out to determine compressive and tensile strength of concrete mixes designed with recycled coarse aggregates and different percentages of Nano-Silica. Moreover, water absorption, density and volume voids of concrete mixes are also examined to ascertain the influence of Nano-Silica on behavior of recycled aggregate concrete. The outcomes of the research depict that properties of concrete mixes are significantly affected with the introduction of recycled coarse aggregates in place of the natural coarse aggregates. However, the study reveals that the depletion of behavior of recycled aggregate concrete could be restored with the incorporation of little amount (3%) of Nano-Silica.

Keywords: recycled aggregate concrete; colloidal Nano-Silica; mechanical properties; water absorption; density; volume of voids

1. Introduction

Currently, several countries have been facing acute shortage of natural aggregates owing to the rapid depletion of natural resources. Therefore, scientists and researchers are trying to find out alternate sources of aggregates to fulfill the increasing the demand of aggregates. Moreover, at the same time, huge amounts of waste concrete are generated due to demolition of aged concrete structures that requires large number landfills for dumping of those waste materials. In recent decades, these construction and demolition wastes have been collected and aggregate are prepared after performing a series of operations such as screening, crushing and sieving. These Recycled Aggregates (RA) produced from waste concrete have been effectively used as novel construction materials in several countries. In other words, a number of problems faced by human civilization like depletion of natural resources, increasing the costs of waste treatment prior to disposal, and environmental pollution could be addressed by utilization of RA as partial or complete replacement of Natural Aggregates (NA) (Oikonomou 2005). However, the large variations in

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characteristics of RA, lower density, and higher water absorption and more porous than NA are some problems associated with the use of these aggregates in concrete. The main cause of the aforementioned problems related to these RA is the attached mortar that differentiates these aggregates from NA. Earlier works reported about the inferior properties these aggregates as compared to NA or virgin aggregates (De Juan and Gutiérrez 2009). Primarily, the waste generated RA can be classified into two types based upon their grading; Recycled Coarse Aggregates (RCA) and Recycled Fine Aggregates (RFA). However, the use of RFA was not advised as these fine fractions of RA had adverse effect on workability of concrete (Buyle-Bodin and Hadjieva-Zaharieva 2002). Previous investigations confirmed about the significant influence of the properties of the parent concrete on the newly prepared concrete prepared with RA (Padmini *et al.* 2009). No significant change in compressive strength (CS) of Recycled Aggregate Concrete (RAC) was reported up to the 30% replacement of Natural Coarse Aggregates (NCA) and reduction in CS of concrete was found beyond this replacement limit (Tabsh and Abdelfatah 2009). However, the reduction in Elastic Modulus (EM) of 100% RAC was found to be in the range of 45% when compared EM of Natural Aggregate Concrete (NAC) (Ajdukiewicz and Kliszczewicz 2002; Xiao *et al.* 2005). The application of RCA retrieved from unknown field sources for production of concrete mixes was studied and reduction of mechanical and durability characteristics as compared to that of NAC was reported (Rao *et al.* 2011). It was observed that target strength could be achieved using RCA up to 80% with acceptable mechanical and durable characteristics. Similar conclusions about the feasibility of use of RCA in concrete mixes with desired mechanical and durability characteristics were reported in other studies (Saravanakumar and Dhinakaran 2013, He *et al.* 2015).

Additions of supplementary cementitious materials in RAC mixes could be useful in improving the properties of RAC. For instance, the incorporation of fly ash in RAC significantly improved the resistance to chloride ingress and sulphate erosion along with enhancement of the long-term resistance to carbonation (Limbachiya *et al*. 2012). Different proportion of fly ash and Blast Furnace Slag (BFC) were incorporated in RAC mixes and the outcome of the study was that the RAC made with 50% BFC produced best results in terms of strength among all trial mixes. However, addition of fly ash in RAC mixtures reduced modulus of elasticity and increased coefficient of permeability and chloride diffusion (Berndt 2009). In addition to above, pulverized fuel ash (PFA) and ground granulated blast furnace slag (GGBS) could be introduced in RAC mixes to upgrade its properties such as the improvement in long-term strength, increased resistance to chloride permeability and reduction of chloride-induced corrosion (Ann 2008). The effect of coating of RCA with pozzonanic powder like Fly ash, SF, BFS or their combination on the workability, strength and microstructure of RAC were investigated. The results of the study revealed that dense ITZ structure along with desired fresh and hardened concrete properties could be achieved with this mixing technique (Li 2009). A Triple mixing method based on surface-coating of RCA with pozzalanic materials such as fly ash, slag and silica fume was developed (Kong *et al*. 2010). It was observed that CS and resistance to chloride ions penetration of the RAC could be further enhanced by adopting Triple mixing method as compared to that achieved by using Two-Stage Mixing Approach.

With the recent advances in field of nanotechnology, application of this novel technology has been gaining popularity in different fields of science and engineering. The development of new materials with new functions or improvements in the properties of existing materials using nanotechnology were growing areas of interest for civil engineering applications (Pacheco-Torgal and Jalali 2011). The application of nano-particles in cement based products were producing substantial modification in parent properties of cement based materials as these particles were very effective in filling the nano-sized pores of the C-S-H gel, augmenting the rate of hydrations by acting as nucleation centers and reducing the size of Ca $(OH)_2$ crystals(Pacheco-Torgal *et al.* 2010). Among recently developed nano-particles, Nano-silica (NS) was proficiently applied in the field of cement-based products for achievement of significant changes from normal grain sized products. Improvement in mechanical and the microstructure characteristics of cement pastes was reported with the addition of NS even in low concentrations. This upgrading of behavior cement paste was because of the fact that silica nano-particles increased packing density of the paste (Stefanidou and Papayiann 2012). However, the incorporation of NS to paste and mortar reduced the mix workability, which was due to the immediate reaction between the NS and the cement paste along with the development of gels characterized by high water retention capacities (Berra *et al.* 2012). The addition of NS enhanced the compressive and tensile strength of cement mortar because of the increased pozzolanic action and improvements in properties of microstructure (Jo *et al.* 2007). The use of colloidal NS in place of dry powder form in concrete was recommended due to its more dispersive nature and less segregation. Moreover, the incorporation of colloidal NS accelerated the cement hydration significantly in the early days of curing owing to the reduction in low-stiffness C-S-H gel and an increase in high-stiffness C-S-H gel (Quercia *et al*. 2012, Hou *et al*. 2013). Previous studies demonstrated that addition of colloidal NS in concrete mixes increased CS and reduced porosity (Said *et al*. 2012). This could be attributed to the fact that NS consumed the portlandite (CH) during the pozzolanic reaction occurred in concrete, hence making concrete stronger and denser than concrete made without NS. Moreover, the resistance to permeability of concrete was also increased with addition of NS owing to the removal of minute pores present in cement mortar matrix and ITZ (Zhang and Li 2011). Addition of 3% of NS of in the fully RAC developed CS more than that of concrete made with NAC. Moreover, the microstructure of RAC became dense, uniform and minute voids had been removed with the incorporation of NS as silica nano-particles effectively filled voids present in concrete. However, higher dosage of the NS affected workability of concrete due to dispersion problems and conglomeration of particles, which prevented the use of higher dosages of Nano-particles in concrete (Hosseini *et al*. 2011).

From the aforementioned studies, it can be concluded that the several investigations have been carried out in the area of utilization of recycled aggregates for making of concrete. Moreover, several methods such as addition of pozzolanic materials, use of novel mixing techniques and treatments for enhancing quality of RCA are proposed in literature for enhancing behavior of RAC. After the development of Nano-technology, NS is applied effectively in the field of cement and concrete to achieve significant modification of behavior of the parent materials, which are widely available in open literature. However, the investigations comprising of the utilization of colloidal NS as a pozzolanic material in RAC mixes are rarely found in literature. Therefore, the aim of the present study is to have a systematic examination the influence NS on the behavior of RAC with different percentages of NS and to compare with NAC mix. .

2. Experimental program

2.1 Materials

Ordinary Portland Cement (OPC) of 43 Grade, meeting the requirements of Bureau of Indian Standard Specifications (IS 8112: 1989) was used to conduct the present experimental work. The planning of experimental program was carried out in such a manner that the whole work was completed within one month of receipt of cement.

The standard tests have been performed to characterize the cement and those results are tabulated Table 1.

The NS used in this experimental was the commercially available colloidal NS that was suspension of fine amorphous, non-porous and typically spherical particles in liquid phase. The properties of NS are illustrated in Table 2.

Table 1 Properties of Portland cement

Specific Gravity	Setting time (min)		Consistency	Fineness (m^2/kg)	Mortar strength (MPa)		
	Initial	Final			3 days	7 days	28 days
3.12	135	295	32%	306	37.96	44.2	48.02

Table 2 Properties of Silica Nano-particles

Colour	Specific gravity	pH value	Solid content	Particle size	SiO_2 content
White	1.12	10.11	39%	8-20 nm	99.1%

TEM is a microscopic technique employed for determination of particle size of nano-particles. The TEM image of NS is shown in Fig. 1, which has been taken in bright field mode. The analysis of TEM picture depicted that the particles were being in spherical shape and present in non-agglomerated form. Moreover, the particle size of the colloidal NS was found to be varying between 8 to 20 nm.

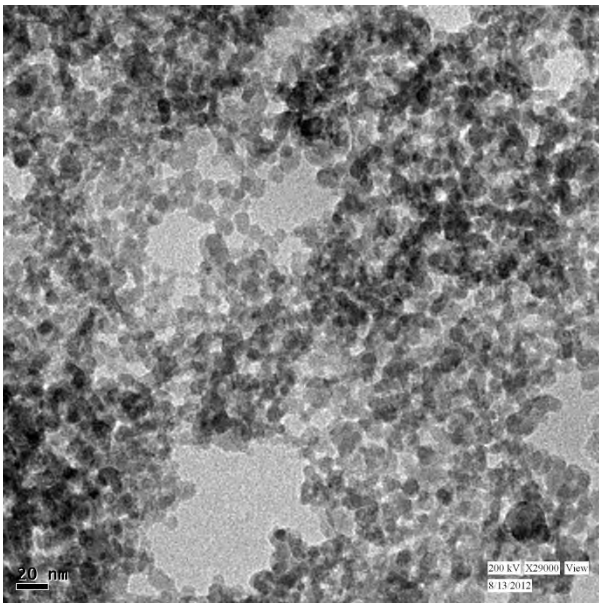


Fig. 1 Transmission Electron Microscope (TEM) of Nano-Silica

Locally available river sand confirming to zone II specification of IS 383 (1970) was used as Natural Fine Aggregate (NFA) in fabricating concrete mixes. The crushed dolerite of 20 mm nominal size was employed as Natural Coarse Aggregates (NCA) and the Recycled Coarse Aggregates (RCA) were prepared by crushing the concrete collected from 30 years old demolished building of Jhargram, West Bengal, (A city of Eastern India). The standard tests have been performed on aggregates and results of those tests are presented in Table 3.

Table 3 Physical and mechanical properties of aggregates

Type of aggregate	Bulk density (kg/m^3)		Apparent specific gravity	Specific gravity	Impact value (%)	Los Angeles abrasion value (%)	Crushing value (%)
	Loose	compact					
NFA	1525	1698	2.66	2.62	-	-	-
NCA	1504	1654	2.81	2.72	15.35	19.72	15.11
RCA	1321	1418	2.67	2.46	34.85	36.56	31.52

Table 4 Mix proportions of concrete mixtures (Unit: kg/m^3)

Mixture	Cement (kg)	NCA (kg)	RCA (kg)	FA (kg)	NS (kg)	Water (kg)
NAC	450.000	1180	-	640	-	180
RAC 1	450.000	-	1067	640	-	180
RAC 2	446.625	-	1067	640	3.375	180
RAC 3	443.250	-	1067	640	6.750	180
RAC 4	436.500	-	1067	640	13.500	180

2.2 Concrete mixtures

Table 4 represents the details of mix proportions of materials per meter cube of concrete mixes containing Recycled Coarse Aggregates and different amount of NS as a replacement of cement. The water cement ratio was kept constant as 0.4 for all concrete mixes and three different amounts of NS (0.75%, 1.5%, and 3%) by weight of cement were used for production of concrete mixes. The reference concrete or control concrete containing natural coarse aggregates without NS was fabricated along with above three mixes. The quantity of water present in colloidal NS was determined and it was taken into consideration while calculating the total amount of water for making concrete mixtures. Normal tap water available in laboratory, which was suitable for drinking purpose, was used for manufacture of concrete mixtures. Slump test for several trial mixes were conducted and it was found that 10 % extra water required in addition to the calculated water for RAC mixes to achieve slump value equivalent to NAC. Therefore, additional 10 % water along with stipulated amount of water was added in RAC mixes to mitigate the additional water requirements of RCA.

2.3 Specimen casting and curing

For preparation of concrete mixes, initially, colloidal NS was mixed with water and stirred

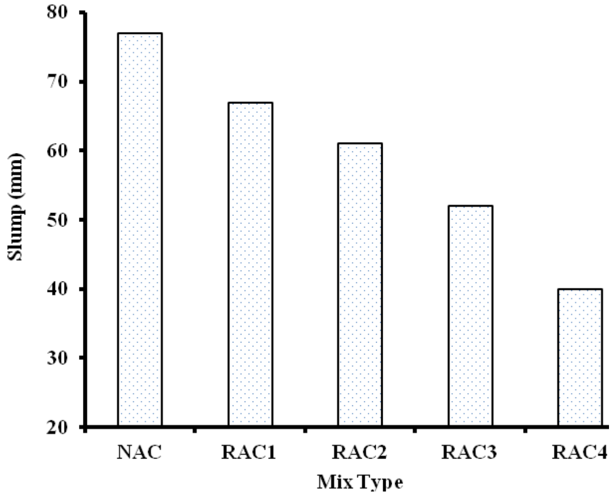


Fig. 2 Variation of slump results of concrete mixes

properly so that uniform dispersion of silica nano-particles could be achieved. After that, the cement, sand and coarse aggregates were mixed at a low speed for 2 min in a concrete rotary mixture. Then mixture of NS and water was slowly poured into the mixer and stirred at a low speed for another 2 min to achieve desired workability. After proper mixing, the fresh concrete was collected from the mixture, poured in to the specified moulds, which were kept for 24h under controlled environmental condition. After 24h, the specimens were unmolded and curing of specimens was done traditionally by storing the specimens under water.

2.4 Testing of specimens

The compressive strength test was conducted on standard cubes of size 100 and 150 mm and cylindrical specimen of 150Φ×300 mm height using 3000 kN compressive testing machine in accordance with the procedures of BIS (IS 516: 1959). The Split Tensile Strength (STS) of concrete at 28 days was performed on cylindrical specimen of 150Φ×300 mm height using 3000 kN compression testing machine according to the procedure given in Indian standards (IS 5816:1989). The Flexural Tensile Strength (FTS) was performed on prisms of size 100×100×500 mm after 28 days curing. The test was executed in accordance with BIS (IS 516:1959) using 100 kN universal testing machine. Specimens of 100 mm cubes were used for determination of density, Water Absorption (WA) and Volume of Voids (VV) of harden concrete according to the procedures given in ASTM C 642 (2006).

3. Results and discussion

3.1 Fresh concrete properties

The results slump test conducted during casting of concrete specimens is shown in Fig. 3,

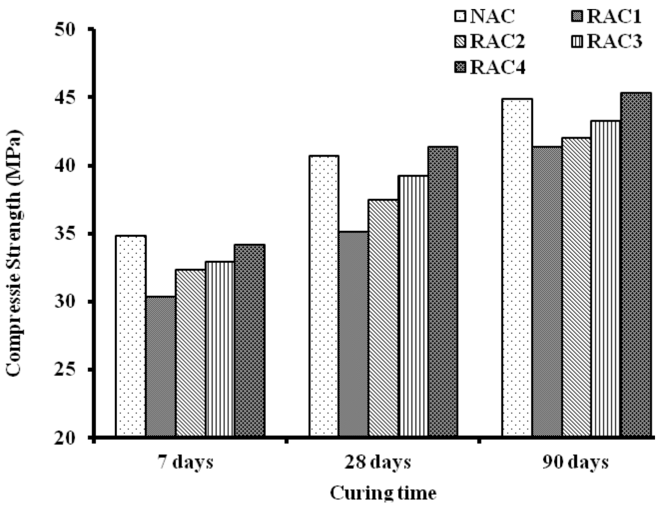


Fig. 3 Variation of compressive strength of cubes

which shows that lower values of slump is obtained with the in RAC mixtures as compared that of control mix. This decrease in slump of RCA mixes could be attributed to increase in water absorption capacity of RCA owing to the presence of the old adhered mortar. This mortar associated with aggregates is more porous in nature and subsequently water absorption of aggregates increases (De Juan and Gutiérrez 2009). To mitigate such additional water demand of RAC, extra amount of water is added to the mix to achieve proper workability during preparation of concrete mixtures. However, loss of slump occurred during this whole process and characteristics of RCA are mainly responsible for slump loss in the concrete containing RAC only. Moreover, further loss of slump takes place in the concrete mixtures containing NS and increase in loss of slump occurs with increasing amount of silica nano-particles. The explanation for the above phenomenon is that silica nano-particles possess a number of unsaturated bonds along with possession of high surface area, which makes them more reactive than micro-particles. Therefore, water molecules are attracted towards the surface of nano-particles and chemical bond formation takes place between them along with formation of silanol groups (Si-OH). Due to this characteristic of nano-particles, some portion of mixing water is lost during mixing process and workability of the mix is affected. Hence, the loss of slump in concrete mixtures containing RCA and NS could be attributed to the combined water absorbing nature of RCA and silica nano-particles (De Juan and Gutiérrez 2009, Quercia *et al.* 2012, Hou *et al.* 2013, Hosseini *et al.* 2011).

3.1 Compressive strength

The development of Compressive Strength (CS) from 7 days to 90 days for different types of mix is presented in Fig. 3. It can be observed that CS increases with the increasing percentage of NS; however, both the 7 and 28 days CS of RAC1 (100% RAC) is reduced to 10% to 15% as compared to that of control concrete (NAC). This decrease in CS is because of inherent characteristics of RCA such as highly porous nature of RCA, presence of large number of cracks, and high level of impurities with in attached mortar (De Juan and Gutiérrez 2009). However, the

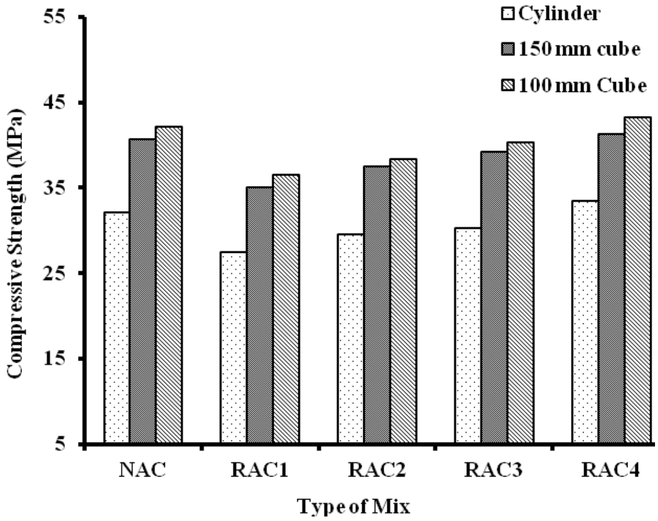


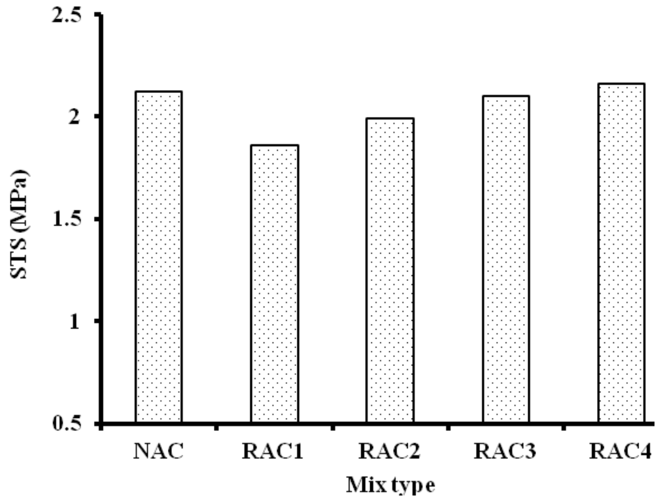
Fig. 4 Comparison of 28 days CS of cubes and cylinders

CS improves with the addition of NS and the CS of RAC containing 3% NS is equivalent to that of NAC. The enhancement of CS with the incorporation of NS is due to the filling of the voids present in C-H-S by silica nano-particles, which leads to a denser and stronger concrete (Hosseini *et al.* 2011). The RAC without NS has CS 8% lower than corresponding NAC mix after 90 days. The improvement in CS of RAC at later stages is because of improvement in bonding between RCA and mortar. The old mortar attached with aggregates develops a stronger bond with the passage of time due to its self-cementing effect. However, the developments in CS of RAC mixes containing NS are similar to that of 7 and 28 days. Fig. 4 represents the comparison of 28 days CS of cubes and cylinders of different concrete mixes.

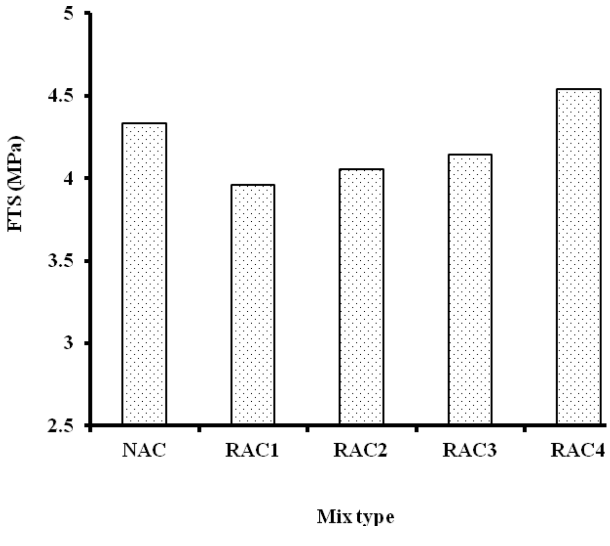
It can observed that for reference concrete mix containing natural aggregates, the CS of 150 mm cubes is 40.67 MPa and 100 mm cubes is 42.16 MPa, whereas CS of cylinders is 32.17 MPa, which indicates that CS 100 mm cubes are highest and cylinders lowest. Similar types of observation are found for all other mixes containing RCA and NS.This difference of CS of cubes and cylinders is owing to the size effect of specimens, which states that increase in the aspects respect ratio leads to decease in CS (IS 456: 2000).

3.2 Tensile strength

Fig. 5(a) shows the variation of Split Tensile Strength (STS) with respect to percentage of NS. It is observed that STS of RAC1 is lower than NAC due to weaker Interfacial Transition Zone as compared to that of NAC. However, STS increases with increasing percentage of NS and RAC with 3% NS, STS of RAC mixes can be comparable to control mix. This improvement of STS is due to the pozzolanic action and filler effects of NS. ITZ plays an important role in determining the tensile behaviour of concrete. The ITZ becomes dense and compact due to addition fine particles of NS and therefore improvement of tensile strength is observed. The variation of flexural strength is presented in Fig. 5(b) and the behaviour is similar to STS. Loss in FTS is observed in case RAC mixes due to inferior quality of aggregates. However, it can be seen that FTS of RAC mixes increases with increasing percentages of NS and the decrease in FTS of RAC could be compensated by adding 3% NS.



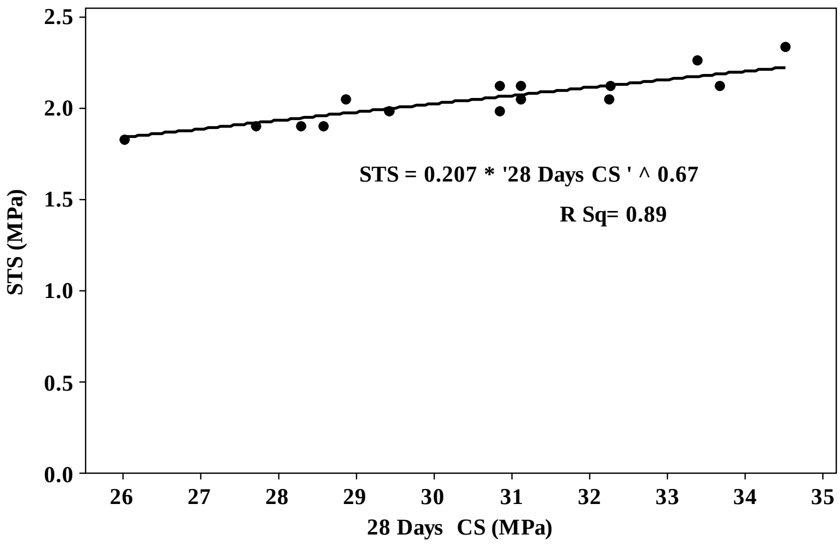
(a)



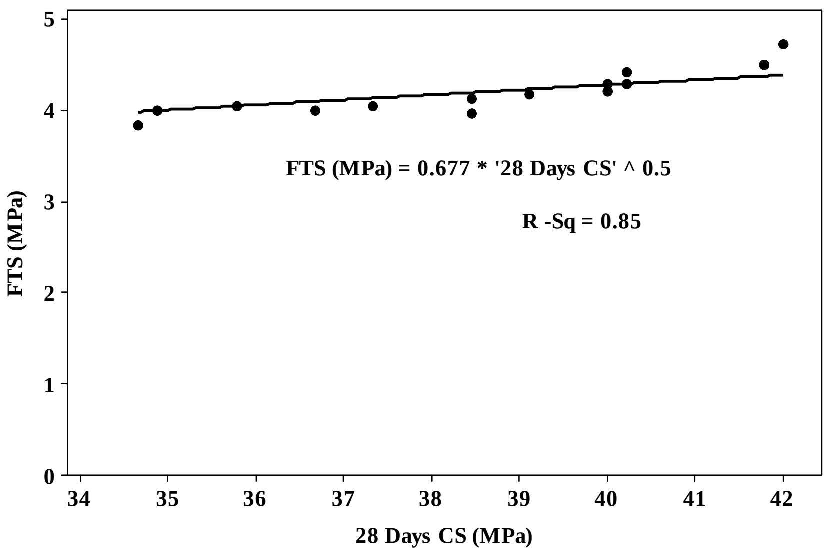
(b)

Fig. 5 Variation of (a) split tensile strength (b) Flexural tensile strength

The relationship between STS and 28 days CS (cylinders) values is shown in Fig. 6(a). The equation correlating the present experimental results of STS and CS of concrete mixes is found to be similar that of Spanish code formulation (EHE 1999). Fig. 7(b) illustrates relationship between FTS and 28 days CS (150 mm cubes) and the equation fitted between these parameters are similar to that provided by BIS specifications (IS 456: 2000).



(a)

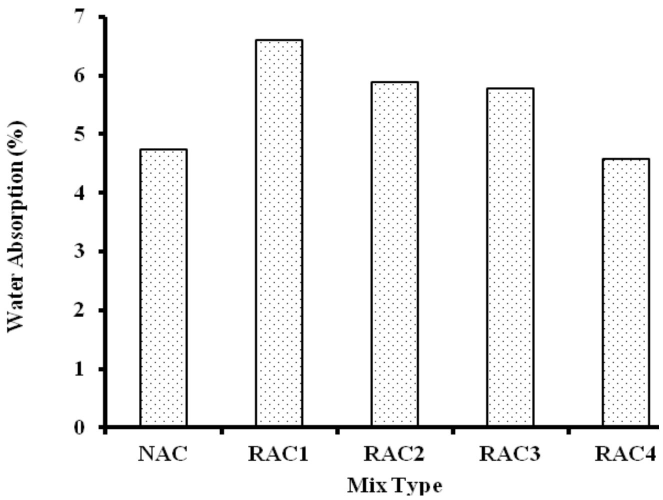


(b)

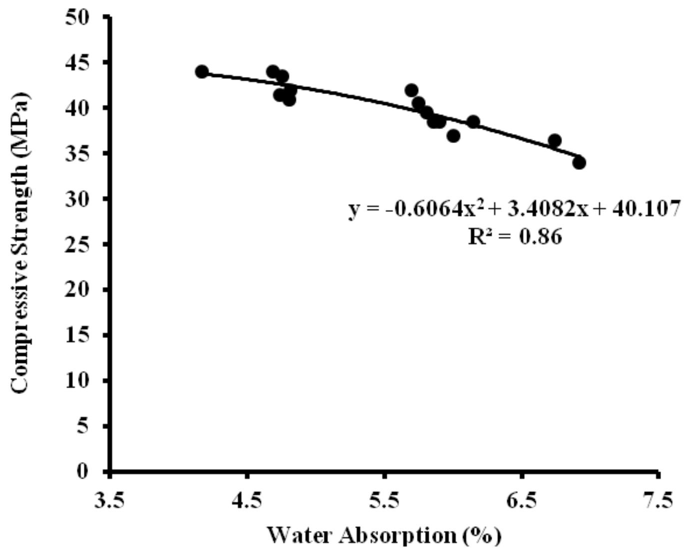
Fig. 6 Relation between CS and (a) STS (b) FTS

3.3 Density, water absorption and volume of voids

The variation of water absorption of concrete mixes containing NS is presented in Fig. 7(a), which indicates that the water absorption increases from 4.74% to 6.60% when the natural coarse aggregates are replaced by recycled coarse aggregates. This increase in the WA of RAC is because of high water absorption capacity of the recycled aggregates (Oikonomou 2005). However, the addition of NS reduces the water absorption from 6.60% to 4.58% hence, the characteristics of



(a)

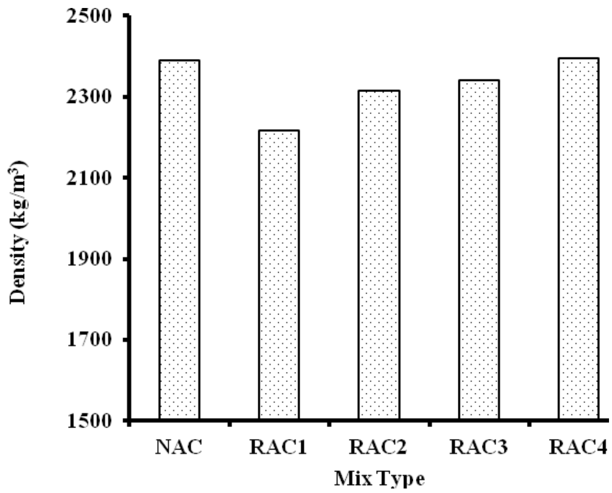


(b)

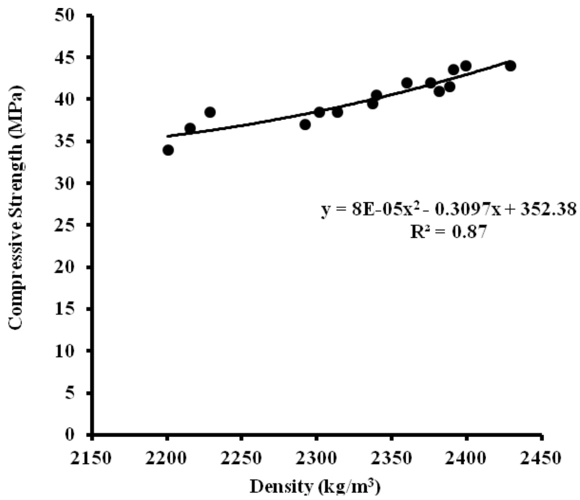
Fig. 7 (a)Variation of Water Absorption (b) Relation between CS and WA

RAC improved due to incorporation of NS. This improvement of WA of RAC due to the filling of minute pores present in ITZ of concrete (Hosseini *et al.* 2011). The correlation between 28 days CS (100 mm cubes) and WA is demonstrated in Fig. 8(b), which illustrates that CS decreases with increase in WA.

A second degree is used to express this relationship and higher value of determinant coefficient (0.86) indicates about the existence strong correlation between WA and CS. The variation of density of concrete mixes is shown in Fig. 8.



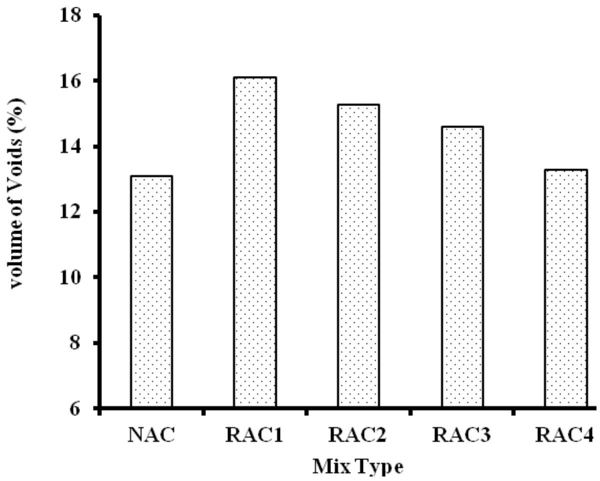
(a)



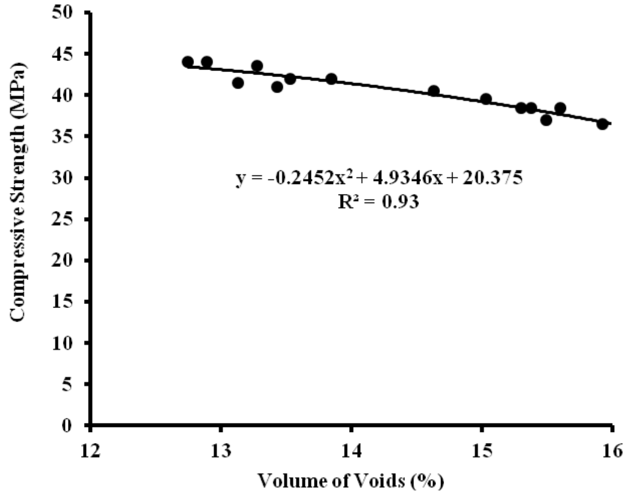
(b)

Fig. 8 (a) Variation of density (b) Relation between CS and density

It is observed that the density of RAC without NS is 2214.90 kg/m^3, which is lower than the control concrete (Fig. 8(a)). This decrease in the density of RAC without NS is due to the lower density of RCA as compared to that of NCA. The density of RCA is lesser than NCA since the mortar attached to these aggregates is porous and lightweight in nature. However, addition of NS to RAC mixes improves the density of the mixes and with three percentage NS density of concrete becomes 2393 kg/m^3, which is similar to control concrete. This enhancement of density of RAC mixes containing NS is owing to the fact that addition of NS fills voids of old adhered mortar of RCA as well as makes new cement mortar dense by removing the voids and thus, making the aggregate-cement interface denser and stronger than that of RAC mixes without NS (Hosseini *et al*. 2011). The relationship between the Density and 28 days CS (100 mm cubes) can be expressed



(a)



(b)

Fig. 9(a) Variation of volume of voids (b) Relation between CS and VV

in terms of quadratic equation, which is presented in Fig. 8(b). Moreover, higher value of determination coefficients (0.87) is indicative of existence of good correlation between two parameters. Fig. 9 represents the variation of volume of voids of the concrete mixes.

It can be seen that the volume of voids of RAC without NS is 16.10%, which is higher than that of control concrete (Fig. 9(a)). This increase is in VV is due to the voids present in the attached mortar of the RCA. However, addition of NS reduced the VV by filling them with the help of nano-particles. The best-fitted line between 28 days CS (100 mm cubes) and VV is a quadratic curve is presented in Fig. 10b. The determination coefficient is found to be 0.93, which states that good correlation exists between compressive strength and volume of voids.

4. General discussion

In the present investigation, the influence of incorporation colloidal NS on the characteristics of RAC has been examined and compared with concrete mixes made with natural coarse aggregates. A detailed experimental program has been executed and after the analysis of the results of those experimentations, the primary findings of the study are summarized in the following bullets

- The workability of concrete mixtures are affected with the replacement of NCA with RCA due to the high water absorption capacity of RCA and further reduction of workability was observed due to the addition of NS. The further loss of slump with the incorporation of NS is because of loss of some mixing water by virtue of formation chemical bond between water and NS.
- The compressive strength of RAC mixes measured at different curing days are found to be 8 to 14 % lower than control mix, which is due to the inferior quality of RCA as compared to NCA. Moreover, the difference between CS of NAC and RAC is lowest at 90 days and this improvement of CS of RAC could be attributed to the improvement in bonding between RCA and mortar by virtue of the self-cementing effect of attached mortar of RCA at later stages. However, the reduction of CS of RAC is recovered with the incorporation of 3% NS, which is due to the filling effect of silica Nano-particles in voids present in concrete and making it stronger and denser.
- The results of the Spit Tensile Strength and Flexural Strength indicate that theses parameters are reduced when natural aggregates are replaced by recycled aggregates owing to the creation of a weaker ITZ in RAC compared to that of NAC. However, experimental findings depict that the reduction of tensile strength of RAC could be recovered by adding NS to the RAC mixes. Incorporation of NS improves the ITZ of RAC by filing the minute pores and subsequently strengthens the bond between cement paste and aggregates.
- Water absorption and volume of voids of RAC are higher than control mix but reduction in these properties are detected with addition of NS. The aforementioned behavior is because of the presence of more voids in RAC mixes as compared to that of NAC and addition NS lessens these voids. Similarly, density of RAC is lower than NAC as the density of recycled aggregates is lower than that of virgin aggregates. However, density could be enhanced with incorporation of NS in RAC mixes.

5. Conclusions

In adopting the recycled coarse aggregates in place of virgin aggregates, the fresh and hardened properties of concrete are found to be significantly affected. The degradation in mechanical behavior of recycled aggregate concrete could be restored by introduction of silica Nano-particles in concrete mixtures. Moreover, increase in water absorption and volume of voids of concrete mixes containing 100% recycled aggregates could be reduced with the addition of Nano-Silica. Concrete with 100% Recycled coarse aggregates has lower density compared to that of natural aggregate concrete and this loss could be compensated with the incorporation of 3% Nano-Silica. The present study recommends the use Nano-Silica as an efficient admixture for production of recycled aggregate concrete mixes.

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