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Influence of Nano-Silica on the properties of recycled aggregate concrete

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HIGHLIGHTS

- Colloidal Nano-Silica is used as partial replacement of cement for production of concrete mixes.
- Recycled aggregate concrete has inferior mechanical properties as compared to that of control concrete.
- Recycled aggregate concrete with 3% Nano-Silica has compressive strength similar to that of natural aggregate concrete.
- Improvement in tensile strength of recycled aggregate concrete is observed with the incorporation of Nano-Silica.
- Non-Destructive parameters are also enhanced with addition of Nano-Silica.

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ABSTRACT

The present work addresses the effect of incorporation of colloidal Nano-Silica on the behavior of concrete containing 100% recycled coarse aggregate. In this study, concrete mixes containing both natural and recycled aggregate are produced by replacing a fraction of Portland cement 0.75%, 1.5% and 3% of colloidal Nano-Silica respectively. The results of experimental investigation depicts that compressive strength, tensile strength and Non-Destructive parameters are enhanced due to addition of NS. Moreover, the study reveals that the characteristics of recycled aggregate concrete resembles with that of natural aggregate concrete with the addition of little amount (3%) of Nano-Silica.

1. Introduction

Concrete, being most extensively used construction material is primarily responsible for depletion of natural resources since its main constituent materials such as aggregates are drawn from nature, therefore, several countries are facing acute shortage of natural aggregates. Simultaneously, huge amount of waste concrete is produced due to demolition of aged concrete structures and sufficient number landfills are not available for dumping such waste materials. In recent decades, these waste concrete are collected and are crushed to produce aggregates and these aggregates are effectively used as novel construction materials in several countries. Therefore, utilization of recycled aggregates (RAs) as a replacement of natural aggregate (NA) is a solution to a number of problems faced by civilization: preservation of natural resources, lessening the costs of waste treatment prior to disposal, and reduction of pollution [1]. However, the main problem in using these recycled aggregates is the attached mortar that distinguishes these aggregates from natural aggregate. Earlier works confirmed that RA had some inferior properties like low density, more water absorption and reduction in quality and durability due to the mortar that remains attached to NA [2]. Several studies were found in literature regarding the application of aggregates produced from waste concrete and those were reported in the previous review works done by Nixon [3] and Hansen [4,5]. The characteristics of parent source concrete had influence in determining the properties of the fresh concrete produced with the recycled aggregates for instance water absorption of RCA increased with an increase in strength of parent concrete from which the aggregates are produced [6]. The behavior of the RAC containing aggregates from various field sources was investigated and reduction of mechanical properties and micro-structural compared to NAC was reported [7]. Previous study confirmed that there was no significant change in compressive strength (CS) of recycled aggregate concrete (RAC)

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when the replacement of aggregates was within 30% and reduction of CS was observed beyond this limit [8]. However, elastic modulus of concrete containing 30% of recycled aggregates was found to be 15% lower than that of NAC [9]. Kwan et al. [10] recommended that target strength could be achieved using recycled aggregates up to 80% with accepted mechanical and durable properties. Moreover, concrete having strength 80 MPa or more than that could be produced using recycled aggregates, however mechanical properties of the concrete is inferior to the natural aggregate concrete (NAC). Moreover, the use of recycled fine aggregate (RFA) was not recommended in place of natural sand since it had an adverse effect on workability and strength of concrete [11]. The development of compressive strength (CS) of both RAC and NAC were maintaining similar trend but strength development was little faster in case of NAC during first seven days and 10% reduction of 28 days CS was reported [12]. The durability properties like creep and shrinkage of RAC increased with replacement of NA with RA due to the inferior properties of aggregates [13].

1.1. Influence of two stage mixing and supplementary cementitious materials

To improve the properties of RAC, researchers adopted two-stage mixing approach and improvement in strength and durability was reported [14]. Detailed and quantitative analysis of Scanning Electron Microscopy (SEM) images and nano-indentation confirmed that the proposed two-stage mixing approach strengthened the interfacial transition zone (ITZ), hence it was an effective method for enhancement of mechanical and durability characteristics of RAC [15,16]. Tam and Tam [17] brought further modification in two-stage mixing approach methods by addition of silica fume (SF) into certain percentages of recycled aggregate (RA) in the pre-mix procedure, which was named as two-stage mixing approach(silica fume) (TSMAs). The other proposed technique was the addition of SF and proportional amounts of cement into certain percentages of RA in the first mix, named as two-stage mixing approach(silica fume and cement) (TSMAsc). The weak areas of the RA were filled by silica fume and proportional cement content, which created a stronger interfacial layer around aggregate, and hence the compressive strength of the concrete was improved. In addition to above mixing techniques, addition of supplementary cementitious materials are another significant method of improvement of properties of RAC. The incorporation of fly ash (FA) in RAC significantly improved the resistance to chloride ingress and resistance to sulfate erosion the long-term resistance to carbonation [18]. The CS of RAC could be improved with incorporation of SF and FA as a fine aggregate replacement and it was observed that the pore structure of RAC is improved, and particularly the volume of macro-pores was reduced due to addition of fly ash [19]. Brendt [20] adopted different proportion of FA and blast furnace slag (BFC) in RAC and concluded that the concrete with 50% BFC had produced best results in terms of strength characteristics among all combinations. However, addition of fly ash in RAC decreased elastic modulus, increased the coefficient of permeability and chloride diffusion coefficient, although the values remained satisfactory for durable concrete. In addition to above, pulverized fuel ash (PFA) and ground granulated blast furnace slag (GGBS) were used to enhance the concrete properties: the long-term strength development, the resistance to chloride permeability and resistance to chloride-induced corrosion [21]. Li et al. [22] investigated the effect of a new mixing technique-coating with pozzolanic powder: Fly ash (FA), SF, blast furnace slag (BS) or their combination on the workability, strength and microstructure. The outcome the study was that a dense ITZ structure along with satisfying workability and strength could be achieved with this new mixing technique-coating with pozzolanic powder. Kong et al. [23] conducted similar type of study by adopting a triple mixing method (TM) to further enhance ITZ and thus properties of the RAC by surface-coating of pozzalanic materials, such as fly ash, slag and silica fume. The outcome of the experimental investigation revealed that the compressive strength and chloride ions penetration resistance of the RAC could be further enhanced by using TM as compared to that by using two-stage mixing approach.

1.2. Application of nano-materials

Currently, the applications of nanotechnology have been gaining popularity in different fields of science and technology [24]. The developments of new materials with new functions or improvements in the properties of existing materials using nanotechnology are new areas of interest in civil engineering [25]. The use of nano-particles in cement based products was increasing day by day as these particles are effective in filling the voids of the C–H–S, enhancing the rate of hydrations by acting as nucleation centers and reducing the size of $Ca(OH)_2$ crystal [26]. Among existing nano-particles, Nano-silica (NS) is efficiently applied in the field of cement and concrete for enhancing the properties of concrete. The use of NS was preferred in place of previously used pozzolanic material SF because the pozzolanic activity of the NS was more than SF at early days due to the higher of rate of consumption of $Ca(OH)_2$ crystals [27]. NS was quite effective in improving the mechanical properties and the microstructure of high-strength cement pastes even in low concentration and this improvement of paste behavior is attributed to the fact that increasing packing among particles [28]. However, the addition of NS to paste and mortar reduced the mix workability, due to immediate reaction between the NS and the cement paste, with development of gels characterized by high water retention capacities [29]. The incorporation of NS enhanced the CS and tensile strength of mortar due to the increased pozzolanic action and filling effect. Moreover, incorporation of NS improved the microstructure of cement mortar [30]. Other studies comprising of addition of NS in mortar were produced similar type of observations [31–33]. Moreover, the fire resistance of high strength fly ash mortar could be improved with addition of NS [34]. The use of colloidal NS in place of dry powder form in concrete was preferred as it was more dispersive in nature and reduced segregation compared to dry powder form of NS [35]. In addition to above, the addition of colloidal NS accelerated the cement hydration largely in the early age with a reduction in low-stiffness C–S–H gel and an increase in high-stiffness C–S–H gel [36].

The application of NS in concrete was proven to be beneficial in enhancing compressive strength (CS) along with reduction of porosity due to fact that the addition of NS led to significant consumption of portlandite (CH) in the pozzolanic reaction, hence making concrete strong and dense [37]. Moreover, the permeability of concrete was also improved with addition of NS due to the removal of minute pores present in cement mortar matrix and ITZ [38]. Hosseini et al [39] confirmed that the replacing cement by 3% of NS of in the concrete made with 100% recycled aggregate produces strength more that of concrete made with natural aggregates. Moreover, microstructure became dense, uniform and even extremely small voids had been omitted due to the filling of small particles of NS in those voids. However, it was proved that higher dosage of the NS affected workability due to dispersion problems and conglomeration of particles.

The critical observations from the detailed literature review are follows:

- The properties of recycled aggregates are inferior to natural aggregates due to the adhered mortar present in them.

- The compressive strength of RAC deceases up to 25%, splitting and flexural tensile strength decrease up to 10% and modulus of elasticity decreases up to 45% for RAC.
- Pozzolanic materials are quite effective in enhancing mechanical properties of RAC.
- The pozzolanic activity of NS is more than SF during early days to higher surface area.
- NS influences the workability of the cementitious mix due to absorption of mixing water.
- The mechanical properties of cement paste and mortar improves with addition of NS.
- Application of colloidal NS is easier than dry form of NS due less segregation.
- NS is successfully applied in concrete for improvement its properties.

From the broad literature survey, it is observed that the investigations on the mechanical and microstructure properties of RAC are often available in open literature. As the properties of RAC are inferior to NAC, several techniques are adapted to improve its characteristics and addition of pozzolanic materials is one among in this regard. Different pozzolanic materials incorporated with different mixing techniques are successfully applied in RAC to enhance its properties. Moreover, after the innovation of nanotechnology, NS is applied in cement, mortar and concrete for improvement of behavior of the parent material, which are well documented in literature. However, the study in the area of application of colloidal NS in the recycled aggregate concrete is rarely found in literature. The aim of the present work comprises of systematic examination the mechanical behavior of RAC with different percentages of NS and Non-Destructive tests are conducted to verify the uniformity in the concrete and pores behavior of RAC. The objectives of the present investigation to fulfill the aim of the work are stated as follows:

- Comparative study of properties of natural coarse aggregates and recycled coarse aggregates collected from field sources.
- Study of influence of NS on the fresh concrete behavior.
- Analysis of the harden properties of RAC containing NS.
- Non-Destructive evaluation of quality of concrete containing RCA and NS.

2. Experimental program

2.1. Materials

Ordinary Portland Cement (OPC) of 43 Grade, meeting the requirements of Bureau of Indian Standard Specifications (BIS) (IS: 8112-1989) [40] was used to conduct the experimental work. The 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 has been performed to characterize the cement and those results are tabulated Table 1.

The X-ray Diffraction (XRD) analysis of the OPC was conducted and the obtained pattern from the test was presented in Fig. 1. The XRD of the powder sample of cement was carried out to have detailed knowledge about the various chemical compounds available cement. Moreover, this analysis was conducted for determination of the crystalline phases and orientation of the chemical compounds, which constitutes the mixture. The results of the analysis of the cement showed that the different chemical compounds were in crystalline form since sharp peaks were visible in the XRD pattern. Moreover, the analysis illustrated that calcium silicates were main constituents of cement and the presence of alumina noticed along with silicates.

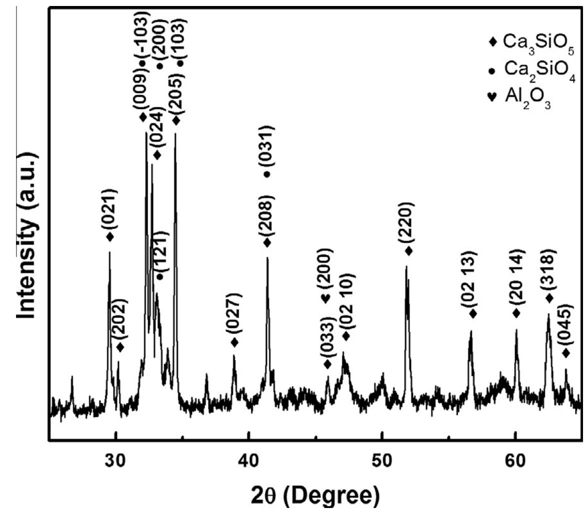

Fig. 1. X-ray diffraction pattern of OPC.

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.

The results of XRD and Transmission Electron Microscope (TEM) analysis are shown in Figs. 2 and 3 respectively. It was observed from the XRD analysis of NS that a broad peak (2θ varies from 13° to 40°) was obtained, which provided information about presence of the chemical compound in nano-form. In addition to above, the presence of silicon oxide in dominant form was also detected from the analysis. XRD analysis of NS reveals that crystallite size of NS was found to be approximately 11 nm. TEM was a microscopic technique employed for determination of particle size of nano-particles, since direct measurement of nano-particles could not be done. The TEM image of NS is shown in Fig. 3, which was taken in bright field mode. It was observed from the analysis that the particles being in spherical shape and present in non-agglomerated form. The analysis TEM picture revealed that the particle size of the colloidal NS was found to be varying between 8 and 20 nm, which was confirmed by the results of the XRD analysis.

Locally available river sand confirming to Zone II specification of IS 383-1970 [41] was used as Natural Fine Aggregate (NFA) in producing concrete mixes. The crushed dolerite of 20 mm nominal size was employed as Natural coarse aggregate (NCA) and the Recycled Coarse Aggregates (RCA) were prepared from the concrete collected from a 30 years old demolished building of Jhargram, West Bengal, (A city of Eastern India). The standard tests were performed on aggregates and the results of those tests are presented in Table 3.

2.2. Concrete mixtures

Table 4 illustrates the details of mix proportions 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 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 NCA without NS was fabricated along with above mixes. The quantity of water present in colloidal NS should be taken into consideration while calculating the total amount of water for making concrete mixes. Normal tap water suitable for drinking purpose was used for manufacture of concrete mixtures. 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 production of concrete mixes, initially, colloidal NS was mixed with water and stirred 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

Table 1
Properties of cement.

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

Table 2
Properties of colloidal Nano-Silica.

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

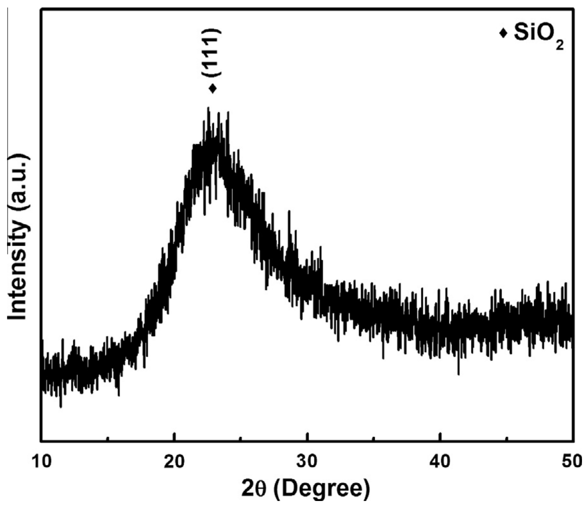

Fig. 2. X-ray diffraction of Nano-Silica.

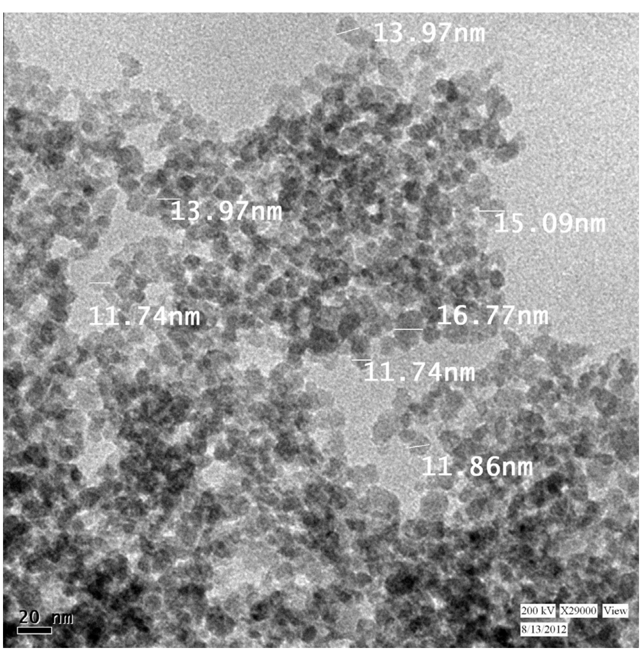

Fig. 3. TEM picture of Nano-Silica.

Table 3
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
Proportions of mixtures per cubic meter of concrete.

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

slowly poured in and stirred at a low speed for another 2 min to achieve desired workability. After proper mixing, the fresh concrete was poured in to the specified molds and kept for 24 h under plastic sheet for moisture control curing. After 24 h, 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 carried out on standard cubes of size 150 mm using 3000 kN compressive testing machine in accordance with BIS (IS: 516-1959) [42]. The compressive strength was determined at 7, 28, and 90 days and rate of loading was maintained at 14 N/mm^2/min throughout the test as per BIS specifications [42]. The split tensile strength (STS) of concrete at 28 days was conducted on cylindrical specimen of 150 mm $\varnothing \times$ 300 mm height using 3000 kN compression testing machine according to the procedure given in Indian standards [43]. The Flexural Tensile Strength (FTS) was performed on prisms of size 100 × 100 × 500 mm after 28 days curing. The test was done in accordance with BIS (IS: 516-1959) using 100 kN universal testing machine [42]. Two types of Non-Destructive tests were conducted on 15 cm cubes after 28 days of curing: Ultrasonic Pulse Velocity (UPV) and Rebound Number (RN). UPV test was performed in accordance with BIS code [44] using TICO ULTRASONIC INSTRUMENT (UPV), supplied by PROCEQ SA, Switzerland. The RN test was carried out in accordance with BIS [45] using Schmit Hammer (TYPE ND) supplied by PROCEQ SA, Switzerland. For RN test, at least 20 measurements were taken at different points upon each specimen. Three numbers of specimens were used for carrying out every test and averages of three results were reported.

3. Results and discussion

3.1. Fresh concrete properties

The results of slump test of fresh concrete mixtures is illustrated in Fig. 4, which indicates that addition of NS in concrete mixtures causes loss of slump and this loss is dependent upon the NS content. The phenomenon of reduction of slump is attributed to the absorption of some parts of mixing water by nano-particles. Silica nano-particles have high surface area and contain many unsaturated bonds, which make them highly reactive, and water molecules are attracted towards the surface these particles. Due to this attraction to wards NS, chemical bond is created between water and these particles along with formation of silanol groups (Si–OH). Therefore, the amount of the free water available for mix, whose role is to improve the fluidity of the mixture, is reduced and viscosity of the mix is increased, hence, workability of the concrete mixes containing NS is reduced [31,32]. However, from the results slump test shown in Fig. 4, it observed that lower values of slump are obtained with the in RAC mixtures

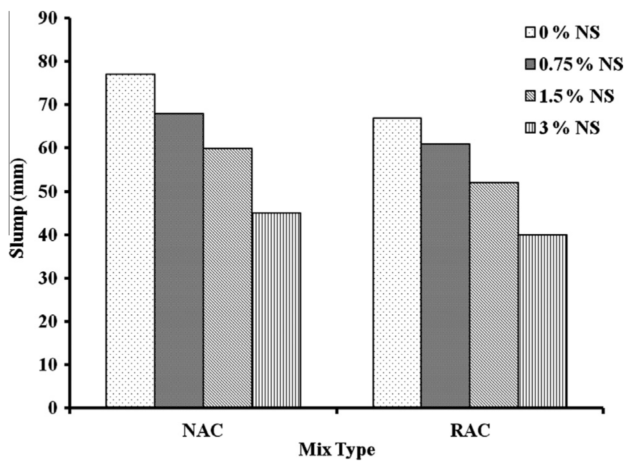

Fig. 4. Variation of slump results of concrete mixes.

compared to the control mix. recycled coarse aggregates are having high water absorption capacity due to the presence of the old adhered mortar in the aggregates, which is more porous in nature. To mitigate this extra water demand of recycled aggregates, additional amount of water added to the mix to achieve proper workability during production of concrete mixtures. However, there is some amount of loss of slump occurred during this whole process and characteristics of RCA are responsible for slump loss in the concrete containing RAC only. Moreover, the loss of slump occurs in the concrete mixtures containing NS and increase in loss of slump with increasing content of silica nano-particles. Hence, the loss of slump in concrete mixtures containing RCA and NS is because of combined water absorption of recycled coarse aggregates and nano-particles [2,31–32,39].

3.2. Compressive strength

The development of compressive strength (CS) from 7 days to 90 days for different types of mix is presented in Fig. 5. The aforementioned figure indicates that the 7 days CS of NAC increases from 34.81 MPa to 39.12 MPa with incorporation 3% colloidal NS. This 12% enhancement of CS of NS incorporated concrete is attributed to the increase in pozzolanic action when NS is added in concrete. However, the 7 days CS of concrete reduces from 34.12 MPa to 30.3 MPa due to replacement of natural aggregates by RCA, which indicates 11% reduction in 7 days CS. 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 impurity and attached cement mortar, of RCA compared to NCA [13]. The effect of NS in improving the 7 days CS of RAC can be visualized in Fig. 5 as the CS increases from 30.3 MPa to 34.13 MPa, which almost equalizes with the 7 days CS of control concrete. This improvement of CS is due to improvement of microstructure of ITZ by NS. Moreover, the 7 days CS of concrete incorporating NS is more than that of concrete without NS because the pozzolanic activity of NS is high in initial days [23,25]. It is observed that 28 days CS of both RAC and NAC increase with increasing percentages of NS, which is due to improvement of quality of concrete. The CS of NAC increases from 40.67 MPa to 49.89 MPa (22% Increase) with addition of small quantity (3%) of colloidal NS. It should be noticed from Fig. 5 that there is 14% reduction 28 days CS of concrete when RCA are used as aggregates in place of natural aggregates. This reduction of CS of concrete mainly due to high water absorption and porous nature of RCA, which make a weak bond between cement matrix and aggregates. The reduction of 28 days CS as obtained present experimental study is in the same line with previous studies as some researchers report 10–15% of reduction of 28 days of CS of fully RAC [9,11]. However, 28 CS of RAC increases significantly with incorporation of NS and 28 days CS of RAC is more than that of reference concrete with addition of 3% of NS. The enhancement of CS is due to the filling of the voids of CHS structure by NS, which leads to a denser and stronger concrete [38,39]. The behavior of CS of concrete mixes at 90 days due to addition of NS is similar to the strength development at 28 days. The development of CS from 7 days to 90 days is uniform for eight different types of mixes.

3.3. Split tensile strength

Fig. 6 shows the variation of split tensile strength (STS) with respect to percentage of NS. It can be seen that STS of concrete increases from 2.12 MPa to 2.63 MPa as the percentage of incorporation of NS changes from zero to three percentages. The improvement STS of concrete is attributed to the strengthening

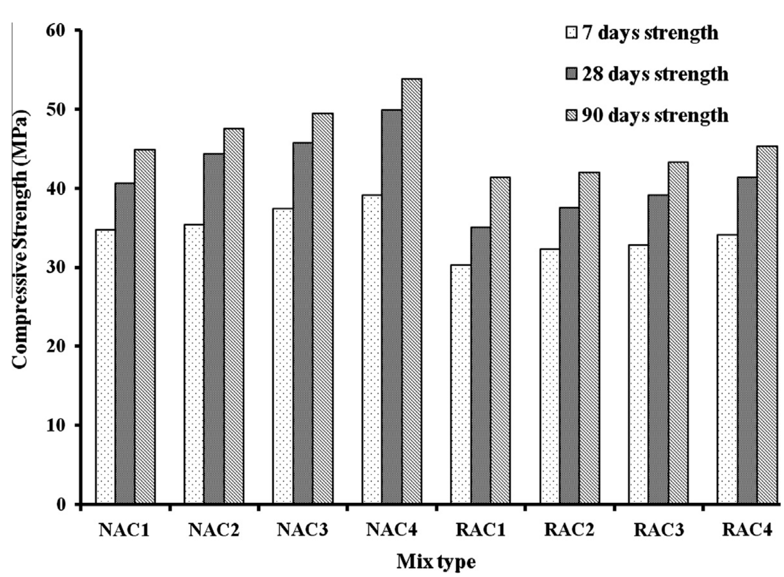

Fig. 5. Variation of compressive strength.

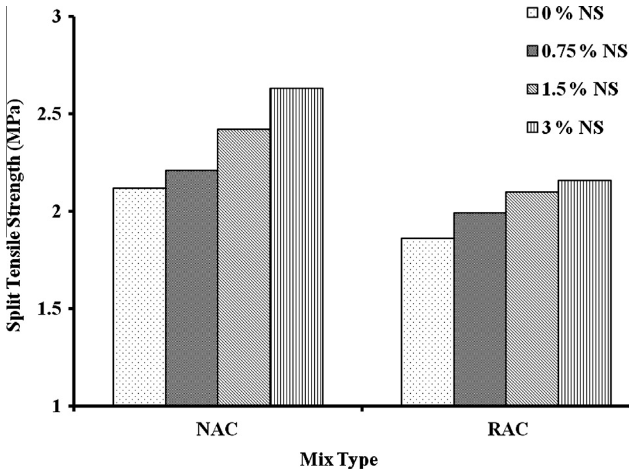

Fig. 6. Variation of split tensile strength.

of ITZ by the silica nano-particles. Primarily the individual components of concrete such as aggregate and cement paste are having more tensile strength when tested individually, however, when they are combined to form concrete lesser tensile strength is found than individual strength. The reason behind the above phenomenon is that ITZ is one the weakest link in concrete. The addition of NS makes a stronger and denser ITZ than normal concrete by reducing the voids present in ITZ [26]. However, the STS of RAC without NS is 1.86 MPa, which is 12% lower than that of control concrete. This reduction of STS is due to weaker interfacial transition zone (ITZ) compared to ITZ of NAC [12]. However, STS increases with increasing percentage of NS and RAC with 3% NS is almost equal value of STS with the control concrete.

This improvement of STS is due to the pozzolanic action and filler effects of NS. Interfacial Transition Zone (ITZ) plays an important role on the tensile strength of concrete. The ITZ becomes dense and compact due to addition fine particles of NS and therefore improvement of tensile strength is observed [24,37]. The comparative study between present experimental results and split tensile strength (f_{sp}) values obtained by using formulation found in literature given in Table 5 is shown in Fig. 7. It should be noted that in all the relations characteristics compressive strength (f_c) referred to 28-day cylinder strength. Therefore, a correction factor of 0.8 is adopted for converting cube strength to cylinder strength [46]. The study indicated that present experimental values are similar to the splitting tensile results of Spanish code formulation [48]. However, higher values of STS are obtained using all other relationships.

3.4. Flexural tensile strength

The variation of FTS with respect to different percentage of NS is presented in Fig. 8, which illustrates that FTS increases with increasing percentage of NS irrespective of type of concrete. FTS of control concrete enhances from 4.33 MPa to 4.97 MPa with addition of three percentages of NS. The improvement of 15% in FTS of NAC is because of the strengthening of concrete with the incorporation NS. The ITZ of concrete becomes stronger as pozzolanic products generated by NS helps in improving the bond between cement mortar and aggregate [26]. However, the FTS of concrete reduces from 4.33 MPa to 3.96 MPa when the NCA are replaced by RCA. This reduction of FTS is attributed to the poor bonding between the RCA and cement mortar. Furthermore, the improvement in FTS of RAC could be achieved by addition of NS as silica nanoparticles have potential to fill the voids of cement mortar and

Table 5
Formulations to predict f_{sp} and f_t from f_c.

Splitting tensile strength		Flexural tensile strength	
CEB [47]	$f_{sp} = 1.56 \cdot \left(\frac{f_c-8}{10}\right)^{\frac{2}{3}}$	CEB [47]	$f_t = 0.81 \cdot \sqrt{f_c}$
EHE [48]	$f_{sp} = 0.21 \cdot f_c^{\frac{2}{3}}$	IS:456 [55]	$f_t = 0.70 \cdot \sqrt{f_c}$
ACI 318 [49]	$f_{sp} = 0.56 \cdot \sqrt{f_c}$	ACI 318 [49]	$f_t = 0.62 \cdot \sqrt{f_c}$
GB 10010 [50]	$f_{sp} = 0.19 \cdot f_c^{0.75}$	DJ/TJ07 [56]	$f_t = 0.75 \cdot \sqrt{f_c}$
NBR 6118 [51]	$f_{sp} = 0.3 \cdot f_c^{\frac{2}{3}}$		
Hueste et al. [52]	$f_{sp} = 0.55 \cdot \sqrt{f_c}$		
Xieo et al. [53]	$f_{sp} = 0.24 \cdot f_c^{0.65}$		
Kau and poon [54]	$f_{sp} = 0.093 \cdot f_c^{0.8842}$		

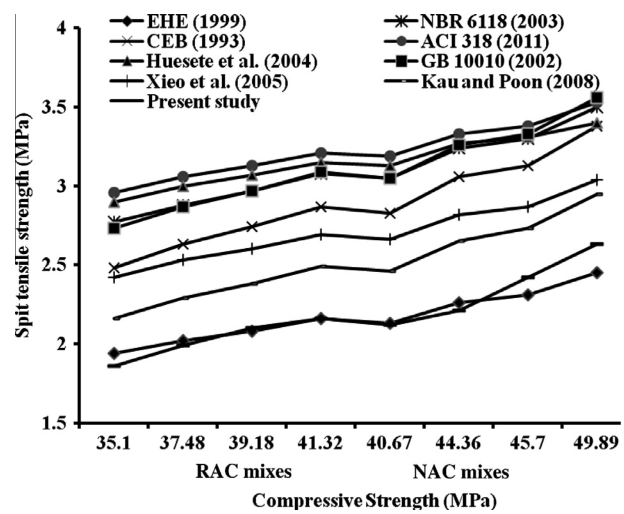

Fig. 7. Comparison of experimental f_{sp} values with various formulations.

aggregate interface. The results of this study indicates about the improvement of FTS with incorporation of NS as the FTS increases from 3.96 MPa to 4.54 MPa with addition of three percent NS. Therefore, the reduction of FTS occurred due to replacement aggregates could be compensated by addition of NS.

Fig. 9 illustrates the relationship between FTS and CS of the present values along values obtained using the formulations given in Table 5. While using the formulations, it should be noted that cylinder strength used in the formula given by ACI 318 [49] and cube strength is used in other formulae. The comparative study

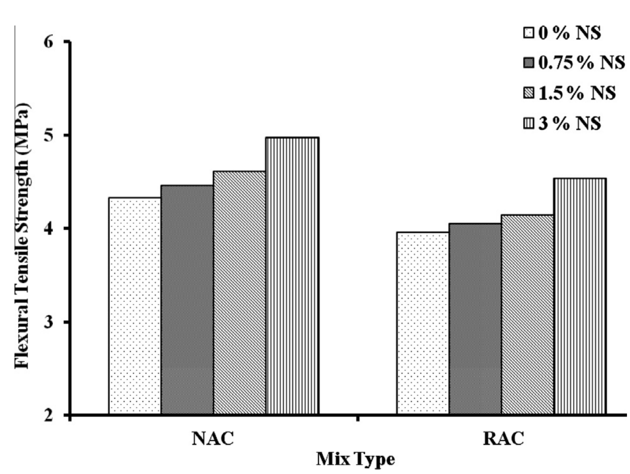

Fig. 8. Variation of flexural tensile strength.

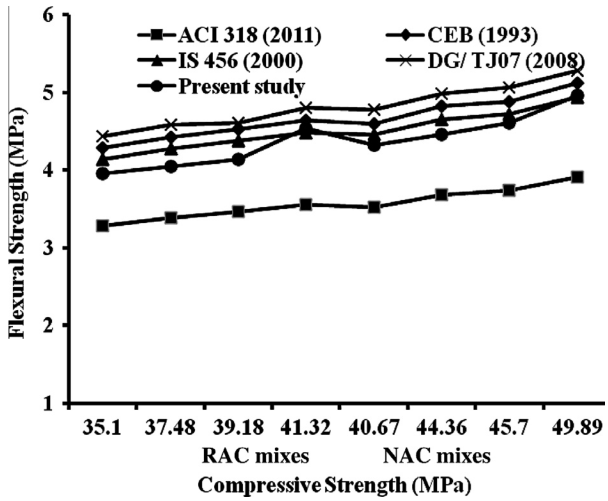

Fig. 9. Comparison of experimental f_t values with various formulations.

indicates that present experimental values of flexural strength are higher than those values predicted by ACI 318 [49] but lower than CEB [47]. The experimental values are comparable to the results obtained by formula given in Indian standard IS 456:2000 [55].

3.5. Non-Destructive test

The Rebound Number and Ultrasonic Pulse Velocity test results are shown in Figs. 10 and 11 respectively. The figure illustrates that both RN and UPV parameters of RAC are lower than those values of NAC, which may be due to inferior quality of aggregates and more porous nature of RCA. However, these parameters improve with increasing percentage of NS, which is due to densification of concrete by addition of NS. The plot between 28 days CS and RN is presented in Fig. 12 and the best fit line is a second degree curve, which resembles with previous study [57]. Fig. 13 demonstrates the best-fit line, which represents the relationship between the UPV and the compressive strength of concrete, which is a second-degree curve. This second order relation is similar to the equation as given reference [57]. There is no universal relation between the compressive strength and UPV, but various empirical relations are found in literature.

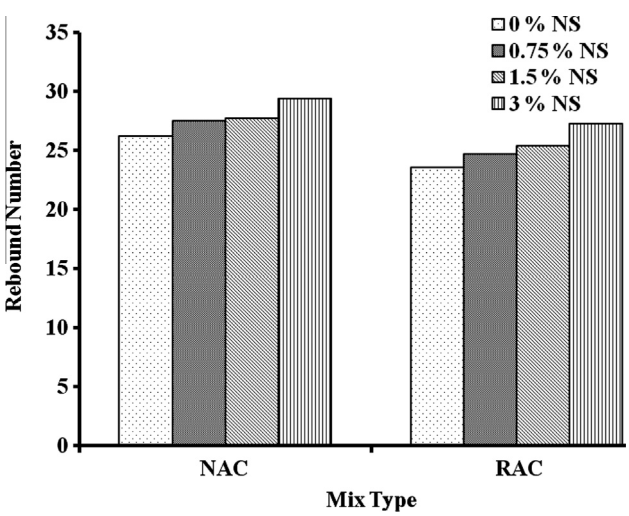

Fig. 10. Variation of Rebound Number.

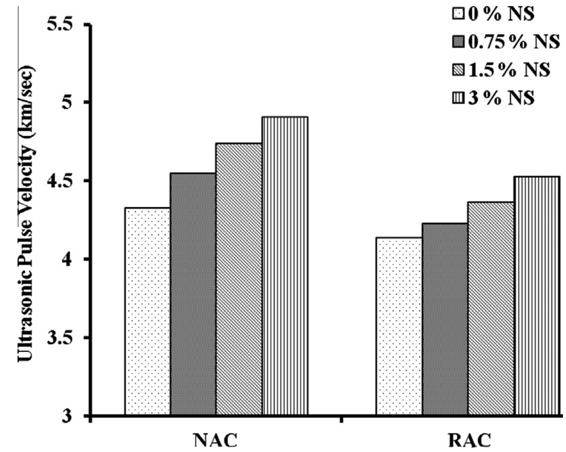

Fig. 11. Variation of ultrasonic pulse velocity.

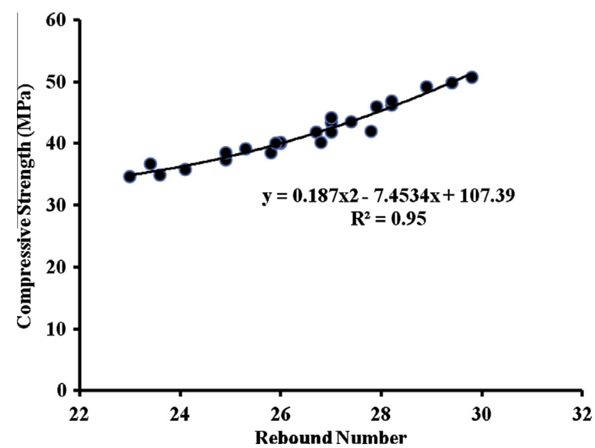

Fig. 12. Relationship between RN and compressive strength.

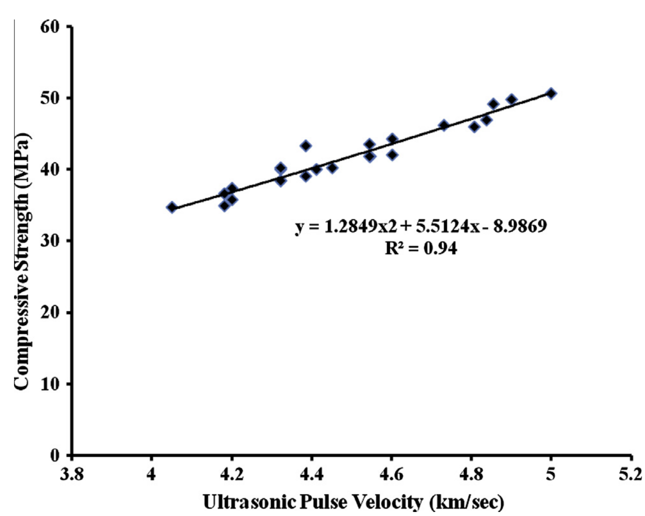

Fig. 13. Relationship between the UPV and compressive strength.

4. General discussion

The present study was designed to test the effects of colloidal NS on the properties of concrete containing recycled coarse aggregates in place of natural coarse aggregates. The main intention of the current research to investigate the feasibility of use of RAC incorporating NS and the primary findings of the experimental work are summarized in the following bullets:

- The colloidal NS could be utilized as a mineral admixture in production of concrete mixes but proper adjustment of amount water should be done considering the amount of solid content of the colloidal NS while designing concrete mixes. The results of slump test indicated that decease in slump values with increasing percentage of NS and the reason could be attributed to the absorption of mixing water by nano-particles due to the high surface area of colloidal NS. This aforesaid reason prevented the use of higher dosages of silica nano-particles in concrete. Moreover, Replacement of natural coarse aggregates with recycled coarse aggregates reduced the workability of concrete mixture due to the high water absorption capacity of RCA and further deceased in workability was observed due to the addition of NS to RAC mixes.
- The enhancement of compressive strength of concrete mixes at early days was resulted because of addition of NS and this improvement of strength could be owing to the high pozzolanic activity of NS at initial periods. The phenomenon of increase of 28 days strength with increasing percentage of NS is caused by the filling of voids C–H–S structure leading to a dense structure. A decrease of 14% of compressive strength was observed when replacement of NCA was done with 100% RCA. This reduction of strength was because of poor quality of RCA compared to virgin aggregates. However, addition of NS enhanced the compressive strength of RAC and with incorporation of 3% NS the 28 days compressive strength equalized with control concrete. This improvement of strength was due to the filling effect of nano-particles and making the concrete strong and dense.
- The enrichment of tensile strength of concrete was achieved by adding NS as the nano-sized silica particles fill voids of concrete and making ITZ stronger and denser compared to control concrete. Both Spit Tensile Strength and Flexural Strength of fully recycled aggregate concrete deceased as the formation of a weaker ITZ in RAC compared to that of NAC. This degradation of tensile strength could be compensated by adding NS, which improve the ITZ of RCA by fling the minute pores, present in it and forming a stronger bond between cement paste and aggregates.
- The Non-Destructive tests were widely conducted to determine the change of quality of concrete without damaging the test specimen. In this work, significant increase in Non-Destructive parameters was observed in concrete containing NS, which confirmed about the improvement in quality of concrete due to addition of NS. However, both the UPV and RN of RAC were lower than those values of NAC confirming about the degradation of quality of concrete due to use of inferior quality of aggregates compared to natural coarse aggregates. However, the improvement of both RN and UPV were observed in concrete mixtures containing NS, which provided confirmation about the reduction voids and denseness of the concrete mix.
- The results of this research could provide the information for construction sector for use of recycled aggregate concrete containing colloidal NS as an admixture. However, further investigations are required to know durability characteristics for field application.

5. Conclusion

From this experimental investigation, it can be concluded that replacement of NCA by RCA for production of concrete mixes decreased workability of concrete. This reduction of slump was further augmented with the incorporation of NS as NS absorbed some part of mixing water. Furthermore, the mechanical and Non-Destructive test results of indicated that these properties of RAC were inferior to those of NAC. However, incorporation of NS improved the mechanical properties of RAC and improvement in non-destructive characteristics of RAC containing NS was a sign of quality of RAC. The properties of RAC containing three percentage NS could be comparable with control concrete and NS could be utilized as an efficient admixture for production of concrete mixes containing recycled aggregates in a large extent intended for construction sector.

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