Use of Nano-SiO_2 to Improve Microstructure and Compressive Strength of Recycled Aggregate Concretes

P. Hosseini, A. Booshehrian, M. Delkash, S. Ghavami, and M.K. Zanjani

Abstract. The purpose of this paper is to provide new type of recycled aggregate concrete (RAC) incorporating nano-SiO_2. In particular, we investigate the effects of colloidal nano-silica solution on the properties of fresh and hardened concrete. The main variables included the dosage of nano-silica (including 0%, 1.5%, and 3% of cement content) and the cement content of the concrete (including 400 and 450 kg/m3). Results were compared with plain concretes. Tests were conducted to determine the mechanical properties (compressive strength) and microstructure (SEM test) of the concretes.

1 Introduction

Concrete is the premier construction material across the world and the most widely used in all types of civil engineering works, including infrastructure, low and high-rise buildings, defence installations, environment protection and local/domestic developments. Concrete is a manufactured product, essentially consisting of cement, aggregates, water and admixture(s). Among these, aggregates, i.e. inert granular materials such as sand, crushed stone or gravel form the major part [1]. Nowadays, because of extreme use of these mineral aggregates and decreasing the amount of sources and mines all over the world, engineers are trying to find a way to reduce using these valuable materials given by nature. On the other hand, the amount of construction and demolition waste has been increased considerably over the last few years [2,3]. One of the construction sector's major contributions to the preservation of the Environment and sustainable development is the reuse and recycling of the waste materials it generates (reducing, reusing, recycling and regenerating the residues that originate the constructive activity) [4].

P. Hosseini, A. Booshehrian, M. Delkash, and S. Ghavami
Department of Civil Engineering, Sharif University of Technology, Tehran, Iran
e-mail: p.hosseini@civil.sharif.edu

M.K. Zanjani
Ati Saz Construction Co. Tehran, Iran

The investigation of the mechanical properties of recycled aggregate concrete is necessary to determine the feasibility of use as well as the impact on durability of structures. There have been an increasing number of studies on the influence of recycled concrete aggregate as partial or total replacement of natural aggregates and its effect on the mechanical properties and durability of the recycled aggregate concrete [4-7], but they always resulted in a lower level of concrete strengths and durability. This was due to the residual impurities on the surface of the recycled aggregates, which blocked the strong bond between cement paste and aggregate [7-10].

The lower mechanical properties of these recycled materials ought to be neutralized by some other substance or procedure to improve the insufficient strength and durability caused by replacing conventional aggregate.

Recently, nano-technology has attracted considerable scientific interest due to the new potential uses of particles in nanometer (10^9 m) scale [11]. Due to this ultrafine size, nano-particles show unique physical and chemical properties different from those of the conventional materials. Because of their unique properties, nano-particles have been gained increasing attention and been applied in many fields to fabricate new materials with novelty functions. If nano-particles are integrated with traditional building materials, the new materials might possess outstanding or smart properties for the construction of different parts and uses in civil structures [12].

The present study used nano-silica particles in binder to enhance the mechanical properties of recycled aggregate concrete in terms of the compressive strength. The influence of the nano-silica on the concrete strength was assessed by measuring the compressive strength at 3, 7, 14, 28 days.

2 Experimental Procedures

2.1 Materials and Mixture Proportions

The cement used is Portland cement type I-425, according to the Iranian national standards (389). Fine aggregate is natural river sand with a fineness modulus of 3.2 and used in all mixtures. The coarse aggregate used is crushed limestone with a nominal maximum size of 20 mm for production of basic mixtures (original mixtures) which used for demolition process. The fine and coarse aggregates had specific gravities of 2.74 and 2.65, and water absorption of 0.1% and 0.8%, respectively. Also, the coarse recycled aggregates had specific gravity of 2.42 and water absorption of 4.8% with a nominal maximum size of 20 mm similar to natural coarse aggregate. The grading of coarse and fine aggregates was in accordance with the requirements of ASTM C143-99.

The water reducer superplasticizer (naphthalene-type with a solid content of 40%) is employed to aid the dispersion of nano-particles in concrete and achieve good workability of concrete. The colloidal nano-silica was purchased from Asan ceram Co (Tehran, Iran) with solid content of 30%. Application of colloidal nano-particles aids better dispersion of nano-particles in the concrete matrix and decreases agglomeration of nano-particles which improves nano-particles performance in concrete. Physical and chemical properties of cement and nano-silica particles are provided in Table 1, respectively.

Table 1 Chemical composition and physical properties of binder materials

	Cementitious materials(%)	
Item	Cement	Nano-silica
SiO_2	21.4	99.8
Al_2O_3	6	-
Fe_2O_3	3.4	-
CaO	64	-
MgO	1.8	-
Cl	-	-
SO_3	1.4	-
KO+Na_2O	1	-
L.O.I	3	2.8
Particle Size (nm)	-	40
Specific Gravity (m^2/kg)	3110	200000

The mix proportions of control concretes (NC-400 and NC-450), concretes containing just coarse recycled concrete aggregates (RA1-400 and RA1-450) and concretes containing coarse recycled concrete aggregates and different dosages of nano-silica particles (1.5% and 3%), are summarized in Table 2. The compressive strength of basic concretes, placed in the range of 30-40 MPa. For producing different mixtures of this study, mix proportions (except the amount of binders) assumed similar to the basic mixtures demolished for producing recycled aggregates.

2.2 Test Procedure

To fabricate the recycled aggregate concrete containing nano-particles, superplasticizer was firstly mixed into water in a mortar mixer, and then colloidal nano-particles are added and stirred at a high speed for 1 min. The cement, sand and coarse aggregate were mixed at a low speed for 2 min in a concrete rotary mixer, and then the mixture of water, water-reducing agent, nano-particles was slowly poured in and stirred at a low speed for another 2 min to achieve good workability.

Table 2 Concrete mixture proportions used in the study

Mix No.	Description	w/b	Water (kg)	Cement (kg)	Gravel (kg)	Sand (kg)	Superplasti-cizer (kg)	Nano-silica (solid) (kg)
NC-400	Control mix	0.4	177.2	400	646.4	1200.4	1.2	0.0
RA1-400	CRA	0.4	201.6	400	625.1	1160.9	1.4	0.0
RA2-400	CRA + 1.5% NS	0.4	201.6	394	611.6	1135.8	1.4	6
RA3-400	CRA + 3% NS	0.4	201.6	388	598.1	1110.7	1.4	12
NC-450	Control mix	0.4	196.3	450	612.3	1137.0	1.6	0.0
RA1-450	CRA	0.4	219.4	450	592.1	1099.7	1.6	0.0
RA2-450	CRA + 1.5% NS	0.4	219.4	443.25	576.9	1071.4	1.6	6.75
RA3-450	CRA + 3% NS	0.4	219.4	436.5	561.7	1043.1	1.6	13.5

To fabricate control and recycled aggregate concrete, superplasticizer is firstly dissolved into water. Cement, sand and coarse aggregate were mixed uniformly in a concrete rotary mixer, then the mixture of water and superplasticizer is poured in and stirred for several minutes. Finally, the fresh concrete is poured into oiled molds to form the cubes of the size 10×10×10 cm for the compressive strength testing. After pouring, an external vibrator is used to facilitate compaction and reduce the amount of air bubbles. The specimens are de-moulded at 24 hours and then cured in a curing room (relative humidity in excess of 95%, temperature 20±2) for 3, 7, 14 and 28 days. For each mix, 8 specimens of 100 mm cubes for compressive strength were made. Compressive strength was determined according to BS 1881: Part 117: 1993 at various ages (3,7,14 and 28 days). The workability tests were carried out in accordance with the requirements of ASTM C143-98.

3 Results and Discussion

The results of compressive and workability tests are shown in Table 3. According to these results, the strength of specimens produced by coarse recycled aggregates (RA1-400, RA1-450) is lower than those for control mixes (respectively NC-400, NC-450). The main factor of strength reduction of concrete with recycled aggregates is the existence of old mortar adhered to recycled aggregates, since the strength of mortar is much lower than the strength of natural aggregates [13]. The workability of concrete with recycled aggregates is generally lower, mainly due to increased specific surface and porosity, leading to high absorption capacity of recycled aggregates. Note that the reduction of workability of recycled concrete is a helpful factor in the formation of micro-cracks which have negative effect on the compressive strength [14].

The presented results, on the hand, clearly confirm that by adding nano-silica particles to the concrete matrix can significantly increase the overall strength. This observation is directly linked to supper-pozzolanic behavior of nanoparticles

Table 3 Workability and average compressive strength (MPa) at different test ages (3, 7, 14 and 28 days)

Mix No.	Curing days				Workability (mm)
	3	7	14	28	
NC-400	15.2	24.3	29.6	34.2	120-130
RA1-400	12.6	19.6	24.3	28.1	90-100
RA2-400	13.9	19.6	24.3	28.1	60-70
RA3-400	15.9	24.6	30.1	35.3	30-40
NC-450	19.4	31.4	37.3	41.8	130-140
RA1-450	16.3	25.1	31.2	35.3	90-100
RA2-450	17.6	29.3	35.4	40.1	60-70
RA3-450	20.9	32.1	39.1	43.7	30-40

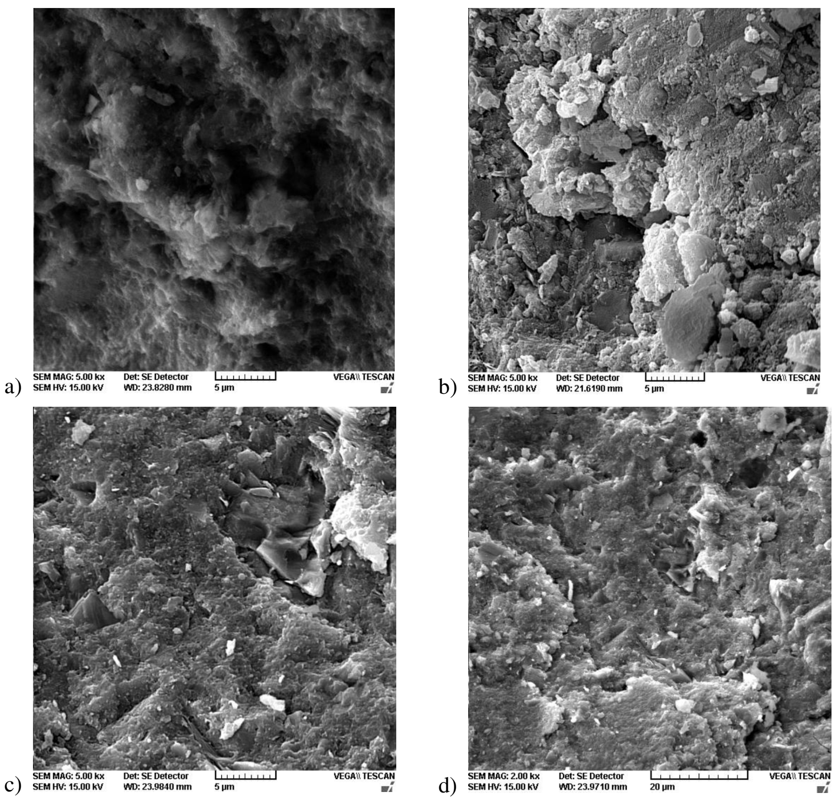

Fig. 1 Results of SEM studies; (a) Control mix (NC-400), (b) Recycled concrete & 0% Nano (RA1-400), (c) RC & 1.5% Nano (RA2-400), (d) RC & 3% Nano (RA3-400)

[16, 17]. Finally, data shown in Table 3 illustrate a considerable reduction of slump in fresh concrete [14] resulting from extremely large specific area of nanoparticles.

The results of SEM studies appear summarized in Figure 1. As shown in Figure 1a) and 1b), the application of recycled aggregates leads to formation of voids with small dimensions due to absorbing cement particles on the surface of aggregates. Therefore, the porosity of ITZ of these types of concrete is slightly higher than that of conventional concretes. On the other hand, when comparing Figures 1b) and 1c), it can be seen that by adding silica nano-particles, the transition zone of recycled concrete has become denser and more uniform and even extremely small voids have been omitted, especially because of exclusive performance of nano-particles. These particles combine with calcium hydroxide crystals ($Ca(OH)_2$) and produce dense calcium-silicate-hydrate gelatin by making pozzolanic reaction and gelatin is the main reason of more uniform and denser transition zone [15, 18,19]. Nano-particles are scattered in cement paste and placed on the surface of recycled aggregates to disperse cement particles in the new transition zone (between cement and recycled aggregate) in a better way and produce a more uniform and denser zone. Regarding to the individual and exclusive performance of nano-particles in the transition zone and in the mortar between aggregates, nano-particles condense these two principal sections of concrete and improve mechanical properties of concrete produced by recycled aggregates.

4 Conclusions

Under the conditions laid down in this research work, the following conclusions can be drawn:

- Replacement of coarse natural aggregates by 100% recycled aggregates decreased compressive strength by 15%-20%
- Increasing the amount of cement leads to an increase in compressive strength.
- It was observed that by increasing the amount of nano-silica as replacement of cement, the compressive strength of specimens increases as well.
- Adding 3% of nano-silica leads to values of compressive strengths higher than for conventional concrete.
- Increasing nano-silica quantity, as well as the amount of recycled aggregates, resulted in lower workability of concrete.

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