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Research Article

Feasibility of Using Nanoparticles of SiO_2 to Improve the Performance of Recycled Aggregate Concrete

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The aim of this paper was to examine the feasibility of using nanoparticles of SiO_2 (nanosilica) to improve the performance of recycled aggregate concrete (RAC) containing recycled aggregate (RA) derived from processing construction and demolition waste of concrete buildings. The examined properties include compressive strength, splitting tensile strength, and water absorption. The study also includes examining the microstructure of RA and RAC with and without nanoparticles of SiO_2. In total, nine mixes were investigated. Two mixes with RA contents of 50% and 100% were investigated and for each RA content; three mixes were prepared with three different nanoparticles dosages 0.4%, 0.8%, and 1.2% (by mass of cement). A control mix with natural aggregate (NA) was also prepared for comparison reasons. The results show that nanoparticles of silica can improve the compressive strength, tensile strength, reduce the water absorption, and modify the microstructure of RAC.

1. Introduction

The world is currently facing a global sustainability and environmental issue due to the increasing generation of massive quantities of waste by construction and demolition activities. The construction and demolition activities are necessary due to the expansion of urbanization which increases the demand for constructing more infrastructures such as housing, roads, bridges, and tunnels. Also, natural disasters such as earthquakes and wars lead to the destruction and devastation of many buildings, bridges, and roads, generating huge amounts of construction material rubbles. For example, vast quantities of building rubbles have been generated in Iraq over the last decades as a result of conflicts and terrorist attacks. At the global level, more than 500 million tons of construction and demolition waste (CDW) and building rubbles are generated worldwide annually [1]. Such a huge quantity of CDW requires substantial areas of land to dispose of, causing serious environmental issues. Also, depletion of natural resources of natural aggregates used in the production of concrete contributes to other environmental and sustainability concerns. These environmental issues and concerns have led the researchers worldwide to examine methods to mitigate the impact of these issues on the environment. One way is recycling the CDW and reusing them as aggregate and as an alternative to the natural aggregate in concrete. The utilization of recycled aggregate (RA) derived from processing CDW in concrete can save the environment through conserving the scarce landfill areas and reduce the consumption rate of the natural resources of aggregates [1, 2].

The use of the RA generated from processing CDW of concrete elements in new concrete has been investigated for decades. Nonetheless, the properties of the recycled aggregate concrete (RAC), as reported by the researchers, are inferior to that of the natural aggregate concrete (NAC). RAC exhibits low compressive, tensile, and flexural strength as well as high water absorption, porosity, and shrinkage [1, 3–5]. For these reasons, most codes of practice allow the natural aggregate in concrete to be only partially (20–30%) replaced by RA, especially in structural applications [6]. Many researchers have attributed this performance of RAC

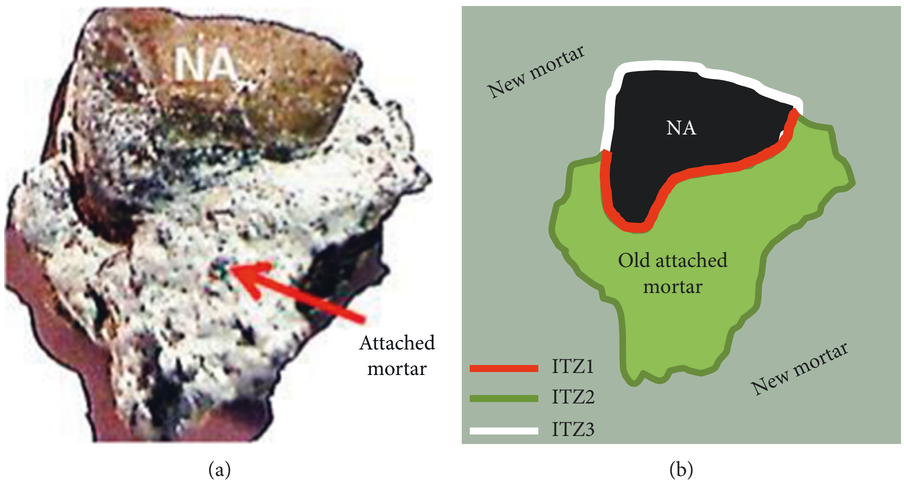


Figure 1: (a) Recycled aggregate (RA) particle. (b) Schematic of the RA particle in RAC showing all ITZs.

to the heterogeneous nature of the RA caused by the attached mortar exist on its surface [7, 8]. The attached mortar is characterized by high porosity, microcracks, and flaws which make the RA particle weak and its microstructure loose. Weak interfacial transition zone (ITZ) between the recycled concrete aggregate (RCA) and the cement matrix has also been identified [1, 9, 10]. Moreover, the presence of more than one ITZ in the RAC is another reason for the low quality of the RAC [1, 9, 11]. In RAC, there are three ITZs : ITZ1 which is between the old attached mortar and the natural aggregate, ITZ2 which is between the natural aggregate and the new cement mortar, and ITZ3 is between the old and new cement mortars [1] (Figure 1). It is reported by Ryu [11] that the relative quality of old ITZ and new ITZs in RAC plays a key role in determining the compressive strength of the RAC.

Therefore, researchers have tried various approaches to improve the properties of RA and RAC. Several studies focused on developing approaches to enhance the properties of the RA particles, whereas many other studies tried to improve the RAC properties through focusing on the technology of concrete production [1, 10], for example, separating the mortar that is attached to the natural aggregate from its surface using different approaches [7, 8, 10]. Despite the fact that the properties of the RA particles were improved using these approaches, they resulted in several drawbacks such as energy consumption, compromising durability aspects, and high cost [1, 8].

Aiming at improving the performance of RAC, other researchers have examined the utilization of fine and ultrafine reactive cementitious materials such as fly ash, ground granulated blast furnace slag, and silica fume in RAC [1, 5, 10, 12–14]. It is reported that these materials help to improve the performance of RAC due to the pozzolanic reaction and the filling ability resulting in a dense microstructure and strong ITZ [1, 9, 10]. However, the use of these materials in RAC does not always lead to a performance comparable to that of NAC. Hence, the need for investigating the use of other materials is vital. Nanomaterials are promising in this regard. The mechanical properties and the microstructure of RAC can be enhanced by the use of materials with reactive nanoparticles.

Over the last decade, the use of nanomaterials has emerged in the construction materials field. Many researchers in this field have explored the use of nanomaterials in concrete aiming at producing constructional materials (such as concrete) with superior performance and novel applications. Nanomaterials are characterized by nanoscale size particles. They have particles with the diameter of less than 100 nm [15]. In previous studies, several types of materials with nanoparticles have been used to improve the mechanical properties, durability behavior, and microstructure of cement paste, mortar, and concrete, for example, nano-SiO_2 [16–18], nano-TiO_2 [15, 19], nano-Al_2O_3 [20, 21], nano-Fe_2O_3 [21], carbon nanotubes [22], nanoclay [15], and nanolimestone [18]. However, among these nanoparticles, nano-SiO_2 (nanosilica) can be considered as the most frequently used one in improving the performance of concrete [15, 17]. Owing to its very small size (in the range of nanometers) and the pozzolanic reaction, nanosilica particles are very effective in enhancing the performance of concrete [23]. Nanomaterial, particularly nano-SiO_2, has the ability to improve the strength [23, 24] and the durability of concrete [17, 25] through accelerating the hydration reaction and filling the micropores in the cement paste structure, thus decreasing the porosity of concrete which in turn results in strength enhancement. Nanosilica can not only reduce the porosity of the cement paste, but also helps to densify the ITZ between the aggregate particle and the cement paste [23]. Studies [18, 24, 25] have shown that the addition of nanosilica results in increased compressive, tensile, and flexural strength of conventional concrete.

Studies on the use of nanosilica to upgrade the performance of RAC are very limited [26]. Hosseini et al. [27, 28] found that the compressive strength of RAC increased to reach a similar strength to that of NAC, when 3% (by mass of cement) of nano-SiO_2 is added to the RAC mixture. Also, Li et al. [29] reported that the static compressive strength of modified RAC with 2% (by mass of cement) of nanosilica was higher than that of the RAC without nanosilica by 21.6%. The addition of 2% of nanosilica also improved the dynamic compressive strength of RAC [29].

Since only few studies have tackled improving the performance of RAC using nanoparticles of SiO_2, this study aims at investigating the effect of using nano-SiO_2 to improve the mechanical properties and modify the microstructure of RAC. In this study, nano-SiO_2 at different dosages was added to RAC to enhance its performance. Compressive strength and splitting tensile strength of RAC with and without nanoparticles of SiO_2 were determined to assess the effect of these nanoparticles on the mechanical performance of RAC mixtures. Furthermore, the effect of these nanoparticles on the water absorption of RAC was also measured to assess its durability. Moreover, the microstructure of RAC mixtures with and without nanoparticles of silica was also evaluated through microscopic and scanning electron microscopy (SEM) observations. The obtained results can help promote the use of RAC in different civil engineering applications and enrich the literature of the research field of methods to improve the performance RAC.

2. Materials and Experimental Program

2.1. Materials

2.1.1. Cement. Portland cement (CEM I type) was used in this study meeting the requirements of Iraqi specifications [9]. The cement is manufactured by Mas company located in Sulymania, Iraq. Table 1 presents the chemical analysis of the cement (as given by the supplier).

Table 1: Chemical analysis of OPC.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Na_2O_{eq}
20.98	4.95	2.85	65.9	0.79	2.8	0.24	0.43	0.52

2.1.2. Aggregates. Two types of coarse aggregates were used, natural, and recycled. The natural gravel was rounded river aggregate with a maximum size of 20 mm, water absorption of 1%, and specific gravity of 2.6. The coarse RA was recycled concrete aggregate produced by crushing old concrete portions generated by demolishing old concrete buildings. The water absorption and the specific gravity of the RA were 3.3% and 2.45, respectively. The fine aggregate used in this study was sand with a maximum size of 5 mm.

2.1.3. Nanomaterials. The material used in this study was nanosilica supplied by HWNANO Company in China. The nano-SiO_2 was in the form of powder (Figure 2(a)) with a purity of 99% SiO_2 (Figure 2). The average particle size of the nanosilica was between 20 and 30 nm with a surface area of 125 m^2/g. The X-ray diffraction (XRD) analysis of the powder sample of the SiO_2 nanoparticles is shown in Figure 2(b), while Figure 2(c) shows an SEM image of the nanoparticles of the nano-SiO_2.

2.1.4. Superplasticizers. Superplasticizers were used to ensure a uniform dispersion of the nanoparticles as explained in Section 2.3. The superplasticizer was an aqueous solution containing polycarboxylate ether (PCE) polymers.

2.2. Variables and Mix Proportions. In total, nine different concrete mixes were prepared. The code of mixes and the variables of the study are shown in Table 2. The mixes are divided into three groups according to the type of coarse aggregate, the content of coarse recycled aggregate, and the content of nanoparticles of SiO_2. The study includes one control mix made with natural coarse aggregate NCA (R0) and two mixes made with recycled coarse aggregate RCA in which the NA is replaced by RA at contents of 50% and 100% and six mixes (three for each RA content) made with three contents (0.4%, 0.8%, and 1.2% by cement mass) of nano-SiO_2. All mixes had the same quantity of cement (400 kg/m^3), water (192 kg/m^3), and fine aggregate (719 kg/m^3), whilst the quantity of coarse aggregate used was 1125 kg/m3. All mixes were made with the same water/cement (w/c) ratio (0.48). For the mixes incorporating RA, the water quantity was adjusted (100% water absorption of the RA was compensated during mixing) to account for the water absorption of the RA to ensure that all mixes have the same effective water to cement ratio.

2.3. Mixing, Preparation of Specimens, and Curing. A pan mixer with a capacity of 0.1 m^3 was used to mix the ingredients and prepare all concrete mixtures. For the mixes containing nano-SiO_2, the nanosilica powder was added to one liter of water and an amount of superplasticizer (0.5% by mass of cement) to form an aqueous solution. The solution was mixed using a high-speed blender to ensure a uniform distribution of the nanoparticles and avoiding the agglomeration of these particles due to the strong attractive forces of van der Waals.

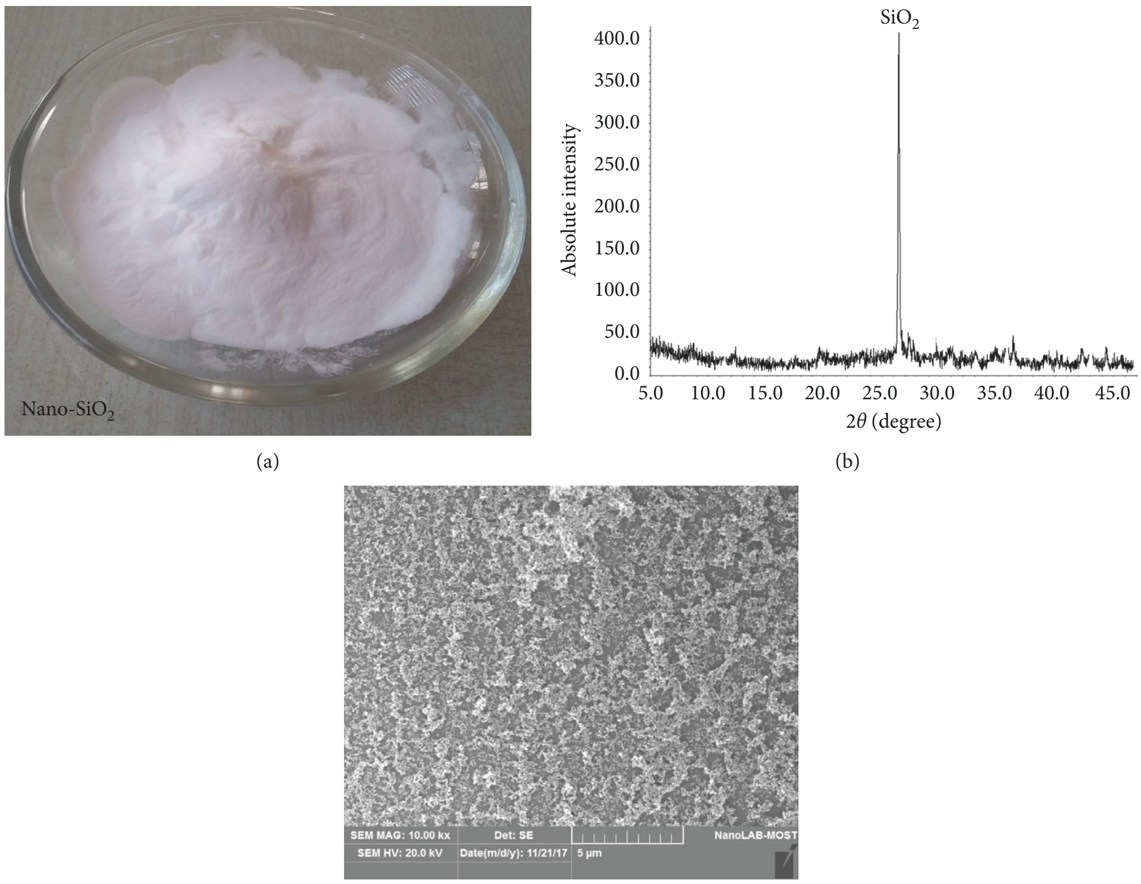
The procedure of mixing the ingredients of the concrete is as follows: Firstly, the coarse aggregate was added and mixed with the aqueous solution of nano-SiO_2 and part of the mixing water for 1 minute. Then, the ingredients were left in the mixer pan for 10 minutes to allow the recycled coarse aggregate to absorb the nanoparticles and form a coating layer on their surfaces. Secondly, the fine aggregate, cement, and the rest of the mixing water were added and mixed for 3 minutes.

After the completion of mixing the ingredients, for each mix, six (100 mm) cubes and three (100 × 200 mm) cylinders were cast. The concrete was mixed using a pan mixer and compacted using a vibrating table. After casting, the specimens were then covered by plastic sheets and allowed to cure for 24 hours before being demoulded. Then, the specimens were kept in water tanks for 27 days for further curing.

2.4. Tests

2.4.1. Compressive Strength Test. The compressive strength was obtained at the age of 28 days using the 100 mm cubes and BS EN 12390-3 [30].

2.4.2. Splitting Tensile Strength Test. The splitting tensile strength was obtained at the age of 28 days using the 100 × 200 mm cylinders and BS EN 12390-6 [31].



(a) (b) (c)

Figure 2: (a) Nano-SiO_2 in powder form; (b) XRD analysis of SiO_2 nanoparticles used in the study; (c) SEM image of the nano-SiO_2.

Table 2: Code of mixes and variables of study.

Mix number	Mix code	Type of coarse aggregate	Nano-SiO_2 content (%)[a]	Coarse recycled aggregate content (%)
1	R0	Natural	0	0
2	R50	Natural + recycled	0	50
3	R100	Recycled	0	100
4	R50N0.4	Natural + recycled	0.4	50
5	R50N0.8	Natural + recycled	0.8	50
6	R50N1.2	Natural + recycled	1.2	50
7	R100N0.4	Recycled	0.4	100
8	R100N0.8	Recycled	0.8	100
9	R100N1.2	Recycled	1.2	100

[a]By cement mass.

2.4.3. Water Absorption (WA) Test. The water absorption of all concrete mixtures in this study was determined by following the procedure described in the standard test of ASTM C642-13 [32]. For each mix, three specimens (cubes) of concrete with dimensions of ($100 * 100 * 100$ mm) were used in the WA test. The specimens were tested at the age of 28 days. After 28 days of water curing, the specimens were dried in an oven with a temperature of 100–110°C for 24 hours. The dried specimens were then weighed, and the dry mass of the specimens were recorded when a constant dry mass was reached. The constant dry mass means when the difference of two successive dry mass readings is equal or less than 0.5% of the lowest mass reading (value). After that, the specimens were fully immersed in water for 24 hours. The specimens, then, were taken out, and the surface moisture was removed using a dry and absorbent cloth. Finally, the mass of the specimens (after immersing in water) were recorded. The WA (%) was calculated as the difference between the saturated mass and the dry mass with respect of the dry mass of the specimen.

2.4.4. Microstructure Observations. Individual particles of recycled coarse aggregate were investigated using a digital microscope. Scanning electron microscopy (SEM) was also

Table 3: Results of compressive strength test.

Mix	Compressive strength			
	Strength (MPa)	Normalized strength to control mix R0	Normalized strength to mix R50	Normalized strength to mix R100
R0	40.6	1.00	—	—
R50	34.1	0.84	1.00	—
R100	30.2	0.74	—	1.00
R50N0.4	37.5	0.92	1.10	—
R50N0.8	40.3	0.99	1.18	—
R50N1.2	41.0	1.00	1.20	—
R100N0.4	32.0	0.79	—	1.06
R100N0.8	34.2	0.84	—	1.13
R100N1.2	35.1	0.86	—	1.16

used to assess the microstructure of the RA particles and concrete samples with and without nanoparticles of SiO_2.

3. Results and Discussion

3.1. Compressive Strength. The results of the compressive strength at the age of 28 days for all mixes are presented in Table 3. The result of each mix is the average of three specimens. The table also shows the normalized strength (with respect to the control mix R0, mix made with 50% RA, mix R50 and mix made with 100% RA, mix R100). It is worth to mention that the addition of nanoparticles of SiO_2 reduced the workability of concrete mixes. However, the workability of all mixes represented by slump test values was equal to or higher than the target value of the mix design which is 50 mm. The values of the slump test ranged between 100 mm for Mix R0 to 50 mm for mix R100N1.2.

As expected, the compressive strength of the RAC mixes without nanosilica (R50 and R100) is lower than that of the control mix (R0), as can be seen in Table 3 and Figure 3. The compressive strength of RAC decreases by 16% and 26% when the natural coarse aggregate is replaced by 50% and 100%, respectively. Similar behavior was reported in [1, 33]. This is mainly due to the heterogeneous nature of the recycled aggregate which is characterized by a weak and cracked surface resulted from the adhered mortar and the crushing process of demolished concrete [9, 10]. In addition, the inferior properties of RA such as low strength and high porosity and water absorption in comparison to natural aggregate (NA) could be another reason for the decline in compressive strength of concrete when NA is replaced by RA [1, 9].

Figure 4 represents the compressive strength of RAC mixes made with 50% and 100% of RA at different nano-SiO_2 contents. The compressive strength of the control mix (R0) is also shown in Figure 4. The figure shows that the addition of nano-SiO_2 enhances the compressive strength of the mixes containing recycled aggregate. It is clear that the content of nanoparticles affects the degree of strength enhancement. It can be seen that the compressive strength increases with the increase of content of nanosilica regardless of the recycled aggregate content. For example, when the nanosilica is added at contents of 0.4%, 0.8%, and 1.2%, the compressive strength increases by 10%, 18%, and 22% for mixes containing 50% RA and by 6%, 13%, and 16% for mixes made with 100% RA. The results also show that the increase in strength for mixes containing 50% RA is higher

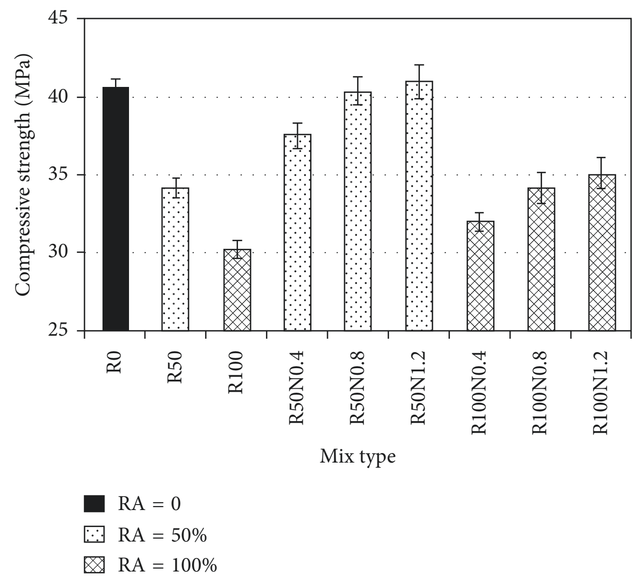


Figure 3: Compressive strength of all mixes.

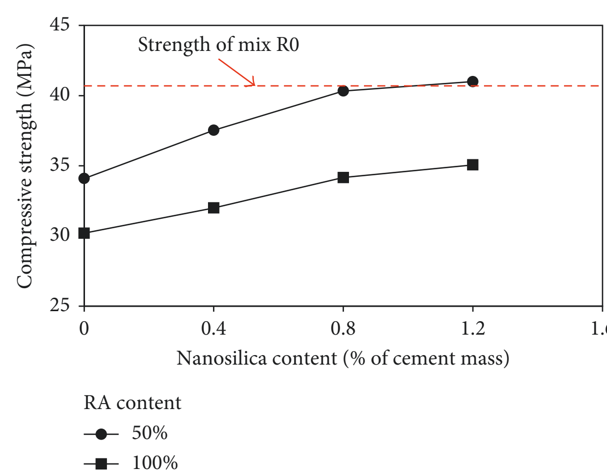


Figure 4: Effect of nanosilica particle content on the compressive strength of RAC mixes.

Table 4: Results of splitting tensile strength test.

Mix	Splitting tensile strength			
	Strength (MPa)	Normalized strength to control mix R0	Normalized strength to mix R50	Normalized strength to mix R100
R0	3.65	1.00	—	—
R50	3.40	0.93	1.00	—
R100	3.31	0.91	—	1.00
R50N0.4	3.56	0.98	1.05	—
R50N0.8	3.74	1.03	1.10	—
R50N1.2	3.72	1.02	1.09	—
R100N0.4	3.37	0.92	—	1.02
R100N0.8	3.46	0.95	—	1.05
R100N1.2	3.58	0.98	—	1.08

than those with 100% RA in all nanosilica contents. It seems that the addition of nanosilica in contents up to 0.8% (by mass of cement) to the RAC mixes is very beneficial and can result in comparable strength to that of the control mix R0 (mix with natural coarse aggregate), in particular at RA content of 50% [34]. Similar compressive strength enhancements were observed by [26, 28, 29] but at different dosages of nanoparticles of SiO_2. The strength enhancement could be attributed to the reduced porosity and modified microstructure of the RA particles and RAC due to the addition of the nanoparticles of SiO_2 [34]. The mechanisms leading to this strength improvement is explained in Section 3.4 where the effect of adding the nanoparticles on the microstructure of the RAC is discussed.

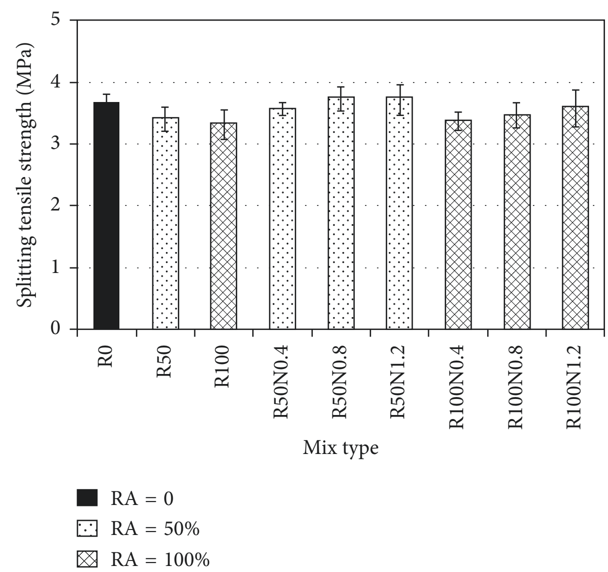


Figure 5: Splitting tensile strength of all mixes.

3.2. Splitting Tensile Strength. The results of the splitting tensile strength at the age of 28 days of all mixes are listed in Table 4 and shown in Figure 5. The result of each mix is the average of three cylindrical specimens. The table also shows the normalized strength (with respect to the strength of the control mix R0). The percentage of strength enhancement due to adding nanoparticles of SiO_2 (compared to mixes R50 and R100) is also presented.

Similar to the results of the compressive strength, the splitting tensile strength of RAC mixes is lower than that of the control mix. In comparison with the tensile strength of the control mix, the splitting tensile strength of RAC mixes declined by 7% and 9% at RA contents of 50% and 100%, respectively, as can be seen in Table 4 and Figure 5. Previous studies [35–37] also reported reduction in the splitting tensile strength of concrete when the natural coarse aggregate was replaced by RA. Positive effect on the splitting tensile strength of the RAC mixes can be observed when nanoparticles are added to these mixes (Figure 5). The tensile strength of RAC mixes made with 50% of RA improved by up to 10% as a result of the addition of nanoparticles of SiO_2. Tensile strength enhancement up to 8% was also obtained for RAC mixes made with 100% of RA.

Figure 6 shows the variation of the splitting tensile strength of the RAC mixes with respect the nanosilica content. It can be seen that the rate of strength increases due to the addition of nanoparticles is higher in RAC mixes made with 50% RA than mixes made with 100% RA. At 50%

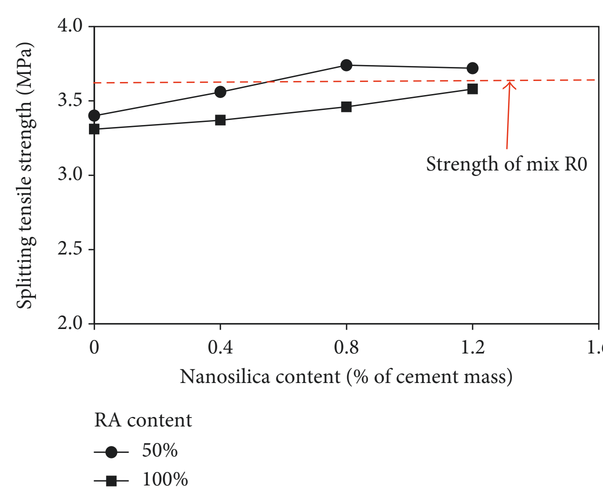


Figure 6: Effect of nanosilica particles content on the splitting tensile strength of RAC mixes.

RA content, the addition of nanoparticles results in comparable splitting tensile strength to that of the control mix at 0.4% nanoparticle content or even higher at 0.8% and 1.2%

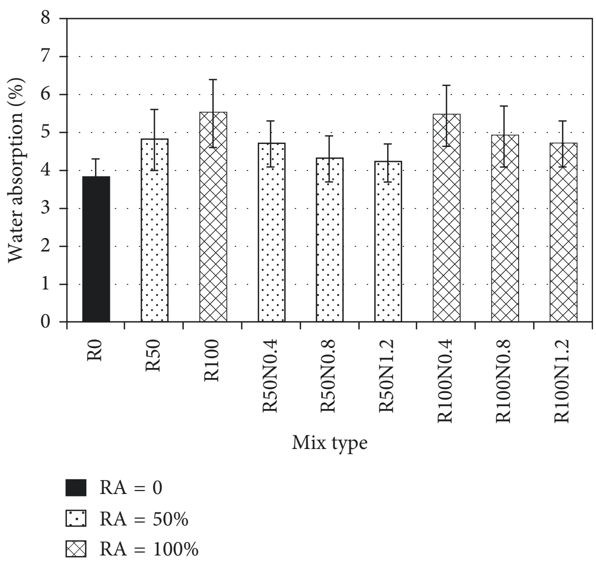


Figure 7: Water absorption (WA) of all mixes.

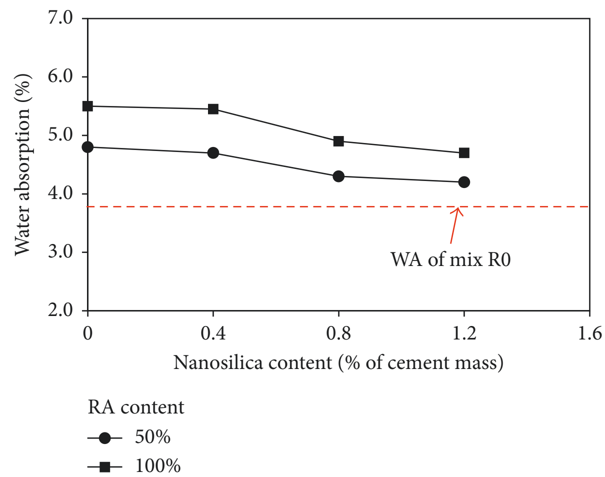


Figure 8: Effect of nanosilica particles content on the WA of RAC mixes.

contents as can be seen in Figure 6. At 100% RA content, the strength increases with the increase of the nanoparticles content to reach just under the strength of the control mix at 1.2% nanoparticles content. Splitting tensile strength improvement due to the addition of nanoparticles of silica was also observed by [28, 38]. This strength improvement of RAC mixes could be attributed to the modification of the microstructure of the RA and the hardened concrete which is explained in detail in Section 3.4.

3.3. Water Absorption. The results of the WA after immersion in water for 24 hours are shown in Figure 7. The age of the specimens at testing was ranged between 28 and 30 days. The results indicate that RAC mixes without nanosilica exhibit higher water absorption than the control mix (R0). The WA of the of the control mix was 3.8%, whereas the WA of the of the RAC mixes with 50% and 100% RA contents were 4.8% and 5.5%, respectively. Water penetrates into concrete because of the ability of the aggregate to absorb water and also due to the presence of micro/macro pores (capillary pores, air voids, and ITZ) in the cement/mortar matrix. The high water absorption of the RAC mixes can be attributed to the inherent nature of the porous microstructure of the RA particles caused by the adhered mortar [1, 3, 4] (as will be explained in Section 3.4).

The influence of adding nanoparticles of SiO_2 with various contents on the WA of RAC mixes is shown in Figure 8 which also shows the WA of the control mix. It can be noticed that although none of the RAC mixes containing nanoparticles of silica shows comparable WA to that of the control mix, the addition of nanoparticles reduces the WA of the RAC mixes. At both contents of RA (50%and 100%), the influence of adding 0.4% of nanoparticles on the WA is insignificant, whilst adding 0.8% of nano-SiO_2 leads to a decline of 10% and 11% in the WA of RAC mixes with 50% and 100% RA contents, respectively. A further slight decrease in WA of the RAC mixes can be observed when the nanosilica content increases to 1.2%. The reduction in WA of the RAC mixes made with nanoparticles of SiO_2 can be mainly attributed to the modification on the RA particles due to the layer of nanoparticles which covers the surface of the RA. This could strengthen the weak, porous, and cracked surface of the RA particles (see Section 3.4) increasing the resistance of the RA against the penetrability of water. The densification of the microstructure of the cement matrix and the ITZ due to the addition of nanosilica particles (as will be explained in next section) could also help in reducing the WA of the RAC mixes.

3.4. Microscopic and Scanning Electron Microscopy Observations. The surface of individual particles of the recycled aggregate with and without nanosilica was observed by a microscope to support and justify the gained enhancement in the compressive strength and tensile strength for the mixes made with recycled coarse aggregate. Also, SEM images for recycled aggregate particles and concrete specimens were taken and studied for the same purpose.

3.4.1. Recycled Aggregate Specimens (Particles). Figure 9(a) shows an image taken by a microscope with a magnification of 20x for the surface of a recycled aggregate particle. Microcracks and voids can be identified on the surface of the RA particle as can be seen in Figure 9(b) which shows part of the surface of the RA particle with higher magnification. These microcracks and voids are the main cause of the weakness of the RA which in turn results in low strength concrete [1, 9, 10]. A weak and cracked zone (ITZ) between the natural aggregate and the attached mortar can be observed. These microcracks and weak ITZ are usually caused by the process of the crushing of the demolished concrete [9]. Similarly, microcracks and weak ITZ can be identified in Figure 4(c) which shows an SEM image for the surface of a RA particle.

To assess the effect of adding the nanosilica as a coat layer around the RA particles on their surfaces, microscopic images were taken for individual particles as can be seen in

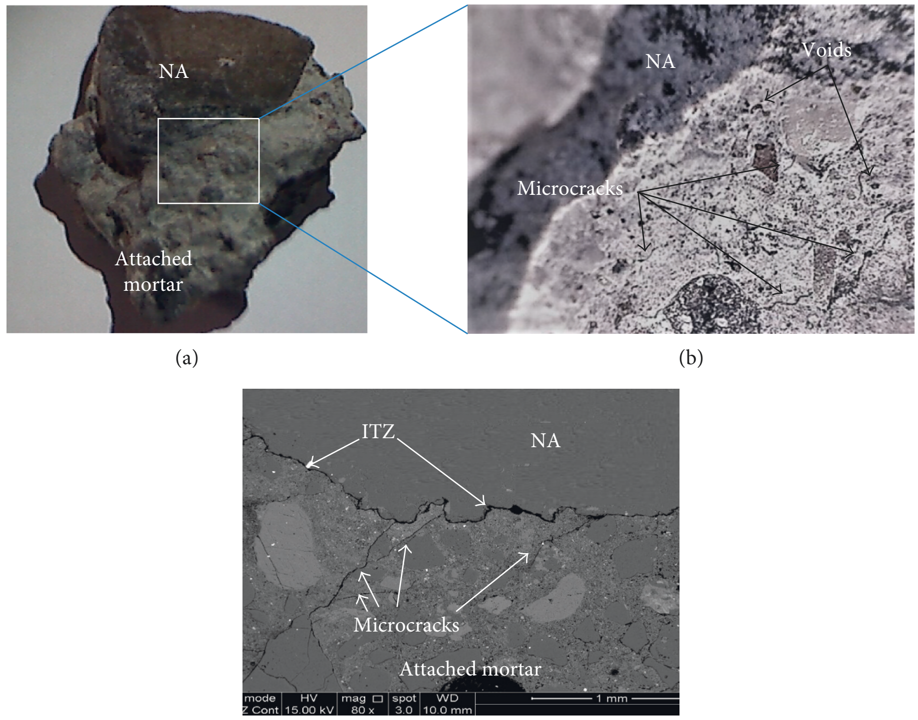


Figure 9: (a) RA particle at 20x magnification. (b) RA surface at 200x magnification. (c) SEM image of the surface of a recycled coarse aggregate particle.

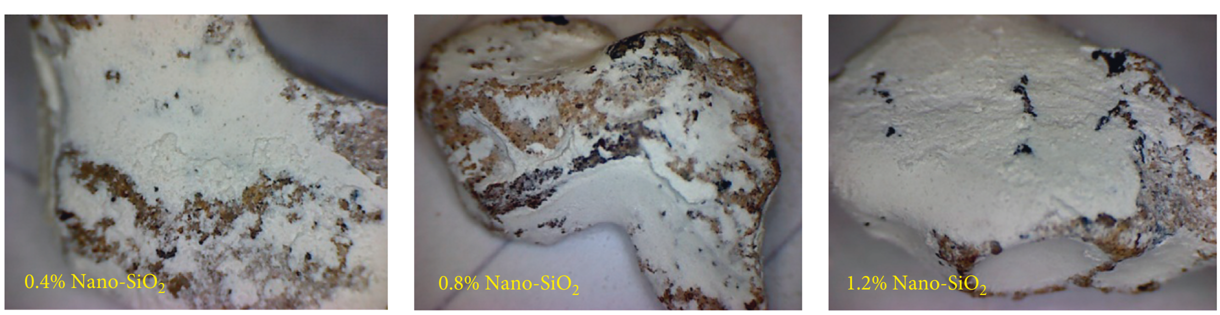


Figure 10: Microscopic images of RA particles with different nanosilica contents: (a) 0.4%; (b) 0.8%; (c) 1.2%.

Figure 10. The effect of nanosilica on the surface of the RA particles is clear. The Nanosilica modifies the surface by sealing all the microcracks and filling all the voids. This modification can partly explain the enhancement in the strength gained by adding nanosilica to the mixes with RA.

3.4.2. Concrete Specimens. The effect of using SiO_2 nanoparticles on the microstructure of RAC was also evaluated through studying concrete specimens with and without nano-SiO_2. The SEM images for the concrete specimens were taken and presented in Figures 11 and 12. Figure 11 shows SEM image for the RAC specimens without silica nanoparticles. The image clearly shows the fact that there are different ITZs in RAC : ITZ1 which exists between the NA particle and the old attached mortar, ITZ2 which lays between the NA particles and the new cement matrix (mortar), and ITZ3 which develops between the new and the old cement mortars. The existence of these ITZs with different microstructures increases the heterogeneous nature of RAC and hence results in a low quality concrete in terms of both strength and durability aspects [34]. Also, the image shows that ITZ3, like the other two ITZs, is porous and can be clearly identified by the very fine black line. The high porosity of this ITZ is due to the high concentration of Ca $(OH)_2$ resulted from the hydration of cement [9, 10].

On the other hand, the ITZ3 in the RAC specimen coated with SiO_2 nanoparticles (Figure 12) cannot be clearly identified with a black line. Although, the old attached mortar and the new mortar can be recognized by their different porosity and microstructure, the two parts seem to be connected very well, and the zone between them

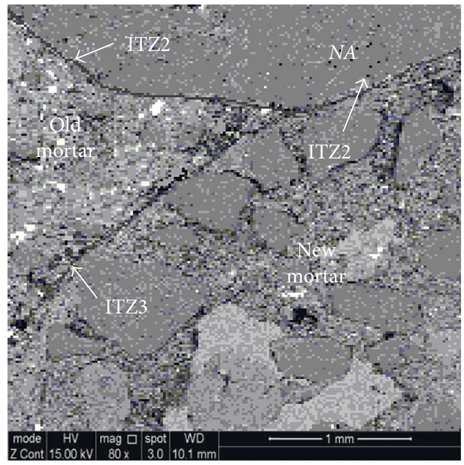


Figure 11: SEM image explains the ITZs in RAC sample without nanosilica.

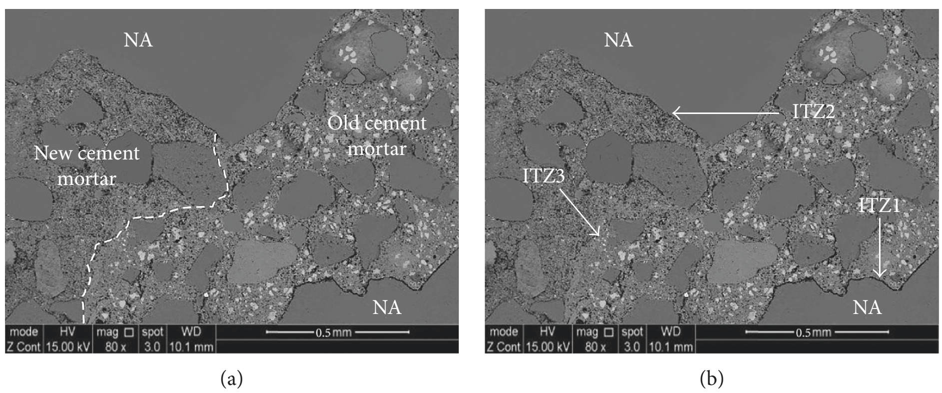


Figure 12: (a) SEM image of a concrete sample with nanosilica; (b) image of the ITZs of a concrete sample with nanosilica.

(which is the ITZ3) is very dense (Figure 12(b)). The densification of the microstructure of the ITZ3 can be attributed to the effect of adding the nanoparticles of silica. These nanoparticles can result in a dense ITZ through two mechanisms: one is physical and the other one is chemical. The latter is attributed to the chemical ability of the SiO_2 nanoparticles to react with the $Ca(OH)_2$ (one of the cement hydration products) and leading to the formation of more gel product, calcium silicate hydroxide (C-S-H), which is the product responsible of the strength of the concrete and dense microstructure of the ITZ in concrete [23, 39, 40]. The former can be due to large surface area and the super-ultrafine size of the nanoparticles. This small size of these particles helps in filling up all the micropores/nanopores and voids exit in the attached mortar and the ITZ resulting in a more densified microstructure of the cement matrix [34, 38, 40]. Hence, these two mechanisms seem to be the main reasons behind the improvement of the strength of the RAC containing nanoparticles of SiO_2.

4. Conclusions

The following conclusions can be drawn based on the results and discussion.

(i) The addition of nanoparticles of SiO_2 can improve the compressive strength of recycled aggregate concrete regardless of the content of RA.

(ii) The increase in compressive strength depends on the content of the nanoparticles of SiO_2 content.

(iii) The addition of nanoparticles of silica at contents of 0.4%, 0.8%, and 1.2% results in an increase in the compressive strength of 10%, 18%, and 22% for mixes containing 50% RA and of 6%, 13%, and 16% for mixes made with 100% RA, respectively.

(iv) Adding nanoparticles to RAC can result in comparable splitting tensile strength to that of the control mix at 0.4% nanoparticles content or even higher at 0.8%; while at 100% RA content, the splitting tensile strength increases to reach just under the strength of the control mix at 1.2% nanoparticles content.

(v) Regardless of the content of RA, the addition of nanoparticles of SiO_2 resulted in reducing the WA of RAC up to 11% at 0.8% of nanoparticle content compared to RAC mixes without nanoparticles.

(vi) The enhancement in strength and the reduction in the WA of the RAC due to the addition of nanoparticles can be attributed to the modification in the pore structure of the concrete.

(vii) Microscopic and SEM observations revealed the heterogeneous nature of the RA particles, which is characterized by weak and cracked attached mortar and porous ITZ.

(viii) RAC microstructure can be positively modified through the addition of SiO_2 nanoparticles which can help densify the microstructure RAC by physical and chemical mechanisms.

(ix) RAC with nanoparticles of SiO_2 can demonstrate comparable strength to that of NAC; hence, great enhancement in terms of sustainability and environmental impact of RA can be achieved.

Data Availability

The authors state that the data for all tests are available. Please contact the corresponding author for the data and further information.

Disclosure

Part of this research has been presented in the 4th International Engineering Conference on Developments in Civil and Computer Applications IEC 2018, Erbil Polytechnic University and Ishik University, Erbil, Iraq, 2018 [34].

Conflicts of Interest

The authors declare no conflicts of interest.

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