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Recycled Aggregate Concrete Made with Silica Fume: Experimental Investigation

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Abstract This research deals with the behavior of recycled aggregate concrete (RAC). In this study an experimental work was undertaken. The study examines the effect of using recycled coarse aggregate (RCA) on the workability and the mechanical performance of RAC. The influences of using silica fume (SF) as cement replacement material on the performance of RAC were also examined. Silica fume was used at four contents (5%, 10%, 15% and 20%). The total number of mixes was six. Four mixes of RAC made with these four contents of SF, one RAC mix was made without SF and one mix was made with natural coarse aggregate (NCA) as a reference mix. The outcomes of this study reveal that workability and mechanical performance of RAC are lower than that made with NCA. Also, Silica fume has an adverse influence on workability of the RAC. However, the silica fume possesses a positive influence on mechanical properties of RAC. Silica fume can be used at contents of (10-20)% of cement mass to obtain mechanical performance for the RAC comparable to the concrete includes NCA.

Keywords Recycled Coarse Aggregate, Compressive Strength, Flexural Strength, Silica Fume

1. Introduction

Concrete is a constructional material which has been utilized in construction industry for more than one century [1]. This is due to its versatility, ease of shaping and low cost. However, concrete has been accused for the high amount of emitted CO_2 during the process of its production including cement manufacturing, aggregate extraction and transportation. Indeed, this emission causes sustainability concerns and environmental issues [1] [2]. Another environmental problem which is related to the industry of construction is the accumulation of huge amounts of construction and demolition waste (CDW). Nowadays, such issues and concerns are recognized at the level of globe. Among these issues are the diminution of areas of landfills and exhaustion of the resources of the raw materials. To alleviate the negative influence of these environmental issues, there are various approaches [3]. One of these approaches is the employment of mineral admixtures such as Silica fume (SF) and fly ash (FA) in the production of concrete. These are by-product materials which can be used to replace ordinary Portland cement (OPC) [4]. The use of such materials can greatly help in reducing consumption of cement which in turn may substantially contribute to reduce the environmental related issues. Another way is the reuse or recycle of CDW to be used as fine or coarse aggregates instead of traditional aggregate. Crushed concrete, for example, can be used as recycled coarse aggregate in the concrete manufacture. This is also very helpful in conserving our environment [5] [6].

The concrete that includes recycled coarse aggregate (RCA) is called recycled aggregate concrete (RAC). Although the use of RCA in producing RAC is beneficial in terms of sustainability and environmental impact, its behavior is not as good as the natural aggregate concrete (NAC) [7]. It has been reported that RAC shows lower performance than that of NAC. RCA affects both conditions of concrete, fresh and hardened. RCA diminishes the workability of concrete and decreases its mechanical properties [3]. Concrete's strengths including compressive strength, splitting tensile strength and flexural strength may reduce by up to 40%, 25% and 20% in comparison to NAC, respectively [8]. The previous studies have related this behavior to the low quality of RCA. RCA comprises natural aggregate with mortar attached to its surface which is porous and characterized with micro-cracks [9]. These characteristics result in a weak RCA with high water absorption and porosity. Such characteristics (high porosity and water absorption) result in lower workability of RAC compared to NAC [3] [10] [11].

The previous studies on the use of SF in NAC have shown that such mineral admixture has a characteristic of the pozzolanic reaction. As a results of this reaction, such mineral materials admixture can improve the mechanical properties and enhance the durability of concrete (NAC) [6] [12] [13].

Therefore, this experimental work examines the effect of using SF at different contents as OPC replacement on the performance of RAC. In this RAC, the natural coarse aggregate is fully replaced with RCA originated from crushing old concrete elements. This study investigates the workability and the mechanical properties of RAC comprising different contents of SF.

2. Experimental Work

2.1. Materials

Normal Portland cement (OPC) type CEM I meeting specifications of BS EN 197 was employed in current study. The chemical composition of the OPC, as provided by the provider, is displayed in Table 1.

Silica fume was used in the current study as mineral admixtures to substitute the OPC. Table 2 displays the properties (physical) of the OPC and SF while the chemical oxides contents of the SF are shown in Table 1, as supplied by the provider.

The coarse aggregate employed in this study can be divided into two types. The first one is natural gravel extracted from the river in the region of Kalak area in Erbil city. It is rounded gravel with a maximum size of 20mm. The second one is recycled aggregate originated from crushing the debris of demolished concrete structures, see Figure 1. Just as the natural gravel, the recycled one has the same maximum aggregate size of 20mm. Some of the physical properties of these aggregates employed in the current work are shown in Table 3.

The fine aggregate utilized in current study is river sand extracted from the river in Kalak area in Erbil city. It had a maximum size of 4.75 mm.

Superplasticizers were used in this study to attain appropriate workability for the concrete mixtures. Slump test was conducted to evaluate the workability of all mixes. The superplasticizer used is a solution contains polymers called poly-carboxylate ether (PCE).

Table 1. Composition of OPC and silica fume (SF) used in current study

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Na_2O
CEM I	**21.04**	**4.83**	**3.01**	**66.5**	**0.76**	**2.65**	**0.35**	**0.52**	**0.56**
SF	**93.4**	**0.8**	**1.5**	**0.8**	**0.2**	**-**	**0.72**	**0.70**	**-**

Table 2. Physical properties of the OPC and SF

Property	**OPC**	**SF**
Specific gravity	3.15	2.3
Fineness (m^2/kg)	446	13200
Initial setting time (min)	100	-

Table 3. Physical properties of coarse aggregates (CA)

Coarse aggregate Type	**Property**			
	Shape	**Surface texture**	**Specific gravity (SSD)**	**Water absorption (%)**
Natural	Rounded	Smooth	2.67	1.1
Recycled	Angular	Rough	2.46	4.6

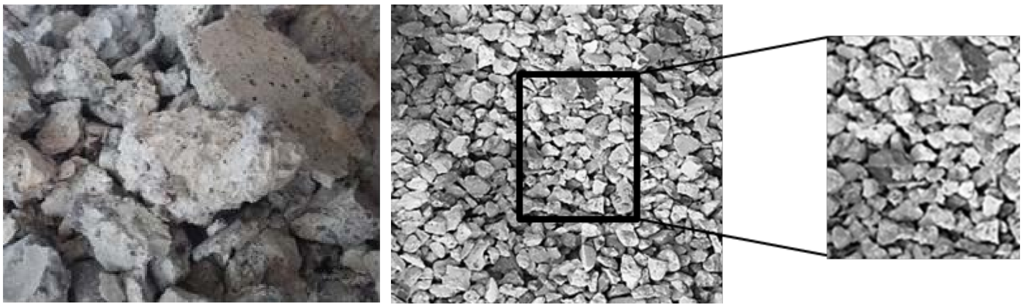

Figure 1. Coarse aggregate (Recycled) used in current study

Table 4. Designation of mixes and proportions of mixes (kg/ m^3)

Number	Mix code	C	SF	W	CA		FA
					Natural	Recycled	
1	NSF0	355	0	170.4	1096	0	739
2	RSF0	355	0	170.4	0	1034	739
3	RSF5	337.25	17.75	170.4	0	1034	739
4	RSF10	319.5	35.50	170.4	0	1034	739
5	RSF15	301.75	53.25	170.4	0	1034	739
6	RSF20	284.00	71.00	170.4	0	1034	739

C= Cement;SF= Silic fume ; W=Water,CA= Coarse aggregate; FA= Fine aggregate

2.2. Proportioning of Mixes, Mixing and Casting

The total number of mixes examined in this study is six mixes. Table 4 includes detailed information about the mixes such as mix number, mix designation and composition of all mixes. All mixes were made with same ratio of water/cement (w/c) which is (0.48). A constant quantity of superplasticizer was added to all mixtures to attain a proper workability. This quantity is equal to 0.4% of cement mass.

The process of mixing included several steps. Firstly, all aggregates (coarse and fine) were placed in the pan of the mixer and mixed for 2 minutes. Secondly, the binders were included and mixing continued for 2 more minutes. Thirdly, water and chemical admixtures were put in the mixer and mixing continued for 3 minutes. The concrete ingredients were blended in a mixer that had a 0.1 m^{3}capacity. After mixing and assessing the workability of concrete, the concrete in fresh state was cast in different types of molds and compacted. An internal vibrator was used for the compaction process. Different types of molds were used to cast the concrete. Three 100 mm cubes, three cylinders 100×200 mm and three prisms 100×100×500 mm were cast for each mix. After casting and compaction, all molds were concealed using nylon sheets and left to cure for 24 hrs. Thereafter, the concrete samples were demolded and moved to water tank where kept for further curing till the day of testing.

2.3. Experiments

Assessment of workability (Slump Test)

In order to evaluate workability of fresh concrete for all mixtures, slump test was undertaken, see Figure 2. The test of slump was conducted as per BS EN 12350-2 [14].

Figure 2. Test of Slump

Compressive strength Assessment

The compressive strength test was carried out as per the specifications of BS EN 12390-3 [15]. The concrete samples (cubes) were assessed for compression after 28 days of water curing. A hydraulic machine for compression loading having capacity of 2000 KN was utilized in this test.

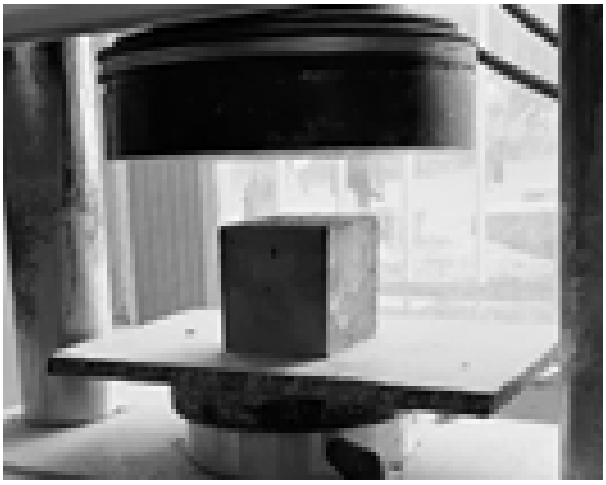

Figure 3. Concrete cube before testing under compression

Splitting tensile strength Assessment

The test of splitting tensile strength was conducted as per specifications of standard test of BS EN 12390-6 [16]. The samples of the test were cylinders having dimensions of 100×200 mm. The test was conducted for the samples after 28 days of curing in water. Figure 4 displays the machine used for the test.

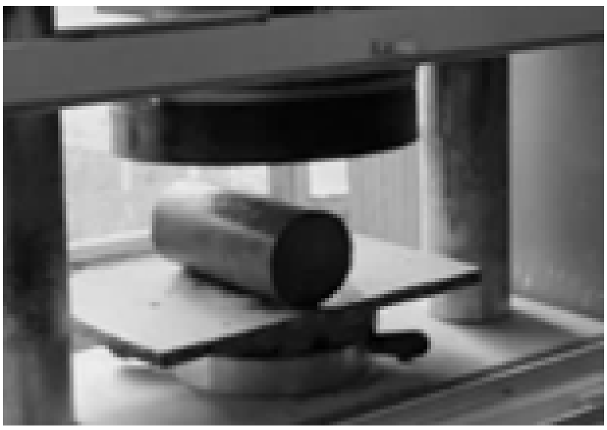

Figure 4. Concrete sample for splitting tensile strength test**.**

Test of flexural strength

The flexural strength test was conducted as per the requirements of BS EN 12390-6 [17]. The concrete samples (prisms) were tested for flexural at age 28 days. A machine for bending having 100 KN capacity was utilized in this test, see Figure 5. The concrete beams were assessed for bending over a length of 300 mm.

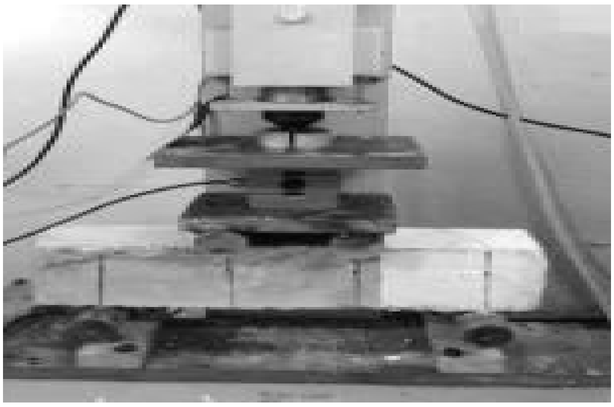

Figure 5. Bending machine used for flexural strength

3. Results of Tests and Discussions

3.1. Results of Workability

The workability of all mixes was assessed using slump test. The results (in mm) of this test for all mixtures are displayed in Table 5 and shown in Figure 6. In this table, the normalized slump (slump value of mix divided by the slump value of mix NSF0 or mix RSF0) are also presented. The normalized values are used to compare the results of the mixes with the results of these two reference mixes.

Table 5. Slump test results (values) and the normalized slump compared to mix NSF0[1] and RSF0[2]

Mix	Slump Test Results		
	Slump mm	**Normalized[1]**	**Normalized[2]**
NSF0	110	1.0	-
RSF0	90	0.82	1.0
RSF5	90	0.82	1.0
RSF10	80	0.73	0.89
RSF15	65	0.59	0.72
RSF20	55	0.50	0.62

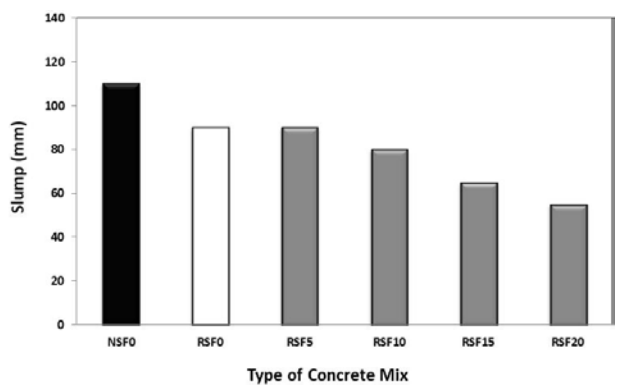

Figure 6. Results of slump test

The replacement of NCA with recycled aggregate decreases the workability of the concrete as the slump value reduced from 110 mm (for mix NSF0) to 90 mm (for mix RSF0) as can be noticed in Figure 6. This means that workability of mix NSF0 reduced by 18% when the RCA was used instead of NCA (see normalized workability in Table 5). This is mainly because of the high capacity of RCA to absorb water (see Table 3) and its rough surface. Studies such as [3] [18] reported similar negative effects of RCA on the workability of concrete. The use of SF also had adverse effect on workability of RAC. This adverse effect depends on the content of the SF as the adverse effect increases with the increase of the content of SF as can be seen Table 5. For instant, compared to the slump value of mix SF0, mixes RSF5, RSF10, RSF15 and RSF20 exhibited lower slump values by 18%, 27%, 39% and 50%, respectively. This behavior is caused by high surface area of silica fume which demands high quantity of water to maintain the workability of the concrete [9].

3.2. Results of Compressive Strength

For each mix, 3 cubes were tested under compression load to assess the performance of all mixes under compression loading. The results (average of 3 samples) from concrete mixtures are displayed in Table 6 and depicted in Figure 7. The normalized values for the compressive strength are used to compare the results of the mixes with the results of the two reference mixes, SF0 and RSF0.

Table 6. Compressive strength test results with normalized strength compared to mix NFS0[1] and RFS0[2]

Mix	Compressive strength Test Results		
	Values MPa	Normalized[1]	Normalized[2]
NSF0	38.8	1.0	-
RSF0	27.7	0.71	1.0
RSF5	31.8	0.82	1.14
RSF10	35.7	0.92	1.29
RSF15	37.5	0.97	1.35
RSF20	40.1	1.03	1.45

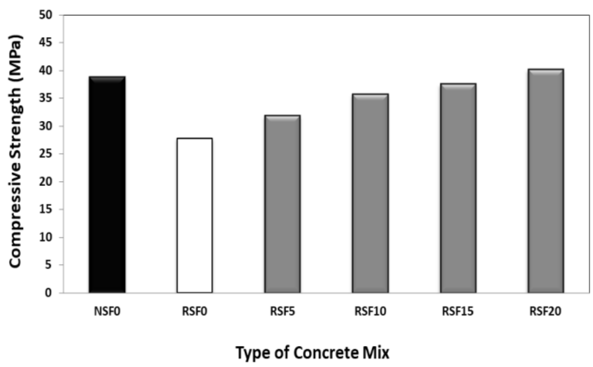

Figure 7. Results of compressive strength of all mixes

Table 6 indicates that the usage of recycled coarse aggregate diminishes the strength of the concrete. For instance, the compressive strength of the mix NSF0 decreased form 38.8 MPa to 27.7 MPa when the NCA was replaced with RCA (mix RSF0). This means that the strength of concrete decreased by up to 29% when RCA was used (see Table 6). This decrease is due to the low performance of RCA as its particles are weak, porous and lighter than NCA; hence leading to lower compressive strength [3] [11].

The substitution of OPC with SF resulted in compressive strength (at 28days) improvement. The content of the silica fume had direct effect on the amount of strength improvement (see Figure 7). For example, the compressive strength of mix RSF0 improved from 27.7 MPa to 31.8, 35.7, 37.5 and 40.1 MPa, when the OPC was replaced with 5%, 10%, 15% and 20% of silica fume, respectively. These values, compared to that of mix RSF0, represent strength improvement of 14%, 29%, 35% and 45% for the mixes RSF5, RSF10, RSF15 and RSF20. Therefore, by replacing OPC with SF at content between 15-20 %, comparable strength to that of the NAC, can be achieved. The positive effect of silica fume on the strength performance of RAC was also reported by [13] [19]. The strength enhancement of the RAC due to the utilization of SF can be mainly attributed to the pozzolanic reaction and partly to the filling capability of this material because of it very small particles [20]. The chemical reaction of the SF (pozzolanic reaction) can result in more calcium silicate hydrate gel; resulting in a stronger concrete [6] [13] [11]. Furthermore, owing to its fine-particles, silica fume has the potential to play a crucial role in filling the micro-voids and pores of the surface of the RCA and in adjusting the microstructure of the concrete; hence leading to denser concrete. Certainly, such mechanism can help in improving the density of the concrete and; thus enhancing concrete's compressive-strength [21] [22] [23].

3.3. Results of Splitting Tensile Strength

Three concrete samples with cylindrical shape were assessed to evaluate the splitting ensile strength for each mix. The results (average of 3 samples) from concrete mixtures are presented in Table 7 and depicted in Figure 8. Normalized values of the splitting tensile strength are employed to make a comparison between results of all other mixes and results of the two reference mixes, SF0 and RSF0.

Table 7. Splitting tensile strength results including normalized values (compared to SF01 and RSF02)

Mix	Splitting tensile		
	Strength MPa	Normalized[1]	Normalized[2]
NSF0	3.30	1.0	-
RSF0	2.77	0.84	1.0
RSF5	2.86	0.87	1.03
RSF10	3.14	0.95	1.13
RSF15	3.26	0.99	1.18
RSF20	3.57	1.08	1.29

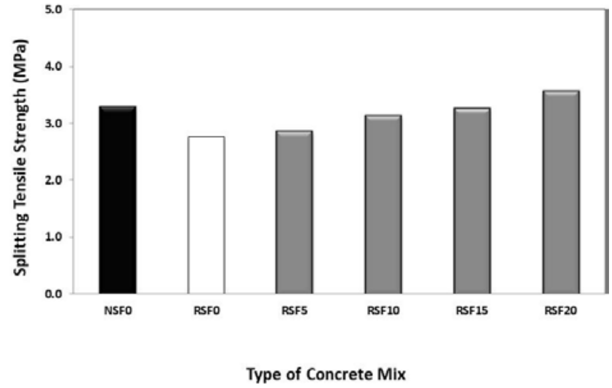

Figure 8. Results of splitting tensile strength

Just as the trend of the outcomes of the compressive strength, the results of splitting tensile strength show lower values for mixes without SF and comparable or larger values for mixes with SF. It is clear from Table7, that mix RSF0 which is made with RCA had splitting tensile strength of 2.77 MPa, whereas mix NSF0 showed strength value of 3.3 MPa. This means that when the NCA was replaced with RCA, the splitting tensile strength of the concrete decreased by up to 16% (see normalized value in Table 7). This reduction is attributed to the low characteristics of RCA such high porosity and low density [13] [18].

Figure 8 shows that when SF was used, enhancement in the splitting tensile strength was observed. For instance, when 5%, 10%, 15% and 20% of SF were used instead of the OPC, the splitting tensile strength increased by 3%, 13%, 18% and 29%, respectively, comparing to the strength of the mix RSF0. Also, comparable (to that of mix NSF0) splitting tensile strength was achieved at SF content of 15% and higher by 8% at SF content of 20% (see Table 7). Hence, silica fume at contents of 15-20 % can be used instead of OPC to obtain RAC that has similar strength in splitting tensile to that of the mixture made with NCA. The improvement in splitting tensile strength can be associated with the pozzolanic reaction and filling ability of SF [13]. The filling ability of the small particles of the SF can reduce the negative effect of the micro-cracks on the RCA; resulting in better splitting tensile strength for the RAC [22-25].

3.4. Results of Flexural Strength

Three prisms were tested under bending to evaluate the tensile strength in flexural for all mixes after 28 days of water curing. The outcomes (average of 3 samples) are illustrated in Table 8 and Figure 9. Normalized values of flexural strength are employed to make a comparison between results of mixes with the results of the two reference mixes, NSF0 and RSF0.

Table 8. Flexural strength results including normalised values (compared to SF0[1] and RSF0[2])

Mix	Flexural Strength		
	Strength MPa	Normalized[1]	Normalized[2]
NSF0	4.27	1.0	-
RSF0	3.60	0.84	1.0
RSF5	3.75	0.88	1.04
RSF10	4.14	0.97	1.15
RSF15	4.24	0.99	1.18
RSF20	4.49	1.05	1.25

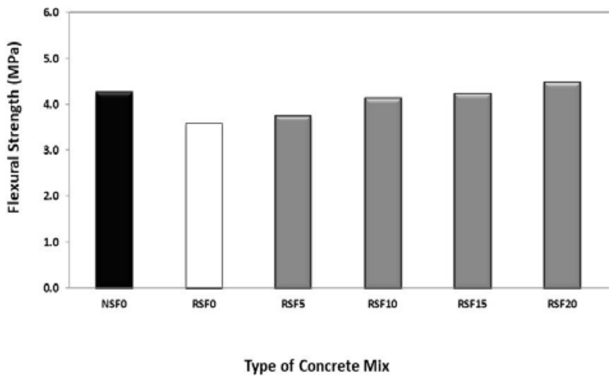

Figure 9. Results of the flexural strength of all mixes

From Table 8, it can be said that the trend of the outcomes of both compressive strength and the flexural strength are alike. The flexural strength of natural aggregate concrete (mix SF0) declined from 4.27 MPa to 3.60 MPa when recycled coarse aggregate was used (mix RSF0) as cane be seen in Figure 9. This decrease in flexural strength of mix RSF0 is about 16% lower than that of the mix SF0. The decline in this strength can also be attributed to the same weaknesses of the RCA mentioned in section 3.2 and 3.3. Similar to the case of the splitting tensile strength, the addition of SF had a beneficial effect on the flexural strength of the mixes made with RCA. The flexural strength increased from 3.6 MPa (for mix RSF0) to 3.75, 4.14, 4.24 and 4.49 MPa when 5%, 10%, 15% and 20 % of OPC was replaced with SF, respectively. In another word, the addition of 5%, 10%, 15% and 20 % of SF increased the flexural strength by 4%, 15%, 18% and 25%, respectively in comparison with mix RSF0 as can be seen in Table 8. Also, flexural strength that is comparable to that of the mix NSF0 can be attained for the mixes with RCA if SF is added at content of 10-20 % of the OPC. This enhancement in the flexural strength of the RAC due to the inclusion of SF can be associated to the pozzolanic reaction [11] [13] [20].

4. Conclusions

The discussion on the outcomes obtained in current research can lead to these conclusions:-

- As a result of its high capacity to absorb water, high porosity and its rough surface, recycled aggregate (coarse) diminish the workability of concrete. The inclusion of SF increases this diminish in the workability of the RAC due to the high surface area of its particles. The decline in the workability can reach 50%.
- All strengths decrease when RCA is used. The diminish in the compressive strength, tensile strength and flexural strength is about 29%, 16% and 16% respectively. The weaknesses of the recycled-coarse aggregate are the key reason for this behavior.
- Replacing OPC with silica fume possess a beneficial influence on compressive strength, splitting tensile strength and flexural strength of RCA mixtures. The pozzalnic reaction of the SF particles is the prime reason behind the strength enhancement.
- Close strength to that mixture incorporating NCA will be obtained if silica fume is replaced with OPC at contents between 10-20%. Thus, the use SF can encourage the utilization of recycled coarse aggregate.

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