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Mechanical Properties of Recycled Aggregate Concrete Incorporating Silica Fume

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ABSTRACT

Concrete properties are usually worsened by the use of high percentages of recycled aggregates of concrete. This paper addresses the efficiency of using recycled concrete as an aggregate by systematically presenting results on the influence of silica fume on recycled aggregate concrete (RAC) properties. The percentages of recycled aggregate replacements of natural aggregate used by weight were 0, 50, and 100%. Silica fume was used as 5, 10, and 15% by weight replacement of cement. The results showed that Recycled aggregate concrete is successfully produced of grade 40/50 MPa using local recycled aggregate. The compressive and tensile strengths values of the RCA increased as the recycled aggregate and the silica fume contents increased. Furthermore, the results indicate that one of the practical ways to utilize a high percentage of recycled aggregate (50%) in structural concrete is by incorporating 5% of silica fume in RAC.

INTRODUCTION

The use of waste materials as a source of aggregate in new construction materials has become more common in recent decades. The depletion of the existing landfills and the scarcity of natural resources for aggregates encourage the use of construction and demolition waste as a source of aggregates in the production of new concrete. The effects of using recycled aggregate as a partial or complete replacement of natural aggregate in concrete are well understood and extensively documented.

Many attempts to develop high-grade uses of construction waste, i.e., as aggregate for the manufacturing of new concrete, are reported in the literature (Topcu and Guncan 1995; Collins 1996; Tavakoli and Soroushian 1996). A decrease in the compressive strength was generally observed in all concretes in which the natural coarse aggregate was replaced with recycled aggregate prepared by the crushing of old concrete. The mechanical properties of the concrete decreased with the increase in the proportion of aggregate replaced (Topcu and Guncan 1995; van Acker 1996; Teranishi et al. 1998). Incorporation of fine aggregate from crushed concrete in the production of new concrete leads to an even greater decrease in the mechanical properties (Hansen and Marga 1988).

Sri Ravindrarajah and Tam (1988) improved the properties of new concrete by altering the water/cement ratio, adding pozzolans, and blending recycled and natural aggregates. These techniques, however, refer to general concrete technology and not to the improvement of the recycled aggregate itself. Montgomery (1998) treated the aggregate with a ball mill in order to remove old cement paste from natural stone. He found that the cleaner the aggregate was, the stronger was the concrete. Winkler and Mueller (1998) and Montgomery (1998) milled recycled fines and used them as a cement replacement. A reduction of 17% in the compressive strength of the concrete, at a replacement ratio of 33%, is reported by Montgomery.

Otsuki et al. 2003 reported that the carbonation resistance of recycled aggregate concrete was inferior compared to that of natural aggregate concrete. Finally, the drying shrinkage and creep of recycled aggregate concrete was found to be higher than those of natural aggregate concrete (Tavakoli and Soroushian 1996; Gomez-Soberon 2003).

Poon et al. 2004 showed that the slump of recycled aggregate concrete was dependent on the moisture state of the recycled aggregate. When oven dry recycled aggregate was used, a high initial slump was observed due to the high amount of water that was used to compensate for the high water absorption of the recycled aggregate. Cho and Yeo 2004 found that, due to the high water absorption of the recycled aggregate, a higher slump loss was observed when compared to that of natural aggregate concrete.

The effects of fly ash on the compressive strength, tensile splitting strength, static modulus of elasticity, drying shrinkage, creep, and resistance to chloride ion penetration on the recycled aggregate concrete were investigated Shi Cong Kou; et al 2007. The results showed that the compressive strengths, tensile strengths, and static modulus of elasticity values of the concrete at all ages decreased as the recycled aggregate and the fly ash contents increased. Further, an increase in the recycled aggregate content decreased the resistance to chloride ion penetration and increased the drying shrinkage and creep of concrete. Nevertheless, the use of fly ash as a substitute for cement improved the resistance to chloride ion penetration and decreased the drying shrinkage and creep of the recycled aggregate concrete.

There is a rapid emerging public concern that can no longer be overlooked, the environmental pollution problems on the one hand and the unlimited depletion of natural resources on the other. A suitable resolution of this concern is essential because, if not resolved, it presents a clear threat to our standards of living and, more importantly, to the entire fabric of the life support systems on which the planet earth is dependent.

The solution to this environmental problem is not to replace concrete with other materials but to reduce the environmental impact of concrete and cement. Again, even a small reduction of the environmental impact per tones of concrete will result in large environmental benefits because of the vast amount of concrete being produced. To move toward the goal of sustainable development, it is imperative that a judicious balance be struck between the two equally important needs of society, namely the infrastructure to support an acceptable standard of living for most of the people in the world, and the protection of the environment. The concrete industry, being an important player in the infrastructural development and a major consumer of natural resources of the earth, needs to be reoriented through the adoption of environment-friendly technology. In other words, the solution to the problem lies in the evolution of “Green Concrete” to implement sustainability in the concrete industry.

Concrete with recycled materials: important way of enhancing the environmental performance of concrete is to use recycled materials in its production. This reduces the depletion of natural reserves of these aggregates. Moreover, such concrete utilizes waste that otherwise will be stored in landfills. The major drawback of these types is that they are normally lower in strength.

It has been shown from previous research studies that some of the drawbacks of recycled aggregate concrete are the lower strengths, the higher drying shrinkage and creep and lower resistance to chloride ion penetration compared to those of conventional concrete. But this shortcoming can be improved by incorporating a certain amount of silica fume into the concrete mixture as silica is known to be able to enhance the mechanical and transport properties concrete. However, silica fume can be used as a replacement for cement or as an additional cementitious material in concrete. The different applications of silica fume produce concrete with totally different properties. In this paper, the results of the use of silica fume as a cement replacement or an addition in proportioning the recycled aggregate concrete are presented. The effects of silica fume on the compressive strength and tensile splitting strength, of the recycled aggregate concrete were investigated.

MATERIALS AND TESTS

Cement and silica fume

Ordinary Portland cement(equivalent to ASTM Type I) with 3.16 gm/cm^3 density was used, constant level of cement content 400 kg/m^3 was used in this work. Silica fume with 2.2 gm/cm^3 density, 25.5 m^2/gm specific surface area, and 97.5% $SiO2$ content was used at different levels as partial replacement of cement content.

Aggregates

Natural Normal weight and recycled aggregates were used as the coarse aggregate in the concrete mixtures. In this study, crushed stone was used as the natural aggregate and recycled aggregate sourced from a recycling facility in the Kingdom of Saudi Arabia (KSA) was used. According to the quality control requirements of the recycling facility, the recycled aggregate contained less than 0.5% by weight of wood and particles less dense than water and less than 1% by weight of other foreign materials. Therefore, the recycled aggregate used in this study could be considered as recycled concrete aggregate. The nominal sizes of the natural and recycled coarse aggregates were 20 mm and their particle size distributions conformed to the requirements of ASTM C-33. The physical and mechanical properties of the coarse aggregate are shown in Table 1. The porosity of the aggregates was determined using mercury intrusion porosimetry. Fine clean sand was used as the fine aggregate in the concrete mixtures.

Superplasticizer

For the concrete mixtures, a sulfonated naphthalene formaldehyde condensate was used. This superplasticizer is available as a dark-brown 40–42% solids aqueous solution with a density of 1,210 kg/m^3. This chemical admixture was used to control the slump at 120 mm ± 25 mm.

Concrete Mixtures

All concrete mixtures with target initial slump of 120mm were prepared in the laboratory. The concrete mixtures were prepared with a water-to-binder W/B ratio and a cement content of 0.45 and 400 kg/m^3, respectively. In this study, silica was used as 5, 10, and 15% by weight replacements of cement and recycled aggregate was used as 0, 50, and 100% by weight replacements of the natural coarse aggregate. The absolute volume method was adopted to design the mix proportions of the concrete mixtures as shown in Table 2. In the concrete mixtures, the 10 and 20 mm coarse aggregates were used in a ratio of 1:2.

Table 1. Properties of natural and recycled aggregates.

Type	Specific Gravity	N.M.S	Water Absorption (%)	Porosity (%)	L.A Abrasion Value
Natural agg.	2.65	20	1.17	1.58	4.3-5.2
Recycled agg.	2.47	20	5.3	7.8	13-16.3

Specimens Casting and Curing

For each concrete mixture, three 150 mm cubes, and 150x300 mm cylinders were casted. The cubes and cylinders were used to determine the compressive strength and to evaluate the tensile splitting strength, respectively. All the specimens were cast in steel molds and compacted using a vibrating table. The specimens were demolded and cured in a water-curing tank at 27±1°C until the age of testing.

Table 2. Mix proportions

Mix No.	Silica fume (%)	R.C.A (%)	Constituent Materials (kg/m^3)					
			Natural Coarse Agg.	R.C.A	Sand	Cementitious materials		Water
						OPC	CSF	
1	0	0	1100	0	710	400	0	180
2	0	50	550	535	710	400	0	180
3	0	100	0	1070	710	400	0	180
4	5 rep	0	110	0	710	380	20	180
5	5 rep	50	550	535	710	380	20	180
6	5 rep	100	0	1070	710	380	20	180
7	10 rep	0	1100	0	710	360	40	180
8	10 rep	50	550	535	710	360	40	180
9	10 rep	100	0	1070	710	360	40	180
10	15 rep	0	1100	0	710	340	60	180
11	15 rep	50	550	535	710	340	60	180
12	15 rep	100	0	1070	710	340	60	180
13	10 add	0	1100	0	710	400	40	220
14	10 add	50	550	535	710	400	40	220
15	10 add	100	0	1070	710	400	40	220

Compressive and Tensile Splitting Strengths

The compressive and splitting tensile strengths of concrete were conducted following the B. S. 1881.52, and ASTM C-496, respectively. The tests were determined using a testing machine with a loading capacity of 3,000 kN. The loading rates applied in the compressive and splitting tensile tests were 200 and 57 kN/min, respectively. The compressive and splitting tensile strengths were measured at the ages of 3, 7, 14, and 28 days.

RESULTS AND DISCUSSIONS

Experimental results of the use of silica fume as a cement replacement or as an addition in proportioning the recycled aggregate concrete are presented. The effects of using different percentages of R.C.A as a partial replacement of natural coarse aggregate at different levels of silica fume are investigated in terms of the compressive and tensile splitting strengths. The cement content was 400 kg m^3. The average test results are reported in Tables 3 and 4.

Strength development:

The behavior of natural and recycled aggregate concrete under compression up to 28 days was plotted in Figure 1. From these figures, it is clear that the compressive strength increases gradually with increasing the hydration age, where the rate of strength gaining increased by nearly constant rate up to 28 days for all R.C.A contents (0, 50, 100 %) at all levels of silica fume. Generally, as an outcome for increasing the amount of hydration products resulting from the hydration of the cement phases which is responsible for the ultimate strengths. Similar behavior was observed for tensile strength results as illustrated in Figure 2.

Table 3. Experimental program & test results for silica fume replacement.*

SF Replacement (%)	Recycled Concrete Aggregate (%)	Compressive Strength (MPa)				Tensile Strength (MPa)			
		Test Age (days)							
		3	**7**	**14**	**28**	**3**	**7**	**14**	**28**
0	0	27.44	30.46	36.60	47.73	2.20	2.41	2.91	3.63
	50	25.23	31.68	33.07	39.43	2.02	2.51	3.21	3.55
	100	24.42	33.33	38.47	50.41	1.71	2.57	2.79	3.10
5	0	21.75	27.81	34.47	42.71	1.95	2.60	3.17	3.23
	50	28.03	32.78	40.53	46.76	2.29	2.69	2.89	2.99
	100	33.83	45.14	49.54	53.46	2.79	3.46	3.55	4.23
10	0	25.46	33.83	42.15	51.72	2.34	2.98	3.40	3.69
	50	25.59	32.25	36.15	41.79	2.05	2.59	2.68	2.73
	100	29.20	34.08	41.45	47.78	2.64	3.26	3.39	3.51
15	0	23.12	31.26	37.57	44.54	2.33	2.74	3.01	3.34
	50	26.65	35.34	42.38	50.09	2.30	2.78	2.96	3.97
	100	28.81	33.69	38.50	47.55	2.45	2.52	3.11	3.28

* Three samples were conducted for each test condition.

Table 4. Experimental program & test results for silica fume addition.*

SF Addition (%)	Recycled Concrete Aggregate (%)	Compressive Strength (MPa)				Tensile Strength (MPa)			
		Test Age (days)							
		3	**7**	**14**	**28**	**3**	**7**	**14**	**28**
10	**0**	33.03	40.16	43.45	48.63	2.80	2.98	3.19	3.75
	50	31.82	39.50	44.24	40.25	2.96	3.24	3.31	4.00
	100	30.84	40.65	47.55	53.34	2.47	3.01	3.07	3.58

*Three samples were conducted for each test condition.

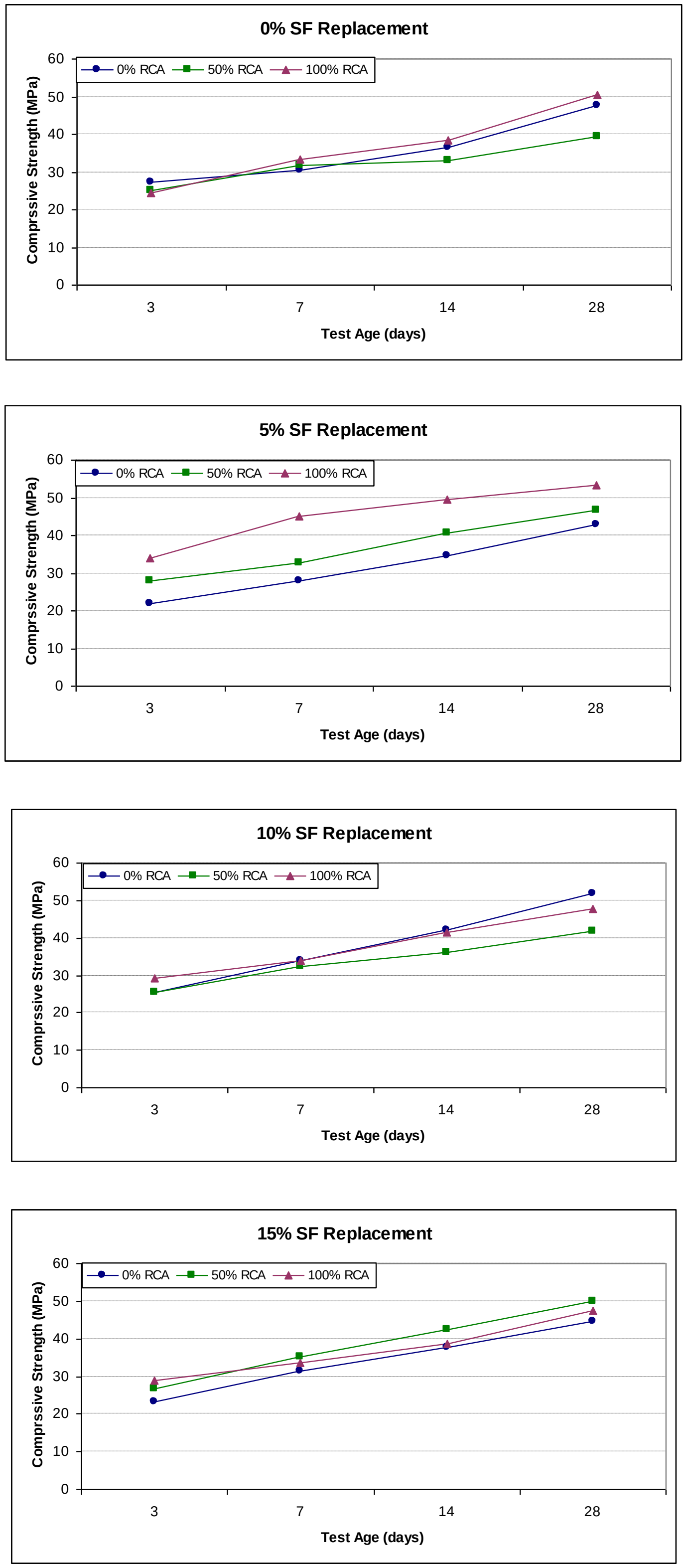

Figure 1. Development of compressive strength for RAC concrete has different recycled aggregate contents.

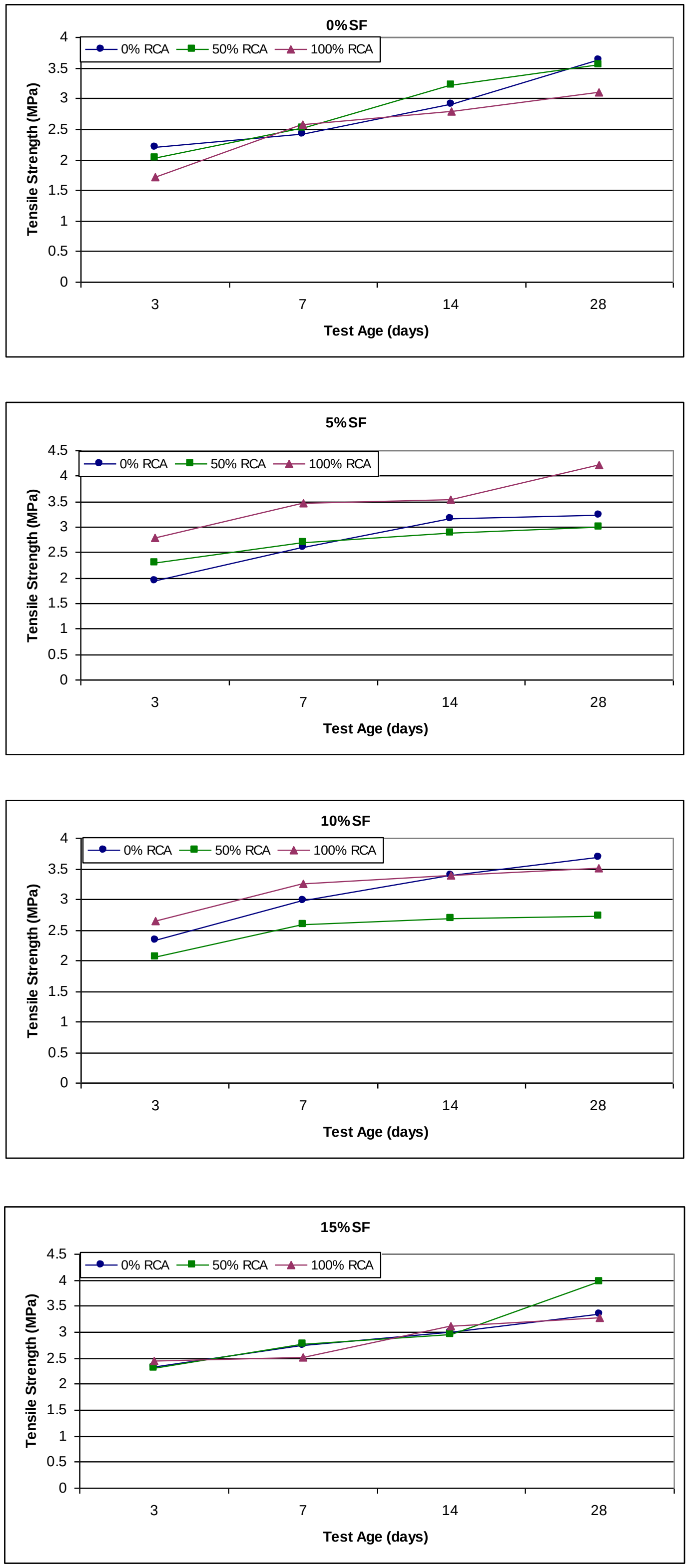

Figure 2. Development of tensile strength for RAC concrete with different recycled aggregate contents.

It was observed that the rate of strength gaining increased by a constant rate as the devolvement compressive strength up to 28 days for all levels of R.C.A contents (0, 50, 100 %) at all levels of silica fume. As the tensile strength of concrete is very much affected by the interfacial transition zone between the aggregate and the cement matrix, the variability of the surface texture of the recycled aggregate was probably the main reason which caused the paradoxical results. However, additional research effort is needed to clearly explain this phenomenon.

Finally, the recorded variation on the development of RCA compressive and tensile splitting strengths depend on the rate of reaction between silica fume and concrete alkali contents and also may be due to high surface reactivity of the recycled concrete which has surface carbonation characteristics, as a result form the reaction of cement free lime ($ca(oh)_2$) with atmospheric carbon dioxide (CO_2) forming calcium carbonate $CACO_3$. So the calcium ion is ready to react with the active amorphous silica forming more than calcium hydrate (C-S-H) resulting more bond strength (Shi Cong Kou, et. al., 2007).

Effect of silica fume

Modification of the interfacial transition zone between the aggregates and the bulk matrix of concrete using silica fume is a common technique applied nowadays to improve concrete properties. The effect of using silica fume as a partial replacement of cement (0, 5, 10, and 15%) at different levels of RCA content on 28-days compressive and splitting tensile strength are represented in Figures 3 and 4. The figures explained that using silica fume as a partial replacement or as an addition of cement content similar behavior of recycled concrete was observed up to 28 days and the rate of strength gaining is nearly the same and equal to 80%, and it was found also that the compressive and tensile strengths are varied according to the content of RCA, this mainly depends on the quality of RCA which is related to the surface reactivity of RCA which has surface carbonation characteristics varied according to crushing method and subjected to atmospheric carbon dioxide. A positive effect when using 5% silica fume as a partial replacement of cement in concrete mix containing 100% RCA, this mainly due to the role of the recycled concrete aggregate as a water reservoir to assist later hydration of cement, as shown in Figures 5 and 6.

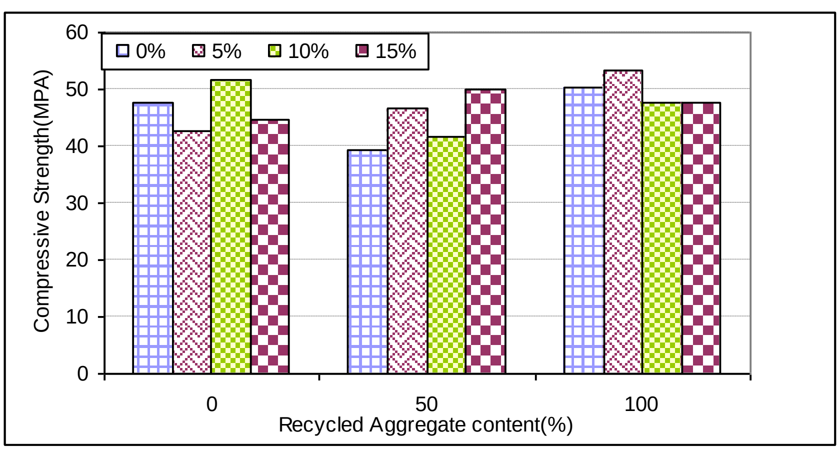

Figure 3. Effect of S.F as cement replacement on compressive strength of different recycled aggregate contents at 28-day.

Using SF as an addition by about 10% of cement content seems to be improve significantly the compressive strength compared with 0% SF at all levels of RCA as shown in Figures 7 and 8. For example this improvement was ranged from 23 to 25% at 3 and 7 days respectively, while at 28 days reached a lesser extent of 5%. It seem that the SF has better effect on strengths at early ages than later ages, this may attributed to the increasing in the density of the cement matrix near the recycled aggregate and improving the composite effect of the material when the new cement matrix is relatively weak. At a later age, the new cement matrix becomes stronger than the recycled aggregates and lesser improvement in strength is observed.

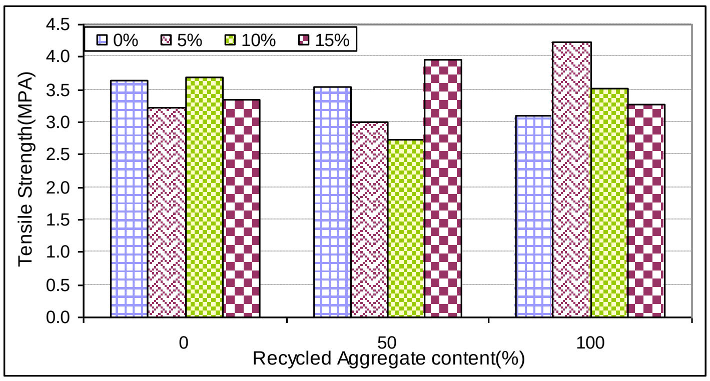

Figure 4. Effect of S.F. as cement replacement on Tensile strength

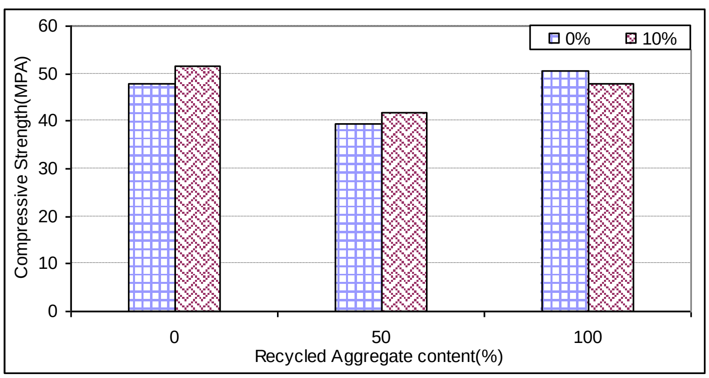

Figure 5. Effect of S.F. as an addition to cement on compressive strength

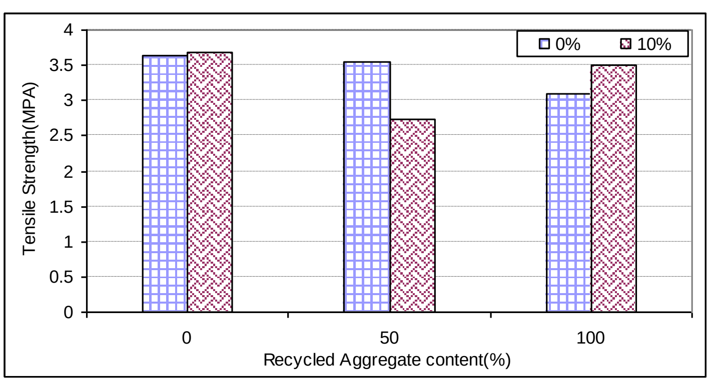

Figure 6. Effect of S.F as an addition to cement on Tensile strength

Similar observations were recorded, where it was found that the splitting tensile strength enhanced by using 10% silica fume as an addition rather 0% or even 5% SF replacement for mixes containing 0% & 50% recycled concrete aggregate and slightly effect was observed at 100% RCA.

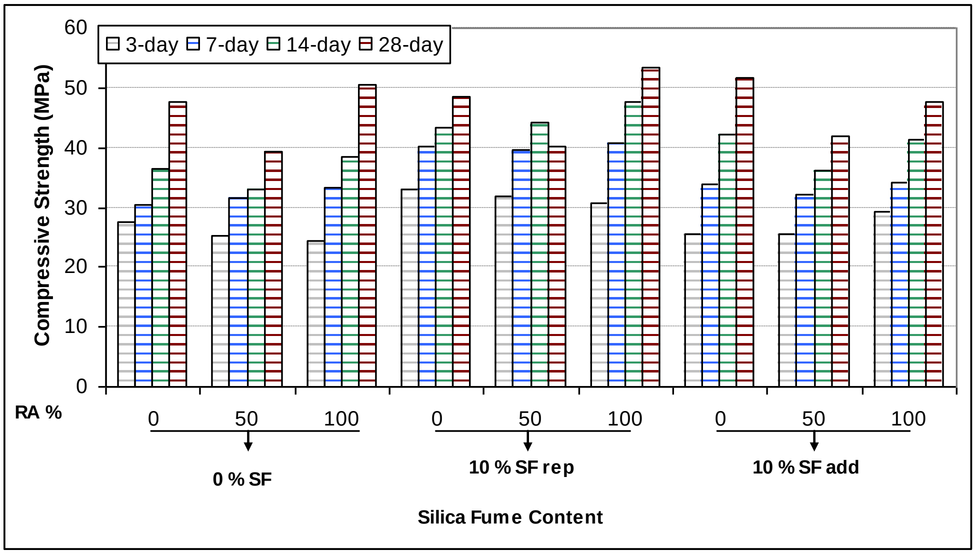

Figure 7. Development of compressive strength for recycled aggregate concrete.

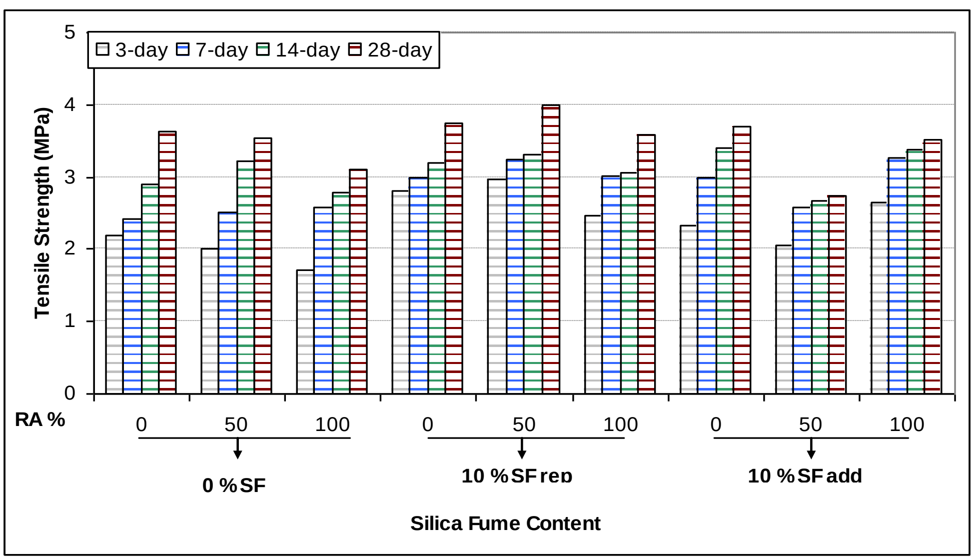

Figure 8. Development of tensile strength for recycled aggregate concrete.

It can be summarized that silica fume improves the properties of recycled made from recycled concrete in two ways: (1) by improving the interface between the RCA and new cement matrix; (2) by strengthening the structure of the old paste that is still adhered to the RCA, which has cracked during the crushing process, in the other words silica fume acts as a microfiller, filling the transition zone between the aggregate surface and the bulk of cement matrix, followed by a pozzolanic reaction at the same place. When porous aggregate is involved, as lightweight aggregate or the RCA used in this study, the interfacial transition zone extends from a certain distance below the surface of the aggregate out the bulk cement matrix.

CONCLUSIONS

Based on the results of this study, the following conclusions may be deduced:

- Recycled aggregate concrete is successfully produced of grade 40/50 MPa using local recycled aggregate.
- The compressive strength and tensile splitting strength varied according to the quality of RCA and its crushing process.
- 5% SF, as a partial replacement and 100% recycled aggregate content give best combination for RAC as compressive and splitting tensile strengths values was observed at all ages.
- At the same recycled aggregate replacement level, the use of silica as a partial replacement of cement was able to enhance concrete strength as a result of the greater long term strength development due to the pozzolanic reaction of silica fume.
- 5- RCA acting as a water reservoir to assist later hydration of cement, while its surface carbonate makes it as limestone filling materials with some chemical reactivity.

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