Effect of Recycled Aggregate Concrete and Steel Fibers on the Strength of Self-Compacting Concrete

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Abstract. The accumulation of waste materials in landfills without treatment threatens public health and the environment. The quantity of solid waste continually increases, causing environmental pollution. One of these wastes that should receive scientific treatment is concrete waste. The use of concrete waste as fine or coarse aggregate in self-compacting concrete (SCC) is one of the useful solutions to this problem. This study aims to reuse concrete waste as coarse aggregate in the production of SCC and find out the influence of different steel fiber contents on the strength of SCC. The steel fibers (SF) were used to reinforce SCC in three different volumes (0, 0.5, and 1 % of concrete volume), and the recycled coarse aggregate (RCA) was used to replace natural coarse aggregate (NCA) in five replacement levels of 0, 25, 50, 75, and 100%. The compressive and tensile strengths of the SCC specimens in the hardened state were determined. The results of the experimental study refer to the steel fiber having a positive effect on the enhancement of mechanical properties, particularly the tensile strength of SCC. The addition of 50% recycled aggregates in the concrete mix contributed to increasing the compressive strength by about 20%. Therefore, it can be said that the dual use of recycled aggregates with steel fibers produced concrete with high specifications compared to ordinary concrete. Another positive effect lies in the disposal of concrete waste, which contributes to an economic return in addition to reducing the effect on the environment.

Keywords: Waste materials; self-compacting concrete; steel fibers; recycled aggregates; compressive strength; tensile strength.

1. INTRODUCTION

Concrete is the main building material that is used in most construction projects worldwide [1]. The demand for concrete increases with time due to the growth of the population, especially to fulfill the increased requirements of new residential and commercial buildings as well as significant infrastructure projects [2]. Some areas of the construction are difficult to fill with concrete, and to solve this problem, another type of concrete, self-compacting concrete (SCC), has been adopted when concrete is thrown from high places [3,4]. On the other hand, the increased production of concrete to fulfill the construction markets has generated a huge amount of concrete waste that might hurt the environment when accumulated in huge quantities. Therefore, to solve this problem, scientists and researchers have used these wastes as concrete aggregates (either fine or coarse aggregates) to mitigate the use of natural aggregates and protect the environment from the depletion of natural sources [5, 6]. The use of recycled fine and coarse aggregate instead of natural aggregate mainly enhances sustainability in the construction industry and produces eco-friendly concrete [7, 8]. The researchers used steel fiber to stop the growth of cracks in reinforced concrete and enhance the low tensile strength of concrete [9, 10].

Silva [11] studied the effect of using recycled aggregates on self-compacting concrete (SCC) by adding mineral residues extracted from construction waste. The results showed, to an acceptable extent, that the recycled coarse aggregate reduced the mechanical properties of SCC. Nili [12] proved that when adding SF to the SCC mix, contributes to improving the strength properties despite its negative impact on its fresh properties. The results of the study conducted by Abed [13] showed that recycled concrete aggregate (RCA) does not harm the new properties of self-compacting high-strength concrete (SCHSC) and that the use of RCA can improve the mechanical properties of concrete that contains recycled aggregate. Zhang [14] used SF and polypropylene fibers (PP) in recycled aggregate concrete to produce SCC. They found that the addition of steel fibers to concrete had a significant synergistic effect, resulting in the improvement of the mechanical properties of SCC. However, few studies investigated the effect of both SF and RCA on the strength of SCC and how to improve the properties of SCC due to the use of recycled aggregate. Therefore, in this study, the RCAs were used to replace natural coarse aggregate at different replacement levels, and the SFs were used in three different proportions to improve the strength of SCC and reduce the development of cracks that occur on the concrete surface.

2. MATERIALS USED AND EXPERIMENTAL PROGRAM

2.1 Materials

Ordinary Portland Cement (OPC) (type I) was used for all the concrete mixtures, with a specific gravity of 3.15 and a fineness of 295 m^2/kg. Class F fly ash (FA) and silica fumes (SC) were used in the SCC mixes as binder additives. The chemical compositions of OPC, SC, and FA that satisfied ASTM standard requirements are listed in Table 1.

Table 1: Chemical analysis of cement and binder additives.

Oxide (%)	OPC	FA	SC
SiO_2	19.11	55.67	93.2
Fe_2O_3	3.37	12.96	1.5
CaO	66.26	5.11	0.4
Al_2O_3	6.42	20.73	0.7
MgO	1.45	2.65	0.1
SO_3	2.31	0.34	0.1
Na_2O+ K_2O	1.08	2.54	1.4
Specific gravity	3.15	2.10	2.2

The natural coarse aggregates (NCA) and natural fine aggregates (NFA) used in all concrete mixes were collected from the same source with a specific gravity of 2.60 and 2.65, with water absorptions of 1.52 and 3.80%, respectively. The sieve analysis and physical properties for coarse and fine aggregates were listed in Tables 2 and 3. The recycled coarse aggregate (RCA) manufactured by the residual concrete block was collected from concrete block factories. The sieve analysis and physical properties of recycled coarse aggregate are listed in Table 3.

Table 2: Sieve analysis of NFA.

Sieve Size (mm)	Percentage passing (%)	ASTM C136-06 limits (%) [15]
4.75	100	95-100
2.36	92	80-100
1.18	79	50-85
0.6	45	25-60
0.3	23	10-30
0.15	4	0-10

Table 3: Sieve analysis of NCA and RCA.

Sieve Size (mm)	Percentage passing (%)		ASTM C136-06 limits (%) [15]
	NCA	RCA	
12	100	100	90-100
9.5	61	46	40-70
4.75	12	7	0-15
Pan	2	4	0-5

Steel fibers (SF) were used to produce fiber-reinforced self-compacting concrete (FR-SCC). Micro-corrugated steel fibers with an aspect ratio of 65 were used, and it was taken into account that their addition had different proportions and effects on the fresh and hardened properties of the FR-SCC. The properties of the SF utilized in the present study are shown in Table 4. To obtain SCC conforming to the specifications, a superplasticizer (SP) with a 1.5% percentage was added to increase the flow ability of the concrete mixtures.

Table 4: Properties of steel fiber (SF) used in the present study.

Material	Low steel wire, copper-coated
Diameter	0.2 mm
Length	12-14 mm
Tensile strength	≥2850 MPa
Feature	Excellent tensile, bending, and shearing strength, resistance against cracking, impact, and fatigue

Fifteen SCC mixtures were prepared: three steel fiber (SF) proportions of 0, 0.5, and 1% and five coarse aggregate replacement ratios of 0, 25, 50, 75, and 100% for each desired strength. After 28 days, all concrete mixtures' compressive and tensile strengths were tested in the experimental program.

2. Mix Proportion

The SCC mix design is different if compared to normal concrete because of the various filling and placing methods. The EFNARC method was used in mix design for all SCC mixtures [16]. All the SCC mixtures have been compared with a reference mix. The recycled coarse aggregate (RCA) was used to replace natural coarse aggregates by 0, 25, 50, 75, and 100%. At the same time, the steel fibers have been added to enhance and reinforce the SCC mix by 0, 0.5, and 1.0%, as illustrated in Table 5.

Table 5**:** Mix design proportion in unit kg/m^3.

Mix Code*	OPC	FA	SC	Water	w/c	w/b	NFA	NCA	RCA	SP
RC00SF#	350	100	50	200	0.57	0.4	730	900	0	1.5%
RC25SF#								675	230	
RC50SF#								450	460	
RC75SF#								225	654	
RC100SF#								0	873	

* # means each mix contains three percentages of SF (0, 0.5, 1.0%).

2.3 Mixture Preparation and Casting

According to the mix preparation given in Table 5, the quantities of materials required for one batch were calculated. Fine aggregate and coarse aggregate with steel fibers were first mixed for two minutes in a concrete mixer with the addition of about 20% water. Then, binder materials consisting of cement, fly ash, and silica fume were added to 60% of the water mixture. Then the remaining water was mixed with the superplasticizer and added to the mixture. To ensure that the mixture is homogeneous and that the fibers do not clump, the mixture is rotated for 4-5 minutes. After the mixing procedure is completed, the required experiments with the mixture in its fresh state are performed to determine the fresh properties of the SCC mixture. As shown in Table 6, the obtained fresh property results conform to the EFNARC limitations [16]. Then, the test specimens are immediately cast without the use of vibrators. After 24 hours, the specimens are de-molded and placed in the treated water for 28 days until testing. Cubic specimens (100*100*100 mm) will be used to determine the compressive strength, and cylindrical specimens (100*200 mm) will be used to estimate the splitting tensile strength of each concrete mix, where the average will be taken from three readings of all strength results.

Table 6: The fresh properties result of FR-SCC mixtures used.

SF%	RC%	Mix code	Filling ability			Passing ability
			T50 slump (sec)	Slump (mm)	V-funnel (sec)	L-box
0.00	0	RC00SF00	1.80	740	3.83	0.94
	25	RC25SF00	2.83	690	5.33	0.90
	50	RC50SF00	3.73	675	9.65	0.86
	75	RC75SF00	2.17	685	6.50	0.89
	100	RC100SF00	3.06	590	9.08	0.91
0.50	0	RC00SF05	2.18	720	4.39	0.92
	25	RC25SF05	3.03	680	6.13	0.88
	50	RC50SF05	4.75	670	11.1	0.83
	75	RC75SF05	2.79	660	7.71	0.86
	100	RC100SF05	3.42	595	9.48	0.89
1.00	0	RC00SF10	3.31	700	4.60	0.88
	25	RC25SF10	3.65	630	7.56	0.84
	50	RC50SF10	5.40	610	12.75	0.81
	75	RC75SF10	3.51	585	9.88	0.85
	100	RC100SF10	3.76	625	10.2	0.87
EFNARC limits			2-5 sec.	550-800 mm	≤ 10 sec.	≥ 0.75

3. STRENGTH PROPERTIES

The compressive and tensile strength results of the concrete used in the present study are presented in Table 7. These results represent an average reading of three specimens, where each value of the compressive strength values was the average of three cubes with dimensions (100*100*100 mm), and the tensile strength was an average of cylindrical specimens with dimensions (100*200 mm) for each concrete mixture. Tested using a universal machine pressure device. In general, the results showed a clear effect of recycled aggregates on the strength properties of the concrete in the present study.

Table 7: Strength properties of FR-SCC mixtures used.

SF (%)	RC (%)	Mix code	Strength Properties	
			Compressive strength (MPa)	Tensile strength (MPa)
0.00	0	RC00SF00	51.1	3.65
	25	RC25SF00	58.3	5.81
	50	RC50SF00	62.2	4.21
	75	RC75SF00	62.8	4.12
	100	RC100SF00	63.3	4.58
0.50	0	RC00SF05	55.3	4.52
	25	RC25SF05	54.7	6.92
	50	RC50SF05	70.4	5.75
	75	RC75SF05	67.7	5.26
	100	RC100SF05	64.8	7.5
1.00	0	RC00SF10	49.7	5.16
	25	RC25SF10	71.2	7.7
	50	RC50SF10	74.3	6.12
	75	RC75SF10	72.5	8.04
	100	RC100SF10	63.2	7.85

3.1 Compressive Strength
3.1.1 Effect of RCA on the Compressive Strength

According to the obtained practical results, the compressive strength increased gradually with the replacement percentage (RCA) increase compared to mixtures containing natural aggregates. This increase might be because the source of the recycled aggregate that was used in this research is the aggregate of concrete used in ready-casting and concrete block factories, where it is in the form of concrete blocks and heaps left aside. The focus was on not grinding or crushing the aggregate, unlike the recycled aggregate resulting from the demolition and rubble of residential buildings, to maintain the strength and durability of the aggregate. In addition to the fact that the reused aggregate was surrounded by concrete residues, which gave it sharp shapes to ensure increased bonding with the cement paste during the casting process, this contributed to obtaining an expected strength higher than that of natural aggregates. The highest compressive strength was achieved when replacing 50% of the natural coarse aggregates with recycled aggregates, as shown in Figure 1. After this percentage, the compressive strength gradually decreased as the replacement rate increased. To some extent, the compressive strength of concrete containing recycled aggregates was higher than that of concrete containing natural aggregate.

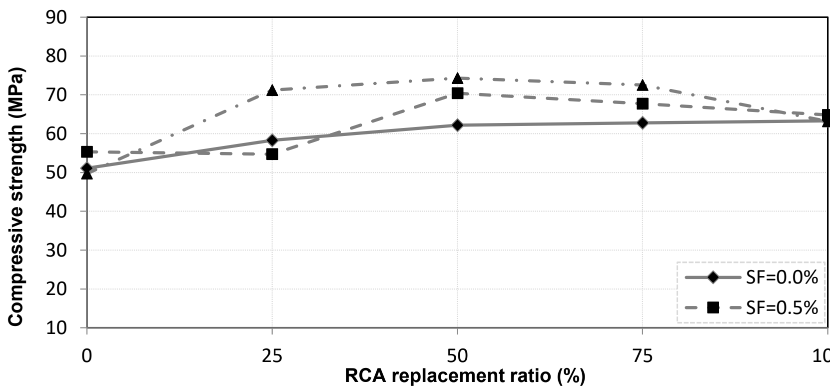

Figure 1: Effect of RCA on compressive strength.

3.1.2 Effect of Steel Fibers on Compressive Strength

To some extent, adding SF to the concrete mixtures containing natural aggregate did not improve the compressive strength of the concrete. This may be attributed to the fact that SFs contribute to reducing the workability of concrete. Fig. 2 shows the compressive strength of self-compacting concrete with and without SF, using different proportions of recycled aggregate. Increasing the percentage of steel fibers improved the compressive strength when replacing the natural aggregate with recycled aggregate. It was also observed that the compressive strength decreases gradually after increasing the replacement ratio to more than 50% for all steel fiber ratios, so it can be concluded that the replacement ratio of 50% represents the optimal replacement ratio for SCCs.

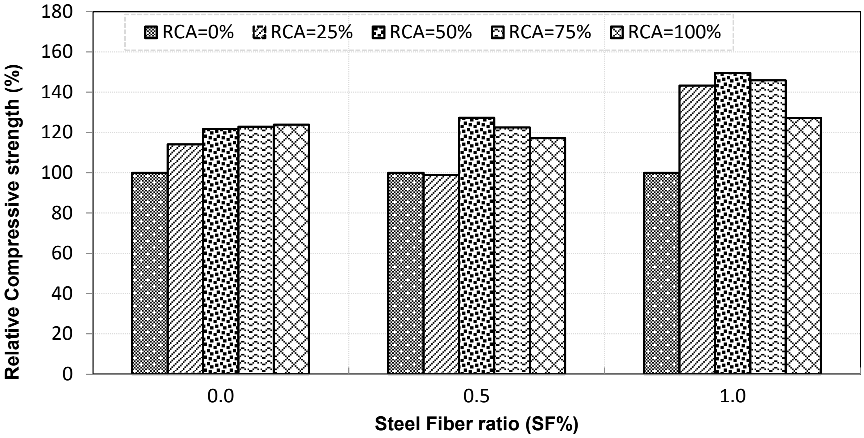

Figure 2: Effect of SF% on relative compressive strength**.**

3.2 Tensile Strength

3.2.1 Effect of RCA on the Tensile Strength

Figures 3 and 4 show the absolute and relative tensile strength results for all concrete mixtures that contain different recycled aggregate replacement ratios. In general, the results showed a relative increase in tensile strength when increasing the Proportion of replacing NCA with RCA, as shown in Figure 3. The improvement in tensile strength might be attributed to the increase in adhesion between the recycled aggregate particles and the concrete mortar due to the presence of sharp edges in the concrete residues that help increase the bonding. As well as containing recycled aggregate, it used a high percentage of cement, unlike the recycled aggregate resulting from the demolition and rubble of residential buildings.

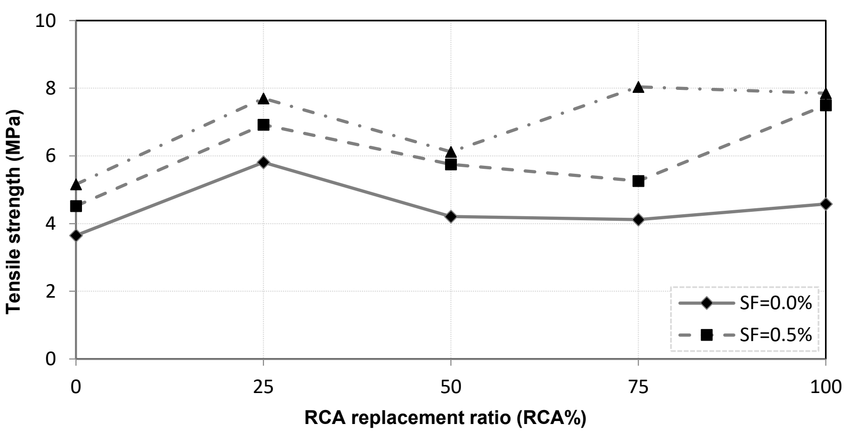

Figure 3: Effect of RCA on tensile strength.

3.2.2 Effect of steel fibers on the tensile strength

It can be said that the presence of SF played a significant role in improving tensile strength and all replacement ratios, as shown in Figure 4. The reason for this can be attributed to the fact that the steel fibers enhance the tensile strength through their ability to bridge cracks or prevent their development, thus reducing or preventing the occurrence of cracks under tensile load. Therefore, it can be concluded that the tensile strength of self-compacting concrete increases with the increase in the volumetric ratio of steel fibers (SF%).

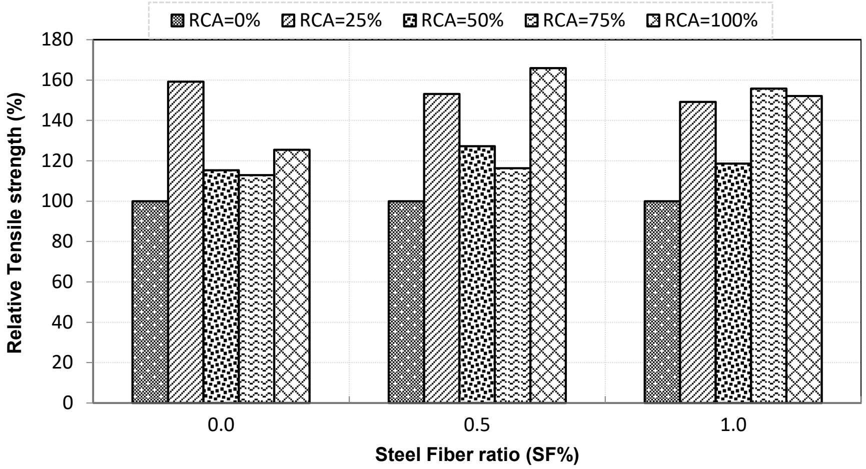

Figure 4: Effect of SF% on relative tensile strength.

4. CONCLUSIONS

This research was conducted to study the effect of replacing natural coarse aggregate (NCA) with recycled coarse aggregate (RCA) and the interaction of steel fiber addition (SF) on the fresh and strength properties of self-compacting concrete (SCC). The following conclusions were drawn from the results, and hardened properties were discussed:

- A clear improvement was observed for the concrete in its hardened condition when replacing the natural aggregate with recycled aggregate. The recycled aggregate used in this research is the aggregate of concrete used in ready-casting and concrete block factories. These aggregates are sharp and contain large quantities of cement, increasing bonding with the cement paste during the casting process. Also, the addition of steel fibers had a clear effect on improving the strength of concrete, as the steel fibers contributed to preventing or developing cracks in the hardened concrete upon loading.
- The results showed that the maximum compressive strength was reached using SF of 1.0% and RCA of 50%, and this may be the optimal ratio for replacement, while 1.0% of SF and 75% RCA can be the optimal tensile strength values obtained in 28 days.

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