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Influence of Superplasticizer Dosage on Workability and Mechanical properties of Concrete made with Recycled Aggregate

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Highlights:

- Discussion the effect of superplasticizer addition on the performance of recycled concrete.
- Investigation of effective dosages of superplasticizer.
- Exploration of the effect of superplasticizer dosage and water/cement ratio on RCA concrete performance.

Abstract. This study investigated the effect of adding a type of superplasticizer (polycarboxylate ether -PCE) on the workability and mechanical properties of concrete containing recycled coarse aggregate (RCA). The effect of increasing the PCE dosage while changing the water/cement ratio on RCA strength was also studied. To accomplish these goals, three groups of concrete mixtures were prepared. The variable in these groups was the water/cement ratio (0.53, 0.57, and 0.615). In each group, the natural aggregate was replaced by two proportions of RCA (50 and 100%) and different proportions of PCE were added for each replacement ratio. The findings encourage the use of PCE in recycled concrete. It was found that the addition of PCE improves the properties of recycled concrete in terms of workability and compactness. The addition of PCE also compensates for the compressive strength that is lost due to the replacement of natural aggregate with recycled coarse aggregate.

***Keywords**: admixture; mechanical properties; recycled aggregate; water/cement ratio; workability.*

1 Introduction

Recycled aggregate is a term used to describe aggregate resulting from concrete debris that is reused in construction. In recent years, the tendency to reuse recycled aggregate has increased in many countries, to benefit from it in the construction process, to preserve the environment, and prevent landfilling [1]. There are now special factories and crushers for crushing construction waste and then sorting and grading it according to the required sizes. Many studies have been conducted to investigate the effect of using recycled aggregate in concrete

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on its behavior, as this aggregate has a clear impact on its performance due to the different properties of recycled aggregate from natural aggregate. It is characterized by high absorption and high surface roughness and it is more angular than natural aggregate [2]. As a result of these properties, the workability of concrete containing recycled aggregate is low [3,4]. It also has a negative effect on the mechanical properties of the concrete, where increasing the proportion of recycled aggregate as an alternative to natural aggregate leads to a decrease in its compressive strength [5,7]. As a result, extensive studies have been done to overcome the challenges associated with concrete, including the use of recycled aggregate, and to develop solutions to make recycled concrete environmentally friendly and more widely used in practice.

Xianfeng, *et al.* [8] conducted a study looking for the possibility of using a crystallizing agent (CA) to pretreat mortar in order to improve the adherence of recycled aggregate (RA). The study compared the behavior of concrete containing treated RA with the behavior of concrete containing untreated RA and with concrete containing natural aggregate. The results showed that the treated aggregate improved the mechanical properties of the concrete and made the concrete denser and less porous. This treatment also proved to be remarkably effective in improving the resistance of concrete against chloride diffusion and reducing the size of voids, thus improving the permeability of concrete containing recycled aggregate [9].

Pereira, *et al*. [10] mention that the use of a superplasticizer in concrete mixes containing fine recycled aggregate makes the behavior of the concrete better than that of concrete without an admixture. Therefore, it can be said that the performance of concrete containing recycled aggregate is similar to that of conventional concrete if superplasticizers are included to reduce the cement/water ratio.

Barbudo, *et al*. [11] conducted a comparison between the behavior of three groups of concrete containing recycled coarse aggregate at four percentages (0, 25, 50 and 100%), where the first group was without admixture, the second group contained a conventional plasticizer, and the third group contained a high-performance plasticizer. The findings were positive for the use of plasticizers in concrete containing recycled aggregate.

Cartuxo, *et al*. [12] observed that the inclusion of recycled fine aggregate in concrete reduces the superplasticizer's efficiency. They also indicated that while producing concrete, the differences in rheological properties of these mixes should be considered.

Bravo, *et al*. [13] examined the influence of superplasticizer on the behavior of concrete incorporating recycled coarse aggregate, concluding that the results were good in terms of the superplasticizer's performance, but its effect is lower than that of conventional concrete.

2 Statement of the Problem

One of the solutions to overcome the high absorbency of recycled concrete is the use of superplasticizers (SP), which can be used to improve the workability of the concrete and reduce the amount of water required. The superplasticizer is added in certain proportions according to the manufacturer's instructions. Despite the use of superplasticizer in concrete containing recycled aggregate in a wide range, no studies have investigated the effect of adding different proportions of superplasticizer on the behavior of recycled aggregate concrete.

Previous studies have not shown what the effective dosage of superplasticizer is nor what the effect of this substance is on the strength properties when added in proportions exceeding this range. Therefore, the effect of adding superplasticizer in different dosages on the strength properties of concrete containing recycled aggregate was investigated in this study.

3 Research Aims

The present study aimed to reveal the effect of adding a locally available type of superplasticizer (Sika Visocrete-5930). This is a polycarboxylate ether (PCE) based superplasticizer that provides different levels of water reduction and slump retention in concrete. This type of superplasticizer was adopted because it is available in Mosul city and because it is more efficient when used with recycled concrete than lignosulfonate-based superplasticizer [13]. It was added in different proportions to several recycled concrete mixtures to determine its effect on the workability and mechanical properties of the concrete and to determine its effective dosage.

4 Experimental Program

4.1 Materials

4.1.1 Cement

In this study, Ordinary Portland Cement was used in accordance with Iraqi Standard (IQS) No. 5 -1984 [14]. The chemical composition and physical properties of the used cement are illustrated in Tables 1 and 2 respectively.

Table 1 Chemical composition of the OPC.

Property	Test result (Percentage)
Oxide composition	
Alumina, Al_2O_3	4.8
Silica, SiO_2	20.34
Ferric Oxide, Fe_2O_3	3.51
Lime, CaO	60.51
Sulphuric Anhydride, SO_3	1.59
Magnesia, MgO	2.27
Compound composition	
C_3A	6.79
C_2S	22.37
C_3S	47.65
C_4AF	10.68

Table 2 Physical properties of cement.

Property	Test result (min)	Standard IQS, No. 5 -1984
Initial setting time	120	≥45 (min.)
Final setting time	225	≤600 (min.)
Compressive strength (MPa)		
at 3 days	20.6	≥15.0 (MPa)
at 7 days	24.5	≥23.0 (MPa)

4.1.2 Coarse Aggregate

River rounded gravel with a maximum aggregate size of 20 mm, identical to ASTMC33-15 [15], was used as coarse aggregate. The recycled coarse aggregate (RCA) used in this study was obtained by manual crushing of tested specimen waste from the concrete laboratory to insure the purity of the aggregate. Next, the crushed concrete waste was sieved to match the same gradation of the normal aggregate used, with a maximum aggregate size of 20 mm.

Figure 1 explains the preparation and gradation of RCA to match the required sizes, while Tables 3 and 4 show the grading and properties of the normal and the recycled coarse aggregate.

(a) tested specimen's waste

(b) crashing concrete waste

(c) RCA before gradient

(d) RCA after gradient

Figure 1 Steps for preparing recycled aggregate.

Table 3 Grading of normal and recycled coarse aggregate.

Grading of Coarse Aggregate MAS 20 mm		
Sieve Size (mm)	**%Specification Limits according to ASTMC33-99a**	**%Passing of used sample**
25	100	100
19	90-100	95
9.5	20-55	38
4.75	0-10	0
2.36	0-5	0

Table 4 Properties of coarse aggregate.

Property / **Type**	**Rounded gravel**	**RCA**
Specific	2.63	2.55
Gravity SSD Absorption %	0.25	2.827
Compact unit weight (kg/m^3)	1087	1419
Loose unit weight (kg/m^3)	1069	1315
Angularity index	0.74	2.7

4.1.3 Fine Aggregate

River sand was used as fine aggregate. The results of the sieve analysis and properties were obtained in accordance with ASTMC33-15 [15] and are shown in Tables 5 and 6 respectively.

Table 5 Grading of fine aggregate.

Sieve Size (mm)	%Specification Limits According to ASTMC33-99a	%Passing of used sample
4.75	89-100	99.5
2.36	60-100	78
1.18	30-100	58
600 μm	15-100	40.5
300 μm	5-70	16
150 μm	0-15	6

Table 6 Properties of fine aggregate.

Type of fine aggregate	Medium sand
Color	Brown
Specific Gravity SSD basis	2.68
Absorption %	1
Compact unit weight (kg/m^3)	1981
Loose unit weight (kg/m^3)	1833
Fineness modulus	3.02

4.1.4 Chemical Admixture

A high-performance concrete admixture (Sika VisoCrete-5930) with a chemical base (polycarboxylate ether) was used in this study. The admixture acted as a high water reducer and to enhance the workability, stability and flow ability. The main properties as recommended from the factory are shown in Table 7.

Table 7 Properties of the chemical admixture.

Chemical base Basis	Aqueous solution of modified polycarboxylate
Appearance	Turbid liquid
Density	1.084 kg/lt ± 0.01
Dosage	0.2-0.8% liter by weight of cement
pH	8 ± 1.0
Chloride Content	Nil (EN934-2)

4.2 Concrete Mix Proportion

The present study focused on analyzing the effect of increasing the superplasticizer dose on the behavior of recycled concrete in conjunction with a change in the water/cement ratio. For this purpose, a concrete mix with compressive strength (38 MPa) at 28 days was adopted, in which the proportions of (cement:fine aggregate:coarse aggregate:water) were (1:2.3:3.15:0.53) with two water/cement (w/c) ratios (0.57, 0.615). Moreover, for each w/c ratio, the natural aggregate was replaced by two percentages of recycled aggregate (50, 100%), and to each mixture, superplasticizer was added, beginning with a percentage (0.2%) of the weight of the cement and blocking when the phenomenon of concrete segregation occurred. Segregation indicates the separation of the coarse aggregate from the cement matrix and thus the formation of an inhomogeneous mixture. It is worth mentioning that all of the materials used in the concrete mixes were dry, and the recycled coarse aggregate received no treatment.

Experiments were carried out on the concrete mixtures containing recycled aggregate to determine the workability, compressive strength and tensile strength. To examine the compressive strength, specimens with dimensions of 100 × 100 × 100 mm were adopted. As for the splitting tensile strength, cylindrical specimens with dimensions of 100 × 200 mm were used. The standard curing regime was used by immersing the specimens in water for 28 days. The compressive strength test was carried out according to BS 1881: Part 116 [16] at 28 and 56 days, while the splitting tensile strength test was carried out according to ASTM C496/C496 M [17] at 28 days. Table 8 illustrates the concrete mix proportion.

Table 8 Details of concrete mixes.

Mix ID	w/c	RCA (%)	Cement (kg/m^3)	FA (kg/m^3)	NCA (kg/m^3)	RCA (kg/m^3)	SP*	
							(%)	(kg/m^3)
M1	0.53	50	350	805	551.5	551.5	0	0
M2			350	805	551.5	551.5	0.2	0.7
M3			350	805	551.5	551.5	0.3	1.05
M4			350	805	551.5	551.5	0.4	1.4
M5			350	805	551.5	551.5	0.5	1.75
M6			350	805	551.5	551.5	0.6	2.1
M7			350	805	551.5	551.5	0.7	2.45
M8			350	805	551.5	551.5	0.8	2.8
M10	0.53	100	350	805	0	1103	0	0
M11			350	805	0	1103	0.2	0.7
M12			350	805	0	1103	0.3	1.05
M13			350	805	0	1103	0.4	1.4
M14			350	805	0	1103	0.5	1.75
M15			350	805	0	1103	0.6	2.1
M16			350	805	0	1103	0.7	2.45
M17			350	805	0	1103	0.8	2.8

*Superplasticizer addition was discontinued when segregation occurred.

Table 8 Continued. Details of concrete mixes.

Mix ID	w/c	RCA (%)	Cement (kg/m³)	FA (kg/m³)	NCA (kg/m³)	RCA (kg/m³)	SP*	
							(%)	(kg/m³)
S1	0.57	50	350	805	551.5	551.5	0	0
S2			350	805	551.5	551.5	0.2	0.7
S3			350	805	551.5	551.5	0.3	1.05
S4			350	805	551.5	551.5	0.4	1.4
S5	0.57	100	350	805	0	1103	0	0
S6			350	805	0	1103	0.2	0.7
S7			350	805	0	1103	0.3	1.05
S8			350	805	0	1103	0.4	1.4
F1	0.615	50	350	805	551.5	551.5	0	0
F2			350	805	551.5	551.5	0.2	0.7
F3			350	805	551.5	551.5	0.3	1.05
F4	0.615	100	350	805	0	1103	0	0
F5			350	805	0	1103	0.2	0.7
F6			350	805	0	1103	0.3	1.05

*Superplasticizer addition was discontinued when segregation occurred.

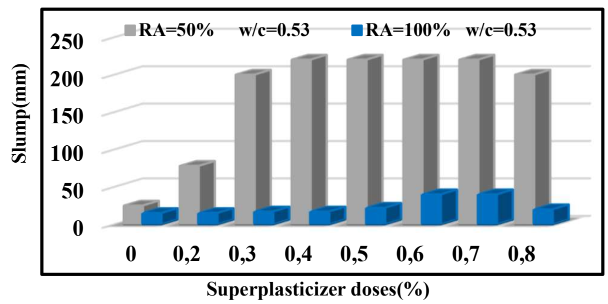
5 Results and Discussion

5.1 Effect of SP Dosage on Workability

To give appropriate workability to the concrete containing recycled aggregate, several dosages of SP were added. It is worth noting that these dosages were highly effective, especially at the lowest ratio of w/c = 0.53 and for mixtures containing RCA at 50%, as presented in Figure 2(a).

It was observed that when superplasticizer was added at a rate of 0.2 to 0.4% of cement weight, a significant increase in slump was reached of up to [4] times the initial slump. This can be attributed to a cause that was not noted in many previous studies, which is that superplasticizer contains water at a certain percentage [18,19]. The water content has an effective role in showing the impact of plasticization, mainly due to the resulting increase in water/binder ratio. Also, the working mechanism of Sika VisoCrete-5930 with a chemical base (polycarboxylate ether), caused by surface adsorption and the steric hindrance effect [10], results in an increase in dispersion and thus increases the fluidity of the concrete. Thereafter, the slump began to stabilize with the increase of the percentage of superplasticizer, as it became clear that the addition percentages of 0.5 to 0.7 % were saturated dosages.

The slump then tended to decrease, due to the plasticization effect being reduced with the overdose of superplasticizer [19]. In addition, we found that excessive amounts of superplasticizer lead to the opposite expected result, as it increases the slump loss and thus leads to an undesirable decrease in slump [20-22]. With regard to the mixtures made with 100% RCA, it was obvious that the superplasticizer exhibited no effect when it was used at rates of 0.2 to 0.4 %.



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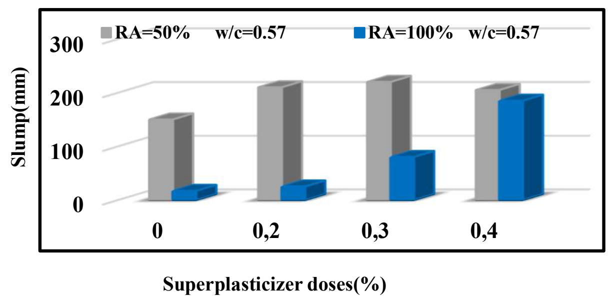

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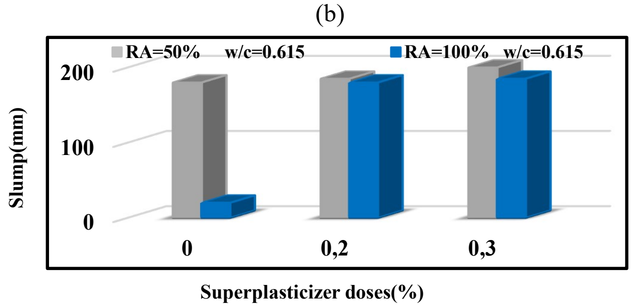

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Figure 2 Effect of SP dosage and w/c on slump.

This can be associated with the high absorption of RCA, the rough surface of RCA, in addition to re-hydrating of the old adhered mortar, which consumes large amounts of water. Figure 2(a) shows that there was a slight increase in slump when the proportion of SP ranged between 0.5 and 0.7 %. Therefore, it can be stated that when using concrete made with 100 % RCA and a low w/c ratio, it is preferable to treat the recycled aggregate either by removing the old mortar or by saturating it with water before use.

In the case of mixtures with w/c = 0.57, it is clear that the slump at SP = 0 is acceptable for concrete mixes made with 50 % RCA, and there is no need to add superplasticizer. When SP was used, the slump seemed slightly improved when compared to the mixes prepared with w/c = 0.53. When the SP dosage ranged between 0.2 and 0.3% the amount of increase in slump reached 1.5 times the initial slump, as can be seen in Figure 2(b). Meanwhile, the slump of the mixtures containing 100 % RCA increased by 8.5 times at SP 0-0.4% when compared to the initial slump. This reveals that the superplasticizer's effect became apparent when the w/c ratio reached 0.57, as it significantly enhanced the workability of the concrete containing 100% RCA.

It is also obvious that the addition of the superplasticizer was discontinued after 0.4% and for mixtures with w/c = 0.615 the addition of superplasticizer was stopped after the ratio 0.3%. This was because segregation of the concrete occurred at these proportions. To sum up, excessive dosages of superplasticizer lead to a decrease and weakness in the cohesion of concrete [23]. This leads to the conclusion that when a high w/c ratio is used, a balance must be found between the proportion of water and the proportion of superplasticizer by reducing the used water in the concrete mixture so that the superplasticizer is more effective, because increasing the w/c ratio and the SP dosage at the same time leads to adverse results on the workability of the concrete. Figure 3 shows the occurrence of the phenomenon of segregation and Table 9 summarizes the effect of the amount of added superplasticizer and the w/c ratio on the behavior of concrete containing RCA.

Figure 3 Segregation phenomenon at w/c = 0.57 and w/c = 0.615.

Table 9 Summary of the influence of SP and w/c ratio on the behavior of the mixes.

w/c	RCA	NCA	SP	Synopsis	Strategies to be taken
0.53	50%	50%	$0 \leq SP \leq 0.4$	effective dosage	-
			$0.5 \leq SP \leq 0.7$	saturation amount	-
	100%	0%	$0 \leq SP \leq 0.4$	no effect	- Increasing the(w/c) ratio or - Removing old adhered mortar or - Saturate the RCA before use
			$0.5 \leq SP \leq 0.7$	slight effect	- Increasing the(w/c) ratio or - Removing old adhered mortar or - Saturate the RCA before use
0.57	50%	50%	$SP = 0$	acceptable workability	- No need for SP dose
			$0 < SP \leq 0.3$	saturation amount	-
			$SP > 0.3$	segregation	- Reduce the water used
	100%	0%	$0 \leq SP \leq 0.2$	no effect	- Increasing the(w/c) ratio or - Removing old adhered mortar or - Saturate the RCA before use - Increasing the dose of SP
			$0.3 \leq SP \leq 0.4$	effective dosage	-
0.615	50%	50%	$SP = 0$	acceptable workability	- No need for SP dose
			$SP > 0$	slight effect	- Reduce the water used
	100%	0%	$0 < SP \leq 0.2$	effective dosage	-
			$SP > 0.2$	segregation	- Reduce the water used

5.2 Effect of SP Dosage on Compressive Strength of the Mixture

Figure 4 displays the relationship between compressive strength and superplasticizer dosage of the mixtures containing 50% recycled aggregate. The figure shows that when the value of w/c = 0.53, an effect of the superplasticizer on the behavior of concrete can be seen at both ages (28 & 56 days).

It was seen that the effective range in which the superplasticizer affects the compressive strength is at ratios ranging from 0.2 to 0.5 %. This can be associated with the fact that superplasticizer has the ability to disperse and deflocculate the cement particles. This dispersion and repulsion lead to an increase in the reaction and thus leads to effective hydration between the cement and concrete components [24,25]. The other reason for the increase in compressive strength is the inclusion of the superplasticizer, which provides the mixture with more water and as a result it does not affect the hydration process. On the other hand, it will accelerate it by providing additional water resulting from the dispersion of cement particles increasing the retained water [26]. Moreover, concrete with the presence of superplasticizer becomes more fluid, as if it is self-compacting concrete.

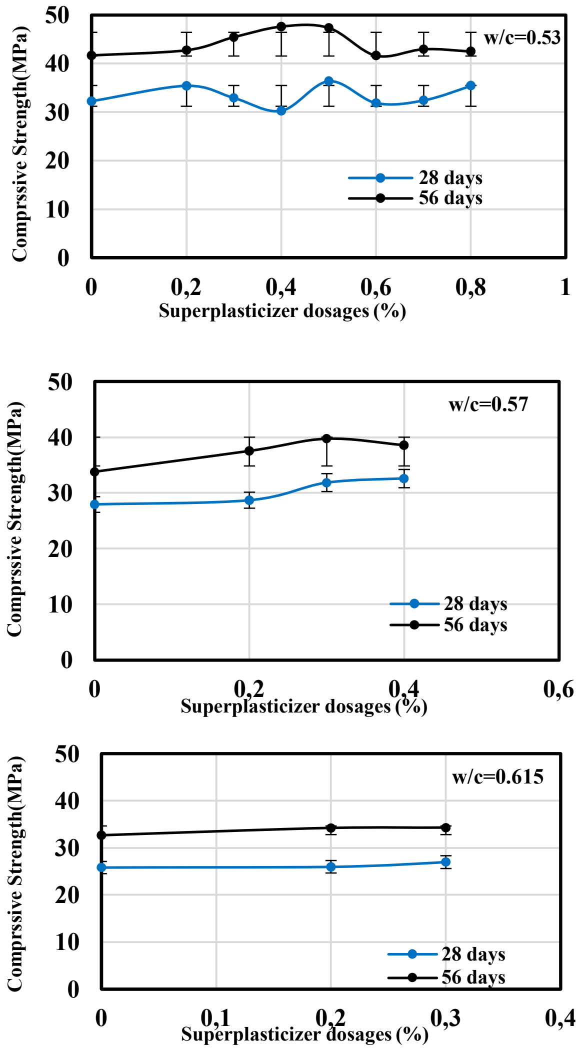


Figure 4 Compressive strength versus SP dosage of mixtures with 50% RCA.

Therefore, this works to reduce voids and finally form more dense concrete, thus leading to an increase in compressive strength [27]. At a ratio of w/c = 0.57, which is a moderate percentage, it can be seen that the effective dosage of superplasticizer appears at rates ranging between 0.2 and 0.3%. However, as mentioned previously, adding 0.4% of superplasticizer had the opposite effect on the mixture, where the aggregate began to separate from the concrete mixture, yielding a decrease in compressive strength. This scenario also applies to the mixture with a ratio of w/c = 0.615 (a high percentage of added water), which did not show a clear effect of adding superplasticizer on the compressive strength, since the segregation phenomenon occurred at SP = 0.3%. Figure 5 shows the relationship between compressive strength and superplasticizer dosage of the mixtures containing 100% recycled aggregate.

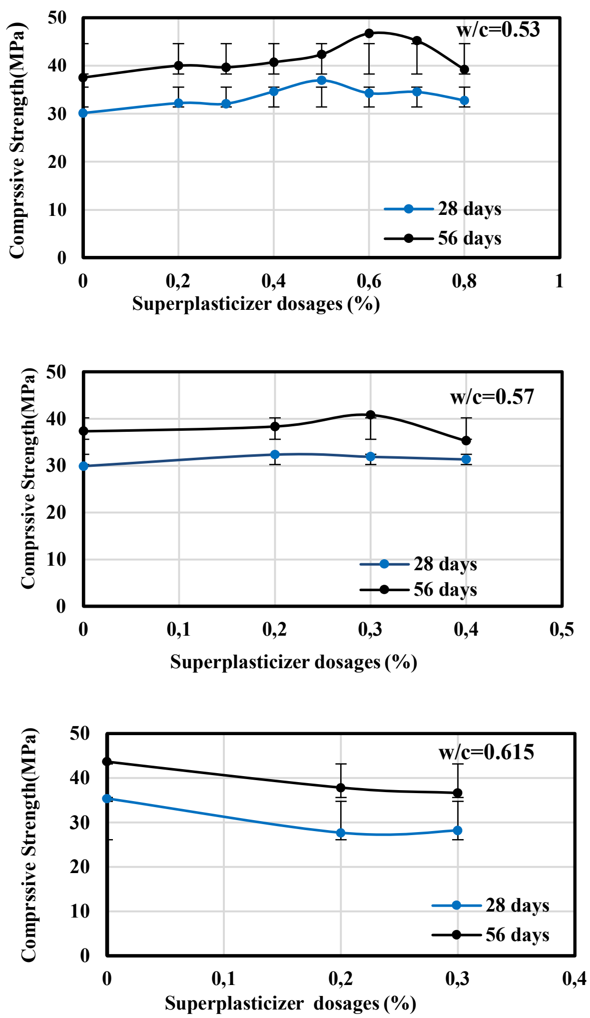


Figure 5 Compressive strength versus SP dosage of the mixtures with 100% RCA.

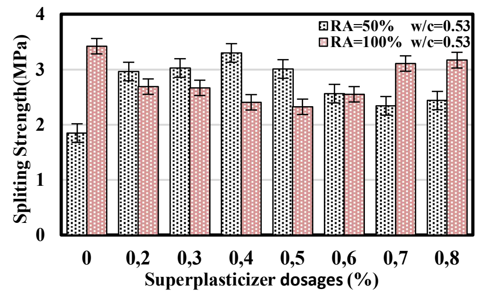
It was found that when w/c = 0.53, there was an effect of adding superplasticizer on the compressive strength, with the effective dosage ranging from 0.2 to 0.6% for both ages (28 and 56 days). At w/c = 0.57, it was noted that the effective superplasticizer dosage ranged from 0.2 to 0.3% and segregation of the mixture occurred after these percentages. As for the mixtures containing w/c = 0.615, there was no observable benefit on the compressive strength of adding superplasticizer. However, it improved the workability of the concrete mixture at 0.2%, and after this percentage, segregation occurred.

5.3 Effect of SP Dosage on Splitting Tensile Strength

The relationship between splitting tensile strength and superplasticizer dosage is shown in Figure 6. Despite the lack of dispersion in the results, there is no evident tendency in Figure 6 that explains the correlation between superplasticizer dose and tensile strength of RCA. However, it can be concluded that there is a negative effect to a certain extent on tensile strength. Most of the findings revealed that as the SP dose was increased, the tensile strength tended to decrease. It is worth noting that when the RA was accompanied by a high percentage of adhering mortar, the density of the recycled aggregate was smaller than that of the normal aggregate, which leads to a lower density and therefore less strength [28].

The reason is that the tensile strength of concrete does not depend primarily on the cement matrix, but rather its increase depends on the aggregate and the extent of its bonding with the cement paste [13]. As the strength of the aggregate is not only the main factor affecting the tensile strength, but the quantity and quality of the connections formed between the aggregate and the cement matrix in the interfacial transition zone and the presence of defects and microcracks are clearly also influential factors [29].

The source of the recycled aggregate is very important, and as mentioned, the recycled coarse aggregate that was used in this research came from concrete samples of unknown properties and content. The mortar attached to the aggregate may contain clay or glass [13], which can cause deterioration of the tensile strength because it contributes to the creation of worse mortar, which negatively affects the tensile strength. As a result, this reduces the effectiveness of the superplasticizer in improving the tensile strength, which is likely to be acquired through compactness that occurs with the addition of the superplasticizer. However, more studies should be carried out in this regard to investigate the effect of the superplasticizer dosage and the effect of different types of SP on the tensile strength.



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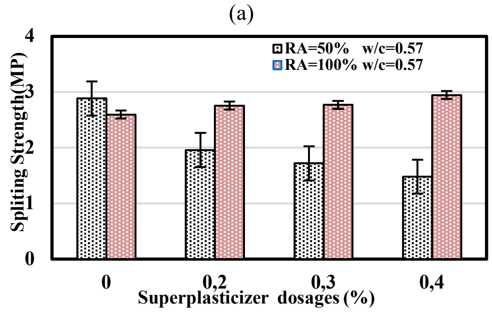

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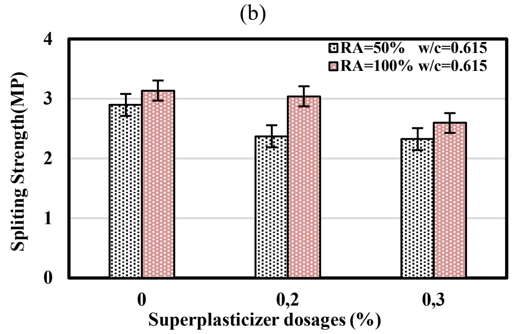

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Figure 6 Splitting tensile strength versus SP dosage.

6 Conclusion

The focus of this paper was to find out the effect of adding superplasticizer on the performance of concrete incorporating RCA, as well as the implications of utilizing polycarboxylate ether-based superplasticizer on the workability and strength characteristics of concrete at varied w/c ratios. The following are the conclusions drawn as a consequence of analyzing the findings:

1. As the proportion of recycled aggregate increases, the effect of the superplasticizer used is reduced in terms of workability.
2. One of the main factors that play an important role in determining the effective dosage of the superplasticizer is the water/cement ratio, as this ratio must be corrected when the proportion of recycled aggregate in the concrete mix increases.
3. It is necessary to calculate the amount of water absorbed by the RA to be able to achieve an appropriate w/c ratio for the mixture.
4. For each ratio of replacement of natural aggregate with recycled aggregate, there are effective dosages of superplasticizer that improve the workability and compressive strength of the concrete, taking into account the water/cement ratio used.
5. The gain in compressive strength of concrete resulting from the addition of superplasticizer was more evident when the percentage of recycled aggregate was 50 %.
6. Superplasticizer can compensate for the compressive strength loss caused by the addition of RA. The increase will be almost noticeable if the amount of mixing water is reduced.
7. The results indicated an increase in compressive strength at both ratios of recycled aggregate when the percentage of superplasticizer was between 0.2 and 0.3 % and when the w/c ratio was 0.57 and 0.615, respectively. Meanwhile, an improvement in compressive strength for the mixture at w/c = 0.53 occurred when the percentage of superplasticizer ranged between 0.2 and 0.6%.
8. The effect of the superplasticizer on improving the tensile strength of concrete was not clearly shown because this property depends on the interfacial transition zone between cement and aggregate more than the cement matrix.

Additional investigations may be carried out to assess the impact of superplasticizer on the tensile strength of recycled concrete. It is also preferable to conduct more studies that investigate the effect of increasing the dosage of superplasticizer on the durability of recycled concrete.

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