

MICROSTRUCTURE AND MECHANICAL PROPERTIES OF CONCRETE WITH TREATED RECYCLED CONCRETE AGGREGATES

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ABSTRACT: Recycled concrete aggregates (RCA) are sourced from construction demolitions. Weaker concrete, however, often resulted when using RCA as partial or full replacement of coarse aggregates due to old mortar in RCA. Several treatment methods target this old mortar to completely remove it, or enhance its properties, to make RCA suitable for construction use. Three treatment methods were employed in this study: (1) sulfuric acid (SA), (2) silica fume impregnation (SF), and (3) the combination of both sulfuric acid and silica fume (SASF). Experimental investigation showed improvement in the physical properties of RCA compared to untreated RCA, however, statistical tests showed that these improvements were not significant. SA treatment was found to have a detrimental effect on the surface of RCA, which developed a weaker layer of adhered mortar on the RCA surface resulting to a reduction in the mechanical strength of the concrete thus, its strength is lower compared to concrete with SF-treated RCA. SF treatment resulted in improved compressive strength in comparison to untreated RCA concrete, SA-treated RCA concrete, and SASF-treated RCA concrete. It was also observed that 50% RCA replacement in all concrete mixes with treated RCA resulted to highest obtained compressive strength.

Keywords: Recycled concrete aggregates, RCA treatment, Sulfuric acid, Silica fume, RCA concrete, SEM

1. INTRODUCTION

Raw materials used in producing concrete are not renewable. Consumption of these raw materials, (e.g. sand, gravel, and crushed rock) is at the rate of 10 to 11 billion tons per year [1]. Disposing of construction and demolition wastes brings another environmental issue as its disposal requires a lot of space. The total amount of waste generated by construction and demolition activities in the European Union in 2012 was 821 million tons and was expected to increase annually [2]. According to [3], 530 million tons of construction and demolition debris was generated in the United States in 2013. Since construction and demolition debris has no reusable components other than steel reinforcement, they are often hauled and shipped to a landfill.

Over the years, many studies were conducted on the use of demolition and construction debris for various purposes. Several studies have proposed the idea of recycled aggregate concrete (RAC) where construction debris and demolition wastes are used as full or partial replacement of coarse aggregates in concrete. However, the use of RCA in concrete often resulted in weaker concrete due to high water absorption, lower concrete workability, and higher drying shrinkage [4]. The strength of RAC with 100% RCA resulted in a 20-25% reduction in strength compared to normal concrete and required more cement to reach comparable strength [5].

Moreover, they showed that cement has to be increased by 6% of cement mass for 50% RCA replacement, and 8.3% increase for 100% RCA replacement to reach similar compressive strength compared to normal concrete. Also, the use of RCA brings about workability issue. Salesa [6] showed that the workability of RCA concrete was reduced due to adhered mortar and higher absorption capacity of RCA.

The use of acid pre-soaking method has been aimed toward removing adhered mortars in RCA. The study [7] used three kinds of acid solution (i.e. hydrochloric acid, sulfuric acid, and phosphoric acid) to treat RCA. Results showed that the properties of RCA improved in terms of water absorption, compression, and flexural strength. The rate of disintegration of adhered mortars depends on the concentration and molarity of the acid solution. Based on [8] & [9], the change in molarities of acid solution enhanced the density, water absorption, and mechanical strength of RCA. Akbarnezhad [7], employed various treatment methods for RCA like mechanical, heating, microwave, and acid-soaking treatment and showed that the quality of RCA relied on the quantity of the adhered mortars on its surface. Additionally, they showed that acid-soaking treatment method removed more adhered mortars than other treatment approaches. Furthermore, [7] showed that for RCA treated with weaker acid reduces water absorption significantly and

improved mechanical properties. Kim [10] combined sulfuric (weak) acid treatment with abrasion in treating RCA and demonstrated improved physical and strength qualities.

Concrete is prone to acid attack, and aggregates react negatively to silica, thus, researchers devised an alternative to treat RCA through silica impregnation. Katz [11] investigated the use of impregnation of silica fume by soaking RCA for 24 hours in silica fume solution. Results showed that silica fume treatment resulted in an increase of 23 to 33%, and 15%, in the compressive strength at ages 7 and 28 days, respectively. Cakir [12] showed that water absorption of concrete with RCA treated with silica fume decreased significantly especially at later ages. This effect is more significant in concrete with RCA using a higher amount of silica fume. However, compressive strength decreased with an increase in the silica fume content in RCA treatment. Huoth [13] used 100% RCA replacement treated with varying silica fume content of 5%, 10%, and 15% and showed comparable compressive strength results of RAC to conventional concrete.

This study explored three treatment methods for RCA, namely; weak acid (sulfuric acid) treatment, condensed silica fume impregnation, and the combination of both. Moreover, the study investigated the influence of these methods on physical properties, in terms of water absorption, bulk density, and abrasion resistance, and microstructure of RCA. Scanning electron microscopy (SEM) was employed to explore the microstructure. Additionally, the investigation was further extended to the compressive strength of concrete with untreated and treated RCA and varying amounts of treated RCA.

2. MATERIALS AND METHODS

2.1 Sourcing And Preparation Of RCA

RCA used in this study was obtained from demolished concrete pavements, which was mainly composed of cement mortar and aggregates. Demolished concrete pavement was then crushed to a maximum nominal size of 50 mm. The crushed recycled concrete was then graded using sieve in accordance with ASTM C136 [14]. Natural coarse and fine aggregates were used for the control concrete mix, while parts of coarse aggregates were replaced by RCA, by volume, in non-control concrete mixes.

2.2 Treatment Of RCA

RCA was treated prior to testing of its physical and, strength properties after it has been incorporated in concrete. In this study, the three methods of treatment used were weak acid

treatment using sulfuric acid (SA-treatment), condensed silica fume impregnation treatment (SF-treatment), and the combination of these two treatments (SA-SF treatment).

2.2.1 Weak acid treatment using sulfuric acid (SA-treatment)

This method of acid treatment was adapted from [7]. The recycled concrete aggregates were soaked in 0.5 molarity of sulfuric acid solution for 24 hours. RCA in the acid bath was shaken occasionally to ensure efficient removal of the bond between adhered mortar and aggregates. After soaking, RCA was washed to remove acidic solvents. A final soaking in water for 24 hours was done to ensure that no residue from acid solvents remains on the aggregates.

2.2.2 Condensed silica fume impregnation treatment (SF-treatment)

This method was adapted from [11], with little modification, as condensed silica fume was used instead of raw silica fume. To create a silica fume solution, 1 kg of condensed silica was mixed with 10 liters of water. RCA was then soaked in this solution for 24 hours for silica fume impregnation to occur. After soaking, the treated RCA was air-dried.

2.2.3 Combined treatment method (SA-SF treatment)

Combined treatment involved repetition of procedure for acid-soaking sulfuric acid treatment followed by repetition of the silica fume impregnation method.

2.3 Physical And Microstructure Characterization of RCA

Several tests were conducted enable to compare the physical properties and microstructure of treated and untreated RCA. These tests are relative density (specific gravity) and water absorption as per ASTM C127 [15], abrasion loss as per ASTM C131 [16], bulk density as per ASTM C29 [17], and surface microstructure using Scanning Electron Microscope as per ASTM C295 [18].

2.4 Concrete Mix Design

Mix design proportions are shown in Table 1. Due to the scarcity of Portland cement locally, this study used Type 1P cement for all concrete samples. The proportions used in the design mix was based on ACI 211.1 design mix procedure adopting water to cement (w/c) ratio of 0.45 for all mixes. Concrete

samples were made with 100%, 75%, 50%

Table 1. Mix Design for 1m³ concrete volume

Type of Mix	Cement (kg)	Fine Aggregates (kg)	Water (kg)	Coarse aggregates (kg)	RCA (kg)
U-RCA	376	948	169	0	948
25SF	376	870	169	1167	258
50SF	376	870	169	779	515
75SF	376	870	169	389	773
100SF	376	870	169	0	1030
25SA	376	880	169	1168	255
50SA	376	880	169	779	510
75SA	376	880	169	389	765
100SA	376	880	169	0	1020
25SASF	376	877	169	1171	256
50SASF	376	877	169	781	512
75SASF	376	877	169	390	767
100SASF	376	877	169	0	1023

Table 2. Average physical properties of untreated and treated RCAs

RCA Physical Properties	Untreated	SF-treated	SA-treated	SASF-treated
Bulk density (kg/m ³)	1142	1223	1229	1234
Specific gravity (SSD)	2.31	2.41	2.37	2.33
Water absorption (%)	7.7	6.6	7.0	9.6
Abrasion loss (%)	29	27	27	27

and 25% replacement of RCA by volume of coarse aggregates.

2.5 Compression Test On Concrete With RCA

All concrete specimens were made in accordance with ASTM C192 [19]. Concrete cylinder sample of size 100mm x 200mm was used. For each mix type, 8 samples were prepared and cured in water for 7 and 28 days. Compressive strength tests were conducted as per ASTM C39 [20].

3. RESULTS AND DISCUSSION

3.1 Physical Properties Of RCA

Table 2 summarized the average values for physical properties both for untreated and treated RCA. Bulk density and specific gravity increased for all treated RCA. Water absorption and abrasion loss decreased for treated RCA. RCA under combined treatment (SASF), however, exhibited an increase in water absorption compared to untreated RCA. Except for bulk density, statistical t-tests showed that changes in physical properties of treated RCA compared to untreated RCA were not significant.

3.2 Surface Microstructure Of RCA

Scanning electron microscope (SEM) of untreated RCA (Fig. 2a) showed noticeable porous surface and covered with different impurities and loose crumbs of cement paste. These impurities and loose crumbs of cement paste can be observed better with higher magnification (x7500) in Figure 3a. These observations were consistent with the study of [7] and [8]. SEM of SA-treated RCA shown in Figure 2b exhibited smaller pores and less jagged surface, represented by dark spots and craggy formations. Both SF-treated RCA and SASF treated RCA (Figures 2c and 2d) exhibited smoother, less porous and jagged surface.

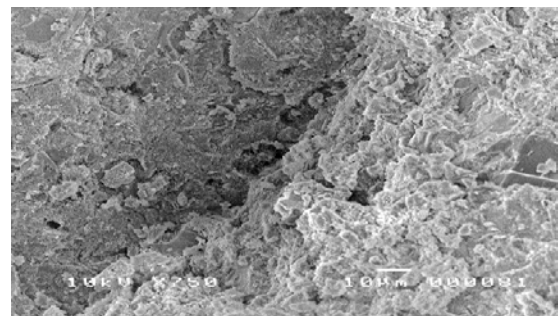


Fig. 1 Cross-sectional surface microstructure of SA-treated RCA

The surfaces of SF-treated and SASF-treated RCA are shown in Figures 2c, and 2d, respectively. Images showed that the porosity of RCA was reduced significantly compared to untreated RCA and SA-treated RCA. The surface of SF-treated

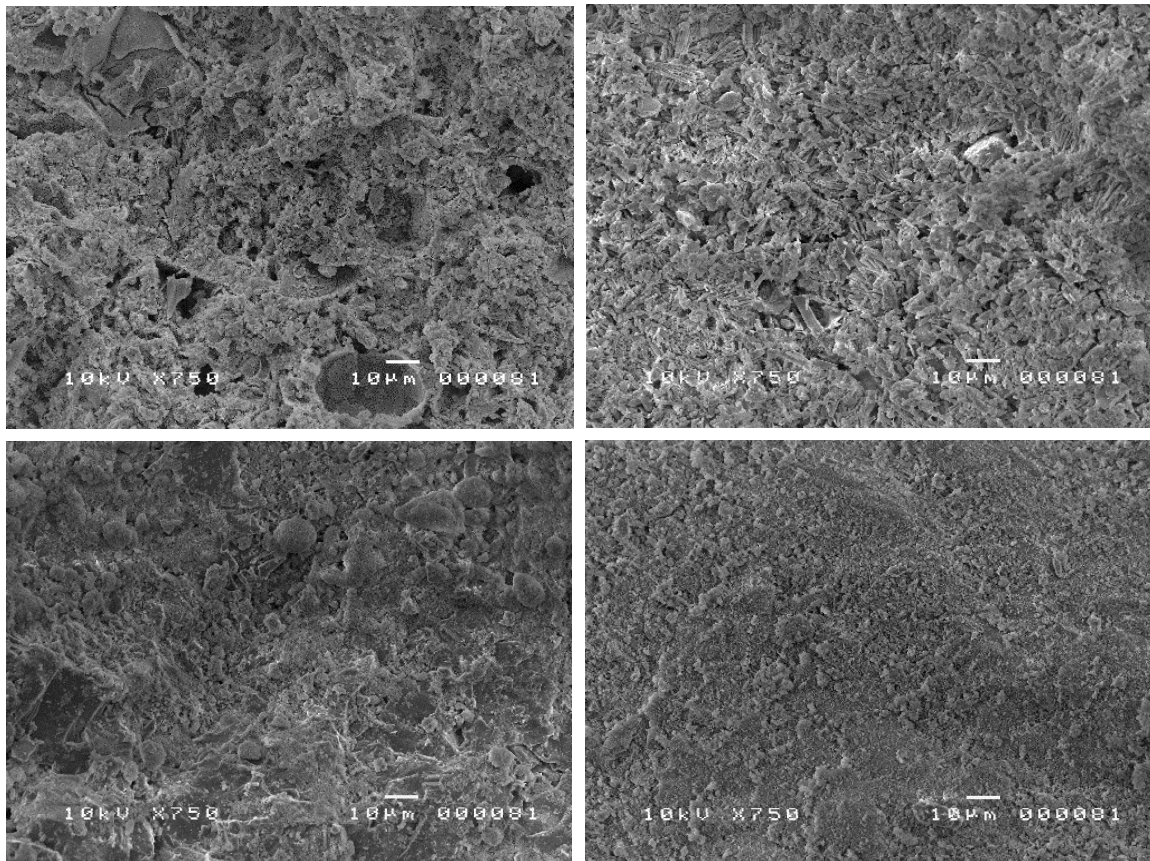


Fig. 2 Surface microstructure of treated and untreated RCA at 750x magnification (a: Untreated RCA, b: SA-treated, c: SF-treated, d: SASF treated)

RCA compared to SASF-treated RCA appeared with much larger irregular crags. Contrary to the effects of sulfuric acid, which altered the surface topography of RCA, silica fume coated the surface resulting in the smoother and less cragged surface.

SEM of treated and untreated RCAs with 7500x magnification was shown in Figure 3. Untreated RCA (Fig. 3a) displayed a rougher surface compared to that of SA-treated RCA (Fig. 3b) with smoother crystalline-like structure. However, the surface structure of the SA-treated RCA appeared more disconnected, with broken strand formations and particles around the sample. In Figures 3c and 3d, it can be observed that small particles were present which were not observed in Fig 3a and 3b. This can be attributed to the presence of micro silica that clung to micro-surfaces around RCA, thus filling the voids along the surface of the RCA.

Figure 1 showed a cross-sectional image of SA-treated RCA. It can be inferred from this image that acid treatment created a layer of weakened mortar on the RCA and that farther exposure to acid may result to complete removal of this layer. Incomplete removal, on the other hand, resulted in weaker

aggregate mortar interface which led to weaker mechanical strength.

3.3 Compressive Strength Of Concrete With RCA

Except for concrete with 100% of coarse aggregates replaced by treated RCA, all other RCA replacement has higher compressive strength than that of concrete with untreated RCA. This was observed in both 7-day and 28-day, as seen in Fig. 4 and 5.

3.3.1 Comparison between concrete with RCA under different treatment method

For 7-day compressive strength, concrete samples with SA-treated RCA and SF-treated gained the higher strength for coarse aggregate replacement of 25% and 50% compared to concrete with SASF-treated RCA. Coarse aggregate replacement higher than 50% (i.e. 75% and 100%) showed varying results but samples with SF-treated RCA consistently got the highest or next to highest compressive strength.

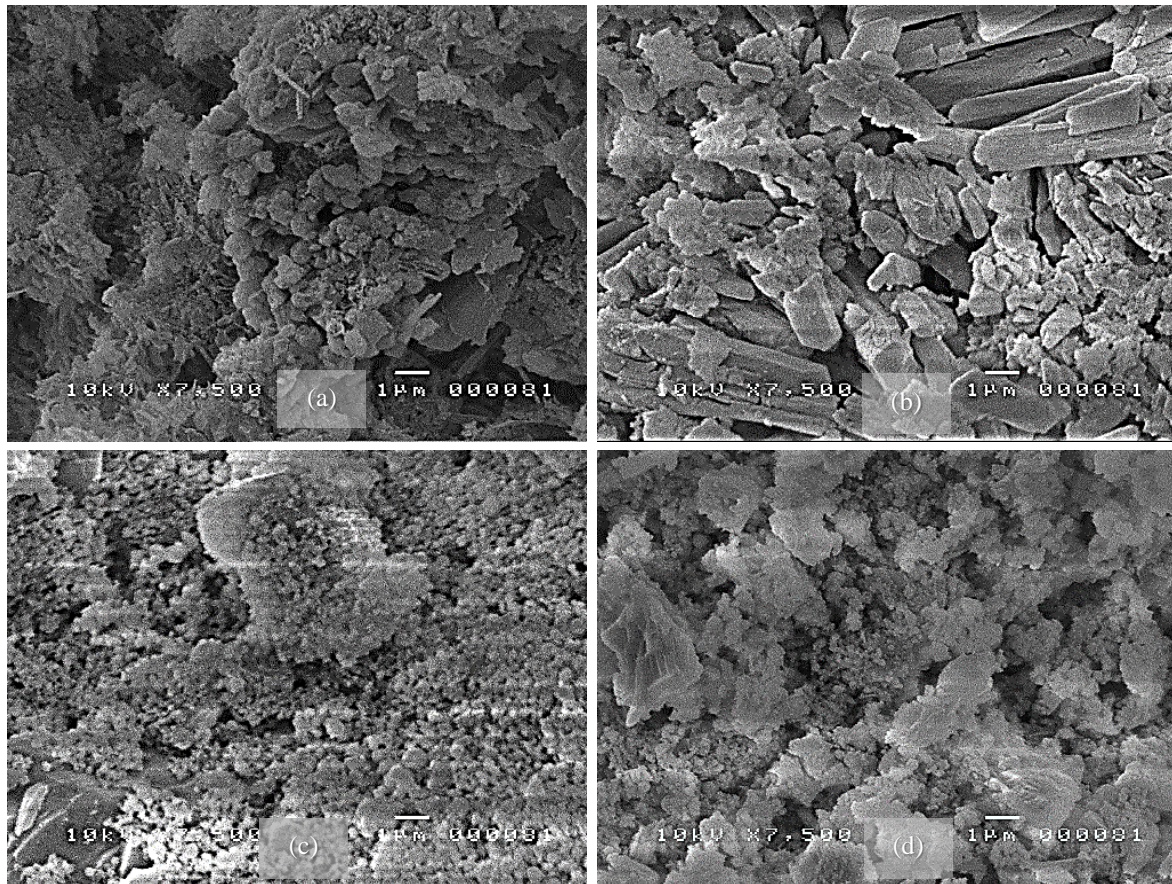


Fig. 3 Surface microstructure of treated and untreated RCA at 7500x magnification (a: Untreated RCA, b: SA-treated, c: SF-treated, d: SASF treated)

Concrete with SF-treated RCA also gained the highest for 28-day compressive strength consistently for all. Concrete with SASF-treated RCA had the lowest strength except for mix with 75% RCA replacement.

Comparison between concrete with SA-treated RCA and with SF-treated RCA revealed that SF-treated RCA concrete had higher mechanical strength for both 7-day and 28-day strength. SASA-treated RCA concrete performed better than SA-treated RCA concrete in 7-day strength but not in 28-day strength.

3.3.2 Effects of varying amounts of RCA replacement

For 7-day compressive strength, an increase was observed for SA-treated RCA concrete for 25% and 50% replacement while SF-treated RCA concrete did not exhibit any strength increase until replacement reached 75%. Concrete with SASF-treated RCA exhibited rising strength pattern from 25% to 75% RCA replacement then drop at 100% replacement. SA-treated RCA concrete and SF-treated RCA concrete exhibited a decrease in strength for more than 50% RCA replacement.

Compressive strength for 28-day showed more consistency with respect to trend in strength gain and loss (Fig. 4 & 5) than 7-day. SA-treated RCA concrete, and SF-treated RCA concrete, both showed increasing strength from 25% to 50% RCA replacement then followed by a decrease in strength for 75% up to 100% RCA replacement. For SASF-treated concrete, however, the strength increase was observed up to 75% RCA replacement then decrease thereafter. This observation was similar to that of SASF-treated concrete for 7-day strength.

4. CONCLUSIONS

There is a slight improvement on the physical properties, such as bulk density, water absorption, abrasion loss, and specific gravity, of RCA treated by sulfuric acid (SA), silica fume impregnation (SF), and the combination of both (SASF). However, a statistical t-test showed that these improvements were not significant.

The microstructured surface of SA-treated RCA was cleaner and free from loose particles compared to untreated RCA. However, the remaining adhered mortar on RCA that the sulfuric acid failed

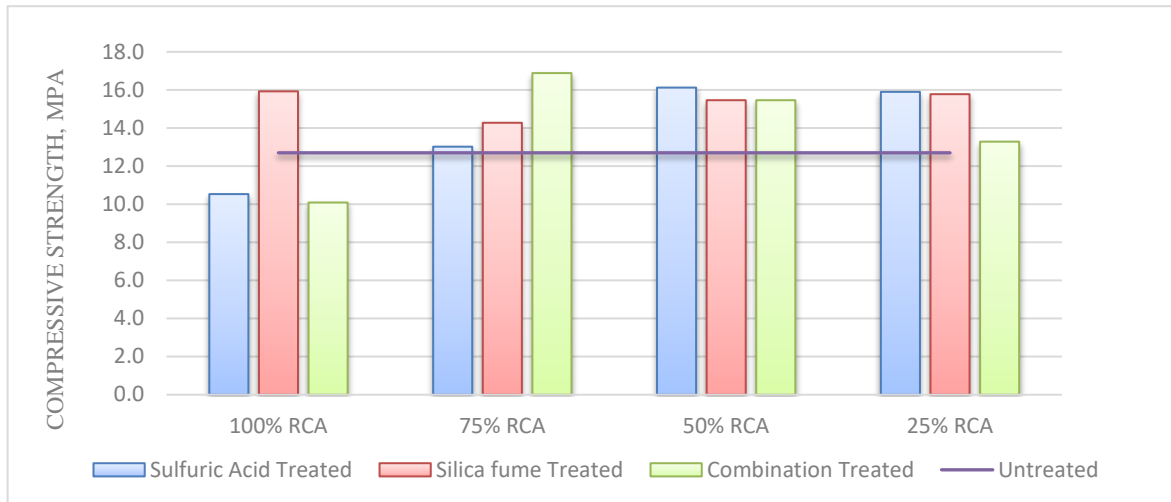


Fig. 4. 7-day compressive strength of concrete with treated and untreated RCA

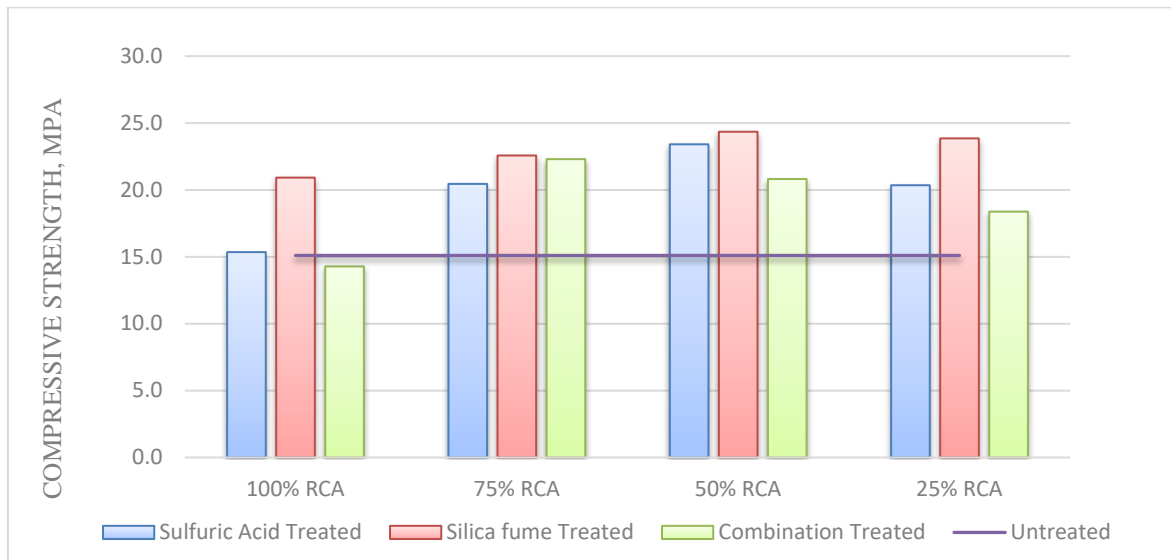


Fig 5. 28-day compressive strength of concrete with treated and untreated RCA

to penetrate became weak and affected the mechanical strength of concrete with SA-treated RCA. Thus, compared to SF-treated RCA concrete, SA-treated RCA concrete had lower mechanical strength.

The microstructured surface of the SF-RCA showed to be smoother than the untreated RCA and SA-treated RCA validating the claim that silica fume particles occupied the void spaces of RCA resulting to smoothing of the rough microstructure surface of RCA.

Treated RCA produced concrete with higher compressive strength compared to concrete with untreated RCA. Combination of SA and SF treatments do not result in better strength compared to concrete with RCA employing separate treatment.

While increasing RCA percentage replacement decreased the compressive strength of RCA concrete, it was observed that with treated RCA, the decrease in strength occurred at replacements higher than 50%. Based on results, SF-treatment was the more effective method of treating RCA.

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