

The Effects of Various Recycled Concrete Aggregate Treatment Techniques on Mechanical Properties

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Abstract - Improving the quality and functionality of the recycled materials is a major factor in the potential replacement of natural aggregates (NA) with recycled concrete aggregates (RCA). Recycled aggregates typically contain adhered mortar, micro-cracks, and impurities, which negatively affect their physical and mechanical properties. This experimental study investigates four different surface treatment methods aimed to enhance the characteristics of coarse recycled aggregates: cement slurry coating, silica fume coating, soaking in 0.1 M hydrochloric acid (HCl), and boiling RCA in hot water at 100° C. The fundamental properties of RCA before and after each treatment were evaluated, along with their influence on concrete performance. The results demonstrate that the SF treatment method reduces the mechanical characteristics of concrete by approximately 6.7% and 7.3%, respectively, for fresh and hardened densities. The concrete's compressive strength was significantly decreased by up to 51.6% through the HCL treatment method. The concrete's tensile strength and modulus of rupture were lowered by up to 42.5% and 53%, respectively, using the boiling treatment method. When compared to other treatments, the boiling method produces a good result for the concrete's compressive strength.

Key Words: Boiling, Coarse aggregate, Mechanical properties, Recycled concrete aggregate, RCA, Treatment.

1. INTRODUCTION

The increasing demand for concrete, driven by rapid urbanization, industrialization, and population growth, has led to a significant depletion of natural aggregates such as gravel and sand [1]. This has sparked a pressing need for sustainable alternatives to mitigate the environmental impact of concrete production. Recycled concrete aggregate (RCA) is considered a complete answer that can successfully manage concrete waste and help reduce the pressure on normal aggregate supplies [2].

When the demolition of old structures, the removed concrete is frequently considered unusable and disposed of as demolition waste. By assembling the recycled concrete and breaking it up, RCA is created.

Concrete containing RCA can be employed in both structural and non-structural applications. One of the main aims to utilize RCA in concrete is to make construction more green

and environmentally friendly which decreases the quantity of non-renewable normal resources produced. The environment benefits greatly from this. Additionally, it uses less area for landfills, which lowers air and water polluting levels.

Many researches have investigated the effects of incorporating RCA into concrete, revealing that RCA's properties are influenced by the source of the original concrete. Generally, compared with natural coarse aggregate RCA exhibits inferior quality, due to surface cracks, irregular surface, extra edges and corners, a lesser apparent density, higher water absorption [3], and numerous interfacial transition zones (ITZs), which may negatively affect the mechanical performance of concrete, workability and durability [4]. Therefore, enhancement of RCA quality is important. Currently, there are two main pathways for producing high-quality RCA [5, 6]. Firstly, removing the adhered mortar from the RCA surface, and secondly, strengthening the adhered mortar.

This study aims to explore the mechanical properties of concrete incorporating treated RCA with different techniques. For this purpose, four surface treatment techniques (three using before and one suggested here) were employed to improve the feature of recycled concrete aggregates, which is (cement slurry coating, silica fume slurry coating, soaking RCA in HCL acid, boiling RCA in hot water (100 °C), that suggested method. Each treatment method was evaluated through four replacement ratios of RCA (0%, 25%, 50%, and 100%) instead of natural aggregate (NA). The RCA properties investigated in this study were density, compressive strength, splitting tensile strength, and modulus of rupture.

2. MATERIALS USED

Cement: ordinary Portland cement that meets the requirements of ASTM C150 [7]. The physical properties of cement were described in Table 1.

Sand: River sand is utilized in all concrete mixes. The sand properties results are in agreement with ASTM C778 [8], as shown in Table 2.

Natural coarse aggregate (NCA): The most common coarse aggregate used is gravel. The coarse aggregate parameters were tested according to ASTM, C33M [9]. The sieving analysis of coarse aggregate are shown in Table 3.

Table -1: Cement Physical Characteristics

Physical Properties	Test Results	ASTM C150 / C150M-19a
Specific surface area (Blaine method) (m ² /kg)	259 m ² /kg	(230 m ² /kg) lower limit
Setting time (vicate apparatus)		
Initial setting:	3 hrs. 15 min	> 45min
Final setting:	5 hrs. 35 min	< 6.25 hrs.
Compressive strength (MPa)		
at 3-day	28.68 MPa	> 15 MPa
at 7-day	39.44 MPa	> 23 MPa

Table -2: THE RESULTS OF THE SAND GRADING TEST

Sieve size	Cumulative Passing (%)	ASTM C778-17
1.18 mm	100	100
600 µm	97	96-100
425 µm	69	65-75
300 µm	28	20-30
150 µm	3	0-4

Table -3: Coarse Aggregate Sieving Test

Sieve size	Cumulative Passing (%)	ASTM C33 / C33M-18
20 mm	100	100
14 mm	99	90 - 100
10 mm	59	50 - 85
5 mm	0.5	0 - 15
2.36 mm	0	0 - 5

Recycled concrete aggregate (RCA): Coarse RCA was taken from a building after demolition and substituted with natural aggregate at four different weight ratios: 0%, 25%, 50%, and 100%. Recycled concrete aggregates (RCA) have a particle size of 5-12 mm. The RCA sieve analysis met the coarse aggregate grading following testing of the prepared RCA sizes. The results of the sieving test are shown in Table 4.

Table -4: SIEVING OF RCA

Sieve size	Cumulative Passing (%)	ASTM C33 / C33M-18
20 mm	100	100
14 mm	100	90 - 100
10 mm	98	50 - 85
5 mm	0	0 - 15
2.36 mm	0	0 - 5

Water: tap water was used in the preparation of concrete mixtures.

Silica fume (SF): It is an ultrafine pozzolanic material resulting from the production of silicon and ferrosilicon alloys, also known as micro silica. It was used to enhance the properties of concrete. The manufacturer has adopted the specification ASTM C1240 [10]. The sort of SF that is used is depicted in Fig. 1.



Fig -1: Silica Fume

Hydrochloric acid (HCl): Hydrochloric acid is an aqueous solution of hydrogen chloride (HCL), occasionally named muriatic acid or salt spirits. It is classified as a strong acid and a colourless solution characterized by an intense smell. The properties are shown in Table 5.

Table -5: Properties of HCL

Product Name	Hydrochloric Acid
Grade	LR
Vapor density	1.3 (vs air)
Vapor pressure	2.23-7.93 Psi
Product line	VETEC
Form	Liquid
Concentration	35-38 %
PH	< 1.0
Density	1.070 g/cm ³

3. EXPERIMENTAL PROGRAM

Surface treatment for recycled concrete aggregate Fig. 2 present the treatment methods of the RCA.

Cement slurry treatment of RCA: In this method, the RCA was soaked in cement slurry, then lifted and exposed to air for 24 hours (see Fig. 3).

Silica fume-treated: The aggregates were submerged in a slurry of silica fume (for 30 min), then taken out and placed on sheets for one day (24 h) (see Fig. 3).

Chemical treatment of RCA using HCL acid: The RCA was treated using hydrochloric acid solution with a concentration of 0.1 M. For this purpose, 336 kg of untreated RCA was used with 160 L of water and 1.5 L of acid. Firstly, the acid was added to the water carefully. Following that, the untreated RCA was soaked in the solution for 24 h at room temperature (22 °C to 26 °C), and then washed thoroughly with water to remove the acidic solution, and left in the sun for one day to reach the SSD condition. The treatment

methodology used in this method followed the treatment methodology proposed by Tam et al. (see Fig. 3).

Boiling in hot water: RCA was treated by boiling it in hot water to weaken and remove the old mortar adhering to its surface. The RCA was placed in a container of clean water, heated to the boiling point (approximately 100 °C), and boiled for 60 minutes. After that, the RCA was removed from the hot water, then left to cool and achieve the saturated surface dry condition (SSD) (see Fig. 3).

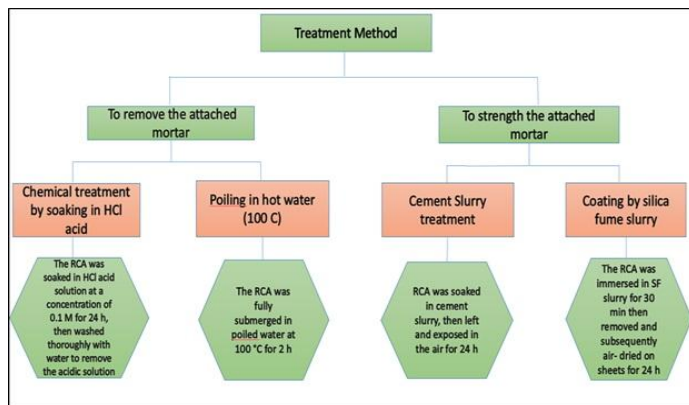


Fig -2: Flow chart of the treatment methods



Fig -3: Treatment methods of RCA

4. MIXTURE PROPORTIONS AND CONCRETE SPECIMENS PREPARATION

The quantities of the mixes are presented in Table 6. As can be seen, the treated recycled concrete aggregate (TRCA) was used in the mixtures instead of the weight of coarse aggregate at a replacement ratio (0%, 25%, 50%, and 100%). The normal concrete (NC or control specimen) was prepared according to ACI 211-22 [11], with a concrete target strength of 35 MPa at the age of 28 days. and w/c ratio was 0.39.

Table -6: QUANTITY AND PROPORTIONS OF THE CONCRETE MIXTURES

Concrete Designation	Cement (kg/m ³)	Water (kg/m ³)	Coarse aggregate NA (kg/m ³)	Fine aggregate (kg/m ³)	Untreated RCA	Cement mortar	Silica Fume	HCl	Boiling	Replacement Ratio
NA	490	191	960	680	0	0	0	0	0	0
RCA25	490	191	720	680	240	0	0	0	0	25
RCA50	490	191	480	680	480	0	0	0	0	50
RCA100	490	191	0	680	960	0	0	0	0	100
TRCA-CM25	490	191	720	680	0	240	0	0	0	25
TRCA-CM50	490	191	480	680	0	480	0	0	0	50
TRCA-CM100	490	191	0	680	0	960	0	0	0	100
TRCA-SF25	490	191	720	680	0	0	240	0	0	25
TRCA-SF50	490	191	480	680	0	0	480	0	0	50
TRCA-SF100	490	191	0	680	0	0	960	0	0	100
TRCA-HCl25	490	191	720	680	0	0	0	240	0	25
TRCA-HCl50	490	191	480	680	0	0	0	480	0	50
TRCA-HCl100	490	191	0	680	0	0	0	960	0	100
TRCA Boiling25	490	191	720	680	0	0	0	0	240	25
TRCA -Boiling50	490	191	480	680	0	0	0	0	480	50
TRCA -Boiling100	490	191	0	680	0	0	0	0	960	100

The procedures of casting, mixing, and combining were carried out. Cement, water, natural fine and coarse aggregates, and TRCA were first weighed with an accuracy of 2.0 grams. The concrete ingredients were mixed using an electric mixer with a 0.3 m³ capacity. To prepare normal concrete, gravel, and sand were added to the electric mixer, followed by 1/3 of the water, while the mixture was continuously mixed for 1 minute to ensure the surfaces of the CA were fully saturated. Then the cement was added after 3 minutes of mixing, followed by the slow addition of the remaining water during the mixing operation until a homogeneous mixture is obtained. The components of treated recycled concrete aggregate mixtures were mixed using the same procedure, substituting 25%, 50%, and 100% of the total weight of coarse aggregate.

5. TESTING OF SPECIMENS

Fresh density: The test was conducted according to ASTM C29 [12] to measure the fresh bulk density of all NC, RCA, and TRCA mixes.

Density Test: In accordance with ASTM C138 [13], the concrete density test was calculated as the average density of three samples in every mixture. (see Fig. 4).

6. MECHANICAL PROPERTIES

Compressive strength test: Concrete cubes of measurement 100 mm × 100 mm X 100 mm were cast for calculating compressive strength after 28 days, followed by the requirements of BS 1881 [14]. Compressive strength is calculated by means of a hydraulic machine with capacity of 2000 kN, and the rate of loading was 3 kN/sec. For each mix,

the average amount of compressive strength from three cubes was determined.

Splitting tensile strength: An electric machine with a capacity of 2500 kN and a loading rate of 3 kN/sec is used for this indirect test to find the tensile strength of a cylindrical sample. Cylindrical concrete specimens were cast, having dimensions of 100 mm in diameter and 200 mm in height. The test was performed after curing for 28 days, and in agreement with ASTM C496 [15]. In each mixture, the mean value of three samples was taken.

Modulus of Rupture Test: To find the concrete's modulus of rupture, prism specimens measuring 100 x 100 x 400 mm were produced. The experiment was implemented under a three-point load after curing in water for 28 days, in agreement with ASTM C78 [16]. Three samples were employed for each blend to calculate the average value. (see Fig. 4)



Fig -4: Concrete specimen's test

7. RESULTS AND DISCUSSIONS

Table 7 demonstrates the results of the mechanical properties of the NA and TRCA concretes.

Table -7: Results of the Mechanical Properties of the Concrete Mixtures

Concrete Designation	Fresh Density (kg/m ³)	Hardened density (kg/m ³)	Compressive Strength (MPa)	Tensile Strength (MPa)	Modulus of rupture (MPa)
NA	2393	2388	40.78	4.61	7.61
RCA25	2340	2338	37.49	4.24	6.93
RCA50	2313	2311	37.7	3.51	6.41
RCA100	2293	2290	38.1	4.03	6.92
TRCA-CM25	2346	2337	37.8	4.15	7.48
TRCA-CM50	2326	2323	36.9	4.68	6.60
TRCA-CM100	2280	2275	36	3.87	5.78
TRCA-SF25	2340	2336	25	4.34	6.83
TRCA-SF50	2340	2329	30.74	4.61	7.19
TRCA-SF100	2233	2213	31.73	3.38	4.55
TRCA-HCl25	2360	2351	27.4	4.04	6.80
TRCA-HCl50	2346	2328	24.36	4.34	6.96
TRCA-HCl100	2280	2276	19.74	3.81	6.79
TRCA-Boiling25	2387	2371	36.92	3.58	6.44
TRCA- Boiling50	2340	2326	35.11	4.15	6.49
TRCA- Boiling100	2307	2286	33.85	2.65	4.03

Figs. 5-10 present the fresh density of the different method of treatment the RCA concretes. Fig. 5 shows the fresh density vs RCA replacement ratio, the fresh density decreases when the RCA increasing up to 4.2% (2293 kg/m³) for RCA100 mixture. When RCA treated using cement mortar, silica fume, HCL, and boiling by water, fresh density also decreases up to 4.7%, 6.7%, 4.7%, and 3.6%, respectively compare with NA mix, this appears in the Figs. 6-9. Less reduction is appearing in the SF treatment method, as presented in Fig. 10. This good result for the suggested method (boiling the water).

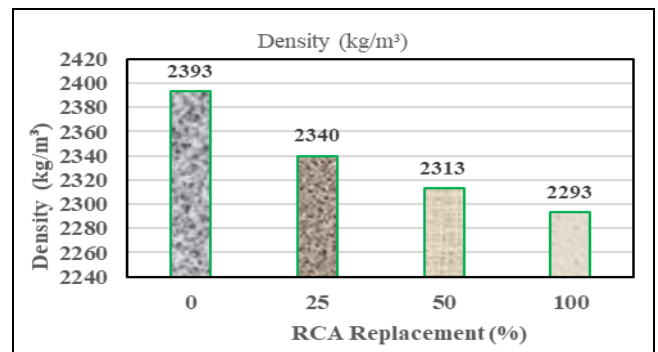


Fig -5: Fresh density vs RCA replacement ratio

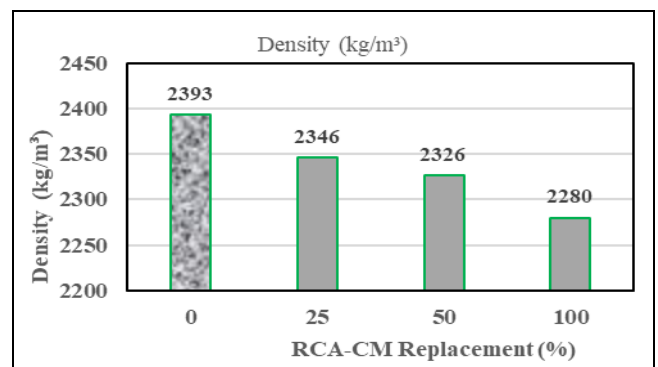


Fig -6: Fresh density vs RCA-CM replacement ratio

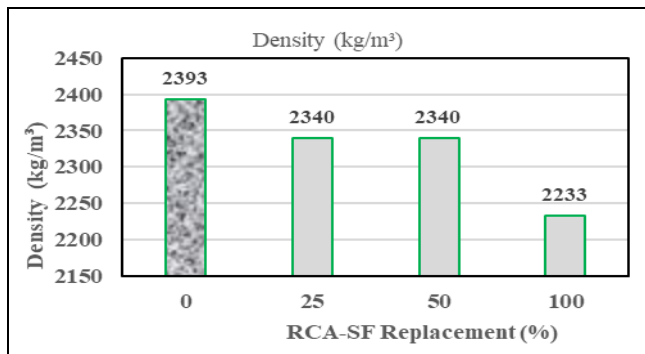


Fig -7: Fresh density vs RCA-SF replacement

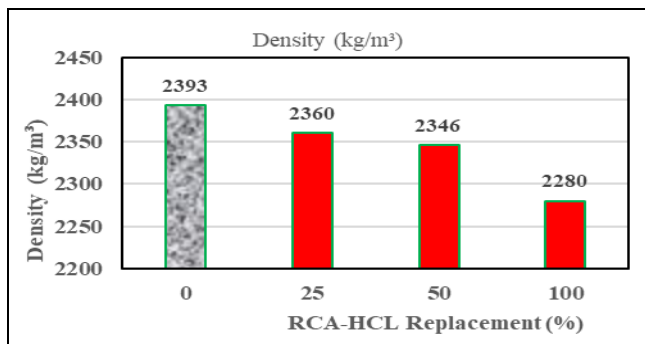


Fig -8: Fresh density vs RCA-HCL replacement ratio

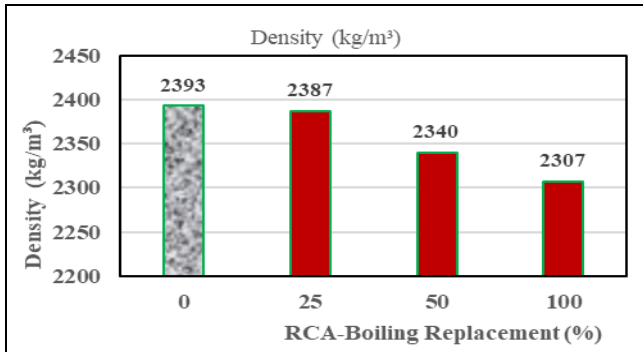


Fig -9: Fresh density vs RCA-Boiling replacement ratio

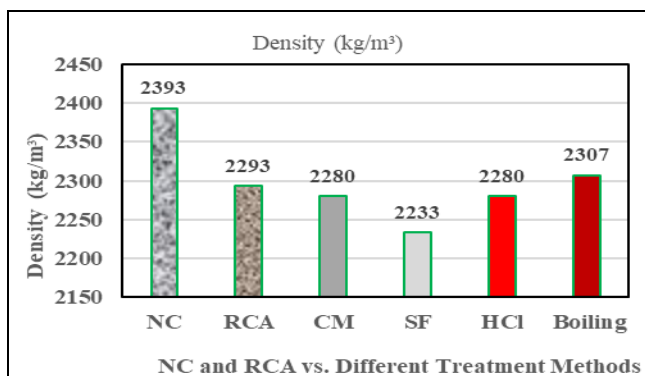


Fig -10: Fresh density vs different treatment methods of RCA concretes

Same behaviour is appearing in the hardened density, as seen in Figs. 11-16. Fig. 11 shows the hardened density vs RCA replacement ratio, the hardened density decreases when the RCA increasing up to 4.1% (2290 kg/m³) for RCA100 mixture. When RCA treated using cement mortar, silica fume, HCL, and boiling by water, hardened density also decreases up to 4.7%, 7.3%, 4.7%, and 4.3%, respectively compare with NA mix, this appears in the Figs. 12-15. Fewer decrease is appearing in the SF treatment method, as presented in Fig. 16. This good result for the proposed method (boiling the water).

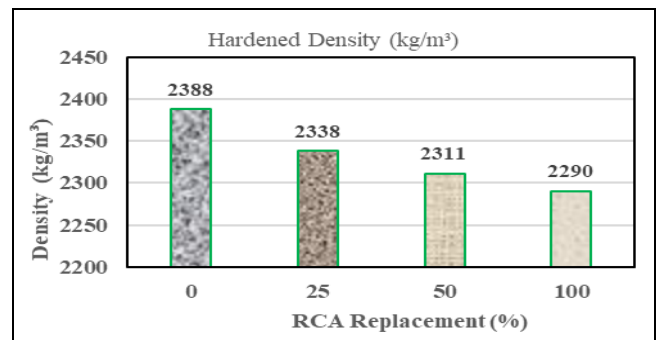


Fig -11: Hardened density vs RCA replacement ratio

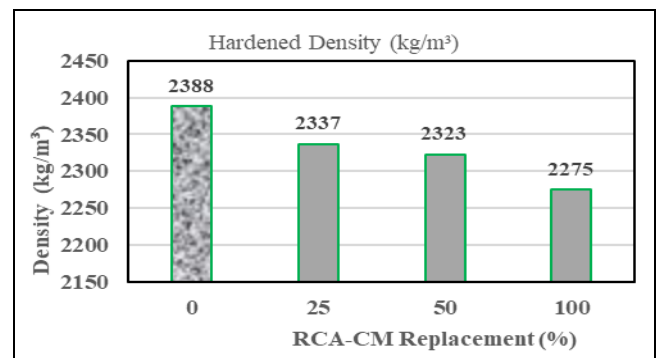


Fig -12: Hardened density vs RCA-CM replacement ratio

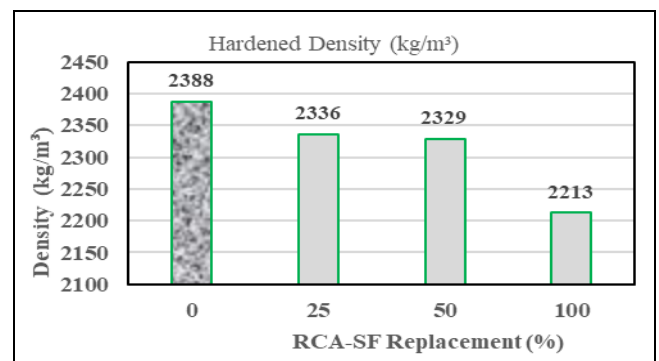


Fig -13: Hardened density vs RCA-SF replacement ratio

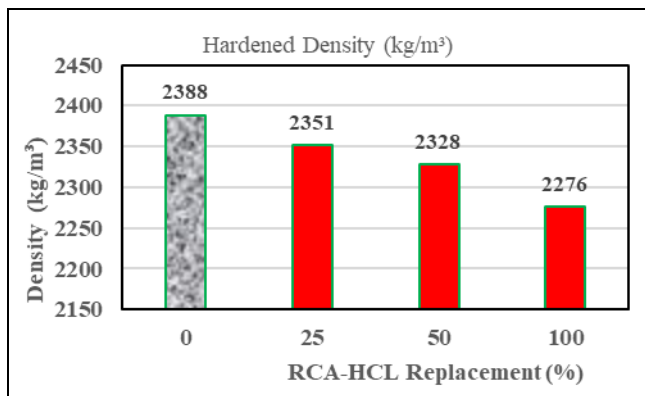


Fig -14: Hardened density vs RCA-HCL replacement ratio

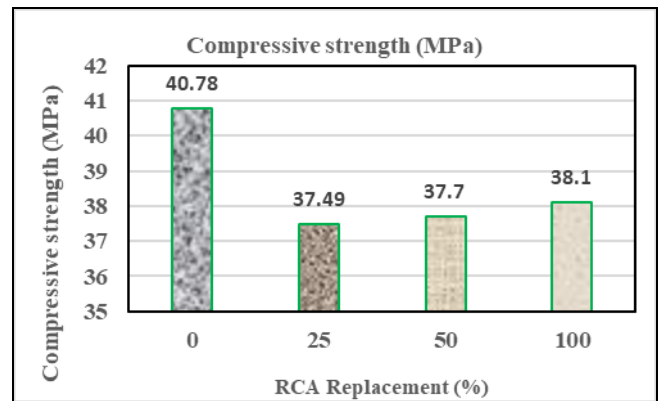


Fig -17: Compressive strength vs. RCA replacement ratio

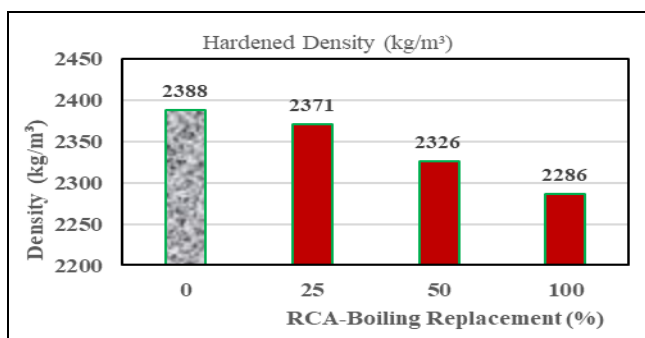


Fig -15: Hardened density vs RCA-Boiling replacement ratio

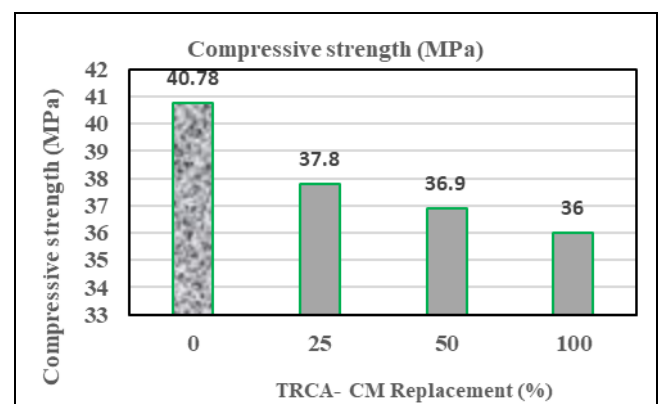


Fig -18: Compressive strength vs. RCA-CM replacement ratio

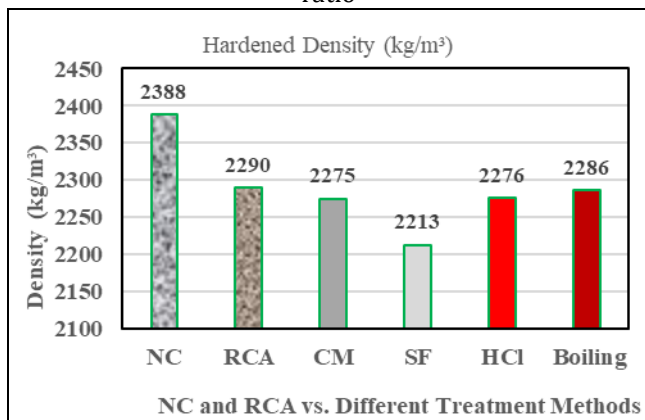


Fig -16: Hardened density vs different treatment methods of RCA concretes

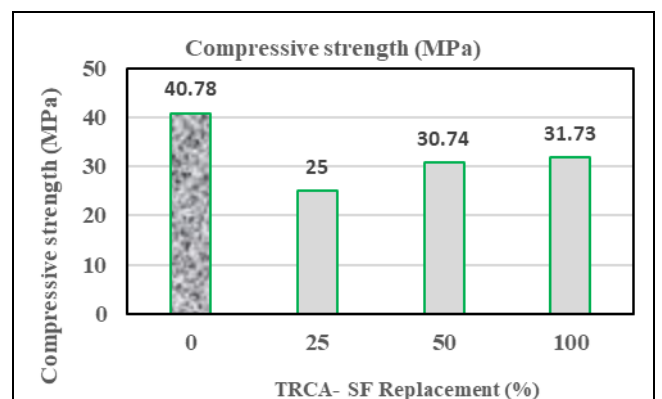


Fig -19: Compressive strength vs. RCA-SF replacement ratio

Figs. 17-22 present the compressive strength of the concretes with different of treatment methods. HCL method gave the less value (reduction up to 51.6 %) of the compressive strength due to make the weak bonding for the mixture than other methods. While the boiling of water method decreases the compressive strength up to 17 %, this result gives good indication for this method compared to the NC and other methods.

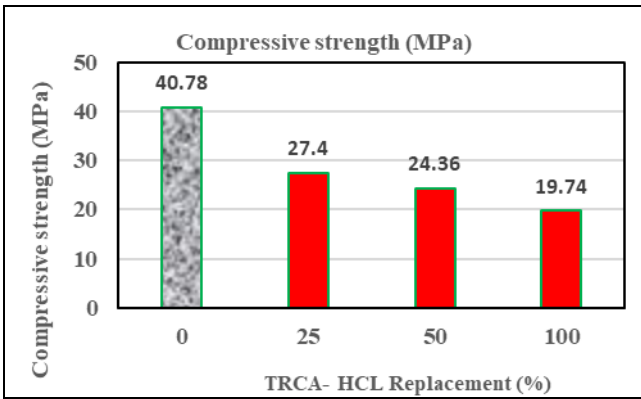


Fig -20: Compressive strength vs. RCA-HCL replacement ratio

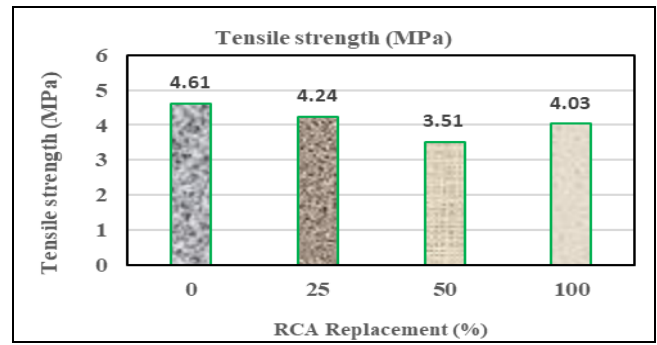


Fig -23: Tensile strength vs. RCA replacement ratio

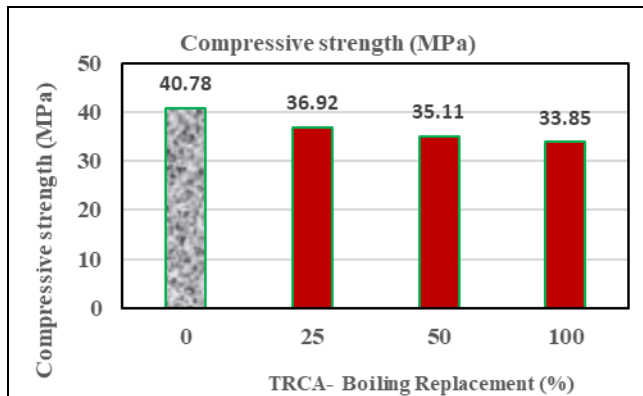


Fig -21: Compressive strength vs. RCA-Boiling replacement ratio

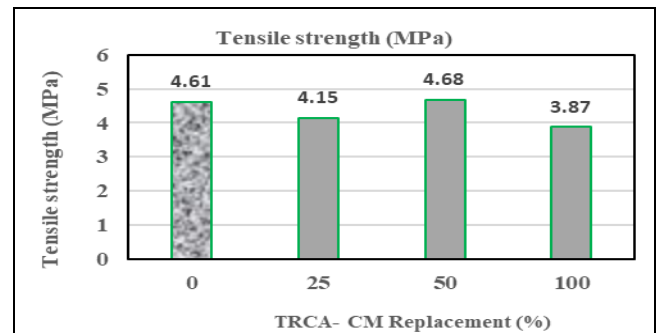


Fig -24: Tensile strength vs. RCA-CM replacement ratio

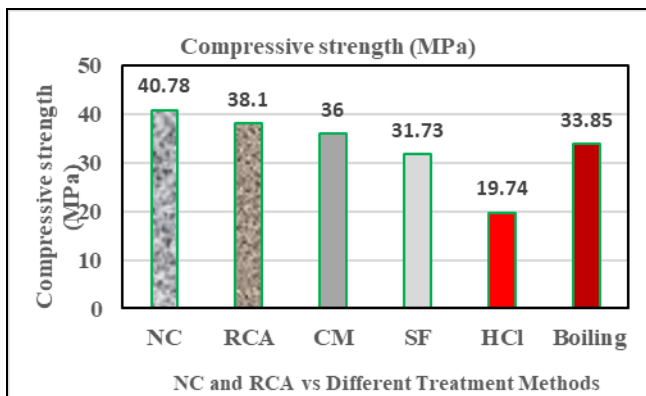


Fig -22: Compressive strength vs. different treatment methods of RCA concretes

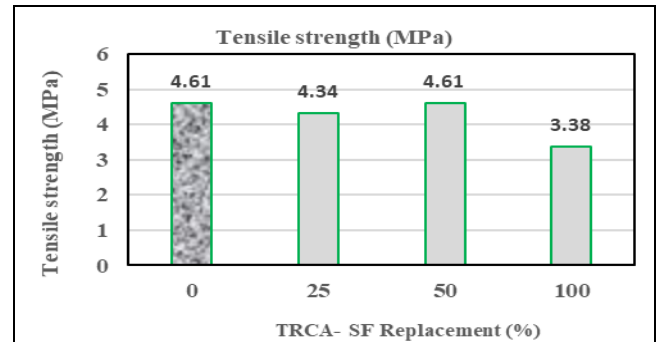


Fig -25: Tensile strength vs. RCA-SF replacement ratio

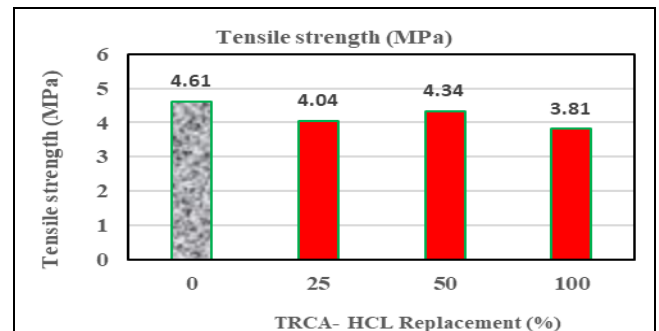


Fig -26: Tensile strength vs. RCA-HCL replacement ratio

Figs. 23-28 present the tensile strength of the concretes with different of treatment methods. Boiling method gave the less value (reduction up to 42.5 %) of the tensile strength due to make the weak bonding for the mixture than other methods, as reveal in Fig. 28.

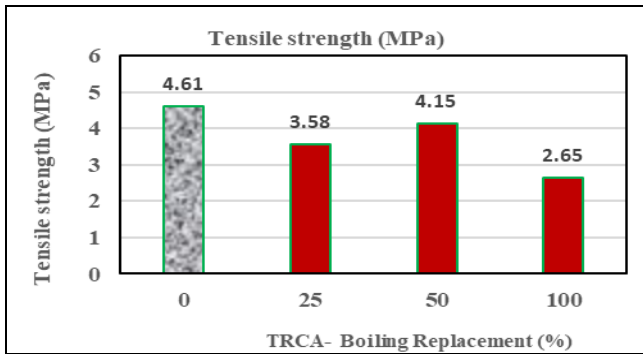


Fig -27: Tensile strength vs. RCA-Boiling replacement ratio

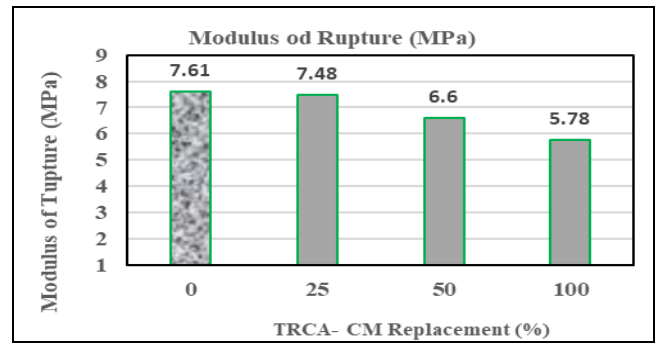


Fig -30: Modulus of rupture vs. RCA-CM replacement ratio

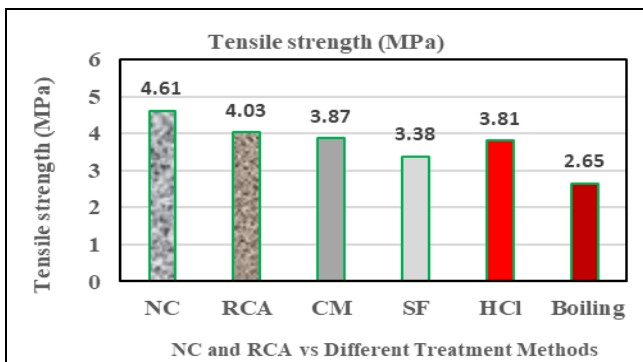


Fig -28: Tensile strength vs. different treatment methods of RCA concretes

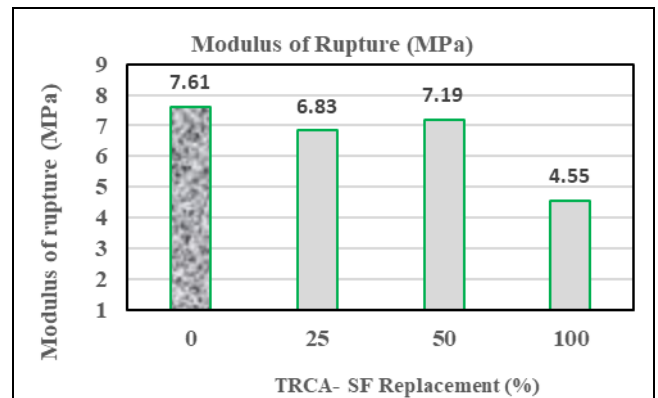


Fig -31: Modulus of rupture vs. RCA-SF replacement ratio

Figs. 29-34 present the modulus of rupture of the concretes with different of treatment methods. Boiling method gave the less value (decrease up to 53 %) of the modulus of rupture due to make the weak bonding for the mixture than other methods, as showed in Fig. 34.

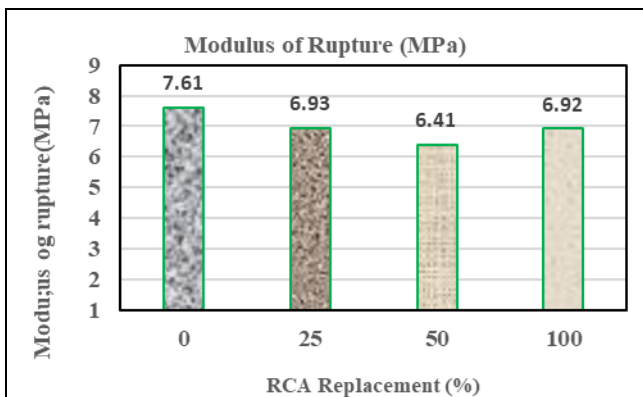


Fig -29: Modulus of rupture vs. RCA replacement ratio

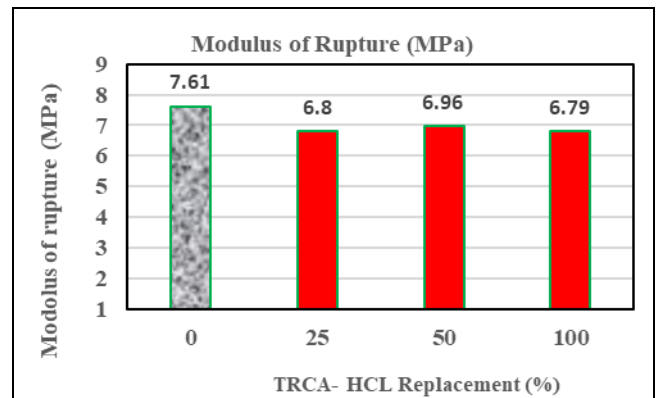


Fig -32: Modulus of rupture vs. RCA-HCL replacement ratio

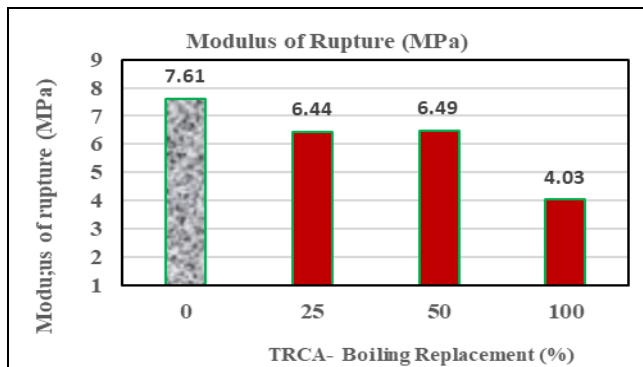


Fig -33: Modulus of rupture vs. RCA-Boiling replacement ratio

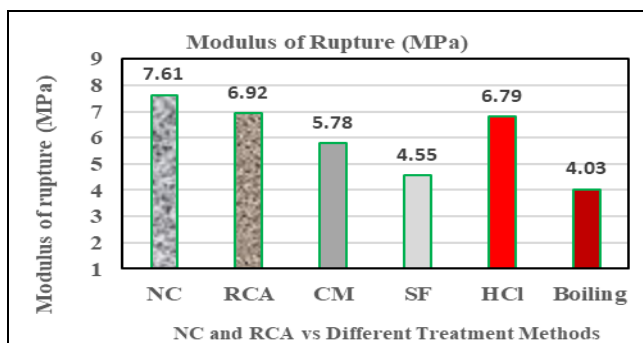


Fig -34: Modulus of rupture vs. different treatment methods of RCA concretes

8. CONCLUSIONS

The mechanical properties of concrete incorporating treated RCA with different methods are presented herein. Four surface treatment methods (three using before and one proposed here) were employed to improve the quality of RCA, which is (cement slurry coating, silica fume slurry coating, soaking RCA in HCL acid, boiling RCA in hot water (100 °C), that proposed method. Each treatment method was evaluated through four replacement ratios of RCA (0%, 25%, 50%, and 100%) instead of natural aggregate (NA). As fellow, we can draw several conclusions: -

1. The fresh and hardened densities were reduced by up to 6.7% and 7.3%, respectively, using the SF treatment method.
2. In comparison to the NC, the HCL treatment procedure significantly reduced the concrete's compressive strength by up to 51.6%.
3. The boiling method of treatment reduced the concrete's tensile strength and rupture modulus by up to 42.5% and 53%, respectively.
4. When compared to other treatment methods, the boiling technique yields a good result for the concrete's compressive strength.

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