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Effect of Treated Recycled Aggregate on Mechanical Properties for Green Self-Compacting Concrete

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Abstract

This work aims to improve the mechanical characteristics of recycled aggregate self-compacting concrete (SCC) mixtures by immersing recycled aggregate (RA) in a cement silica fume slurry (CSFS). An experimental study was conducted on several mixtures made up of a variety of aggregate type (normal aggregate, untreated recycled aggregate, treated recycled aggregate) utilizing different replacement ratios of 0%, 30%, 60%, and 100% of recycled aggregate. All mixes were tested for their fresh characteristics using slump flow, T_{500}, and V-funnel tests, and their hardened characteristics were measured by compressive, splitting, and flexural concrete strength. The results indicated that the suggested treatment approach was effective for the physical characteristics of treated recycled aggregate, which exhibited greater specific gravity and reduced water absorption compared to untreated recycled aggregate. Regarding the fresh properties, research results indicated that most of the untreated RA-SCC mixtures met the Self-Compacting Concrete criteria (EFNARC guidelines), influencing the stated slump flow diameter of 600–685 mm, T_{500} ranging from 2.2–3.8 seconds, and V-funnel flow time between 5.1–13.7 seconds. For hardened characteristics, it was observed that replacing natural aggregate (NA) with recycled aggregate (RA) resulted in a significant reduction in compressive and tensile concrete strength values. In contrast, SCC mixtures, including treated RA, exhibited enhanced compressive, splitting tensile, and flexural strengths proportional to the replacement percentage. Thus, the results indicated that it is possible to produce SCC mixtures using treated recycled aggregates that offer reliable structural performance when utilized in reinforced elements. Finally, the effects of untreated RA, treated RA, and replacement ratio on the mechanical properties of the SCC mixes were individually quantified by the power equations, and a model for predicting the splitting and flexural strength of sustainable concrete mixes was proposed and verified.

Keywords: Green concrete, Treated recycled aggregate, Hardened characteristics, Sustainable, Splitting strength prediction, Flexural strength prediction.

1. Introduction

Concrete is the main construction material utilized in almost all global building projects, which is one of the main reasons for the development that one may observe in our lives. It is generally recognized that the normal coarse aggregates are the main component of the concrete matrix. Nevertheless, in numerous areas, natural aggregates are expensive due to their limited resources. In reaction to the current global growth in construction, there has been a higher use of normal coarse aggregates in the building industry. The utilization of natural aggregates increasingly rises with the speed of infrastructure development. Additionally, repair efforts and catastrophic events, such as winds and earthquakes, produce substantial amounts of building waste [1–4]. The Environmental Protection Agency estimates that annually the amount of waste through construction demolition trash and building repair were roughly 170 million tons. Eurostat shows that the volume of Construction and Demolition Waste (CDW) produced in the EU is around 850 million tonnes, whereas the UK generates roughly 110 million tons [5]. The generation of daily waste material in India was ranked fourth in worldwide consumption [6]. Further, the rapid increase of building waste has highlighted the necessity of utilising efficient techniques for waste management to resolve this issue. Disposing of waste in unacceptable neighbouring areas can lead to significant environmental problems. Numerous developed and developing countries are facing problems with controlling and disposing of trash due to the lack of landfills and increasing transportation costs.

To address these issues and protect the environment, researchers may consider using a different type of coarse aggregate in place of normal aggregates in the concrete mixture through recycling. This approach reduces environmental pollution, conserves landfill space, and protects natural aggregate resources [7-10]. Recycling is the process of converting wasted materials into new products. The theory of recycling Construction and Demolition Waste (C&DW) developed post-World War II, as a result of the extensive bombarding from 1939 to 1945 in the United States of America [11]. The waste was utilized as a substitute for cement, fine aggregates (sand), and coarse aggregates (gravel) in concrete mixture. However, the replacement of natural aggregate (NA) particles with recycled aggregates (RA) obtained from crushed waste was more commonly used as coarse aggregates represent a larger volume inside the concrete matrix. Therefore, the benefits of recycling waste concrete included conserving conventional aggregates and a decrease in the waste management demand in a certain amount [3]. In general, wasted concrete is crushed and screened to produce RA as a substitute for NA. Therefore, numerous experimental studies have been performed to evaluate the fresh and mechanical properties of RA. The initial study on RA from Japan was published in 1988 [4]. The effect of RA on compressive concrete has been investigated in numerous research studies [12-16]. In this regard, Çakır [17] investigated the effect of utilising a full replacement ratio of recycled concrete aggregate (RCA) substitution on the compressive concrete strength (f_{cu}). It was found that concrete strength made with a 100% substitution of recycled concrete aggregate (RCA) decreases by about 24% when compared with concrete made with natural aggregate (NA). Further, Bai et al. (2020) and Sayhood et al. (2019) [18–19] observed a reduction in the concrete strength and splitting strength mixture when incorporating recycled aggregates (RA). A significant reduction in concrete strength was seen when normal aggregates were replaced with RA [20]. Corinaldesi [21] studied the mechanical characteristics of concrete made from recycled concrete aggregate. The required concrete compressive strength may be achieved with a substitution of up to 30% RCA. Nevertheless, with this RCA substitution, the elastic modulus (E) dropped by 15% relative to that of NA-based concrete. Sayhood et al. (2019) [19] found that using 100% recycled aggregate (RA) led to a significant decrease of about 25% in compressive concrete strength and 20% in indirect splitting concrete strength. Malešev et al. [22] investigated the performance of both fresh and hardened concrete properties with varying replacement ratios of recycled concrete aggregate (0%, 50%, and 100%). The researchers observed that the bulk density of fresh mix concrete, wear resistance, and modulus of elasticity dropped when the amount of RCA increased. Nevertheless, the properties of concrete produced from RCA were influenced by the source of RCA utilised [17, 20]. Generally, a significant reduction in concrete strength was noticed with an increase in the RA substitute level. The full replacement of normal aggregate with recycled aggregate led to a decrease in tensile concrete strength of approximately 30% compared to NA concrete mixture. Concerning the elastic modulus (E) of recycled aggregate concrete mixture, Zhou et al. [23] observed that the elastic concrete modulus decreased by approximately 25% relative to that of natural aggregate concrete mix. However, a more significant reduction in the elastic recycled concrete modulus was noted when normal aggregate was substantially replaced in RA. It is important to mention that the previous literature studies above have mainly focused on the characteristics of conventional concrete (CC); nevertheless, there are only a few studies that have highlighted the incorporation of recycled aggregate in self-compacting concrete (SCC) mix. Grdic et al. [24] reported that self-compacting concrete (SCC) mixes may be efficiently produced by utilising recycled aggregate (RA) with a variety replacement ratio of 50% and 100%. However, an increase in the water content of the mix was required for obtaining the identical slump flow spread when utilising full replacement of recycled material. Therefore, this adversely affected the mechanical characteristics of the created SCC mixtures. Yue et al. [25] conducted an experimental investigation for creating SCC mixes which incorporating two different replacement ratio of RA (50% and 75%). Both of these replacement ratios (50% and 75%) showed a negative influence on the fresh and hardened SCC concrete mixed fresh and mechanical performance. This may be attributed to the angular morphology of RA particles, which enhances their water absorption capacity. As noted by Doaa and Abo Daheer [26], SCC mixtures presenting adequate performance may be achieved by using an optimal quantity of RA, powder, and superplasticizers. Further, they showed that adding soaked RA may reduce its adverse effects on the workability and mechanical performance of SCC-tested mixtures. The experimental work conducted by Kou and Poon [27] showed that the characteristics of SCC mixes using RA were slightly affected. Based on the above-reviewed literature, it is indicated that the RA concrete is always accompanied by inferior mechanical performance in terms of compressive strength, tensile strength, and modulus of elasticity. This reduction in fresh and mechanical behavior is attributable to many variables, including old cement mortar on recycled aggregate (RA) surface and increasing water absorption resulting from a higher porosity in RA compared with normal aggregate (NA) [28]. RA has slight adhesion capacity in the interfacial transition zone (ITZ) compared to NA. Additionally, RCA has many transition zones, including an interfacial transition zone (ITZ) between the newly added aggregate and the pre-existing cement mortar on recycled aggregate (RA), as well as an ITZ between the pre-existing mortar and the new mortar [29]. Generally, ITZ is influenced by the type of coarse aggregate used and the water transport at the mortar paste-aggregate interaction in the hydration process [30-33]. Thus, poor adhesion efficiency, along with the increased interfacial transition zones, negatively affects the mechanical characteristics of recycled concrete aggregate [29, 31].

To solve this issue, numerous studies were evaluated that enhanced the performance of RCAs using different treatment techniques. Shi et al. [34] published an extensive literature assessment on these methods. The authors classified the treatment methods as follows: They grouped the treatment methods into these categories: (1) grinding with machines or heat; (2) soaking in water or acid; (3) using a polymer mixture; (4) using a pozzolan mixture; (5) using calcium carbonate from biological sources; (6) using a sodium silicate solution; and (7) using carbonation. Generally, the treatment procedures for RCA involve either an enhancement or removal of the adhering cement mortar. Pre-soaking old cement mortar is recognised as one of the most effective, environmentally friendly, and practical procedures for enhancing the mechanical characteristics and durability of recycled concrete aggregates (RCA). Various techniques for improving adhered mortar, including modifying the concrete mix ratios, incorporating supplementary cementitious materials (SCM), treating recycled concrete aggregate (RCA) with organic or inorganic additives, implementing cementitious solutions, utilising the carbonation technique, soaking lime in carbonation, and coating it with polyvinyl alcohol (PVA). Several investigations [35-37] indicate that improving the concrete mixing process resulted in an increase in its compressive strength. In addition, the addition of inorganic compounds increased f_{cu} by 15% [38]. Mineral compounds, including fly ash or volcanic ash, have been reported to improve the durability properties of RCA when used [39]. Moreover, researchers recommend the use of silica fume and fly ash in recycled concrete aggregate (RCA) as the most efficient technique for enhancing compressive concrete. Moreover, the coating treatment techniques, which involved presoaking recycled aggregate in 0.1 M hydrochloric acid, effectively removed loose old cement particles, therefore significantly improving the properties of the RCA [40]. Regarding these treatments' techniques, one that produces adequate performance involves protecting the adhering old cement from RA to reduce its adverse effects. This can be performed by using an enhanced treatment technique for RA [41-43]. These methods included saturating recycled aggregate particles in a cement-silica fume slurry (CSFS) solution before being used in concrete mixes. Several investigations have indicated that the addition of specific amounts of CSFS to RA concrete resulted in enhanced mechanical concrete properties [43]. Alqarni et al. [44] examined the fresh and hardened characteristics of recycled aggregate concrete mixtures affected by various parameters, involving four replacement proportions of 0%, 33%, 67%, and 100% RA, as well as two maximum coarse aggregate sizes of 10 mm and 20 mm using the CSFS treatment process. The increased substitution ratio of recycled aggregate adversely affected the fresh characteristics of concrete, regardless of the aggregate size. An identical behaviour was observed in mechanical characteristics compared to the control mixture. Treated RCA using CSFS increased slump flow by about 15%-35% relative to the untreated RCA. Additionally, the treated RCA exhibited a more significant improvement in compressive concrete strength, independent of the maximum coarse aggregate particle size. Abdullah et al. [43] conducted laboratory work to improve the mechanical properties of RA-SCC mixtures. The recommended treatment technique has been shown to be beneficial, as the physical characteristics of TRA exhibited higher specific gravity and decreased water absorption compared to untreated RA. In untreated RA mixtures, substituting NA with RA resulted in a significant reduction in f_{cu} and f_{st} values. Nevertheless, a slight decrease in these values was observed when TRA was utilised instead of NA.

The previously mentioned study indicates that limited laboratory work has examined the fresh and mechanical properties of treated recycled concrete aggregate in self-compacting concrete. Thus, additional experimental investigation will be needed in this area. This research aims to investigate the possible enhancement of the fresh and mechanical properties of TRA-SCC mixtures. For this purpose, seven mixtures were prepared utilising four different replacement ratios of recycled aggregate (0%, 30%, 60%, and 100%), with one testing mix as the control mix. Recycled aggregate particles were subjected to a basic improvement method by being submerged in a cement-silica fume slurry (CSFS solution). Following the treatment procedure, a number of SCC mixtures were created and evaluated in both fresh and hardened conditions. The former was assessed by slump flow, T500, and V-funnel tests, while the other was assessed utilising compressive concrete strength, indirect splitting tensile concrete strength, and flexural concrete strength.

2. Experimental Work

2.1. Material properties

2.1.1. Cement, Silica fume, and Limestone powder

In this work, Ordinary Portland cement (CEMI) produced by the AL-JISR Cement Plant was used (Fig. 1a). This conformed to Iraqi Standard Specification (IQS) Iraqi Specifications No. (45), 1984 for Portland Cement [45]. A finer grey color powdered form, known as silica fume, was utilised in the production of a cement-silica fume slurry (CSFS solution), which was used to treat recycled aggregate (soaking) before being used in SCC mixes. The silica fume utilised meets the requirement specifications of ASTM C1240-04. A locally available limestone powder (LP) (named Al-Gubra) was used to improve fluidity and cohesiveness as well as enhance resistance to segregation of the mix (Fig. 1b). The used LP (less than 0.125 mm) satisfies EFNARC guidelines for SCC requirements, EFNARC Guidelines, 2005 [46].

(a) AL-JISR (b) Al-Gubra (LP) (c) Glenium 54 (SP)

Fig. 1. Material used in prepared SCC mixes.

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2.1.2. Superplasticizer

A high-range water-reducing chemical admixture (superplasticizer), commonly known as Master GLENIUM® 54, was utilized in the present investigation. Fig. 1c shows the superplasticizer used in this study. It meets the requirement of ASTM C-494.

2.1.3. Aggregate

Three different types of aggregates were employed. These are fine aggregates (Sand), natural and recycled coarse aggregates (Gravel). Well-graded natural sand readily available was used in this study. This material originates from the Al-Najaf quarry. The sand conforms to IQS 45/1984, zone 2 [47]. Fig. 2a illustrates the sieving analysis for this type of aggregate, as well as its specific gravity and fineness modulus, which are presented in Table 1. Natural coarse aggregates (NA) have a bulk density of 1600 kg/m³, specific gravity of 2.68, and water absorption of 0.80% were used in the experiments of this work. Local sources in Iraq provided the gravel, which had a maximum size of 20 mm. Fig. 2b presents the distribution of coarse aggregate particles in accordance with IQS No. 45/1984 [48]. On the other hand, for recycled aggregate, two types of RA were used, which included: Untreated recycled aggregate (URA) and treated recycled aggregate (TRA). All RAs satisfied the Iraqi recommendation (IQS) No. 45/1984 [38]. Recycled aggregate (RA) is produced from crushed old concrete cubes, cylinders, slabs, beams, and other specimens (Fig. 3). All coarse aggregate types were used in saturated surface dry (S.S.D.) state.

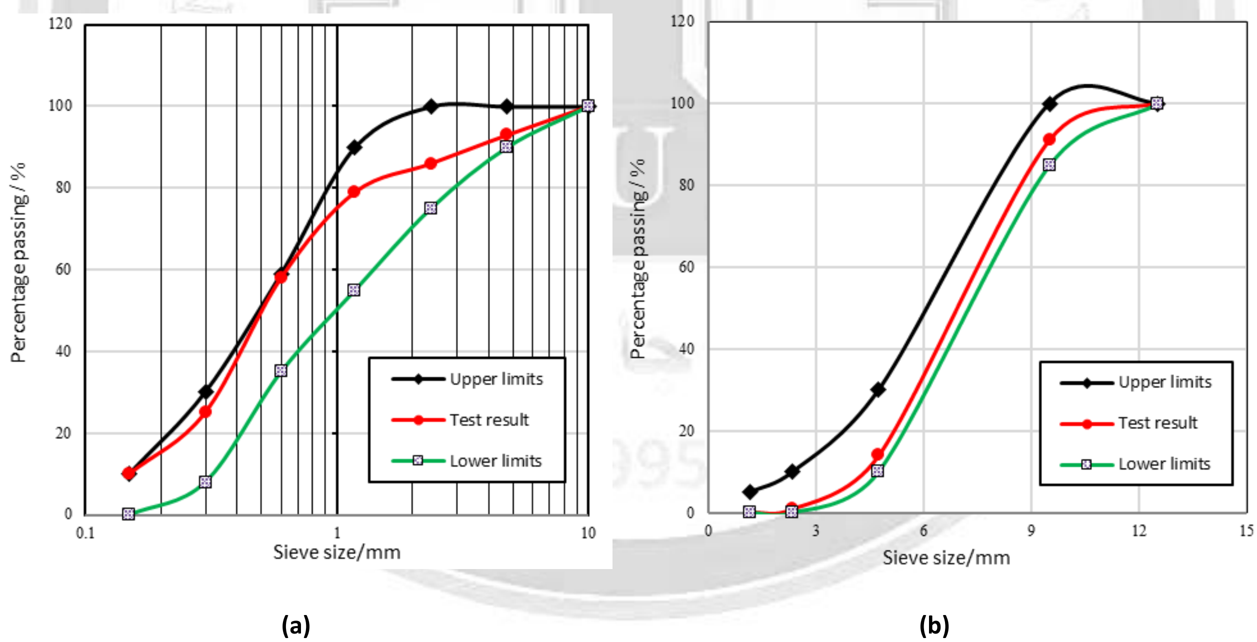

Fig. 2: Sieving analysis of: (a) Natural fine aggregate, and (b) Natural coarse aggregate.

Table 1. Results of Physical testing for fine aggregate components.

Physical properties	Result of testing fine aggregate	Limit of No.45 /1984 [47]
Specific gravity	2.59	--
Sulphate content %	0.13%	≤ 0.5
Fineness modulus	2.54	--
absorption rate	2%	--

Fig. 3. Concrete cubic, cylinders, beams, and slabs are available in Al-Qadisiyah University laboratories.

2.2. Soaking of RA in CSFS

A high volume of old cement-bonded mortar remained on the exterior surface of RA particles during the crushing operation. This may result in the appearance of weak and brittle layers on the recycled aggregate surface, leading to increased water absorption, increased porosity, and reduced density. To enhance the quality and efficacy of recycled particles, it is essential to use a successful treatment approach that the aggregate microstructure. Thus, an effective treatment technique, as suggested by Alqarni et al. [44], was utilized to enhance RA characteristics in the current study. The suggested technique involves submerging crushed RA in a cement-silica fume slurry (CSFS). The RA was first immersed in the slurry solution and then subjected to air-drying in the surrounding environment. After a period of 24 hours, the treated RA was wrapped in wet gunny bags and then cured for a duration of up to seven days. The treated recycled aggregate (TRA) particles showed enhanced physical properties relative to untreated RA, indicating improvements in specific gravity and water absorption. The specific gravity increased to 2.44, in contrast to 2.35 for RA. A notable reduction in water absorption (from 5.1% to 2.9%) was seen on the implementation of this effective treatment technique for RA.

2.3. Proportion of the Prepared SCC Mixes

Seven treated and untreated recycled aggregate SCC mixtures including one made with NA (as a reference mix) were cast in this experimental work with the goal of producing SCC with a targeted 40MPa cubic compressive concrete strength and a 0.44 water-to-cement (w/c) ratio. The mixes were proportioned according to the mix design recommended in [49]. The aggregates substitution was done volumetrically (based on the specific gravity of the aggregates) to keep the amount of remaining mix ingredients constant (cement, aggregate, and water) and to achieve a mix volume of one cubic meter. In the cast mixes, replacement ratios of coarse recycled concrete were considered, as described in Table 2. The concrete quantities are illustrated in Table 3.

Table 2. Identification of the assessed SCC mixtures.

Mixture ID	Mix details
S0-NA	Self-compacting concrete + 0% substitutions untreated recycled concrete aggregate (Reference mix.)
S30-URA	Self-compacting concrete + 30% substitutions untreated recycled concrete aggregate
S60-URA	Self-compacting concrete + 60% substitutions untreated recycled concrete aggregate
S100-URA	Self-compacting concrete + 100% substitutions untreated recycled concrete aggregate
S30-TRA	Self-compacting concrete + 30% substitutions treated recycled concrete aggregate
S60-TRA	Self-compacting concrete + 60% substitutions treated recycled concrete aggregate
S100-TRA	Self-compacting concrete + 100% substitutions treated recycled concrete aggregate

Table 3. Proportional mix of conventional and recycled concrete mixtures (Kg/m^3).

Mixture ID	w/c	C	W	SP%	LP%	FA	CA	RA%
S0-NA	0.44	400	176	4.4	130	770	840	0
S30-URA	0.44	400	176	4.6	130	770	234	30
S60-URA	0.44	400	176	4.7	130	770	468	60
S100-URA	0.44	400	176	4.9	130	770	780	100
S30-TRA	0.44	400	176	4.6	130	770	234	30
S60-TRA	0.44	400	176	4.7	130	770	468	60
S100-TRA	0.44	400	176	4.9	130	770	780	100
C= cement, W= water, SP= superplasticizer, FA=fine aggregate, CA= coarse aggregate, and RA= recycled aggregate.								

2.4. Concrete Mixing process

The mixed ingredients were mixed to achieve the required workability recommended by the EFNARC guideline and homogeneity [46]. A vertically mixing machine with a mixing volume of 0.2 m³ was utilised for the mixing of fresh self-compacting concrete (SCC). This machine was kept clean and moist before starting the mixing process. All materials were placed in a plastic container, and their weights were recorded prior to placing them in the mixing device. Furthermore, all tested materials have been utilized in a saturated surface dry (SSD) state. The next procedure was employed for creating the SCC mixture: Portland cement and coarse aggregate (either normal or recycled) were added with one-third of the total water volume and mixed for approximately two minutes. Limestone powder and sand particles (fine aggregate) were subsequently incorporated and combined with the residual water, that contains superplasticizer, for two minutes. Afterwards, the last third of the water was incorporated and mixed for another minute. The last step involved mixing the slurry materials for an additional minute to ensure homogeneity.

2.5. SCC Casting, Placing, and Curing

After mixing, a slump flow test was performed for all mixtures before they were placed into the moulds. This work investigated both fresh and mechanical testing methods for all SCC mixtures. The flowability of the prepared SCC mixes was checked by performing the slump flow test, the T_{500} test, and the V-funnel test, according to the EFNARC Guidelines (2005) [46]. On the other hand, the hardened properties of the tested mixes were evaluated in terms of compressive, splitting, and fracture strength. The average of three samples were considered for each mix and test. Cubes with dimensions of 100 x 100 x 100 mm, cylinders with dimensions of 100 x 200 mm, and prisms with dimensions of 100 x 100 x 500 mm were utilized. Fig. 4 shows the mouldings utilized and the samples created after casting. The internal surfaces of the molds have been oiled and cleaned well to prevent the concrete from bonding to the molds after hardening. The SCC mixture was cast in the form without an electrical vibrator. Then, the upper surfaces of the modules were modified (Fig. 5). The specimens were left in the moulds for about 24 hours to harden, and then they were opened and cured with water for 28 days (Fig. 6). After that, all the cured specimens were prepared for testing as shown in Fig. 7.

Fig. 4. Moulds used to prepare SCC mixes.

Fig. 5. Casting of SCC mixes.

Fig. 6. Curing concrete.

Fig. 7. Specimens prepared for mechanical tests.

2.6. Fresh SCC Concrete Testing

The slump flow, T_{500}, and V-funnel test was conducted to determine the flow-ability of the prepared SCC mixes according to EFNARC Guidelines (2005) [46]. T500 describes the period of time necessary for the fresh mixture to expand at a diameter of 500 mm in horizontal flow. The instrumentation utilised consisted of an Abram cone on an upper diameter of 100 mm, a bottom diameter of 200 mm, and an overall height of 300 mm, and a smooth plate measuring 900×900 mm, as illustrated in Fig. 8. However, the V-funnel test was implemented to evaluate the filling capacity and viscosity of SCC. The test was carried out according to EFNARC (2005)

[46] utilising the instrumentation illustrated in Fig. 9. While filling the funnel, the tiny door at its base was opened to permit the SCC to flow out by gravity, and the duration from the gate's opening until the first light appeared at the top of the funnel was first seen was measured with a timer.

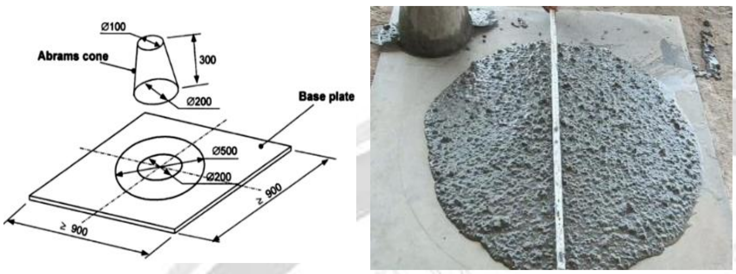

Fig. 8: T_{500} and Slump test for concrete mixture.

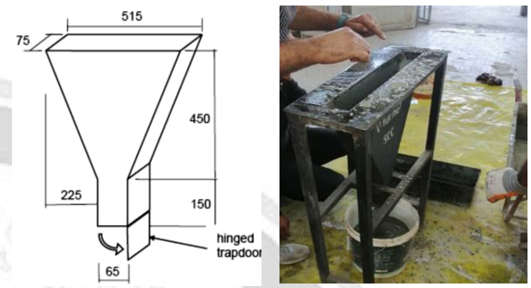

Fig. 9: V-funnel test apparatus.

2.7. Hardened Concrete Testing

The hardened properties of the tested SCC mixes were evaluated in terms of compressive strength, splitting tensile strength, and modulus of rupture. The average of three samples was considered for each mix and test. The compressive strength test was performed by casting concrete cubes having dimensions of 100x100x100 mm. An average value of these cubes was taken, complied with the requirements of BS EN 12390-3 (2009) [50]. The specimens were tested (Fig. 10a), and they were placed in the center of the testing device. After applying the load to the specimens, the failure load was recorded. Each mix was based on an average of three readings. However, indirect tensile concrete strength was measured using cylindrical specimens according to BS EN 12390-6 [51]. The cylinder has a diameter of 100 mm and a height of 200 mm. Thin wood strips were put over and under bearing base plates of the testing equipment (Fig. 10b). The values reported in this investigation were averaged from three cylinders aged 28 days. Further, to determine flexural strength (f_r), prism specimens of 100 x 100 x 500 mm were evaluated under three-point bending (Fig. 10c) according to ASTM C 293 [52] specifications. All testing was carried out using equipment provided in the Engineering College Material Lab at Al-Qadisiyah University.

(a) Cubes concrete under compression.

(b) Cylinder concrete under splitting strength.

(c) Three-point load flexural test.

Fig. 10. Testing process for mechanical proprties.

3. Results and Discussions

3.1. Characteristics of Fresh Mixes

The slump flow test was used to evaluate the filling capacity of self-compacting concrete in the presence of obstacles. According to the EFNARC Specifications (2005) [46], self-compacting concrete (SCC) is categorised into three groups based on how far it flows: SF1 (550 to 650 mm), SF2 (650 to 750 mm), and SF3 (750 to 850 mm). The prepared SCC mixes conform to the SF2 classification, the most common type in concrete buildings. The slump diameters for tested SCC mixtures varied between 600 and 685 mm. Fig. 11 showed the prepared SCC mixtures met the required flow specifications. This was achieved by incorporating an optimum amount of superplasticizer. Other studies have observed a similar result [41, 43]. However, Figure 12 indicates that T_{500} varied from 2.2 to 3.8 seconds, which remains within the specified slump flow group (SF2). It is important to mention that the T_{500} test of fresh mixes of SCC containing RA was slightly higher compared with that of NA. Nevertheless, T_{500} was slightly affected when treated RA was utilized instead of natural aggregate. The proposed treatment method improves the adhesion of old mortar on RA surfaces, leading to slightly rounder aggregates. Furthermore, the tested fresh SCC mixes reported no segregation. The V-funnel test was performed to evaluate the flowability, stability, and viscosity of concrete through a tiny opening. The measurement indicates the time required for concrete to exit the funnel. Furthermore, the higher flow time seen in this test signifies that the slurry has significantly higher viscosity. The EFNARC specification for V-funnel flow duration specifies a range of 7 to 11 seconds for SCC mortars [46]. The recorded duration for the V-funnel testing in this investigation varied from 5.1 to 13.7 seconds (Fig. 12). The minimal value of the V-funnel indicated perfect flowability in the fresh mixture.

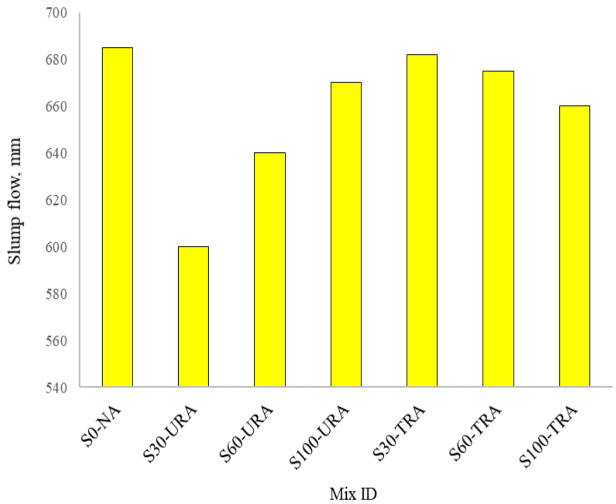

Fig. 11. Variation of slump flow in the tested mixes.

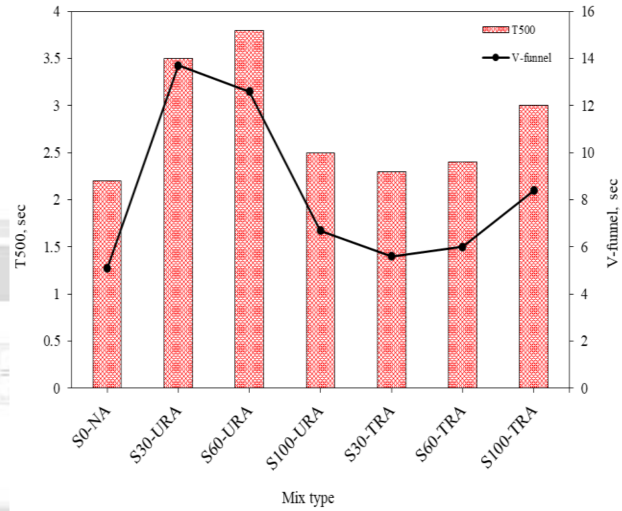

Fig. 12. Variation of T_{500} and V-funnel in the tested mixes.

3.2. Mechanical Properties

3.2.1.Compressive strength

The fracture and concrete compressive strengths for experimental testing concrete mixes were affected by various factors, including material characteristics and mixing and casting techniques. In recycled aggregate (RA) concrete, this characteristic (under specific conditions) can be influenced by various elements, such as the water/cement ratio (w/c), the characteristics and proportion of RA, and the volume of adhering mortar connected with the RA particles [53]. Cube moulds were utilized to evaluate the compressive concrete strength (f_{cu}) of SCC mixtures at 28 days, which contained various types of aggregates, including natural aggregates, untreated recycled aggregates, and treated recycled aggregates, as well as different substitution ratios. Table 4 and Fig. 13-14 illustrate mechanical properties of the test results. As indicated by the results, the untreated and treated recycled aggregate concrete mixes exhibited a lower f_{cu} when compared to the control mix (S0-NA mix). For mixes that replaced 30%, 60%, and 100% of the recycled aggregate, the compressive strength decreased by about 21.39%, 22.68%, and 31.44%, respectively, compared to the reference mixture. This may be attributed to the reduced capacities of untreated recycled aggregate to loads in comparison to normal coarse aggregate [41-43]. When TRA was incorporated into SCC mixes with substitution levels of 30%, 60%, and 100%, the enhancements observed were 17.01%, 16.24%, and 3.61%, respectively, in comparison to the control mix (S0-NA mix). This means that the f_{cu} improved by 5.57%, 28.39%, and 88.52% relative to untreated RA. This enhancement is due to the treatment method, which involved adding cement and silica fume slurry. This supported the appropriate performance of the treatment, which enhanced the RCA's new ITZ connect [44].

Table 4. Mechanical properties of hardened concrete used in the SCC mixes.

Mix ID	Compressive strength (f_{cu}), MPa	% Reduction in f_{cu}*	Splitting tensile strength (f_{st}), MPa	% Reduction in f_{st}*	Flexural strength (f_r), MPa	% Reduction in f_r *
S0-NA	38.80	0.00	3.80	0.00	6.66	0.00
S30-URA	30.5	-21.39	2.96	-22.11	6.01	-9.76
S60-URA	30.00	-22.68	2.69	-29.21	5.21	-21.77
S100-URA	26.60	-31.44	2.32	-38.95	4.90	-26.43
S30-TRA	32.20	-17.01	2.89	-23.95	6.32	-5.11
S60-TRA	32.50	-16.24	3.02	-20.53	5.59	-16.07
S100-TRA	37.40	-3.61	2.93	-22.89	5.40	-18.92
* Relative to control mix (SCC-0URA)						

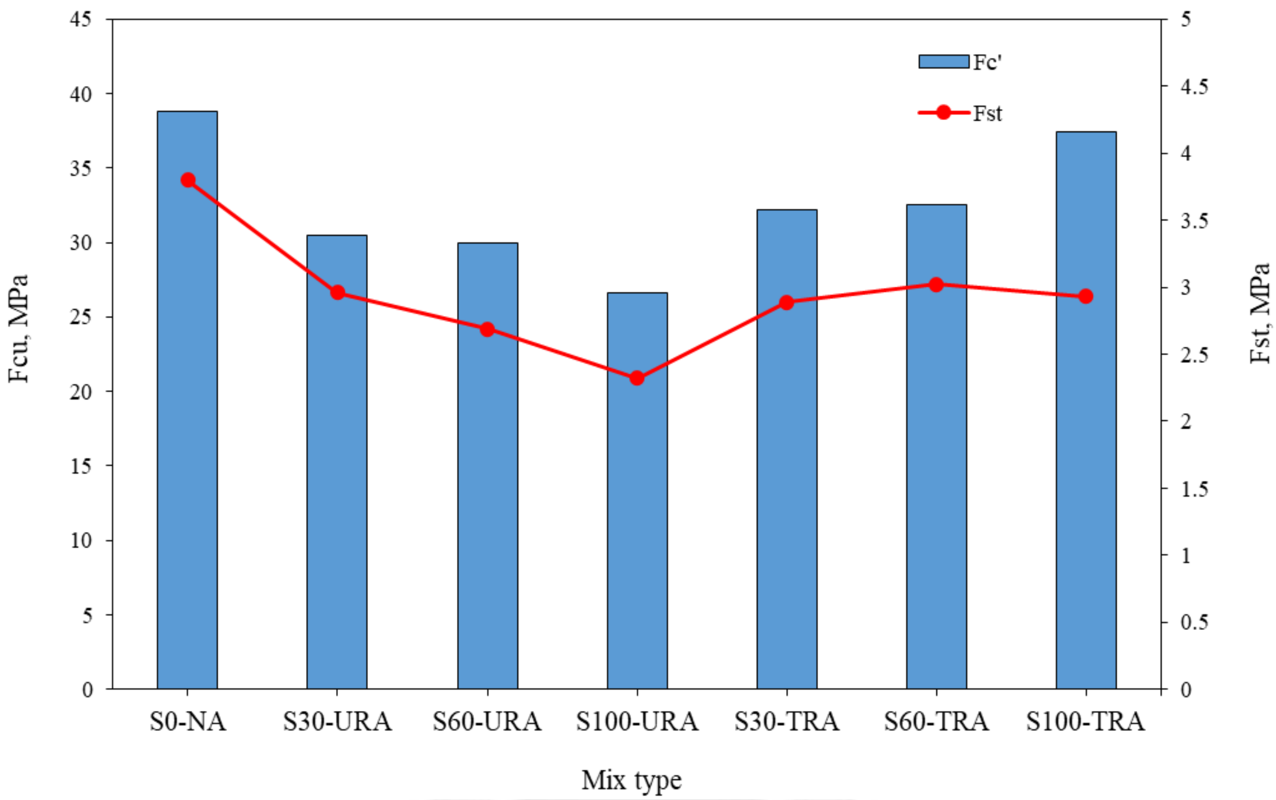

Fig. 13. Mechanical properties of the tested SCC mixes.

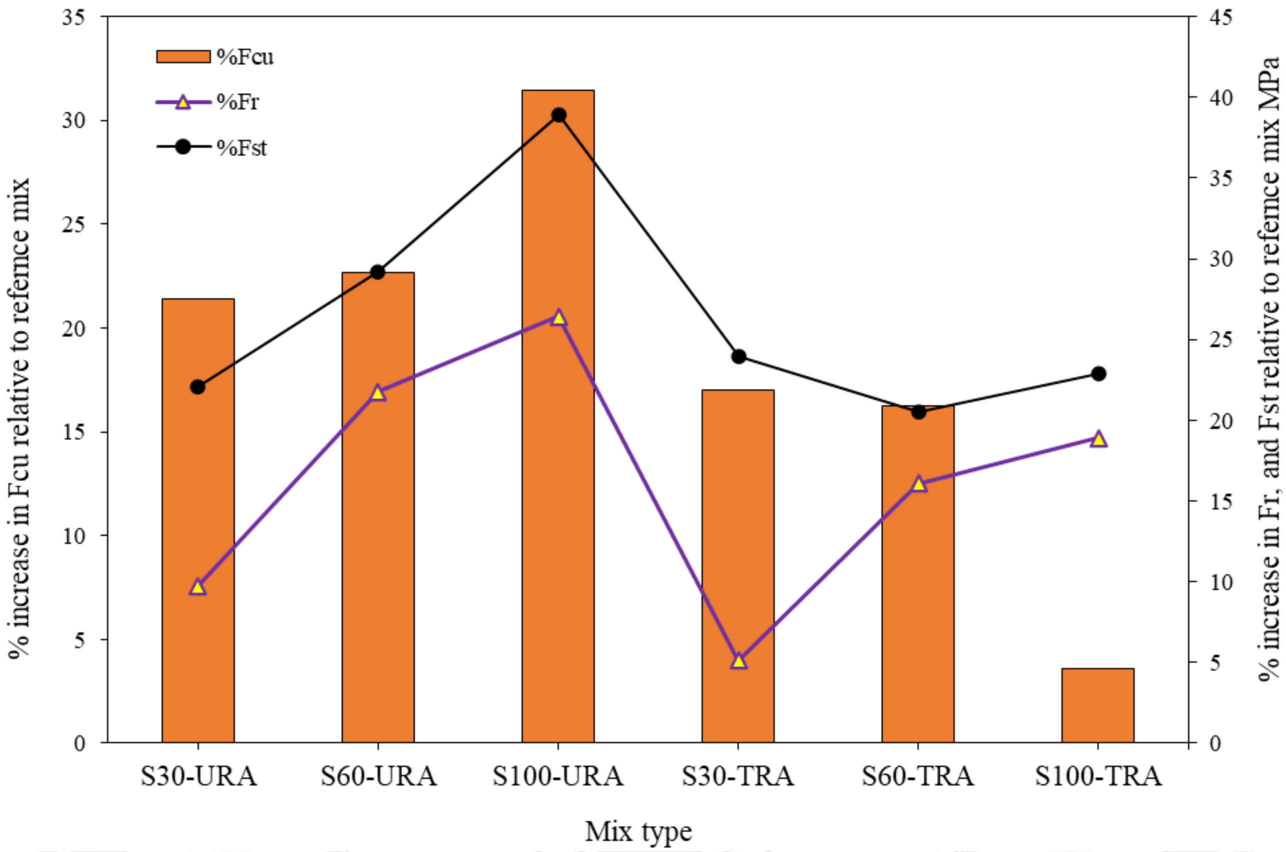

Fig. 14. Percentage increase in the f_{cu}, f_{st} and f_r relative to control mix (S0-NA mix).

3.2.2. Splitting tensile strength

The compressive and splitting tensile strengths of concrete are directly related, and the ratio between the two strengths depends on the level of concrete strength. The current research conducted a splitting tensile strength (f_{st}) testing at 28 days of SCC mixes utilizing recycled material with varying replacement ratios of 0%, 30%, 60%, and 100%. The results and conclusions of the tested SCC mixture are illustrated in Fig. 13-14 and Table 4. The effect of mixing untreated RA and treated RA on SCC mixes has been shown as similar in terms of compressive strength. In comparison to the control mix, both of the first mixtures, including untreated RA and treated RA, decreased by 22-39% and 20-24%, respectively. Fig. 12 shows that the incorporation of recycled aggregates (mixes S30-URA, S60-URA, S100-URA, S30-TRA, S60-TRA, and S100-TRA) resulted in a reduction of f_{st} by approximately 22.11%, 29.21%, 38.95%, 23.95%, 20.53%, and 22.89%, respectively, in comparison to the control mix containing normal aggregate (S0-NA mix).This behavior was similarly observed by Andreu and Miren, as well as Bairag et al. [54-55], which noticed a significant reduction in f_{st} when replacing NA with RA. This reduction may be attributed to RA's inferior resistance to tensile stresses compared to NA. The inferior interfacial transition zone (ITZ), which affects the adhesion between recycled aggregate (RA) surfaces particles and cement paste, could explain the

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decreased tensile strength for RA [56]. In contrast, the utilization of treated recycled aggregate (with substitute ratios of 30%, 60%, and 100%) resulted in enhancements of 2.36%, 12.27%, and 26.29% in f_{st}, respectively, as compared to the untreated RA mix. The FST of SCC mixtures which include TRA was greater than that of RA mixtures when compared to the reference mix. These findings concurred with those of the most recent study [44]. Abdullah et al. [41] exhibited a comparable tendency while utilizing SCC mixtures with treated RA.

3.2.3. Flexural strength

The effect of aggregate types on the 28-day flexural concrete strength for mixes of SCC is shown in Fig. 15 and Table 4. To determine the flexural strength (f_r) of the SCC mixes, prism specimens of 100 x 100 x 500 mm were tested under three-point bending. Table 4 presents the results of the f_r testing. The fracture strength of the mixtures made with recycled aggregate (S30-URA, S60-URA, S30-TRA, S60-TRA, and S100-TRA) decreased by about 9.76%, 21.77%, 26.43%, 5.11%, 16.07%, and 18.92%, respectively, in comparison to the reference mix (S0-NA mix). This outcome is compatible with previous research results obtained by Dimitriou et al. (2018) [57]. Remarkably, substituting untreated RA with treated RA significantly enhances the f_r of the studied SCC specimens, offering improvements of approximately 5.16%, 7.29%, and 10.20% for S30-TRA, S60-TRA, and S100-TRA, respectively, in comparison to the untreated recycled aggregate mixtures. This signifies that the suggested treatment method is effective.

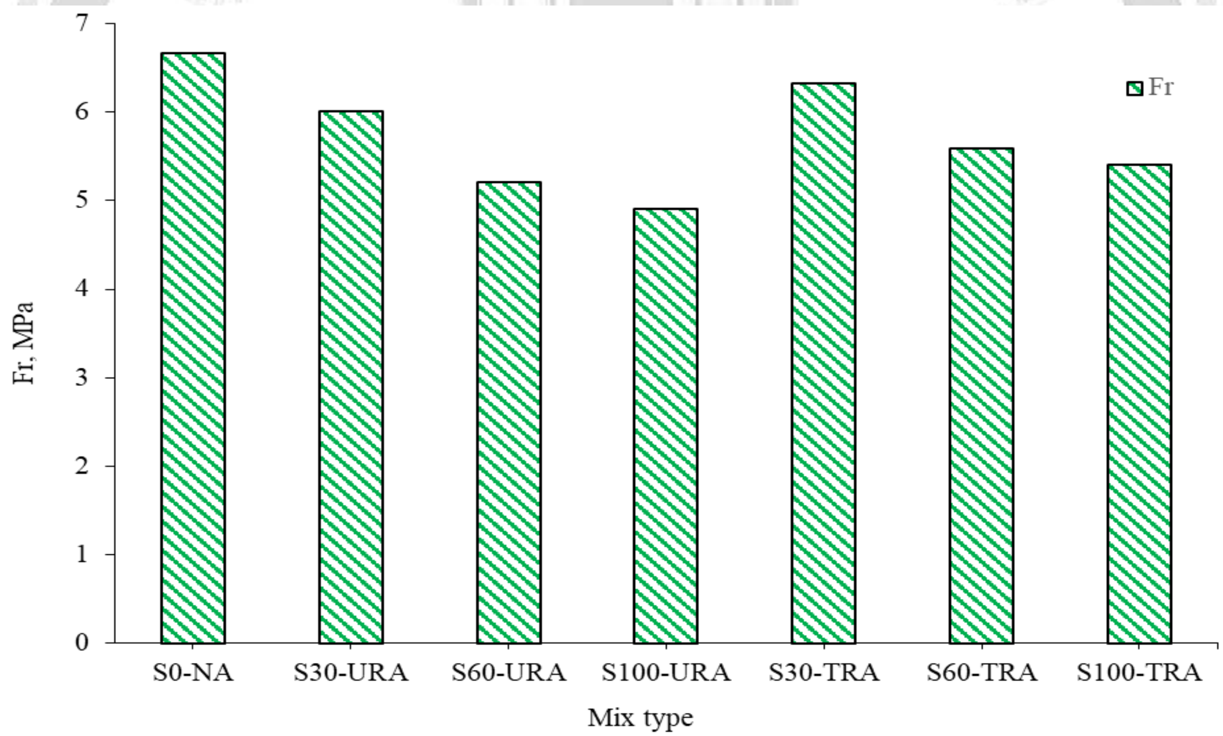

Fig. 15. Flexural strength of the tested SCC mixes.

4. Mechanical properties prediction

Based on the laboratory results for seven SCC mixes in this research, the splitting tensile and flexural strengths of the self-compacting concrete mixes with normal, untreated and treated recycled aggregate were calculated using the equations in the codes and by different researchers, such as ACI 363R (1998) [58], ACI 318 (2002) [59], CEB-FIP (1990) [60], and Nath et al. [61], as shown in Table 5. Fig. 16-17 illustrates a comparison between the estimated values determined by the previously mentioned equations and the experimental data.

Table 5. Prior efficient calculation method for mechanical characteristics.

Code or Authors	Equation for splitting tensile strength for concrete mixes
ACI 363R (1998) [58]	f_{st}=0.96 $(f_c)^{0.5}$
ACI 318 (2002) [59]	f_{st}=0.4 $(f_c)^{0.5}$
CEB-FIP (1990) [60]	f_{st}=0.59 $(f_c)^{0.5}$
Nath et al. (2021) [61]	f_{st}=0.10 $(f_c)^{1.03}$
Code or Authors	**Equation for flexural strength of concrete mixes**
ACI 363R (1998) [58]	f_r=0.49 $(f_c)^{0.5}$
ACI 318 (2002) [59]	f_r=0.62 $(f_c)^{0.5}$
CEB-FIP (1990) [60]	f_r=0.46 $(f_c)^{2/3}$
Nath et al. (2021) [61]	f_r=0.99 $(f_c)^{0.51}$
Where, f_{st}: splitting tensile strength (MPa), f_c: cylinder compressive strength (MPa), and f_r: Flexural strength (MPa)	

The formulas often provided are generally estimates of the mechanical characteristics of concrete mixtures containing natural and recycled aggregates. This study proposed the following empirical equation to illustrate the relationship between split-tensile strength and compressive strength:

$$\boldsymbol{f_{st}}=0.1\ (\boldsymbol{f_c})^{0.97} \qquad (1)$$

On the other hand, the below equation is expected to illustrate the relationship between flexural strength and compressive strength:

$$\boldsymbol{f_r}=0.9\ (\boldsymbol{f_c})^{0.52} \qquad (2)$$

Fig. 16 illustrates a significant relationship between compressive strength and splitting tensile strength having a regression coefficient (R^2) of 0.71, indicating a reliable test response. Consequently, it is seen that the projected values obtained from Nath et al. and ACI 363R are consistent with the experimental results for each standard. In contrast, the data points derived using ACI 318 are the most distant from the experimental results compared to all four equations. The recycled addition significantly increases the ratio of $f_{sp}$to fc, with an R^2 value of 0.71. This suggests that the results of the current research may explain the real correlation between f_{sp} and f_{cu} of SCC recycled aggregate mixtures with varying replacement ratios.

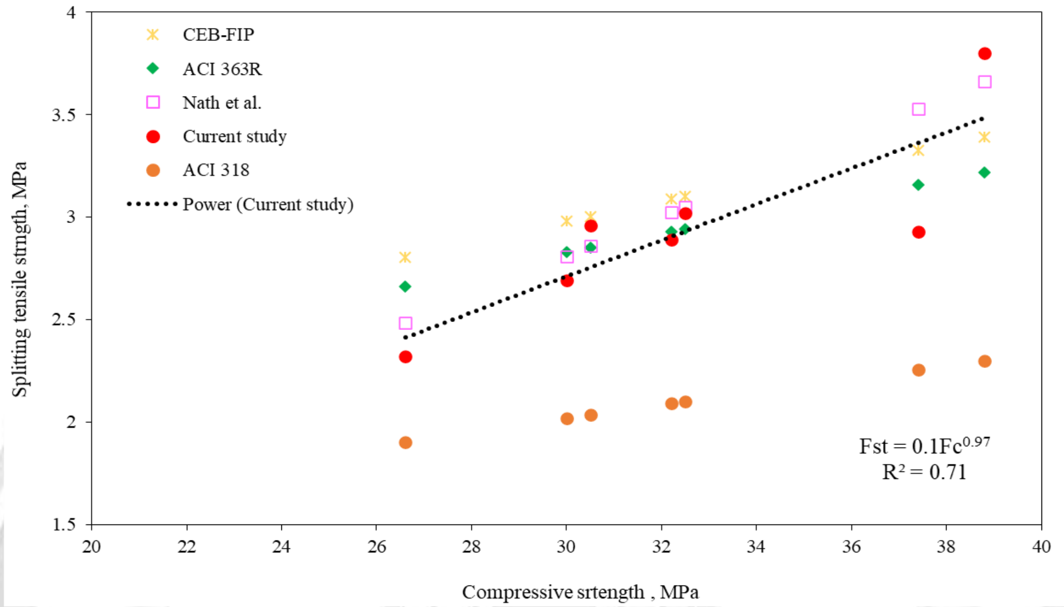

Fig. 16. Correlation between splitting tensile strength and compressive strength of SCC testing mixtures.

Regarding the correlation between compressive strength and flexural strength, Fig. 17 illustrated a moderate correlation (R^2 = 0.37) in SCC mixtures containing recycled aggregate, indicating an adequate reliability of the test results. For all standards, the predicted values determined by Nath et al. [61] are the closest to the experimental results. As a result, the predicted data points derived using ACI 363R are the farthest from the experimental data among the four equations. The notable increase in the proportional line is attributable to the recycled addition [62], providing an R^2 value of 0.37. This value indicates that the study's prediction may be utilized for evaluating the flexural properties of SCC-RAC mixtures through compressive strength analysis.

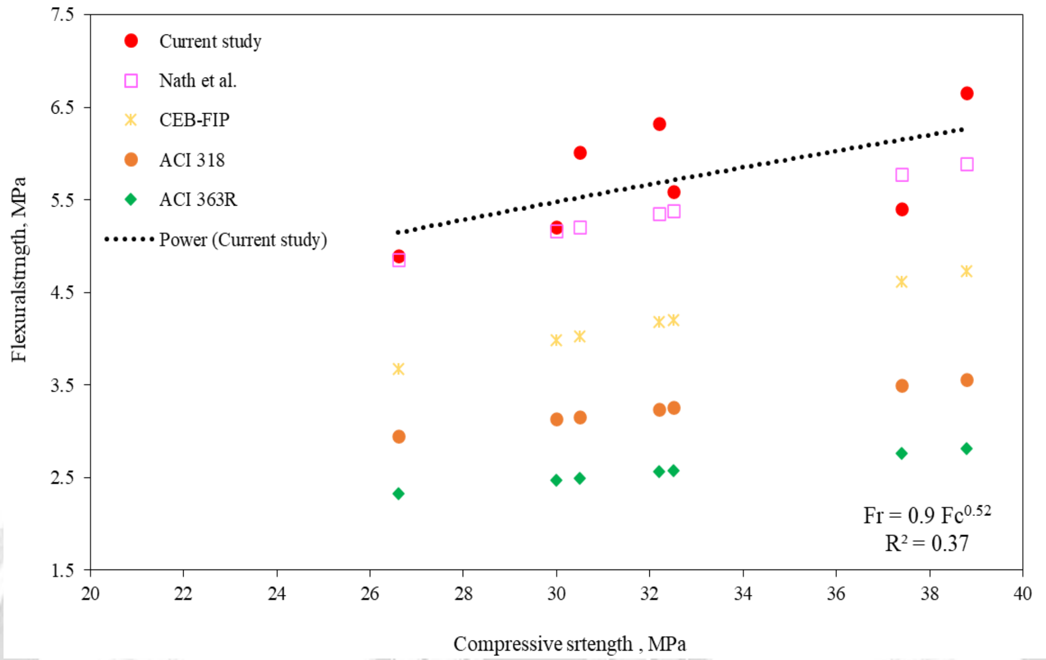

Fig. 17. Correlation between flexural strength and compressive strength of SCC testing mixtures.

5. Conclusions

This study performed an experimental analysis on sustainable self-compacting concrete mixtures, including treated recycled aggregates at different substitution ratios. From the experimental test results of this research, the following conclusions and recommendations can be drawn:

1. The use of recycled aggregate adversely affected the workability of the tested SCC mixture.
2. All created mixtures met the required self-compactibility requirements, exhibiting a slump flow range of 600-685 mm.
3. The SCC mixtures made from TRA, have been shown to meet the requisite characteristics for self-compactibility, including flow, passing ability, and resistance to segregation.
4. In terms of compressive strength, splitting tensile strength, and flexural strength, SCC mixes incorporating TRA consistently exhibit improved mechanical properties compared to untreated RA, regardless of the mix substitution ratio. However, the improvement is more pronounced in SCC mixes with full replacement ratios.
5. The laboratory results of TRA were beneficial and clearly demonstrated that the suggested treatment technique is an easy and reliable method to enhance the RA characteristics for effective application in self-compacting concrete.
6. The improved characteristics of RA are anticipated to provide dependable structural performance when employed in reinforced SCC components.
7. The relationship between compressive strength, tensile, and flexural strength offers a feasible prediction for SCC-based RA that shows an acceptable correlation with the standards.

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تأثير الركام المُعاد تدويره المعالج على الخواص الميكانيكية للخرسانة الخضراء ذاتية الرص

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الخلاصة

يهدف هذا البحث إلى تحسين الخصائص الميكانيكية لمخاليط الخرسانة ذاتية الرص (SCC) من الركام المعاد تدويره عن طريق غمر الركام المعاد تدويره (RA) في خليط من الأسمنت وغبار السيليكا .(CSFS) أجريت دراسة تجريبية على عدة مخاليط مكونة من أنواع مختلفة من الركام (ركام عادي، ركام معاد تدويره غير معالج، ركام معاد تدويره معالج) باستخدام نسب استبدال مختلفة تبلغ 0%، 30%، 60%، و100% من الركام المعاد تدويره. تم اختبار جميع المخاليط لخصائصها الطازجة باستخدام اختبار تدفق الركود، واختبارT_{500} ، واختبار القمع على شكلV ، وتم قياس خصائصها المتصلبة باستخدام قوة الخرسانة الانضغاطية، والانقسامية، والانثنائية. أشارت النتائج إلى أن نهج المعالجة المقترح كان فعالاً للخصائص الفيزيائية للركام المعاد تدويره المعالج، والذي أظهر كثافة نوعية أعلى وامتصاصًا منخفضًا للماء مقارنةً بالركام المعاد تدويره غير المعالج. فيما يتعلق بالخصائص الطازجة، أشارت نتائج البحث إلى أن معظم خلطات RA–SCC غير المعالجة استوفت معايير الخرسانة ذاتية الدمك إرشادات (EFNARC)، مما أثر على قطر تدفق الانكماش المذكور البالغ 600–685 مم، و T_{500}يتراوح بين 2.2 و3.8 ثانية، وزمن تدفق قمعي على شكل V بين 5.1 و13.7 ثانية. بالنسبة للخصائص المتصلبة، لوحظ أن استبدال الركام الطبيعي (NA) بالركام المعاد تدويره (RA) أدى إلى انخفاض كبير في قيم قوة الانضغاط والشد للخرسانة. في المقابل، أظهرت خلطاتSCC ، بما في ذلك RA المعالجة، قوى انضغاط وشد انقسام وانحناء محسنة تتناسب مع نسبة الاستبدال. وبالتالي، أشارت النتائج إلى أنه من الممكن إنتاج خلطات SCC باستخدام الركام المعاد تدويره المعالج الذي يوفر أداءً هيكليًا موثوقًا به عند استخدامه في العناصر المسلحة. أخيرًا، تم تحديد تأثيرات RA غير المعالجة، و RA المعالجة، ونسبة الاستبدال على الخصائص الميكانيكية لمخاليط SCC بشكل منفصل من خلال معادلات الطاقة، وتم اقتراح نموذج للتنبؤ بقوة الانقسام والانحناء لمخاليط الخرسانة المستدامة وتم التحقق منه.

الكلمات الدالة: الخرسانة الخضراء، الركام المعالج المعاد تدويره، الخصائص الميكانيكية، تدفق الانهيار، الاستدامة، التنبؤ بقوة الشد، التنبؤ بقوة الانحناء.