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Development of treated coarse recycled aggregate-based sustainable fibrous high-strength concrete with fine recycled aggregates

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This research aims to develop sustainable high-strength concrete (SHSC) by replacing 100% fine and/or coarse aggregates with fine recycled aggregate (RA) and/or coarse RA. Due to the high surface water absorption of coarse RA, a surface treatment method was adopted, consisting of immersing it in a cement and silica fume slurry. Moreover, to improve the performance of the produced SHSC, steel fibers were employed at a relatively low volume fraction (0.5%). Eleven blends were cast and tested in this experimental study. A control SHSC mix (without RA) and ten other mixtures, including fine natural and RA, treated and untreated coarse RA, with and without steel fibers, were prepared. Compressive, splitting, and flexural strengths, water absorption, density, and ultrasonic pulse velocity (UPV) of the resulting SHSC were conducted. The results indicated that the use of RA in SHSC resulted in an average drop of 25% in its mechanical properties and an increase of about 30% in water absorption. However, using treated RA compensated the compressive and tensile strength reductions in SHSC by 9% and 7%, respectively, compared to mixes containing untreated RA. On the other hand, adding fibers helped improve compressive, flexural, and splitting tensile strengths by about 8%, 23%, and 31%, respectively, compared to the corresponding control mix. Consequently, the results showed that it is possible to produce durable SHSC made from 100% RA and 0.5% steel fibers with a reduced density and improved mechanical performance to a comparable level or even superior to high-strength concrete (HSC) with only natural aggregates (NAs).

Keywords: *High-strength concrete; recycled concrete aggregate; aggregate treatment; steel fibers; recycling*

1. Introduction

Concrete has been an increasingly common composite material throughout history. It is presently the predominant construction material for buildings and infrastructure, and its popularity is projected to remain significant in the future. However, conventional concrete is not typically regarded as an eco-friendly building material. This is based on the viewpoints of diminishing natural resources, excessive energy use, and disposing of building waste [1]. It was reported that the concrete construction has a major impact on the environment, specifically in terms of CO_2 emissions and global warming [2]. Moreover, many building projects require utilizing massive amounts of concrete, and such utilization could considerably worsen the situation by raising the demand for non-renewable natural resources. Consequently, the issue of sustainability in building construction is currently of prime concern, and thus, the current tendency is to seek alternative sources of construction materials instead of relying solely on natural resources. In light of this, recycling waste materials is one of the reasonable approaches to producing sustainable building materials. Furthermore, using recycled materials (RA) in concrete industries as a coarse and/or fine aggregate substitute can be helpful in addressing the problem of concrete waste, reducing the demand on natural resources (e.g. coarse and fine aggregates), and minimizing landfill space for environmental protection [3].

Over the past two decades, there has been a strong focus on utilizing RA in concrete construction, and extensive research has been

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conducted to explore its potential. In many construction applications, RA is typically deemed to have potential as a structural concrete [4]. Despite its significant importance in the environment and industry, the addition of RA to concrete can negatively impact its fresh, physical, and mechanical performance. When comparing RA and natural aggregate (NA) particles, it is observed that the former have more angular shapes and textures, a more porous structure, and increased absorption of water [1]. The mortar adhered to the RA surfaces might be the source of its inferior physical properties [5]. Additionally, owing to its high porosity and presence of adhered cement mortar, RA has a 4% to 7% lower specific gravity than NA [6]. Regarding the fresh properties, the presence of mortar adhered to RA surfaces can negatively affect the mix workability, leading to harsh and rough fresh mixes [7]. The reduced workability of RA concrete can be explained by the presence of crushed and angular particles with rough surfaces, leading to a higher level of inter-particle interaction [8]. Thus, it is necessary to fully saturate the RA in water for a sufficient period prior to adding it to the rest of the concrete components. As stated by Fan et al. [9], the mix containing fine RA exhibited less slump than the mix having fine NA, and therefore the former mix has a higher water demand than the latter one.

When it comes to the mechanical properties, some of the previous literature encourages the use of RA, especially fine RA, because their disadvantages can be mitigated by implementing different methods (e.g. using supplementary cementitious materials) [9–11]. Even though the porous nature of fine RA, as stated by Geng and Sun [11], results in increased water absorption, which in turn leads to the formation of numerous microflaws within the concrete. These microflaws compromise the concrete's resistance to permeability, making it susceptible to carbonation. The amount of the old cement paste increases as the minimum particle size decreases. The increased water adsorption of fine RA results in a reduced amount of water available for cement hydration reactions. As a result, the microstructure of fine RA, particularly the interface zone between the new cement paste and RA, deteriorates. Thus, the fine RA's porosity increases, making it easier for CO_2 to enter [11].

There are some defects in RA due to the presence of old cement paste combined with the old aggregates. The defects primarily arise from the significant porosity and numerous interfaces caused by old cement paste [12]. As judged by SEM and microanalysis of the RA, it was revealed that the crack developed at the interfacial transition zones (ITZ), about 25 mm from the interface with the NA [13]. This means that the ITZ is the link between the two parts of the old cement paste and the NA. If the quality of this link (ITZ) is inferior, it will be the point where damage takes place [13]. Zhou et al. [14] successfully produced green lightweight high-performance engineered cementitious composites using fine RA sizes of 0-0.42, 0-0.72, and 0-1. It was found that using the latter fine aggregate size improved the compactness of the concrete matrix by densifying its microstructure. Furthermore, the developed mix, which possesses compressive strength of up to 80 MPa and a tensile strength of 6.4 MPa, demonstrates a feature of low density with a slight drop in compressive strength. Ravindrarajah and Tam [15] investigated the utilization of crushed concrete fines (CCF) obtained from waste concrete as a full replacement for fine aggregates (i.e. 100%). They concluded that the difference in strength between conventional concrete and fine RA-based concrete is almost negligible at later ages of curing, though the strength is lower for the latter at early ages. This is because further hydration reactions occur at later ages as RA contains cement particles. Moreover, Sim and Park [10] conducted an experimental investigation on structural concrete members that were constructed using 100% coarse RA. They also examined the effects of replacing NA with fine RA and adding various levels of fly ash. It was determined that, regardless of the inclusion of fly ash, the compressive strength exceeded the design strength of 40 MPa when the coarse aggregate was completely replaced and up to 60% of the natural fine aggregate was replaced with fine RA. They also approved the sufficient resistance of this type of aggregate to chloride ion penetration. Khatib [16] used two types of fine RA in concrete, namely

those produced from crushing old concrete and old bricks. Though there was a strength reduction of 15–30% with the use of fine RA, there was only a 10% reduction with the use of recycled brick aggregate. Evangelista and Brito [17] also mentioned that the replacement percentage of up to 30% of fine RA did not deteriorate the mechanical properties. In another experimental study, it was generally found that incorporating fine RA lowered the mechanical strength, particularly in high-strength concrete [18].

Focusing on coarse RA substitution, several studies have shown that using of this material instead of coarse NA can lead to a decline in both compressive and tensile strengths of concrete [19–21]. In particular, when NA are completely replaced by coarse RA (i.e., 100% RA), a more significant drop in concrete strength is observed [22]. Sayhood et al. [19] observed a considerable drop in splitting tensile and compressive strength of around 25% and 20%, respectively. The same findings were documented in [5], reflecting the poorer quality of RA characteristics in comparison to NA. Such lower quality is, to a considerable extent, related to the residual mortar particles adhered to RA surfaces, resulting in weak ITZs through which the failure occurs [1]. As a result, the microstructure of RA needs to be enhanced in order to achieve a satisfactory quality when utilized in concrete buildings.

To address the challenges presented by RA's inferiority, considerable investigations have been performed to enhance the performance of RA through the use of different process enhancement techniques. Soaking the RA in water, acid, polymer emulsion [23, 24], pozzolanic slurry [25], calcium carbonate [26, 27], sodium silicate [28], and sodium metasilicate pentahydrate solution [29] are some of these methods. Removing old cement mortar adhering to the RA surface is a notable approach suggested for improving its properties [23]. This can be accomplished by applying mechanical grinding and chemical treatment to RA. A mixture of water reducer [30] and mineral admixtures (e.g. metakaolin, silica fume, and fly ash) [8, 31, 32] can be incorporated in order to enhance the mechanical characteristics of RA. It is worth noting that all these strategies, with the exception of the one proposed in [29], have their own drawbacks and are unable to effectively address the RA's inferiority (i.e., RA concrete's performance remains inferior to that of NA concrete).

Recently, there has been a substantial focus on enhancing the characteristics of RA concrete by adding a certain amount of fiber reinforcement. A variety of fiber kinds are commercially available, including synthetic, natural, glass, and steel. The latter type is widely employed as concrete reinforcement and continues to be a building material that is undergoing extensive research [33]. Similar to fibrous NA-based concrete, the literature has demonstrated several advantages of fibrous RA-concrete, including tensile strength enhancement, crack bridging, and stress redistribution across the concrete matrix [1]. Moreover, the inclusion of fibers improves the durability of concrete through enhancing the capacity to sustain loads, and reducing the likelihood of fracture formation [34]. On the other side, while enhancing its overall characteristics, fibers have a detrimental influence on the mix workability; thus, it is essential to maintain a minimal fiber volume fraction. In addition, if comparatively large quantities of fibers (e.g., 2%), there may be a slight drop in compressive strength, and that drop could be attributed to irregular fiber distribution [35].

2. Research significance

From the reviewed literature, significant focus has been given to individual investigations on RA-based concrete utilizing treated RA, untreated RA, fine RA, and steel fibers. The combined impact of these materials on the fresh and hardened characteristics of RA-based concrete has, however, not received much attention in the literature. More specifically, the vast majority of the examined research, in this regard, focused mostly on normal-strength concrete rather than high-strength concrete. It is crucial to emphasize that researchers have been concerned about the differences in composition between NA-based concrete and RA-based concrete since the latter was shown to have inferior fracture behavior. Such a situation could

be aggravated when both fine and coarse NA are substituted by coarse and fine RA, particularly at full substitution (i.e. 100% RA). A possible justification for this would be related to the produced concrete that possesses additional ITZs, leading to more complex microstructures compared to NA concrete [21]. Here, the integration of a reasonable amount of steel fibers with treated RA could prove to be a feasible approach for producing environmentally friendly high-strength concrete structures. Therefore, the current study looks at the possibilities of improving the mechanical performance of high-strength mixes with treated coarse RA, fine RA, and steel fibers. To achieve this objective, RAs were first exposed to a straightforward technique that involved submerging them in a slurry made of cement and silica fume. Following the completion of the treatment process, a series of high-strength concrete mixes were cast and investigated in both fresh and hardened states. The cast specimens were assessed using several tests, comprising slump, compressive strength, splitting tensile strength, flexural strength, water absorption, and density. Additionally, non-destructive testing (ultrasonic pulse velocity (UPV)) was also executed to evaluate the prepared high strength RA-based fibrous and non-fibrous concrete mixes.

3. Experimental program

This section is dedicated to the materials used in the experimental program, concrete mix proportioning, specimens casting, and testing.

3.1. Materials

Gravel and sand, both sourced from Karbala region, were used as NAs. Additionally, as seen in Figure 1, two types of recycled aggregates (RAs) (coarse and fine) were utilized. Crushing old concrete specimens were the source of these RAs. All the aggregates used were in saturated surface dry (SSD) conditions. Tables 1 and 2 show the sieve test for the four types of aggregate used, which meet the requirements of Iraqi specifications [36]. Ordinary Portland cement was used in the experiments, which complies with the requirements of IQS 5 [37] (see Table 3). Silica fume, which satisfies the ASTM C1240 specification [38], was utilized in the process of preparing the impregnating slurry. A superplasticizer satisfying the ASTM C494 standards [39] was utilized to improve the workability of the fresh mixes. Steel fibers (Figure 1c) of the hooked end having 1300 MPa tensile strength and being 30 mm long, 0.5 mm diameter, yielded an aspect ratio of 60 and they were used at 0.5% by volume.

Table 1. Sieve analysis of the used fine aggregates

Sieve size mm	% Cumulative passing		Limits of IQS No.45 [36]
	NFA	RFA	
10	100	100	100
4.75	95	98	90–100
2.36	86	91	75–100
1.18	75	77	55–90
0.6	54	59	35–59
0.3	19	26	8–30
0.15	3	6	0–10

Table 2. Sieve analysis of the used coarse aggregates

Sieve size mm	% Cumulative passing		Limits of IQS No.45 [36]
	NC	RC	
37.5	100	100	100
20	98	95	95–100
14	66	60	—
10	37	32	30–60
5	1	2	0-10

3.2. Preparation of treated coarse RA

In order to enhance RA properties, a practical treatment strategy suggested by Alqarni et al. [40] was exploited in this study. This method involved impregnating coarse RA in a slurry of cement and silica fume (see Figure 2a). The two materials were 20% of the weight of the water solution. The coarse RA was immersed in the slurry for a duration of two hours. Following that, they were taken out and subsequently treated with damp gunny bags for a duration of one week. When compared with coarse RA, the qualities of the produced treated coarse RA (Figure 2b) were shown to indicate an improvement in their physical properties, namely



a: Coarse RA **b**: Fine RA **c**: Hooked-end steel fibers

Fig. 1. RAs and steel fibers used

Table 3. Chemical and physical test results of cement

Chemical tests		
Oxides	**Test results**	**Limits of IQS No.5 [37]**
SiO_2%	23.78	—
Al_2O_3%	3.120	—
Fe_2O_3%	3.09	—
CaO%	62.07	—
MgO%	2.25	≤5%
SO_3%	1.032	≤2.8% if C3A > 5% ≤2.5% if C3A < 5%
Insoluble residue%	0.81	≤1.5%
Loss on Ignition%	1.17	≤4%
L.S.F	0.82	0.66 – 1.02
Main compounds		
C_2S%	36.548	—
C_3S%	41.927	—
C_3A%	3.040	—
C_4AF%	9.403	—
Physical tests		
Setting time, min.,		
initial	73	≥45 min.
final	5:50	≤10 hr.
Fineness (Blaine), cm^2/g	2984	≥2500
Compressive strength, MPa,		
2 days	17.1	≥10
28 days	38.6	≥32.5

water absorption and specific gravity. The absorbed water dropped from 5.85% to 3.04% after subjecting coarse RA to this treatment approach. Also, the treated coarse RA' specific gravity was 2.45, while it was 2.33 for untreated coarse RA.

3.3. Concrete mix proportioning, casting, and testing

In order to evaluate high-strength concrete produced from RA, hardened properties involving compressive strength (*fcu*), flexural strength (*fr*), and splitting tensile strength (*fst*) were conducted on 10×10×10 cm cubes, 10×20 cm cylinders, and 10×10×50 cm prisms, respectively, following the respective standards of BS EN 12390-3 [41], BS EN 12390-6 [42], and ASTM C78 [43].

The compressive strength test was calculated by dividing the load at failure by the cross-sectional area of the cube. The splitting tensile strength of the cylinder was calculated using equation (1). The flexural strength was performed using the third-point loading method according to equation (2). To test for water absorption, the samples were first dried in an oven at a temperature of 100–110°C until their weight became stable (unchanged). Then, they were immersed in water until their weight became constant. Finally, the water absorption was calculated using equation (3).

$$fst = \frac{2P}{\pi L d} \tag{1}$$

Where, P is the failure load, L is the height of the cylinder, d is the diameter, and *fst* is the splitting



a: Impregnating Coarse RA

b. Sample of treated coarse RA

Fig. 2. Treatment procedure of coarse RA

tensile strength.

$$fr = \frac{fl}{b\,w^2} \tag{2}$$

Where, f is the maximum load, l is the length of span, w is the depth of the prism, b is the width of the prism, and fr is the flexural strength.

$$Wa = \frac{Ww - Wd}{Wd} \times 100 \tag{3}$$

Where, Wd is the dried mass, Ww is the wet mass, and Wa is the water absorption %.

Also, ASTM 143/C 143M [44] was adopted to assess the slump of concrete mixes. Non-destructive testing, represented by UPV, was measured through concrete samples and complies with ASTM C597 [45]. The velocity of ultrasonic pulses was measured by dividing the distance between the transducers by the time taken for the wave to travel through it. Eleven high strength concrete mixes (Table 4) were prepared, taking into account the effects of fine RA, coarse RA, treated coarse RA, and hooked end steel fibers.

The control mix was proportioned according to ACI 211.1 [46]. The coarse and fine aggregate of the reference mixes (NC+NF-Ref) were coarse and fine NA at a 0% RA substitution ratio. In the rest of the mixtures, coarse NA was substituted either with 100% untreated coarse RA or 100% treated coarse RA, whereas fine NA was substituted by 100% fine RA. The ingredients of all the cast mixes are shown in Table 5. A pan-type mixer was used, and the following procedure was carried out: primarily, aggregates with a little portion of water added and mixed. Then, the remaining water and cement were added untill achieving mix homogeneity. Finally, steel fibers were added slowly to the mixtures. After pouring the concrete, the specimens were covered with polyethylene sheets and left for 24 hours. Next, the samples were remolded and put in a water tank for 28 days.

4. Results and discussion

This section involves the physical and mechanical test results. The former was assessed considering density and water absorption, whereas the latter was evaluated in terms of compressive strength, splitting tensile strength, flexural strength, and UPV.

4.1. Density

The findings of the density test are illustrated in Figure 3. The results indicated that the density of

Table 4. Designation of the tested mixes

Mix details	Mix details
NC+NF-Ref	Natural coarse aggregates + Natural fine aggregates- Reference mix
NC+RF*	Natural coarse aggregates + Recycled fine aggregates
RC*+NF	Recycled coarse aggregates+ Natural fine aggregates
TRC+NF	Treated recycled coarse aggregates + Natural fine aggregates
RC+RF	Recycled coarse aggregates + Recycled fine aggregates
TRC+RF	Treated recycled coarse aggregates + Recycled fine aggregates
NC+RF0.5F	Natural coarse aggregates + Recycled fine aggregates + 0.5% Steel fibers
RC+NF0.5F	Recycled coarse aggregates + Natural fine aggregates + 0.5% Steel fibers
TRC+NF0.5F	Treated recycled coarse aggregates + Natural fine aggregates + 0.5% Steel fibers
RC+RF0.5F	Recycled coarse aggregates + Recycled fine aggregates + 0.5% Steel fibers
TRC+RF0.5F	Treated recycled coarse aggregates + Recycled fine aggregates + 0.5% Steel fibers

** For the above mixes, the replacement levels of fine and/or coarse RA are 100%.*

Table 5. Mix ingredients (kg/m^3) of the prepared mixes

Mix designation	C	W	SP	NF	RF	NC	RC	SF
NC+NF-Ref	498	160	5.5	704	0	1060	0	0
NC+RF	498	160	6.4	0	572	1060	0	0
RC+NF	498	160	5.8	704	0	0	915	0
TRC+NF	498	160	6.1	704	0	0	960	0
RC+RF	498	160	7.0	0	572	0	915	0
TRC+RF	498	160	7.4	0	572	0	960	0
NC+RF0.5F	498	160	8.5	0	572	1046	0	39
RC+NF0.5F	498	160	8.0	704	0	0	903	39
TRC+NF0.5F	498	160	8.6	704	0	0	948	39
RC+RF0.5F	498	160	9.3	0	572	0	903	39
TRC+RF0.5F	498	160	9.7	0	572	0	948	39

C, W, SP, NF, RF, NC, RC, and SF refer, respectively, to the used cement, water, super-plasticizers, natural fine aggregates, recycled fine aggregates, natural coarse aggregates, recycled coarse aggregates, and steel fibers.

the control mixture was greater than that of all the other mixtures made from RA. The NC+RF mixture showed a decrease of 6.4%, while the density of the mixture containing recycled coarse aggregate (RC+NF) decreased by 6.6%. The RC+RF mix, made of 100% RA (i.e both fine and coarse RAs), exhibited a 12.5% reduction in density compared to the control mix ((NC+NF-Ref). The higher void content and lower specific gravity of the adhered mortar (attached to the RA) may be the main reasons for this decline in density [47]. Additionally, the mixtures containing treated coarse aggregate (TRC+NF and TRC+RF) recorded densities of 2311 and 2184 kg/m^3, respectively. This behavior is believed to be due to the closing of aggregate voids and the increased interlayer quality when treated aggregates were used. However, the density of these mixtures did not reach the value of NA-based concrete, which registered as 2406 kg/m^3.

When fibers at a vf of 0.5% were added to the RA-based concrete, there was a slight increase in the density, but it remained lower than the control mixture. This increase in density after adding fiber is due to its high specific gravity [48]. The lowest density value was observed in the mixture RC+RF, which was less than the control sample by 12.5%. Moreover, it can be concluded that the reduction in the density of RA-based sustainable high-strength concrete (SHSC), in comparison to high-strength concrete (HSC) with NA, helps to reduce the overall weight of the structures. Despite the weight reduction, the compressive strength of fibrous SHSC was comparable or even higher than the reference mixture. In other words, these results provide the possibility of producing lightweight SHSC while maintaining the compressive strength values without reduction due to the role of surface treatment of the RA and the presence of steel fibers.

4.2. Water absorption

The water absorption outcomes for all SHSC mixtures are presented in Figure 4. The findings demonstrated that the control mixture exhibited the lowest absorption compared to the RA mixture. Additionally, the concrete containing only recycled fine or coarse aggregate had a lower absorption compared to the one including a complete substitution of NA with recycled one. The absorption percentages were 3.8%, 3.9%, and 5.5% for the NC+RF, RC+NF, and RC+RF, respectively, compared to 1.8% for the control mix. This increase

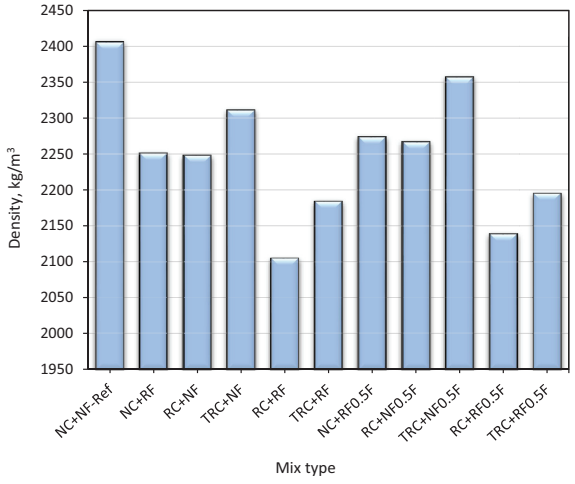


Fig. 3. Densities of the tested concrete mixtures

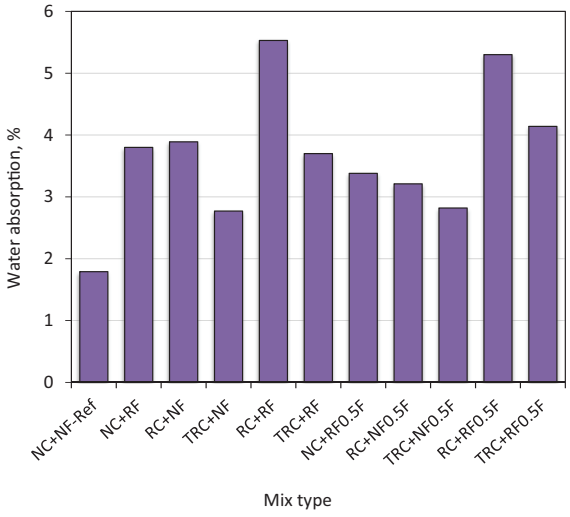


Fig. 4. Water absorption of the concrete mixes

could be justified by the fact that the overall porosity and the average diameter of pores in the RA are higher than that of the NA [49]. As a result of the increased amount of RA in the mixture, there was a rise in water absorption, which explains the increased water absorption of the RC+RF mixture compared to the NC+RF and RC+NF mixtures.

Additionally, the study found that treating the RA with a cement and silica fume solution led to a significant improvement in absorption resistance. The improvement was 28.8% (i.e., the absorption was 2.8%) for the TRC+NF mix compared to the RC+NF mix, and 33.1% (i.e., the absorption was 3.70%) for the TRC+RF mix compared to the RC+RF mix. This behavior may be associated to the penetration and filling of the cement and silica fume solution into the porous materials of the bonded mortar, which has a high absorption rate and permeability capacity [40]. Ultimately, this leads to improving the quality of concrete and reducing its water absorption.

Moreover, it was noted that the inclusion of steel fibers at vf of 0.5% resulted in a decrease in the water absorption for mixtures that contained RA, in both treated and untreated mixes. The reason behind this behavior is the densifying effect of steel fibers on the concrete matrix [50]. The only exception was the TRC+RF0.5F mixture, where the absorption increased from 3.7% to 4.1%. However, for mixtures containing treated aggregates, the absorption decreased compared to their previous values before treatment. The reason behind that might be related to the role of fibers and surface treatment of aggregate in improving the ITZ of the concrete matrix. In this regard, previous studies [51, 52] suggested that concrete with an absorption of less than 10% is deemed to be of good durability. As all the tested mixtures in the present study had absorption values ranging from 1.8% to 5.5%, the concrete produced with RA is considered good quality and durable.

4.3. Compressive strength results

The compressive strength outcomes are presented in Figures 5 and 6. The results revealed that substituting NA with a recycled one decreased the compressive strength of SHSC compared to the reference mixture (free of RA). The reduction percentage was 10% for the NC+RF mixture and 16% for the RC+NF mixture, while the reduction was 25% when using RF and RC together. This reduction in strength is likely because the high porosity of the RA, along with the weaker mortar matrix that binds them, contribute to their tendency to break down faster [53]. Additionally, there are more weak layers in the concrete containing RA because the ITZ is thinner in such concrete in comparison to those containing NA and paste [53, 54].

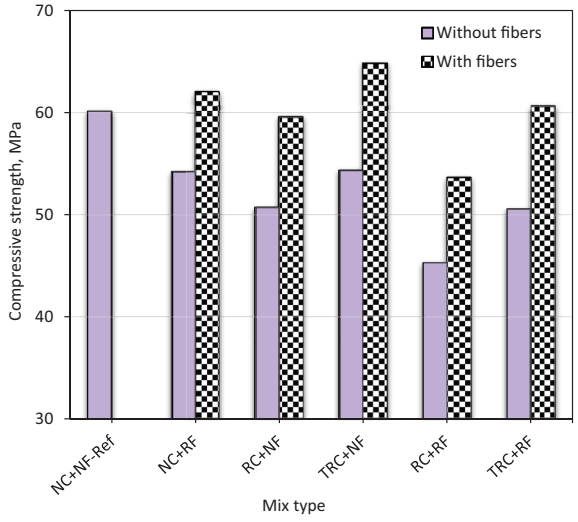


Fig. 5. Compressive strength of the tested mixes

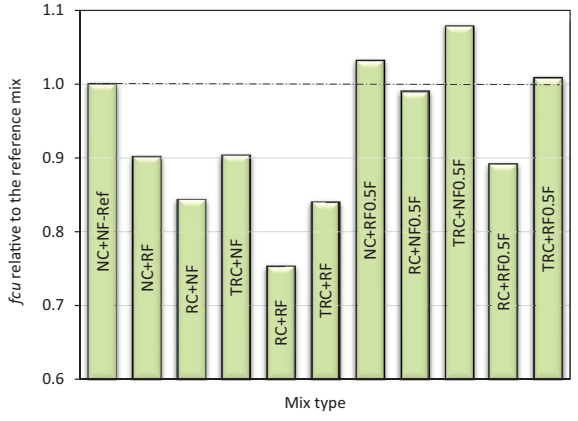


Fig. 6. Compressive strength relative to the reference mix (NC+NF-Ref)

Moreover, the results demonstrated that treating RC with cement and silica fume slurry improved the compressive strength of SHSC compared to untreated RC-based mixtures. When using TRC, the compressive strength improved by 6% for the mixture containing TRC+NF and 10% for the mixture containing TRC+RF compared to that of the untreated ones. This behavior may be due to the improved bonding strength between the aggregate and mortar (which improved the ITZ) resulting from the hydration of cement and the pozzolanic reaction of silica fume used in treating the surface of the RC, which increased the compressive strength [40]. Despite this improvement, the strength remained lower than that of the reference specimen.

Furthermore, the results indicated that the addition of steel fibers at volume fraction (vf) of 0.5% improved the compressive strength of all mixtures to varying degrees compared to those without fibers. The percentages of change (improvement) in compressive strength for SHSC mixtures after adding fibers compared to those without fibers are shown in Figure 7. The improvement percentage for the NC+RF0.5F mix was 3%, while the TRC+NF0.5F mix recorded the highest increase in compressive strength, 8% (64.8 MPa) higher than the reference specimens (60.1 MPa). When compared the findings of the NC+RF0.5F and TRC+NF0.5F mixtures to their counterparts without fiber (NC+RF and TRC+NF), both mixtures were found to be 10% less than the reference mixture. This means that the improvement in strength after adding fibers was 13% for the NC+RF0.5F mixture and 18% for the TRC+NF0.5F mixture when compared to their respective mixtures without fiber (TRC+NF mix). The compressive strength of the RC+NF0.5F and TRC+RF0.5F mixtures was equal to the reference mix, while it was 11% less for the RC+RF0.5F mixture. The improvement in compressive strength after adding fibers is attributed to the role of fibers in restricting cracks and preventing them from expanding, which requires a higher load (absorbs more energy) to fail the specimen and thus increases the concrete strength [55]. Moreover, it was found that the improvement in compressive strength in the presence of fibers was more evident in the mixtures containing treated aggregate, which indicates the impact of treatment in strengthening the bond with the fibers and improving the performance of RA, as it requires higher energy to cause the failure.

4.4. Splitting tensile strength results

The splitting tensile strength findings are displayed in Figures 8 and 9. These results indicated that the tensile strength of mixtures made from RA is lower than that of the control sample. This is true for both fine and coarse aggregate types, with the RC+RF mixture showing the lowest tensile

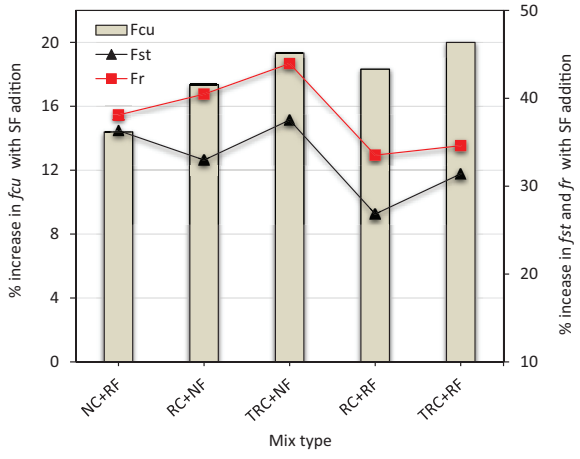


Fig. 7. Percentage increase in the mechanical properties (*fcu*, *fst* and *fr*) with the addition of steel fibers (SF)

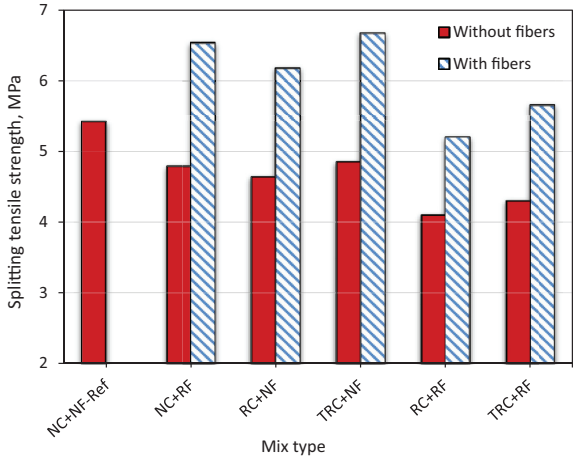


Fig. 8. Splitting tensile strength of the tested mixes

strength. In other words, the tensile strength follows the same pattern as the compressive strength of the corresponding mixtures. The reason for the reduction in tensile strength is that the RA contains voids and micro-cracks during the aggregate preparation [56] and increased water absorption on the surface of the aggregate [13]. The results also showed that treating the coarse aggregate helped to compensate the decrease in tensile strength by improving the bond between the cement paste and aggregate. However, the tensile strength did not reach that of the reference mix values. Moreover, it was noted that the improvement in tensile strength when using treated aggregate was less than that for compressive strength. This difference in improvement is due to the fact that the tensile strength of concrete is more affected by the presence of gaps or capillary cracks and the quality of the transitional overlap zone between the aggregate and the interfacial material than the compressive strength.

Additionally, the compressive strength of fibrous SHSC mixes (apart from the RC+RF0.5F mix) is comparable to or exceeds that of the reference mix (NC+NF-Ref), which is the fiber-free mix. This means that the presence of fibers did not fully compensate for the compressive strength reduction of the RC+RF mix compared with the control mix (NC+NF-Ref). This is expected since the fine and coarse NAs are totally replaced by fine and coarse RAs in the RC+RF mix. Nevertheless, the compressive strength of the RC+RF0.5F mix (with 0.5% steel fiber) was higher than that of the corresponding fiber-free mix (RC+RF) by about 18% (as clearly seen in Figure 7). The change in splitting tensile strength after adding steel fibers can be seen in Figure 7. The highest improvement in tensile strength (23%) was recorded for the mixture TRC+NF0.5F. This suggests that the treatment played a significant role in improving the transitional interface between the RA and fibers and the cement paste. Furthermore, the results indicated that the mixture made entirely of RA (TRC+RF0.5F) showed an increase of 4% over the reference mixture. The fibers worked to prevent the expansion of cracks and bridged both sides of microcracks, ultimately improving the tensile strength of concrete.

4.5. Flexural strength results

The findings of the flexural strength are illustrated in Figures 10 and 11. The outcomes demonstrated that the flexural strength of high-strength concrete decreased when fine or coarse NA was replaced with RA. The mixture containing both replacement types (100% RA showed the greatest reduction in flexural strength. This reduction amounted to 22% of the flexural strength value of the mixture containing NA, which is related to

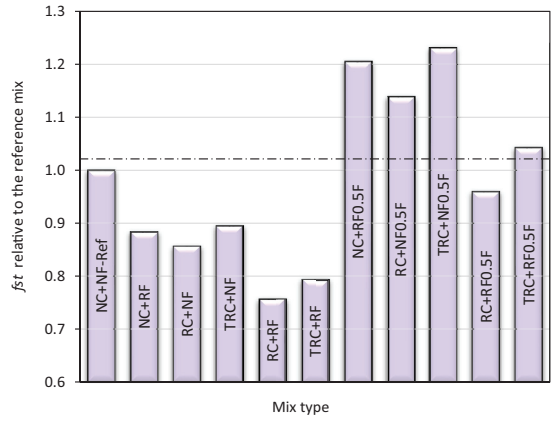


Fig. 9. Splitting tensile strength relative to the reference mix (NC+NF-Ref)

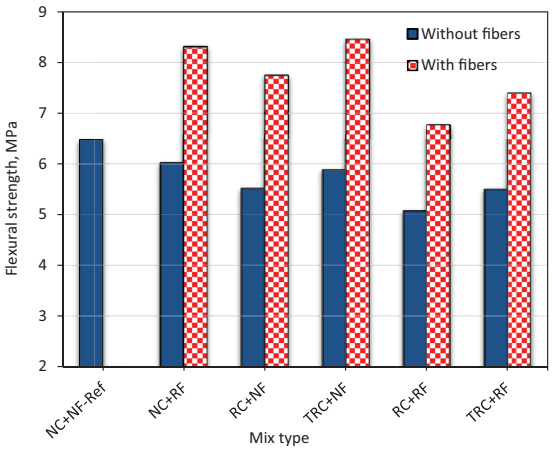


Fig. 10. Flexural strength of the tested mixes

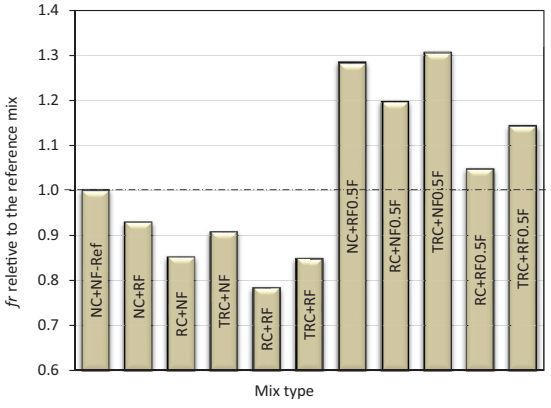


Fig. 11. Flexural strength relative to the reference mix (NC+NF-Ref)

the weak bond between cement and RA, and the presence of gaps and/or microcracks in RA [20].

Conversely, the mixture containing recycled fine aggregate only experienced the lowest amount of reduction, which was 7% less than the reference mixture. Treating the surface of the coarse aggregate resulted in a partial recovery of the flexural strength. The percentage of change increased from 85% for the RC+NF mix to 91% for the TRC+NF mix. Similarly, the TRC+RF mix recorded an improvement of 7% (85% of the reference mix) over its previous value before treatment. The improvement could be related to the formation of additional C-S-H gel in the bonding region between the TRC and the cement paste. This formation reduces the surface voids and enhances the flexural strength of the mixture containing treated RA. In this perspective, normal strength self-compacting concrete specimens made of such treated RA also exhibited better mechanical and structural performance when compared to corresponding specimens made from untreated RA [57, 58].

It is worth mentioning that the inclusion of fibers significantly enhanced the flexural strength of all mixtures containing RA, irrespective of whether they were treated or untreated. The change in flexural strength after adding steel fibers is presented in Figure 7. The mixture containing treated aggregate (TRC+RF0.5F) showed the highest improvement value, with a 31% increase compared to the mixture without fiber. The RC+RF0.5F mixture also showed an improvement of 5% over the reference mixture, which was a smaller increase than the other mixtures. Moreover, the mixture made from completely RA exhibited a 14% improvement compared with the control mixture. This can be attributed to the improved bond between the TRC and cement paste as a result of the rough surface of the RA and the crosslinking effect between the microfibers and the RC [59].

4.6. Ultrasonic pulse velocity (UPV)

The UPV (Figure 12) of the tested specimens was performed at the structural laboratory of the College of Engineering at Al-Qadisiyah University. Apparently from Figure 13, the velocity values of the mixture containing normal-weight aggregates



Fig. 12. Ultrasonic pulse velocity test

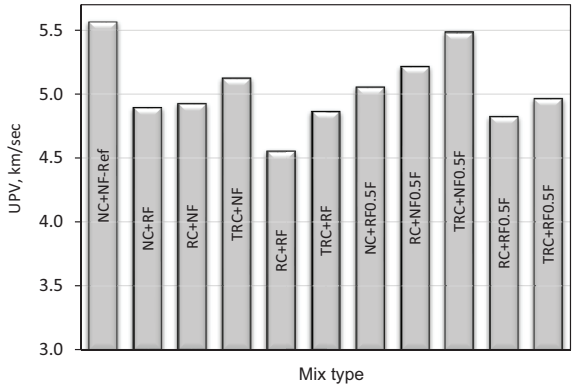


Fig. 13. UPV results of the concrete mixtures

were higher than those containing RAs. This was in agreement with the previously published literature [60]. The reduction in velocity is mainly attributed to the increased air trapped in the RA concrete, which in turn, affects the transmission of UPV waves [61]. The mixture with a fine RA only had a velocity 12.1% lower than the reference specimen. On the other hand, the reduction in UPV was between 11.5% and 18.2% for mixtures containing recycled coarse aggregate, namely RC+NF and RC+RF. However, when treated aggregate was used for the same two mixtures, the UPV reduction (compared to the reference mixture) was only 7.9% and 12.6% for TRC+NF and TRC+RF mixtures, respectively, indicating a decrease in the voids associated with recycled coarse aggregate and an improvement in the ITZ and microstructure of the produced mixtures.

In addition, the inclusion of a low amount of steel fiber (only 0.5%) led to a significant improvement in the UPV in all mixtures containing RAs, regardless of whether they were treated or untreated. The highest wave velocity value was recorded for the TRC+NF0.5F mixture, which was only 1.5% lower than the reference mix. Furthermore, according to the literature [62,63], the concrete quality can be classified as very poor, poor, doubtful, good, and excellent when UPV values are $<$ 2000, 2000–3000, 3000–3500, 3500–4500 and $>$4500 m/s, respectively. According to this classification, the quality of the produced concrete for all mixtures was excellent.

5. Conclusions

This research aimed to investigate the impact of using silica fume and cement slurry for the treatment of coarse RA on the characteristics of SHSC. The study focused on completely replacing (100%) the coarse and/or fine aggregate and examining the mechanical and durability properties of the SHSC mixes. To these mixes, steel fibers at a vf of 0.5% were also added to enhance their mechanical properties. Based on the conducted experimental tests and their outcomes, the subsequent conclusions are deduced:

1. SHSC with RA has 10–25% lower compressive strength than the reference mixture. Treatment of coarse aggregate increased compressive strength by up to 9%. Adding 0.5% steel fiber further improved the strength, with the best results achieved in the TRC+NF0.5F mix, which performed 8% better than the control mix.
2. Replacement of NA with untreated RA lowered splitting tensile and flexural strengths by 14–24% and 15–22%, respectively. However, using treated aggregates compensated for the tensile strength drop by 3% for splitting and 7% for flexural strength. Here, both properties were significantly improved when steel fibers were added. The highest improvement was recorded in the TRC+NF0.5F mix, with a 23% improvement in splitting tensile strength and a 31% increase in flexural strength.
3. Using RA in SHSC has increased its water absorption. However, treating the coarse aggregate surface and adding steel fibers have helped to increase its resistance to

absorption. As all the tested RA mixes in the present study had absorption values ranging from 2.8% to 5.5%, the RA-based SHSC produced is considered to have good quality and durability.

4. The presence of RAs in SHSC reduced UPV between 11.5% and 18.2% compared to concrete with NAs. Despite this, the velocity values for all mixtures exceeded 4500 m/s, which is within the excellent category for concrete. In this regard, the use of treated aggregate (with or without fibers) improved the pulse velocity, pointing out a decline in the voids within the concrete structure.
5. The density of RA-based SHSC decreased after replacing the NA with the recycled one. The reduction ranged from 6.5% to 12.5% for the NC+RF and RC+RF mixes. However, the respective drop was within the range of 4% to 9.2% after treating the coarse RA.
6. As far as the test results obtained were concerned, eco-friendly SHSC can be produced containing 100% RA with 0.5% steel fibers and with comparable mechanical properties, good durability, and a density loss of about 9% compared to the NA-based SHSC.

Conflicts of Interest

The authors declare no conflicts of interest.

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