Journal of Building Engineering

ENHANCEMENT OF MECHANICAL PROPERTIES OF CONCRETE WITH TREATED DEMOLITION WASTE AGGREGATE

--Manuscript Draft--

Manuscript Number:	JBE-D-22-03685R2
Article Type:	Research Paper
Section/Category:	Building materials
Keywords:	Compressive strength; Flexural strength; Tensile splitting strength; Elastic modulus; Microstructure
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Abstract:	The utilization of recycled aggregate (RA) from the construction and demolition waste (C&DW) in civil engineering applications, has proven to be an eco-efficient environmentally friendly approach to overcome the current environmental concerns. Nevertheless, the poor quality of RA has limited its utilization in high-grade civil engineering applications. To maximize and promote the use of RA, it is essential that an appropriate process of treatment methods is included in the production of RA to improve its properties. This research aimed to examine the effects of various enhancement methods on the mechanical properties (consistency, compressive strength, flexural strength, tensile splitting strength, and elastic modulus) of recycled aggregate concrete (RAC). This research also included microstructure investigation using Scan Electron Microscopy (SEM) images. The enhancement methods used were treating RA by Soaking in Cement-Pulverized Fuel Ash-Silica Fume solution (SCP), Sand Envelope Mixing Approach (SE), and their combination (SCP+SE). The enhanced RACs showed an increased 28-day compressive strength of up to 46MPa suitable for structural applications. The tensile splitting strength, flexural strength, and modulus elasticity values of the enhanced RACs were 10%, 16%, and 6% higher than that of the untreated RAC. The improved mechanical performance of the enhanced RAC was attributed to the strengthened interfacial transition zone, better overall interlocking of the treated RA with the new cement paste, filled-up pores and micro-cracks, reduced water absorption, and improved aggregate impact value. The SEM images for the enhanced RACs showed better-compacted microstructure, lesser pores and microcracks. The application of the proposed innovative regime of enhancement methods is anticipated to promote the use of RA in the construction industry and provide a better scientific understanding of the performance of concrete produced with 100% treated RA from the C&DW for structural applications.
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ABSTRACT

The utilization of recycled aggregate (RA) from the construction and demolition waste (C&DW) in civil engineering applications, has proven to be an eco-efficient environmentally friendly approach to overcome the current environmental concerns. Nevertheless, the poor quality of RA has limited its utilization in high-grade civil engineering applications. To maximize and promote the use of RA, it is essential that an appropriate process of treatment methods is included in the production of RA to improve its properties. This research aimed to examine the effects of various enhancement methods on the mechanical properties (consistency, compressive strength, flexural strength, tensile splitting strength, and elastic modulus) of recycled aggregate concrete (RAC). This research also included microstructure investigation using Scan Electron Microscopy (SEM) images. The enhancement methods used were treating RA by Soaking in Cement-Pulverized Fuel Ash-Silica Fume solution (SCP), Sand Envelope Mixing Approach (SE), and their combination (SCP+SE). The enhanced RACs showed an increased 28-day compressive strength of up to 46MPa suitable for structural applications. The tensile splitting strength, flexural strength, and modulus elasticity values of the enhanced RACs were 10%, 16%, and 6% higher than that of the untreated RAC. The improved mechanical performance of the enhanced RAC was attributed to the strengthened interfacial transition zone, better overall interlocking of the treated RA with the new cement paste, filled-up pores and micro-cracks, reduced water absorption, and improved aggregate impact value. The SEM images for the enhanced RACs showed better-compacted microstructure, lesser pores and microcracks. The application of the proposed innovative regime of enhancement methods is anticipated to promote the use of RA in the construction industry and provide a better scientific understanding of the performance of concrete produced with 100% treated RA from the C&DW for structural applications.

Keywords: Enhancement method, Adhered mortar, Compressive strength, Slump, Flexural strength, Tensile splitting strength, Elastic modulus, Microstructure.

1. Introduction

The most abundant waste stream throughout Europe is the construction and demolition waste (C&DW) resulting from activities of the construction industry, accounting for about 800 million tonnes per year [1]. According to DEFRA [2], the UK generated around 66.2 million tonnes of C&DW in 2016, which is almost 30% of the total waste in the UK. In view of this, recently, efforts have been made with an attempt to minimise the amount of C&DW sent to landfills through recycling. For instance, the EU's Waste Framework Directive urged all the European member states to achieve a minimum of 70% recycling rate of C&DW by 2020 [3]. Although the UK managed to achieve around a 91% recovery rate in 2016, more than 75% of the recovered C&DW was used for backfilling [4]. This low-grade application is mainly due to the poor and inconsistent quality of recycled aggregate (RA) from the C&DW, the presence of the porous adhered mortar and the weak old interfacial transition zone. Other reasons may include, pre-loading, accelerated weathering, and processing [5]. These factors have caused RA to have low density, low aggregate impact value, low crushing value, and high water absorption compared to natural aggregate (NA) [6].

Extensive studies have been carried out in the past few decades on the feasibility of incorporating RA into concrete. These studies generally agreed that as the RA replacement level increased the following changes in concrete properties were observed, reduced consistency [7], reduced density [8], and reduced mechanical properties [8]. Given the poor quality of RA, studies with the aim of improving the quality of RA and recycled aggregate concrete (RAC) have been carried out extensively to expand the application of RA into structural concrete [9]. The current methods used for enhancing RA and RAC can be categorized into three main approaches; (i) removing the adhered mortar, (ii) strengthening the adhered mortar, (iii) and batching techniques.

Techniques involving removing the adhered mortar can provide great improvement to RA engineering properties and it may include methods such as soaking RA in acid [10], thermal or traditional heating [11], microwave heating [6], and mechanical treatment [9]. Nevertheless, studies showed that there are some drawbacks to the use of removing the adhered mortar, for instance, there is a possibility of introducing micro-cracks and damage to RA surface through soaking in acid and/or mechanical treatments [12]. In addition, this technique may result in fine aggregate after the treatment which in turn would increase waste materials generation especially if the resulted fines are not utilized.

On the other hand, strengthening the adhered mortar offers greater advantages compared to removing the adhered mortar [12]. It may include techniques such as coating RA with pozzolanic slurry [13], soaking RA in sodium silicate solution [14], soaking in cement-pozzolan solution [15], and accelerated carbonation [16]. Batching techniques may include, stone envelope with pozzolanic powder [17], two-stage mixing technique [12], sand envelope mixing approach [18], and mortar mixing approach [18]. Although there are a significant amount of studies that dealt with the effects of different treatments on the performance of recycled aggregate concrete, little attention, has been devoted to the effects of replacing 100% RA from the C&DW enhanced with different methods such as, strengthening the adhered mortar, batching techniques, and combination of these treatments, on the mechanical properties of recycled aggregate concrete (RAC). Aggregates as inert fillers play a significant role in altering the properties of fresh and hardened concrete. To this end, this study aims at enhancing the engineering properties of RA and the mechanical properties of RAC including consistency, compressive strength, tensile splitting strength, flexural strength, and modulus of elasticity. The present study also included a microstructure investigation for the treated RACs. Soaking RA in cement-pulverized fuel ash – silica fume solution (SCP) was used to treat RA prior to mixing, and sand envelope mixing approach (SE) was used as batching technique for mixing RAC.

2. Materials characteristics

2.1 Aggregates

Crushed limestone coarse aggregate (NA) of two particle sizes, 20/10 mm, and 10/4 mm, were used throughout this study The limestone aggregate was sourced in bulk from Jewson UK Limited in Caerphilly, South Wales, UK, conforming to BS EN 12620:2002+A1: 2008 [19]. The recycled aggregate (RA) utilized was sourced from Derwen Group, Neath Abbey, UK. It is a mix of construction and demolition waste with a size range of clean 20/10 mm and 10/4mm. According to Derwen Group [20], the RA provided was produced to industry standards, in accordance with WRAP Quality protocol and BS EN 13242: 2013 [21] specifications.

The RA consisted of different recycled materials i.e., brick, glass, bituminous, rounded stones, and recycled concrete aggregates. Figure 1 shows the NA and RA utilized throughout this study. Table 1 shows the compositions of RA in accordance with BS 8500-2: 2015+A2: 2019 [22]. The mechanical and physical properties of the NA and RA are shown in Table 2, while the particle size distribution of NA and RA is shown in Figure 2.

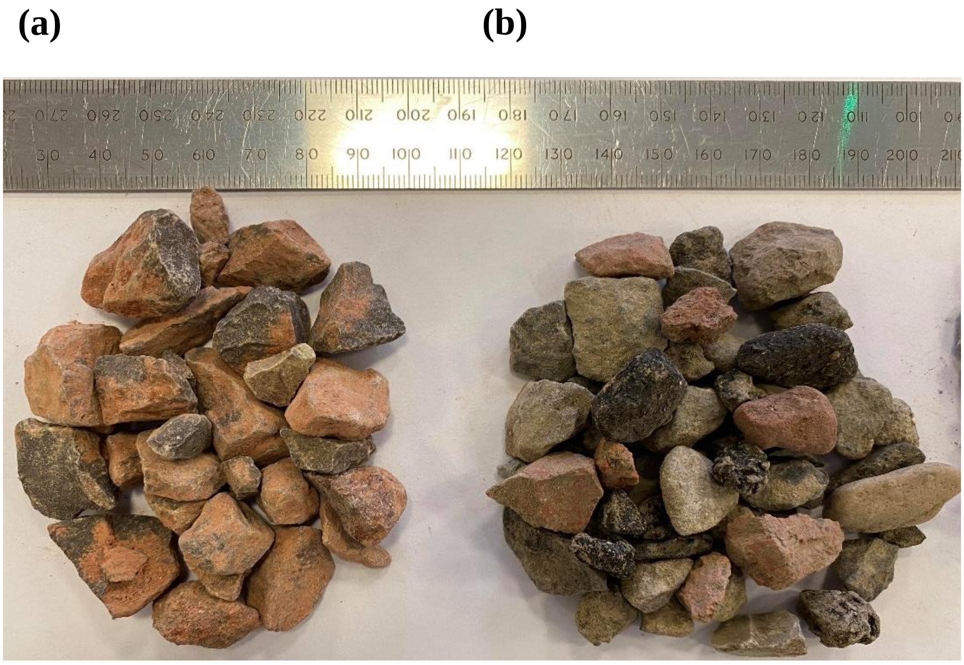

Figure 1: (a) coarse NA, (b) coarse RA

	R_c (%)	R_u (%)	R_b (%)	R_g (%)	R_a (%)	X (%)
Sample 1	49.14	29.47	12.51	0.17	8.38	0.34
Sample 2	47.5	28.06	11.5	1.12	11.00	0.48
Sample 3	50.6	25.8	13.4	0.00	9.5	0.37
BS limits	–	–	–	–	≤10%	≤1%
Mean	49.08	27.78	12.47	0.42	9.6	0.39

Notes: R_c - cement-based products, R_u - unbound aggregates and/or natural stones, R_b - clay masonry units i.e., bricks and tiles, calcium silicate masonry unit, R_a - bituminous materials, and X - miscellaneous materials and/or non-floating wood, plastic, and rubber, R_g - crushed glass.

Table 1: Compositions of recycled aggregates in this study (BS 8500-2:2015 +A2: 2019) [22]

Characteristic	NA	RA	BS limits	Standard
Flakiness Index (FI) (%)	18	27	< 40	BS EN 933-3:2012 [23]
Shape Index (SI) (%)	12	18	< 55	BS EN 933-4:2008 [24]
Water Absorption (WA) (%)	1.5	6.1	< 8	BS EN 1097-6:2013 [25]
Density kg/m^3	2480	2120	–	BS EN 1097-6:2013 [25]
Aggregate Impact Value (AIV) (%)	14	17	< 32	BS EN 1097-2:2020 [26]
LA (%)	18	26	< 50	BS EN 1097-2: 2020 [26]

Table 2: Characteristics of the RA compared with NA and relevant BS EN standards

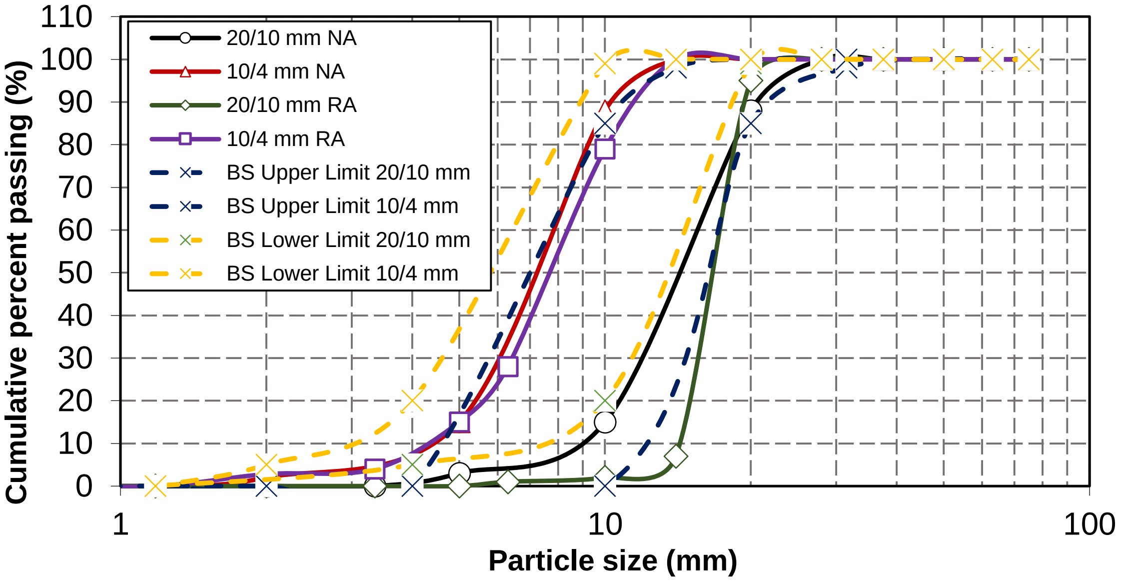

Figure 2: Particle size distribution of coarse RA and coarse NA

2.2 Portland cement

A commercially available Portland cement (CEM I-42.5 N) which was manufactured in accordance with BS EN 197-1: 2011 [27] was used throughout the study. The CEM I was sourced from Jewson UK limited based in Caerphilly, South Wales, UK. The oxide and physical composition of the cement used are shown in Table 3.

2.3 Pozzolanic materials

The pulverized fuel ash (PFA) used throughout this study was supplied by a local supplier and was compliant with BS EN 450-1:2012 [28]. The silica fume (SF) utilized throughout this study was an un-densified silica fume with a commercial code 971U and was to the conformity of BS EN 13263-2:2005+A1:2009 [29]. It was manufactured by Elkem Silicon Materials based in Norway and had a 97.1% purity.

Oxide	**Composition by (wt%)**		
	PC	SF	PFA
CaO	61.49	−	0.22
SiO_2	18.84	97.1	59.04
Al_2O_3	4.77	0.1	34.08
Fe_2O_3	2.87	0.2	2.00
SO_3	3.12	0.06	0.05
Na_2O	0.02	−	1.26
	Physical properties		
Colour	Grey	Dark Grey	Light Grey
Bulk density (kg/m^3)	1400	120-220	800-1000
Specific gravity (Mg/m^3)	3.16	2.20	2.90

Table 3: Oxide compositions and physical properties of materials used throughout this study

3. Experimental program

3.1 Enhancement methods for RA and RAC

3.1.1 Soaking RA in cement-PFA+SF solutions (SCP)

The recycled aggregates were treated by soaking in Portland cement - pulverized fuel ash - silica fume solution. These pozzolan materials were selected with the aim of fulfilling the environmental and economic criteria. The solution was prepared by blending the raw materials with water (twice the weight of RA) for several minutes. Then recycled aggregate was added into each solution and soaked for 4 hrs at 10% concentration level. Thereafter, the recycled aggregates were removed from the solution bath and let to drain for 10 min and then air-dried at room temperature for 24 hrs prior to testing. Table 4 shows the mix composition of the SCP treatment solution.

Treatment solution	**Binder (g)**			**RA (g)**	**Water (g)**	**Concentration level**
	PC	**PFA**	**SF**			
PC - PFA+SF	80	60	60	1000	1800	10%

Table 4: Proportions of the SCP treatment solution for 1000g of RA

3.1.2 Sand envelope mixing approach (SE)

Sand was firstly blended with 75% of the mixing water for 30 seconds, cement was then added to the mixture and mixed for 45 seconds. Thereafter, the recycled aggregate was added to the mixture with the rest of the mixing water and mixed for 90 seconds.

3.1.3 Bi-combination of SCP + SE

The untreated RA were firstly dried to constant mass and then soaked in pre-prepared cement-SF+PFA solution for 4 hrs, and then air-dried at room temperature for 3 days. Thereafter, the treated RA were incorporated in the mixing design of RAC and mixed via sand enveloped mixing approach (SE).

3.2 Concrete mix design

Table 5 shows concretes mix proportions produced with various enhancement methods at three different water to cement ratios, 0.4, 0.5, and 0.6.

Specimen designation	PC (kg/m^3)	Water (kg/m^3)	w/c ratio	NA (kg/m^3)	RA (kg/m^3)	FA (kg/m^3)	Mixing method	Notes
W040/NAC1	450	180	0.4	1257	0	677	NMA	NAC (control 1)
W040/RAC2	450	180	0.4	0	1206	677	NMA	Un-treated RAC (control 2)
W040/SCP	450	180	0.4	0	1206	677	NMA	Soaking RA in PC-SF+FA solution
W040/SE	450	180	0.4	0	1206	677	SE	Untreated RA
W040/SCP+SE	450	180	0.4	0	1206	677	SE	Soaking RA in PC-SF+FA solution
W050/NAC1	350	175	0.5	1257	0	677	NMA	NAC (control 1)
W050/RAC2	350	175	0.5	0	1206	677	NMA	Un-treated RAC (control 2)
W050/SCP	350	175	0.5	0	1206	677	NMA	Soaking RA in PC-SF+FA solution
W050/SE	350	175	0.5	0	1206	677	SE	Untreated RA
W050/SCP+SE	350	175	0.5	0	1206	677	SE	Soaking RA in PC-SF+FA solution
W060/NAC1	250	150	0.6	1257	0	677	NMA	NAC (control 1)
W060/RAC2	250	150	0.6	0	1206	677	NMA	Un-treated RAC (control 2)
W060/SCP	250	150	0.6	0	1206	677	NMA	Soaking RA in PC-SF+FA solution
W060/SE	250	150	0.6	0	1206	677	SE	Untreated RA
W060/SCP+SE	250	150	0.6	0	1206	677	SE	Soaking RA in PC-SF+FA solution

Note: NMA – normal mixing approach (conventional mixing approach), SE – sand envelope mixing approach, FA – fine aggregate, NA – natural aggregate, NAC – natural aggregate concrete.

Table 5: Concrete mix proportion for various RAC produced with different enhancement methods

3.3 Specimens Preparation & Testing of Concrete

Standard dimension of cube (100 mm × 100 mm × 100 mm), standard dimension of cylinder (150 mm × 300 mm) and (100 mm × 200 mm), and standard dimension of prismatic beam (100 mm × 100 mm × 500 mm) test specimens were utilized in the production of the concrete. The test specimens were prepared in accordance with BS EN 206:2013+A1:2016 [30]. The consistency of fresh concrete was assessed using the slump test in accordance with BS EN 12350-2:2019 [31]. The de-moulding of the test specimens was carried out after 24 hrs of casting at room temperature. The curing of the test specimens was done in accordance with BS EN 12390-2:2019 [32]. The cube test specimens were tested for compressive strength at 7 and 28-day in accordance with BS EN 12390-3:2019 [33]. The 100 mm × 200 mm concrete cylinders were tested for 28-day tensile splitting strength in accordance with BS EN 12390-6:2009 [34]. The 100 mm × 300 mm concrete cylinders were tested for 28-day modulus of elasticity in accordance with BS EN 12390-13:2021 [35]. The 100 mm × 100 mm × 500 mm prismatic concrete beams were tested for flexural strength in accordance with BS EN 12390-5: 2009 [36]. For all the mix compositions, the reported results are the average obtained from three individual test specimens for compressive strength, two for tensile splitting strength, two for flexural strength, and two for modulus of elasticity. Superplasticizer was only used for concretes produced at 0.4 w/c ratio at a 1% dosage to reach satisfactory consistency. The microstructure investigation was carried out Using a MIRA3 TESCAN Scanning Electron Microscope (SEM), fitted with a Solid-state Backscattered (electron) Detector (SBD).

4. Results and discussion

4.1 Effects of soaking RA in cement-PFA+SF solution on the AIV and WA

Table 6 shows the aggregate impact value (AIV) and water absorption (WA) of RA after treating by soaking in cement-PFA+SF solution.

Notation	AIV (%)	Enhancement (%)	WA (%)	Enhancement (%)
Un-treated RA	17	—	6.1	—
Treated RA by soaking in PC-PFA+SF	14.7	13	2.8	54

Table 6: Effects of soaking RA in cement-PFA+SF solution on the AIV and WA of RA

The main principle behind soaking RA in cement-pozzolan solution is to cover the RA surface with a thin layer of hydration products, hence improving the RA engineering properties. After the treatment, a dense coated layer was formed around the RA surface after the reaction of the pozzolanic materials with the $Ca(OH)_2$ in the adhered mortar. According to Singh et al. [37], the additional hydrated calcium silicate (C-S-H) gel fill the pores and voids of the adhered mortar as shown in Equation 1. The incorporation of cement in the solutions is important for the treatment because it releases additional (C-S-H) gel and $Ca(OH)_2$ during hydration, as given in Equation 2.

$$\textbf{Pozzolanic reaciton}: \mathbf{Ca(OH)_2 + S \rightarrow C - S - H} \qquad \textit{Equation 1}$$

$$\text{Cement reaction}: C_3S + H \rightarrow C - S - H + CH \qquad \textit{Equation 2}$$

This additional production of C-S-H gel efficiently fills the voids and pores of the weak adhered mortar, resulting in a much denser microstructure of RA. These findings are in agreement with Shaban et al. [15] who reported 40% reduction in the AIV and 51.4% reduction in water absorption of RA after soaking in pozzolan solution.

4.2 Effects of SCP and SE on the consistency of fresh RACs

The results for the consistency of the fresh concrete measured using the slump test are shown in Figure 3. The slump values observed for the NAC1 mix recorded the highest slump values across all the concrete mixes, whereas the RAC2 mixes experienced the lowest slump values among all the fresh concrete mixes irrespective of water to cement ratio. This is mainly because of the porous nature of RA which reflects on its higher ability to absorb water compared to NA, and hence the slump values for the RAC2 mixes are lower than for the NAC1 mixes. This is in line with Malesev et al. [38] and Kou & Poon [39], who reported higher slump loss for RAC compared with NAC. Kurda et al. [40] stressed that the reduced consistency of RAC was mainly ascribed to the higher water absorption capacity of RA, the rougher surfaces, and more angularity of RA compared to NA. Nonetheless, the poor consistency of the RAC2 mixture at low w/c ratio of 0.4 was improved by the addition of superplasticiser, and this is because of the efficiency of superplasticiser in increasing the concrete workability.

The highest increase in slump values was observed with SCP+SE mix (soaking RA in cement-PFA+SF solution combined with mixing via sand envelope mixing approach) across all the designated enhanced RAC mixes at all the w/c ratios. The synergetic effect of the combined treatments presented in SCP+SE mix increased the slump value by 33% (from 45mm to 60mm) at 0.4 water to cement ratios. It should be noted that, during mixing of the concrete and whilst performing the slump tests, no segregation of concrete was found in any of the concrete mixes. This is ascribed to firstly the effects of soaking RA in cement-PFA+SF solution which strengthened the adhered mortar by the coated pozzolana layer/ film around the RA particle surface, filling up the micro-pores and cracks of the RA. This ultimately prevented the RA from absorbing high amounts of mixing water, thus improving the workability [17].

Secondly, the utilization of sand envelope mixing approach (SE) was able to further enhance the consistency of RAC by mixing RA with the premixed cement-sand-water mixture that filled the pores and voids of RA and limited its absorption of the mixing water. This is in line with Liang et al. [18] who proposed this mixing method, and reported that the consistency of RAC was enhanced significantly after using the SE method.

Overall, it can be concluded that the poor consistency of untreated RAC can be overcome by the incorporation of either superplasticiser, or the treatment and batching techniques proposed. The best performed treated RAC mixes in terms of consistency are the mixes with the combination of SCP+SE treatment.

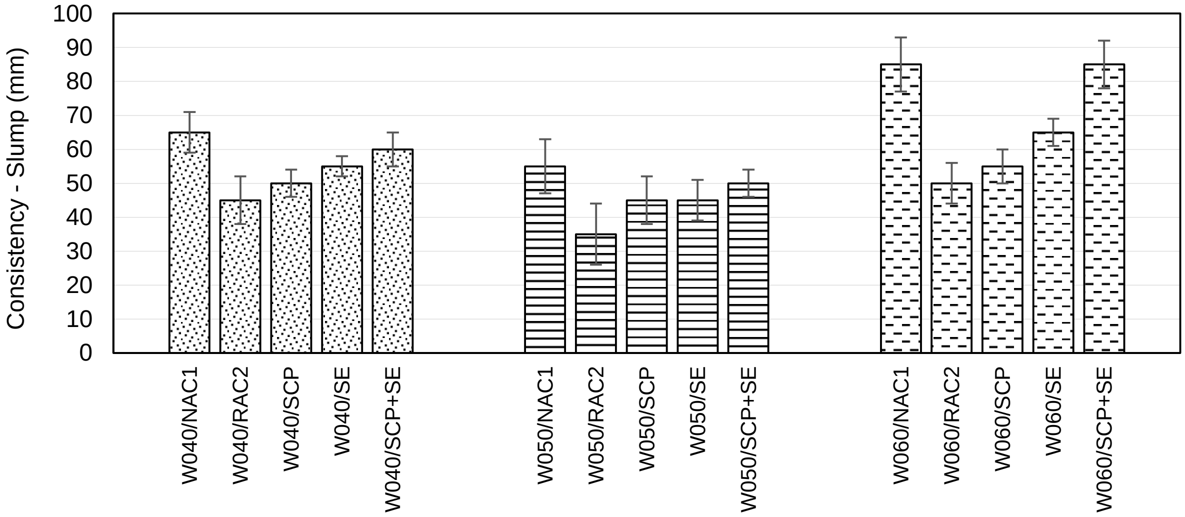

Figure 3: Effects of different enhancement methods on consistency - slump of RACs

4.3 Effects of SCP and SE on the compressive strength of RACs

Figure 4 shows the compressive strength results for all concrete mixes at 7 and 28-day. The NAC1 mixtures showed the highest 7 and 28- day compressive strength among all the concrete mixtures of 39MPa and 49MPa, respectively, whilst the untreated RAC2 mixtures produced the lowest 7 and 28-day compressive strength of 29MPa and 37MPa, respectively.

This inferior compressive strength of the RAC1 stems from various factors such as the poor bonding between the adhered mortar and the RA from one side and between the RA and the cement paste within the concrete matrix from another side. The presence of microcracks and fissures on the RA surface due to processing. The porous nature of the adhered mortar and the higher water absorption capacity of RA. The different composition of RA and the poor engineering properties of RA [41]. These aspects contributed to a lower compressive strength of RAC compared to NAC. Figure 5 shows SEM images for different concrete specimens. Figure 5a shows the presence of two ITZ (interfacial transition zone) and the weak old ITZ in the RAC2 specimen which also resulted in reduced compressive strength for RAC.

Similar observation of the inferior compressive strength of RAC was reported by Butler et al. [42] and Xiao et al. [43] who observed a 30% reduction in compressive strength when RA replaced NA at 100%. Tan et al. [44] studied the complete failure mechanism and cracking mode of a modelled untreated RAC during a uniaxial compression test using digital image correlation and concluded that the old ITZ was the most critical factor in controlling the microcracking process of RAC. This was because the old ITZ possessed the lowest physical strength in RAC compared to the old and new cement paste, aggregate, and the new ITZ. In addition, Tang et al. [45] stated that, given the higher strength of the natural aggregate (natural aggregate covered by old mortar) compared to the old mortar and the old ITZ, none of the tensile cracks was observed in the natural aggregate region. The tensile cracks observed were mostly in the old mortar region and in the old ITZ. Whereas the shear cracks were observed to appear mostly along the old ITZ. This was also confirmed by Tang et al. [45], who reported that it was more frequent that the cracks passed through the RA particles compared to NA particles at the final pattern of cracks.

It can also be observed that an increase in 7- and 28-day compressive strength occurred when the w/c ratio of the concrete mix was reduced for all the RAC1 mixes and the treated RACs mixes specimens. This indicates that the RAC whether it was treated or untreated shows a similar trend in strength development compared to natural aggregate concrete.

All the enhancement methods utilized, and their combinations were able to increase the 28-day compressive strength of RAC to a minimum of 30MPa, hence changing the classification of RAC to concrete suitable for structural application. Among all the enhanced RAC mixes, the synergetic effects of soaking RA in cement-PFA+SF followed by mixing using sand envelope mixing approach showed the highest increase in the 7-day and 28-day compressive strength. For instance, the 7-day compressive strength of SCP+SE mixes increased from 29 to 36.7MPa (27% enhancement), and from 18.2 to 26.8MPa (47% enhancement), at 0.4 and 0.5

w/c ratios, respectively. This can be attributed to the coupled effects of these two methods which led to a relatively stronger and compacted microstructure with the fewest pores and microcracks, as can be seen in Figure 5d.

The enhanced 7-day and 28-day compressive strength of the SCP mixes (soaking RA in cement-PFA+SF solution treatment) can be ascribed to the strengthened adhered mortar, enhanced particle density, enhanced AIV, improved water absorption of RA, and strengthened bond in the existing ITZ after this treatment (see Figure 5c). The enhanced compressive strength of the SCP mixes can further be explained as the adhered mortar on the RA surface consists of a significant amount of calcium hydroxide that can react with the pozzolana materials (SF and PFA). Thus, forming a dense coating layer around the RA surface. In addition, the formation of the additional calcium silicate hydrates and calcium aluminate hydrates due to the presence of aluminate in PFA, leads to filling up the pores and the voids of the adhered mortar [46]. The presence of cement in the treatment solution can also lead to an additional formation of calcium silicate hydrates. These additional produced calcium silicate products further fill up the pores and microcracks in the weak ITZ and the adhered mortar on the RA surface, leading to a much denser microstructure of RA.

It is also worth noting that given the fine nature of SF, filler effect, high specific surface area, and better packing density, it can efficiently fill the pores and voids in the adhered mortar, and ultimately enhance the compressive strength of RAC [15]. Liang et al. [18] examined the effects of treating RA by soaking in cement-SF solution and reported a 29% increase in the 28-day compressive strength of RAC, compared to the untreated RAC. This is also in line with the results of Alqarni et al. [47] who reported a 32% enhancement in the 28-day compressive strength for the treated RAC by soaking in cement-SF solution produced. Similarly, Lei et al. [48] concluded that treating RA with cement slurry can enhance the interface strength and the bonding force of RA with the new cement paste. The cement slurry can fill the pores and voids of RA leading to increase RA strength and integrity. This is also in line with the Lei et al. [49] study who pointed out that the pozzolan impregnation treatments can lead to the pore filling and sealing of RA and enhance its interface structure due to the pozzolanic reaction.

The enhanced compressive strength achieved by the SE mixes can be ascribed to the sequential mixing process of this mixing approach, as sand and 3/4 of the total mixing and cement are mixed first for a certain period of time which allow forming a cement paste prior to the addition of RA, hence less water (effective mixing water) will be absorbed by the RA. The use of sand enveloped mixing approach has also led to a better compacted and formed microstructure, but the presence of the voids and micro-cracks was more evident compared to the SCP specimen as shown in Figure 5b.

To the best of the author’s knowledge, the only study that dealt with the use of SE is the study carried out by Liang et al. [18]. Liang et al. [18] study did not show the effects of this mixing approach on the compressive strength of RAC in comparison with RAC produced with a normal/conventional mixing approach, but only reported its effects on the compressive strength of RAC compared with mortar mixing approach (MMA) and two-stage mixing approach (TSMA), in which SE performed better than both MMA and TSMA.

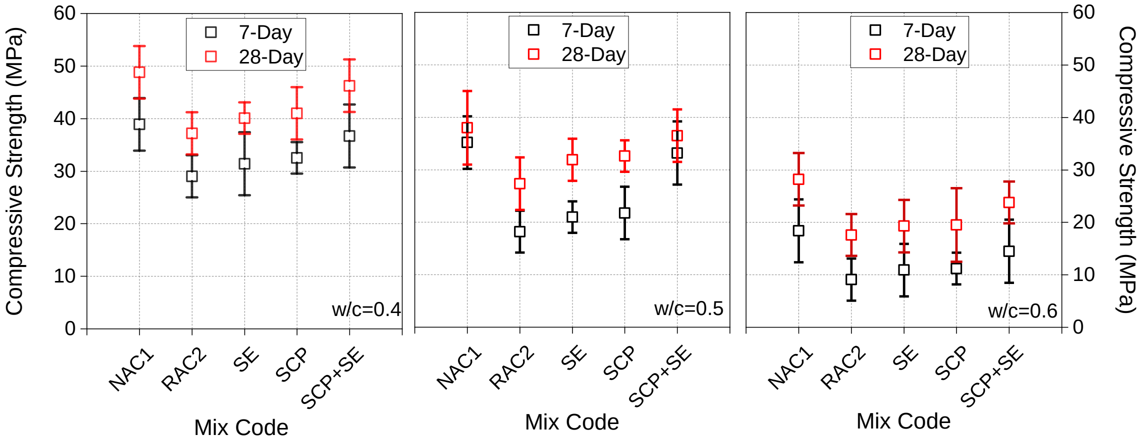

Figure 4: Compressive strength development of the various concrete mixtures at 7-day, and 28-days

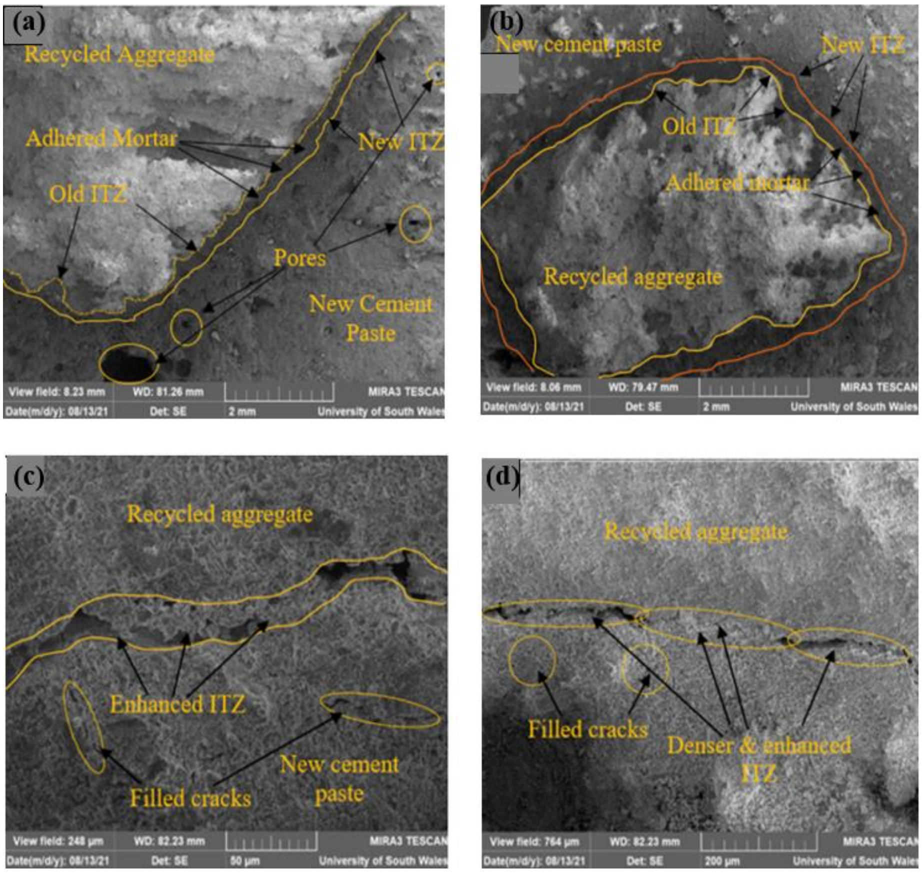

Figure 5: SEM images for different test specimens, (a) RAC with untreated RA, (b) SE specimen, (c) SCP specimen, (d) SCP+SE specimen

4.4 Effects of SCP and SE on the tensile splitting strength of RACs

The tensile splitting strength results of the cylindrical enhanced RACs specimens water cured for 28 days, are shown in Figure 6. Similar to the trend observed in the compressive strength results, the highest tensile strength value across all the test concretes was recorded for the NAC1 mixes of 3.8MPa, whilst RAC2 mixes obtained the lowest tensile strength value of 3.3MPa, regardless of the w/c ratio. This is ascribed to the poor quality of RA especially the adhered mortar which acts as a weak point that failed under compressive load and leads to a lower split tensile strength. This is in line with Alqarni et al. [47] who reported a reduction in the split tensile strength of 52% and 39% compared with conventional concrete, for 10mm aggregate size and 20mm aggregate size, respectively, Alqarni et al. [47] added that this reduction was due to the excessive amount of the porous adhered mortar on the RA surface.

Among all the enhanced mixes, RAC mixes produced with the combination of soaking in cement-PFA+SF followed by mixing using sand envelope mixing approach presented in the SCP+SE mixes achieved the highest tensile strength enhancement. SCP+SE mixes increased the tensile strength of RAC from 3.3 to 3.65MPa (10% enhancement) at 0.4 w/c ratio. This is can be attributed to the strengthened adhered mortar on the RA surface and especially the ITZ being densified after this treatment. This is in line with Kukadia et al. [50] who treated RA by soaking in cement solution, and reported a 20% enhancement in the tensile splitting strength of concrete produced with 30% RA and 70% NA. Overall, all the enhanced mixes led to enhancements in the tensile strength of RAC, but the enhancements were not as high as were in the case of compressive strength. This might be because the efficacy of enhancement methods is higher in enhancing the ability of RAC to withstand compression compared to tension. In addition, one of the main factors that influence the tensile splitting strength of RAC is the interlocking and bonding behavior between RA (the old ITZ to be specific) and the new cement paste. Thus, another possible reason behind the lower enhancements achieved in the tensile splitting strength compared to compressive strength, could be that the enhancement methods utilized could not efficiently enhance the bonding strength of the old ITZ with the new cement paste.

The SE mixes also exhibited enhancement in the split tensile strength, as the sand envelope mixing approach (SE) procedures involved adding the untreated RA to the initially premixed sand-rich mortar during the first stage of mixing. This sand-rich mortar coated the RA surface, and ultimately strengthened the adhered mortar by sealing the RA surface [51].

The literature showed very limited studies were carried out on the effects of the batching approaches on the tensile splitting strength of RAC. Jagan et al. [52] in their investigations, mixed the RAC using sand envelope mixing approach (SE), and stated that the tensile splitting tensile strength was enhanced by 14% after using SE method. The combination of soaking RA in cement-PFA+SF solution prior to mixing followed by sand envelope mixing approach presented in the SCP+SE mixes in enhancing the tensile splitting strength followed the same trend of enhancement to the compressive strength. The SCP+SE mixes obtained the highest enhancement in the tensile splitting strength of the RAC, this can be explained as the coupled effects of both SCP and SE, ultimately enhancing the RA properties and the RAC matrix. There are no studies to be found in the literature that examined the couple effects of these treatment methods on the tensile splitting strength of the RAC.

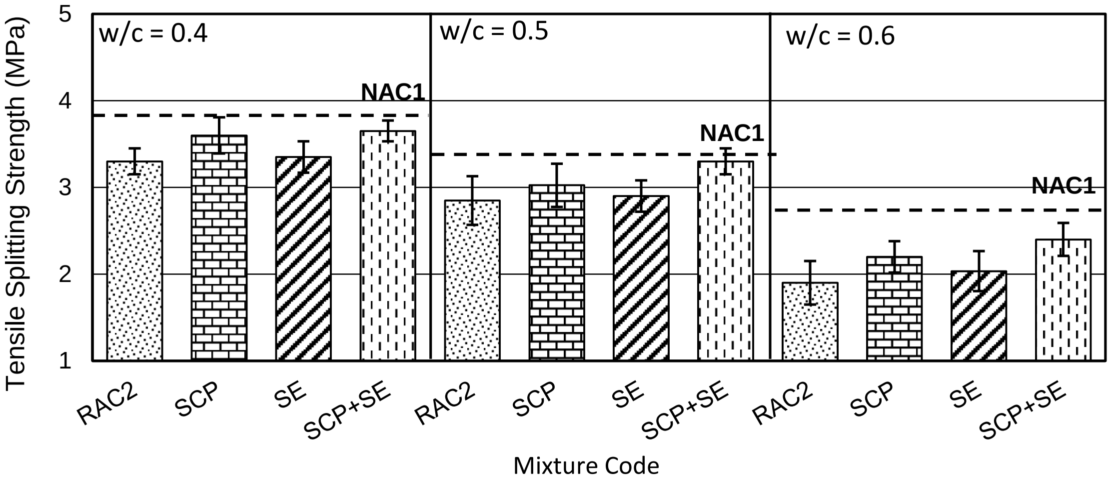

Figure 6: Variation in tensile strength development at 28-day for the enhanced RACs mixes at different w/c ratios, compared to NAC1 and RAC2

4.5 Effects of SCP and SE on the flexural strength of RACs

The results of the flexural strengths of the different RACs produced with different enhancement methods are given in Figure 7. A similar trend to tensile strength development was noticed in the 28-day development of the different RACs flexural strength. The NAC1 mixes exhibited the highest flexural strength of 6.5MPa at a 0.4 w/c ratio, among all the concrete test specimens, whilst the untreated RAC2 mixes seem to develop significantly lower flexural strength compared to NAC1. The Untreated RAC2 mixes obtained 4.6MPa at a 0.4 w/c ratio. This trend of reduction in flexural strength can be attributed to the weak bonding between the RA and the new cement paste within the concrete matrix owing to the poor quality of the adhered mortar on the RA surface and the poor quality of the developed ITZ [53]. Similarly, Majhi et al. [54] concluded a 6.5% reduction in the flexural strength of the RAC in comparison with NAC.

All the enhancement methods utilized were able to enhance the flexural strength of RAC. The results of the flexural strength also showed that all the enhanced RAC specimens presented in the SCP, the SE, and the SCP+SE specimens, followed similar flexural strength enhancement patterns to tensile splitting strength and compressive strength. Amongst all of these methods, the combination of soaking in cement-PFA+SF followed by mixing via sand envelope mixing approach presented in SCP+SE mixes, provided the best enhancements in the flexural strength. The synergetic effects of SCP+SE treatment resulted in a significant increase in the flexural strengths of RAC from 4.6 to 5.36MPa (16% enhancement), at a 0.4 w/c ratio. This can be ascribed to the denser developed ITZ after the treatment of the RA resulting in better bonding between the RA and the cement paste. The literature showed very limited studies on the effects of coating/ soaking RA with cement-pozzolan slurry/ solution on the flexural strength of the RAC. Ahmed & Lim [55] coated the RA with pozzolan slurry and reported 13% enhancement in the flexural strength of the RAC. Ahmad and Lim, pointed out that the enhancement in the flexural strength after the use of the pozzolan slurry is mainly attributed to the counteracting the microstructural deficiencies by the formation of the secondary calcium silicate hydrates which contributed to the enhancement of the flexural strength of the RAC.

There are very scarce studies that deal with the effects of the sand envelope mixing approach on the flexural strength of the RAC. Jagan et al. [52] reported 11% enhancement in the flexural strength of RAC after mixing using sand envelope mixing approach (SE). The combination of soaking RA in cement- PFA+SF solution prior to mixing followed by mixing using sand envelope mixing approach obtained better enhancement compared to the sole use of each method. This can be explained as the coupled effects of the two methods significantly strengthened the adhered mortar on the RA surface and densifying the ITZ resulting in a stronger bonding between the RA and the cement paste within the RAC matrix. There are no studies that examined the synergetic effect of these two methods on the flexural strength of the RAC.

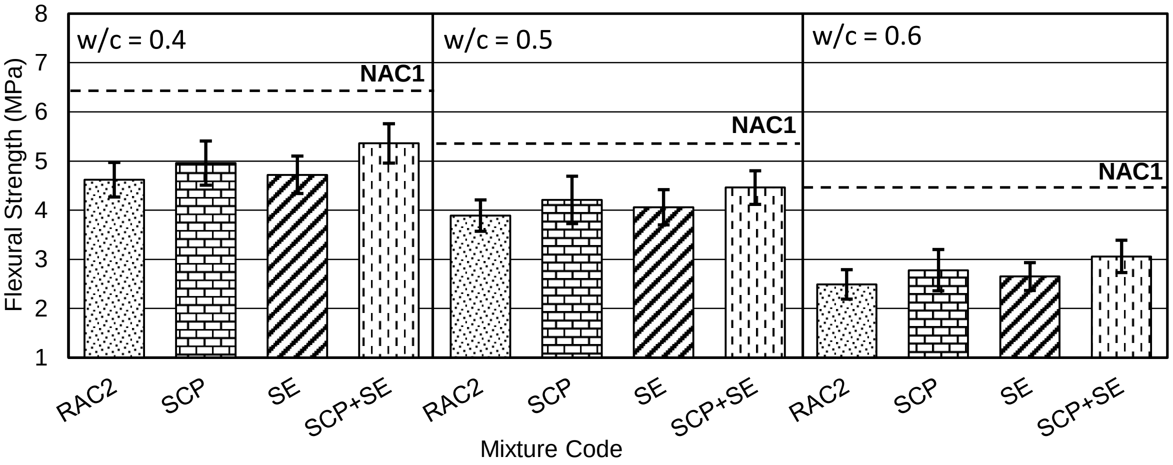

Figure 7: Flexural strength development for treated RAC mixes at different w/c ratios, compared to the NAC1 mixes and the untreated RAC2 mixes

4.6 Effects of SCP and SE on the modulus of elasticity of RACs

The results of the elastic modulus of the treated RACs cylindrical specimens after 28 days of water curing are presented in Figure 8. The highest modulus of elasticity was recorded for the

NAC1 mixes, with ranges between 27–33.5GPa. Like the compressive strength, the tensile splitting strength, and the flexural strength, a similar reduction trend has also been observed for the modulus of elasticity of the RAC2 specimens compared to the NAC1 specimens. The untreated RAC2 mixes exhibited the lowest modulus of elasticity values, ranging from 23.5–28.6GPa. This is possibly ascribed to the higher water absorption capacity of RA due to the porous adhered mortar, lower density and the weak bonding between the old ITZ and the new ITZ because of the presence of pores and micro-cracks around the RA [41]. According to Belen et al. [56], the RA adversely affects both the longitudinal and the transverse modulus of elasticity and owing to the lower elastic moduli of the RA, the peak strain and ultimate strain of RAC are increased, thus, large deformation in the RAC is endured.

Following the same enhancements trend observed in the compressive strength, tensile strength, and flexural strength, the highest enhancements in the modulus of elasticity of RAC were recorded for SCP+SE mixes. The coupled effects of SCP+SE treatment enhanced the modulus of elasticity of RAC by 8%, 7%, and 9%, at 0.4, 0.5, and 0.6 w/c ratios, respectively. Whereas SCP and SE mixes showed close enhancements in the modulus of elasticity of RACs, but slightly lower compared to SCP+SE mixes. There are very limited studies on the effects of soaking RA in cement-pozzolan solution and sand envelope mixing approach on the Young’s modulus of RAC. Nonetheless, the enhanced modulus of elasticity of RAC achieved by the SCP specimens can be ascribed to the enhanced modulus of elasticity of RA after soaking in cement-PFA+SF solution along with the enhanced compressive strength and other related mechanical properties. Mixing RAC using sand envelope mixing approach presented in the SE specimens has also enhanced the modulus of elasticity of the RAC.

This is possibly attributed to the formed pre-mixed stiff matrix during the first stage of SE method which filled the pores and micro-cracks of the RA, resulting in a stiffer and enhanced modulus of elasticity of the RA. This is in line with Jagan et al. [60] who investigated the effects of sand envelope mixing approach on the elastic modulus of RAC and reported 12% and 14.8% enhancement in the modulus of elasticity of RAC at 28-day and 90-day, respectively.

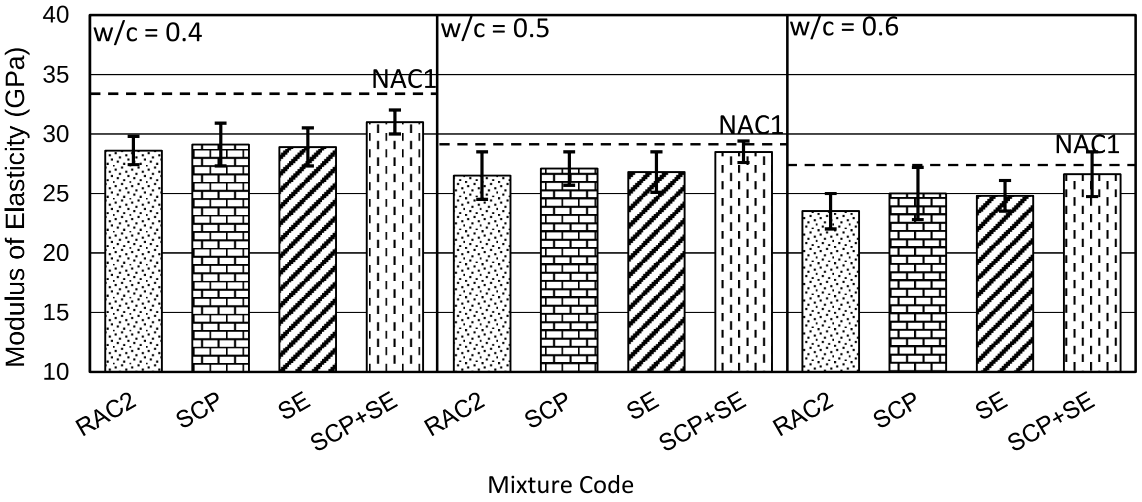

Figure 8: Variations in modulus of elasticity of the different treated RACs mixes in comparison with untreated RAC2 and NAC1 mixes

4.7 Correlation analysis of mechanical properties

Figure 9 shows the relationship developed between the different mechanical properties using the obtained experimental data. It can be seen from Figure 9 that a direct relationship exists between the mechanical properties of the enhanced RACs. It can be also indicated that the mechanical properties of the enhanced RACs are proportional to each other. The correlation between the different mechanical properties was obtained from the maximum correlation coefficient and can be expressed as follows:

$f_{ctm}=1.1f_{ct}^{1.198}$ (R^2=0.98) ***Equation 3***

$E_{cm}=12.8f_{ck}^{0.22}$ (R^2=0.91) ***Equation 4***

$f_{ct}=0.28f_{ck}^{0.67}$ (R^2=0.98) ***Equation 5***

$f_{ctm}=0.24f_{ck}^{0.8}$ (R^2=0.99) ***Equation 6***

Where is f_{ct} is the flexural strength and f_{ctm} is the splitting tensile strength, E_{cm} is the modulus of elasticity, and f_{ck} is the cube compressive strength. The R-factor of all the above-derived correlations was above 0.9, which indicates that the modulus of elasticity, tensile splitting strength, and flexural strength of the enhanced RAC can be predicted with relatively reasonable accuracy if the compressive strength was known.

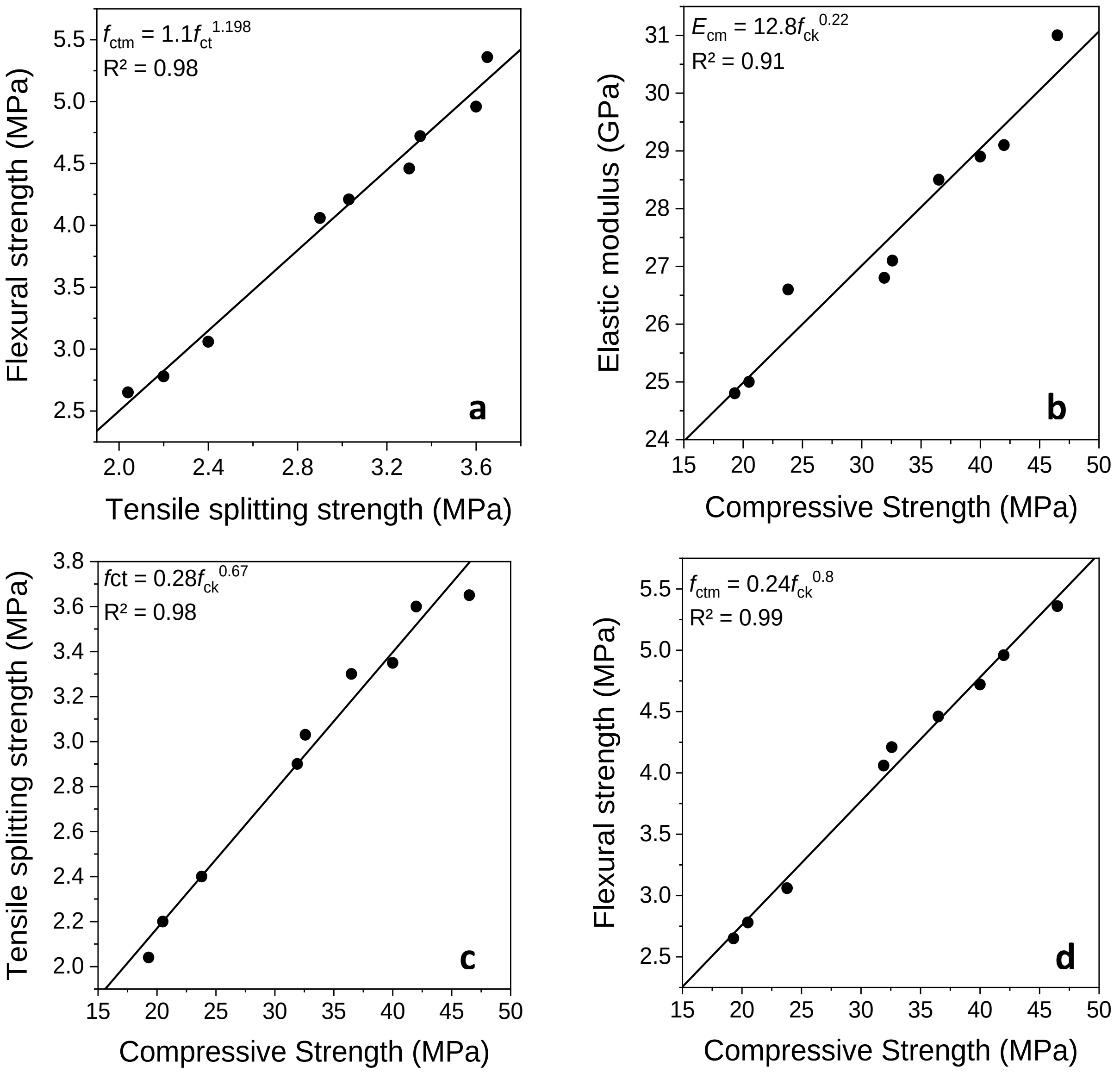

Figure 9: Relationship between different mechanical properties of the obtained experimental data (a) flexural strength vs. tensile splitting strength, (b) elastic modulus vs. compressive strength, (c) tensile splitting strength vs. compressive strength, (d) flexural strength vs. compressive strength

5. Conclusions

Recycled aggregate concrete with untreated RA has demonstrated low-quality engineering performance compared to NAC in terms of concrete mechanical properties due to several factors. Two of the main factors are the adhered mortar on the RA surface and the old weak ITZ which results in a weak interfacial transition zone and weak bonding within the recycled aggregate concrete matrix. Other concerns include variation in composition, previous loading, processing, and weathering compared to freshly crushed natural aggregates. This paper has presented a laboratory-based investigation of the effects of different enhancement methods on enhancing the mechanical property of RAC. Accordingly, based on the data presented, the following specific conclusions can be drawn.

1. ***Recycled aggregate concrete with untreated RA:*** the RAC with untreated RA showed inferior consistency, lower compressive strength, lower tensile splitting strength, reduced flexural strength, and inferior elastic modulus compared to the natural aggregate concrete. This was due to the poor engineering properties of RA compared to NA and mainly due to the presence of two ITZs in the RAC in which the old ITZ acted like a weak link in the RAC matrix. The inferior flexural strength, tensile splitting strength, and modulus of elasticity performance of RAC were mainly due to the lower bond strength and poor interlocking of RA with the cement paste because of the ITZ. In addition, the lower modulus of elasticity of RAC was associated with the lower elastic moduli of RA compared to NA. The high porous nature of RA owing to the presence of pores and micro-cracks on the RA surface along with the old ITZ was also related to the inferior mechanical performance of RAC. The SEM images of the RAC microstructure confirmed the poor mechanical performance of RAC. The microstructure of RAC was full of micro-pores, voids, and micro-cracks around the ITZ.

2. ***Soaking RA in cement-PFA+SF solution (SCP):*** treating RA by soaking in cement-PFA+SF solution increased the consistency by 20%. The SCP achieved a minimum of 30MPa compressive strength suitable for structural applications. The splitting tensile strength, flexural strength and modulus of elasticity were enhanced by 9%, 7%, and 2%, respectively, after the SCP treatment. These enhancements were due to the filling and sealing effect of the SCP method. The SEM images of the SCP mix showed a better and denser microstructure, lesser pores and filled micro-cracks.

3. ***Sand Envelope mixing approach (SE):*** the SE batching technique significantly enhanced the consistency of RAC. A minimum of 30MPa compressive strength was achieved by the SE batching technique. The splitting tensile strength, flexural strength, and elastic modulus exhibited an increase of 1%, 2%, and 1%, respectively, after batching using the SE method. The developed stiffed sand-rich cement paste during the early stage of mixing covering the RA surface was mainly the key factor responsible for the overall enhancement of the SE mix. The microstructure of the SE mix was denser with lesser voids and micro-cracks compared to the untreated RAC,

but the presence of the voids and micro-cracks was more evident compared to the SCP mix.

4. ***Bi-combination of SCP+SE:*** the combination of soaking RA in cement-PFA+SF solution prior to mixing followed by mixing using sand envelope mixing approach exhibited the highest 28-day compressive strength of 46MPa. This bi-combination of the enhancement method also achieved 14%, 13%, and 7% enhancements in the tensile splitting strength, flexural strength, and modulus of elasticity, respectively. The coupled effects of SCP and SE method resulted in reduced water absorption of RA, reduced aggregate impact value of RA, further filling of the pores and micro-cracks, and a better-compacted matrix of RAC. In addition, a higher C-S-H gel amount was produced as a result of soaking in cement-PFA+SF solution. All these factors resulted in higher strength RAC and improved its mechanical performance. The SEM images observed for the SCP+SE mix showed the most desired better-compacted microstructure. The synergetic effects of these two methods led to a relatively stronger and compacted microstructure with the fewest pores and microcracks.

5. Overall, it can be concluded that the proposed innovative enhancement methods in this research are powerful tools to promote the use of recycled aggregate in the construction industry. The findings of the present research can be of great interest to stakeholders, such as recycling plant owners, relevant government sectors and bodies, the construction industry, design engineers, and researchers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or non-profit sectors.

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