Silica fume and crumb rubber as partial replacement of cement and fine aggregate concrete

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ABSTRACT

This study investigated nine mixes containing 0 or 15% silica fume as the cement replacement and 0 or 10% treated and untreated crumb rubber as the fine aggregate replacement. The fresh and mechanical properties of these concrete mixes were correlated with non-destructive test results including rebound hammer and Ultrasonic Pulse velocity (UPV). One curing scheme was adopted here in this study which was normal curing. Microstructure characterization was carried out using X-ray diffraction Analysis (XRD) and Scanning Electron Microscope (SEM). The XRD showed that the crumb rubber must be washed in clean water after pretreatment with sodium hydroxide (NaOH) to avoid ettringite formation in the concrete pores. The results showed that combining the silica fume and crumb rubber enhanced the compressive strength of the rubberized concrete. The rebound hammer numbers were closely correlated linearly with the compressive strength of the test mixes.

Introduction

Rubber extracted from waste tires, commonly called crumb rubber (CR), can be used in concrete as a partial replacement for aggregate, reducing its carbon footprint [1]. Several researchers [2 -7] investigated the properties of rubberized concrete containing various percentages of CR. Gholampour et al. [3] found that rubberized concrete has a high deformation capacity, making it an attractive choice for structural elements designed against dynamic and impact loads. Khaloo et al. [4] found that rubber concrete had a higher tensile strain at failure, indicating a more energy-absorbent mix. They also noted that rubber concrete had a low coefficient of thermal expansion, and the rubber mixes were more resistant to thermal changes. Gerges et al. [8] and Ling [9] concluded that including rubber can enhance concrete's flexibility, impact strength, and toughness and described a successful process to manufacture concrete paving blocks using CR as a partial replacement for sand. Schimizze et al. [10] recommended that rubber concrete be used in light-duty concrete pavements.

Some reports apply non-destructive testing (NDT) to rubber concrete [11, 12, 13] to assess the compressive strength and correlate their results with the destructive values. Relationships between mechanical properties and NDT results have been established for unheated concrete [14, 15].

Limited reports are available on the behavior of concrete containing NaOH-treated crumb rubber and silica fume, subject to normal heating in service. In addition, no research addressed the assessment of the rubberized concrete with silica fume inclusion using NDT. Thus, filling these research knowledge gaps is crucial by assessing the rubberized concrete while pretreated and untreated crumb rubber with silica fume. This will address whether this type of concrete has potentially beneficial uses in the wider construction industry.

Experimental Program

Concrete mix design

The concrete mixes were designed following the ACI PRC-211.1 [16]. Five mixes containing CR and an additional control mix, without rubber, were designed for the test program. Table 1 shows the physical properties of cement, fine, and coarse aggregate used for mix design. Table 2 presents the concrete mix design for a one-meter cube. For each test variable, the following specimens were prepared: nine cubes of side dimensions of 150 mm, three cylinders of a diameter of 150 mm and height of 300 mm, and three prisms dimensioned 100 x 100 x 500 mm. The five mixtures include 10% fine aggregate replacement by treated or untreated CR. For the mixes with silica fume, 15% silica fume cement replaced the exact weight of cement. As shown in Table 2, mixes 1 and 3 represent the use of untreated CR at 10% of fine aggregate replacement, while mixes 2 and 4 contained similar content for treated CR replacement. It should be noted that mixes 3 and 4 contained 15% cement replacement by silica fume.

Table 1. Concrete ingredients and data used for concrete mix design.

Type of concrete	Non-Air-Entrained Concrete
Maximum size of Aggregate (MSA)	25 mm
Fineness Modulus for Fine Aggregates	2.6
Specific Gravity of Cement	3.15
Specific Gravity of Coarse Aggregate	2.65
Specific Gravity of Fine Aggregate	2.60

Sample Preparation

The concrete mixes were mixed in a mechanical mixer and poured into the molds. The molds were placed onto the vibrating table, ensuring the compaction of the concrete thoroughly. The specimens were left in the molds in the laboratory for 24 hours. Then, the specimens were taken out of the molds and placed inside curing tanks for 7 and 28 days until testing. Forty cube specimens were tested for compressive strength at 7- and 28 days of age, along with Rebound Number testing at 28 days. Fifteen-cylinder specimens were prepared for the direct Ultrasonic Pulse Velocity (UPV) test after 28 days. Finally, fifteen prism specimens were prepared for the UPV indirect test for concrete homogeneity. All samples were prepared, and water cured as per BS EN 12390-3 [17].

Table 3. Concrete quantities used for concrete mix design in 1 m^3.

I.D.	Water, Kg	Cement, Kg	Coarse Aggregate, Kg	Fine Aggregate, Kg	Crumb Rubber, Kg	Silica fume, Kg	Rubber treatment
Mix 0	200	500	1024	631	0	0	N/A
Mix 1	200	500	1024	567.9	26.69	0	Non treated
Mix 2	200	500	1024	567.9	26.69	0	Treated*
Mix 3	200	425	1024	567.9	26.69	54.76	Non treated
Mix 4	200	425	1024	567.9	26.69	54.76	Treated*

* Rubber treated in NaOH for 30 minutes

Test Methods

A slump test for the fresh concrete mixes was conducted as per ASTM C143 / C143M [18]. The density of the hardened concrete was conducted according to ASTM C642 [19] at

28 days. NDT using Rebound hammer Number (RN) and Ultrasonic Pulse Velocity (UPV) measurements were conducted before testing specimens for mechanical properties according to the ASTM C805 / C805M [20] and ASTM C597 [21]. The RN apparatus and corundum stone were used to smooth the surface before the test. The RN test took place before testing the cubes in compression, during which the cubes were mounted in a universal machine. Each cube surface was divided into nine 5 cm x 5 cm equal cells using a permanent marker. The apparatus was repeatedly placed perpendicular to the cube specimen's surface at the center of each cell, and hence nine readings were taken to obtain the mean RN for each cube at 28 days of age to measure the RN. UPV was applied as an indicator of the voids/pores in the internal structure of the prism samples. This method was indirectly used to evaluate the concrete homogeneity in the prisms' samples indirectly. The wave propagation time between the transmitter and receiver and the distance was recorded in all UPV tests. Table 3 addresses the ultrasonic pulse velocity classification [22] as per the UPV values.

Table 3. Ultrasonic pulse velocity classifications of concrete [23]

S/N	UPV range of values (m/s)	Concrete Classification / Quality Rating
1	UPV > 4500	Excellent
2	4500 > UPV > 3500	Good
3	3500 > UPV > 3000	Medium
4	3000 > UPV > 2000	Doubtful
5	UPV < 2000	Very weak

Experimental Results and Discussion

Slump

The test results for the slump of the mixes are reported in Table 4. In all mixes, the inclusion of CR, treated or untreated, leads to a slump reduction compared to the control mix (Mix 0). The results also show that the mixes with fine aggregate replaced by untreated CR (mix 1 and mix 3) had a lower slump reduction than those with treated rubber (mix 2 and mix 4). The reduction in slump relative to the control mix was 15%, 28%, 32%, and 36% for mix 1, mix 2, mix 3, and mix 4, respectively. It should be noted that in mix 3 and mix 4, the slump exhibited a higher reduction than in mix 1 and mix 2 as the cement was replaced by 15% silica fume. Therefore, rubber pretreatment and the inclusion of silica fumes caused a further reduction in mix workability, and the reduction was observed when untreated rubber was used in the mix.

Table 4 Typical slump, density values, and compressive strength results

Mix, ID	Slump - mm	The density of hardened concrete at 28 days ρ (g/cm³)	Compressive strength - Age N/mm² (MPa)		Rebound number, (x)	Predicted compressive strength (y) (y=0.804 (x) + 12.581) (R^2=0.9929)
			7 days	28 days		
0	24.0	2.50	30.0	40.50	45	45.14
1	20.0	2.40	20.0	26.90	34	34.21
2	17.0	2.40	21.0	28.0	35	35.09
3	16.0	2.44	23.0	29.40	36	36.22
4	15.0	2.44	24.0	30.80	38	37.34

ElNemr [24] reported that adding silica fume to mortar reduced the workability by 16%, on average, relative to the mixes without it. Youssf et al. [25] reported an 88.2% reduction in a slump when 15% silica fume partially replaced cement in the mix. However, the reduction in a slump was only 25% in the mixes containing 20% rubber and 15% silica fume.

Density

The results of the density of the test mixes are shown in Table 4. It can be observed from these results that the concrete density was slightly reduced due to the inclusion of CR; however, the silica fume inclusion decreased this reduction, as evident in mixes 3 and 4. Replacement of fine aggregate by 10% CR reduced density by 4 and 2% for the mixes without and with silica fume, respectively. It can be noted that the rubber treatment did not significantly affect the density of the rubberized concrete.

Pham et al. [26] prepared mixes with 15% rubber by volume and concluded that the effect of rubber on density was negligible. In contrast, Ramli and Dawood [27] noted that partially replacing cement with 10% silica fume in mixes with superplasticizers led to a 13% increase in concrete density. Both reports align with the current study's findings.

Siddique and Naik [28] suggested that the non-polar nature of rubber particles may result in the ability to repel water and entrap air on the rubber surface, which would subsequently increase the number of air voids and thus decrease the concrete density. In addition, Raffoul et al. [29] studied the physical properties of CR and reported that rubber has a specific gravity of 1.10 and a bulk density of (400 - 460 kg/m^3). These values are significantly lower than those for sand, as reported in Table 2, which contributes to the reduction in the density of rubberized concrete, mainly when high rubber content values are utilized.

Compressive Strength of Rubberized Concrete

The average compressive strength results of the cube specimens at age 7 and 28 days are reported in Table 4. The influence of the treated and untreated CR inclusion and the addition of silica fume on the mechanical properties of concrete are discussed in the following sections.

Effect of crumb rubber inclusion

Table 4 shows the average compressive strength results of the cube specimens at age 7 days. It can be observed that mixes 1, 2, 3, and 4 showed a reduction in compressive strength by 33%, 30%, 23%, and 20% compared to the control mix (Mix 0), respectively. At 28 days. Table 4 shows that the reduction in compressive strength was 34%, 31%, 27%, and 24%, respectively.

Mavroulidou and Figueiredo [30] reported 32% and 40.9% loss of compressive strength at 7 and 28 days, respectively, with 10% rubber replacement. Their mixes did not contain silica fumes. The results of Jalal et al. [31] indicated a loss in compressive strength of 46.0% and 46.1 % for mixes with 10% CR and without silica fume and a loss of 43.6% and 48.1% for mixes with 10% silica fume at 7 and 28 days, respectively. Both above studies did not apply any rubber pretreatment. Roychand et al. [32] explained that the reduction in strength with the increase in rubber content could be attributed to three main reasons, these were: (a) the high deformability of the rubber particles compared to the surrounding paste matrix, resulting in crack initiation, (b) weak interfacial bond between the CR and hardened paste matrix, and (c) reduction in density leading to a detrimental effect on the strength.

Effect of Crumb Rubber Pre-treatment with NaOH

When comparing the results of (mix 2 with mix 1) and (mix 4 with mix 3) in Tables 4. The mixes with treated CR exhibited limited improvement in mechanical properties compared to their counterparts containing untreated CR, both when normal curing was applied. For instance, for the samples with and without silica fume, the improvement in compressive strength at 28 days was 4.2 % and 4.8%, respectively,

Copetti et al. [33] reported similar findings as they found that rubber pretreatment did not significantly affect the mechanical properties of their concrete. On the same note, Marques et al. [34] tested mortar samples with and without CR treatment and reported that rubber treatment slightly reduced the strength of the mortar in compression. Similarly, Balaha et al. [35] and Chiraz et al. [36] showed approximately 13% and 15% improvement in compressive strength in rubber concrete containing NaOH-pretreated CR, respectively. Saloni et al. [37] attributed the improvement in mechanical properties of their mixes with CR treatment to modifying the CR surface by the treatment. Hence, there are conflicting reports on the benefits of pretreatment. It is apparent from the findings of this investigation that the effect of CR pretreatment depends on how it is applied, that is, its duration and whether washing with water occurred after any pretreatment.

Effect of Silica Fume Inclusion in Mixes with Crumb Rubber

When comparing the results of mix 3 and 1, mix 4 and 2 as in Table 4, the mixes containing silica fume exhibited some improvement in mechanical properties compared to their counterparts without silica fume under the application of normal curing. For compressive strength at 28 days, silica fume inclusion enhanced the strength by 9.3% in untreated rubber mixes. In contrast, the improvement was 9.9 % for the mixes with treated rubber.

Gu¨neyisi et al. [38] reported a 9.6% increase in compressive strength with 15% silica fume in a mix with 10% rubber. The CR replaced fine aggregate in their mixes, and crumb rubber replaced coarse aggregate. When no rubber was utilized in the mixes, the compressive strength increased due to silica fume inclusion of 10.8%. It appears that silica fumes offered a lower contribution to mechanical properties for the rubber mixes. A similar effect was noted by Li et al. [39], who found that adding 10% silica fume to a mix without rubber increased the compressive strength by 41.6%, whereas when the mix contained 20% CR, the increase in compressive strength, due to silica fume addition at 28 days, was only 35.7%. It is worth mentioning that Sun and Young [40] found that for a mix with 18% silica fume, only 44.1% of the silica fume had reacted at 28 days. Therefore, its effect on strength at this age is not profound. Indeed, Gesoğlu and Güneyisi [41] found that silica fume continued to contribute to the strength of rubberized concrete with extended curing of up to 90 days. All these reports support the findings of the current investigation on the effect.

Non-Destructive Test (NDT)

Rebound Hammer Number Results

The results of the Rebound Hammer Number (RN) test are reported in Table 4, whereas Fig. 1 shows the relationship between the RN and compressive strength results for the test samples. It can be noted from Table 4 that the RN values recorded at 28 days for the mixes with 10% CR varied between 31 and 38, depending on rubber treatment, and silica fume inclusion.

Mohammed et al. [14] reported an RN value at 28 days of 33, for a comparable mix to those in the current investigation. Akshay and Sofi [42] reported an RN value of 39 for the 10% CR rubber mix. These values are of a similar order of magnitude to the results in the current study. However, Kumar and Dev [23] reported an RN of 48 for a mix with 10% CR, but their mix had a higher strength; hence, a higher RN was recorded. It can be seen from Fig. 1 that the RN is reasonably correlated with compressive strength values for all mixes in the current investigation, regardless of whether or not the samples included silica fume, or the CR was treated.

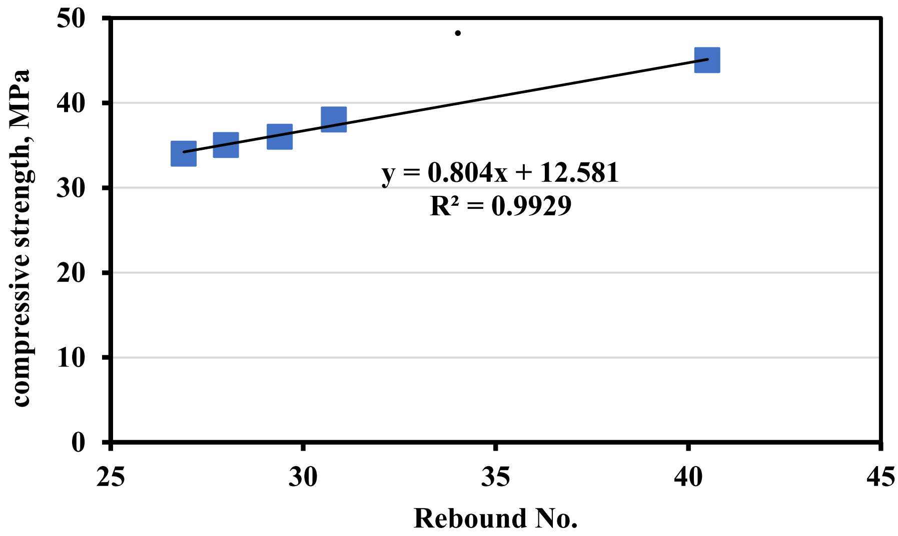


Fig. 1 Correlation of Rebound Number of cube specimens with compressive strength at 28 days

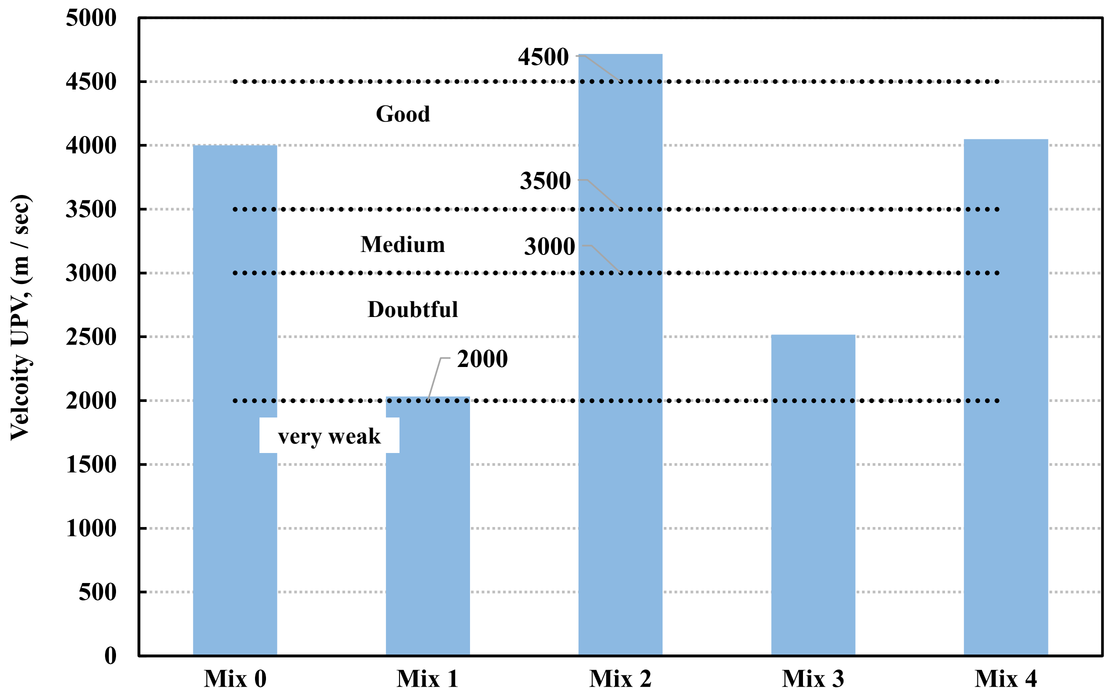
Ultrasonic Pulse Velocity (UPV)

Fig. 2a shows the direct Ultrasonic Pulse Velocity (UPV) test results. BS 1881: Part 203 [22] gives guidelines to classify the concrete quality based on UPV values, as shown in Table 4. It can be seen from Fig.2a that the test mixes exhibited different classification qualities. The inclusion of CR reduced the UPV by 49.1%. Fig. 2b shows that, unlike the RN values, the UPV results for all the test mixes could not be correlated with the compressive strength on one trend line. For a comparable level of compressive strength, the mixes exhibited different UPV values, reflecting different classifications. A distinct difference is seen between mixes with untreated CR and those with treated CR.

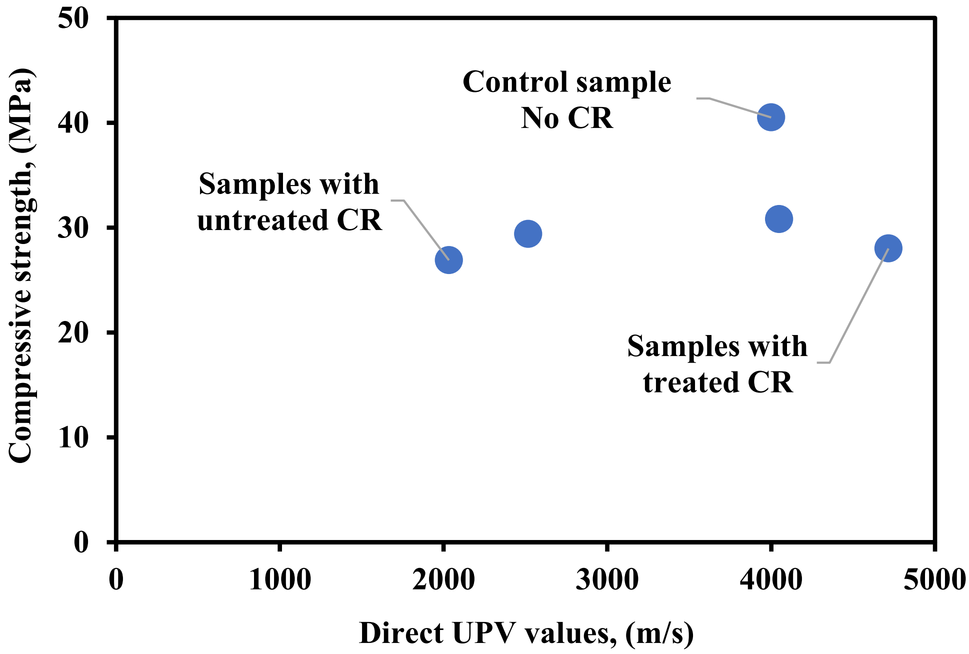
The indirect UPV test is applied to study the CR mixes' homogeneity. The results of the tests are shown in Fig. 3. The inverse of the slope of the lines is the indirect UPV for each mix. It can be seen that the results showed high sensitivity to the mixed variables.

Albano et al. [11] found a reduction in UPV of 56% with similar CR content. In general, rubber treatment and/or the inclusion of silica fumes had an evident impact on the classification. Rubber treatment affected the UPV values by 72.1% and 54.9% for the mixes without and with silica fume, respectively. These values contradict the findings of Najim and Hall [43], who reported no improvement in UPV with CR treatment. The reasons for the difference between the UPV result of the current study and those of Najim and Hall [43] shall be further explained when discussing the SEM results.

In the current study, the inclusion of 15% silica fume increased the UPV by 23.8% and 11.4% for mixes containing untreated and treated CR, respectively. In mixes with untreated rubber, Gesoğlu and Güneyisi [41] found that with 10% silica fume inclusion, the UPV was increased by 8% at 28 days. The low improvement in UPV can be attributed to the lower percentage of silica fume compared to the current study, which leads to more pores in the matrix, as rubber was utilized as a partial replacement for combined fine and coarse aggregates in their mixes. Mohammed et al. [14] also found that the UPV test was more realistic in evaluating the quality of the mixes with CR.



(a) UPV values for the different test mixes showing classification for concrete quality



(b) Scatter diagram for the compressive strength and UPV values

Fig. 2 Experimental results of direct ultra-sonic pulse velocity test (UPV)

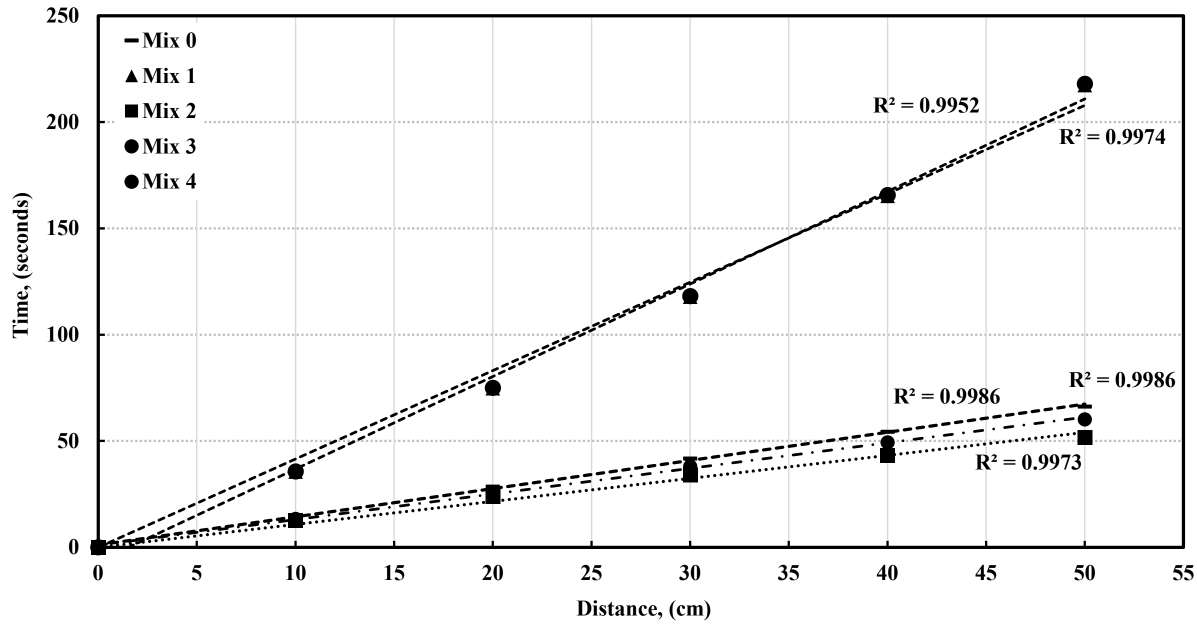


Fig. 3 Indirect Ultrasonic pulse velocity (UPV) for homogeneity testing

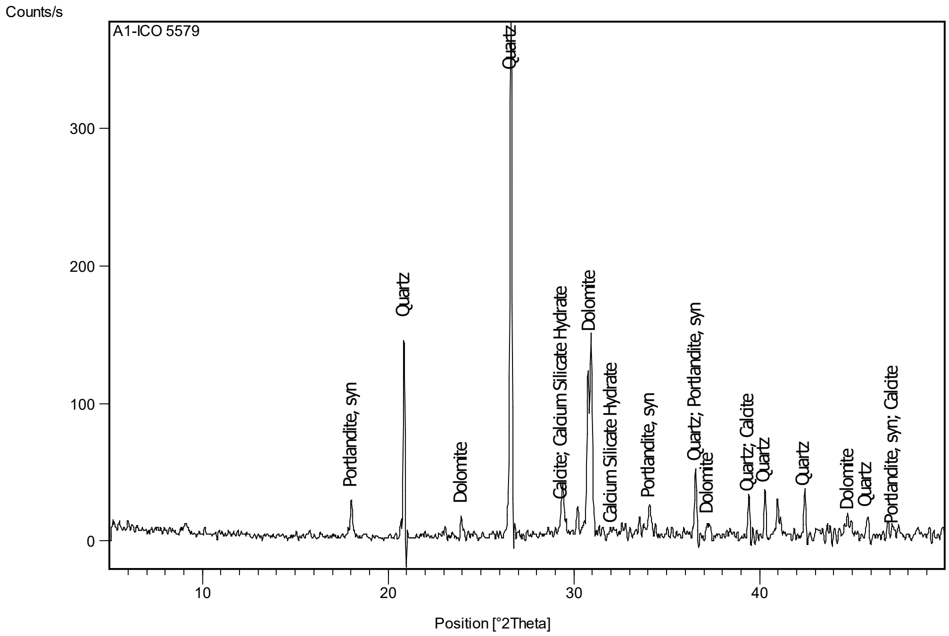
Micro-structural Studies Some of the Test Mixes

X-RAY Diffraction

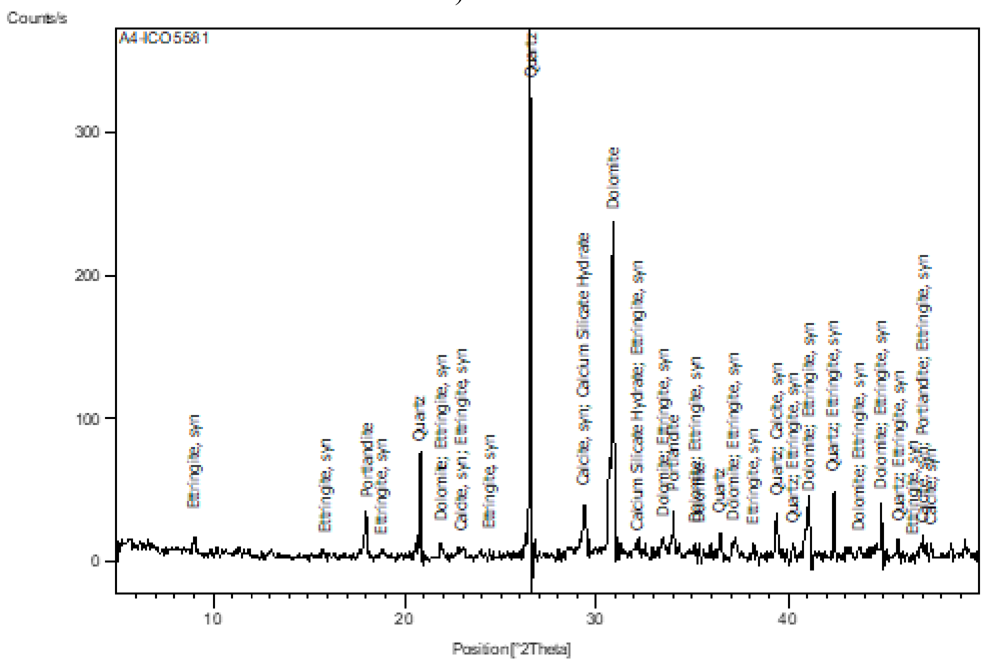
Fig. 4a, and 4b show X-ray diffraction for Mix 0, and Mix 2, respectively. Fig. 4a, for the control mix without CR, shows the usual formation of Calcium Silicate Hydrate (C-S-H) and Portlandite (C-H). In addition, the usual peaks characteristic of quartz is present due to fine aggregates. In contrast, the Dolomite peaks are attributed to the coarse aggregate utilized, forming approximately 43% of the mix by weight. It can be seen that the peaks characteristic of C-H and C-S-H were weak, indicating the presence of un-hydrated cement particles. This behavior is reflected in the moderate strength of 40 MPa exhibited by Mix 0 at 28 days, although it was a 0.4 w/c mix containing 500 kg/m^3 of cement.

Fig.5b, for Mix 2 contained treated rubber shows that the characteristics of C-H were higher than the corresponding peaks for samples Mix 0. However, the peaks characteristic of C-S-H were found to be lower than the corresponding peaks in sample Mix 0. Furthermore, more significant amounts of ettringite (E) were observed. The increased C-H and the appearance of ettringite are probably due to the deposition of NaOH from treating the CR before adding it to the mix. It should be noted that in the current study, the CR was not washed after NaOH treatment. In contrast, the C-S-H phase's peak characteristics were higher than Mix 0; thus, it indicates that silica fume reacted with C-H, forming more C-S-H gel. In addition, lower quartz was exhibited because of the dilution effect of adding silica fume. However, the presence of CR still adversely affected the mechanical properties, and the silica fume contribution to the mechanical properties was less than expected, as discussed earlier.

Mernerdaş et al. [44] developed a mix with the same type of cement and identical proportions as the current study and achieved nearer to 70 MPa cylinder compressive strength at 28 days. This behavior indicates a lower volume of quartz because of the dilution effect of adding silica fume, as explained earlier.



a) Mix 0



b) Mix 2

Fig. 4 X-ray Diffraction of rubberized concrete specimens

Scanning Electron Microscope (SEM)

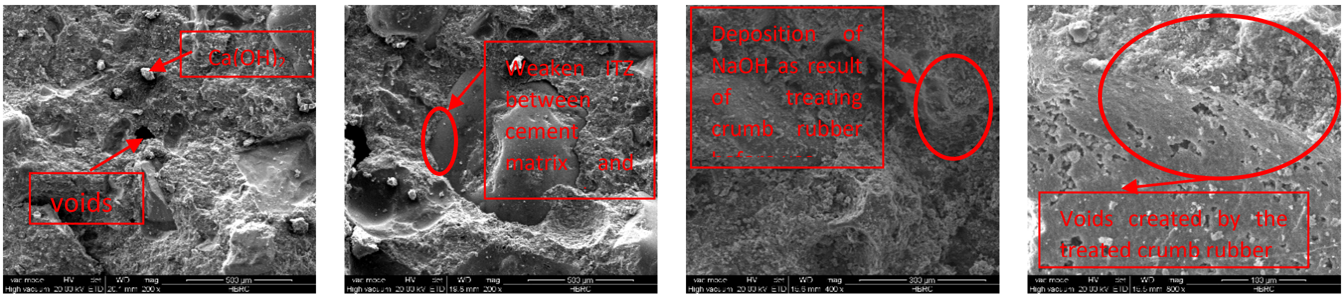
Fig. 5a, and 5b present the SEM for Mix 0, and Mix 2, respectively. These mixes were the same as those tested for XRD above. Fig. 5a, for the control mix without CR, exhibits many voids resulting from un-hydrated particles, inadequate mixing, or interlayer and capillary pores in the matrix. In addition, Fig 5a shows the weak bond between the cement matrix and fine aggregate particles. This poor micro-structure was reflected in the mechanical properties of the control mix, as discussed above.

Fig 5b shows the SEM of Mix 2, in which the NaOH was deposited as the result of treating CR before using it in mixing. The deposits filled the voids created by the poor hydration around the CR particles. However, these deposits are not a substitute for hydration products. However, normally cured concrete containing CR, including rubber, was shown to have a detrimental effect on the matrix.

Wang et al. [45] extensively studied the interface between sand and cement paste (ITZ-S) and between CR and cement paste (ITZ-R) in rubberized concrete. They concluded that the addition of rubber inhibited the hydration of cement, thereby reducing the formation of C-S-H. They explained this formation by the hydrophobicity of the rubber surface, leading to a water reduction around the CR. Therefore, the hydration reactions become slow. They also noted that the micro-crack widths in ITZ-R were more significant than those for ITZ-S, indicating that the bond between cement paste and rubber is poor. Similar findings were reported by Albano et al. [11]. Marques et al. [34] reported that rubber treatment using NaOH did not affect the bond quality between the CR and the matrix. This conclusion contradicts the findings of Segre and Joekes [46], who reported that the bond between treated and washed CR and the cement paste is improved compared to that of a mix containing untreated CR.

Sugapriya and Ramkrishnan [47] support this finding and reported that raw rubber, possessing a smooth surface, exhibited a poor bond with the surrounding matrix. In contrast, treated rubber, where the zinc stearate layer has been removed, possessing a rougher surface, bonded well with the matrix. It seems that rubber washing after pretreatment with NaOH is essential to realizing better bonding with the matrix. However, the deposition of NaOH in the pores of the treated samples in the current investigation significantly improved the UPV results by reducing the internal spaces in the matrix. This improvement is probably the reason for the differences in the improvement of UPV in the current study compared to the observations of Najim and Hall [43]. Since they washed the rubber after pretreatment, probably no deposits of NaOH remained in the pores, and hence rubber pretreatment did not significantly improve their recorded UPV.

Similar to the current study's findings, Li et al. [39] found that the bonding surface between the rubber and cement paste was weak, but partially replacing the silica fume helped to improve this weakness. It seems that silica fume filled some of the gaps in the ITZ zone between the CR and cement paste leading to a more compact transition zone.



(a) Mix 0 (b) Mix 2

Fig. **5** Scanning electron microscope (SEM) for specimens; (a) Mix 0, and (b) Mix 2,

Conclusions

Based on the results of the current investigation, the following conclusions can be drawn:

Crumb rubber reduced the slump, whether it was pretreated or untreated. The reduction reached 16 and 42 % for untreated and pretreated rubber, respectively. The silica fume inclusion along with crumb rubber increased this reduction by 20 and 11.7 % for untreated and treated crumb rubber, respectively. The crumb rubber inclusion reduced the concrete density by 4%, which is considered a slight reduction considering the crumb rubber replacement was just 10%. On the contrary, the silica fume inclusion increased the density.

Treated crumb rubber reduced the compressive strength at 7 days by 25% on average, while untreated rubber reduced the compressive strength by approximately 28%. The silica fume inclusion enhanced the compressive strength better for those treated crumb rubber than untreated one.

The rebound hammer numbers of the studied mixes were closely correlated with the measured compressive strength of those mixes, exhibiting a linear trend. The RN results were not sensitive to the mixed ingredients, or rubber pretreatment.

The direct UPV results were not correlated with the compressive strength results on a single linear trend line since the mixes exhibited different UPV values. However, UPV was improved with rubber pretreatment and silica fume inclusion. The indirect UPV results highlighted the effects of mixed contents, and rubber pretreatment while showing good homogeneity.

The XRD results explained the mechanical properties in terms of compressive strength. Heat treatment and silica fume offered slight support to the compressive strength due to the formation of additional C-S-H. Still, the presence of rubber treated or untreated leads to reduced mechanical performance. The main concern with rubber pretreatment is the deposition of NaOH in the pores leading to Ettringite formation, adversely affecting the concrete matrix and the compressive strength. This behavior was evident in the current study as the rubber was not washed after treatment.

The SEM results explained UPV observations, as weak zones and deposits were observed. Rubber pretreatment and silica fume inclusion reduced the voids in the matrix; hence, a compact structure is detected in UPV.

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Keywords: Silica fume; rubberized concrete; untreated and treated crumb rubber; non-destructive testing (NDT)

Biography:

My line of work in civil engineering included laboratory and in-situ testing of building materials, structural design, retrofitting of structures for change of use, construction site supervision, and providing evidence in courts of law/public hearings regarding the state of structures after inspection. In October 2015, I joined the University of Liverpool as a visiting professor. In 2019, I moved to the University of West London for a teaching and research post. My research interests include innovative materials, structural design, and concrete durability, and have published 95 journal and conference papers.