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TECHNICAL PAPER

Durability properties of treated coconut shell-used concrete for sustainability

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Abstract
The absorption capacity of coconut shell (CS) aggregates is 20–25% absorption due to their inherent porosity. Hence, if CS is treated, there are chances of reducing its porosity from 2.370 to 0.315% and, in turn, may enhance its durability performances when used in concrete production. Therefore, this study has investigated the impact of treated CS aggregate with six different treatments on the durability performance of concrete produced with treated CS. Six treatments are: treated with polyvinyl alcohol (PVA), ferrous sulphate (FS), slaked lime (SL), acetic acid (AA), sago flour (SF), and corn flour (CF), respectively. Scanning electron microscope (SEM) images were taken to examine the treated CS, and ImageJ software was utilized to analyse the percentage of pore area. The treated coconut shell concrete (TCSC) shows better performance in durability properties than the untreated coconut shell concrete (CSC). In that, TCSCT5 shows better performance in durability properties, such as 7.32–4.54% in the water absorption test, 11–7.32% in the volume of permeable voids test, 0.111–0.031 mm/min$^{0.5}$ in sorptivity test, and 2492–2450 coulombs in rapid chloride ion permeability test, from 3 to 56 days, respectively. In the temperature resistance test, TCSC and CSC mix resulted in resistance against a temperature of 200 °C for 2 h, and both CSC and TCSC mixes fall under type 3 constructions. Thus, the results of this study suggest that the treatments of CS aggregate encourage the production of durable concrete when used as coarse aggregate by reducing the water absorption of the CS aggregates immensely.

Keywords Coconut shell · Waste management · Treatments · SEM images · ImageJ · Concrete durability

Introduction

Coconut shell (CS) aggregates are gaining attention as an environmentally friendly alternative to traditional coarse aggregates in concrete production. Widespread coconut cultivation in countries like Indonesia, the Philippines, and India leads to significant waste, with discarded CS comprising a substantial portion of solid waste in tropical regions. By crushing these shells into lightweight aggregates, it is possible to reduce waste and promote sustainability [1–3]. Research has shown that CS can effectively serve as a lightweight aggregate in producing lightweight concrete (LWC) that meets quality standards. This alternative material helps mitigate environmental degradation and supports sustainable construction practices. Furthermore, the availability of coconut shells in areas with high coconut production makes them a cost-efficient option for construction projects [1, 2, 4].

While producing CS aggregates, the shells are crushed into suitable sizes for concrete. Due to the flaky nature of CS, a sieve size of 12.5 mm is commonly employed to limit the maximum dimensions of the aggregates. CS exhibits higher water absorption compared to conventional aggregates, so it is advisable to soak the shells in water for a before to their use in concrete production. On the day of concrete production, the CS is allowed to surface dry and is then weighed in a saturated surface dry (SSD) condition during the batching process. These additional steps differentiate the production of CS concrete (CSC) from conventional concrete (CC) [5, 6].

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In the realm of lightweight concrete (LWC) production, CS serves as a suitable coarse aggregate. Despite the inherent humidity and air content in CS, it falls under the non-biodegradable solid agricultural waste category. Besides its use in concrete, CS finds applications in various products like decorative items, home appliances, and activated carbon production [7, 8]. The utilization of CS as a sustainable alternative to traditional coarse aggregates in concrete production plays a vital role in promoting environmentally responsible construction practices. The construction industry can contribute to a more sustainable and ecologically conscious future by reducing dependence on natural resources and effectively utilizing waste materials.

The durability properties of lightweight concrete (LWC) produced using coconut shell (CS) aggregates were found to be different from those of conventional normal-weight concrete (NWC). Specifically, the LWC exhibited variations in water absorption, permeable void volume, sorptivity, rapid chloride ion permeability, and temperature resistance when compared to NWC [5]. It is important not to compromise the durability aspects of both NWC and LWC.

To improve the quality of CS aggregates, various chemicals have been identified in the literature for their treatment. These include concentrated borate solution, sodium dichromate solution, ferrous sulphate solution, cupric sulphate pentahydrate solution, acetic acid solution, slaked lime solution, and polyvinyl alcohol (PVA) solution [9, 10]. Additionally, adhesive solutions such as sago flour and corn flour have been used in treating coconut charcoal and noodles, respectively [11–13]. For this study, six different chemicals were selected to treat the CS aggregates and enhance their quality by reducing porosity and water absorption [14]. These chemicals include polyvinyl alcohol (PVA), ferrous sulphate (FS), slaked lime (SL), acetic acid (AA), sago flour (SF), and corn flour (CF). Sago flour and corn flour have been selected for treatment because of their adhesive property on a trial-and-error basis. The aim of this research is to utilize these treatments on CS aggregates to produce solid and durable concrete, thus improving the overall quality of coconut shell concrete (CSC).

Research significance

Generally, concrete is a solid which is durable under normal conditions. Problems begin when different concrete components are added to the concrete, which may affect their durability performance. The durability properties of CSC have been previously reported and recommended in other studies [5]. During the study of the durability properties of CSC, untreated CS was employed as coarse aggregate and denoted as "RCS". In this study, the durability properties of raw CS aggregate were extracted using polyvinyl alcohol (T1), ferrous sulphate (T2), slaked lime (T3), acetic acid (T4), sago flour (T5), and corn flour (T6), respectively. To examine the durability performance of treated CS, this study was conducted. CSC is also considered in this study to correlate the results in parallel. The volume of permeable voids (VPV), sorptivity, water absorption, rapid chloride ion permeability test (RCPT), and resistance to elevated temperatures are all considered durability parameters. The tests were conducted on both CSC and treated CS concrete (TCSC) with T1, T2, T3, T4, T5, and T6 separately, after curing for 3, 7, 28, and 56 days, except for resistance to elevated temperature after the respective ageing age of 28 days [6, 15].

Study of pore structure in treated and untreated CS

The RCS aggregates of size maximum of 10 mm were selected and treated using PVA, FS, SL, AA, SF, and CF. Once the raw coconut shell aggregates were treated, Scanning electron microscope (SEM) images were taken randomly on the selected treated CS aggregates by using High-Resolution Scanning Electron Microscope (HRSEM), Thermo Scientific Apreo S, in standard imaging mode of magnification 5000 × and resolution of 20 μm at 10.00 kV. Each SEM image that was incorporated in ImageJ software is shown in Fig. 1. With the aim of taking SEM images to find the pores present in the treated CS and for the same, these images need to be exported to ImageJ software. However, the black spots seen in the SEM images are pores present in the CS.

ImageJ is software that is widely accessible and used for various purposes. Wayne Rasband initially developed it and is currently utilized in the research branches of the National Institute of Mental Health in Bethesda, Maryland, USA. The software is compatible with different systems supported by Java 1.1 or higher versions. It is available for free download from the website https://imagej.net/ij/download.html/. Once downloaded, ImageJ can be installed on a computer by executing the program package. There are three versions available: 8-bit, 32-bit, and 64-bit. The pore area analysis was done by using ImageJ, converting the image to binary and setting the threshold limit. It was analysed in two different ways, 8-bit & Red, Green and Blue (RGB) methods. ImageJ program was used to measure pore area for the six different types of treated and untreated CS aggregates analysed in 8-bit and RGB methods. The process of image processing can be seen in Fig. 2. The first step was done with the scale of the image of the arrangement to adjust the scale of the image of the scale with basically implemented by clicking on a straight; and draw a line in accordance with long image pictures the scale that we want to know. Analyse; set scale to see how pixels that read within a range of 1 mm. The next

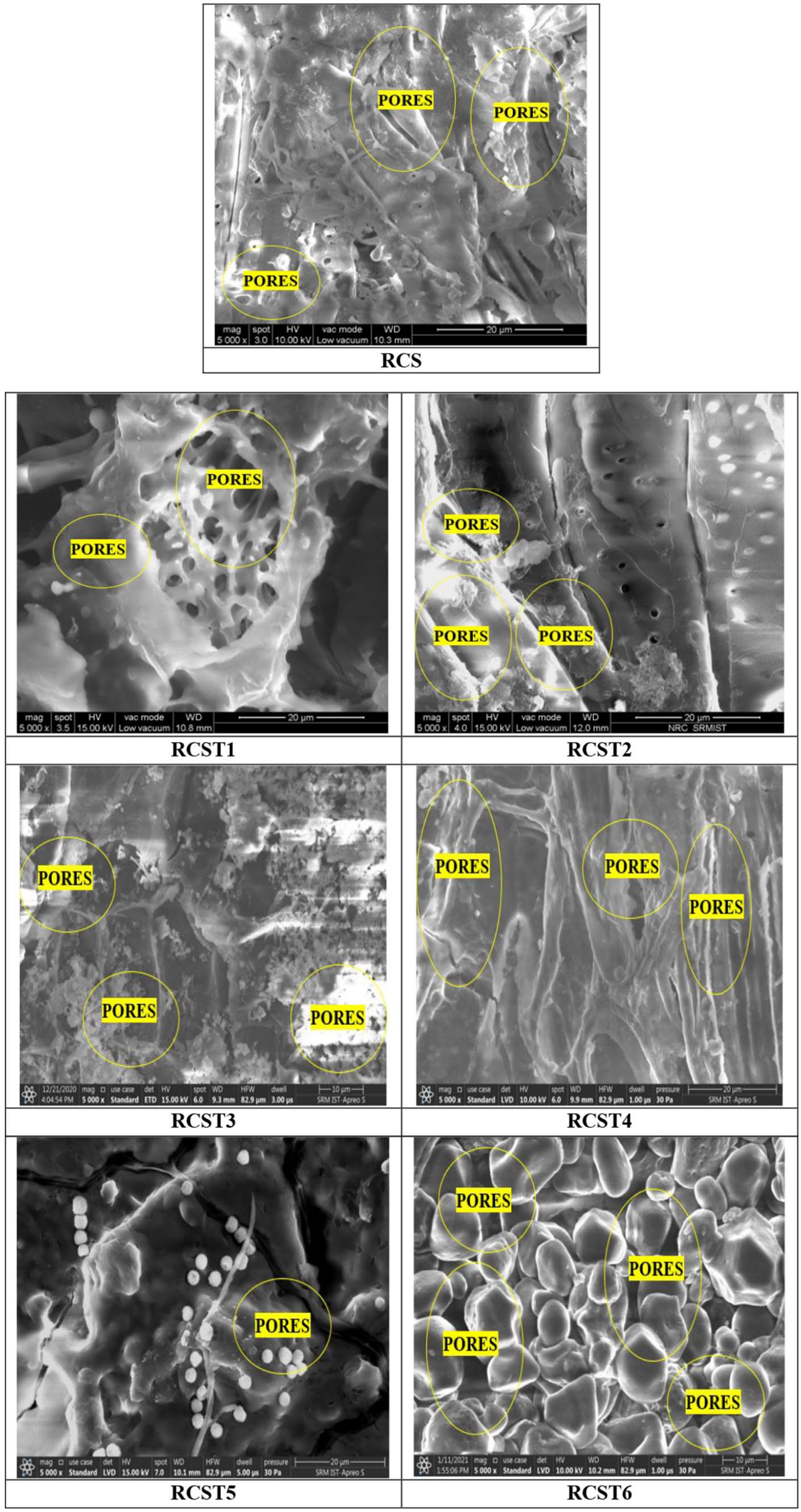


Fig. 1 SEM images of untreated and treated CS

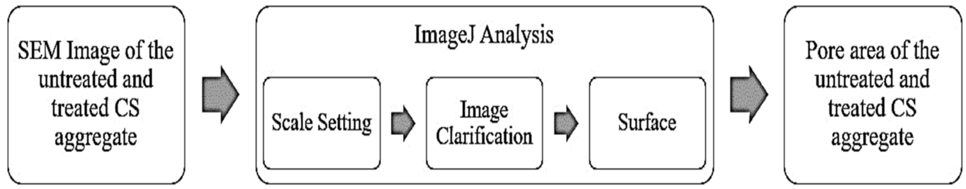


Fig. 2 Process flowchart for pore area calculation

step is the stage of image clarification. The stage of image clarification is to get a black white image (binary). This process will get through several stages: first set the limit of the analysed image. Then, sharpen the image of the process of thresholds, change into 8 bits, binary. The purpose of this process was to achieve the level of firm overcast on image observation. The surface analysis is made out of the imagery result [16].

The range to identify the size of pore ranged from 2 μm^2 to infinity. To determine the percentage of pore area, length and breadth of incorporated SEM image is measured using ImageJ software, then total image area is calculated for each SEM image. Total pore area is determined by adding each pore area present in the sample which is given by ImageJ software; then percentage of pore area is determined.

The ImageJ software results provide the presence of the maximum pore area, the minimum pore area, the mean pore area, the number of pores, and the location of the pores in the SEM images and they were directly inferred to calculate the pore area of the untreated and treated CS aggregates as highlighted in Fig. 3. Table 1 shows the percentage of pore area for the different treatments and is ranked according to the percentage of pore area of the treated CS. Compared with RCS aggregate, T1, T2, T3, T4, T5, and T6 aggregates have a lower percentage of pore area. A significant reduction in pore area can be achieved by treating the CS aggregate with various treatments.

Materials and mix ratio used

According to IS 12269: 2013 [17], ordinary Portland cement (OPC) 53 is utilized as a binder. River sand is utilized as fine aggregate, and it is consistent with IS 383: 2016, zone II [18]. A raw CS is shown in Fig. 4a, which was sourced from a nearby coconut industry, and CS crushed is shown in Fig. 4b as coarse aggregate. This study collected PVA, FS, SL, AA, SF, and CF from the local market. Some of the treatments are found in the literature for wood-based materials. Oil palm shell (OPS) is treated with PVA, FS, SL, and AA and changes the surface of OPS [9]. SF has been used as an adhesive in CS charcoal powder [11, 12], and CF has been used as a pasting material [13]. The mix ratio used for producing the CSC in this study was 1:1.47:0.65:0.42 with a cement content of 510 kg/m^3 [5, 6, 15].

Treatment methods

The solution for each treatment of CS was prepared in a specific way, respectively, based on the literature. To prepare the PVA solution, 20 g of PVA was added to 500 ml of hot water [9, 19]. Similarly, to prepare the FS solution, 20 g of FS was added to 500 ml of drinking water [9]. To prepare the SL solution, 20 g of SL was added to 500 ml of drinking water [9, 10]. Similarly, to prepare 100 ml of AA solution, 10 ml of AA and 90 ml of distilled water were mixed [9]. To prepare the SF solution, 20 g of SF was added to 250 ml of drinking water [11, 12]. Similarly, to prepare the CF solution, 50 g of CF was added to 100 ml of deionized water [13]. In this study, crushed untreated CS was immersed in PVA, FS, SL, AA, SF, and CF solution separately for 24 h and was allowed to surface dry. Designations for coconut shell concrete and treated coconut shell concrete with T1, T2, T3, T4, T5, and T6 aggregate are listed in Table 2. Figure 5 shows untreated and treated concrete materials used in this study.

Research programme

In accordance with the guidelines provided in IS 516:1959, concrete cubes measuring 100 mm × 100 mm × 100 mm were produced and subjected to compressive strength tests after 3, 7, 28, and 56 days. Additionally, cylinders measuring 100 mm (ϕ) in diameter and 200 mm in height were cast and allowed to cure for 3, 7, 28, and 56 days in preparation for durability testing. The study focused on investigating the effects of durability properties and resistance to high temperatures using a conventional curing system, and compared the results for different types of concrete samples (CSC, TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6). All tests were conducted at an ambient temperature ranging from 27ºC ± 8ºC, with relative humidity levels between 45 and 85%.

Results and discussions

This section shows properties of treated CS, concrete properties, water absorption, the volume of permeable voids, sorptivity, rapid chloride ion permeability, and resistance at elevated temperatures.

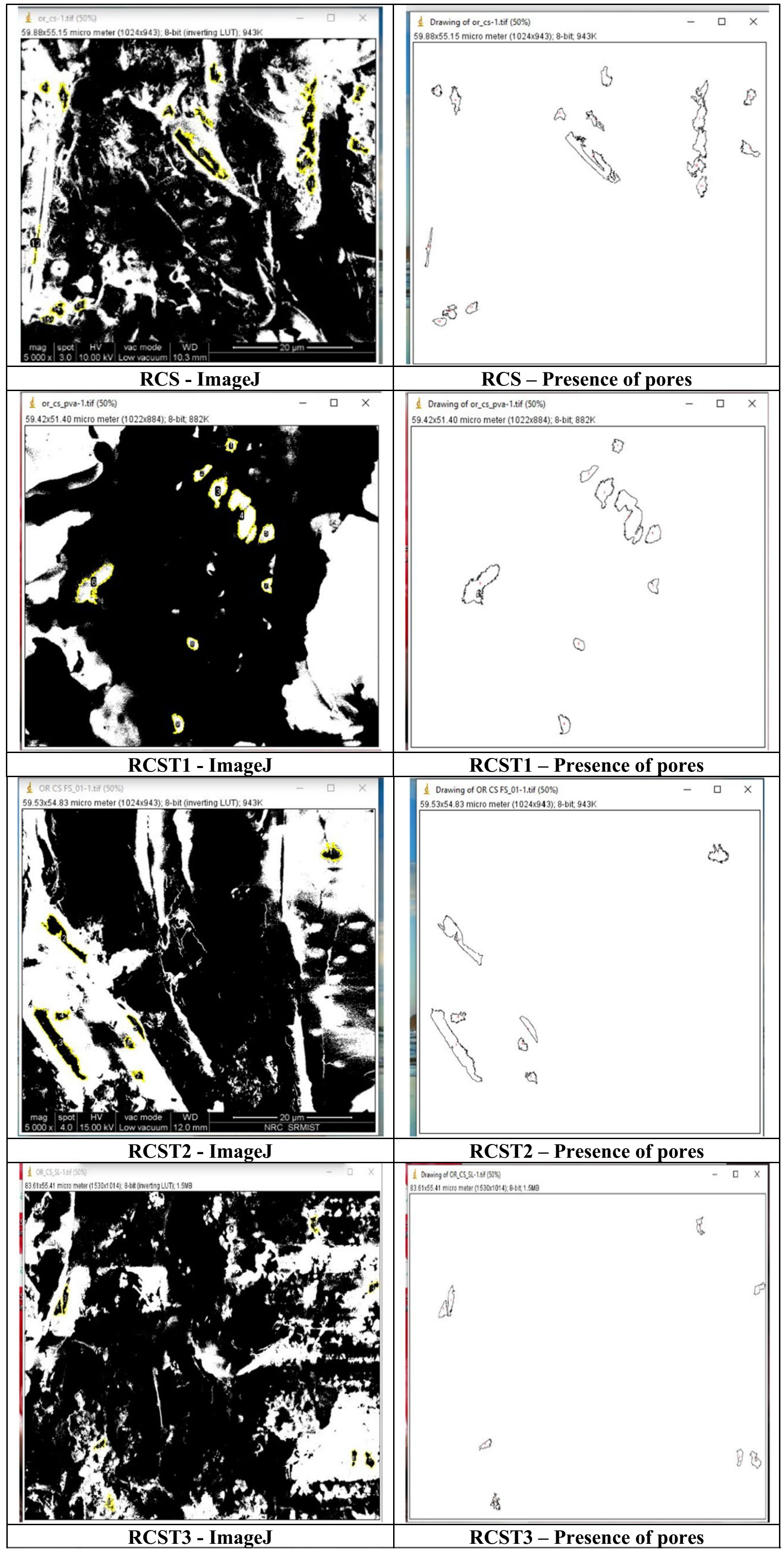


Fig. 3 Untreated and treated CS for pore presence using ImageJ

Fig. 3 (continued)

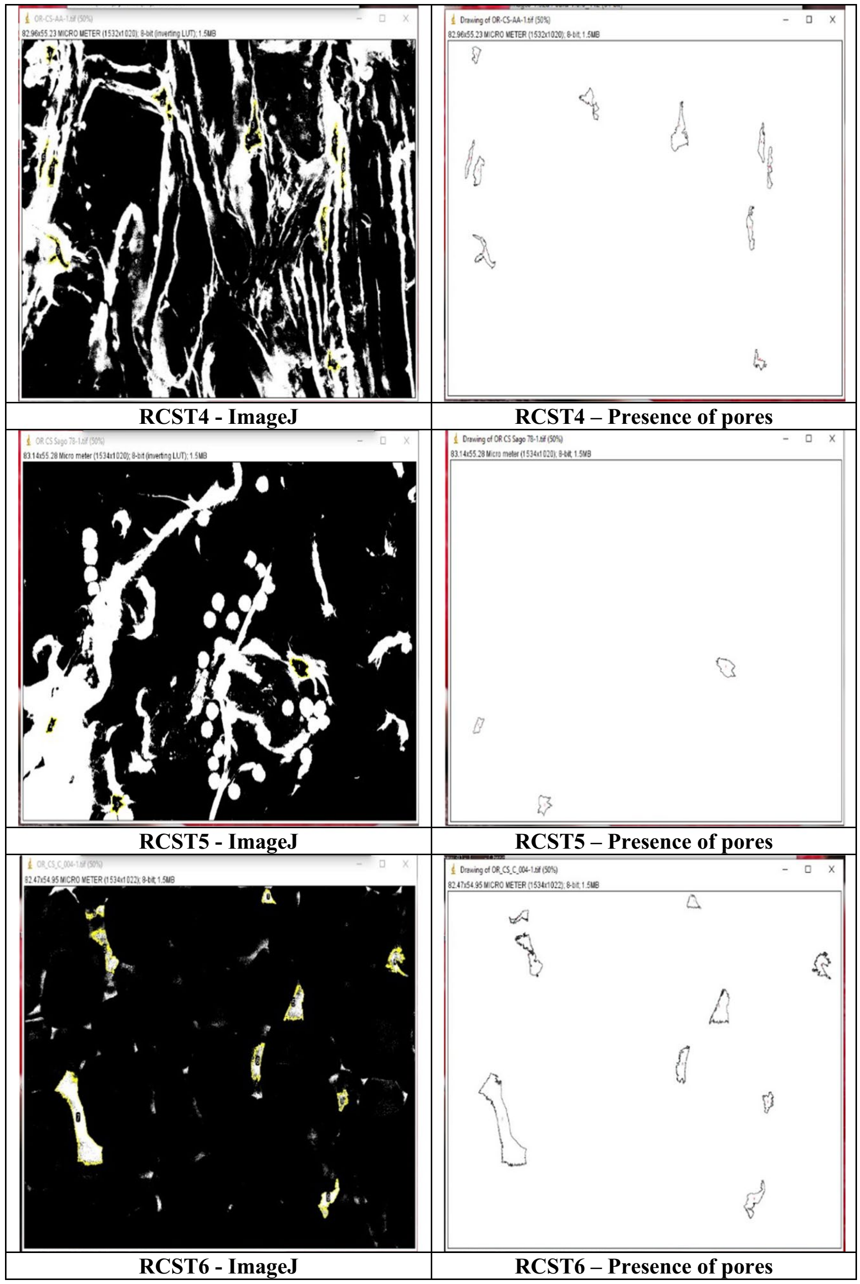


Table 1 Size of images, pore area, and ranking details obtained from various treatments

Designation	Image size studied		Total Image area under study (μm)^2	Pore area (μm^2)		Pore area (%)		Ranking with respect to pore area presence
	Length, L (μm)	Breadth, B (μm)		8-bits	RGB	8-bits	RGB	
RCS	59.53	51.40	3059.842	72.521	69.700	2.370	2.277	–
RCST1	59.36	51.25	3042.200	64.808	64.433	2.130	2.118	5
RCST2	59.36	51.25	3042.200	53.607	65.018	1.762	2.137	4
RCST3	83.03	55.36	4596.540	23.185	22.770	0.504	0.495	2
RCST4	82.80	55.10	4562.280	49.783	50.144	1.091	1.099	3
RCST5	82.80	55.20	4570.560	14.395	14.266	0.315	0.312	1
RCST6	82.25	54.94	4518.815	98.506	98.506	2.180	2.180	6

Fig. 4 (**a**) Raw coconut shell (**b**) Crushed raw coconut shell

Table 2 Notation used for the treated CS concrete

Designation used	Indications
CSC	Untreated CS in concrete
TCSCT1	Treated CS with PVA in concrete
TCSCT2	Treated CS with FS in concrete
TCSCT3	Treated CS with SL in concrete
TCSCT4	Treated CS with AA in concrete
TCSCT5	Treated CS with SF in concrete
TCSCT6	Treated CS with CF in concrete

Properties of treated CS

The specific gravity of untreated and treated CS was determined to be in the range of 1.2–1.5, in accordance with IS:2386–1963. These values are lower than the typical value for normal-weight aggregate (NWA), which is 2.4–3.0 [20]. Therefore, when CS is used as coarse aggregate, the resulting concrete is classified as LWC [21]. Since all treatments used formed only a very thin layer of the film, it is found that there is not much effect on the specific gravity of CS because of treatments.

In this study, the crushing and impact values of the CS aggregate were measured according to IS 383-1970 [22]. The results showed that the crushing value ranged from 2.6 to 6.4%, while the impact value ranged from 3.9 to 7.9%. These values fall within the specified limits for aggregates used in concrete. According to the standards, the crushing and impact values should not exceed 45% for aggregates used in concrete other than for wearing surfaces, and 30% for wearing surfaces. Determining crushing and impact strengths was conducted per IS: 2386-1963 (Part IV) and IS:5640-1970 [23, 24]. Although there were minimal variations in the results of crushing and impact strengths, some differences were observed in the resistance against crushing and impact strengths. These variations may be attributed to the reactivity of the chemicals used in the treatment process. However, a comprehensive investigation into this matter was beyond the scope of the present study, and only the results are presented here. Further research is recommended to delve deeper into the chemical reactivity and its impact on the crushing and impact resistance of treated CS aggregates.

Overall, the low crushing and impact values indicate that CS, whether it has been untreated or treated, has good energy-absorbing capacities. Hence, CS gives significant resistance to crushing and impact than NWA [25], and it is listed in Table 3. Like specific gravity, there is also not much effect on the crushing and impact resistance of CS because of treatments.

Concrete properties

According to IS 516-1959, the slump test was carried out to assess the mix's workability [26]. According to ACI 211, slump values in the 20–100 mm range are considered desirable for structural components such as beams, columns, and slabs since workability is a crucial factor when designing LWC [27]. Although the slump values in this study for CSC, TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 are 5, 10, 10, 15, 5, 5, and 10 mm, respectively, they did not encounter any difficulties all through the casting process.

Compared to its 28-day air-dry density, the fresh concrete density of CSC is 2125 kg/m^3, about 150 kg/m^3 higher. The fresh concrete density of TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 varies from 2110 to 2150 kg/m^3 which is about 105–140 kg/m^3 greater than its 28-day air-dry density 1985–2020 kg/m^3. Similar trends were reported by Newman [28], one of the lightweight aggregates used in concrete. The hardened density of LWC ranges from 300 to 1850 kg/m^3. From the literature, concrete should have a density of less than 2000 kg/m^3 for LWC [25]. The 28-day hardened density of CSC, TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 concrete varies from 1975 to 2020 kg/m^3. This range of hardened density at 28 days shows that the CS concrete produced in this study also falls under LWC, and there are not many influences on the density of the mixes because of the treatments used in this study though there

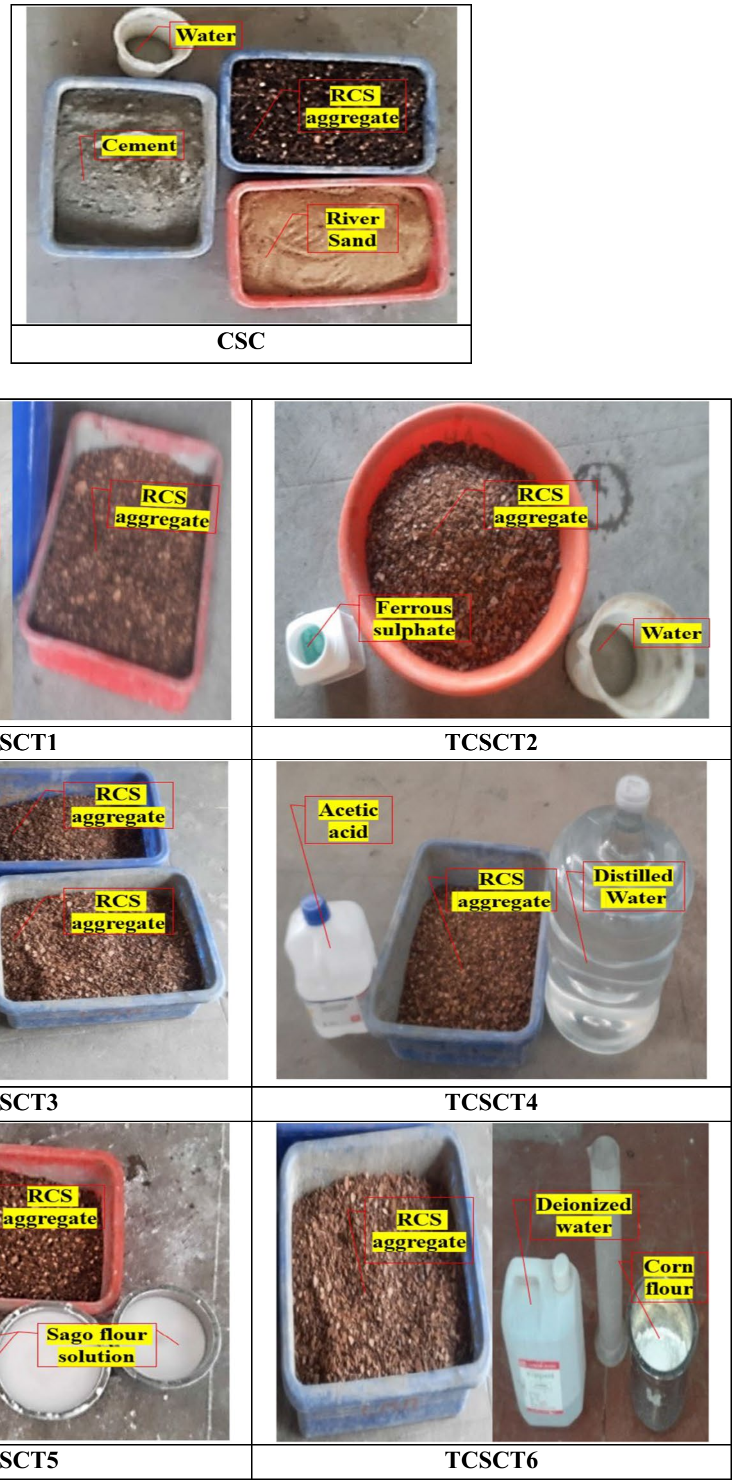


Fig. 5 Materials for CSC and TCSC concrete

are some variations in the density of materials used for treatments. The density of each chemical utilized in this study is shown in Table 4.

The hardened concrete density of CSC, TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 at 3, 7, 28, and 56 days is shown in Table 5.

Compressive strength of CSC, TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mixes at different ages is given in Table 6.

In this study, when CS aggregate is treated with PVA, FS, SL, AA, SF, and CF, a thin or thick film over the CS aggregate is formed and this decreases the water absorption by the

Table 3 Characteristics of untreated and treated CS aggregate

Various Treatments	Specific Gravity	Crushing Strength of CS aggregate (%)	Impact Strength of CS aggregate (%)
RCS	1.2	2.6	8.2
T1	1.4	5.5	5.5
T2	1.5	2.6	7.9
T3	1.3	4.4	5.2
T4	1.4	2.6	4.3
T5	1.4	2.6	4.1
T6	1.5	6.4	3.9

Table 4 Density of chemicals used for treatments

Abbreviation	Density (kg/m^3)	Density of the treatment solution (kg/m^3)
PVA	1310	1010
FS	2840	1016
SL	2340	1052
AA	1050	1005
SF	1000	1191
CF	800	1140

Table 5 Fresh and hardened density of untreated and treated CS concrete

Designation	Fresh density (kg/m^3)	Hardened density (kg/m^3)			
		3 days	7 days	28 days	56 days
CSC	2125	2045	2005	1975	1980
TCSCT1	2125	2050	2010	1985	1995
TCSCT2	2150	2070	2045	2020	2025
TCSCT3	2130	2060	2020	2000	2010
TCSCT4	2115	2040	2005	2010	2015
TCSCT5	2120	2045	2010	1985	1990
TCSCT6	2110	2040	2005	1980	1990

Table 6 Compressive strength vs various treatments

Type of treatments	Pore area (%)	Compressive strength (N/mm^2)			
		3 days	7 days	28 days	56 days
CSC	2.370	18.10	21.00	26.65	26.75
TCSCT1	2.130	18.15	21.20	27.40	28.20
TCSCT2	1.762	18.90	21.85	27.85	28.60
TCSCT3	0.504	18.40	21.25	27.65	28.15
TCSCT4	1.091	18.25	21.15	27.30	27.40
TCSCT5	0.315	18.30	21.10	27.15	27.30
TCSCT6	2.180	18.20	21.00	27.15	27.20

treated CS aggregates during the concrete production which ensures the SSD condition of the treated CS aggregates and thus moisture content in the concrete is also effectively preserved. This resulted in improved workability. The aggregate surface of the treated CS has considerable influence on the bond between mortar and aggregate as these treatments effectively prohibit the drying to take place in or on the test specimen [29]. As a result, treated CS aggregates perform better when it comes to cement mortar and aggregate bonding in the TCSC than in the CSC. The results of the compressive strength test illustrate this. Also, when the transition zone between the treated CS aggregate and cement mortar was examined using a hand-held microscope, the transition zone had no crack formation and the breakdown of CS was observed in later ages. Thus, it may be that there is no bond failure in the TCSC mix's transition zone.

In general, the strength development of concrete is influenced by the interparticle bonding, paste porosity, paste strength, and aggregate strength [30]. When compared to the CSC mix, TCSC mixes have better interparticle bonding that influences strength development. The failure pattern of TCSC specimens is similar to CSC specimens as observed in Fig. 6. The majority of compressive strength development was shown to occur in the early phases, and for all mixes, compressive strength continued to improve with age. However, though there is no degradation when treated CS is used and found improvements in compressive strength compared to untreated CS, bond strength tests need to be conducted in the future.

Figure 7 shows the compressive strength of TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mixes as 2.81, 4.50, 3.75, 2.44, 1.88, and 1.88% higher than CSC mix at 28 days, respectively, and it is not that many significant improvements as far as compressive strength is concerned. Therefore, it can be stated that there are not many influences on the compressive strength of the mixes because of the treatments used in this study. From the literature, the 28-day compressive strength of structural LWC should have a minimum of 17 N/mm^2 [25]. From the results, the 28-day compressive strength of TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mixes is more than 17 N/mm^2. Therefore, it can be used for structural LWC.

Water absorption

Water absorptions of the CSC, TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mixes at different ages are given in Fig. 8.

The results of the water absorption test indicate that the CSC mix exhibited a range of water absorption capacities, ranging from 11.87% at 3 days to 8.03% at 56 days. Similarly, the TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mixes showed varying water absorption

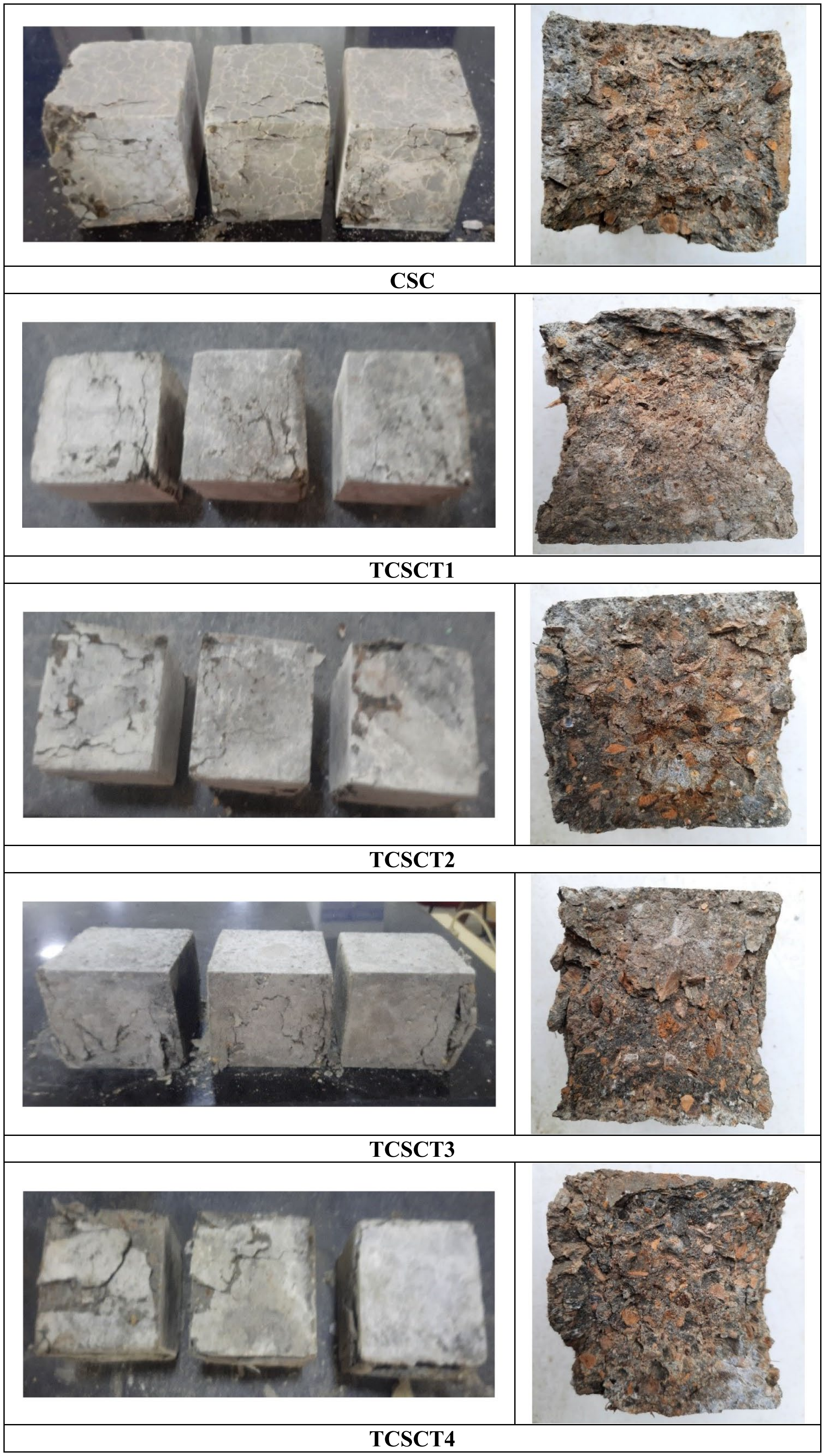
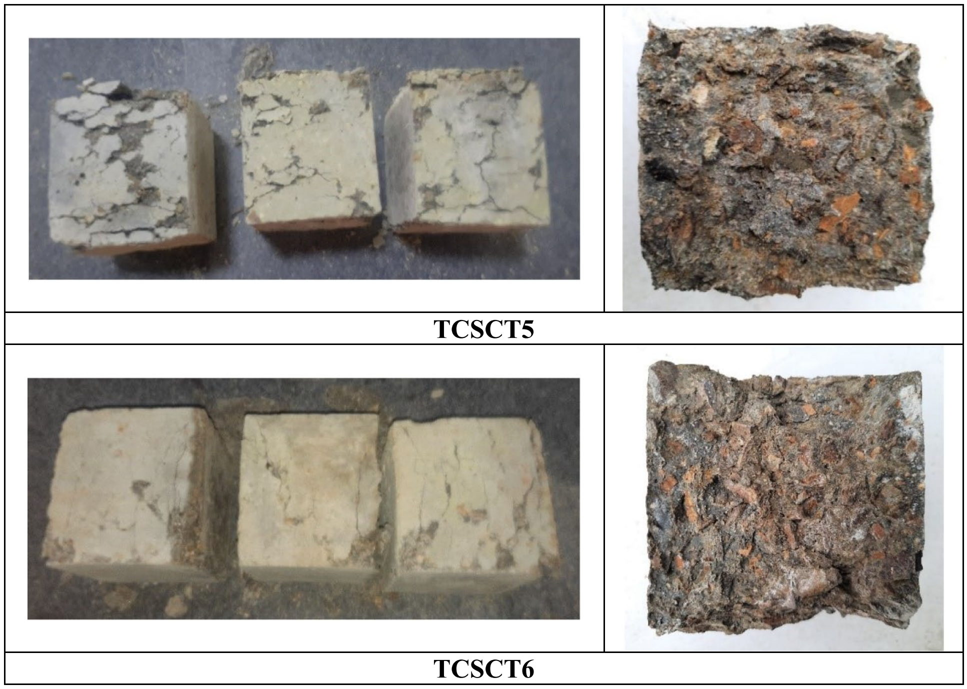


Fig. 6 Specimens after compressive strength testing

Fig. 6 (continued)



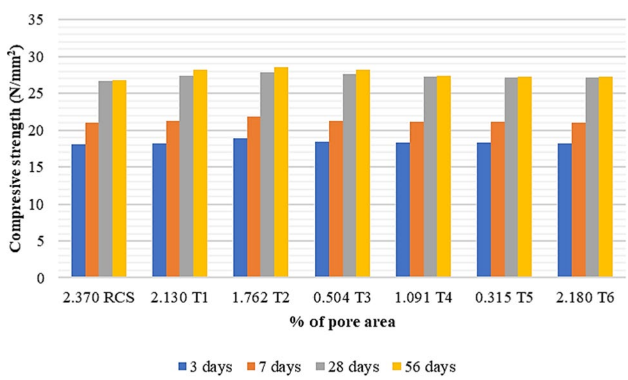


Fig. 7 Results of compressive strength test versus % pore area

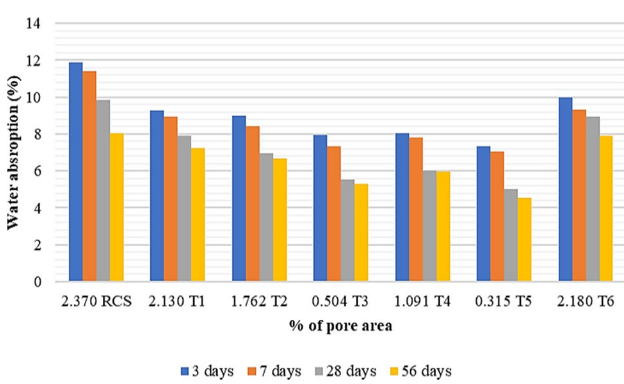


Fig. 8 Water absorption versus %Pore area

percentages, ranging from 9.25 to 7.25, 8.97 to 6.69%, 7.96 to 5.30%, 8.03 to 5.95%, 7.32 to 4.54%, 9.97 to 7.88% at 3 to 56 days, respectively. Notably, all TCSC mixes demonstrated lower water absorption compared to the CSC mix. Among the TCSC mixes, TCSCT5 exhibited the best performance in terms of water absorption, surpassing TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT6, and even the CSC mixes. The individual addition of T1, T2, T3, T4, T5, and T6 aggregates to the concrete resulted in reduced voids within each treated CS concrete matrix. This reduction in voids likely contributed to the improved water absorption properties observed in the TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mixes. Consequently, treating the water absorption property of untreated CS aggregate can lead to significant improvements in its quality.

Volume of permeable voids (VPV)

Figure 9 shows the VPV results for CSC, TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mixes at different ages.

According to the VPV test results, CSC mix VPV capacities range from 23.55% to 18.51% at 3–56 days. Similarly, TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mix VPV capacities vary from 15.31 to 11.98%, 13.18 to 11.07%, 11.31 to 9.58%, 12.12 to 10.25%, 11.00 to 7.32%, and 17.70 to 12.73% from 3 to 56 days. It can be noted that in TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mix, VPV results in decreases when

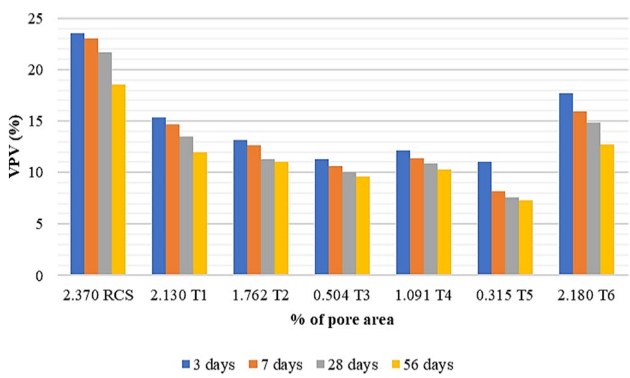


Fig. 9 VPV versus %Pore area

compared to CSC. TCSCT5 mix shows better performance in VPV when compared to TCSCT1, TCSCT2, TCSCT3, TCSCT4, and TCSCT6 and also with CSC mixes. As mentioned earlier, the improvement in the quality of untreated CS aggregate and reduction of voids in concrete resulted in a decrease in the VPV property of each concrete mix, respectively.

Sorptivity

Figure 10 shows the sorptivity results of the CSC, TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mixes at different ages.

The sorptivity test results indicate that the sorptivity measures for the CSC mix ranged from 0.126–0.046 mm/min$^{0.5}$ from 3 to 56 days. Likewise, it was noted that TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mix the sorptivity results varies between 0.121 and 0.040 mm/min$^{0.5}$, 0.118–0.036 mm/min$^{0.5}$, 0.112–0.034 mm/min$^{0.5}$, 0.116–0.035 mm/min$^{0.5}$, 0.111–0.031 mm/min$^{0.5}$, and 0.125–0.041 mm/min$^{0.5}$ from 3 to 56 days. In TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mix, sorptivity results decrease when compared to CSC. TCSCT5 mix performs better sorptivity when compared to TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT6, and CSC mixes. Sorptivity measures provide a practical indication of the pore structure of concrete, with lower values indicating higher quality [3, 4, 7]; this study provides evidence that substituting T1, T2, T3, T4, T5, and T6 in concrete mixes leads to improved quality by reducing the sorptivity value, compared to using untreated CS aggregate. This suggests that enhancing the quality of untreated CS aggregate and decreasing voids in concrete has resulted in a decreased sorptivity property in each TCSC mixes, respectively. The reduced sorptivity and increased resistance to water absorption in concrete incorporating treated CS aggregate could be attributed to this factor. The sorptivity value of high-quality concrete is typically less than 0.1 mm/min$^{0.5}$ [5, 6, 15]. This investigation shows that sorptivity measurements are less than 0.1 mm/min$^{0.5}$ after 28 days.

Rapid chloride ion permeability test (RCPT)

Figure 11 shows the RCPT results for CSC, TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mixes at different ages.

The RCPT outcomes reveal that the coulomb measurements for the CSC mix ranged from 3353 to 3326 coulombs. Similarly, for TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mixes, the RCPT results varied between 3317 and 3287 coulombs, 3176–3146 coulombs, 2880–2832 coulombs, 2985–2828 coulombs, 2492–2450 coulombs, and 3343–3317 coulombs from 3 to 56 days, respectively. The reason behind the reduction in RCPT values in TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mixes is attributed to the utilization of T1, T2, T3, T4, T5, and T6 aggregates in place of untreated CS aggregate in the concrete mix, each used separately. As previously mentioned, the enhancements in the untreated CS aggregate's quality and the reduction of voids in the concrete matrix led to a decrease in the RCPT property for

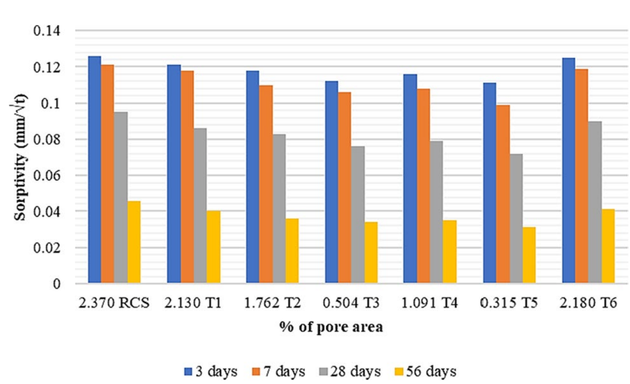


Fig. 10 Results of the sorptivity test versus %Pore area

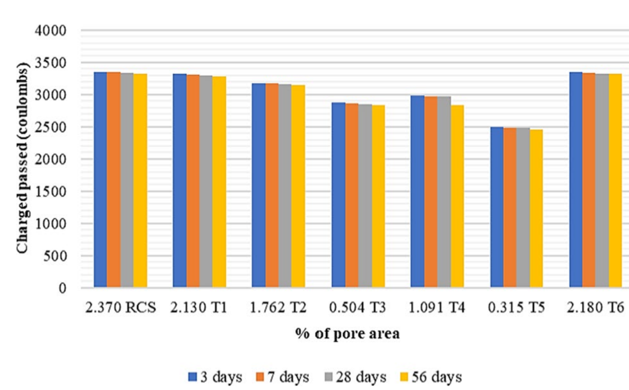


Fig. 11 Results of RCPT test versus %Pore area

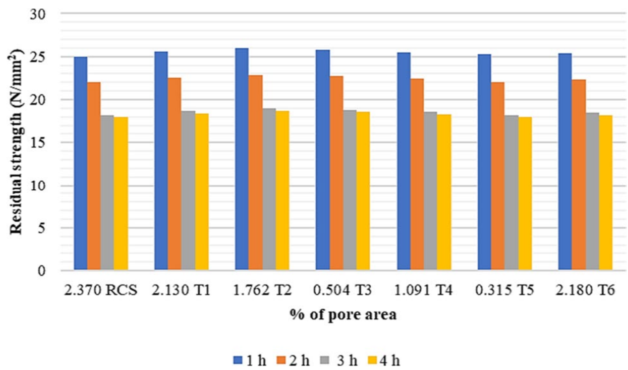


Fig. 12 Residual strength for various treatments at 100 °C

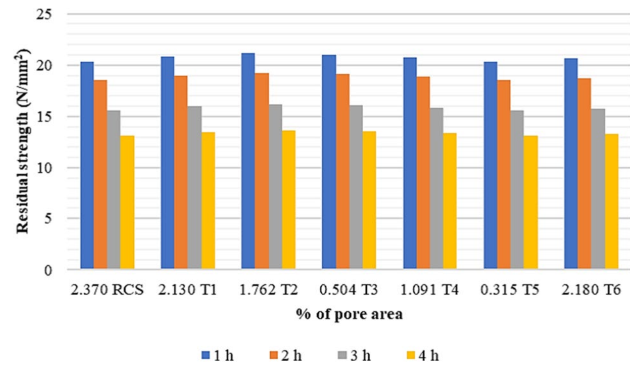


Fig. 13 Residual strength for various treatments at 200 °C

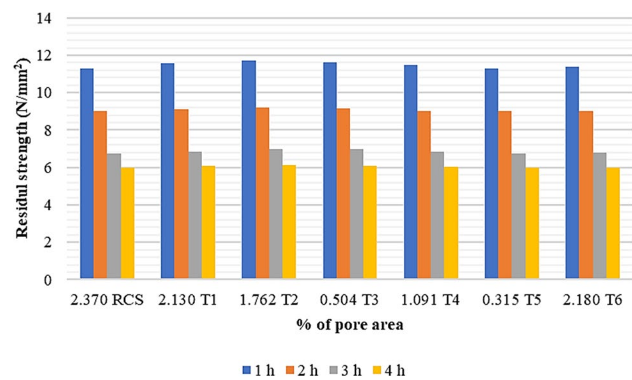


Fig. 14 Residual strength for various treatments at 300 °C

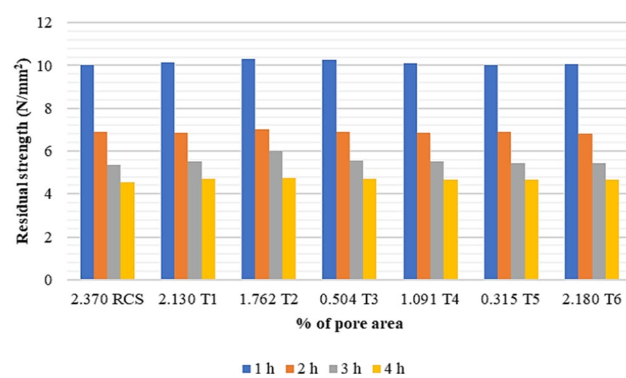


Fig. 15 Residual strength for various treatments at 400 °C

each respective concrete mix. A comparison of treated and untreated concrete mixes reveals that treated concrete exhibits better resistance to chloride penetration. Thus, improving the quality of untreated CS aggregate through treatment can significantly enhance the RCPT properties. The CSC, TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mixes exhibit moderate chloride permeability even after 28 days. Consistent with the findings reported in previous studies [5, 6, 15], this investigation also confirms that the decrease in charge passed over time, as reflected in the RCPT values, indicates moderate chloride permeability and an improvement in the pore structure of the TCSC mixes. Consequently, this RCPT study demonstrates that replacing treated CS aggregate with T1, T2, T3, T4, T5, and T6 aggregates enhances the concrete quality compared to using untreated CS aggregate in the concrete mixes.

Resistance at elevated temperature

The compressive strengths of CSC, TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 cubes were tested at an age of 28 days without subjecting them to any temperature, and the results were 26.65, 27.40, 27.85, 27.65, 27.30, 27.15, and 27.15 N/mm^2, respectively. The specimens were subjected to a particular temperature for a specific duration, after which their residual strength was tested. The results were obtained by averaging the results of triplicate specimens. The residual strength values for the mixes of CSC, TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 that were exposed to various temperatures and durations are shown in Figs. 12, 13, 14, and 15, respectively.

This study examined the residual compressive strength of CSC, TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 for different temperatures and duration, respectively, of its initial strength which are shown in Table 7.

Buildings with a height of 15 m or more must have a minimum fire rating of 2 h. For taller buildings, as well as hospitals and theatres where quick and easy evacuation is not feasible, a 2-h fire resistance rating provides adequate protection. Only large buildings with hazardous fire loads, such as mercantile, high-hazard industrial, and medium-hazard industrial occupancies, require a 3-h fire rating. According to ASTM C 330-09 [31], the minimum compressive strength of LWC should be 17 N/mm^2 to satisfy the structural concrete requirements. Typically, the maximum resistance to temperature rise on the unanticipated face of the structural

Table 7 Residual strength for various treatments

Temperature	Hours	Residual Strength (N/mm^2)						
		CSC	TCSCT1	TCSCT2	TCSCT3	TCSCT4	TCSCT5	TCSCT6
100 °C	1 h	24.95	25.55	26.00	25.80	25.50	25.30	25.35
	2 h	22.00	22.50	22.85	22.70	22.40	22.00	22.30
	3 h	18.20	18.65	18.95	18.80	18.60	18.20	18.50
	4 h	18.00	18.40	18.70	18.55	18.30	18.00	18.20
200 °C	1 h	20.35	20.85	21.20	21.00	20.75	20.35	20.65
	2 h	18.50	19.00	19.25	19.10	18.85	18.50	18.75
	3 h	15.55	16.00	16.15	16.05	15.85	15.55	15.75
	4 h	13.15	13.50	13.65	13.55	13.40	13.15	13.30
300 °C	1 h	11.30	11.55	11.70	11.60	11.50	11.30	11.40
	2 h	9.00	9.10	9.20	9.15	9.00	9.00	9.00
	3 h	6.75	6.85	7.00	7.00	6.85	6.75	6.80
	4 h	6.00	6.10	6.15	6.10	6.05	6.00	6.00
400 °C	1 h	10.00	10.15	10.30	10.25	10.10	10.00	10.05
	2 h	6.90	6.85	7.00	6.90	6.85	6.90	6.80
	3 h	5.35	5.50	6.00	5.55	5.50	5.45	5.45
	4 h	4.55	4.70	4.75	4.70	4.65	4.65	4.65

components is up to 180 °C and/or an average temperature of 150 °C. It is important to make sure that no constructions collapse prematurely or even at all as a result of temperature variations. The behaviour of a structural components under high temperatures is the major factor that determines whether it can prevent collapse [5]. Based on the results, it can be implied that the residual strength of the CSC, TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mixes at 100 °C at 1-, 2-, 3-, and 4-h duration and at 200 °C at 1- and 2-h duration was greater than 17 N/mm^2. As a result, there is a minimum assurance that both CSC and TCSC mixes offer resistance against temperatures of 200 °C for 2 h and thus can be considered safe for construction since CSC and all TCSC mixes offer resistance against a temperature with a minimum residual strength of 17 N/mm^2; hence, both CSC and TCSC mixes may be classified under type 3 constructions [5, 6, 15, 32].

Recommendations

Recommendations of treated coconut shell aggregates and concretes are presented in Table 8, where they are ranked based on their water absorption, porosity, durability, and high temperature properties.

Conclusion

The aim of this study was to assess the durability performance of variously treated CS concretes. Concrete made with untreated coconut shells was used as a reference for comparison. The following significant conclusions were drawn from the test results on durability properties and elevated temperature resistance:

The percentage of pore area present reduces in the treated CS aggregates when compared to untreated CS aggregates. T1, T2, T3, T4, T5, and T6 aggregate shows 10.13, 25.65, 78.73, 53.9, 86.71, and 08.02% less pore area when compared to RCS aggregate.

There are not many influences on the density of the mixes because of the treated CS aggregates used in this study though there are some variations in the density of materials used for treatments.

Compressive strength of TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mixes is 2.81, 4.50, 3.75, 2.44, 1.88, and 1.88% higher than CSC mix at 28 days, respectively, and it is not that many significant improvements. As a result, the compressive strength of the mixes was not significantly affected by the treatments used in this study.

It can be concluded that in TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT5, and TCSCT6 mix, water absorption, the volume of permeable voids, sorptivity, and rapid chloride ion permeability resistance have better performances when compared to CSC. TCSCT5 mix shows better performance when compared to TCSCT1, TCSCT2, TCSCT3, TCSCT4, TCSCT6, and also with CSC mixes. These results show that the improvement in the quality of untreated CS aggregate and reduction of pores present in CS aggregates resulted in significant improvements in the aspect of durability performances of concrete mixes used in this study.

There is a minimum assurance that both CSC and TCSC mixes offer resistance against temperatures of 200 °C for 2 h

Table 8 Recommendations of treated coconut shell aggregates and concretes

Treatment Methods	Properties Ranking						
	Porosity	Durability				High temperature	Recommendations on treatments and mixes
		Water absorption test	VPV test	RCPT	Sorptivity test		
T1	5	–	–	–	–	–	Based on porosity of aggregates results, sago flour and slaked lime treatments are recommended
T2	4	–	–	–	–	–	
T3	2	–	–	–	–	–	
T4	3	–	–	–	–	–	
T5	1	–	–	–	–	–	
T6	6	–	–	–	–	–	
TCSCT1	–	5	5	5	5	5	For better durability and high temperature resistance, CSC incorporated with sago flour and slaked lime-treated aggregates is recommended
TCSCT2	–	4	4	4	4	4	
TCSCT3	–	2	2	2	2	2	
	–	3	3	3	3	3	
TCSCT5	–	1	1	1	1	1	
TCSCT6	–	6	6	6	6	6	

and thus can be considered safe for construction since CSC and all TCSC mixes offer resistance against a temperature with a minimum residual strength of 17 N/mm^2; therefore, it can be concluded that both CSC and TCSC mixes fall under type 3 constructions.

Based on porosity of aggregates results, sago flour and slaked lime treatments are recommended. For better durability and high temperature resistance, CSC incorporated with sago flour and slaked lime-treated aggregates is recommended.

Since the given treatments to CS aggregates improved the quality of CS aggregates and also resulted in better durability properties of concrete mixes, treatments to CS aggregates should be recommended on the durability aspect.

Declarations

Conflict of interest Authors declare that there is no conflict of interest on this study and this manuscript as well.

Ethical approval The solution for each treatment of CS was prepared in a specific way respectively based on the literature. Since the solution for each treatment prepared is acknowledged with the respective references, the same can be considered ethical approval.

Informed consent For this study, formal consent is not required.

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