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Study on Durability Properties of Coconut Shell Concrete with Coconut Fiber

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Abstract: Coconut fiber was used in coconut shell concrete (CSC) and its durability properties were studied. The properties include: water absorption, volume of permeable pore voids, rapid chloride penetration test, sorptivity and resistance at elevated temperature. For comparison purpose, these properties were also studied on conventional concrete (CC) with coconut fibers. Three different curing conditions viz. full water immersion, site curing and air-dry conditions were employed except for temperature resistance study in which only full water immersion was used. Test results show that the durability properties were better in full water immersion condition in case of CC mixes and in site curing condition in case of CSC mixes. Temperature resistance tests gave a minimum guarantee of both CC and CSC mixes without and with coconut fibers for 2 h resistance and hence they were deemed safe for construction.

Keywords: coconut fiber; coconut shell; concrete; durability; temperature; properties

1. Introduction

To save the natural resources from over extraction of aggregates from rocks and sand from rivers, many alternate materials are tried in the production of concrete. These alternate materials are found from the wastes generated from domestic, industrial and agricultural sectors [1]. When these wastes are used in concrete composites, it enables the production of green concrete and helps in the reduction of carbon dioxide (CO_2) emission. As an example, using coal fly ash in concrete production leads to an improvement of fracture toughness and making green concrete, in turn leading to the reduction of CO_2 emission [2]. Literature states that the introduction of supplementary materials into the concrete can be divided generally into six classes, namely industrial wastes (fly ash, silica fume, ground granulated blast furnace slag, metakaolin etc.), nano industrial wastes (nanosilica, nanotitanium, tiania–silica nanosphere, nanoalumina, nanometakaolin, carbon nano tubes etc.), agriculture–farming wastes (bamboo, wheat, barley, corn, olive, banana, sisal, date palm, elephant grass etc.), aquaculture–farming wastes (oyster, periwinkle, mussel etc.), minerals (calcite, diatomite, zeolite, perlite etc.) and dust and powders (limestone powder, brick powder, waste marble dust and powder, waste ceramic powder, ground pumice powder, quartz powder etc.) [3]. In line with these alternate materials, coconut shell and coconut fibers can be added to the agriculture–farming group, and it has been proven that coconut shell (CS) waste can be used as an aggregate in place of conventional stone aggregate [4–10].

In general, conventional concrete (CC) is strong in compression but weak in tension. To overcome this deficiency in CC, steel bars are normally used where tensile stresses are developed or tension zones are identified, which is normally referred to as reinforced cement concrete (RCC). However, to enhance the inherent tensile strength of concrete itself, fibers are introduced, leading to a special type of concrete called fiber reinforced concrete (FRC). Coconut shell concrete (CSC) also exhibits the deficiency of weak tension. Therefore, to overcome the same in CSC, coconut fibers were introduced and the aspect ratio and volume fractions were optimized in an earlier study and were compared with CC with coconut fibers [11]. Fresh and hardened concretes with and without coconut fibers were tested for flexural strength, split tensile strength, impact resistance and bond properties for the optimized aspect ratio and volume fraction.

Any concrete structure needs to have adequate durability if it has to perform in agreement with its intended level of functionality and serviceability over an expected or predicted life cycle. The penetrability of concrete structures, particularly when the concrete structures are in severe environmental conditions, decides its ultimate serviceability and durability [10]. Since the mechanical and bond properties of CSC with coconut fibers were already shown to be in acceptable range [9], we investigated its durability properties in this study.

2. Significance of the Study

Durability indicates the life period of the material under the given environmental conditions. In general, concrete is durable under normal environmental situations. The durability issues arise due to either unknowingly introducing deleterious materials while adding the constituents or when the concrete is exposed to severe harmful environmental conditions not expected earlier. External moisture or air can penetrate through the concrete which can facilitate the corrosion of steel embedded in the concrete in case of reinforced cement concrete. This corrosion activity may lead to an increase in volume of steel which in turn initiates cracking and spalling of concrete cover.

Therefore, this study aimed to estimate the durability performance of CSC with coconut fibers. Additionally, since CS and coconut fibers are wood based material, the effect of three different curing conditions—full water immersion W1, site curing condition W2, (method adopted in field—covering the specimen with wet gunny bags) and no curing W3 (air-dry) were considered in this study as per literature [8,12]. The durability parameters studied include water absorption, volume of permeable pore voids (VPV), rapid chloride penetration test (RCPT), sorptivity and resistance at elevated temperature.

3. Materials and Mix Proportions Used

Ordinary Portland cement (OPC) 53 grade conforming to Indian Standard IS 12269: 2013 [13] was used as a binder. The chemical composition of the cement used is presented in Table 1. Palar river sand was used as fine aggregate and it conformed to Indian Standard IS 383: 2016, zone III [14]. Coconut shells were crushed to the maximum size of 12.5 mm and used as coarse aggregate. Figure 1a,b shows the raw CS and coconut fibers collected from the local coconut industry and used in this study. For comparison, 12.5 mm of conventional crushed stone aggregate was used in the production of CC. Since in an earlier study, the mechanical and bond properties were studied for the optimized aspect ratio and volume fractions with the selected mix proportions of both CC and CSC [11], the same mix proportions with the same optimized aspect ratio and the volume fractions were considered in this study. That is, mix proportion used for CC was 1:2.22:3.66:0.55 with a cement content of 320 kg/m^3, and for CSC, it was 1:1.47:0.65:0.42 with a cement content of 510 kg/m^3. Coconut fiber, having an optimum aspect ratio of 83.33 and a volume fraction of 3%, was was used in CC mix proportion in this study following [11]. Similarly, coconut fiber having an optimum aspect ratio of 66.67 and volume fraction of 3% was used in CSC mix proportion. For identification purposes, mixes without fibers are abbreviated as CC for conventional concrete and CSC for coconut shell concrete. Similarly, mixes with fibers are abbreviated as CCF and CSCF, respectively.

Table 1. Chemical properties of OPC 53 grade cement used.

Chemical Name	Chemical Formula	Percent Content (%)
Lime	CaO	63.5
Silica	SiO_2	22.2
Alumina	Al_2O_3	4.9

Table 1. *Cont.*

Chemical Name	Chemical Formula	Percent Content (%)
Iron oxide	Fe_2O_3	3.3
Magnesium oxide	MgO	2.6
Sulphur trioxide	SO_3	2.2
Alkalis	Na_2O	0.8
	K_2O	0.5
Loss on ignition		1.2

(**a**) (**b**)

Figure 1. (**a**) Raw coconut shell (**b**) coconut fiber at coconut industry.

4. Test Methods

The test methods followed to determine the durability properties of the concrete are explained in the subsequent segments.

4.1. Water Absorption and Volume of Permeable Pore Voids

Volume of permeable pore voids (VPV) is a vital property of any concrete. This property is responsible for allowing the moisture and air into the concrete [15]. An oven-drying method recommended by the American Standards ASTM C 642-97 [16] was used to determine the water absorption and VPV properties. This standard suggested to use the cylindrical specimen of size 100 mm diameter and 100 mm height (Figure 2a) cut from the center core of a cylinder of size 100 mm diameter and 200 mm height. After the specified days of curing, specimens were allowed to air-dry to remove the surface moisture. Specimens were allowed to absorb water for at least 48 h as per ASTM C 642-97 [16]. This test was performed on three specimens for each curing condition (W1, W2 and W3). Average results of three specimens are reported.

First, specimens were placed in an oven and maintained at 100 °C–110 °C for 24 h. After this period, specimens were allowed to cool at room temperature for 24 h and then the weights were measured frequently until the weights became constant. This value was considered as mass of the specimen and noted as A. The specimens were then immersed in water for 48 h and surface dried properly. The weights were taken in the surface dried condition and noted as B. Then the specimens were kept in boiling water for 5 h (Figure 2b). They were then cooled at room temperature for 14 h. The mass of the specimen was determined and noted as C. The samples were tied with thin copper wire and immersed in water with spring gauge. In this immersed condition, weights of the specimens were taken and noted as D. Water absorption and VPV were calculated as follows:

$$\text{Water absorption in } \% = \frac{(B-A)}{A} \times 100 \tag{1}$$

$$\text{Volume of voids in } \% = \frac{(C - A)}{(C - D)} \times 100 \quad (2)$$

(a) (b)

Figure 2. (a) Center core cut specimens (b) specimens under boiling.

4.2. Rapid Chloride Penetration Test (RCPT)

Chloride ingress is one of the major forms of environmental attack for RCC, and in turn, it leads to initiation of corrosion of embedded steel bars. This may be one of the causes for the reduction of strength, performance and view of the structure. A general method to avoid this is the prevention of chloride ingress into the steel bars by using impermeable concrete to the extent possible [17]. Therefore, for design purposes and controlling the quality of concrete, it is necessary to know the ability of chloride ions to penetrate the concrete. However, it is a long-term process and it is not possible to find in a short time. Instead, an accelerating process is followed [18]. ASTM C1202 [19] suggests a simple laboratory test to determine the chloride penetration of a concrete sample using a triplicate specimen of 100 mm diameter and 50 mm height cut from the center core of a cylinder of 100 mm diameter and 200 mm height. These specimens are to be subjected to 60 V applied through direct current for a duration of 6 h. The sample tested for RCPT is shown in Figure 3. One of the chambers contains 3% sodium chloride solution and the other chamber contains 0.3 mole sodium hydroxide solution was used. The total charge passed was calculated, measured in coulomb. Tests were performed on the three specimens for each curing condition. Average results of three specimens are reported. Table 2 illustrates the rating of RCPT with respect to the charge passed in coulombs versus chloride ion penetrability.

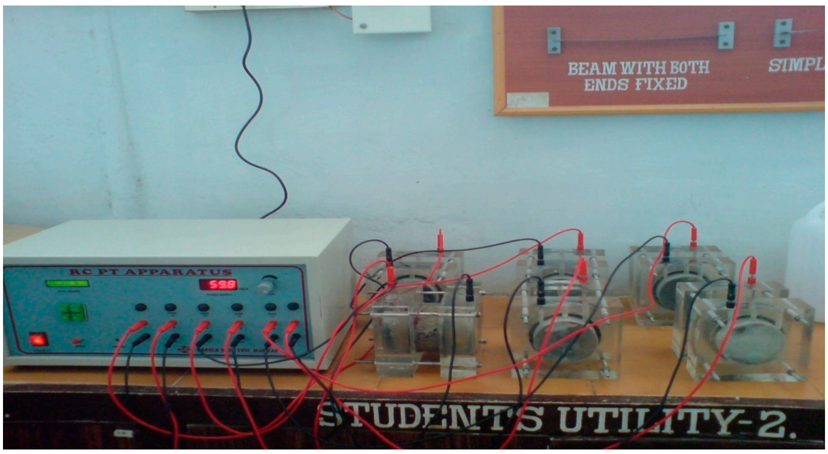

Figure 3. Specimens under RCPT testing.

Table 2. RCPT ratings (as per ASTM C1202).

Charge Passed (Coulombs)	Chloride Ion Penetrability
>4000	High
2000–4000	Moderate
1000–2000	Low
100–1000	Very Low
<100	Negligible

4.3. Sorptivity Test

The measure of unsaturated flow of water/fluids inside the concrete is known as sorptivity [20]. It is also referred to as a measure of the capillary forces exerted by the pore structure of concrete causing water/fluids to be drawn into the concrete. For this test, the concrete sample should be dried consistently and the flow conditions well defined. Using least squares regression, it is relatively easy to get a good fit while plotting a graph between cumulative water absorption per unit area of concrete surface (i) and the square root of time (√t). A simple technique is suggested by ASTM C1585 [21] for the measurement of rate of absorption of water by concretes. Apparatus required for this test were a scale, a stopwatch and a shallow pan of water. The test required the use of triplicate specimens of size 100 mm diameter and 50 mm thickness cut from the center core of a cylinder of size 100 mm diameter and 200 mm height.

At first, prepared samples were preconditioned to a certain moisture condition, by drying the specimens for 7 days at 50 °C. After seven days, these samples were allowed to cool in a container and sealed for three days. After this process, samples were sealed using insulation tape on the circumference of full depth of the specimen in such a way that the top and bottom surfaces were exposed for testing. The mass of the specimen was taken initially at time 0 and then specimens were immersed in a depth of 5–10 mm water (Figure 4). Once the testing of specimen started, at the selected times (i.e.,) 1, 2, 3, 4, 6, 9, 12, 16, 20, 25, 30, 45, and 60 min, the specimen was removed from the water and weighed after the excess water was blotted off with damp paper and towel. A graph was then plotted between the mass gain (gm) per unit area (mm^2) over the density of water and the square root of the time elapsed. From the graph, sorptivity can be reported as the slope of the line of best fit. The experimental results can be related using the equation: $i = S\,t^{0.5}$, where i is the cumulative water absorption per unit area of concrete surface, S is the sorptivity coefficient and t is the time at which the weight was determined.

Figure 4. Specimens under sorptivity test.

4.4. Resistance to Elevated Temperatures

Indian National Building Code, SP-7 (2005) specifies that the resistance to elevated temperature on the unexpected face of the specimens can be up to a maximum of 180 °C and/or average temperature of 150 °C. Hence, it is necessary that the elements are to be designed with sufficient backup strength to support the loads applied for the projected time of rise in temperature [12]. Since CS has organic matter, it is susceptible to damage at high temperatures. But it does not mean that the use of CSC in construction is not safe. The capacity of the members can be boosted up by designing the members for strength and because of this, members may have residual strength to carry the loads when subjected to raised temperature [12]. Therefore, resistance to elevated temperature by the CSC members with coconut fiber are studied.

Only full water immersion (W1) curing was adopted on the specimens used for this test. After 28 days curing, concrete cube specimens were placed in an oven at 100 °C, 200 °C, 300 °C and 400 °C for 1, 2, 3 and 4 h, respectively. Specimens were then allowed to cool to room temperature before being tested for compression strength. The results of temperature tests are reported on an average of triplicate specimens.

5. Results and Discussion

5.1. Water Absorption

Figure 5 shows the water absorption of CC, CCF, CSC and CSCF mixes under W1, W2, and W3 curing conditions. For the CC specimen, the water absorption at 28-days was found as 3.98%, 4.04% and 6.48% for the curing conditions W1, W2 and W3, respectively. For the CCF specimen, the results were found as 4.11%, 4.19% and 6.63% for the curing conditions W1, W2 and W3, respectively. Similarly, for the CSC specimen, the water absorption at 28-days was found as 11.32%, 11.14% and 11.45% for the curing conditions W1, W2 and W3, respectively. Likewise, for the CSCF specimen, the results were found as 11.38%, 11.28% and 11.74% for the curing conditions W1, W2 and W3, respectively. In case of the CC and CCF mixes, water absorption results are better in case of W1 curing condition which is the traditional method compared to W2 and W3 curing conditions. But in the case of CSC and CSCF mixes, W2 curing condition performed better compared to W1 and W3 conditions. It is concurrent with one of the earlier studies [12] that the water absorbed by the CS during the course of soaking is stored by the CS which behaves like a reservoir, and that this helps in internal curing, leading to a continuation of hydration process. This is lacking in the W3 condition. Therefore, it can be said that proper curing is required for CSC and CSCF to achieve better durability properties. Literature states that the water absorption of CC is limited to 5.00% [12]. In this study, in all the cases of CC and CCF mixes, it was found that the water absorption was less than 5% under W1 and W2 conditions. However, this limit was not fulfilled in the case of CSC and CSCF mixes. But compared with the water absorption of lightweight concrete (LWC) with pumice aggregates [22–24] these results are better.

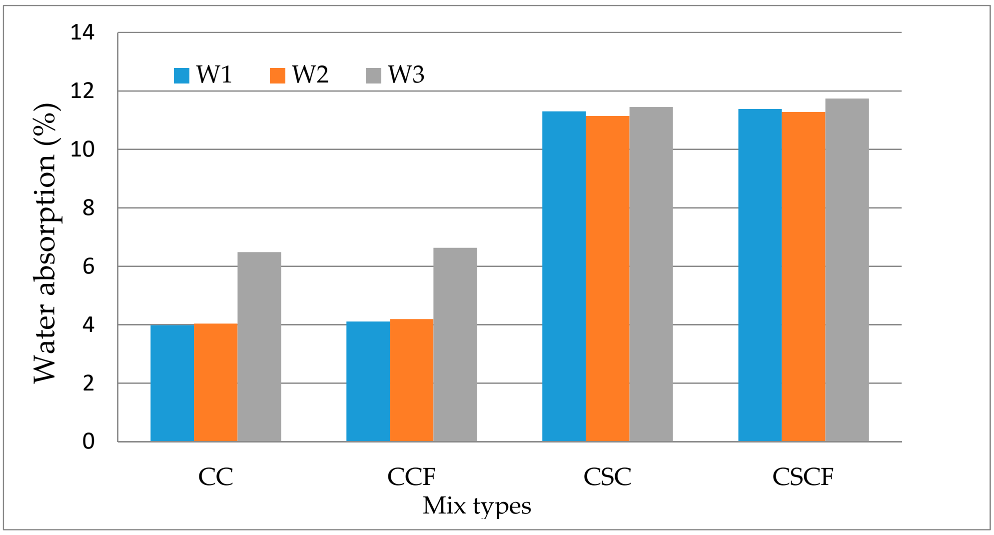

Figure 5. Results of water absorption test.

5.2. Volume of Permeable Voids

VPV test results on CC, CCF, CSC and CSCF mixes for W1, W2, and W3 curing conditions at 28 days are shown in Figure 6. For CC specimen, the VPV value at 28-days was found as 3.19%, 4.79% and 8.34% for the curing conditions W1, W2 and W3, respectively. For CCF specimen, the results were found as 5.11%, 7.52% and 9.55% for the curing conditions W1, W2 and W3, respectively. Similarly, for CSC specimen, the VPV values at 28-days was found as 13.23%, 11.55% and 16.58% for the curing conditions W1, W2 and W3, respectively. Likewise, for CSCF specimen, the results were found as 13.63%, 12.41% and 17.03% for the curing conditions W1, W2 and W3, respectively. These results indicate that the use of CS aggregates contributes to the increasing VPV. This may be due to the porous nature of CS in comparison with conventional aggregate. The results of VPV of CSC and CSCF mixes are comparable to that of other LWC in which VPV values ranged from 8.6 to 22.5%. Additionally, VPV ranged from 20.1 to 21.2% for oil palm shell concrete, which is similar to CSC [12]. For CC and CCF mixes, VPV results are better in W1 curing condition compared to W2 and W3 curing conditions and in case of CSC and CSCF mixes, W2 curing condition performed better compared to W1 and W3 conditions.

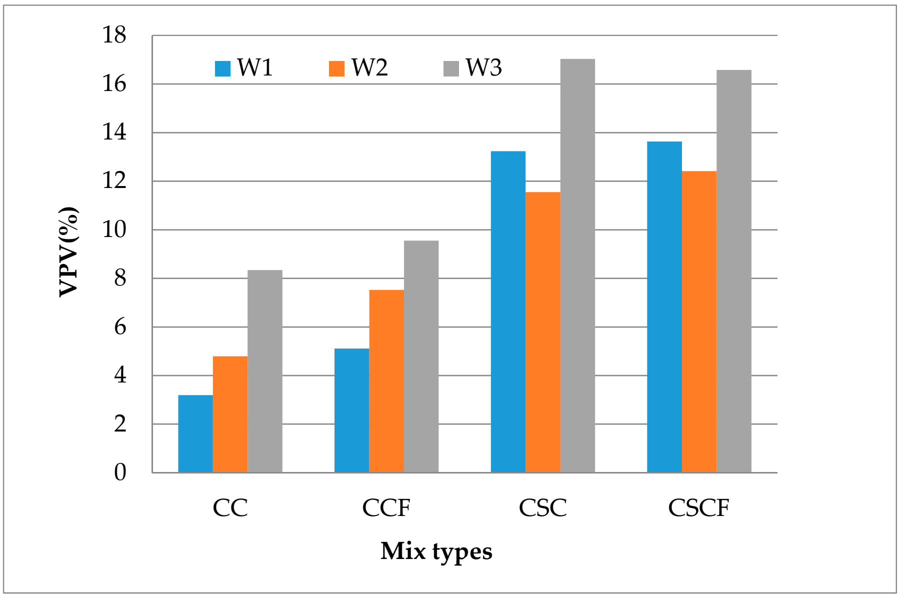

Figure 6. Results of VPV test.

5.3. RCPT

RCPT test results on CC, CCF, CSC and CSCF mixes for W1, W2, and W3 curing conditions at 28 days are shown in Figure 7. For CC specimen, the RCPT test value at 28-days was found as 2443, 2570 and 2659 coulombs for the curing conditions W1, W2 and W3, respectively. For CCF specimen, the results were found as 2408, 2515 and 2590 coulombs for the curing conditions W1, W2 and W3, respectively. Similarly, for the CSC specimen, the RCPT values at 28-days were found as 3254, 2916 and 3705 coulombs for the curing conditions W1, W2 and W3, respectively. Likewise, for the CSCF specimen, the results were found as 3158, 2907 and 3693 coulombs for the curing conditions W1, W2 and W3, respectively. Additionally, RCPT ranged 2115 to 3336 coulombs for expanded clay LWC [25]. Additionally, RCPT ranged from 3581 to 4549 coulombs for oil palm shell concrete, which is similar to CSC [26]. From the study results, all the mixes show moderate chloride-ion penetrability.

During testing, it was noticed that the specimen's temperature continued to increase throughout. At the end of the test, high temperatures were observed and felt. The reason for this phenomenon is that quality of concrete is lower in comparison with high strength, and high-performance concrete tends to rise in temperature since it is related to the product of the current and the voltage [27]. Therefore, if the quality of the concrete is low, the current passing will be greater at a given voltage and hence it may cause greater heat energy. In turn, this will lead to increase in charge passed.

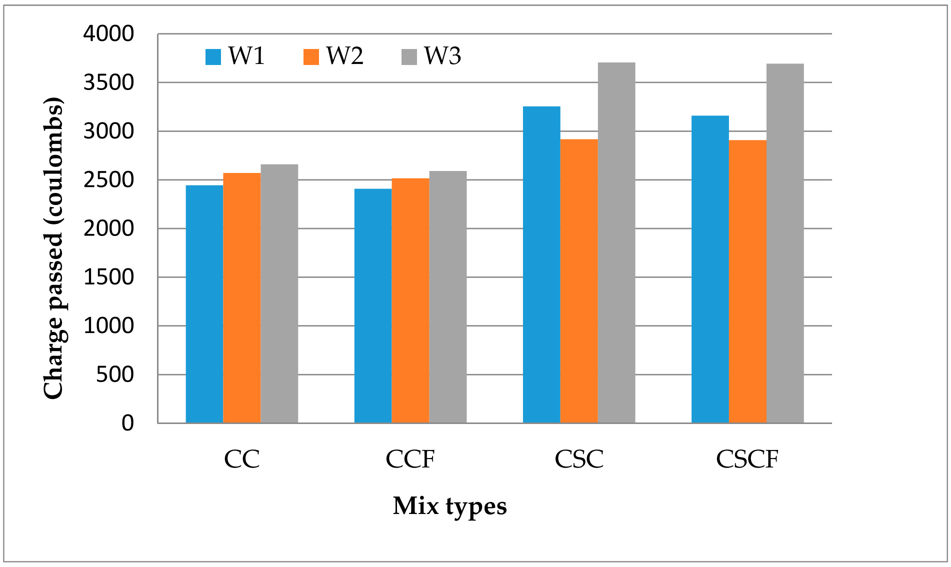

Figure 7. Results of RCPT test.

5.4. Sorptivity

Sorptivity test on a concrete specimen will give information about the pore structure of concrete [28]. If the sorptivity is low it indicates that the quality of concrete is high against the resistance of water absorption. Generally, the sorptivity value should be less than 0.1 mm/min$^{0.5}$ for the quality of concrete to be high [12]. Sorptivity test results on CC, CCF, CSC and CSCF mixes at W1, W2, and W3 curing conditions at 28 days are shown in Figure 8. For the CC specimen, the sorptivity test value at 28-days were found as 0.083, 0.090 and 0.117 mm/min$^{0.5}$ for the curing conditions W1, W2 and W3, respectively. For the CCF specimen, the results were found as 0.090, 0.097 and 0.128 mm/min$^{0.5}$ for the curing conditions W1, W2 and W3, respectively. Similarly, for the CSC specimen, the sorptivity values at 28-days was found as 0.108, 0.098 and 0.130 mm/min$^{0.5}$ for the curing conditions W1, W2 and W3, respectively. Likewise, for the CSCF specimen, the results were found as 0.117, 0.108 and 0.144 mm/min$^{0.5}$ for the curing conditions W1, W2 and W3, respectively. The results of sorptivity of the CSC and CSCF mixes are comparable to that of oil palm shell concrete ranged from 0.06–0.14 mm/min$^{0.5}$ [26]. In certain lightweight aggregates, the cement paste infiltrates the aggregate surface to a particular depth, as a result improving the aggregate interfacial zone [29] and this may be the case in this study also. The improved aggregate interface zone coupled with the capability of CS aggregate to provide internal curing resulted in the lower sorptivity of cured specimens (curing W1 and W2) compared to the uncured specimens (curing W3). Therefore to lower the sorptivity of concrete, proper curing is necessary.

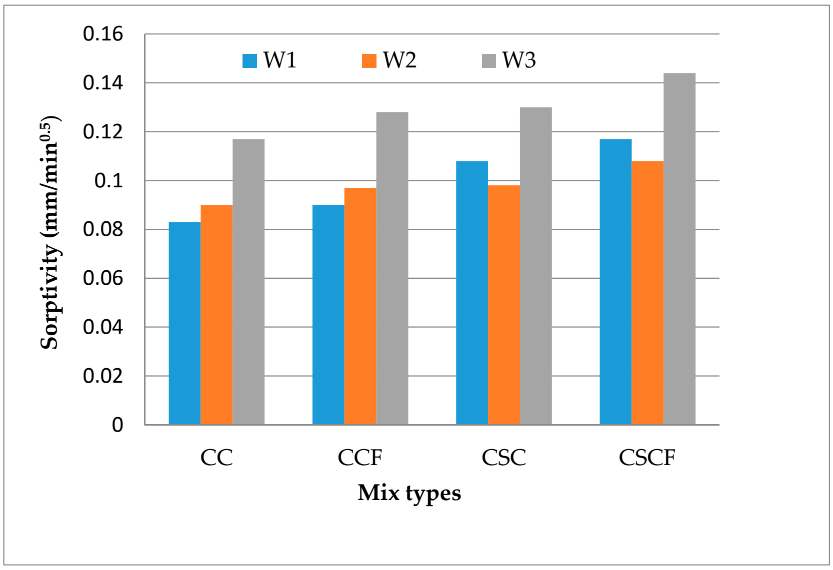

Figure 8. Results of sorptivity test.

5.5. Resistance at Elevated Temperature

Compressive strengths of CC, CCF, CSC and CSCF cubes that are not subjected to temperature at an age of 28 days under W1 curing conditions were 30.10, 43.80, 25.60 and 30.01 N/mm^2, respectively. For this temperature resistance study only W1 condition cured specimens were used. After the application of a specific temperature for a specific time duration, specimens were tested for their residual strength. Results are the average of triplicate specimens. The results of residual strength of CC, CCF, CSC and CSCF mixes subjected to different temperatures and for different durations are presented in Figures 9–12, respectively.

From the literature, it is noticed that in case of CC, up to 300 °C, the residual strengths are 98, 92, 88, and 70% at 100 °C, 200 °C, 300 °C, and 400 °C, respectively [30,31]. In this study, the residual compressive strength of CC is approximately 96, 94, 90 and 88% at 100 °C at 1, 2, 3 and 4 h duration, 88, 83, 77 and 74% at 200 °C at 1, 2, 3 and 4 h duration, 77, 67, 61 and 57% at 300 °C at 1, 2, 3 and 4 h duration, 61, 54, 49 and 43% at 400 °C at 1, 2, 3 and 4 h duration, respectively of its original strength. Likewise, the residual compressive strength of CCF is approximately 94, 90, 85 and 81% at 100 °C at 1, 2, 3 and 4 h duration, 84, 80, 76 and 69% at 200 °C at 1, 2, 3 and 4 h duration, 74, 67, 62 and 57% at 300 °C at 1, 2, 3 and 4 h duration, 61, 53, 51 and 44% at 400 °C at 1, 2, 3 and 4 h duration, respectively of its original strength. Similarly, the residual strength of CSC is approximately 94, 87, 75 and 68% at 100 °C at 1, 2, 3 and 4 h duration, 77, 67, 60 and 52% at 200 °C at 1, 2, 3 and 4 h duration, 49, 36, 29 and 21% at 300 °C at 1, 2, 3 and 4 h duration, 34, 28, 22 and 16% at 400 °C at 1, 2, 3 and 4 h duration, respectively of its original strength. Likewise, the residual compressive strength of CSCF is approximately 94, 87, 84 and 77% at 100 °C at 1, 2, 3 and 4 h duration, 82, 70, 64 and 58% at 200 °C at 1, 2, 3 and 4 h duration, 67, 57, 48 and 37% at 300 °C at 1, 2, 3 and 4 h duration, 42, 33, 27 and 21% at 400 °C at 1, 2, 3 and 4 h duration, respectively of its original strength.

As per ASTM C 330-09 [32], minimum strength should be 17 N/mm^2 to satisfy the structural concrete. From the results, it can be inferred that the residual strength of the mix CC at 100 °C, at 200 °C, at 300 °C at 1, 2, 3 and 4 h duration and at 400 °C at 1 h duration was more than 17 N/mm^2. Likewise, the residual strength of the mix CCF at 100 °C, at 200 °C, at 300 °C, at 400 °C at 1, 2, 3 and 4 h duration was more than 17 N/mm^2. Similarly, the residual strength of the mix CSC at 100 °C at 1, 2, 3 and 4 h duration and at 200 °C at 1 and 2 h duration was more than 17 N/mm^2. Likewise, the residual strength of the mix CSCF at 100 °C, at 200 °C at 1, 2, 3 and 4 h and at 300 °C at 1 and 2 h duration was more than 17 N/mm^2. Therefore, there is a minimum guarantee that all these four mixes offer resistance against temperature for 2 h and hence are safe for construction.

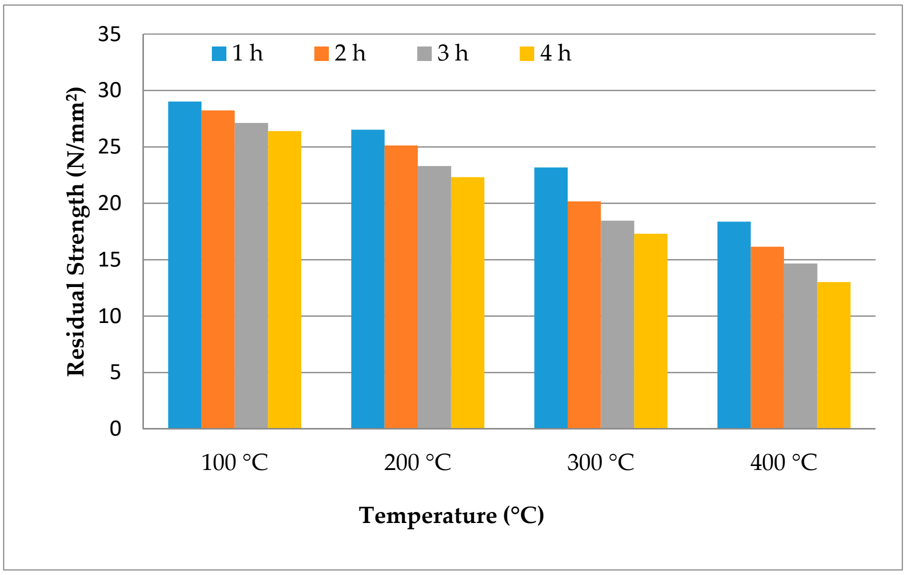

Figure 9. Temperature versus residual strength of CC mix.

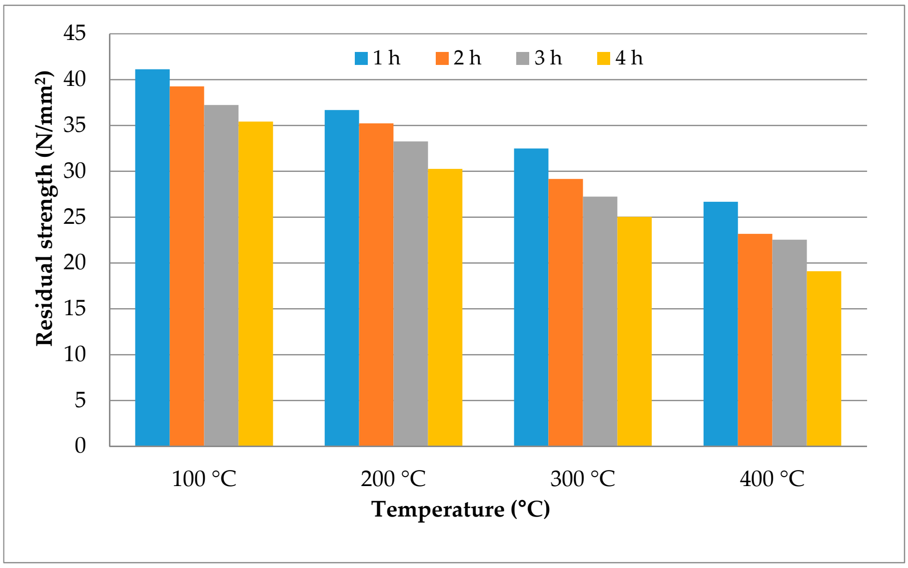

Figure 10. Temperature versus residual strength of CCF mix.

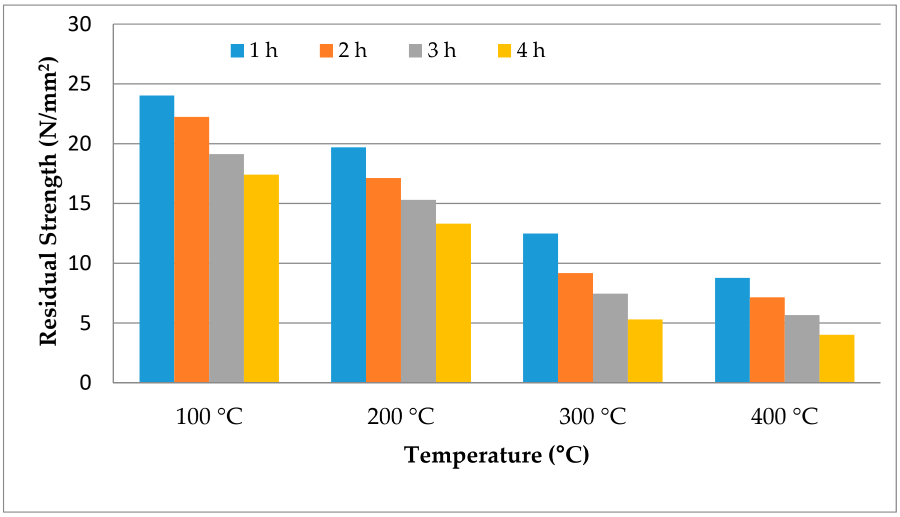

Figure 11. Temperature versus residual strength of CSC mix.

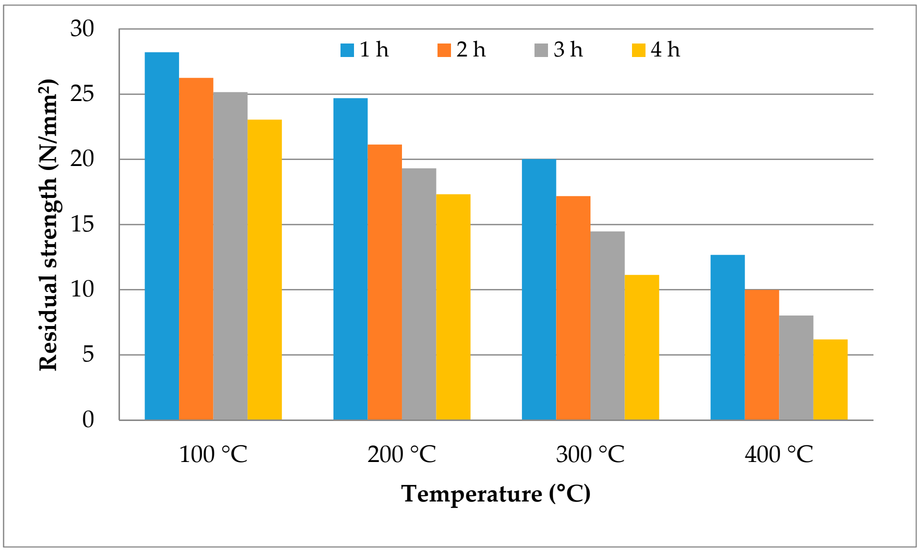

Figure 12. Temperature versus residual strength of CSCF mix.

6. Conclusions

This study was aimed at the durability performance of coconut shell concrete with coconut fibers. For comparison, conventional concrete with coconut fibers was also considered. From the test results on durability properties and elevated temperature resistance, the significant conclusions drawn are:

In case of conventional concrete mixes without and with coconut fibers, water absorption and volume of permeable pore voids results are better in the case of full water immersion compared to site curing and air-dry curing conditions. But in the case of coconut shell concrete mixes without and with coconut fibers, the site curing condition performed better compared to full water immersion and air-dry curing conditions.

All the mixes, conventional concrete and coconut shell concrete without and with coconut fibers, are rated as having moderate chloride-ion penetrability.

Sorptivity test results on the conventional concrete mixes without and with coconut fibers are less than 0.1 mm/min$^{0.5}$ in case of full water immersion and site curing conditions. Sorptivity is also less in case of coconut shell concrete mix without coconut fibers under site curing condition. Therefore, it can be stated that in these cases, the quality of concrete is high compared with other mixes.

There is a minimum guarantee that both conventional concrete and coconut shell concrete mixes without and with coconut fibers provide resistance against temperature for 2 h and hence are safe for construction.

Finally, this study encourages the idea that though both coconut shell and coconut fibers are wood based in nature, these materials can be used in the production of concrete and can be used in practice without any hesitation considering their durability properties.

Author Contributions: The conceptualization of this manuscript was initiated and methodology adopted was also decided by both the authors A.S. and G.K. Test investigations were handled by the author A.S. and supervised by the author G.K. Results analysis were done by the author A.S. and checked by the author G.K. Original draft was prepared by the author A.S. under the guidance of G.K. In the same way review and editing were also done.

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Conflicts of Interest: The authors declare no conflict of interest.

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