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Original Article

Permeability properties of lightweight self-consolidating concrete made with coconut shell aggregate

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ABSTRACT

Liquid substance intrusion into concrete is one of the issues that gradually damage its physical and structural integrity. The permeability properties of lightweight self-consolidating concrete containing coconut shell aggregate was investigated in this study. A partial replacement of crushed rock (granite) with coconut shell from 0 to 100% in step of 25% was considered for the mixtures. Rice husk ash (RHA) and Silica fume (SF) were considered for developing binary and ternary blended self-consolidating concrete with total powder content of 450 kg/m^3 and 550 kg/m^3. The testing of concrete involved the saturated water absorption, sorptivity and chloride ingress, which were used to examine the permeability properties of the concrete developed. The laboratory investigations showed encouraging results with better performance up to 75% replacement of crushed granite with coconut shell aggregate.

1. Introduction

Rapid urbanization is one of the major causes of high consumption of construction materials, which mainly comprised of natural aggregates. However, various strategies are being deployed by researchers to conserve and restore the natural eco system. Utilizing alternate aggregate for construction industry has become essential due to the economic, environmental and technological benefits [1]. Aggregates have been commonly considered as a volumetric material in concrete, which accounts for 66–78% of volume [2]. The conventional crushed granite stone aggregates are stronger than the remaining concrete ingredients and hence the strength of coarse aggregate is not an issue in normal concrete. On the other hand, when lightweight aggregates are used, it may influence the strength of concrete. Shape, texture, moisture content, specific gravity and bulk unit weight of lightweight aggregate influence properties of concrete such as: work-

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Table 1 – Physical properties and oxide composition of cement, RHA and SF.

Materials	Physical properties		Chemical Composition (%)					
	Specific gravity	Blaine (m^2/kg)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	LoI
Cement	3.15	295	22.40	5.20	3.80	61.60	1.70	1.40
RHA	2.92	317	91.85	0.31	0.26	0.78	0.55	3.49
SF	2.28	2165	87.10	0.78	2.10	0.90	1.40	1.09

ability, strength and durability of lightweight concrete [3]. The grading limit of aggregate is another important physical characteristic as it determines the requirements of workable concrete. Also, the workability requirement plays vital role for adjusting strength and durability of concrete.

Volcanic pumice [4], sintered fly ash [5], ceramics [6–8], slags [9–11] and many more construction and demolition wastes are currently used as alternatives to the conventional aggregates. The usage of these aggregates has increased due to its lightweight, lower density and availability. The light weight aggregates are typically 25–35% lighter in weight than the crushed stone aggregate. Naturally generated agricultural by-products also exist in this category. In developing countries like India, the abundant amounts of agricultural wastes are discarded, which normally can be used in the construction industry in place of the conventional materials. It has been reported that Palm Kernel Shell (PKS) as an alternate to the conventional coarse aggregate in concrete is feasible [12,13]. This was also corroborated in a related study that Oil Palm Shell (OPS) can be considered as coarse aggregate [14]. Similarly, recent investigations have proved that the coconut shell has also been suitable as a constituent material in concrete in place of granite aggregate in concrete [3]. In a study that focused on the use of coconut shell and PKS as coarse aggregate in concrete, it was articulated that coconut shell aggregate (CSA) was more suitable than PKS aggregate [15]. This may be attributed to the larger thickness of coconut shell, which also contributes to its higher strength. Alegaram et al. [16] reported an improvement in mechanical and bond strength properties of PKS based concrete. Some other studies also employed coconut shell in concrete [17,18]. Teo et al. [19] conducted an investigation on durability of OPS based light weight concrete under different curing condition and concluded that the results were reasonably well compared with other light weight concretes.

Self-consolidating concrete (SCC) is well known for its ability to compact and flow without any form of vibration [20]. Almost all the research works were focused on the rheological properties of SCC [21,22]. The basic drawback of SCC is its cost associated with the use of high powder content and chemical admixtures. In order to reduce the cost of preparing SCC, other alternative aggregates are tested for potential use in SCC. For instance, Slag was considered as coarse aggregate for developing light weight self-consolidating concrete (LWSCC) by Khayat [23]. Among several issues that are encountered in concrete, permeability is one that requires critical consideration. A permeable concrete tends to fail under loading and moreover, it does not last the design life. While several investigations have been carried out on concrete incorporating coconut shell as aggregate, however, not so much has been reported on the use of the material in self-consolidating concrete. Therefore, the current study aimed to investigate permeability properties of CSA based LWSCC, namely saturated water absorption, sorptivity and presence of total chloride, which constitute major durability concern in concrete.

Table 2 – Properties of aggregates used.

Materials	Fine aggregate	Coarse aggregate	Coconut shell
Specific gravity	2.61	7.19	1.71
Fineness modulus	2.67	2.78	–
Water absorption (%)	2.45	3.47	5.88

2. Materials and methods

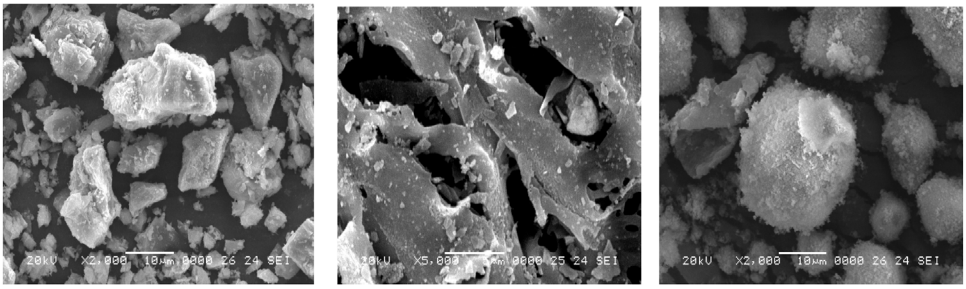
2.1. Materials

In this study, Ordinary Portland cement conforming to the requirements of IS 269:2015 [24] was used. Rice husk ash (RHA) and Silica fume (SF) were considered as supplementary cementitious materials (SCM) for developing LWSCC [25]. Table 1 shows the physical properties and chemical compositions of the SCMs used. The Scanning Electron Microscopy (SEM) micrographs, obtained in the secondary electron mode, revealing the surface nature of cement, RHA and SF particles are shown in Fig. 1. It shows the amorphous nature of the materials, with visible large crystals.

Table 2 shows the properties of the aggregate used. River sand (Fine aggregate) of features corresponding to grade limit zone-II as per IS: 383–1978 [26]. Granite (coarse aggregate) of size 12 mm was used. The density coconut shell used was 1683 kg/m^3. In order to achieve the preferred workability, Polycarboxylic based superplasticizer (SP) with specific gravity of 1.07 was used.

2.2. Mix proportions

The mix proportion for self-consolidating light weight concrete were determined according to the procedure suggested by Su et al. [27] and Su and Miao [28]. Mix proportioning for two series of LWSCC were developed with the total powder content of 450 kg/m^3 and 550 kg/m^3. After several trials, the final combinations were reached and labelled as SCC450 and SCC550. The control concrete mix proportion is given in Table 3. The cement and RHA were assorted to develop the binary blended concrete and SF were varied along with cement and RHA to develop the ternary blended SCC. The revised mix proportions of all the proposed SCC with 25%, 50%, 75% and 100% replacement of CA by CSA are given in Table 4.



a) Cement b) RHA c) SF

Fig. 1 – SEM analysis of cementitious materials.

Table 3 – Mix proportions for control SCC.

Mix Designation		Ingredient (kg/m^3)						
		Cement	RHA	SF	Sand	CA	w/p	SP (kg/m^3)
SCC450	Binary(B450)	330	120	–	850	940	0.35	2.61
	Ternary(T450)	318	100	32			0.37	2.68
SCC550	Binary(B550)	400	150	–	810	860	0.33	2.61
	Ternary(T550)	385	125	40			0.35	2.68

Table 4 – Mix proportions.

Mix designation	Quantity (kg/m^3)		CA (kg/m^3)		CSA (kg/m^3)	
	Cementitious material (C)	Sand (FA)	%	Wt.	%	Wt.
SCC450	450	850	100	940	0	0
			75	705	25	90.5
			50	470	50	181
			25	235	75	271.5
			0	0	100	362
SCC550	550	810	100	860	0	0
			75	645	25	131
			50	430	50	262
			25	215	75	393
			0	0	100	524

2.3. *Testing methods*

2.3.1. *Determination of fresh concrete properties*

Slump-flow and L-box tests were conducted to determine the fresh properties of LWSCC [29]. The slump-flow test had also been used to find out the time for spreading the concrete to 500 mm (T_{500}) in diameter [30]. The final diameter of concrete circle had been measured in two directions (D1 and D2) perpendicular to each other. The L-box test was conducted to evaluate the passing ability of LWSCC through steel bars [31]. The blocking ratio of L-box test indicated the capacity of concrete flowing through the re-bars. Generally, an SCC mix is considered to have good passing ability when the L-box value is more than 0.8 [32–34].

2.3.2. *Determination of saturated water absorption (SWA)*

150 mm size cube specimens were used to determine the saturated water absorption of all the designated mix as per ASTM C 1585-04 [35]. The specimens were allowed to the desired curing period and dried in hot air oven at a temperature of 105 °C to constant mass (W_d). Then placed it under submerged condition and weighed at regular intervals of time after surface dried. This process was continued till the weight reached the constant value which indicates that the specimens were fully saturated (W_s). The increase in mass of the specimens were measured and expressed in percentage of dry mass.

$$\mathrm{SWA} = \left[\frac{(W_s - W_d)}{W_d}\right] \times 100 \tag{1}$$

2.3.3. *Determination of sorptivity*

The rate of capillary rise through absorption of water by oven dried cubes at 105 °C for 72 h in accordance with ASTM C 1585 – 13 [36]. To prevent entry of water in all four sides, protective coating of epoxy resin was smeared to all the sides. All the specimens were weighed before placing them in water and the level of water was maintained at 5 mm above the bottom of the cube. The capillary absorption was measured along with the weight gain of the specimens at the intervals of 1 h, 2 h, 3 h, 6 h, 12 h, 24 h and 48 h from the commencement of the test. The weight of water absorbed per unit area (mm^2) of concrete surface plotted against the square root of elapsed time (min) and the slope of the plotted line (S) indicates the sorptivity of the concrete related by the equation [37],

$$i = S[t^{0.5}] \quad (2)$$

2.3.4. *Determination of total chloride*

Rectangular concrete specimens of size 350 × 250 × 75 mm were prepared as specified by ASTM C 1556 [38]. Following 24 h of setting of the mixture, they were then cured for maximum regime of 90 days by immersion water curing tank. Specimens were subsequently immersed in a sodium chloride (NaCl) solution for ponding test. A Perspex sheet, fixed on faces of the specimens using silicone gel, was used for damming during ponding. Evaporation from the vessel was prevented by sealing the dam using a plastic wrap. A constant concentration of the solution was ensured by regular changing it. During exposure to salt solution, chloride ions tend to diffuse through the concrete. After exposure, powdered samples in steps of 5 mm from the surface of the concrete were obtained using a diamond cutter. The collected powdered samples were sieved through 300-micron sieve and allowed to determine the presence of chloride. 10 g of sample was dispersed in 75 ml of distilled water in a 250 ml beaker. 25 ml of 1:1 Nitric acid was added slowly without delay and any lumps arising out of this addition were broken with a glass rod. The covered beaker was digested for 4 h in a water bath. Then it was filtered and collected as 50 ml of extract. 25 ml of 0.1 M silver nitrate was added to the extract the precipitated free chloride present in the solution. Few drops of ferric alum indicator were added and titrated against 0.1 N Potassium Thiocyanate. Appearance of red colour is the result and this process was repeated till the concordant values were obtained. The chloride content was expressed in percentage as against the cement content as outlined by Roy et al. [39].

3. Results and discussion

3.1. *Properties of fresh concrete*

The slump-flow values of B450 and T450 mix SCC specimens with 0% CSA substitution were observed as 680 mm and 700 mm respectively and the values were 705 mm and 720 mm in the case of B550 and T550 mix SCC respectively. As shown in the Table 5, it was observed that increasing the replacement level of CA by CSA also increased the slump-flow value of the LWSCC within the target range between 650 mm and 800 mm. The secondary indication of slump-flow was measured as the time to reach 500 mm slump-flow circle (T_{500}) in seconds and the results are shown in Table 5. The results of T_{500} satisfied the criteria of SCC. L-box test results are shown in Table 6 and the critical value of blocking ratio (H_2/H_1) of all the mixes is greater than 0.8 but less than 1. The range is called the self flow zone. From the Table 6, it can be seen that incorporating CSA as aggregate in SCC has satisfied the workability requirements for SCC based on the L-box test. Therefore, it is believed that the CSA based LWSCC possess good fluidity and passing ability.

3.2. *Density and compressive strength*

Figs. 2 and 3 show the density and compressive strength for binary and ternary LWSCC 450 and LWSCC 500, respectively. As can be seen, the density of 28 days cured SCC was decreased with increasing the CSA content. Usually the density of light weight concrete ranges from 1400 kg/m^3 to1850 kg/m^3 [40]. The density of LWSCC450 decreased to the threshold limit of lightweight concrete and the value of B450 mix at 75% and 100% levels of CSA substitution were determined as 1840 kg/m^3 and 1765 kg/m^3 respectively. The T450 specimen densities were 1810 kg/m^3 and 1735 kg/m^3 at 75% and 100% levels of CSA substitution respectively in the case of ternary blended concrete. In LWSCC550, the density of both B550 and T550 mixture has also decreased to the threshold limit of lightweight concrete. However, the results obtained from both binary and ternary blended SCC with more than 75% substitution of CSA are comparable with the results reported by Okafor [12] and considered as structural light weight concrete. The compressive strength of 28 days cured CSA based LWSCC was also presented in Table 6. It was observed that the compressive strength decreased when increasing the CSA substitution. Meantime, the compressive strength of 28 days cured B450 and T450 specimens with 75% CSA was observed as 21.72 MPa and 24.51 MPa respectively. This minimum observed compressive strength of 75% CSA substitution is quite above the strength requirements for structural lightweight concrete and comparable with other results reported [1, 2 & 12].

3.3. *Scanning electron microscopy (SEM)*

It was found that small cracks and discontinued pores in 28 days cured SCC in the SEM images of binary blended LWSCC as shown in Fig. 4. The SEM image of SCC reveals the liberated calcium hydroxide compound [$Ca(OH)_2$] during the primary hydration process throughout the samples. The reduction of pore sizes and the micro cracks was observed in the 90 days cured samples due to the secondary hydration products [14]. Fig. 5 shows the SEM image of microstructure of ternary blended dense cement paste when SF added as mineral admixture by arresting the cracks and pores due to the early secondary hydration products [41].

3.4. *Saturated water absorption (SWA)*

The effects of CSA in saturated water absorption of both 28 days and 90 days cured binary blended and ternary blended LWSCC are illustrated in Fig. 4 (a) and (b) respectively. It can be observed from Fig. 6 that the ternary blended concrete becomes less permeable in 0% replacement level of CSA. At the age of 90 days, the SWA of B450 and T450 mix specimens were about 27% and 35% lower than that of respective 28 days cured specimens. The similar kinds of result were also observed in B550 and T550 mix specimens. This shows that the hydration of cementitious material can continue beyond 28 days curing when sufficient amount of water present in the concrete. As a result, the total porosity of concrete is reduced as the micropores in the concrete being either blocked or narrowed down by continued formation of secondary hydration products.

Table 5 – Slump-flow (mm) and T_{500}(sec) results of LWSCC.

CA replacement level		0%	25%	50%	75%	100%
Mix designation		Slump (T_{500})	Slump (T_{500})	Slump (T_{500})	Slump(T_{500})	Slump (T_{500})
LWSCC450	B450	680 (4.8)	705 (4.4)	736 (3.8)	755 (3.2)	780 (3)
	T450	700 (4.2)	725 (3.6)	745 (3.1)	765 (2.8)	790 (2.5)
LWSCC550	B550	705 (4.3)	715 (4)	735 (3.3)	760 (3.1)	785 (2.3)
	T550	720 (4)	735 (3.2)	745 (3)	770 (2.4)	785 (2.1)

Table 6 – Blocking ratio results of LWSCC.

CA replacement level		0%	25%	50%	75%	100%
LWSCC450	B450	0.81	0.83	0.85	0.91	0.93
	T450	0.82	0.84	0.87	0.93	0.95
LWSCC550	B550	0.81	0.84	0.87	0.89	0.94
	T550	0.83	0.86	0.89	0.91	0.96

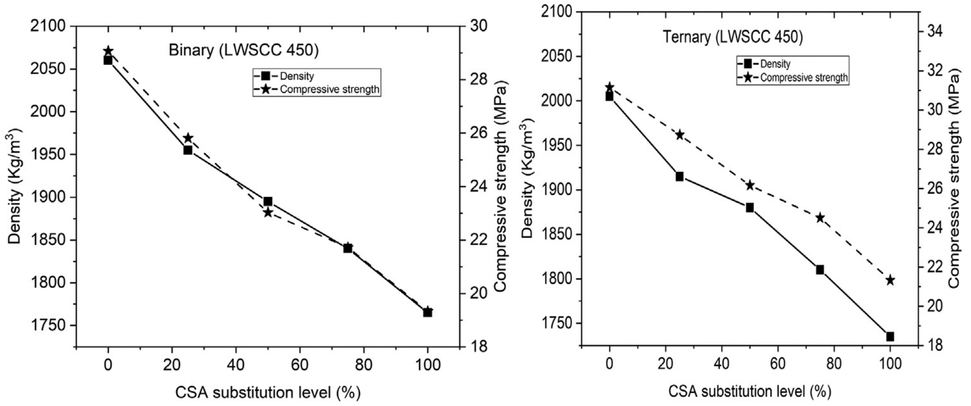


Fig. 2 – Density and compressive strength for binary and ternary LWSCC 450.

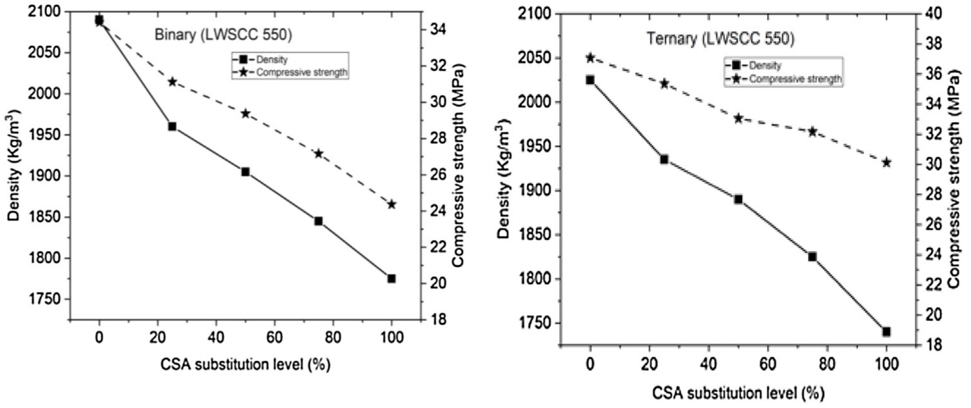
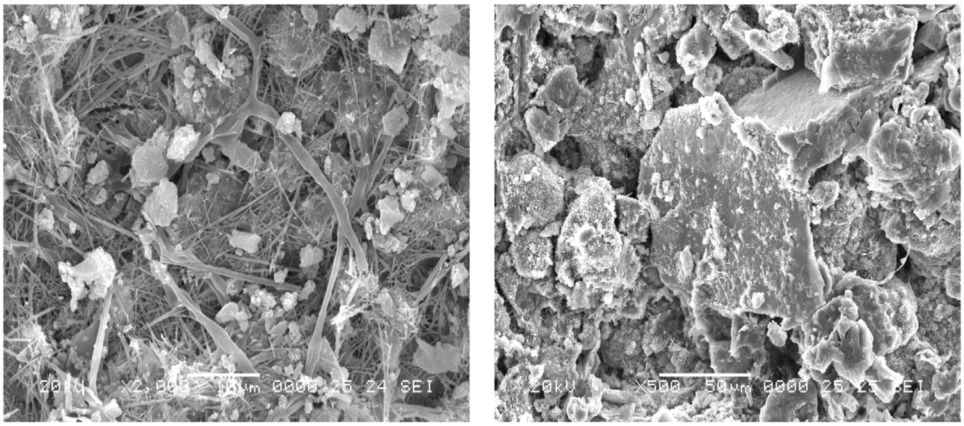


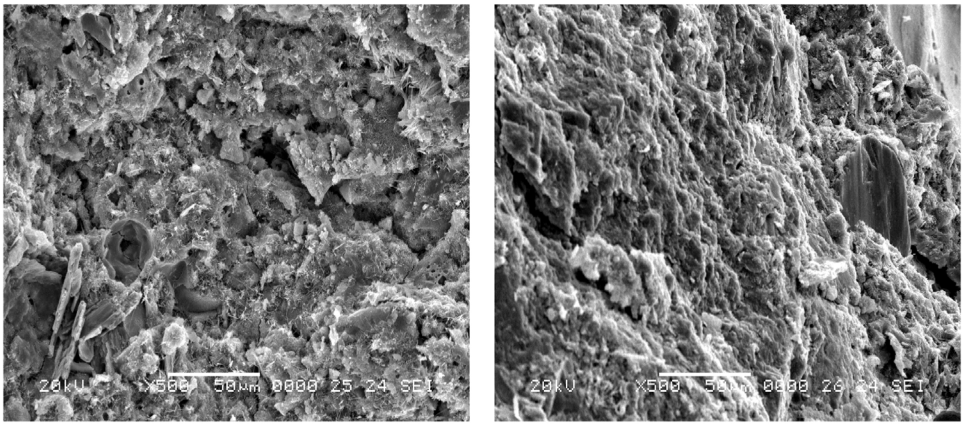
Fig. 3 – Density and compressive strength for binary and ternary LWSCC 550.

It was also observed from Fig. 4 that the replacement of CA by CSA increases the SWA in both the designated mixture specimens. Olanipekun et al. [15] and Teo et al. [40] have shown that the percentage of water absorption increases with increase in the replacement level of CA with CSA and PKS. Though the CSA is porous in nature, it can be seen that the SWA of 28 days cured LWSCC having more than 75% CSA based ternary blended T450 and T550 concrete specimens are lesser than that of binary blended B450 and B550 concrete specimens with 0% replacement level during the same curing time. Since the ternary blended concrete was reasonably impermeable and established high quality dense matrix with reduction of pore structure in the concrete. The similar kinds of result were also noticed in 90 days cured LWSCC specimens. The low amount of water absorption is an indication of good compaction achieved by self-compaction [22]. However, the SWA of CSA based LWSCC is comparable to that of other light weight concrete as shown in Table 7.



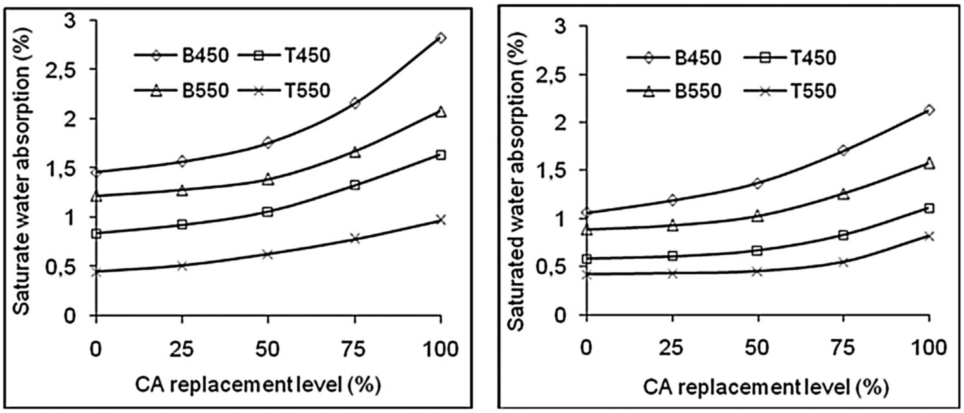
a) 28 days cured b) 90 days cured

Fig. 4 – Scanning electron microscopy images of RHA based binary blended SCC.



a) 28 days cured b) 90 days cured

Fig. 5 – Scanning electron microscopy images of RHA + SF based ternary blended SCC.

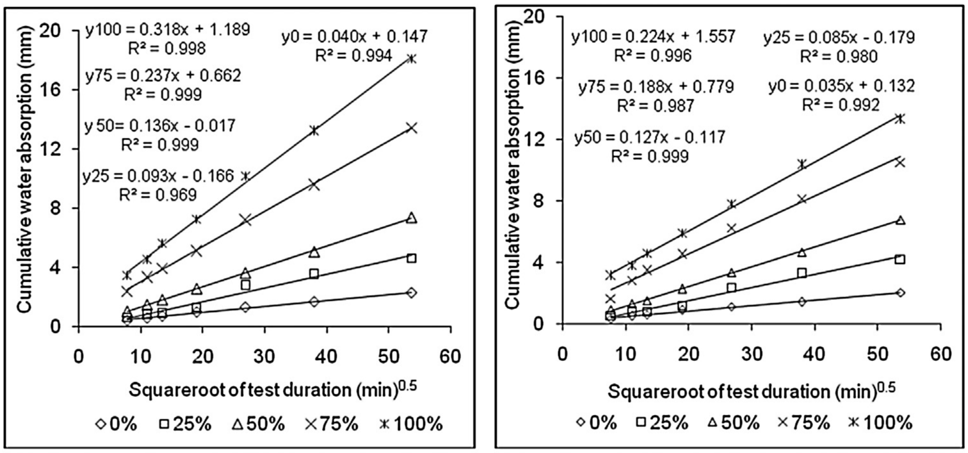


a) 28 days cured specimen b) 90 days cured specimen

Fig. 6 – Saturated water absorption of CSA based LWSCC.

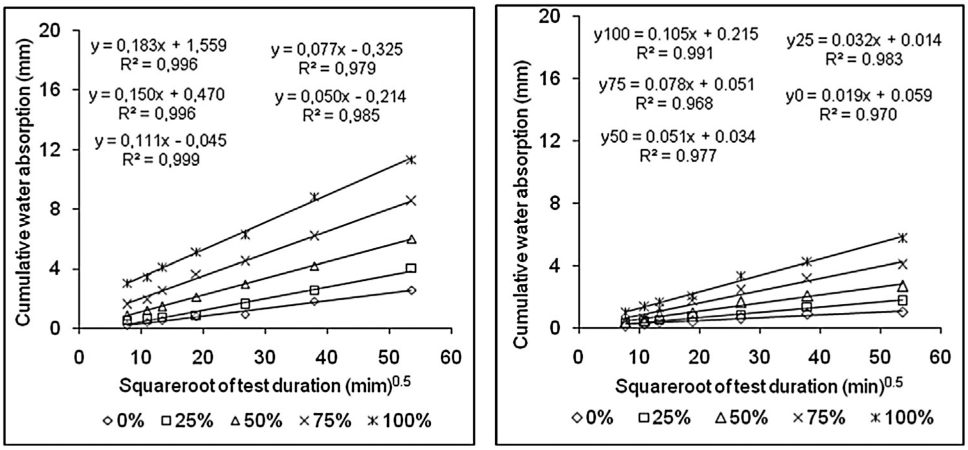
3.5. *Sorptivity*

The results of cumulative water absorption with square root of test duration in minutes for observations were plotted for all the specimens of both the designated concretes in this study. Figs. 7 and 8 show the relationship between cumulative water absorption and test duration for T450 mixture concrete, respectively. The best fit linear relationship using the equation $y = a + st^{0.5}$ and the correlation coefficient (R) were calculated to identify the slopes of each lines [34]. For all the samples



a) 28 days cured specimen results b) 90 days cured specimen results

Fig. 7 – Relationship between cumulative water absorption and test duration for T450 mixture concrete.



a) 28 days cured specimen results b) 90 days cured specimen results

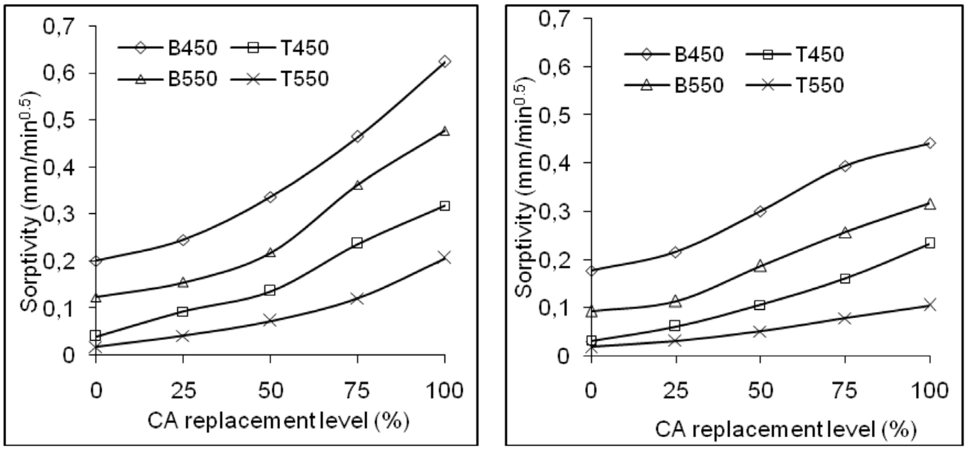
Fig. 8 – Relationship between cumulative water absorption and test duration for T550 mixture concrete.

Table 7 – Absorption results of various LWSCC.

Authors	Light weight aggregate	Absorption
Olanipekun et al. [15]	Coconut shell	0.41–3.98%
	Palm kernel shell	0.41–5.88%
Teo et al. [39]	Oil palm shell	10.64%
Topcu and Uygunoglu [41]	Pumice	15.1–21.8%
	Tuff	13.7–16.4%

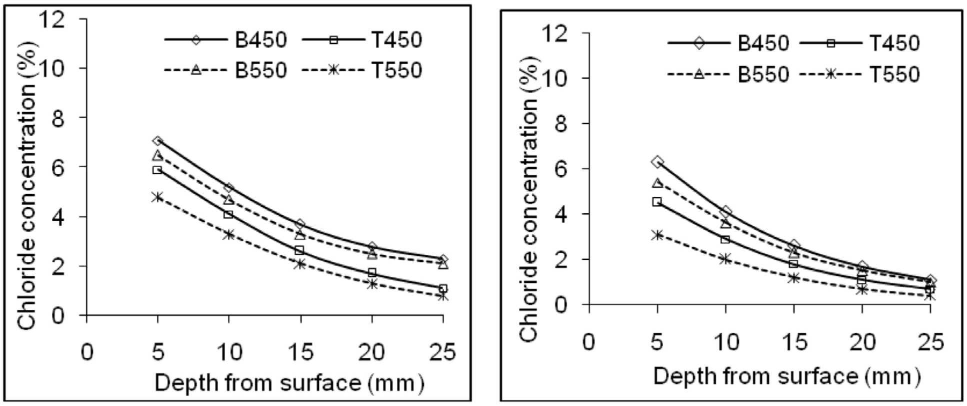
tested, the time duration produced linear relationship with capillary water absorption which gave correlation coefficients of greater than 0.966.

The sorptivity values for all the replacement levels of both the designated concretes are presented in Fig. 9. The calculated sorptivity of B450 and B550 mixture specimens after 28 days curing time were 0.201 mm/min$^{0.5}$ and 0.123 mm/min$^{0.5}$ respectively for 0% of CSA substitution. When the curing time was increased to 90 days, the sorptivity were further decreased to 0.177 mm/min$^{0.5}$ and 0.093 mm/min$^{0.5}$ respectively due to the development of dense concrete by the pore filling effect of RHA. The similar kinds of results were also observed in T450 and T550 mixture specimens due the presence of RHA and SF. For example, the sorptivity value of ternary blended 28 days cured T450 mixture specimens was 0.04 mm/min$^{0.5}$, which is 80% lesser than that of RHA based binary blended B450 mixture SCC specimens. It can also be seen from Fig. 9 that the sorptivity of SCC continues to increase with increase in the replacement level of CA by CSA owing to the porous nature of CSA. As water absorption increased, the sorption is also increased in all the cases. From the investigation, the sorptivity of ternary blended concrete exhibited better results than the binary blended concrete specimens up to the 75% CSA substitution level. The sorptivity of ternary blended T450 and T550 designated LWSCC at the age of 28 days at 75% replacement level of CSA was 0.18 mm/min$^{0.5}$ and 0.10 mm/min$^{0.5}$ respectively which are lesser than B450 and B550 designated SCC with 0% replacement level at the same age, since the impermeable nature of ternary blended concrete reduces the sorptivity of LWSCC. The similar kinds of result were also noticed in 90 days cured LWSCC specimens. Teo et al. have shown that the sorptivity value of oil palm shell based lightweight concrete



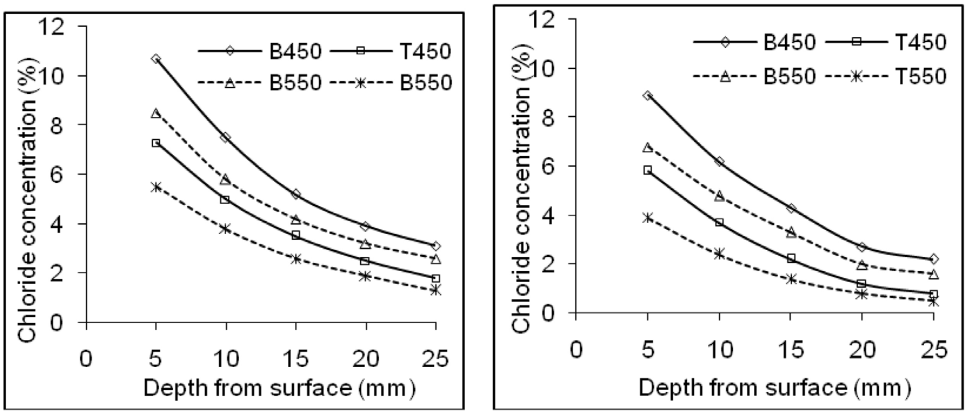
a) 28 days cured specimen b) 90 days cured specimen

Fig. 9 – Sorptivity of CSA based LWSCC.



a) 28 days cured specimen b) 90 days cured specimen

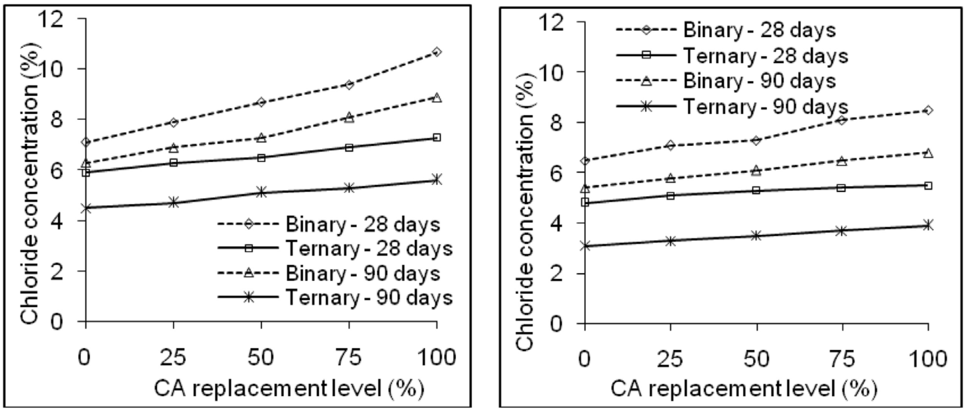
Fig. 10 – Chloride concentration of SCC with 0% substitution of CSA.



a) 28 days cured specimen b) 90 days cured specimen

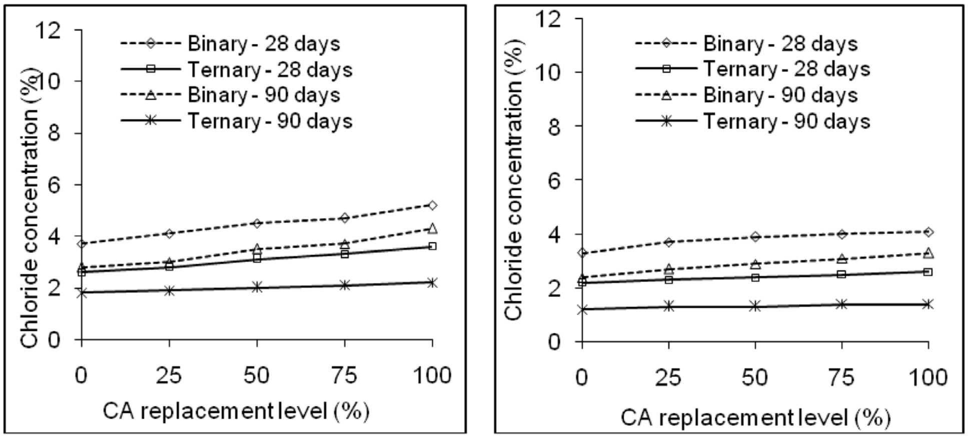
Fig. 11 – Chloride concentration of SCC with 100% substitution of CSA.

was about 0.06 to 0.14 mm/min$^{0.5}$ [41]. These values compare well with those of other lightweight self consolidating concrete containing pumice and tuff as lightweight aggregate ranged 0.22 to 0.29 mm/min$^{0.5}$ [42]. Therefore, it is believed that the development of dense impermeable SCC is required to reduce the sorption of CSA based LWSCC.



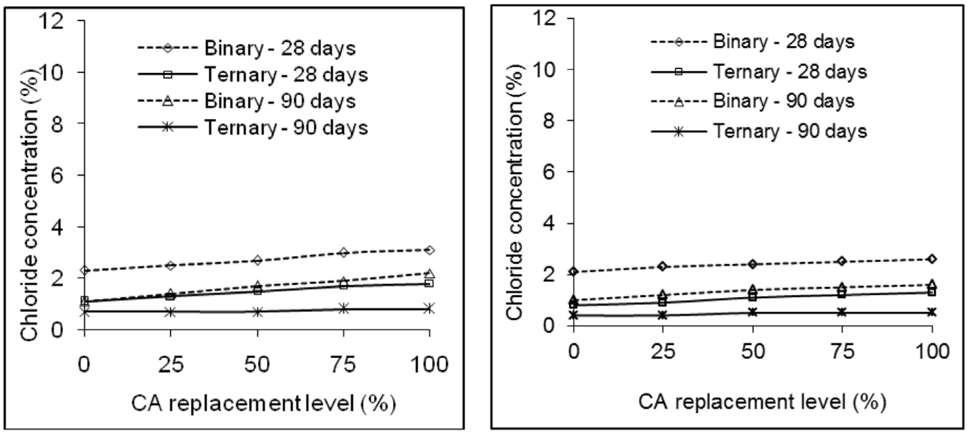
a) Total powder content of 450 kg/m3 b) Total powder content of 550 kg/m3

Fig. 12 – Chloride concentration of CSA based LWSCC at 5 mm depth from surface.



a) Total powder content of 450 kg/m3 b) Total powder content of 550 kg/m3

Fig. 13 – Chloride concentration of CSA based LWSCC at 15 mm depth from surface.



a) Total powder content of 450 kg/m3 b) Total powder content of 550 kg/m3

Fig. 14 – Chloride concentration of CSA based LWSCC at 25 mm depth from surface.

3.6. *Presence of total chloride*

The chloride profiles of SCC with 0% and 100% of CSA substitution for the designated concrete specimens are illustrated in Figs. 10 and 11, respectively. It was observed from the chloride profile that the total chloride concentration at the surface of the concrete was relatively high and decreases as the depth increases from 5 mm to 25 mm. In both control and LWSCC specimens, the binary blended concrete showed higher chloride content than the ternary blended concrete. It is interesting to note that the total chloride content decreases when the curing period was increased from 28 days to 90 days due to dense concrete matrix formation [35]. The chloride concentrations of CSA based LWSCC were moderately higher in order than the control SCC at the same mix and curing period. For example the total chloride content in B450 mix control SCC at the age of 28 days was 2.3% and that of 100% CSA based light weight SCC was 3.1% and at the age of 90 days the results were 1.1% and 2.2% respectively at a depth of 25 mm from the surface concrete. The chloride concentration at various depths of 5 mm, 15 mm, 25 mm from the surface of the concrete are shown in Figs. 12–14.

It was observed that the chloride concentration decreases when the powder content in a mix increases with the presence of SF and also increased the depth of concrete from the surface. Less than 1% of chloride concentration values were detected in all the substitution level of CSA at 90 days cured ternary blended LWSCC. This is due to the fact that the presence of super fine mineral admixture did not allow the chloride to ingress into the concrete mass as it enhanced pore size distribution, decreased capillary pores and reduced permeability. These results emphasize the importance of curing period required and proper identification of mineral admixture combinations of concrete exposed to saline environment, so that the intrusion of chlorides into the concrete can be minimized.

4. Conclusions

The permeability properties of lightweight self-consolidating concrete containing coconut shell aggregate has been investigated in this study. Based on this experimental investigation, it is practicable to use CSA as aggregate to produce light weight concrete with satisfactory performance. The following conclusions were drawn from the study:

- Incorporating CSA as aggregate satisfied the workability requirements for SCC and hence, the CSA based LWSCC mixes are good in fluidity, deformability, passing ability and filling ability.
- At 75% and 100% levels of CSA substitution, the density of RHA based binary blended SCC decreased to 1825 kg/m^3 and 1740 kg/m^3 respectively and in the case of RHA and SF based ternary blended concrete, the density of SCC decreased to 1845 kg/m^3 and 1775 kg/m^3 respectively and considered as structural light weight concrete.
- The compressive strength for 75% CSA in 28 days was observed more than 21.72 MPa which is quite above the strength requirements for structural lightweight concrete.
- 75% CSA based ternary blended LWSCC had shown the lower SWA values than that of binary blended SCC with 0% replacement level during the same curing time due to formation of dense paste.
- 28 days cured ternary blended LWSCC with 75% CSA had also shown lesser sorptivity because of the impermeable nature of blended concrete.
- Less than 1% chloride concentration values were detected in all the 90 days cured ternary blended specimens of both the mixes in all the substitution level of CSA.
- The ternary blended LWSCC with 75% CSA has lower chloride concentration at 25 mm depth from surface than binary blended SCC with 0% replacement level.

Conflicts of interest

The authors declare no conflicts of interest.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jmrt.2020.01.092.

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