Optimizing lightweight concrete with coconut shell aggregates for high strength and sustainability

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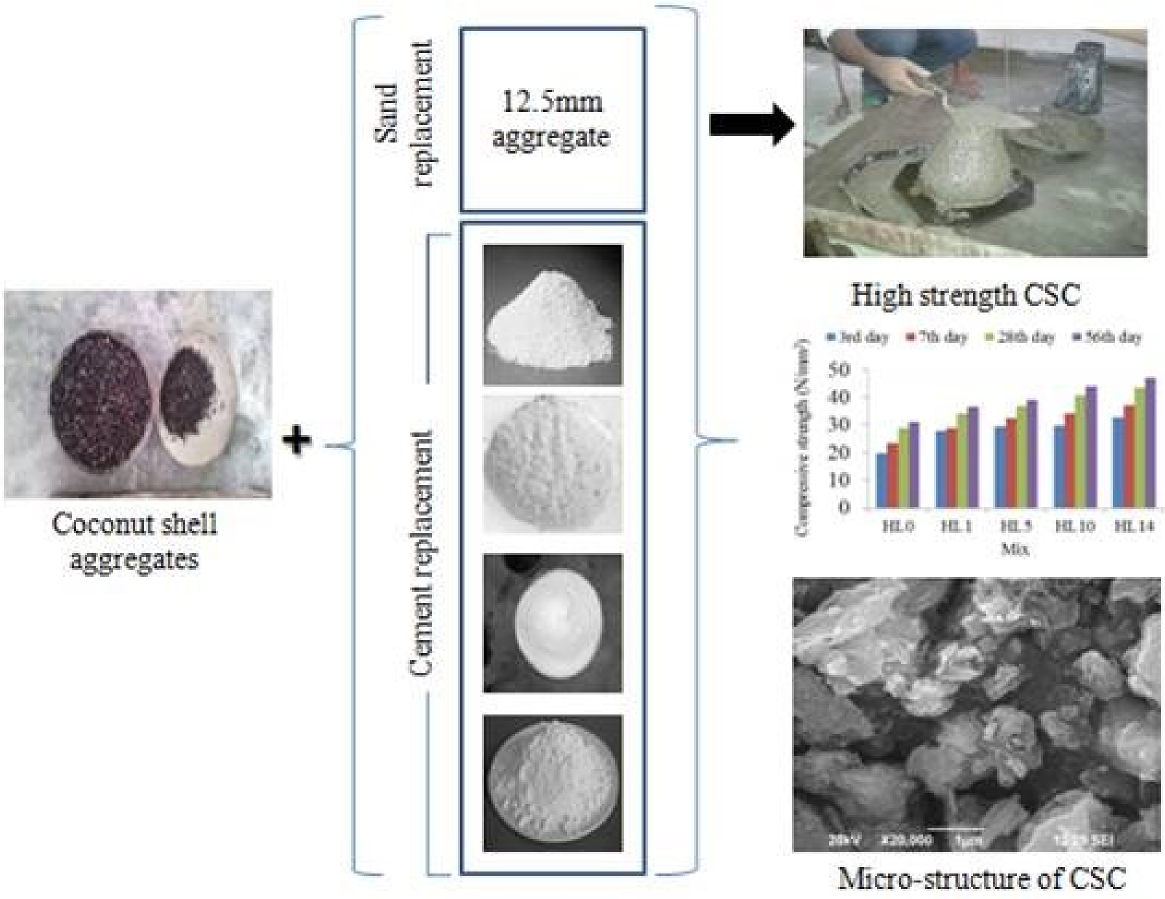
Graphical abstract



ABSTRACT

In this investigation, coconut shell, a lightweight agricultural waste, is used to completely replace coarse material. Based on previous findings, it is suggested that coconut shell be used as coarse aggregate in structural lightweight concrete. Therefore, thepurpose of the study was to develop coconut shell concrete with high strength by varying the size of coconut shell aggregates, adding a higher quantity of cement, adjusting the water content, utilizing metakaolin, nanosilica, limestone powder and silica fume as cement substitutes, and using coarser fine aggregate.Trial and error method wasutilised to find the appropriate ingredient ratios. Fifteen different mixes were used to optimize the strength of coconut shell concrete. Slump, ultrasonic pulse velocity, density (fresh, demoulded and air-dry) and compressive strength (3, 7, 28, and 56 days) were tested in each mix. Coarser fine aggregate improved the performance of coconut shell concrete. Density ranged from 1980 to 1996 kg/m^3 for this lightweight structural concrete made from coconut shells. In just 7 days, 80-93% of28-day strengthwas achieved. The small size of the coconut shell aggregates allowed for an improved paste-aggregate bond, which increased the compressive strength.By using a coarser fine aggregate in coconut shell concrete, the 28-day compressive strength of the resulting concrete was 43.6 N/mm^2, above the minimum requirement for high-strength lightweight concrete.

Keywords: Sustainability, Coconut shells; Lightweight concrete; Mineral admixture; Compressive strength; Bond strength and High strength concrete

1. Introduction

High strength concrete (HSC) is employed by civil and structural engineers because of its advantages over ordinary strength concrete, such as greater strength, stiffness, and toughness. However, its self-weight is high, which is a drawback. In order to avoid this, lightweight concrete (LWC) can be used (Mehta and Monteiro 2006).Structural LWC is becoming increasingly popular as a result of its many practical benefits, including its ability to reduce transportation and installation expenses by virtue of its lower self-weight, thinner sections, less reinforcing steel, and less foundation cost (Kayali 2008; Xu et al., 2012).

The aggregate type, size, and shape contribute to the strength of LWC. Mineral admixtures improve LWC's mechanical qualities by reinforcing the link between the aggregate and cement paste (Jerlin et al., 2017). In accordance with ASTM C330 (1999), the minimum compressive strength for LWC is 17N/mm^2. Medium strength LWC had a compressive strength between 17 and 35N/mm^2 (Mindess et al., 2003). High-strength lightweight concrete (HSLWC), as per Holm and Bremner(2000), has a minimum compressive strength of 35N/mm^2.When the aggregate sizes are less than 9.5mm, the flakiness index decreases as the aggregate edges are more likely to be rough and spiky, improving the binding between the aggregate and cement paste (Basri et al., 1999). Small-sized lightweight aggregate (LWA) combined with high cement content allows for the production of LWC with exceptional strength (Mehta and Monteiro 2006). LWC is made stronger by the incorporation of high-range water reducers and a variety of pozzolans. The compressive strength of HSLWC ranges between 34 and 69N/mm^2(Aitcin 1998). To produce HSLWC, Shafigh et al., (2011a) investigated using crushed oil palm shell (OPS) aggregate in LWC with a particle size of 9.5mm (Shafigh et al., 2011b). The researcher found that the resultant concrete had a compressive strength of around 43 to 48N/mm^2 after 28 days and a dry density of about 1870 to 1990kg/m^3. Using old broken OPS aggregate, as further examined by Shafigh et al.,(2011b), significantly increases workability and 28-day compressive strength within the levelof 34 to 53 N/mm^2. Compressive strengths of 35-50N/mm^2 were measured after Lytag aggregate was added to LWC in a study by Haque et al., (2004).

In the present scenario high prices and a lack of availability of raw materials have created many difficulties for the construction industry. Waste products, once treated appropriately, can alleviate these issues.Being such a lightweight agricultural waste material, coconut shell (CS) has the potential to be utilised in the manufacturing of LWC as a coarse aggregate. The Food and Agricultural Organization (FAO 2015) claims that India is a major player in the global coconut industry. The southern Indian states of Tamil Nadu and Kerala are rich in coconut resources. Waste coconut shells can be used as a sustainable building material in the construction sector, reducing the need for non-renewable resources. According to recent studies,agricultural waste CS can be used in the manufacturing of structural LWC as a coarse aggregate (Jerlinand Vincent 2013; Jerlin et al., 2014; Jerlin et al., 2017;Jerlin et al., 2019;Jerlin et al., 2020; Gunasekaran et al., 2011; Gunasekaran et al., 2013; Maheshwaran et al. 2023).By subjecting coconut shell aggregate (CSA) to strong alkaline, acidic, and sulphate solutions, Jerlin et al. (2020)determined that the CSA may not degrade when coupled with concrete. Furthermore, compressive and split tensile strengths of coconut shell concrete (CSC) increased with heat treatment (Maheshwaran et al. 2023).

CSA is used to make LWC more workable because of its smooth one-side surface (Jerlinand Vincent 2013; Jerlin et al., 2014). Also, CSC is more resilient to impacts than regular concrete. The maximum compressive strength of CSC designed by Gunasekaran et al.,(2011) is 26.7N/mm^2. CSC has an ultimate bond strength that exceeds the theoretical value and exhibits nobond failure even at the later ages (Gunasekaran et al., 2011). Good ductility behaviour and acceptable deflection have been observed in the CSC beam (Gunasekaran et al. 2013). Unlike regular weight concrete, CSC provides advance notice of its impending breakdown. Using 10% silica fume (SF) and 10% fly ash (FA) as cement substitute in CSC has been found to strengthen its mechanical qualities by the authors Jerlinand Vincent 2013,andJerlin et al., 2014. Chemical resistance to acid, alkaline, and sulphateattacks was further improved by the inclusion of 10% SF and 10% FA in CSC, as revealed by Jerlin et al.,(2017), who also found that this combination produced an optimal compressive strength of 31.78N/mm^2.Additionally, Prakash et al. (2021) increased the compressive strength of CSC by up to 37.6 N/mm^{2}with the use of sisal fiber. Kumar et al. (2016) have used 12.5mm size CSA in combination with mineral admixtures (silica fume and alccofine) to obtain a high-strength CSC of 43.2 N/mm^2. Sujatha and Deepa (2024) developed HSCSC using 9.5mm size CSAs and achieved a compressive strength of 39.34MPa under concealed curing.

HSCSC, as seen from the aforementioned studies, has been produced from a single-size CSA. Therefore, the objective of the present study is to use different sizes of CSA, a lower water-to-binder ratio, mineral admixtures, and without mineral admixtures to produce HSCSC. The novelty lies in the development of lightweight HSCSC made with coarser fine aggregate and various sized CSAs as a replacement for granite aggregate.

2. Materials and methodology

2.1. Materials

In this investigation, 43 grade Ordinary Portland cement (OPC) having specific gravity of 3.15 was utilized.The fine aggregate consists of river sand collected from the surrounding area and had a specific gravity of 2.68. Its fineness modulus was 2.65 and conformedto zone II as per IS 383:1970.

In the process of developing a HSLWC and comparing it to 12.5 mm aggregate, crushed CSA with an optimal particle size of 9.5 mm was employed as the coarse aggregate. CSA was collected from a nearby oil plant in Kanyakumari (India). Figure 1 shows the sample of crushed CSAs. As observed in Table 1, CSAs often possesses a greater capacity for absorbing water. Because of this, the crushed

CSAs were first soaked in water for 24 hours before being added to the concrete in order to achieve the saturated surface dry state, also known as SSD. The CSA's mechanical and physical properties are listed in Table 1. Figure 2 presents the gradingof CSA and granite aggregate.By incorporating mineral admixtures, compressive strength could be increased. Using the superplasticizerGlenium B233 allows for a considerable improvement in the workability ofLWC.

Table 1 Properties of granite aggregate and CS

Physical and mechanical characteristics	20mm size granite aggregate	4.75 to 12.5mm size CSA	2.36 to 9.5mm size CSA
24h Water absorption test (%)	1.5	17.67	20.1
Shell thickness (mm)	-	3-8	3-8
Specific gravity	2.76	1.15	1.14
Crushing value (%)	8.4	2.3	-
Impact value (%)	19.7	7.7	-
Abrasion value (%)	1.71	1.92	-
Fineness modulus (%)	7.68	6.56	5.803
Elongation index (%)	21	14.9	12.28
Flakiness index (%)	13	71.43	52.39
Loose Bulk density (kg/m^3)	1460	570	586
Compacted bulk density (kg/m^3)	1644	695	712

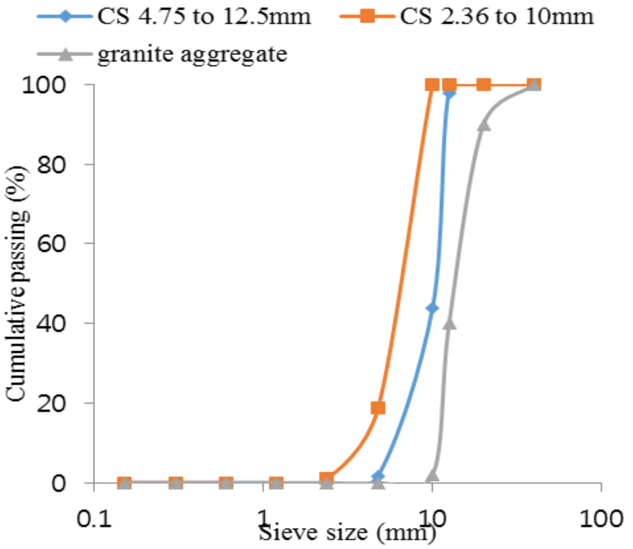


Figure 1.CS aggregate of different size**Figure 2.**Grading of CSA and granite aggregates

2.2. Concrete proportions and specimen preparation

It is possible to develop a high strength lightweight CSC by employing a small CSA size, low w/b ratio, and a substantial quantity of cement material. Aitcin(1998) suggested that fine aggregate can be used for HSC with a higher fineness module of around 3.0, since coarser fine aggregate use less volume of water to achieve the similar workability. Also, using 12.5 mm crushed granite instead of someportion of the fine aggregate will result in coarser fine aggregate (Aitcin1998),Shafigh et al., (2011b) studied a similar pattern in lightweight OPS concrete and found that it led to a high compressive strength of 53N/mm^2. Table 2 displays the mix proportions of all the mixes by the varying quantities of ingredients used.

The natural agricultural waste aggregate CS is different in their physical properties such as texture and shape from other lightweight aggregates. In the same manner, the properties of CSA are different from other LWAs such as Leca, foamed slag, Aglite and Lytag, which have smooth texture and different shapes. Gunasekaran et al. (2011) have specified that the targeted design strengths of CSC could not be attained by using mix design by ACI method, IS method and also method by Short &Kinniburgh(1978). Hence, a mix proportion was arrived at for CSC by using trial and error method (Gunasekaran et al. 2011; Jerlin et al. 2017). A trial mix ratio of 1:1.58:0.6 was adopted in this study.There have been a total of fifteen trials with different mixes (HL_0 to HL_{14}). The maximum size of CSA(12.5 mm) could be found in mix HL_0, and this was used as the base mix. The 9.5mm size of CSA was utilised for all of the other blends. The range of possible CS sizes for HL_1 to HL_4 mixes was 4.75 to 9.5 mm, but the range for HL_5 to HL_{14} mixes was 2.36 to 9.5 mm. The HL_4 mix must have a minimum cement content of 480 kg/m^3, as specified in the specification. Mix HL_{10} has a composition of 30% CSA ranging from 2.36 to 4.75 mm and 70% CSA ranging from 4.75 to 9.5 mm. The coarser fine aggregate that was employed in mixes HL_{11} and HL_{14} was achieved by replacing 20% of the sand with 12.5mm granite aggregate, following the study by Shafigh et al. (2011b). Mix HL_8used 10% silica fume and 4% nanosilica as cement replacements. While; HL_9used 5% silica fume and 2% nanosilica as cement replacements. In mixes HL_{12} and HL_{13}, respectively, 20% of the cement was substituted with powdered limestone and metakaolin.

Table 2HSCSC mix proportion (kg/m^3)

Mix id	**Cement**	**Water**	**Sand**	**Coconut shell**	**w/b**	**Stone Aggregate**	**Superplasticizer**	**Metakaolin**	**LSP**	**NS**	**SF**
HL_0	550	209	869	330	0.38	-	1.15	-	-	-	-
HL_1	550	209	869	330	0.38	-	1.1	-	-	-	-
HL_2	500	177	726	435	0.318	-	1.22	-	-	-	-
HL_3	550	192.5	891	333	0.35	-	0.8	-	-	-	-
HL_4	480	182	1050	293	0.38	-	1.2	-	-	-	-
HL_5	550	209	869	330	0.38	-	1	-	-	-	-

HL$_6$	550	179	869	303	0.324	-	1.1	-	-	-	-
HL$_7$	500	162	735	325	0.324	-	0.8	-	-	-	-
HL$_8$	430	262.5	800	390	0.5	-	0.7	-	-	20	50
HL$_9$	511.5	231	880	440	0.42	-	1.2	-	-	11	27.5
HL$_{10}$	550	209	869	330	0.38	-	1.1	-	-	-	-
HL$_{11}$	550	167.8	713	333	0.305	178	1.2	-	-	-	-
HL$_{12}$	440	192.5	836	273	0.35	-	1.3	-	110	-	-
HL$_{13}$	440	192.5	869	330	0.35	-	1.3	110	-	-	-
HL$_{14}$	550	176	695	330	0.32	174	1.3	-	-	-	-

w/b- water to binder ratio,LSP- Lime Stone Powder, NS- Nano-Silica, and SF- Silica Fume

In order to prepare CSC, CSA and sand were placed in a concrete mixer and mixed in a dry mode for a period of one minute. Then, for 1 minute, the cementitiousmaterialswere added and mixed together. After that, some of the water that had been mixed with the superplasticizer was added, and the mixture was blended for a full minute. The remaining amount of water was then added to the mixture, and it was thoroughly blended for a period of five minutes prior totheslumpmeasurement. The freshly mixed CSC was placed into moulds measuring 100 mm cubes and then tamped down with a needle vibrator. After a casting period of 24 hours, the specimens were dismantled from the moulds and preserved in water until the age at which they were to be tested.

A total of 180 cubes were cast for the investigation which comprised twelve 100x 100 mm cube specimens for each mix. Slump of the fresh concrete was measured for each mix. Hardened properties such as demoulded density, air-dry density, Ultrasonic Pulse Velocity (UPV) and compressive strengths were determined. UPV and air-dry density of cubes were determined after 28 days while; their compressive strengths were evaluated at 3, 7, 28, and 56 days according to IS 516:1959. When determining the compressive strength of concrete at a specific age, the average of the results from three separate cubes of concrete was employed. The micro-structure of CSC was determined using a scanning electron microscope (SEM).

3. Result and Discussion

3.1. Slump value of HSCSC

The workability of HSCSC was evaluated using a slump test. The slump values that were measured are presented in Table 3. In the current investigation, all the CSC mixes exhibited a medium level of workability, with the exception of mix HL$_{14}$exhibiting high level of workability. The amount of LWA, sand fineness and the w/b ratio all have an impact on workability of LWC (Mehta and Monteiro 2006). In addition, the strength and workability of LWC reduces when there is a greater quantity of LWA. Mixes of HL$_0$, HL$_1$, HL$_5$, and HL$_{10}$ with proportions that were the same served to verify the influence that different sizes of CSA had on the material's workability. There is a drop in the value of slump as a result of increasing the size of the CSA from 9.5 mm to 12.5 mm. According to the findings, it is known that the mix HL$_{14}$, which had particles ranging in size from 2.36 to 9.5 mm and coarser fine aggregate (so as to reduce the total surface area), had a slump value that was approximately 130mm higher than any other mix. Although mix HL$_{14}$ had a lower w/b ratio, the quantity of superplasticizer used was higher than that used for HL$_o$ mix. The amount of superplasticizer used was higher than that used for the base mix, HLo, by about 13%. This higher amount enabled more flowability in the concrete.

In comparison to the HL$_0$ mix, the w/b ratios of the HL$_{11}$ and HL$_{14}$ mixes were much more favourable, coming in at 24.6% and 18.75%, respectively. These mixtures utilised coarser fine aggregate, which necessitated lower water content and ultimately resulted in a better slump value. Because the HL$_0$ mix utilised larger particles ranging from 4.75mm to 12.5mm in size, the slump value was increased to 60mm. When contrasted with the HL$_1$ mix, the HL$_2$ mix contained a lower percentage of cement and a greater proportion of CSA, both of which contributed to a lower slump for the HL_2 mix than that of the HL_1 mix. In comparison to HL_1 mix, HL_3 mix has a w/b ratio that is approximately 8.5% lower and has a significantly higher percentage of sand. This resulted in a drop in the slump value, despite the fact that both mixes contained the same volume of CSA. The use of a higher proportion of sand and a lower proportion of cement in the HL_4 mix resulted in a slump value of around 48mm. As compared to the values of other mixes, this one has the lowest slump value. According to Mehta and Monteiro (2006), the slump value of 50-75 mm may be required for lightweight concrete in order to obtain workability equal to the slump of 100-125 mm for normal weight concrete.

To investigate the impact of mineral admixtures on workability, Mixes HL_8, HL_9, HL_{12}, and HL_{13} conducted several trials. The findings imply that CSC becomes less practical when SF is included. Slump value was significantly diminished by utilising a high concentration of nanosilica and SF in the HL_8 blend. HL_{12} and HL_{13} combinations were used to test the efficiency of limestone powder and metakaoline on the workability of the material. These granules were used to make a concrete with a medium level of workability.

3.2. Density of HSCSC

Densities of CSC in their fresh, demoulded, and air-dried states after 28 days are listed in Table 3. The current investigation found that the fresh density of CSC varied from 2.30 to 1.17 kg/m^3. After 28 days, its density had decreased by 130-182 kg/m^3. LWC's fresh density is typically 100–200 kg/m^3 higher than its hardened density after 28 days (Mannan and Ganapathy 2004). The HL_7 mix has a lower fresh density because of the low amount of fine aggregate present. The air dry density at 28 days was below the maximum allowable value of 2000 kg/m^3 for lightweight aggregate concrete across all mixtures (Gunasekaran et al., 2011). This lighter weight was achieved by completely removing the heavyweight coarse aggregate by CSA. The air dry density of HSCSC was between 1880 and 1996 kg/m^3 after 28 days. The low fine aggregate composition of mixtures may be at least partially responsible for their low hardened density after 28 days.Coarser fine aggregate was employed in the HL_{11} and HL_{14} mixes, which allowed for the development of CSC with higher strength and density that was less than 2000 kg/m^3, meeting the minimum density requirement for structural LWC according to ASTM C330.Consistent with these results, it is observed that aggregate size has a significant role in determining LWC density. HSCSC had a somewhat lower hardened air dry density after 28 days when its overall CSA size was reduced from 12.5mm to 9.5mm. A dead load reduction of 16.83% to 21.66% was possible when using HSCSC instead of standard weight concrete.

Table 3 Slump and density values of HSCSC

Mix	Slump (mm)	Fresh Density (kg/m^3)	Demoulded density (kg/m^3)	28-day air dry density (kg/m^3)
HL_0	65	2125	2005	1977
HL_1	80	2103	1992	1968
HL_2	55	2080	1984	1942
HL_3	60	2138	2003	1973
HL_4	50	2151	2026	1988
HL_5	90	2100	1995	1960
HL_6	70	2092	1976	1946
HL_7	65	2030	1905	1880
HL_8	60	2052	1926	1897
HL_9	50	2070	1950	1915
HL_{10}	95	2086	1994	1952
HL_{11}	95	2178	2030	1996
HL_{12}	60	2048	1958	1918
HL_{13}	50	2065	1965	1930
HL_{14}	130	2166	2037	1992

3.3. Ultrasonic Pulse Velocity

After 28 days, the UPV test for HSCSC was carried out and Table 4 contains an analysis of the findings as well as a summary of the findings. These numbers are appropriate for use with regular aggregate concrete, and equivalent values may also be utilised as a benchmark for calculating CSC requirements. According to Table 4, the findings of the current study indicate that the value of the UPV after 28 days for HSCSC can range anywhere from 3.730 to 4.128 km/s. It was discovered through IS 13311-Part I (1992) that CSC with these velocity readings might be in the range of 3.5 to 4.5 km/s and considered to be in good grading of concrete quality.

Table 4. Pulse velocity and compressive strength of HSCSC

Mix	UPV km/sec	Compressive strength (N/mm^2)			
		3rd day	**7th day**	**28th day**	**56th day**
HL$_0$	3.782	19.72 (68%)	23.38 (80.6%)	29	31 (106.90%)
HL$_1$	3.87	26.5 (77.9%)	29 (85.3%)	34	36.5 (107.35%)
HL$_2$	3.91	23 (70.8%)	25.46 (81.5%)	31.25	32.5 (104%)
HL$_3$	3.92	22.1 (71.3%)	25 (80.64%)	31	32 (103.23%)
HL$_4$	3.73	16 (80%)	18.5 (92.5%)	20	21.5 (107.5%)
HL$_5$	4.005	29.5 (79.73%)	32.5 (87.84%)	37	39.2 (105.95%)
HL$_6$	3.986	27.5 (79.25%)	31 (89.33%)	34.7	38.5 (110.95%)
HL$_7$	3.972	24.5 (73.13%)	30.5 (91%)	33.5	37 (110.45%)
HL$_8$	3.952	22.4 (70%)	27 (84.38%)	32	36 (112.5%)
HL$_9$	4	24.52 (68.11%)	29.1 (80.83%)	36	38 (105.56%)
HL$_{10}$	4.083	29.72(72.84%)	34.13 (83.65%)	40.8	44 (107.84%)
HL$_{11}$	4.019	25.37 (69.5%)	29.93 (82%)	36.5	38 (104.11%)
HL$_{12}$	4.03	26 (68.78%)	31.4 (83%)	37.8	39.2 (103.7%)

HL_{13}	4.06	28.88 (74%)	34 (87.2%)	39	42 (107.72%)
HL_{14}	4.128	32.7 (75%)	37.22 (85.36%)	43.6	47 (107.88%)

(Values inside parenthesis indicate the development of strength as compared to the 28thday strength)

Figure 3 illustrates the association that exists between UPV and compressive strength after 28 days. Based on this relation, it was hypothesized that an increase in compressive strength would accompany an increase in UPV value. On the basis of their research, Tharmaratnam and Tan (1990)as well as Lianga and Wub (2002) expressed a link between UPV of concrete and its compressive strength, which may be represented by equation (1).

$$f_c = a_1 e^{b_1 v} \text{ ------ (1)}$$

Where f_c is the compressive strengthin N/mm^2, a_1 and b_1 are parameters determined by the characteristics of the material, and $v$is the UPV in km/sec.

Based on the findings of the tests, an empirical equation was developed using the relationship between compressive strength and UPV represented by equation (2). The compressive strength of CSC may be determined based on the values of UPV with an R^2 value of 0.8532 by utilizing equation (2).

$$f_c = 0.0688\, e^{1.5646 v} \text{ ------ (2)}$$

Where f_c is the compressive strengthin N/mm^{2}and v is theUPV value in km/sec.

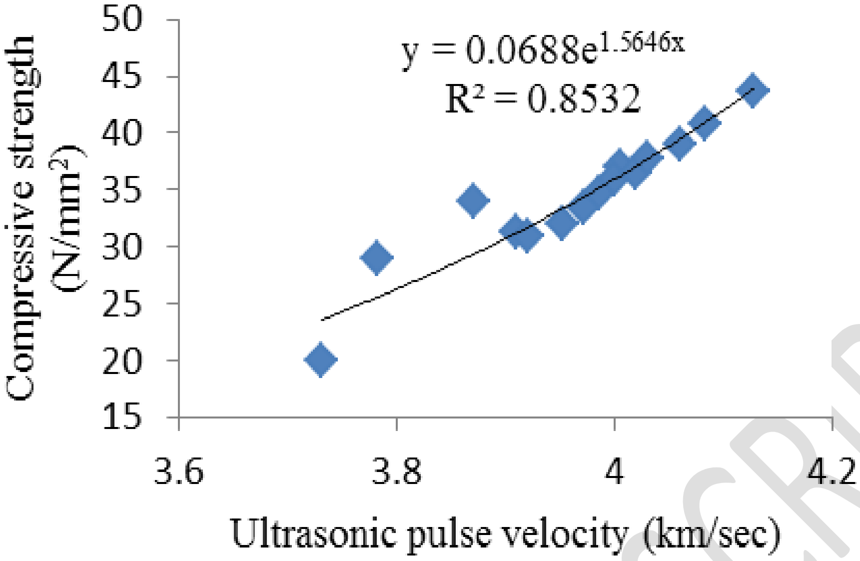


Figure3. Relation between UPV and compressive strength of HSCSC

3.4. Compressive Strength of HSCSC

The compressive strength of CSC is outlined in Table 4.The values within the parenthesis indicate the percentage of early strength reached in 3 and 7 days and at later age (56th day) with respect to the 28th day strength. It has been discovered that the compressive strength of CSC at 28 days ranged from 29 to 43.6 N/mm^2. The compressive strength obtained exceeded the lower limit of 34 N/mm^2 for structural HSLWC (HolmandBremner 2000). The strength of the LWC was determined by the quality and strength of the interfacial zone of the LWA in addition to cement paste (Lo et al., 2007). In most cases, CSA will have a smooth surface texture on one side while also having a high flakiness index score. As a direct consequence of this, the compressive strength of the CSC with an aggregate size of 12.5 mm (HL$_o$) is reduced. By breaking down the CSA into pieces smaller than 9.5mm in size, the flakiness index was able to be significantly reduced. The fractured edges had a spiky and rough appearance, which facilitated a stronger bond between the cement paste and the aggregate.

In the present study, HSCSC was made by crushing CSA to a size of 9.5 mm and was compared to CSA concrete with a size of 12.5 mm. This particular CSA size was smaller than those that were utilised in the vast majority of the preceding experiments (Jerlin et al., 2013; Jerlin et al., 2014; Gunasekaran et al., 2011). The association between the early compressive strength (measured on the 3rd and 7th day) and the strength measured after 28 days is depicted in Figure 4. In this study, 68 to 80 percent of the 28-day strength was reached in three days, and in seven days 80 to 93 percent of the strength was reached.In most casesthe ratio of 7-day strength to 28-day strength for HSLWC falls anywhere between 80 and 90 percent (Fujji et al., 1998). The linear link between early age strength and strength at 28 days is shown in Figure 4. This association was found to exist as a result of this investigation. The strength correlation on the seventh day (R^2=0.9396) was superior to the strength correlation at the three-day mark for HSCSC.

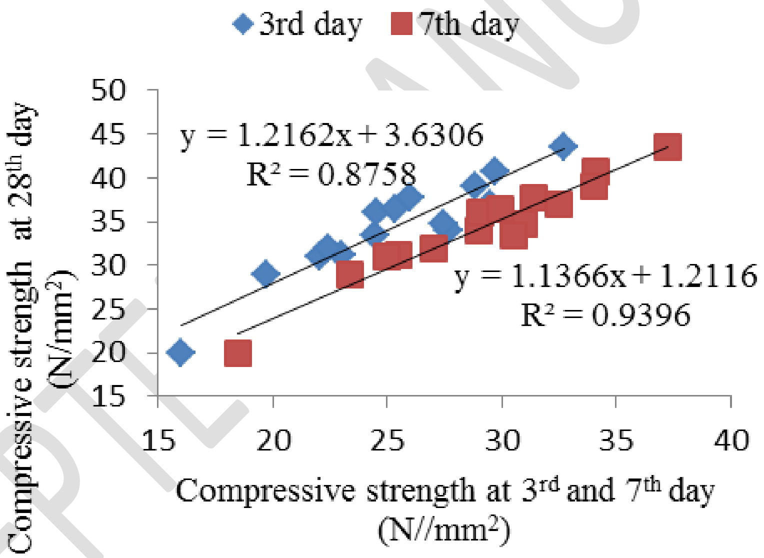


Figure 4. Relation between early CSC compressive strength (3 and 7 days) and 28 days

3.*4.1 Influence of CSA size on compressive strength*

For the similar mix ratio, Figure 5 indicates CSC's compressive strength growth with various CSA sizes. In developing the strength of concrete, the aggregate size takes a critical part. It is possible that internal bleeding, the development of micro fractures, and a weaker transition zone are to blame for the decrease in the compressive strength of concrete that results from the use of large size CSA

(Shetty2019). This issue can be remedied by making use of smaller aggregates, which facilitate the formation of a more robust bond between the cement paste and the aggregate, leading to an increase in compressive strength (Caliscan and Karihaloo 2002). Also, high amount of cement was also used in this mix which compensates for the strength loss by having the required paste at the ITZ.Mix HL_0, in contrast to other high strength mixes, utilised CSA ranging from 4.75 to 12.5 mm in size and had a compressive strength of 29 N/mm^2. The addition of CSA larger than 9.5 mm may have contributed to this reduction by reducing the bond between the cement matrix and large aggregates (Caliscan andKarihaloo 2002).Another possible cause might be the smoother surface of the large-size CSA, which has a size greater than 9.5mm.

Mix HL_1utilised CSA sizes ranging from 4.75 to 9.5mm and had a strength that was 17% greater than HL_0. This could be the result of the maximum size of the aggregate being reduced from 12.5 mm to 9.5 mm. This resulted in a significant improvement in the strength of the concrete, which can be attributed to both a reduction in the flakiness index and the transformation of the smooth surface into one that is rough and spiky.The result also revealed that the 56-day strength of CSC was greatly boosted by reducing the size of the CSA. An identical pattern was observed with high strength OPS concrete as well (Shafigh et al., 2011b). Themix HL_5utilised CSA sizes ranging from 2.36 to 9.5mm, which resulted in a strength that was 8.8% and 27.6% greater than that of HL_1 and HL_0, respectively. The HL_5 mix which has a higher density used 10 to 15% of aggregate with a particle size of less than 4.75mm. These smaller particles serve to fill in the gaps, which in turn improves the material's strength. Compressive strength of 40.8N/mm^2 was achieved by the mix HL_{10}. This figure for strength is greater than that of any earlier papers in CSC that did not include any mineral admixtures.This value is also greater than strength of CSC (37.6 N/mm^2) developed by Prakash et al. (2021).The HL_{10} mix has approximately 10.27% more 28-day strength than the HL_5 mix, according to the findings of a comparison between the two mixes. This could be due to the fact that 30% of the very small size of

CSA concrete ranging from 2.36 to 4.75 mm was utilised to fill the pores in 70% of CSA concrete ranging from 4.75 to 9.5 mm. This strength is also 40.7% greater than the CSCwithCSAof12.5 mm in size (HL_0). In order to investigate the influence that CSA size has on the enhancement of strength, the mixes HL_0, HL_1, HL_5, and HL_{10} are utilised. Among these, the HL_1, HL_5, and HL_{10} mixes offered high strength and satisfied the criterion for HSLWC.

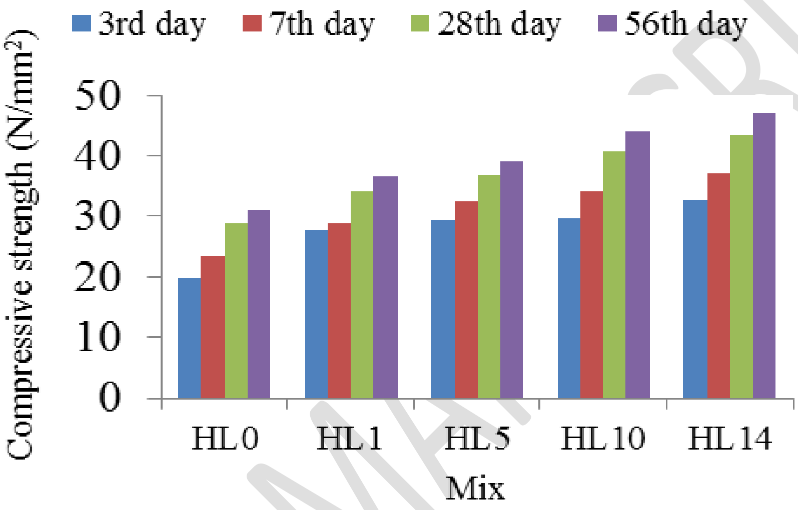


Figure 5. Variation of CSC Compressive strength with various CSA sizes

3.4.2. Effect of coarser fine aggregate on compressive strength

In mixes HL_{11} and HL_{14}, coarser fine aggregate was produced in a manner analogous to that described by Shafigh et al., (2011b). This was accomplished by exchanging 20% of the fine aggregate for crushed granite measuring 12.5 mm in size. It is clear from examining Figure 5 that the HL_{14} mix achieved the optimal compressive strength of around 43.6 N/mm^2 in a period of 28 days. This may be due to the smaller size of 2.36 to 9.5 mm CSA, which reduces the flakiness index and increases stiffness. By crushing the larger aggregate into smaller ones, the edges became rough and spiky, which caused a stronger physical bond between the aggregate and the cement paste (Caliscan and Karihaloo 2002). This improves the strength of the CSC.This is also due to the use of coarser fine aggregate, which reduced both the total surface area and the amount of water required by approximately 18.75% in comparison to mix HL_5, consequently increasing the compressive strength by approximately 17.8%. This result was notably higher than the 12.5mm size CSA concrete mix HL_0 by 50.34%. Mix HL_{11} had a strength that was 19.5% less than that of mix HL_{14}, despite the fact that it produced 36.5N/mm^2 and used a coarser fine aggregate. This could be due to the high ratio of fine aggregate to cement used in the mix. This is higher than the basic mix HL_0 by 25.86%, which means that it satisfies the lower limit for HSLWC.

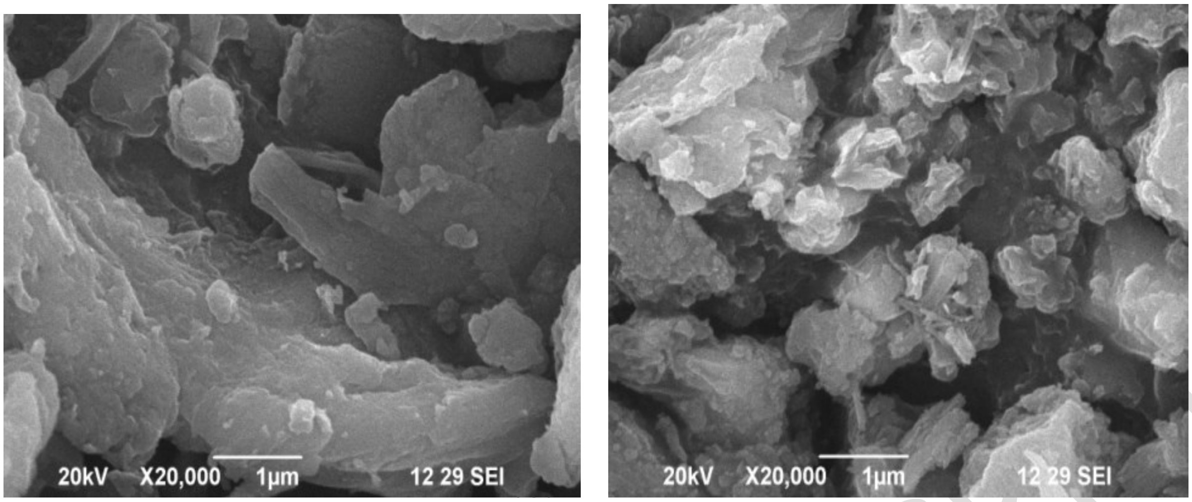
3.4.3. Effect of cementitious materials on compressive strength

In order to investigate the influence that mineral admixtures have on the compressive strength of CSC, the mixes HL_8, HL_9, HL_{12}, and HL_{13} are utilised. As seen from Table 4, the addition of mineral admixtures, such as metakaolin and powdered limestone, results in a significant increase in the strength. At 28 and 56 days, the strength of the CSC with limestone power (HL_{12}) and metakaolin (HL_{13}) is 37.8N/mm^2, 39.2N/mm^2, and 39N/mm^2, 42N/mm^2,respectively. Lime and metakaolin, which are filler elements, increased the strength by 2.8% (HL_{12}) and 5.4% (HL_{13}) in comparison to HL_5, which had the same CSA size but no filler additives. Results indicated that 20% metakaolin offered greater compressive strength than 20% powdered limestone. In addition to the presence of 5% silica fume and 2% nano silica as cement substitute, mix HL_9 had roughly 33.33% more CSA content than HL_5. However, HL_9 had a strength that was equivalent to that of HL_5. A high strength of 36 N/mm^2 was attained as a result of the filler effect, which was 2.8% lower than HL_5. This could be owing to the presence of 33.33% higher CSA content than HL_5.

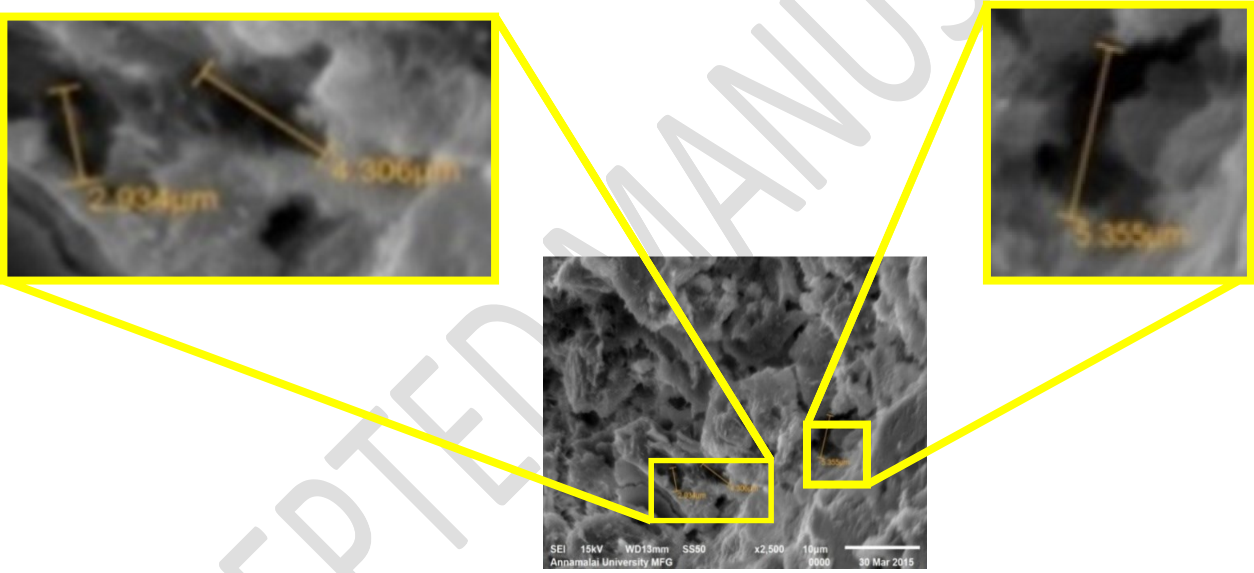
There was less cement content used indeveloping mix HL_7, which nonetheless had 28-day strength of roughly 33.5N/mm^2 and was close to higher strength (34 to 64 N/mm^2). This is an increase of 25% from the value found by Gunasekaran et al., (2011) and 15.5% from the base mix (HL_0). When comparing two mixes with the same amount of cement, CSA size in HL_2 ranged from 4.75 to 9.5 mm, CSA in HL_7 ranged 3.5 to 6.5 mm, an increase of 34%. The compressive strength of the HL_2 mix, however, was roughly 31.25 N/mm^2 after 28 days, making it competitive with the HL_7. When contrasting the HL_3 and HL_5 mixes, it became clear that the HL_3 mix included 14.3% less water and 2.5% more sand than the HL_5 mix. The potential power of HL_3 mix was reduced because of the lower w/b ratio. However, the compressive strength in 28 days of the HL_3 mix was around 13% lesser than that of the HL_5 mix. It is possible that the weakness is due to the bigger size CSA employed in the HL_3 mix as opposed to the HL_5 mix. HSLWC standards are also met by the HL_6 mix.

3.5 Micro-structural behavior of CSC

The micro-structure of CSA and CSC was examined through a SEM. Figure 6 shows the SEM images of CSA and CSC with and without the addition of any mineral admixtures. The image reveals the presence of gaps between CSC and matrix. This is an indication of the formation of weak interfacial transition zone. The production of C-S-H gel was also less that led to lesser compressive strength of concrete. On the other hand, C-S-H gel was well formed with fewer pores in the concrete with mineral admixtures. Further, the formation of C-S-H gel was more. The higher C-S-H gel formation led to the increase in compressive strength of the concrete. The distance between the cement paste and the CSA is roughly 2.934 – 5.355µm for CSC with SF. According to Gunasekaran et al. 2012, the distance between CSA and cement paste is between 24.94 and 26.63µm for CSC without any mineral admixtures. This comparison demonstrates that the addition of SF to lightweight CSC reduces porosity and increases the concrete's strength.



(a) CSA **(b) CSC**



(c) CSC with SF

Figure 6.SEM images ofCSC

4. Conclusion

The use of natural aggregate in high strength concrete has always been the objective of various researchers to ensure the use of sustainable natural materials and minimize the use of natural recourses. This study confirmed that the use of CSA has effectively enhanced the strength as well as reduced the density of the HSC. Based on this experiment the following conclusions have been drawn.

- High strength CSC can be developed conforming to LWC specifications. When the largest CSA size was increased from 9.5mm to 12.5mm, the concrete slump decreased slightly. The combination with the coarser fine aggregate achieved the highest slump value, 130mm.
- In accordance with ASTM C330, the 28-day air dry density of HSCSC is below the LWC standard for structural use. The maximum density of the coarser fine aggregate mixture was at 1996 kg/m^3.
- High values of UPV for HSCSC, which varied from 3.730 to 4.128 km/s, indicate that the developed CSC is of high quality. With an R^2 of 0.8532, an empirical connection between UPV and 28-day compressive strength was found.
- A range of 29–43.6 N/mm^2 is achieved for the compressive strength of CSC after 28 days. 80 to 93 percent of the full 28-day strength was achieved after seven days. The results on the impact of CSA size on compressive strength exhibits that stronger bonding between the aggregate and the paste lead to greater compressive strength when the CSAs were smaller.
- The optimal compressive strength of the mixture containing the coarser fine aggregate was attained after 28 and 56 days, with 43.6 and 47N/mm^2 respectively. These values suggest that it is possible to produce M40 grade CSC by using coarser fine aggregate.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request

Funding Statement

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Conflict of interest

The authors don’t have any conflict

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