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Engineering and Durability Properties of Modified Coconut Shell Concrete

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Abstract

Making low-cost concrete from coconut shell ash and coconut shell aggregate increases sustainability and reduces pollution. This research investigates untreated Coconut Shell Particles (CSP) incorporated with coconut shell ash (CSA) to improve the durability properties at elevated temperatures and in sulphuric acid. Initially, the physical and mechanical properties of cube and cylinder specimens after 7, 28, 56, and 90 days of moist curing were studied. The durability properties were then carried out after the pozzolanic component of CSA in modified concrete was activated. CSA and CSP were used as partial substitutes for ordinary Portland cement and coarse aggregate in class 30 concrete with a constant water to cement ratio of 0.55. Concrete mixes included control, 5% CSP, 10% CSA, and a mixture of 5% CSP incorporated with 10% CSA. According to test results, adding 10% of CSA to CSP concrete decreased the workability, density, and water absorption properties compared to the rest of the concrete mixes. However, these results were within acceptable limits. The compressive strength of 10% CSA concrete at 90 days of moist curing was reduced by 3.23% when 5% CSP was added compared to control. The addition of 10% of CSA to 5% CSP concrete improved the split tensile strength by 2.76% higher than concrete with only 5% CSP. Concrete containing the combination of 10% CSA and 5% CSP showed a 9.37% increment in the split tensile strength compared to concrete having only 5% CSP after sulphuric acid exposure. Also, the compressive strength of 10% CSA and 5% CSP concrete improved by 30.7% when the temperature was elevated to 500 °C for 1 hour compared to the control concrete. Moreover, the reduction in the compressive strength after exposure to the elevated temperature of 500 °C for 1 hr. was still much less by an average of 75.38% compared to other waste materials blended into the concrete by previous works.

Keywords: Control Concrete; Coconut Shell Particles; Coconut Shell Ash; Compressive Strength; Split Tensile Strength.

1. Introduction

Concrete materials are frequently employed in the construction industry. Ordinary Portland cement (OPC) is usually expensive, a critical concrete component of concrete, and produces CO_2 [1]. The cement industry has reduced cement output and partially replaced cement with alternative cementitious materials due to environmental and social concerns about sustainability and energy conservation. Partially replacing cement with materials with the required qualities can help to conserve natural resources while lowering CO_2 emissions [2]. Waste materials in concrete make it more affordable and decrease dumping issues, making it a more environmentally acceptable waste disposal method [3]. Pozzolans are among the most widely used waste materials to improve concrete properties. Pozzolans are inorganic

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compounds that harden when treated with calcium hydroxide $Ca(OH)_2$ in the presence of water [4]. The pozzolanic reaction has been described as delayed, and the resulting strength growth and heat of hydration production have likewise been described as slow [5]. Calcium silicate hydrates (C-S-H) are formed when dissolved Ca_2+ ions provided by cement react with dissolved SiO_2 [6, 7].

Concrete elements, such as foundations, are vulnerable to sulfuric acid invasion from groundwater and acid rain [8]. Acid assault has a negative impact on concrete due to the dissolving effect caused by hydrogen ions [9]. Leaching of calcium sulphate [10], generated during the attack of sulphuric acid on calcium hydroxide, causes concrete specimens to lose strength, weight, and diameter. The brittle silica gel that forms due to the reaction with calcium silicate hydrates (C-S-H) is destroyed. The calcium sulphate produced in the initial response reacts with cement (calcium aluminate) to form the calcium aluminate phase. As a result, strength loss, concrete disintegration, cracking, and concrete expansion occur [10]. The addition of pozzolanic materials such as fly ash has increased the durability of concrete when exposed to sulphuric acid [11]. Pozzolans combine and stabilize the calcium hydroxide produced during the hydration of cement in concrete, resulting in the formation of additional cementitious compounds, primarily calcium silicate hydrate (CSH). The resulting binder matrix is more chemically resistant due to the denser microscopic pore structure [12]. The acid attack is slowed in concrete with mineral admixtures [13, 14]. Roy et al. [14] investigated the acid resistance of mortars using silica fume, metakaolin, and low-calcium fly ash. The addition of silica fume yielded the best results in terms of chemical resistance. In another study by Koushkbagh et al. [15], rice husk ash (RHA) concrete decreased calcium hydroxide content, which increased its acid resistance. Regin et al. [16] investigated the effect of high-volume mineral admixtures on treated lightweight coconut shell concrete exposed to sulphuric acid and reported that less strength and weight loss were observed when 10% fly ash was added.

During construction and service life, the ambient temperature of concrete structures is generally anticipated to be at room temperature. The safety of these structures regarding room temperature levels is addressed by current design and building guidelines [17]. When the ambient temperature rises dramatically or fluctuates regularly, the design strength of the structure is frequently compromised [18]. Concrete mechanical and physical properties are affected by high temperatures, resulting in the progressive disintegration of the C-S-H gel structure, lower durability, increased drying shrinkage, structural cracking, and associated aggregate color changes [19]. An increase in temperature has a minor influence on concrete strength up to around 250 degrees Celsius, but over 300 degrees Celsius, a significant loss of strength occurs [20]. Osuji et al. [21] investigated the effect of high temperatures on normal concrete and found that a peak loss of 53.47% in compressive strength was found at a temperature of 300 degrees Celsius. Asadi et al. [22] published a review of the heat conductivity of several types of concrete. The thermal conductivity of concrete was affected by a number of parameters, including its density, the type of aggregate used, the humidity level, the type of cementitious material used, and the temperature. Thermal conductivity was decreased when lightweight porous aggregate was used in place of standard aggregate in concrete [22]. Sukontasukkul et al. [23] studied the thermal properties of lightweight concrete with a high proportion of phase change materials (PCM), concluding that the parameters improved as the percentage of PCM aggregate increased. Mathew et al. [24] reported that compressive strength and density decreased as the fraction of lightweight porous coconut shell aggregate increased. Gunasekaran et al. [25] studied a change of color and compressive strength reduction of coconut shell concrete when the temperature was increased.

Coconut shell is a biodegradable organic material. Improving concrete performance with coconut shells as an aggregate in an aggressive environment becomes a significant area of interest for many researchers. It is also evident that many researchers have utilized fly ash and silica fume to improve the durability of lightweight concrete, with limited studies on the use of CSA to improve the durability of normal-weight concrete. CSA is substantially less expensive than fly ash and silica fume, making it a more cost-effective way to increase the durability of concrete. The effect of sulphuric acid and varying high temperatures versus time on the durability properties of untreated coconut shell particles in concrete modified with coconut shell ash is still not clear. As part of its commitment to sustainability, the building sector should examine advances in engineering and durability properties when exposed to extreme environments. Therefore, the key contributions of this research include:

- Investigation of the engineering properties of untreated CSP modified with CSA in concrete;
- Examination of the durability properties of untreated CSP modified with CSA in concrete subjected to 5% sulphuric acid solution;
- Assessment of the durability properties of untreated CSP modified with CSA in concrete exposed to high temperatures of 100-500℃ for 1-3 hours.

2. Materials and Methods

2.1. Methodology Flowchart

Figure 1 highlights the chronological steps that were followed to achieve the research objectives.

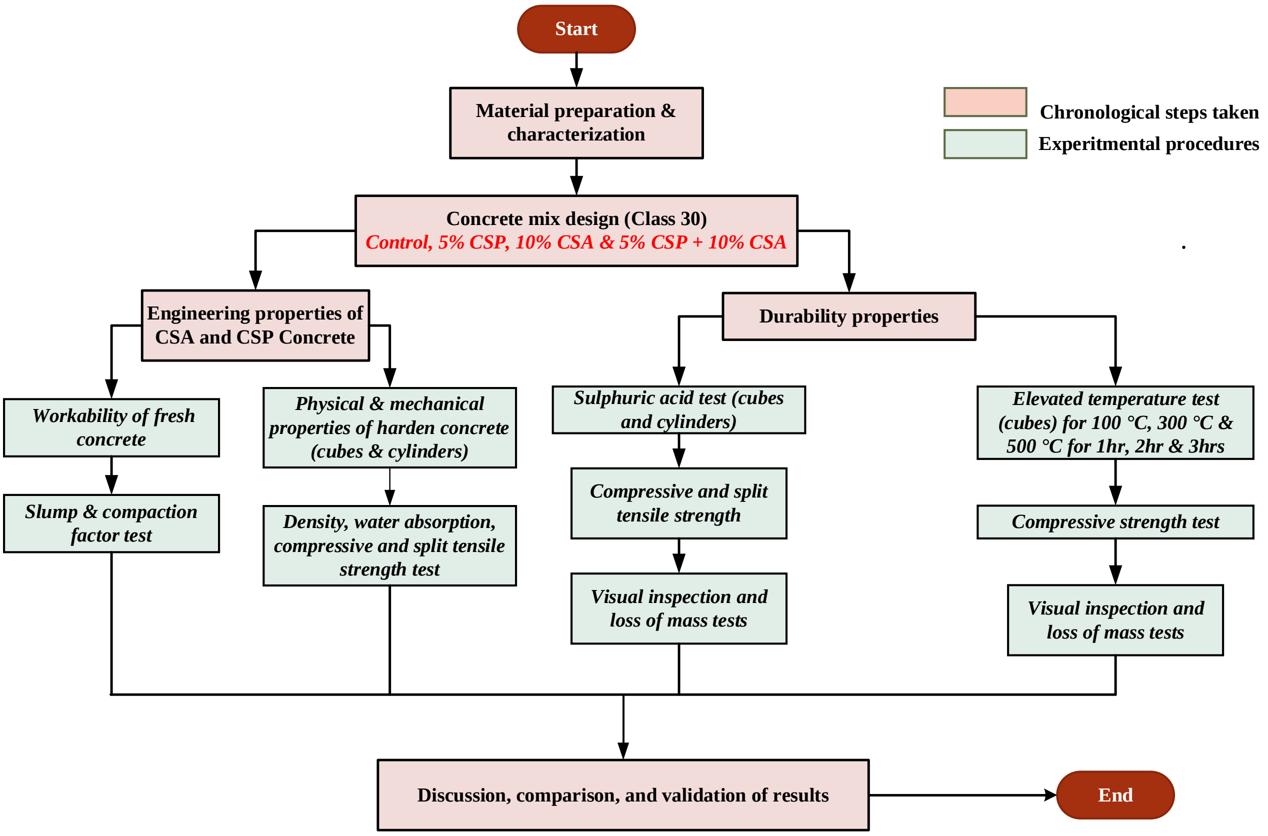

Figure 1. Methodology flow chart

2.2. Material Properties

The cement used was Ordinary Portland Cement (OPC) class 42.5, which met the BS EN standard requirements [26]. The OPC had a specific gravity of 3.11, which was satisfactory. CSA was sieved with the aid of 0.075 mm sieve and had the specific gravity of 2.06. CSA specific gravity was less than 2.4, making it a lightweight material [27]. In Table 1, the chemical compositions of OPC and CSA are listed. As shown in the table, the sum of (SiO_2 + Fe_2O_3 + Al_2O_3) in CSA was greater than 70%, which met the ASTM C618 standards for Class N pozzolan and cementing agent in concrete. The CSA was then utilized to replace cement in concrete manufacturing partially. Crushed stone as coarse aggregate with a maximum size of 20 mm and natural sand as fine aggregate was used conforming to the standard [28, 29], respectively. Fine aggregates had a specific gravity of 2.57 and a 2.14% water absorption, while coarse aggregates had a specific gravity of 2.53 and a 3.33% water absorption. In an aggressive environment, CSP may decay over time. Coconut shell particles pretreatment in an aggressive solution was not considered because the research was primarily focused on examining coconut shell particles that had not been pretreated. The specific gravity and water absorption of CSP with a maximum size of 20 mm were 1.28 and 29.67%, respectively. CSP was utilized as a partial substitute of coarse aggregate in concrete. Figures 2 to 4 show fine aggregates, coarse aggregates, and CSP grading, respectively. Table 2 summarizes the characteristics of the aggregates employed in this study. Figures 5 and 6 depict the CSA and CSP preparation processes.

Table 1. Chemical composition of Portland cement and coconut shell ash

Composition	OPC (%)	CSA (%)
SiO_2	25.17	52.55
AL_2O_3	5.64	13.74
Fe_2O_3	2.63	7.65
Cao	61.86	3.55
MgO	-	1.60
Na_2O	0.08	0.47
K_2O	0.65	2.35
MnO	0.02	0.08
SO_3	2.79	0.57
Loss on ignition	2.81	7.69

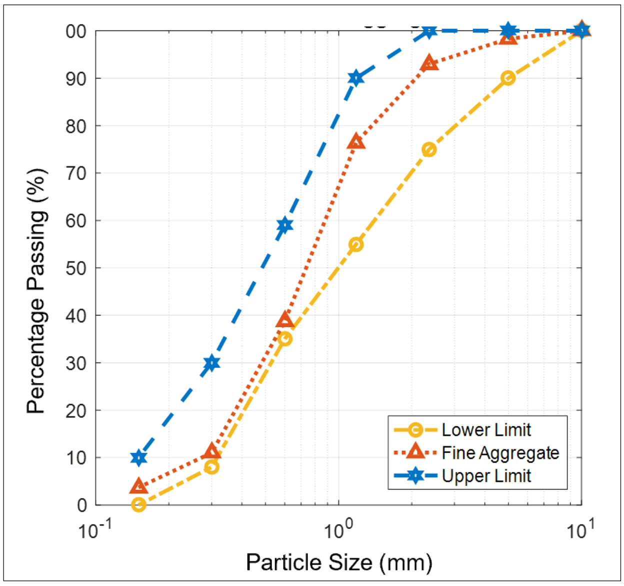

Figure 2. Fine Aggregate Particle Size Distribution

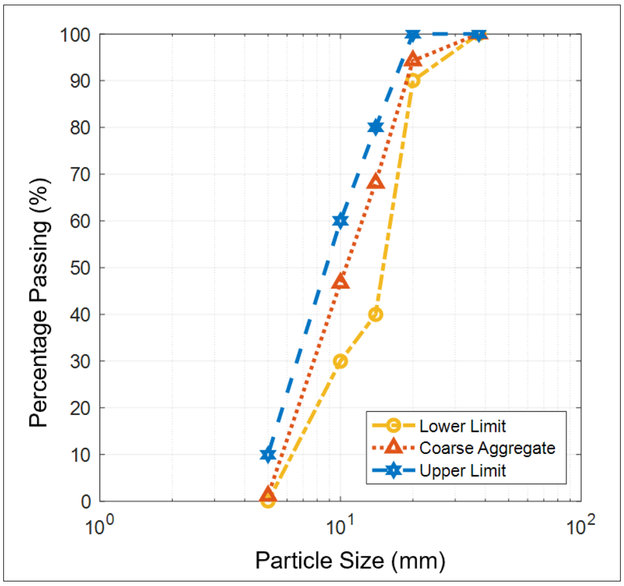

Figure 3. Coarse Aggregate Particles Size Distribution

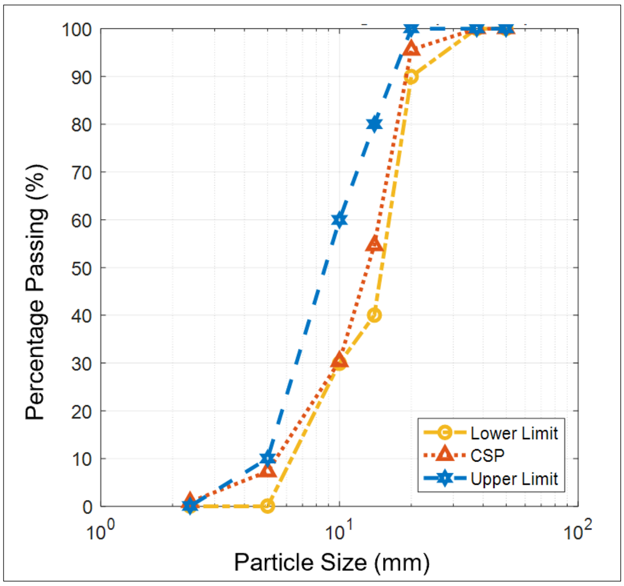

Figure 4. Coconut Shell Particles Size Distribution

Table 2. Aggregate Properties

Properties	FA	CA	CSP
Specific Gravity on SSD	2.57	2.53	1.28
24 hr. Water Absorption (%)	2.14	3.33	29.67
Bulk Density Compact (Kg/m^3)	1,609.11	1457.05	514.8
Bulk Density Loose (Kg/m^3)	1,579.91	1389.35	501.2
Percentage of Void (%)	39.61	39.79	50.04
Aggregate Crushing Value, A.C.V. (%)	--	16.74	2.62
Fineness Modulus	2.78	--	--
Silt Content (%)	2	--	--
Aggregate Impact Value, A.I.V. (%)	---	12.69	8.14

(a) Open Air Combustion (b) Furnace Combustion (c) CSA

Figure 5. Preparation of Coconut Shell Ash

(a) Crushing (b) Sieving (c) Graded CSP

Figure 6. Preparation of Coconut Shell Particles

Figures 7 shows Ordinary Portland cement and coconut shell ash (CSA) images obtained using the scanning electron microscopy (SEM) technique. The SEM method was used to determine the roughness and shape of the particle surface. This technique evaluates materials' shape, formation, and size by probing them onto a scale [30, 31]. CSA material has larger pores and a finer particle shape than OPC, enhancing water absorption in fresh concrete, increasing setting time, affecting the water-to-cement ratio, lowering slump, and increasing cement paste consistency [32]. Consequently, due to its particle fineness, CSA in concrete is recommended to reduce slump and decrease the water absorption of hardened concrete.

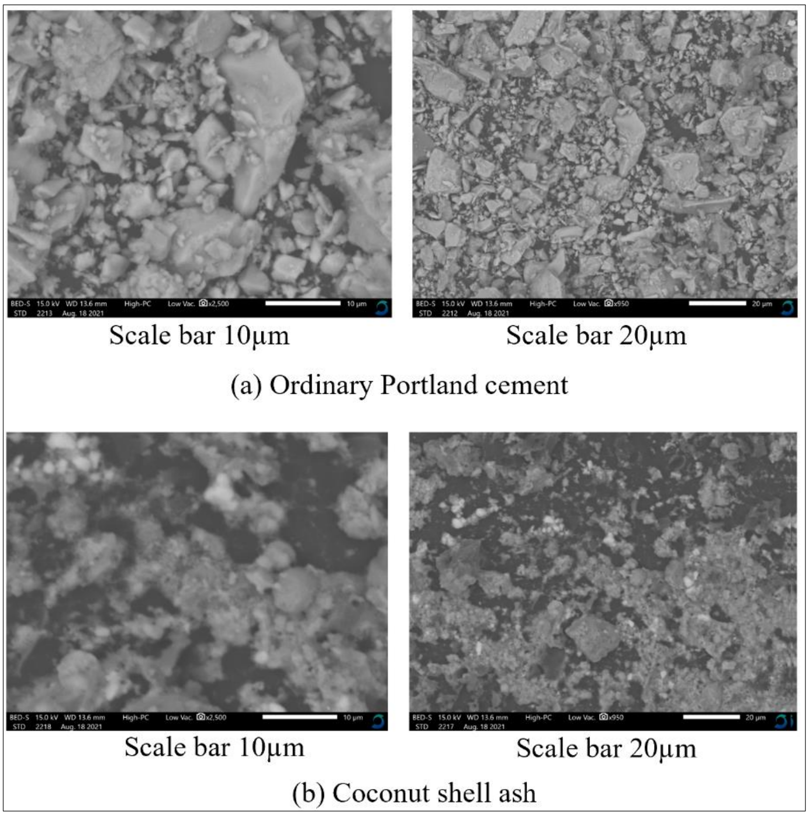

Figure 7. SEM of OPC and CSA

2.3. Mixing and Casting of Samples

According to the British Research Environment (BRE), class 30 concrete mix was used. Table 3 shows the concrete mix design. Preliminary trial mixes were conducted before the mix design for class 30 was adopted. According to the findings, fresh Concrete with slump values of 30 to 60 mm at the constant water-cement ratio of 0.55 was utilized. Control concrete, mix with 5% coconut shell particles (CSP5), mix with 10% coconut shell ash (CSA10), and mix with the combination of 10% coconut shell ash and 5% coconut shell particles (CSA10&CSP5) were the four mixes used in the study. On 100×100×100 mm cubes and a cylinder sample of 100 mm diameter × 200 mm long cured in water for 7, 28, 56, and 90 days, density, water absorption, compressive, and split tensile strength tests were performed. The slump and compaction factor tests were done conforming to BS 1881-102 & 103 [33, 34].

Table 3. Mix Proportion

Mix ID	Cement (Kg/m^3)	C.S.A. (Kg/m^3)	Sand (Kg/m^3)	Crushed stone aggregate (Kg/m^3)	C.S.P. (Kg/m^3)	Water to cement ratio (w/b)
Control	381.82	0	759.44	1048.7	0	0.55
CSP5	381.82	0	759.44	996.26	52.44	0.55
CSA10	343.64	38.18	759.44	1048.7	0	0.55
CSA10&CSP5	343.64	38.18	759.44	996.26	52.44	0.55

2.4. Testing of Samples Exposed to Sulphuric Acid

The durability of control and modified concrete were measured on cubes and cylinders following ASTM [35] to determine its resistance to sulfuric acid invasion. Three cubes and three cylinders specimens each of control, 10% CSA, 5% CSP, and the combination of 10% CSA and 5% CSP were submerged in a 5% sulfuric acid solution after 56 days of moist curing (Figure 8-b). Before immersion, initial weights and diameters of specimens were measured. Following [36], the total duration for immersion in sulfuric and moist curing was one hundred twelve (112) days. Stirring the solution once a week helped to ensure that the sulphuric acid was distributed uniformly. Twenty-four (24) samples were removed from the sulfuric acid solutions after the 112 days. The loose components were alleviated by gently washing sulfuric acid-exposed samples with portable water (Figure 8-c). The samples were then exposed to a 50% relative humidity setting for 24 hours. The acid invasion on cubes and cylinders, followed by weight loss and strength loss, was measured using a weighing balance and universal testing machine (UTM). Measurements with a vernier caliper captured cylinder diameter reductions, which supported the results of weight and strength losses. Visual inspection also compared the samples' resilience to sulphuric acid attacks.

Figure 8. Conducting durability test for concrete samples exposed to sulphuric acid

2.5. Testing of Samples Exposed to High Temperatures

The cube specimens from the control concrete and the combination of 10% CSA and 5% CSP were placed in an electric furnace after 56 days of moist curing. They were heated to targeted temperatures until their residual properties were investigated. Cube specimens were put in a furnace and heated to 100° C, 300° C, and 500° C, respectively. For each temperature, the time was varied for 1, 2, and 3 hours respectively. After heating, the samples were allowed to cool at room temperatures to avoid cracking due to temperature differences.

After cooling, the samples were reweighed and examined for any damage that may have occurred after exposure to high temperatures. The weights recorded were then utilized to calculate the overall percentage of weight loss due to elevated temperature and the change in color due to the temperature effect. With the aid of a compressive strength testing machine, the compressive strength of each cube sample after exposure to high temperatures was determined. Finally, the results of heated samples were compared to the unheated samples (control and modified concrete).

3. Result and Discussion

3.1. Effect of C.S.A. and C.S.P. on Engineering Properties

3.1.1. Workability of Fresh Concrete

As seen in Figure 9, the recorded slump varied from 36 to 55 mm. The slump value was within the 30 to 60 mm mix design range. On the other hand, the compaction factor assessed the compatibility properties of fresh Concrete. Compaction factor values obtained from the study ranged from 0.87 to 0.93. If the results obtained are within the limits of 0.7 to 0.98, compaction factor measurement can be used to determine concrete workability [37].

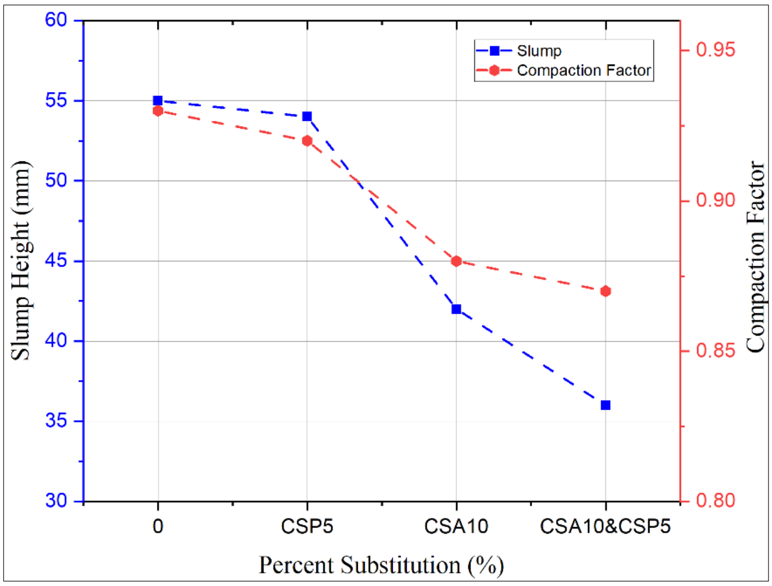

Figure 9. Workability of CSA and CSP Concrete

Reduced workability for the fixed water-cement ratio was observed due to the inclusion of 10% CSA and 5% CSP in concrete production. Figure 9 depicts the workability of control, CSP5, CSA10, and the combination of CSA10 and CSP5 concrete. When 10% CSA was added to 5% CSP concrete, there was a further decline in concrete workability compared to control and other individual percent substitutions. One possibility is that the influence of CSA is to blame because of its fineness and ability to fill gaps between the cement particles [38]. More so, CSP's low specific gravity, which necessitates the utilization of more surface area, can also reduce concrete workability. Additionally, CSP's high water absorption and porous characteristics necessitate more water for increased workability [39]. According to Adajar et al. [40], the absorbent characteristic and particle fineness of CSA may have also contributed to the loss in workability. Various pozzolanic components, including CSA, stiffen concrete mixtures [41], which may have led to a further decline in workability. As illustrated in Figure 9, the 10% CSA had a more effect on lowering the slump and compaction factor than the 5% CSP. This is owing to the higher proportion of CSA in concrete than CSP.

3.1.2. Density of Hardened Concrete

Concrete density reduction is advantageous in cost, thermal characteristics, and fire resistance [42]. Figure 10 illustrates the density of the concrete mixes. The combined addition of 10% CSA and 5% CSP lowered the density of the concrete more than the other substitution. After 56 days of moist curing, the density of concrete containing 10% CSA and 5% CSP was roughly 4.8% lower than the control, 3.03% lower than 10% CSA, and 0.05% higher than 5% CSP substitution. Compared to control and 10% CSA concrete, the combined inclusion of 10% CSA and 5% CSP resulted in a proportional decrease in concrete density. The low specific gravity of the CSA and CSP, as evident by section 2.2, is responsible for concrete density reduction. The behavior of the concrete density obtained in this research followed similar behavior to those of Iffat (2015), Kanojia & Jain (2017) & Gunasekaran et al. (2011) [43-45].

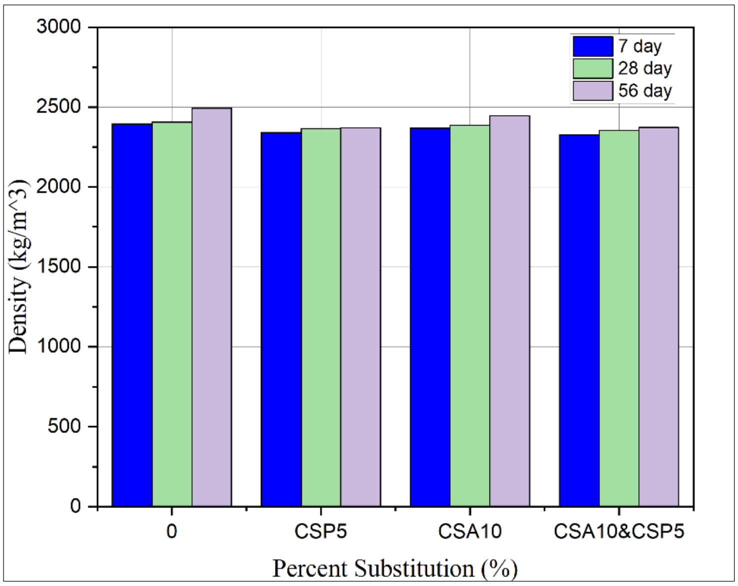

Figure 10. Density of C.S.A. and C.S.P. Concrete

Several studies have also indicated that replacing cement and coarse aggregate with supplemental materials reduces density [41, 46–49]. More so, it is essential to note that the density of all the concrete studied in this research was above 2000 kg/m^3 making them all normal weight concrete. The introduction of CSA and CSP reduced concrete density, demonstrating that they are feasible materials that may be utilized to replace cement and coarse aggregate when concrete constructions need to be lighter to save cost.

3.1.3. Water Absorption of Hardened Concrete

Water absorption findings of coconut shell ash concrete comprising shell particles and various individual percent replacements are shown in Figure 11. According to the results, replacing cement and coarse aggregate with 10% CSA and 5% CSP decreased water absorption by 10.5% compared to the control concrete. Concrete containing 10% CSA yields the lowest water absorption, which is 21.1% lower than control concrete. It is also clear that adding 10% CSA in 5% CSP concrete reduced the water absorption to 19.04% compared to 5% CSP concrete. The low water absorption is due to the CSA fineness, which decreases concrete pores [50]. Figure 11 also shows that individual substitutions of 5% CSP increased water absorption to 9.6% compared to control concrete. The water absorption capacity of CSP concrete was improved by adding 10% CSA. The behavior of CSP in concrete, where it absorbs a large volume of water, is consistent with previous research [51]. The surface area of CSP in the mix increases is responsible for this phenomenon. More specifically, the water absorption test revealed the absorbent nature of coconut shells particles, as evident by Table 2. Hence, all of the results meet the British Standard [52] requirements for water absorption not exceeding 20%.

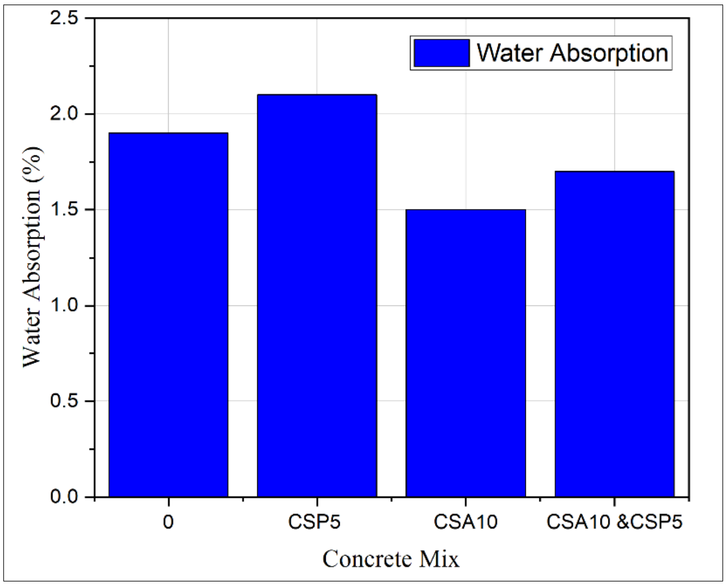

Figure 11. Water absorption of control and modified concrete at 28 day

3.1.4. Compressive Strength of Hardened Concrete

As seen in Figure 12, the compressive strength of all mixes increased with age. At 28, 56, and 90 days, the compressive strength of the combination of 10% CSA and 5% CSP is 30.82%, 39.54%, and 40.39%, respectively, higher than at 7 days. At 28, 56, and 90 days, the compressive strength of the individual mixtures of 10% CSA, 5% CSP, and control concrete is: 30.95%, 35.73%, and 37.63%; 30.1%, 33.43%, and 33.61%; 28%, 28.69%, and 28.88%, respectively, higher than that of the seven (7) day strength. Beyond 28 days, it is obvious that concrete containing CSP and CSA grows in compressive strength more than control concrete. The continuous hydration of Portland cement and the CSA-delayed pozzolanic reaction result in a denser microstructure. Coconut shell particles collect water and hold it in their pore structures, which act as reservoirs for long-term concrete curing and strength development [39].

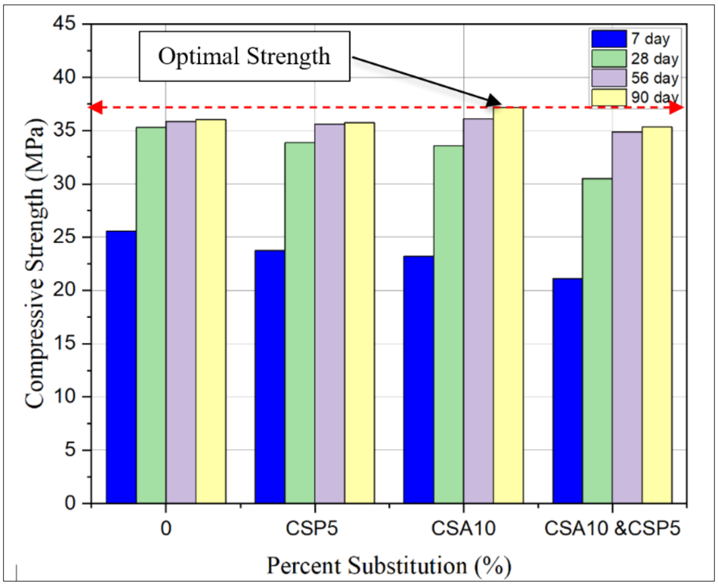

Figure 12. Compressive strength of C.S.A. and C.S.P. concrete

It is also worth noting that concrete with 10% CSA had the optimal compressive strength compared to control, 5% CSP, and the combination of 5% CSP and 10% CSA after 56 and 90 days of curing. This is because of $Ca(OH)_2$ reaction with SiO_2 was triggered beyond the 28-day curing period, thus releasing a large about of C-S-H gel. The compressive strength of the combination of 10% CSA and 5% CSP was slightly lower than control at 56 and 90 days of curing. The majority of the blame lies with the high flakiness index and failure of the link between the coconut shell aggregate and the hardened cement paste. Compared to control concrete, the combined inclusion of 10% CSA and 5% CSP resulted in compressive strength of 35.4 MPa, which was 3.23% lower than control concrete after 90 days. The compressive strength output obtained in this research differ from those of Tomar et al. [53], who studied the comprehensive study of waste coconut shell aggregate as raw material in concrete. The difference is due to the existence of the CSA SiO_2 compound, which combines flawlessly with cement-free lime, and the amount and size of coconut shell particle gradation, which occupies less surface area, thus making a workable concrete. The result is also consistent with those of Mo et al. [54], who studied the properties of metakaolin-blended with oil palm shell lightweight concrete, but this research focused on incorporating 10% CSA in concrete with a low volume of untreated CSP.

3.1.5. Split Tensile Strength of Hardened Concrete

Figure 13 illustrates the overall effect of 10% CSA and 5% CSP content, as well as individual substitutions, on split tensile strength at various ages. Split strength increased with age in all combinations, comparable to compressive strength. This can also be linked to the binder component's continual reaction with water in the composite. In addition, Figure 13 shows that after 56 and 90 days of moist curing, the optimum concrete mix was 10% CSA. The split tensile strength of all the concrete increased after 28, 56, and 90 days. Following 90 days of curing, concrete with 10% CSA had a higher split tensile strength of 5.4% than control concrete. The result of the split tensile strength followed similar behavior of the result obtained by Subasi [55], who studied the effect of fly ash on high strength lightweight concrete by varying the cement content but differ with the level of improvement due to less content of CSP used.

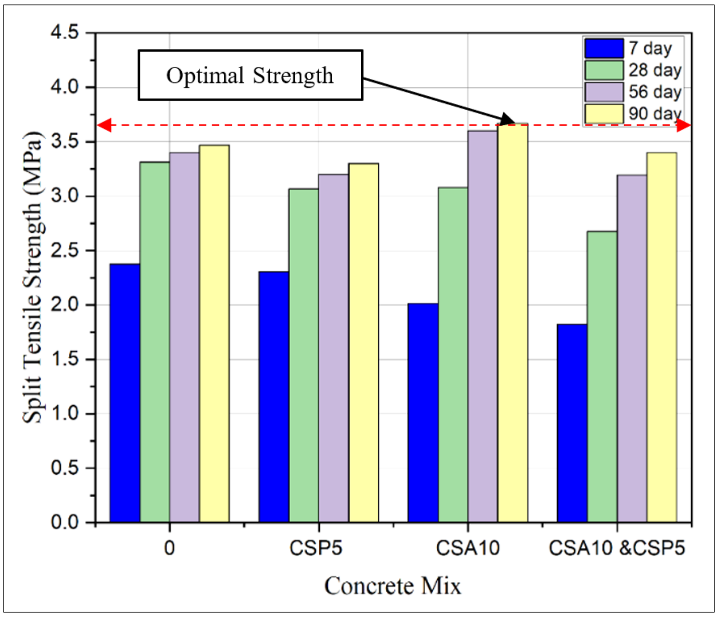

Figure 13. Split tensile strength of control and modified concrete

Moreover, after 90 days of curing, the split tensile strength of 5% CSP and modified concrete (5% CSP and 10% CSA) were lower than control by 5.71% and 2.94%, respectively. This is because the smooth texture of the interior portion of the coconut shell particles results in a weaker inter-particle connection during the formation of mechanical strengths [45, 56]. As a result, the key variables for lightweight concrete are lower stiffness and strength [53]. Adding 10% of CSA in concrete containing 5% of CSP improved split tensile strength 2.76% higher than 5% CSP concrete. Again, modified concrete containing the combination of 10% CSA and 5% CSP can perform well when subjected to tensile stress, making it a viable alternative for reducing the rapid depletion of raw materials.

3.2. Effect of Sulphuric Acid on the Durability Properties of Control and Modified Concrete

3.2.1. Compressive and Split Tensile Strength

Figure 14 shows the compressive strength of control and modified concrete mixes after exposure to sulphuric acid. Differences in compressive strength of 20.5, 17.83, 23.25, and 15.19 MPa were recorded for control, CSP5, CSA10, and CSA10+CSP5 concrete mixes after submerged in sulphuric acid solution, respectively. After being subjected to sulfuric acid, the compressive strength of control, CSP5, CSA10, and CSA10+CSP5 were reduced by 43.5%, 49.9%, 35.6%, and 54.8%, respectively. Furthermore, the compressive strength of modified concrete containing CSA10+CSP5 was the lowest. The inclusion of 5% CSP contributed to the decrease in compressive strength. The split tensile strengths of cylinder specimens exposed to sulphuric acid are shown in Figure 15. Control, CSP5, CSA10, and CSA10+CSP5 all had a reduction in split tensile strength of 38.24%, 50%, 33.33%, and 40.63%, respectively. It was also noted that 5% CSP in 10% CSA reduced the split tensile strength. The loss of strength was attributed to the pores present in CSP and the increased waster absorption, as evident by Figure 11.

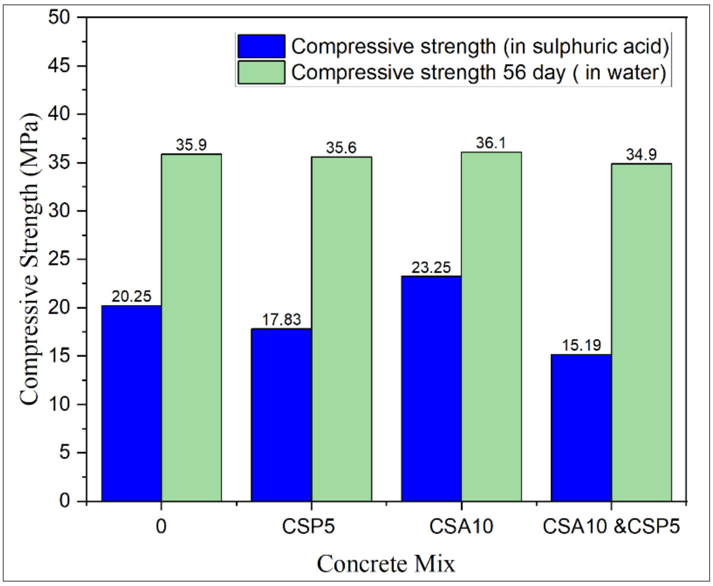

Figure 14. Compressive strength of samples subjected to sulphuric acid vs. 56-day compressive strength

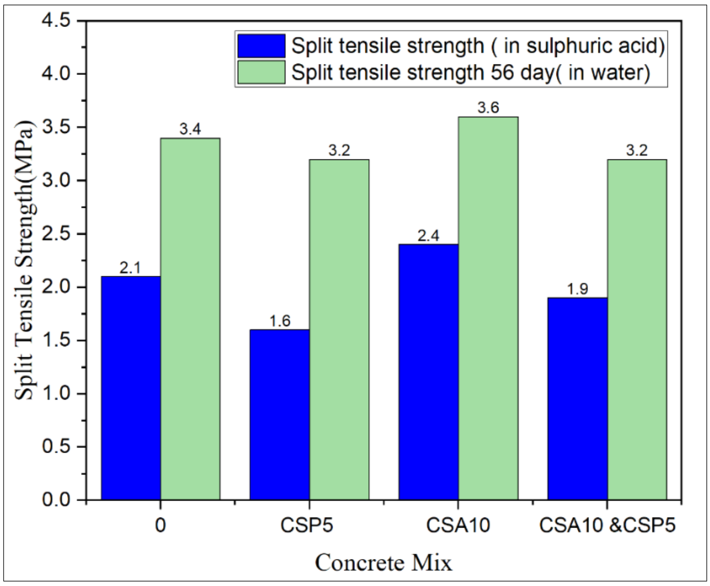

Figure 15. Split tensile strength of samples subjected to sulphuric acid vs. 56-day split tensile strength

Moreover, Figure 14 and 15 also shows that concrete with 10% CSA has higher compressive and split tensile strength than control concrete, with a 12.8% and 12.5% increase in compressive and split tensile strength compared to control. The amount of water that concrete absorbs affects its durability. As indicated in Section 3.1.3, 10% CSA had the lowest water absorption value of all the concrete mixes. According to the findings of a recent study by Rao [57], less water absorption can ensure enhanced concrete durability. Pozzolans react and solidify the calcium hydroxide $Ca(OH)_2$ released during cement hydration in concrete to form additional cementitious compounds, principally calcium silicate hydrate (CSH), which may account for the increase in strength in sulfuric acid [11]. Due to the filling effect, the acid attack is slowed in concrete with mineral admixtures [58, 59]. The results obtained in this study are consistent with those obtained by Roy et al. [14], who studied the acid resistance of mortars with silica fume, metakaolin, and low-calcium fly ash. The result also collaborates with [16, 60]. After sulphuric acid exposure, concrete consisting of a mixture of 10% CSA and 5% CSP showed a 9.37% increase in split tensile strength compared to concrete containing only 5% CSP. The addition of 10% CSA can be credited for this improvement.

3.2.2. Weight and Diameter Losses

Weight losses of specimens subjected to sulphuric acid for control and other concrete mixtures are shown in Figure 16. The diameter losses have been given in Table 4. Weight loss improves sulfuric exposure in samples containing 10% CSA, which means that the sulphate resistance was improved when 10% CSA was added. Concrete with only 5% CSP substitution lost more weight than concrete containing 10% CSA and control concrete. When 5% CSP was added to concrete containing 10% CSA, significant concrete deterioration was observed, resulting in weight and dimension losses.

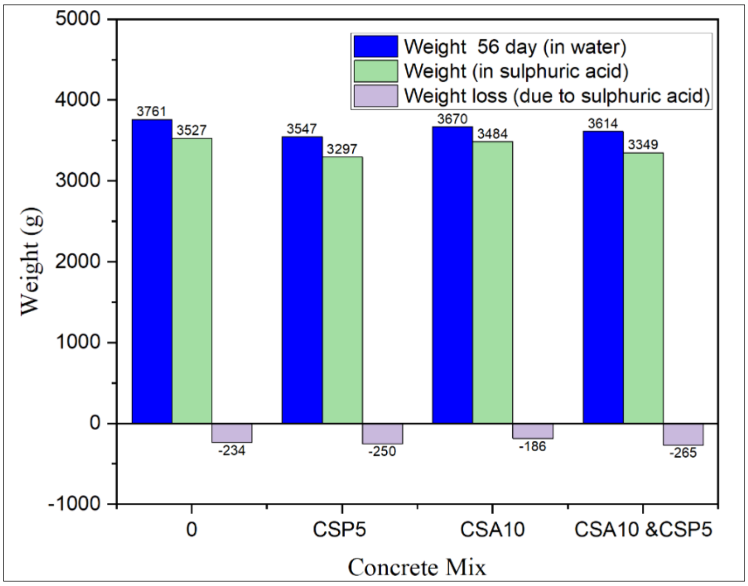

Figure 16. Weight loss of control and modified concrete placed in sulphuric acid

Table 4. Average Weight loss and Diameter loss for control and modified Concrete after cylinder specimens exposure to sulphuric acid

Specimen Identification	Weight before placing in acid (kg)	Weight after placing in acid (kg)	Weight loss (kg)	Diameter loss (mm)
		Control		
CA	3.759	3.56	0.199	-2
CB	3.703	3.551	0.152	-1.5
CC	3.822	3.471	0.351	-2
Average	**3761**	**3.527**	**0.234**	**-1.8**
		10% CSA		
CSA10 A	3.697	3.506	0.191	-1
CSA10 B	3.693	3.541	0.152	-1
CSA10 C	3.62	3.405	0.215	-1.5
Average	**3670**	**3484**	**0.186**	**-1.2**
		5% CSP5-20 mm		
CSP5-20 A	3.56	3.23	0.330	-2.5
CSP5-20 B	3.53	3.34	0.190	-2.5
CSP5-20 C	3.55	3.32	0.230	-1.5
Average	**3547**	**3297**	**0.250**	**-2.2**
		10% CSA + 5% CSP5-20 mm		
CM A	3.66	3.382	0.278	-2.5
CM B	3.572	3.364	0.208	-3
CM C	3.611	3.301	0.310	-1.5
Average	**3614**	**3349**	**0.265**	**-2.7**

The weight and diameter losses of concrete specimens subject to sulphuric acid can be used to evaluate the degree of failure of structures in such an environment [61, 62]. As a result, it's critical to comprehend concrete's behavior when submerged in sulphuric acid. The introduction of 10% CSA improved weight and diameter losses in this investigation, which were attributable to pozzolanic response and micro-aggregate filling [63]. Weight and diameter losses were found to be slightly lower when 5% CSP was added to 10% CSA concrete, as shown in Figure 16 and Table 4, because of the poor bonding of the inner section of the coconut shell particles and their enhanced water absorption.

3.2.3. Visual Inspection

Images of the durability samples for control and modified concrete containing various mixes exposed to sulphuric acid are revealed in Figure 17. Washing the cylinder samples resulted in removing loose particles from the samples' external faces, as was shown in Figure 17. Due to sulphuric acid invasion, the top layer of concrete on all specimens was entirely removed.

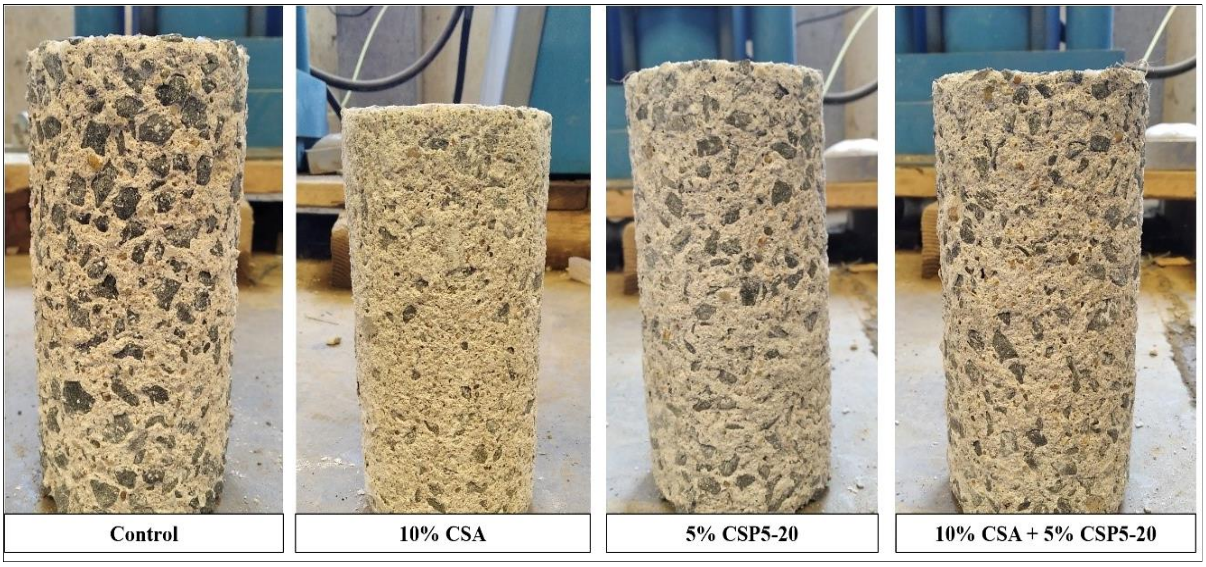

Figure 17. Visual inspection for control and modified concrete samples exposed to sulfuric acid

In comparison to other cylinder specimens, the 10% CSA specimen in Figure 17 appears to have a minor deterioration on the surface compared to the rest of the samples. The increased resistivity is due to the increased C-S-H gel produced during the pozzolanic reaction [64] and the low water absorption of 10% CSA concrete. When exposed to weakly acidic conditions, C-S-H releases a large amount of lime while leaving strong silica and alumina silicate layer that protects the cement paste from further corrosion [65]. In contrast, due to decalcification of C-S-H and dissolution of $Ca(OH)_2$ and calcium sulphoaluminates, concrete containing 100% Portland cement forms a porous deteriorated layer [64].

3.3. Effect of High Temperature on The Durability Properties of Control and Modified Concrete

3.3.1. Compressive Strength

Control and modified concrete (10% CSA and 5% CSP) cubes specimens subjected to no temperature had compressive strengths of 35.9 MPa and 34.9 MPa, respectively, after 56 days of full water curing. Specimens were also evaluated for residual compressive strength after being exposed to elevated temperatures versus time. The control and modified concrete cubes' compressive strength were decreased by 1 hour, 2 hours, and 3 hours at 100, 300, and 500 °C, respectively, as shown in Figure 18. After one hour, two hours, and three hours of exposure to 100°C, control concrete cubes lost 5.57%, 12.17%, and 18.11% of their strength, respectively, whereas modified concrete cubes lost 10.23%, 12.72%, and 20.08% of their strength. After 1 hour, 2 hours, and 3 hours at 300 °C, control concrete cubes lost 14.76%, 19.78%, and 28.97% of their strength, respectively, while modified concrete lost 26.05%, 17.74%, and 30.32%. After one hour, two hours, and three hours at 500°C, control concrete cubes lost 38.55%, 47.54%, and 56.27% of their strength, respectively, while modified concrete lost 8.42%, 43.21%, and 52.64%. Under 300 °C, the temperature has less influence on the compressive strength of both control and modified concrete, according to the strength reduction captured in Figure 18. The findings are consistent with those of Shetty [60], who stated that while temperature has a minimal effect on concrete strength up to roughly 250 degrees Celsius, temperatures above 300 °C result in a significant loss of strength. Compared to modified concrete, control concrete experienced a lower strength reduction at 100 °C. In both concrete, the compressive strength reduction was greater at 300 °C for 1 hour, 2 hours, and 3 hours than at 100 °C for the same duration. At this temperature, internal thermal stress develops around the pores, which causes small cracks to form. The dissociation of portlandite could also cause this loss of $Ca(OH)_2$ into CO_2 and CaO, as well as its expanding rehydration [66]. Another explanation could be the disintegration of the C–S–H gel, which at high temperatures decomposes into - C_2S [67].

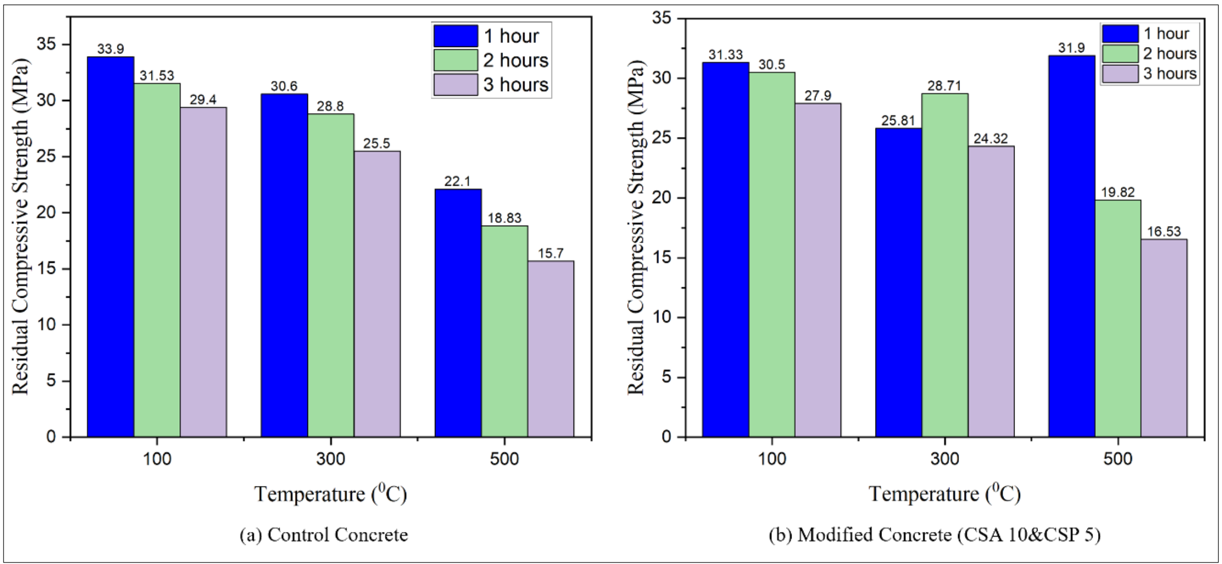

Figure 18. Residual compressive strength of control and modified concrete

Furthermore, it was discovered that modified concrete with a combined inclusion of 10% CSA and 5% CSP concretes outperformed the control concrete at 300 and 500 °C for 1 hour, 2 hours, and 3 hours. In addition, at 500°C for 3 hours, concrete with 10% CSA and 5% CSP increased by 5.02% compared to control. The results obtained are comparable with [68, 69]. The increased strength is most likely due to the pozzolanic influence during the hydration process, which results in a huge number of C–S–H, which is responsible for strength growth [68]. More so, CSA functions as a micro filler, strengthening the system's microstructure [58].

The compressive strength of the modified concrete also decreased with increasing fire duration. The void generated by the burning of coconut shell particles in the modified concrete (Figure 19-b) and the breakdown of the C-S-H gel in the control concrete (Figure 19-a), which appears as a light gray powder, may explain the devastation caused by high temperatures on both concrete.

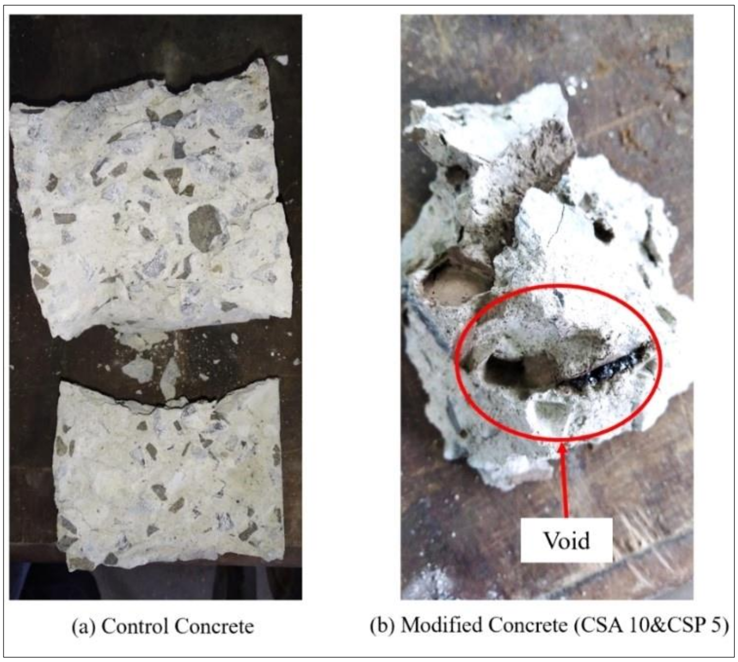

Figure 19. Crushed cube samples after exposure to high temperature

Table 5 compares the compressive strength results obtained in this study for concrete containing 10% CSA and 5% CSP to those obtained in earlier investigations. The proposed methodology indicates a 66.08%, and 80.37% less reduction in the compressive strength at 500 °C for 1hr compared to the use of neem seed husk ash and fly ash in concrete [68, 69], respectively. Incorporating a small quantity (5%) of untreated CSP in CSA concrete can still significantly enhance concrete durability.

Table 5. Comparison of compressive strength reduction to previous literature

Reference	Concrete Mix	Temperature (°C)	Time (hr.)	Before (MPa)	After (MPa)	Reduction in strength (%)
Proposed	10% coconut shell ash & 5% coconut shell aggregate	500	1	34.9	31.9	8.5
Proposed	10% coconut shell ash & 5% coconut shell aggregate	500	3	34.9	16.53	52.6
[25]	Coconut shell aggregate (full replacement)	400	3	26.8	5.30	80.2
[59]	Coconut shell aggregate (full replacement)	500	0.5	24	16	`33.3
[68]	10% Neem seed husk ash	600	1	27.3	20.3	25.6
[69]	25% Pulverized fly ash	650	1	60	34	43.3

3.3.2. Weight Loss

For the determination of weight loss, cube samples of control and modified (10% CSA and 5% CSP) concrete cubes sample weight were taken before and after introduction to extreme temperatures. Figure 20 illustrates the significant weight loss compared to the original weight of control, and 10% CSA blended with 5% CSP concrete samples fully cured for 56 days with increasing exposure to high temperature at 1hr, 2hrs, and 3hrs. It is evident from Figure 20 that both concrete samples investigated showed a gradual percent loss in weight.

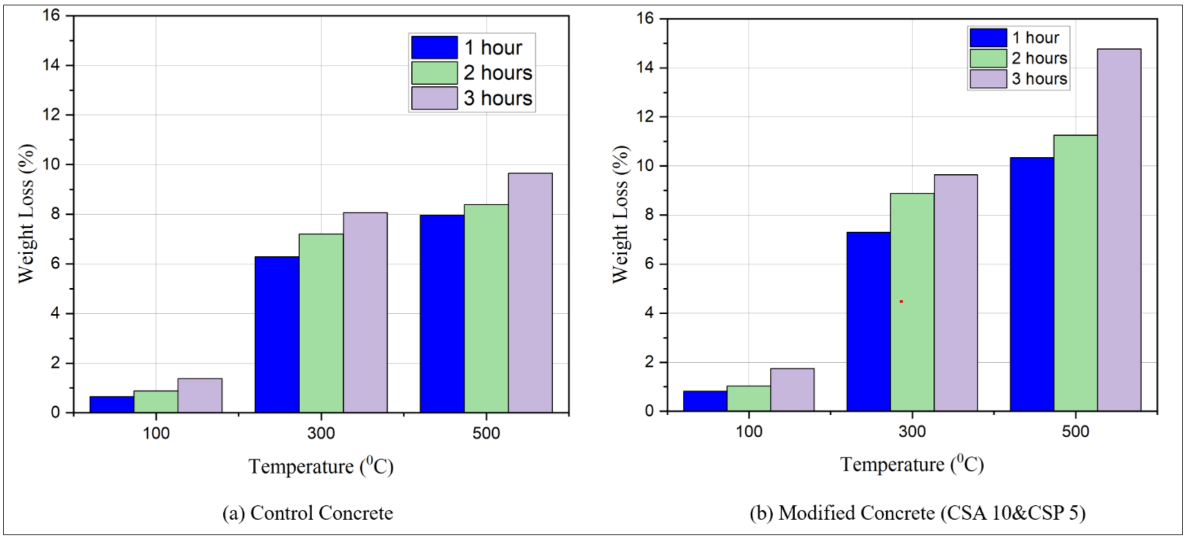

Figure 20. Weight loss in percent after exposure to high temperature

The percent loss in weight for both samples increased when the temperature and time increased. At 100 ^{0}C for 1, 2 and 3 hours, there was a percent loss in mass of 0.65%, 0.88% and 1.38% for control and 0.82%, 1.03%, and 1.74% for modified concrete, respectively. Both concrete showed a small percentage of mass loss at this level of time versus temperature. There was a significant percentage of weight loss in control and modified concrete at temperatures ranging from 300°C to 500°C for 1hr, 2hrs, and 3hrs. The weight loss is caused by $Ca(OH)_2$ breakdown, which results in the loss of both free and bound water due to increased temperatures. Modified concrete containing 10% CSA and 5% CSP had a higher percentage of mass loss, especially when the temperature was increased to 500 ^{0}C. The burning, spalling, and disintegration of CSP leave some holes in concrete Gunasekaran et al. [25]. This investigation's findings also support those of Fares et al. [70], who testified that at 300ºC, more than 70% of the water in the concrete, both free and bound, escapes.

3.3.3. Visual Inspection

The impairment of control and modified concrete cubes exposed to elevated temperatures was comprehensively evaluated, with observed alterations to the concrete specimens' surface. In analyzing the damages of fire on cube samples, visual observation of color changes was considered. Figure 21 illustrates the physical properties of concrete at various durations versus temperatures at 300 and 500°C. Neither the control nor the modified concrete changed color when heated to 100ºC for 1 to 3 hours. The color of the modified concrete has altered slightly more than control at 300ºC for 2 and 3 hrs, respectively. Internal concrete cracking and spalling could have begun at this temperature for both concrete. The change of color in both concrete became more noticeable at 500°C for 2 and 3 hours, particularly the modified concrete when the time was increased. The deterioration behavior is linked to the generated pore pressures and crack growth, influenced by the heating rate and the heterogeneous concrete's composition [68]. The early color change of modified concrete can be attributed to the burning of coconut shells in concrete. No exterior cracks were seen at 500°C for 2 to 3 hours. The lack of an external crack is due to the temperature not exceeding 500 degrees Celsius because the furnace used for the experiment had a low heating capacity.

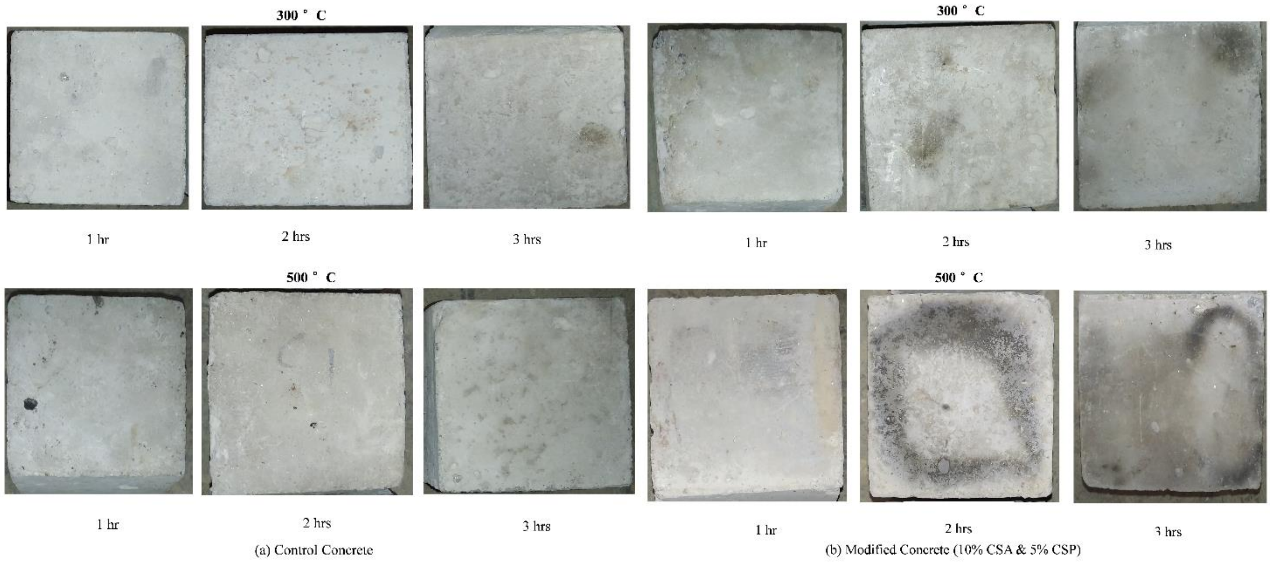

Figure 21. Control and modified cubes at 300, and 500°C for 1, 2 & 3 hrs. duration

4. Conclusions

From the investigations carried out in this work, the following conclusions can be made:

- The addition of coconut shell ash in coconut shell particle concrete reduced the workability of fresh concrete compared to control, 5% CSP, and 10% CSA concrete.
- Adding 10% CSA to 5% CSP concrete enhanced density by 0.05% at 56 days and reduced water absorption by 19.04% and 9.52%, respectively, when compared to 5% CSP and control concrete.
- The compressive strength of all mixes increased with curing age. The compressive strength of 10% CSA concrete at 90 days of moist curing was reduced to 3.23% when 5% CSP was added compared to control due to the flakiness index and smooth texture of the CSP inner part and increased water absorption. Adding 10% of CSA to concrete containing 5% of CSP improved split tensile strength by 2.76% higher than 5% of CSP concrete due to its decreasing pores in concrete fineness and increased hydration products.
- Concrete with 10% CSA showed considerable gains in compressive strength and split tensile strength compared to conventional concrete, and the rest of the other concrete mixes placed sulphuric acid. Moreover, concrete containing the combination of 10% CSA and 5% CSP showed a 9.37% increase in split tensile strength compared to concrete having only 5% CSP after sulphuric acid exposure.
- Concrete with 5% CSP lost more weight than concrete with 10% CSA and control concrete. Significant concrete deterioration was seen when 5% CSP was added to 10% CSA concrete, resulting in weight and dimension losses. Incorporating 5% CSP with 10% CSA also underperformed the control concrete in terms of strength and diameter losses due to the weak bonding of the coconut shell particles' interior section, and it increased water absorption.
- Due to sulphuric acid invasion, the top layer of concrete on all specimens was destroyed, except 10% CSA, which appears to have little surface damage compared to the other samples.
- Under 300 °C, the temperature has little effect on the compressive strength of both control and modified concrete. The compressive strength for modified concrete (10% CSA and 5% CSP) performed better when the temperature was increased to 500 °C.
- The compressive strength of 10% CSA and 5% CSP concrete improved by 30.7% when the temperature was elevated to 500 °C for 1 hour compared to the control concrete. Modified concrete had more weight loss and a change in color than control concrete due to the burning and disintegration of CSP.

To better understand and improve the engineering and durability properties of untreated coconut shell particles in concrete modified with coconut shell ash, a comparable experiment using self-compacting concrete with superplasticizer is recommended for future studies. Also, due to the study scope, the microstructure of untreated coconut shell particles in concrete modified with coconut shell ash at high temperatures and in sulphuric acid was not explored. Nevertheless, microstructure behavior can be incorporated in future studies.

5. Declarations

5.1. Author Contributions

Conceptualization, T.C.H., J.N.T. and T.N.; T.C.H.; formal analysis, T.C.H.; writing—original draft preparation, T.C.H.; writing—review and editing, J.N.T. and T.N.; supervision, J.N.T. and T.N. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding and Acknowledgements

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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