

## Article

# Innovative Eco-Friendly Concrete Utilizing Coconut Shell Fibers and Coir Pith Ash for Sustainable Development

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**Abstract:** Concrete is the most commonly used and essential material in the construction industry, and it is also the most widely utilized product globally. The construction industry is a rapidly expanding industry. To improve the efficiency and strength properties of concrete, researchers from all over the world continue to search for supplementary cementitious materials (SCMs) and industrial by-products that can be incorporated as alternative materials. The current study aimed to determine the effects of partially substituting coir pith ash (CPA) for cement in coconut shell concrete, in addition to utilizing steel and coconut fibers. Various percentages of CPA were used to replace cement in the concrete mixes, ranging from 5% to 20% by cement weight. Steel fibers were utilized in this study at volume ratios of 0.25%, 0.5%, 0.75%, and 1.0%, and coconut fibers were utilized at volume ratios of 0.1% to 0.5% with an increment of 0.1% in the concrete to achieve the desired results. Various properties have been examined, such as workability, mechanical, durability, and morphological tests. The addition of coir pith ash to concrete increased its compressive, flexural, and tensile strengths by 10.36%, 8.75%, and 7.7% at 28 days compared to control concrete. The incorporation of coconut fiber and coconut shell in concrete production improves its performance and strength while also preserving natural resources and offering a solution to the problem of disposing of solid waste.

**Keywords:** coir pith ash; coconut fiber; coconut shell; steel fiber



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## 1. Introduction

Cement is the primary component in concrete, which is one of the most widely used building materials worldwide [1]. As demand increases in response to the expanding need for concrete worldwide, the use of cement is currently increasing at a rate of about 9% on an annual basis [2]. The production of cement employs a variety of raw resources and contributes significantly to greenhouse gas emissions. Current research has concentrated on strategies to lower the world's cement consumption in order to lower carbon emissions. Coir pith ash (CPA) is the by-product of the continuous global burning of millions of tons of coir fiber.

Alternate supplementary cementitious material such as coconut shell ash [3], hypo sludge [4–6], bagasse ash [7], rice husk ash [8], fly ash [9,10], and eggshell [11] has been previously employed in concrete and showed better performance at optimal percentage. According to a previous investigation [12], the agro waste product coir pith ash has demonstrated the effectiveness of CPA in the production of concrete. Sumesh et al. observed that using CPA as SCM in concrete had a positive impact on the mechanical properties [13]. An increase in concrete compressive strength of less than 20% CPA was observed to have a positive effect, according to Balagopal and Viswanathan [14]. Retaining people's capacity to solve problems in the future while meeting present demands for housing, infrastructure, and a workplace is the aim of sustainable construction [15]. The shifting to lightweight aggregate from normal-weight aggregate concrete has become an emerging source due to its

enhancing strength and structural performance [16]. The concept of producing lightweight concrete (LWC) by using lightweight aggregates like foamed slag and coconut shells has been promoted in the research field in tandem with the endeavor to realize sustainable construction [17]. Lightweight concrete (LWC) offers many well-known benefits, including lower dead load, which eventually permits increased flexibility and decreased cost of structural parts and foundation construction [18,19]. An additional benefit of LWC generated from waste materials is the use of alternative materials to replace these traditional materials, as the misuse of virgin minerals has created an ecological imbalance [20].

Over the past 20 years, many studies have focused on the utilization of coconut shell (CS) as an aggregate of lightweight for the development of lightweight coconut shell concrete [21,22]. In comparison to lightweight concretes, coconut shell concrete exhibits similar durability characteristics, including resistance to elevated temperatures, efficiency in absorbing chloride, color changes, and the volume of porous voids [23]. Coconut shell concrete beams exhibited behavior that was comparable to that of regular concrete when they were subjected to torsion. Coconut shell concrete exhibits mechanical properties and fracture resilience that are quite similar to those of lightweight concrete [24]. Using fibers is one more technique for enhancing the ductility and tensile strength of lightweight concrete, as it is well known that the incorporation of fibers into concrete improves flexural strength and other important properties. It is well-recognized that fibers enhance flexibility and post-cracking behavior. The purpose of fibers in fiber-reinforced concrete (FRC) is to improve performance by means of fiber–cement matrix interfacial bonding and crack bridging [25]. According to a recent study, adding glass fiber, natural fibers, or nylon to lightweight concrete can strengthen it and reduce stresses like tensile and shear that appear at different cross-sections [26]. A variety of applications have been predominantly replaced by materials derived from natural fibers [27] due to the numerous benefits of natural fibers, which include their abundant availability, biodegradability, lightweight nature, affordability, and ease of production. Many researchers have studied coconut fiber in an effort to improve concrete's performance by employing it as a fiber-reinforcing material [28]. Furthermore, coconut fibers reduce the weight of concrete while simultaneously improving its tensile, flexural, and compressive strengths due to their low heat conductivity, strength, and stiffness [29].

The production of coconut is high in Erode and Coimbatore district, Tamilnadu. Due to the extensive production of coconuts, it is highly feasible to obtain significant quantities of coir fiber and coir ash. Coir fiber and coir ash are by-products of the coconut industry. The usage of agricultural products such as coir pith ash and coir fiber promotes sustainability, and environmental pollution will be reduced. Coir pith ash possesses the properties of cement; it is partially substituted for cement in concrete, and it improved its performance. The addition of coir fiber in concrete can improve tensile strength and durability, making it less prone to cracking and structural failure. Utilizing these natural materials promotes sustainable construction methods by lowering reliance on non-renewable resources and reducing the environmental effect of construction activities. It is economically feasible to use coir by-products in buildings as it might lower total costs.

The current study investigates the application of coir pith ash in the production of sustainable, long-lasting concrete with excellent mechanical properties. The primary objective of this study is to ascertain the effects of substituting coir pith ash (CPA), coconut fibers (CF), steel fibers (SF), and cement substitution on characteristics of lightweight concrete, including coconut shells as coarse aggregate. To the best of the author's knowledge, no prior research has been conducted on the addition of coir pith ash to concrete as a replacement for cement, as well as the addition of coconut fibers and steel fibers in lightweight concrete. Much research has been conducted on coconut shell lightweight aggregate with partial replacement of coarse aggregate. The experimental investigations of materials coconut shell ash and coir pith ash have been examined individually. The current research focused on lightweight concrete using coconut shells as a full replacement for coarse aggregate, incorporation of coir pith ash with natural fiber as coir fiber, and inorganic fiber as steel

fiber in concrete. Thus, in order to assess its strength properties, the current study uses CPA as binding materials in percentages of 5%, 10%, 15%, and 20% by weight of cement and coconut fiber percentages of 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% and steel fiber additions of 0.25%, 0.5%, 0.75%, and 1.0%. The authors of this study are attempting to use coconut shell (CS) as a coarse aggregate in the manufacturing of concrete in order to assist the studies that are now accessible on making concrete green and sustainable.

## 2. Experimental Methodology

### 2.1. Materials

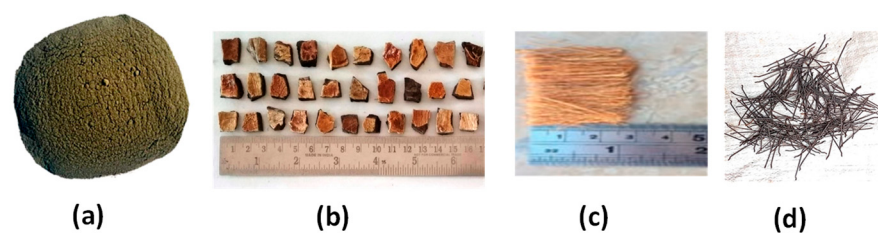
In accordance with IS:12269–2013 [30], Grade 53 Ordinary Portland Cement (OPC) is used in this study. Coir pith ash (CPA), having a specific gravity of 2.2 and passed through 90 microns, is utilized as a supplementary cementitious material. Table 1 displays the chemical characteristics of CPA and cement. River sand that was obtained locally was used for the fine aggregate. According to IS 383:2016 [31], the parameters of the sand were evaluated, and it had a specific gravity of 2.6 and a bulk density of 16 kN/m<sup>3</sup> in Zone II. As a coarse aggregate, coconut shell aggregate weighing 650 kg/m<sup>3</sup> was used. The material employed was a well-graded aggregate of coconut shells with sizes ranging from 4.75 mm to 12.5 mm. The properties of the fibers used, which include both coconut and steel, are displayed in Table 2. To improve workability, Conplast SP430, a superplasticizing admixture, was used. Figure 1 depicts the materials utilized for the investigation.

**Table 1.** Chemical composition of cement and coir pith ash.

| Composition       | SiO <sub>2</sub> | Cao   | Fe <sub>2</sub> O <sub>3</sub> | Al <sub>2</sub> O <sub>3</sub> | MgO  | SO <sub>3</sub> | K <sub>2</sub> O | Na <sub>2</sub> O | TiO <sub>2</sub> | KCL   |
|-------------------|------------------|-------|--------------------------------|--------------------------------|------|-----------------|------------------|-------------------|------------------|-------|
| Cement (%)        | 23.00            | 64.00 | 2.00                           | 4.00                           | 2.00 | 2.00            | 1.00             | 1.00              | -                | -     |
| Coir pith ash (%) | 34.50            | 14.40 | 4.34                           | 1.76                           | 2.84 | -               | 0.50             | 1.00              | 2.76             | 17.38 |

**Table 2.** Properties of steel and coconut fiber.

| Properties    | Length (mm) | Diameter (mm) | Aspect ratio | Tensile Strength (MPa) | Density (kg/m <sup>3</sup> ) |
|---------------|-------------|---------------|--------------|------------------------|------------------------------|
| Steel fiber   | 50          | 1.0           | 1            | 1100                   | 7850                         |
| Coconut fiber | 25          | 0.5           | 0.25         | 405                    | 6800                         |



**Figure 1.** Materials used. (a) CPA, (b) Coconut shell, (c) Coconut fiber, and (d) Steel fiber.

### 2.2. Preliminary Investigation and Mix Proportions

Coconut shell (CS) concrete was made by entirely substituting crushed coconut shells for the coarse aggregate typically used in concrete. The water-to-binder ratio is kept constant at 0.33. To determine the ideal percentage of components, such as coir pith ash (CPA), steel fiber (SF), and coconut fiber (CF), to be added to the final mix for further study, initial investigations have been conducted. Coir pith ash (CPA) is used as a partial replacement for cement in the amounts of 5%, 10%, 15%, and 20%. All percentages of variation in compressive strength have been examined, and an optimized range has been obtained. Coconut fibers have been added to the concrete at a level of 0.1% to 0.5% and steel fibers at a level of 0.25% to 1% at an increment of 0.25%. Table 3 lists the general

characteristics of the final mixes that were identified based on the results and will be investigated further. Table 4 presents the mix proportions of the final mix.

**Table 3.** General characteristics of various mixes.

| S.No | Mix Id   | Description                        |
|------|----------|------------------------------------|
| 1    | CS       | Coconut shell concrete             |
| 2    | CSA10    | CS + 10% CPA                       |
| 3    | CSSF     | CS + 1% SF                         |
| 4    | CSCF     | CS + 0.3% CF                       |
| 5    | CSA10SF  | CS + 10% CPA + 1% SF               |
| 6    | CSA10CF  | CS + 10% CPA + 0.3% CF             |
| 7    | CSA10CSF | CS + 10% CPA + 0.75% SF + 0.25% CF |

Note: CS—coconut shell, SF—steel fiber, CF—coconut fiber, CPA—coir pith ash.

**Table 4.** Mix proportions for 1 m<sup>3</sup> of concrete.

| Mix Id   | w/b  | Coir Pith Ash<br>(kg/m <sup>3</sup> ) | Cement<br>(kg/m <sup>3</sup> ) | FA<br>(kg/m <sup>3</sup> ) | CSA<br>(kg/m <sup>3</sup> ) | SP<br>(%) | Steel<br>Fiber<br>(%) | Coconut<br>Fiber<br>(%) |
|----------|------|---------------------------------------|--------------------------------|----------------------------|-----------------------------|-----------|-----------------------|-------------------------|
| CS       | 0.33 | 0                                     | 510                            | 750                        | 332                         | 1.2       | -                     | -                       |
| CSA10    | 0.33 | 52                                    | 458                            | 750                        | 332                         | 1.2       | -                     | -                       |
| CSSF     | 0.33 | 0                                     | 510                            | 750                        | 332                         | 1.2       | 1.00                  | -                       |
| CSCF     | 0.33 | 0                                     | 510                            | 750                        | 332                         | 1.2       | -                     | 0.30                    |
| CSA10SF  | 0.33 | 52                                    | 458                            | 750                        | 332                         | 1.2       | 1.00                  | -                       |
| CSA10CF  | 0.33 | 52                                    | 458                            | 750                        | 332                         | 1.2       | -                     | 0.30                    |
| CSA10CSF | 0.33 | 52                                    | 458                            | 750                        | 332                         | 1.2       | 0.75                  | 0.25                    |

### 3. Testing Methods

#### 3.1. Fresh Concrete and Mechanical Properties

The workability of the concrete mix in its fresh state can be tested by carrying out a slump test. Hardened concrete property tests such as compressive, split tensile, and flexural strength tests were carried out to analyze the performance of the various concrete mixes. The quality of the concrete is determined by the compressive strength, and it is considered an important factor. Cubes with dimensions of 150 mm × 150 mm × 150 mm are considered for compressive strength determination, prisms with dimensions of 100 mm × 100 mm × 500 mm are considered for flexural strength determination, and tests were carried out as per Indian standard 516-2013 [32]. According to code 5816-1999 [33], split tensile strength tests were carried out on a 300 mm × 150 mm dia cylinder specimen.

For every experimental mix combination for compressive strength, three cubes with dimensions of 150 mm × 150 mm × 150 mm have been placed through testing using a compression testing machine. At a loading rate of 2.3 kN/s, a compression measuring machine with a kN capacity is used. The load is gradually added until the object breaks. To find the ultimate cube concrete compressive strength, divide the ultimate load by the cross-sectional area of the object. At 7 days, 28 days, and 56 days, the concrete's compressive and, at 28 days, flexural, split tensile strength were tested. The ultra-sonic pulse-velocity (UPV) method is one of the well-known non-destructive testing (NDT) methods and is conducted mainly to determine the uniformity and relative quality of existing structures and specimens. The test was carried out with reference to IS: 13311-1992 [34].

#### 3.2. Durability Properties

According to ASTM C-642 2013 [35], cube specimens of 150 mm by 150 mm by 150 mm were tested for water absorption after 28, 56, and 90 days of curing. Higher water absorption results in decreased durability since water includes numerous adverse substances that immerse into the concrete, causing concrete disintegration and resulting in less durability. The capillary movement of water is measured by the sorptivity test, and it

was performed on 150 mm cube specimens as per ASTM C-1585 2013 [36]. The concrete quality for rapid chloride penetration test can be assessed based on the limits and tested as per ASTM C1202 201 [37].

### 3.3. Microstructural Properties

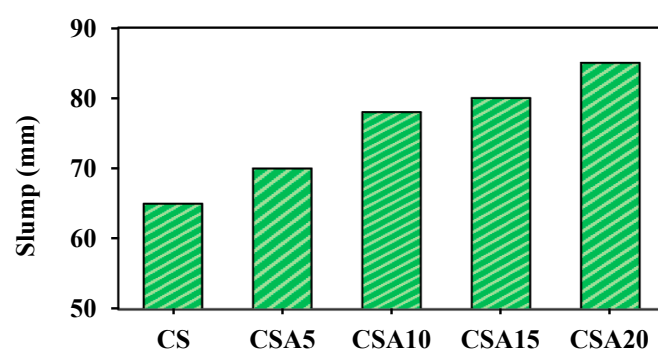
The hardened concrete microstructure has a significant impact on the properties of concrete. The morphology of cementitious composite materials is analyzed using scanning electron microscope (SEM) images. The microstructure of the various mixes at the age of 28 days was observed using a scanning electron microscope, FEG Quanta 250 ESEM. Concrete examples measuring approximately 5 mm × 20 mm × 20 mm were cut with a high-speed marble cutter. To prepare the specimens for analysis, their surfaces were ground using 400, 600, and 1000 grit silicon carbide abrasive sheets and then polished with a sequence of progressively finer grades of diamond paste. This process ensures that the specimen surfaces are flat and clean. A tiny layer of carbon was sputtered onto the polished surface. Every specimen was examined with a scanning electron microscope (SEM) that was fitted with a silicon drift detector.

## 4. Results and Discussions

### 4.1. Mechanical Properties—Preliminary Test Results

#### 4.1.1. Slump Value

Figure 2 depicts the workability of fresh concrete after the addition of coir pith ash. The slump values of mix CS, CSA5, CSA10, CSA15, and CSA20 are 65 mm, 70 mm, 78 mm, 80 mm, and 85 mm, respectively. Compared to control concrete, the mix CSA5, CSA10, CSA15, and CSA20 had an increase in slumps of 5%, 13%, 15%, and 20%, respectively. When compared to CS, the addition of CPA increased the slump value. The partial replacement of cement with coir pith ash enhanced the slump value and, consequently, the workability. The primary factor contributing to the increase in slump values with the addition of CPA may be attributed to the spherical shape of the ash particles, which was validated by the microstructural analysis. Also, the cement particles have oppositely charged surfaces, which prevent ash particles from flocculating, and cement particles are thus distributed in an efficient manner. Similar observations were recorded by previous investigations [38].

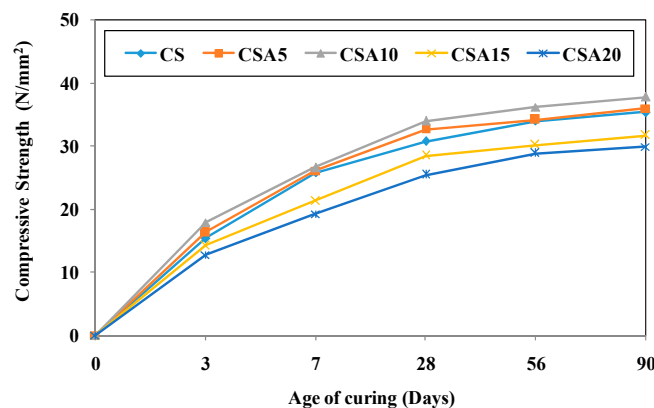


**Figure 2.** Slump value of coconut shell concrete with CPA at various proportions.

#### 4.1.2. Compressive Strength

The compressive strength associated with various curing periods was determined. Figure 3 presents the results of experiments conducted on compressive strength with the addition of CPA at various percentages. Regardless of the curing periods, CSA10 exhibited improved strength compared to all other percentages of CPA in coconut shell concrete. From the results, it is evident that the compressive strength value decreased as the ash content increased beyond 10%. In addition, the strength of the CSA10 mix was significantly higher than that of the control concrete (CS) under prolonged curing conditions. The test results indicate that the CPA has the potential to be used as a supplementary cementitious material (SCM). Various agro-based materials such as rice husk ash, coconut shell ash [3],

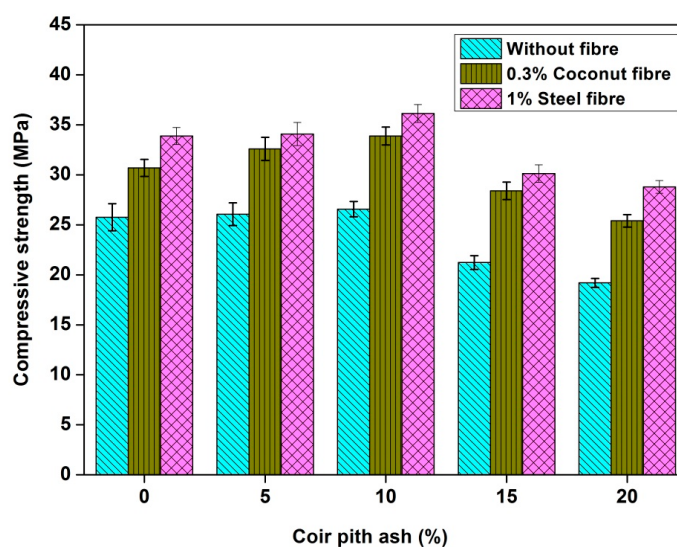
and bagasse ash have already been utilized as SCM in previous research and resulted in enhanced performance in the strength aspects. The optimum dosage of those materials was found to be 15% [39,40]. Even though the addition of CPA improved the strength, the optimum percentage of CPA addition is lower compared to other agro products.



**Figure 3.** Compressive strength of concrete with CPA at various proportions.

#### 4.1.3. Compressive Strength of Concrete with Steel and Coconut Fiber

From the preliminary investigation trials, the addition of steel fiber tends to increase the compressive strength with the addition of 0.25%, 0.5%, 0.75%, 1%, 1.25%, and 1.5%. The compressive strength value of concrete with the addition of steel fiber and coconut fiber optimized percentage with CPA concrete is shown in Figure 4. The increased fiber proportions of the concrete increase its compressive strength. But, beyond the addition of 1% steel fiber, the workability of concrete is reduced. So, the percentage of steel fiber added to concrete is limited to 1% in the coir pith ash. The coconut fibers were added at 0.1% to 0.5%, and the optimized proportion was found to be 0.3%. Beyond the addition of coconut fiber, it showed a reduction in compressive strength. The reduced workability of fresh concrete due to the greater length and higher quantity of fibers, along with improper compaction that led to the production of air voids, could be the reason for the decrease in compressive strength. Compared to steel fiber, the strength of concrete with coconut fiber is reduced. Previous research found that the addition of coconut fiber at 0.25% in concrete improved the concrete compressive strength up to 19% at a 28-day curing period [41].



**Figure 4.** Compressive strength of concrete with steel and coconut fiber at optimized proportions at 28 days.

## 4.2. Optimised Test Results

### 4.2.1. Compressive Strength

The compressive strength of the optimized proportion of materials for all the mixes is shown in Figure 5. Compared to control concrete, the addition of coir pith ash at 10% in coconut shell concrete enhanced the compressive strength by 3.14%, 10.36%, and 11.51% at 7, 28, and 56 days, respectively. The increase in strength is due to the fineness of CPA more than other concrete materials, which fills the gap left by other constituents of concrete. In comparison to that, the addition of steel fibers achieved greater strength of 30.37 MPa, 36.18 MPa, and 41.40 MPa at 7, 28, and 56 days compared to that of coconut fiber-added concrete. Even though the addition of steel fibers attained maximum strength, the strength reduction while using coconut fibers is insignificant. The crack-bridging effect of steel fibers in lightweight concrete (LWC) is a significant mechanism that contributes to the enhancement of compressive strength and overall performance [42]. Steel fibers are often added to concrete mixtures to enhance their mechanical properties. These fibers are typically short, discrete strands of steel dispersed throughout the concrete matrix. Cracks were initiated and propagated through the weak plane of concrete as the compressive stress increased. Because of the inadequate CS–cement mortar bonding, the CS concrete plane was weak. When the fracture extended to randomly distribute steel fiber, the fiber bridging caused the crack to close and transferred the crack edge stress between the fiber–mortar interface bonds, resulting in an increase in compressive strength. Previous investigations have shown that the incorporation of steel fibers into LWC substantially enhances its compressive strength. Similarly, it has been reported that the addition of steel fibers to Oil palm shell concrete (OPSC) also increases its compressive strength [43,44]. Previous studies have shown the use of expanded clay aggregate to increase the compressive strength of LWC [45]. Also, an increment of 23% compressive strength was obtained [46] in LWC using lightweight shale aggregate. According to previous research, fibers increased the compressive strength of concrete up to certain amounts before it lost workability [47].

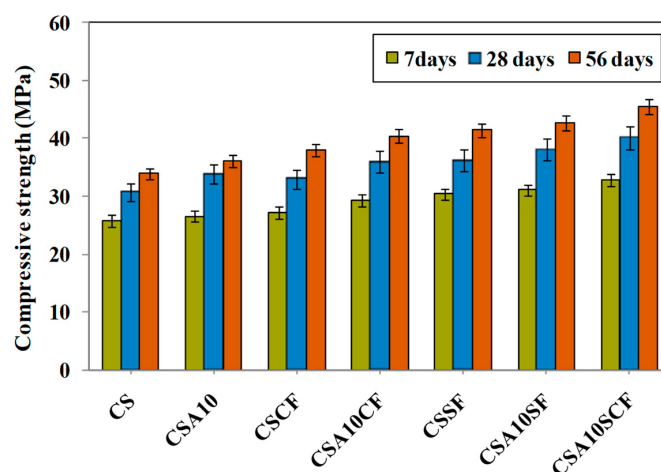


Figure 5. Compressive strength of concrete of various mixes.

### 4.2.2. Split Tensile Strength

The split tensile strength of coconut shell concrete mixes over control concrete at 28 days is presented in Figure 6. Compared to control concrete, the specimens CSA10, CSCF, CSA10CF, CSSF, CSA10SF, and CSA10SCF exhibited increases in split tensile strength of 8.1%, 14.5%, 17.7%, 22.6%, 29.0%, and 32.3%, respectively. The specimens with fibers improved their strength significantly. The addition of fibers considerably increases the splitting tensile strength of LWAC. The addition of coconut fiber in CPA concrete improved the strength by 9% compared to the CPA10 mix. In accordance with the current investigation, splitting tensile strengths of CS lightweight concrete are improved by the addition of fibers. The fiber bridging effect contributes to this improvement in strength, and compara-

ble outcomes were noted. The addition of steel fiber significantly improved the concrete splitting tensile strength. There was a more significant enhancement in splitting tensile strength with the inclusion of fiber. When high tensile stress was applied to plain concrete, micro cracks first appeared, then macro cracks. The failure resulted from the crucial crack spreading to the macro crack tips as the applied stress increased. The random distribution of steel fibers delayed the advancement of the macro crack by distributing tensile stresses throughout it; thus, the concrete's splitting tensile strength improved [48].

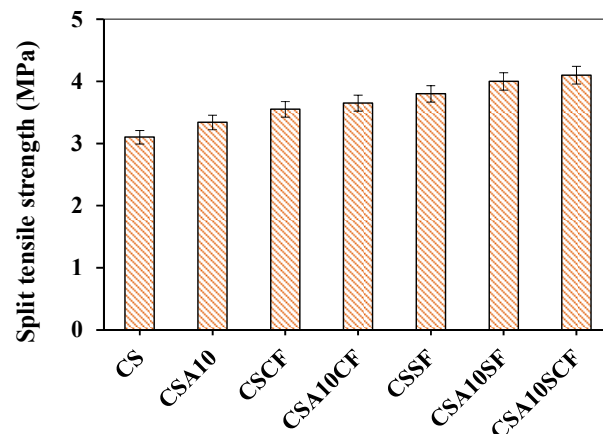


Figure 6. Split tensile strength of concrete of various mixes at 28 days.

#### 4.2.3. Flexural Strength

The flexural strength of all mixes at 28 days is shown in Figure 7. With the addition of coir, pith ash improved the strength by 8.75% compared to control concrete. The specimens CSCF, CSA10CF, CSSF, CSA10SF, and CSA10SCF improved the flexural strength by 10.5%, 13.75%, 16.25%, 20%, and 22.5%, respectively, compared to CS concrete. Incorporating steel fibers into the mix imposed its exceptional strength. The flexural behavior of concrete has been observed to be significantly impacted by the addition of steel fiber [49]. Steel fibers are responsible for this improvement because they effectively limit the spread of cracks [50]. The strength of CPA10 increased by 5% with the addition of coconut fiber. However, this improvement was negligible. Coconut fibers improve flexural capacity by minimizing fractures from developing. The load is directly transferred to the coconut fibers due to the interfacial between the concrete components and the fibers. Coconut fibers allow the fracture to flow around the fibers and transmit the tension, preventing cracks from breaking. Consequently, in 28 days, the strength was increased by 11.25% with the addition of steel fiber to CPA10. The observed enhancement in flexural strength relative to tensile strength in mixtures reinforced with CS fibers appears to be the result of fracture bridging.

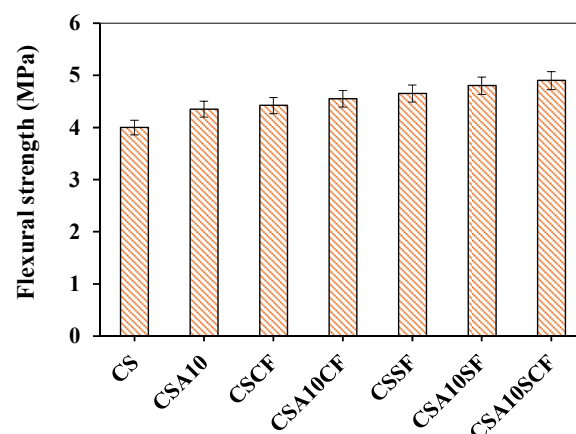


Figure 7. Flexural strength of concrete of various mixes at 28 days.

Figure 8 displays a regression model that relates compressive and flexural strength. The  $R^2$  value is about 94%, which shows that there is a significant relationship between compression and flexural strength. A greater  $R^2$  value signifies a more robust correlation between the two variables.

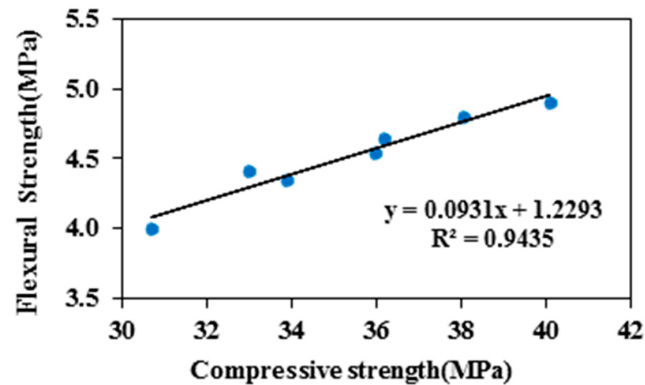


Figure 8. Correlation between flexural and compressive strength.

#### 4.2.4. Ultrasonic Pulse Velocity

The homogeneity and integrity of the concrete can also be predicted by the UPV test. In comparison to the CS mix, the CSA10 exhibits the greatest UPV values at 3.9 km/s. This may be attributed to the addition of coir pith ash, which increases the mix's compressive strength and prevents any discontinuities. Hence, the UPV of concrete is helpful to assess its compressive strength. Concrete having UPV values between 3.66 and 4.58 km/s seemed to be in good condition (Table 5). The relation between UPV and compressive strength is shown in Figure 9, and a correlation coefficient of 0.921 was obtained.

Table 5. UPV of optimized mix combination.

| S.No | Mix Id   | UPV<br>28 Days | Compressive<br>Strength<br>28 Days |
|------|----------|----------------|------------------------------------|
| 1    | CS       | 3.70           | 30.70                              |
| 2    | CSA10    | 3.90           | 33.88                              |
| 3    | CSSF     | 3.95           | 32.98                              |
| 4    | CSCF     | 4.00           | 35.97                              |
| 5    | CSA10SF  | 4.10           | 36.18                              |
| 6    | CSA10CF  | 4.21           | 38.04                              |
| 7    | CSA10CSF | 4.23           | 40.06                              |

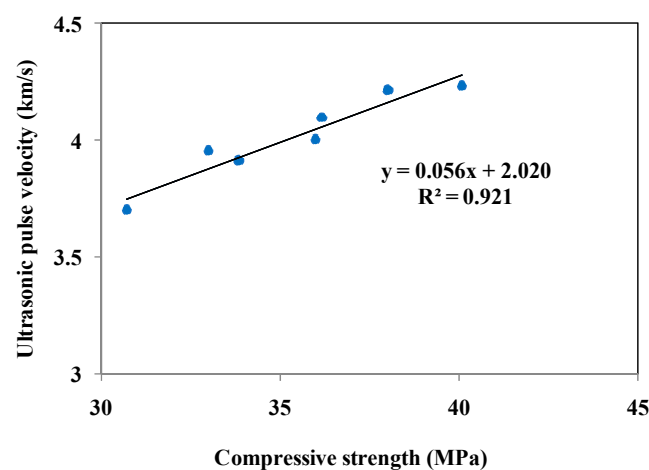


Figure 9. Relationship between compressive strength and UPV.

### 4.3. Durability Properties

#### 4.3.1. Water Absorption

The volume of open pores is determined by the water absorption of the specimens [51]. Figure 10 depicts the water absorption of the different combinations. The water absorption for the mix CS was determined to be 11.00% and 10.80% at 7 and 28 days. At 56 and 90 days, respectively, the rate of water absorption decreases with age. This could be attributed to the water in the CS aggregate completely evaporating while the concrete was being mixed. Furthermore, it was found that the CS mix including coir pith ash had lower water absorption than the mix without CPA. This is outlined by the fact that the fineness of the coir pith ash reduces the pores in the concrete, which, in turn, reduces the specimen's ability to retain water. The rate at which the specimens absorb water decreases with the addition of fibers. Coir fibers' hydrophilic surface improves the overall performance on the durability of the concrete. Additionally, it has been noted that adding steel fibers at a rate of 2% resulted in low water absorption [52].

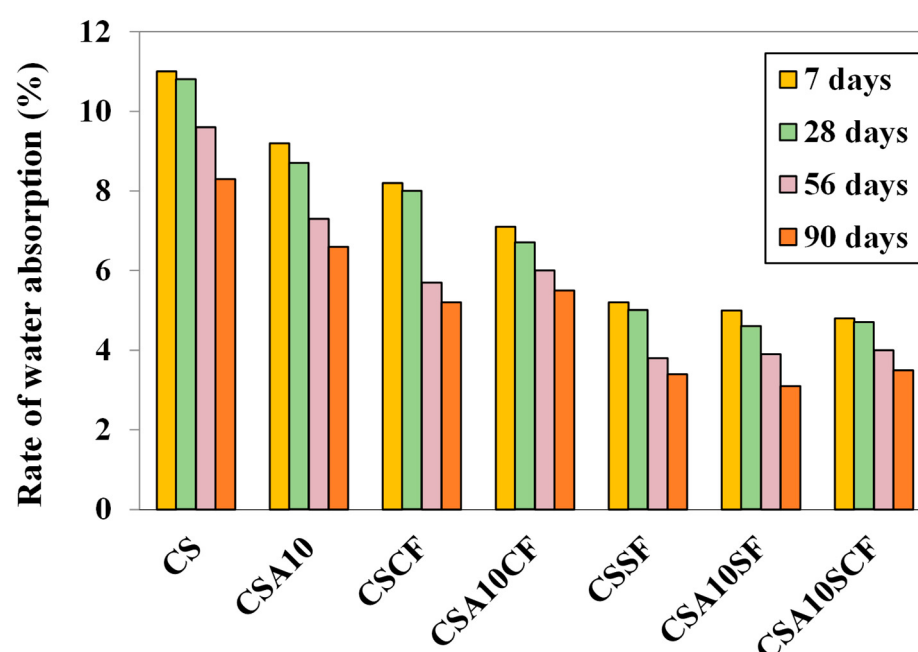


Figure 10. Rate of water absorption for all mixes at various curing ages.

#### 4.3.2. Sorptivity

Sorptivity in concrete refers to the ability of the material to absorb water through capillary action [4]. It is a measure of the rate at which water is absorbed into the concrete matrix under the influence of capillary suction. Sorptivity is a valuable parameter because it provides insights into the pore structure of concrete, which, in turn, influences the material's durability and performance. Generally, high-quality concretes have sorptivity values of less than  $0.1 \text{ mm/min}^{0.5}$ . The sorptivity of all mixes at 28, 56, and 90 days is presented in Figure 11. The sorptivity of Mix CS at the ages of 28, 56, and 90 days was about  $0.095$ ,  $0.084$ , and  $0.074 \text{ mm/min}^{0.5}$ . The minimum sorptivity values were found for 10% coir pith ash replacement in the CS mix, with the values being  $0.093 \text{ mm/min}^{0.5}$ ,  $0.068 \text{ mm/min}^{0.5}$ ,  $0.050 \text{ mm/min}^{0.5}$ . In coir pith ash-added mixes at 56 and 90 days, the sorptivity values were found to be significantly less than 28 days values. The delayed reaction of ash in concrete may be the reason for the reduced value of sorptivity. Because of the high quality and quantity of cement paste that is generated with a low w/c ratio of 0.33, CS mixes have relatively low sorptivity. Large pores in the paste are eliminated or reduced when there is a higher degree of compaction, according to published research, which increases the sorptivity of concrete [53]. The sorptivity of the concrete appears to be low when using the compaction process for CS concrete. According to some studies on coarse LWA, CS

concrete may benefit from the cement paste's ability to penetrate the aggregate to a specific depth, hence enhancing the aggregate interfacial zone [54]. The reduced sorptivity was caused by the enhanced aggregate contact zone and CS aggregate's capacity to perform internal curing.

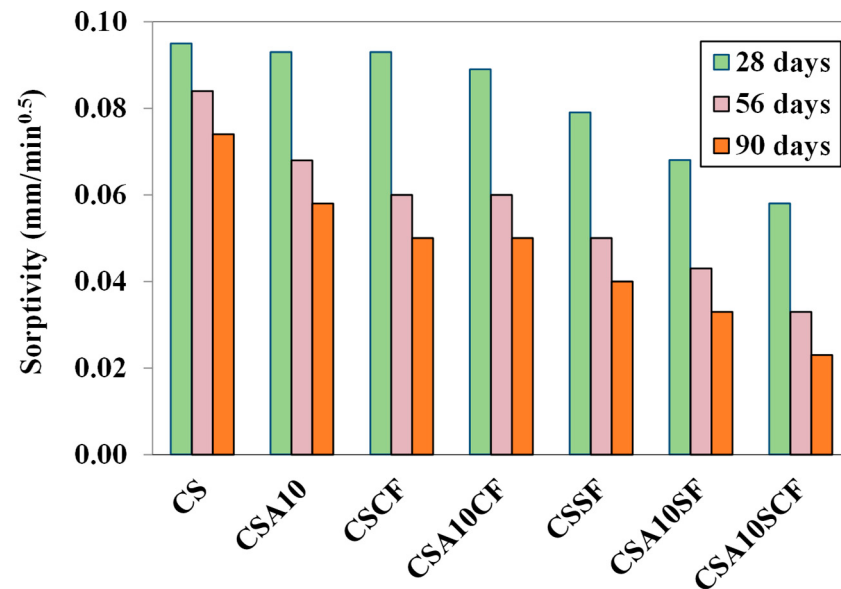


Figure 11. Sorptivity of all mix at 28, 56, and 90 days.

#### 4.3.3. Rapid Chloride Penetration Test

The rapid chloride penetration test (RCPT) value of various mixes is shown in Figure 12. At 28 days, the RCPT value of the specimen CS was found to be 3993.7 coulombs and slightly decreased at 56 and 90 days. In coir pith ash-added CSF mixes, a significant reduction of charges passed was found at 56 and 90 days. In general, the values are decreased for increasing the age of concrete. The literature states that for LWC made from expanded clay, the RCPT values have varied from about 2115 to 3336 coulombs [55]. The CS mix shows very low chloride-ion penetrability according to ASTM C1202. Additionally, it was noted that the temperature of the specimens continued to increase steadily during every stage of the investigations.

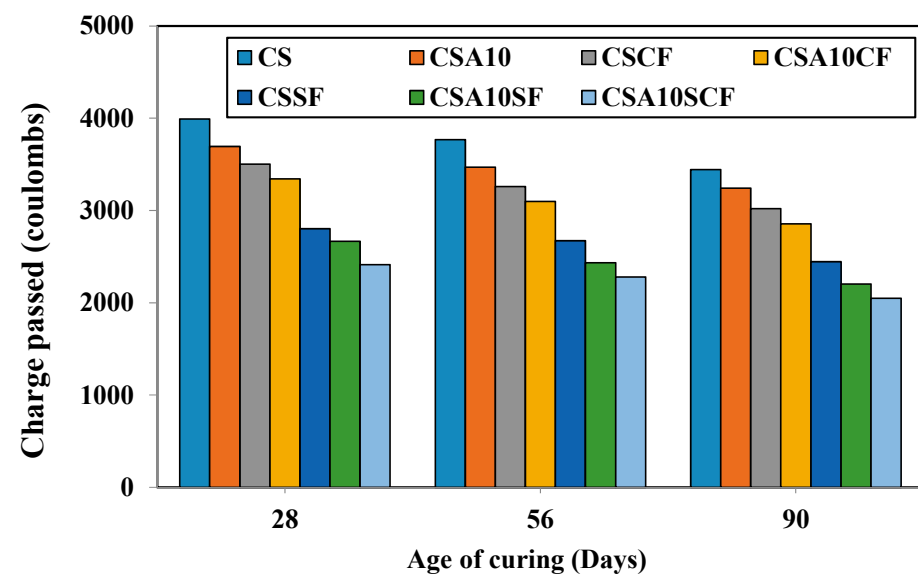


Figure 12. RCPT results comparison at 28, 56, and 90 days.

#### 4.4. Microstructural Properties

The SEM pictures of a coconut shell when it is saturated surface dry (SSD) and when it is air-dried for both convex and concave sides are shown in Figures 13 and 14, respectively. Coconut shell concrete has a strong bond because of the rough, convex texture of the coconut shell. The coconut shell that has been soaked for 24 h has a rougher convex face texture than the coconut shell that has been air-dried, which will strengthen the binding between the coconut shell and the matrix of the binder. Concrete is more workable when the coconut shell's smooth, concave texture is used. Figure 15 displays the results of a thorough microstructural investigation performed on a coir pith ash sample using a scanning electron microscope. The microstructural study is critical because microstructural parameters can have a large impact on acceptable concrete qualities. The presence of ash particles that were comparatively spherical was detected by SEM images.

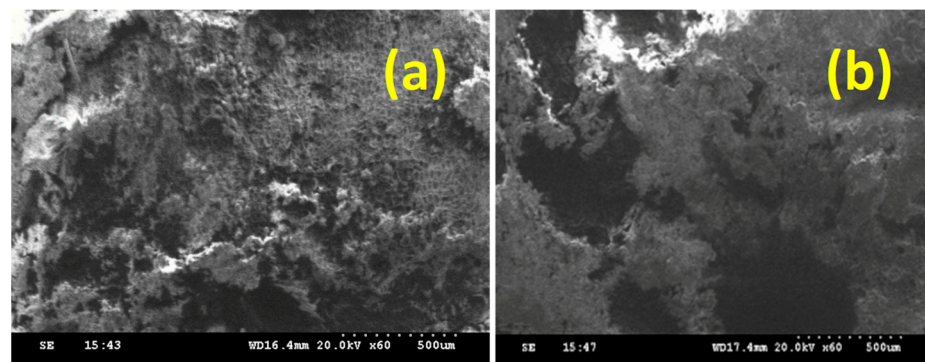


Figure 13. Coconut shell SEM images on convex side. (a) Soaked, (b) Air-dried.

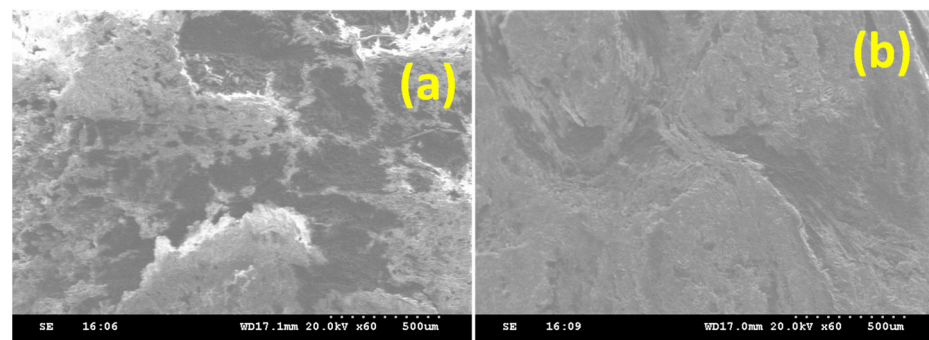


Figure 14. Concave side SEM images of the coconut shell. (a) Soaked, (b) Air-dried.

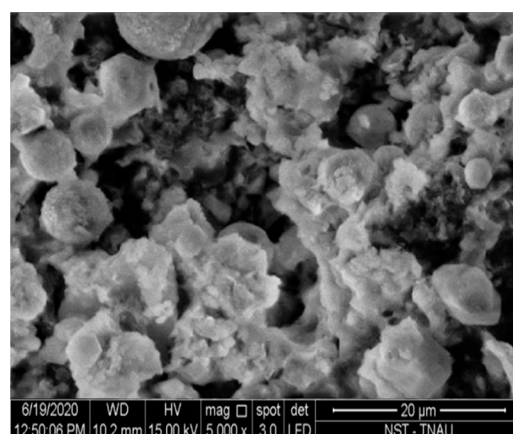
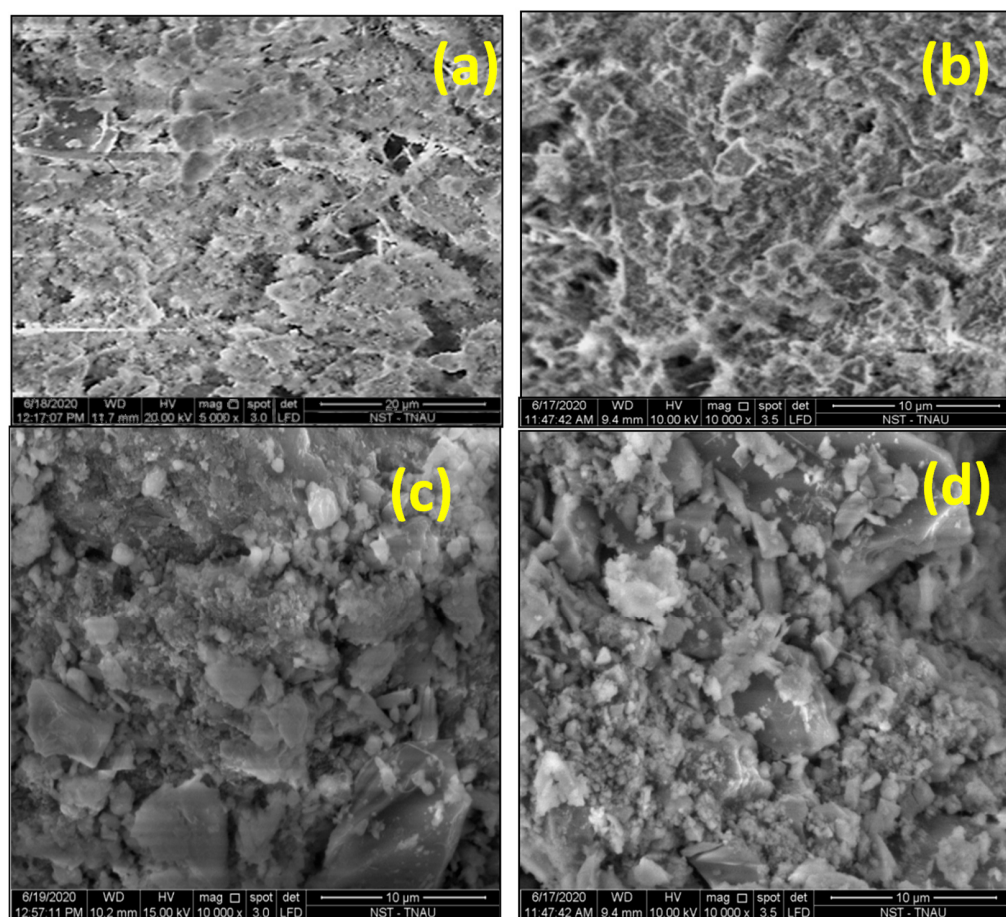


Figure 15. SEM images of coir pith ash.

The microstructural images of coconut shell concrete with coir pith ash at 5%, 10%, 15%, and 20% are shown in Figure 16. Comparing the SEM images of CPA5% and CPA10% reveals that the CPA10 mix comparatively possesses a denser microstructure than CPA5%. The number of pores also decreased to a greater extent. The image analysis revealed that the percentage of pores present in CPA15% and CPA10% were 10.52% to 7.92%, respectively. All these details proved the pozzolanic reaction of CPA, which eliminated the  $\text{Ca}(\text{OH})_2$  quantity in the matrix. C-S-H originated from  $\text{Ca}(\text{OH})_2$  occupied the empty void spaces and led to the creation of a denser microstructure. This, in turn, resulted in the superior performance of CPA10. Figure 16c,d show the SEM images of CPA15 and CPA20, respectively. Concerning voids and microstructure compactness, a CPA concentration increase above 10% resulted in the creation of a microstructure that was less compacted and had more pores. For CPA15 and CPA20, the percentage of pores discovered using image analysis was 11.28% and 15.60%, respectively. Although the pozzolanic reaction has reduced the amount of  $\text{Ca}(\text{OH})_2$  present, there are still more voids since the cement content has decreased and less hydration product production has occurred.

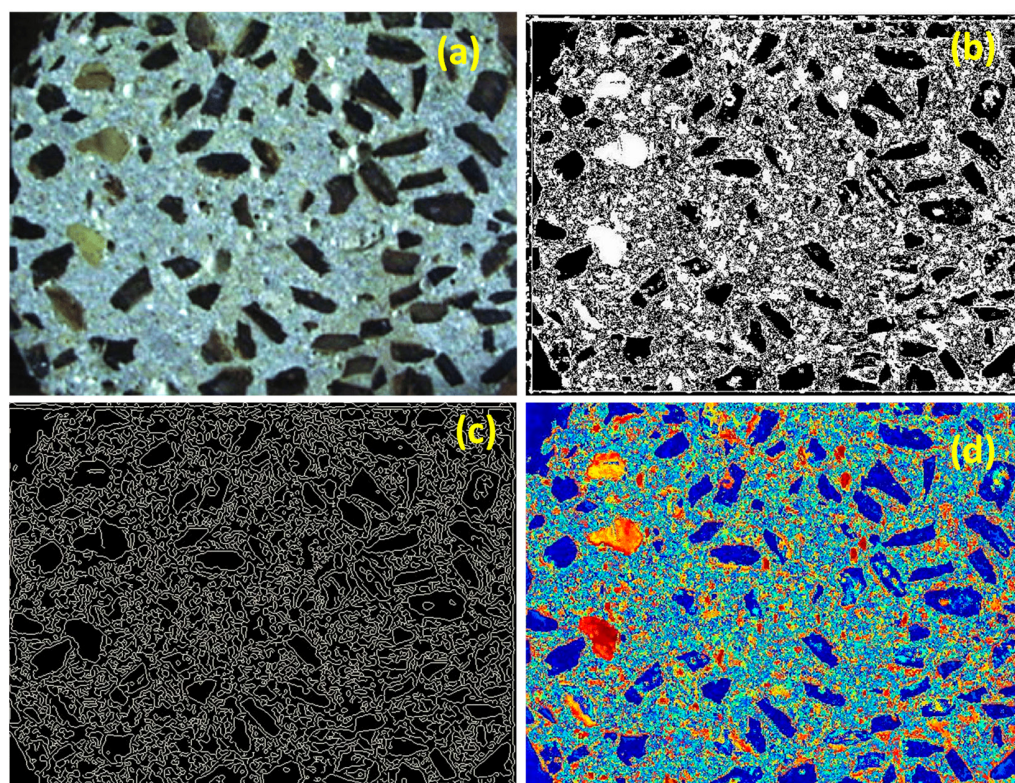


**Figure 16.** SEM images. (a) CPA5%, (b) CPA10%, (c) CPA15%, (d) CPA20%.

#### 4.5. Image Processing Technique

Image processing deals with the manipulation of acquired images. Image acquisition is the first step involved in image processing. An acquired image is a two-dimensional representation  $f(x, y)$  of a three-dimensional scene, where  $x$  and  $y$  are spatial coordinates and the amplitude of any pair of coordinates, and  $(x, y)$  is the intensity of the image at that point. The function's value is a numerical value that changes depending on how much light is reflected from a specific area in the visual scene at any given point. MATLAB software 2018 is used to analyze the acquired images. The source image is transformed into a grayscale version, which is then subjected to additional processing to determine the

concrete composition's boundary intensity. The volumetric information of the concrete composition is derived from an analysis of the cement, aggregate, fiber inclusion, and air-void contents. Three steps are involved in processing the image by using image processing techniques. The first step involved removing unwanted variations in pixel values from an image by using noise removal techniques to improve the quality of the image. After the pre-processing steps, the second step involves finding the threshold image to enable efficient analysis and interpretation of the pre-processed image. The pixel value of the original image is resized to  $256 \times 256$  pixels. The final step is used to apply the edge detection techniques to improve further analysis of the processed image. This is conducted on the raw image, and the compositions are separated using the processed image. The filtered and grayscale image generated for the specimen with a fiberless coconut shell aggregate is displayed in Figure 17. The fiber-free concrete cracked severely and failed right away. The fiber's significant role as a fracture bridge in the concrete caused the specimens containing fiber to break gradually. Similarly, it is clear from the image processing results that the addition of fiber to concrete significantly influenced the material's behavior with regard to ductility, load-carrying capacity, flexural toughness, and failure mode. The yellow areas in Figure 17d represent the main crack formation. It is evident that fewer cracks are forming and that the majority of the concrete is still intact.



**Figure 17.** Image processing of coconut shell aggregate concrete. (a) Concrete image, (b) Threshold image, (c) Greyscale image, (d) Filtered image.

## 5. Conclusions

Based on the various mixes developed to explore the properties of coconut shell aggregate concrete, it can be determined that the inclusion of 1% steel fiber, 0.75% steel, and 0.25% coconut fiber hybrid fibers considerably increased the compressive and tensile strengths of the concrete. In addition, this investigation may lead to the following conclusions:

- The slump value increased with an increase in the percentage of coir pith ash in the concrete. This could be due to the relatively globular shape of CPA particles and the presence of free water due to the reduction in the surface area of particles compared to cement. At an optimized quantity of 10% CPA, the slump value increased by 13%.

- Experimental research has proved that replacing cement with CPA up to 10% enhanced the overall performance of concrete. The compressive, flexural, and split tensile strength is enhanced by 10.36%, 8.75%, and 7.7% compared to control concrete. Through the implementation of CPA, the formation of micro cracks was significantly reduced due to the enhanced cohesiveness of the concrete.
- The addition of steel and coconut fiber reduced the flowability of the concrete because of the fiber's greater surface area, which increased internal friction between the different ingredients, making the mix less workable.
- The incorporation of fibers into the concrete resulted in a substantial improvement of compressive strength by 30.49% at 28 days.
- The behavior of concrete as it cracks is significantly impacted by the presence of fibers. Fibers can help prevent brittle fracture that occurs shortly after the first crack forms; this makes them a crack-arrester.
- Future research evaluating the possible use of composite materials incorporating agricultural leftovers for construction should take into account the long-term performance of these materials.

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