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*Original Article*

# Effect of Chicken Eggshell Powder and Coconut Shell Ash Blend on Workability, Microstructure, and Mechanical Performance of Concrete

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***Abstract*** *- This study evaluates the workability, microstructure, and mechanical performance of concrete with cement partially replaced with a blend of Chicken Eggshell Powder and Coconut Shell Ash. Concrete specimens were prepared with Portland limestone cement partially replaced with Chicken Eggshell Powder (CESP) and Coconut Shell Ash (CSA) blend in proportions of 0%, 5%,10%,15%, and 20%. Tests conducted included XRF, slump, compressive strength, and flexural strength tests. The study revealed slump values for all levels of partial replacement to be a true slump, S1: 10-40 mm slump, thus suitable for low-workability applications, and that workability decreased as percentages of partial replacement increased. Compressive, tensile, and flexural strengths rose progressively to 10% partial replacement levels at ages 7 days, 28 days, and 63 days, beyond which compressive, tensile, and flexural strengths decreased. Compressive strength at 28 days was 22.30 N/mm$^2$, 22.75 N/mm$^2$, 23.40 N/mm$^2$, 19.12 N/mm$^2$, and 16.12 N/mm$^2$ for 0%, 5%, 10%, 15% and 20% respectively, with 10% being the optimum level of replacement. The study was geographically limited to Ghana, and CESP and CSA were sourced locally.42.5 R Portland composite cement was used for the experiment. A regression model to guide construction practitioners in obtaining optimum compressive strength in CESP and CSA blended concrete was developed. The study found an alternative use for the CESP and CSA blend, agricultural waste polluting the environment, in concrete production, thereby promoting material circularity, waste valorization, and sustainability. Incorporating CESP and CSA blended concrete has the potential to reduce the carbon footprint of cement concrete, combat climate change, and thus address SDG 13: Climate Action. The study has established the chemical composition of CESP and CSA blend, which hitherto was not known, likewise the effect of CESP and CSA blend on workability, compressive strength, tensile strength, flexural strength, and microstructure of a concrete.*

***Keywords*** *- Cementitious, Concrete, Materials, Sustainability, Ghana.*

## 1. Introduction

Concrete is a composite construction material widely used for infrastructure construction globally [1]. The annual production of concrete worldwide is estimated to be 24 billion tons per year, accounting for about 7–10% of carbon dioxide emissions into the atmosphere [2]. In the quest to incorporate sustainability in concrete production, some supplementary cementitious materials such as fly coal ash [3], eggshell powder, which is obtained from eggshells [4], and sugarcane bagasse ash [5] have been used to partially replace cement in concrete mix within some national contexts such as India, Sri Lanka, and Nigeria. However, little is known of studies, if any, that blended Chicken Eggshell Powder (CESP) and Coconut Shell Ash (CSA) to partially replace a Portland composite cement. This reveals that the domain of CESP and CSA blended concrete is an emerging one with limited available literature, thus justifying the need for this study, as it contributes to advancing knowledge within the domain of CESP and CSA blended concrete. Among the few studies in existence that focused on CESP and CSA blended concretes, there is a lack of consensus regarding the optimum replacement levels, early strength development of CESP and CSA blended concretes, with long-term strength of CESP and CSA blended concretes being rarely reported and validated [6, 7]. The few studies have blended CESP and CSA in proportions of CSA (50%) and CESP (50%) and investigated the mechanical properties largely [6, 7]. However, the studies were limited in establishing the chemical composition of the CESP and CSA blend, and failed to provide guidance as to the mechanical properties of CESP and CSA blended concrete beyond the blend of CSA (50%) and CESP (50%). Also, none of the studies reported on the total $CO_2$ (kg) of the CESP and

CSA blended concrete, as well as the $CO_2$ reduction compared to the control (%). Thus, these limitations in existing studies underscore the relevance of this current study as it attempts to address them.

According to Ogbonna [6], although supplementary cementitious materials are mostly used individually, a blend of two or more different supplementary cementitious materials can be used to take advantage of the characteristics each offers. Eggshell powder alone has been found to be rich in (CaO), characteristics of limestone [8], while CSA is rich in $SiO_2$ [1]. Therefore, this study seeks to evaluate the workability, microstructure, and mechanical performance of concrete with cement partially replaced with a blend of chicken eggshell powder and coconut shell ash. The specific objectives that guided the study were:

- To assess the workability of concrete with cement partially replaced with a blend of chicken eggshell powder and coconut shell ash,
- To assess the mechanical performance of concrete with cement partially replaced with a blend of chicken eggshell powder and coconut shell ash,
- To examine the microstructure of concrete with cement partially replaced with eggshell powder and coconut shell ash blend at the optimum level.

Mechanical performance assesses the concrete when subjected to loading and was evaluated using the compressive, tensile, and flexural strengths (see [6]). Workability measures the consistency and fluidity of concrete [1]. Examination of the microstructure of concrete focuses on the underlying physical structure that determines concrete's mechanical properties [1].

## 2. Empirical Review of Related Literature on CESP and CSA Blend in Concrete in Existing Studies

### *2.1. Empirical Review*

Whereas a number of studies have replaced cement partially with CSA or CESP, little is known of studies that have evaluated the blend of CESP and CSA to replace cement partially. The few studies in existence that were quite related to this current study were the study by Bhartiya and Dubey [7] in India and the study by Ogbonna [6].

In India, Bhartiya and Dubey [7] partially replaced cement with a blend of CESP (50%) and CSA (50%) in proportions of 0%, 5%, 10%, 12%, and 13%, targeting a design strength of 20 N/mm$^2$. Water-cement ratio was 0.5. Slump was found to be decreasing with an increase in percentages of partial replacement. The performance of the concrete was evaluated based on the slump and compressive strength at ages 7 days and 28 days. The optimum mix proportion was 10%, and the corresponding slump value was 19 mm. Up to 12% partial replacement, compressive strength values were slightly greater than the control. CESP was obtained through the processes of washing, air drying, grinding, and sieving using a 90-micron sieve. CSA was obtained through the processes of removing the husk, sun drying, combustion, and sieving using the 90-micron sieve. Natural river sand of size not exceeding 4.75 mm was used as a fine aggregate, while natural crushed stone of size not exceeding 20 mm was used as the coarse aggregate. Whereas the study established the chemical compositions of CESP alone and CSA alone, it did not establish the chemical composition of the CESP and CSA blend. It was not theoretically underpinned by any theory, and the long-term performance of the concrete was not evaluated, as well as the microstructure. Thus, addressing these weaknesses in this current study underscores the study's relevance and contribution to knowledge.

More so, the study by Ogbonna [6] partially replaced a hydraulic cement with a blend of CSA (50 %) and CESP (50%) in proportions of 0%, 5%, 10%, 15%, and 20% in producing Roller Compacted Concrete (RCC) for pavement structure. The performance of the concrete was evaluated using the compressive, tensile, and flexural strengths. The results indicated that the CESP and CSA blended concrete did not perform better than the control mix (0% partial replacement) at early strength development and at standard 28 days in terms of compressive strength, tensile strength, and flexural strength. This was attributed to the delayed pozzolanic reaction of the CESP and CSA blend [1]. However, for long term compressive strength at ages 56 days and 91 days, 5% partial replacement recorded the maximum compressive strength of 48.61 N/mm$^2$ and 58.32 N/mm$^2$ respectively, exceeding the control values of 47.81 N/mm$^2$ and 56.44 N/mm$^2$ for ages 56 days and 91 days.

Regarding water absorption of concrete specimens at 28 days and 91 days, it was revealed that as the percentage of partial replacement increases, water absorption of concrete specimens decreases. However, the study was not underpinned by any theory, microstructure investigations were not done, temperatures of the concrete mixes were not reported, and there were inconsistencies in stating the mix design. According to Ranatunga et al. [1], Neville and Brooks [9], and Mehta and Monteiro [10], parameters such as temperature and microstructure properties significantly influence the strength performance of concrete; hence, they are essential parameters to report. Thus, addressing these weaknesses in this current study underscores the study's relevance and contribution to knowledge. Synthesizing the related studies revealed that the domain of CESP and CSA blended concrete is an emerging one with limited available literature, thus justifying the need for this study, as it contributes to advancing knowledge within this domain. Also, there is a lack of consensus regarding the optimum replacement levels, early strength development of CESP and CSA blended concrete, among the few studies, hence the need to reconsider CESP and CSA blended concrete with materials from different geographical contexts to strengthen consensus building around the subject matter. Again, the long-term strength of CESP and CSA blended concrete is rarely reported and needs to be validated by other studies, hence the relevance of this current study from Ghana. Also, beyond the blend of CSA (50 %) and CESP (50%) reported in previous studies, could a variation in the blend improve the properties of concrete, especially mechanical properties? Thus, posing the overarching question: could a variation in proportions of CESP and CSA blend influence properties of CESP and CSA blended concrete? Also, none of the related studies reported on the total $CO_2$ (kg) of the CESP and CSA blended concrete, as well as the $CO_2$ reduction compared to the control (%). Also, none of the studies had replaced Portland composite cement with CESP and CSA blend, and the chemical composition of the CESP and CSA blend that partially replaced cement had not been reported. Thus, the relevance of this current study as it attempts to address these weaknesses in existing studies.

### 2.2. Theoretical Review

Theories that guided the study were the Dilution theory and the Complementarity theory.

#### 2.2.1. Dilution theory

This theory espouses that partially replacing cement with SCM beyond a certain threshold results in a dilution effect, which leads to loss of cementitious binder, notwithstanding the gains from pozzolanic activity [11]. Hence, the optimum level of partial replacement is essential in the use of CESP and CSA blend as SCM.

#### 2.2.2. Complementarity Theory

The complementarity theory posits that when two or more SCMs are blended to replace cement partially, their combined effect is greater than the sum of their individual effects [6, 12]. Thus, Ca-rich CESP activates $SiO_2$-rich CSA to improve the performance (workability, microstructure, and mechanical performance of concrete) up to an optimum level.

#### 2.2.3. A Synthesis of Literature

Based on the theoretical and empirical literature reviews, this current study conceptualizes that partially replacing cement with CESP and CSA blend leads to an increase in mechanical performance of concrete (compressive strength, tensile strength, and flexural strength). However, beyond the optimum level of partial replacement, the mechanical performance of concrete decreases.

## 3. Materials

The following materials were used for the study:

### 3.1. Portland Composite Cement

Portland Limestone Cement (PLC), CEM II/B-L, rated strength class 42.5 R, was used in this study. X-ray Fluorescence (XRF) analysis was performed to determine the properties of cement. With reference to BS EN 197-1:2000 and BS EN 196-2:1995, standard chemical composition requirements, especially the oxide contents in PLC, that give it a binding property and required in a cement include: CaO (Calcium Oxide) $SiO_2$ (Silicon Dioxide), $Al_2O_3$ (Aluminium Oxide), $Fe_2O_3$ (Iron (III) Oxide), MgO (Magnesium Oxide), $SO_3$ (Sulphur Trioxide), $Na_2O$ (Sodium Oxide), $K_2O$ (Potassium Oxide) [13, 14].

### 3.2. CESP and CSA Blend

A blend of CESP (80%) and CSA (20%) was used as an SCM to replace PLC partially. XRF analysis was performed to determine the chemical composition of the CESP and CSA blend and to compare it with PLC to ascertain its suitability as an SCM.

### 3.3. Water

Potable water, per BS EN 1008:2002, was used for the concrete specimens [15]. It was clean and odourless when smelled [15].

### 3.4. Fine and Coarse Aggregates

The sieve analysis test was performed in accordance with BS EN 933-1:2012 and BS 1377-3:1990 to determine the particle size distribution of the fine and coarse aggregates for the concrete specimens [16, 17].

### 3.5. Experimental Procedure

#### 3.5.1. Preparation of Coconut Shell Ash (CSA)

Fresh coconut shells, an agricultural waste, were then cleaned, pulverised and dried in the sun for 6 days to remove moisture. Then oven-burnt at a temperature of 700 °C for 2 hours, limiting the burning time to minimize the negative environmental impact. The weight of the coconut shells was reduced by about 40% after the burning. The sample was then sieved using a 75µm sieve [1].

#### 3.5.2. Preparation of Chicken Eggshell Powder (CESP)

Chicken Eggshells, an agricultural waste, were cleaned and air-dried under the sun for 6 hours to remove moisture. The sample was milled with the help of a blender into smaller particles and then sieved using a 75µm sieve [6].

#### 3.5.3. Preparation of Chicken Eggshell Powder and Coconut Shell Ash Blend

CESP and CSA were carefully blended in a proportion of 80% CESP and 20% CSA to leverage the strength of both SCMs. The proportion of the CESP and CSA blend was driven by reducing the carbon footprint of the blend.

CSA, per the processes involved, requires burning, unlike the CESP, hence likely to emit carbon into the atmosphere more than CESP, although it is more sustainable than cement, as advanced in previous studies, for example, Ranatunga et al. [1] and Bheel et al. [2].

### *3.6. Development of Eggshell Powder and Coconut Shell Ash Blended Concrete*

Concrete mix design, following a design mix approach, was developed to guide the process (see Table 1, appendix). Firstly, the control concrete, which had 0% CESP-CSA blend, was prepared to achieve the targeted compressive strength of 20 N/mm$^2$ at 28 days of curing. In the design, the water-to-cement ratio was selected as 0.58. Then, PLC was partially replaced with CESP-CSA blend in proportions of 5%, 10%, 15% and 20%. The proportion of partial replacement was selected guided by similar studies in the past, such as Ogbonna [6] and Bhartiya and Dubey [7]. Concrete mixes were named as CESP-CSA 0, CESP-CSA 5, CESP-CSA 10, CESP-CSA 15, and CESP-CSA 20, when CESP and CSA blend Partially Replaced Cement (PLC) in proportions of 0%, 5%, 10%, 15%, and 20%, respectively. Three concrete specimens were tested at each of the ages (7 days, 28 days, and 63 days) for compressive strength following BS EN 12390-3:2019 [18], tensile strength following BS EN 12390 -6: 2009 [19], and flexural strength following BS EN 12390-5: 2019 [20]. Concrete was mixed and cured in accordance with BS EN 12390-2:2000 [21].

### *3.7. Assumptions for Carbon Footprint Calculation Based on the Mix Design*

The calculation of carbon foot print of the materials was based on the assumptions that from cradle-to-gate: according to Abbas and Jabr [22], the carbon emission factor (kg $CO_2e$/kg) for CESP was 0.07 [22], Portland Composite Cement (PCC, CEM II) was 0.77 [23]; sand was 0.004, crushed rock was 0.007, and water was 0.0003 [22]. Carbon emission factor of CSA was estimated as 0.1720 kg $CO_2e$/kg based on electricity consumption during milling, and transportation emissions. In accordance with carbon accounting principles of the Intergovernmental Panel on Climate Change (IPCC), biogenic emissions from biomass combustion were excluded [24]. The emission factor for the CESP and CSA blend (80:20) was computed to be 0.0904 kg $CO_2$/kg. Total carbon footprint for each mix ratio was computed using the formula:

$$Total\ CO_2\ foot\ print = \sum(Material\ mass \times Emission\ factor).$$

### *3.8. Determining the Properties of Materials for Concrete Production*

#### *3.8.1. X-ray Fluorescence (XRF) Test: PLC, as well as CESP and CSA blend.*

This is a non-destructive test. It was used to extract the elements and chemical oxide composition of materials, including cement. X-ray Fluorescence (XRF) considers the sum of all the elements in the material as the total weight of the material and gives the relative percentage of the elements present in the material [1]. The XRF was carried out using the Rigaku NEX CG desktop XRF in this study. The device analyses from $_{11}$Na to $_{92}$U non-destructively. PLC and CESP-CSA blend samples were subjected to XRF to obtain major oxides and elemental constituents using the fundamental parameters method, double determination approach analysis. Four measurement conditions or secondary targets of Aluminum (Al), Molybdenum (Mo), Copper(cu), and Rigaku Crystal 9(RX9) were used to determine the elements and molecules in the samples. The following parameters were used: FP (fundamental parameters) method, an atmosphere of Helium at a flow rate of 0.660 l/min for powder/liquid samples, tube voltage = 50 kV, and tube current = 1.00 mA. The software used was Rigaku Profiling Fitting-Spectra Quant X(RPF-SQX).

#### *3.8.2. Grading Test for Coarse Aggregate*

The grading test for coarse aggregates for the concrete mix followed the procedures outlined in BS EN 933-1:2012, which specify the sieving method for determining aggregate size [16]. The sieves used were: 22mm, 20mm, 19mm, 14mm, 12.5mm,10mm, 4.75mm, and 2.36 mm.

#### *3.8.3. Grading Test for Fine Aggregate (sand) for Concrete*

Grading test was done in accordance with BS EN 933-1:2012 (Tests for geometrical properties of aggregates – Determination of particle size distribution – Sieving method) [16], and classified following BS 882:1992 and BS EN 12620:2013 to belong to zone III: well-graded fine sands suitable for most concrete mixes [25, 26]. The specific sieves used for the test were: 5mm, 4.75mm, 2.36mm, 1.18mm, 0.6mm, 0.3mm, 0.15mm, and 0.075mm.

#### *3.8.4. Energy Dispersive X-ray Spectroscopy (EDX) and Scanning Electron Microscope (SEM) for Concrete Specimens*

Energy Dispersive X-ray Spectroscopy (EDX) is also known as EDAX or EDS. It is used to determine the elemental composition of materials, including concrete. It is often integrated with a Scanning Electron Microscope (SEM) to provide both chemical composition and morphological information of a specimen [27]. The sample was cut into pieces (specimens) and dried. The surfaces of the specimens were polished and carbon-coated to prevent charging under the electron beam. The specimens were placed in the SEM-EDX chamber for analysis [28].

Firstly, the specimens were imaged using SEM to locate regions of interest such as unreacted particles, hydration products, and/or voids. The EDX detector collected X-rays emitted from the regions of interest during the SEM imaging. The resulting energy spectrum showed peaks corresponding to the presence of different elements in the specimens. A quantitative report of the elemental composition in weight (%) or mass (%), or atomic (%) was generated with the aid of software. It provided information about the texture, microstructure, cracks, and bonding characteristics within a concrete specimen [10].

Also, from Table 1 (see Appendix), the mix design becomes increasingly sustainable (carbon footprint reduces) as the level of partial replacement of cement with CESP and CSA blend increases from 0% to 20%.

## 4. Results and Discussions

### *4.1. Fine Aggregates*

The Fineness Modulus (FM) index aided in establishing the mean particle size of the fine aggregate and ascertained how coarse or fine the aggregate was using specific sieves, in reference to BS EN 933-1:2012; BS EN 12620:2013 [16, 26]. This was essential for the concrete mix design towards the realization of a workable concrete mix. According to Neville [31], fine aggregates are classified as fine (FM < 2.3), medium (FM = 2.3–2.9), or coarse (FM > 2.9). Therefore, with an FM value of 2.40, the fine aggregate for the concrete mix was classified as medium-grained sand, in reference to BS EN 933-1:2012; BS EN 12620:2013 [16, 26, 31]. Also, with 57.43% passing through the 0.6mm sieve (see Figure 1), the fine aggregate falls within zone II: medium sand, in reference to BS 882:1992 and BS EN 12620: 2013 [25, 26].

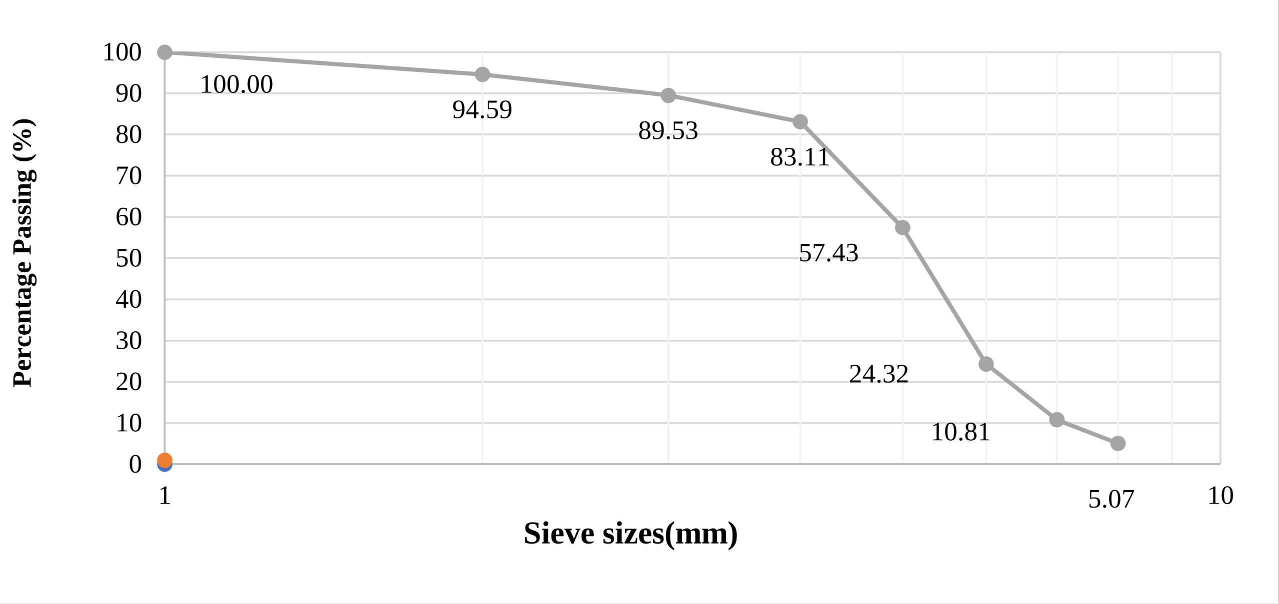

**Fig. 1 Gradation curve for fine aggregate**

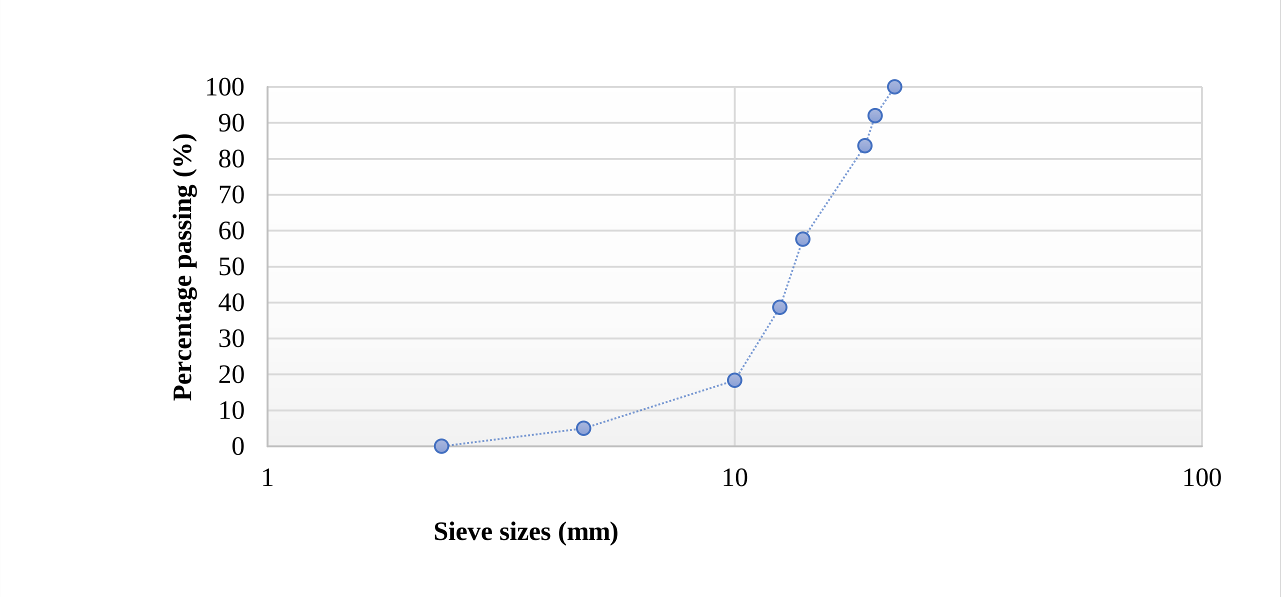

**Fig. 2 Gradation curve for coarse aggregates**

### *4.2. Coarse Aggregates*

The coarse aggregate was well graded with an upper limit not exceeding 20mm and a lower limit not exceeding 4.75mm (see Figure 2). The aggregate met the grading limits for 20mm for coarse concrete, in reference to BS 882:1992 and BS EN 12620:2013 [25, 26], suggesting a well-graded coarse aggregate for a concrete mix.

### *4.3. Chemical Composition of CESP and CSA Blend*

Since there is no reference standard in existence, a reference standard to evaluate the chemical composition of the CESP-CSA blend as an SCM, the provisions for evaluating clinker were followed. BS EN 197-1:2000 and BS EN 196:1995 expressed the constituents of clinker in oxide forms as CaO, $SiO_2$, $Al_2O_3$, $Fe_2O_3$, and small quantities of other materials [13, 14]. It also consists of at least two-thirds by mass of calcium silicates, the rest consisting of iron and aluminum. The ratio by mass (CaO)/(SiO2) is not less than 2.0, while the content of Magnesium Oxide (MgO) does not exceed 5.0 % by mass [14]. Thus, the CESP-CSA blend met requirements for clinker, likewise, the PLC. For instance, the ratio by mass (CaO)/(SiO2) of CESP-CSA blend was 129.6, thus not less than 2.0. Also, Magnesium Oxide (MgO) was 1.82% and did not exceed 5.0% by mass. Hence, the CESP-CSA blend met the requirements of a clinker (see Table 2, appendix section), making it suitable for use as an SCM. In relation to existing literature, CESP alone is rich in (CaO), characteristics of limestone [8], while CSA is rich in $SiO_2$ [1]; however, a blend of CESP and CSA resulted in properties of an SCM meeting the requirements for a clinker, which is a major ingredient in the manufacturing of cement.

Objective one: To assess the workability of concrete with cement partially replaced with a blend of chicken eggshell powder and coconut shell ash

### *4.4. Slump of Fresh Concrete*

From Figure 3, the slump value decreased with a percentage rise in CESP and CSA blend, an indication of a decrease in workability as the CESP and CSA blend increases in a concrete mix. This affirms the position of [7] that workability decreases with an increase in partial replacement. Reference to BS EN 206-1:2000, true slump is ideal for concrete mix, and it ranges from (10mm to 220mm), and it could be further classified based on the level of workability as (S1: 10-40 mm slump: suitable for low-workability applications; up to S5: >220 mm slump, suitable for specialized applications) [29]. Thus, the level of workability for all concrete mixes falls within the range of S1, indicating suitability for low workability applications.

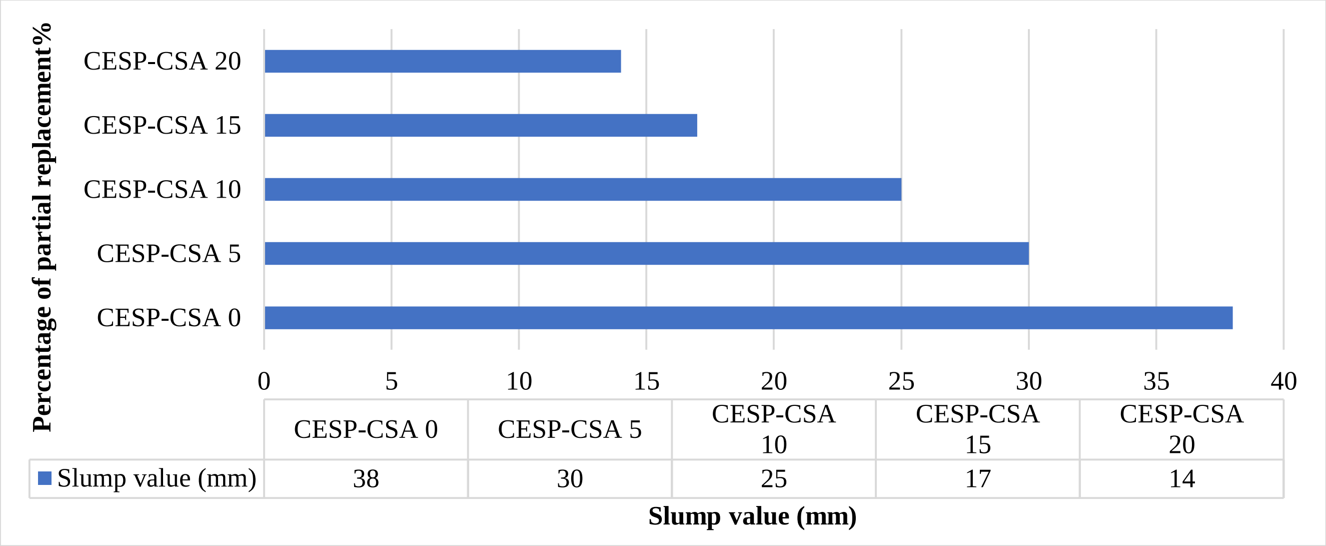

**Fig. 3 Slump performance of concretes with CESP and CSA blend partially replacing cement**

### *4.5. Temperature*

The temperature of a concrete mix influences the workability and strength of concrete, among others, as referenced in ACI Committee 305:2019 [30]. The temperature for freshly mixed normal concrete should typically range between 10 °C and 32 °C, with 20 °C–27 °C being considered the optimal range for normal concrete [31]. Thus, from Figure 4, the temperature of freshly mixed concrete ranged from 27 °C to 20 °C. The trend suggests a decreasing temperature as the percentage of partial replacement of cement with CESP and CSA blend increases from 0% to 20%. According to Neville and Brooks [9], Neville [31] and Mehta and Monteiro [10], as the level of partial replacement increases, it reduces the heat generated during hydration, thereby lowering the temperature of the fresh mixed concrete [9, 10, 31].

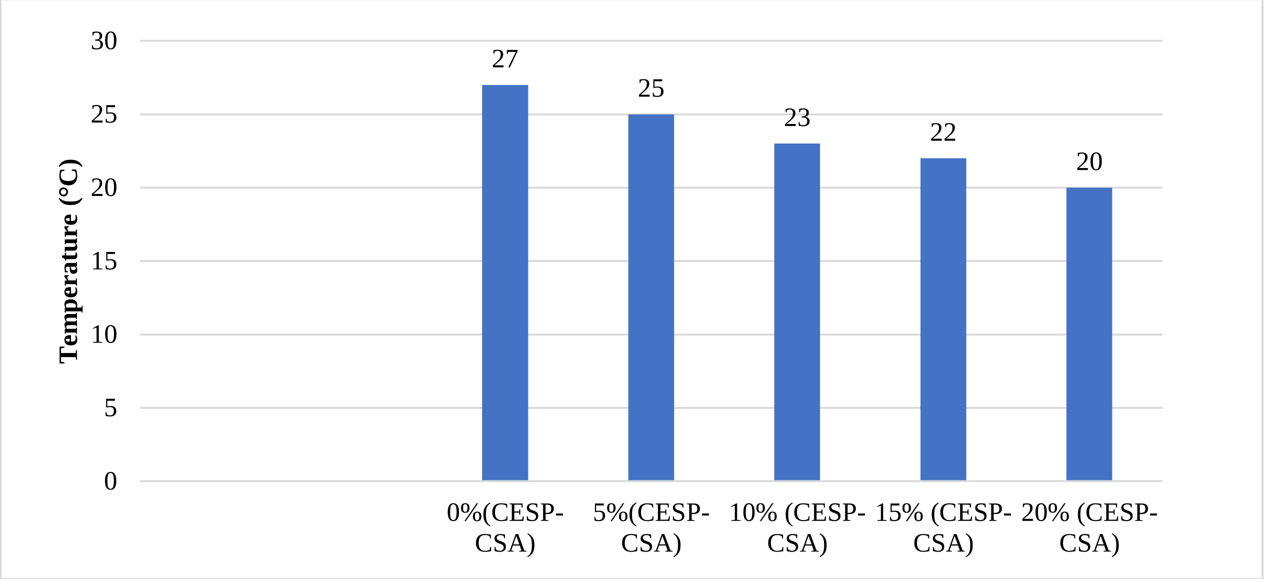

**Fig. 4 Temperature of concrete with CESP and CSA partially replacing cement**

Objective two: To assess the mechanical performance of concrete with cement partially replaced with a blend of chicken eggshell powder and coconut shell ash.

### *4.6. Compressive Strength*

The targeted compressive strength at 28 days of curing was 20 N/mm². A one-way ANOVA was performed to ascertain if there is a statistically significant difference in the mean compressive strength of CESP and CSA blended concrete across the curing ages: 7 days, 28 days, and 63 days. From Table 3 (see Appendix), the results revealed F (2, 12) = 4.48, and p = 0.035; indicating that for a degree of freedom between groups of 2, and degree of freedom within groups of 12, the ratio of explained variance to unexplained variance was 4.48; meaning the variation between the group means was 4.48 times larger than the variation expected within the groups due to random error. A p-value of 0.035 suggested that curing age significantly influenced compressive strength development of CESP and CSA blended concrete. Thus, there was an increase in compressive strength of the concrete specimens from ages 7 days, through 28 days, to 63 days—an indication of continuous hydration and pozzolanic reaction within the concrete specimen [1]. Also, for all the days (7 days, 28 days, and 63 days), compressive strength rose progressively to 10% partial replacement level, beyond which any additional percentage of CESP and CSA blend resulted in a decrease in compressive strength. This effect is attributable to the dilution effect of concrete [11]. Comparing with the targeted strength of 20 N/mm² at 28 days, all the specimens exceeded the targeted strength, apart from 20% partial replacement level, with the 10% partial replacement recording the maximum (optimum) compressive strength value (23.40 N/mm2), followed by 5% partial replacement (22.75N/mm2), then 0% partial replacement level (22.30 N/mm2). Comparing this optimum level with the long-term optimal level of partial replacement of 5% as advanced by Ogbonna [6], it is worth mentioning that the effect of the CESP and CSA blend on compressive strength of concrete resulted in an improved optimum level (ie. 10%). Also, the early strength values of concrete specimens at 7 days exceeded those of the control specimen for all levels of partial replacement except at the 20%. Indicating an enhanced early strength development.

This contrasts with the findings of Ogbonna [6] and Bhartiya and Dubey [7], who reported lower early strength development values compared to the control specimen when the researchers in separate studies partially replaced cement with CESP and CSA blend. Finally, a regression model was developed to explain the relationship between compressive strength and the level of partial replacement of cement with CESP and CSA blend. This has been presented in Table 4 (Appendix).

Regarding the interpretation of the regression model in Table 4 (see Appendix), Kutner et al. [34] and Montgomery et al. [33] asserted that $R^2$ values range between 0 and 1. $R^2$ value below 0.2 signifies a very weak relationship, 0.2–0.4 signifies a weak to moderate relationship, 0.4–0.6 signifies a moderate relationship, 0.6–0.8 represents a strong relationship, and values above 0.8 signify a very strong relationship between the variables [32, 33]. The $R^2$ values for the 7-day compressive strength model, 28-day compressive strength model, and 63-day compressive strength model were 0.96, 0.88, and 0.93, respectively (see Table 4, Appendix). Indicating a very strong relationship. From Table 4, y is the compressive strength. The models confirmed that the optimum level of partial replacement was 10%, as it yielded the maximum compressive strength.

### *4.7. Tensile Strength*

From Figure 5, the tensile strength of concrete with CESP and CSA blend partially replacing cement increases with age of concrete: 7 days, 28 days, and 63 days; an indication of continuous hydration and pozzolanic reactivity within the concrete specimens. Also, for each age of concrete, 7 days, 28 days, and 63 days, the trend revealed that the tensile strength of concrete specimens rises progressively to 10% partial replacement level, beyond which the dilution effect of cement sets in. This strength performance of the concrete in tension departs from the findings of the study by Ogbonna [6], which revealed that the tensile strength only decreases with increasing partial replacement levels and thus, none of the tensile strength values exceeded the value of the control specimen [6]. The increase in optimum partial replacement level could be attributed to the synergistic effect of the proportion of CESP and CSA blend employed in this current study.

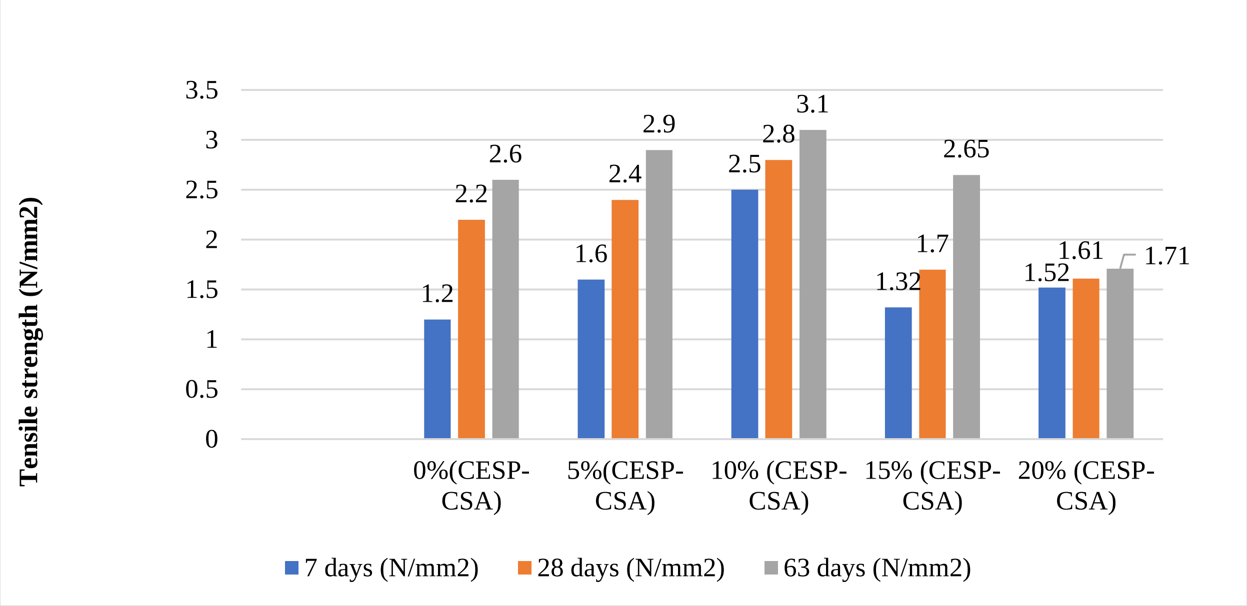

**Fig. 5 Tensile strength performance of concretes**

### *4.8. Flexural Strength*

According to Ogbonna [6], as the percentage of partially replacing cement with CESP and CSA blend increases, flexural strength decreases. This position was found to be not supported by the findings of this current study. From Table 5 (appendix), flexural strength increased from day 7 to day 63, an indication of continuous hydration and pozzolanic reactivity within the concrete specimens. The optimum level of partial replacement was 10%. Thus, this study's departure from the study by Ogbonna [6] is attributable to the effect of the chemical composition of the CESP and CSA blend.

### *4.9. Durability of Concrete*

In ascertaining the durability of CESP and CSA blended concrete, the concrete was buried in a soil that supports plant growth. The long-term compressive strength and water absorption values were determined at age 140 days. Long-term compressive strength and/or water absorption had been the basis for evaluating the durability in previous studies, such as Ranatunga et al. [1]. From Table 6 (see Appendix), the loss of ignition value was 13 %. This is an indication of organic-rich soil, fertile soil that is supportive of plant growth and microbial activities [34, 35]. Also, The PH was 6.3. Soil of PH ranging from 6.0 to 7.0 is considered suitable for plant growth. The PH value of 6.3 is an indication that the soil within which the CESP and CSA blended concrete was buried supported plant growth and encouraged microbial activities [35]**.** Again, the PH of 6.3 indicates mild chemical aggressiveness to concrete by the soil [9]. The water absorption values were all less than 1%, just like the control. The water absorption value for (CESP-CSA 0) was 0.70, (CESP-CSA 5) was 0.60, (CESP-CSA 10) was 0.40, (CESP-CSA 15) was 0.30, and (ESP-CSA 20) was 0.20. This is an indication that the CESP and CSA blended concrete is equally low-permeability and of good quality, like the control concrete specimen. Contrary to the assumption by Parthasarathi et al. [36] that eggshell will reduce the permeability of concrete in the long run, the results indicated that CESP and CSA blended concrete resulted in enhanced permeability of concrete. Also, none of the concrete specimens, including the control, showed any defect such as a change in color, cracks, shape, swelling, corner roughness, or traces of salt deposits at the surface (white efflorescence) after 140 days of burial in soil. These are manifestations of biodegradation and defects according to Neville and Brooks [9]. Thus, suggesting the specimen had not suffered any form of degradation or defect. Also, according to Neville and Brooks [9], degradation of concrete manifests in the form of loss of strength over time. The long-term compressive strength values at 140 days of concrete specimens buried in the soil indicated that all specimens (CESP-CSA 0), (CESP-CSA 5), and (CESP-CSA 10), (CESP-CSA 15), and (CESP-CSA 20) recorded compressive strength scores of 28.00 N/mm$^2$, 28.70 N/mm$^2$, 24.00 N/mm$^2$, 21.25 N/mm$^2$, and 20.25 N/mm$^{2,}$ respectively. These values were higher than the targeted strength of 20N/mm$^2$ at 28 days of water curing, an indication of continuous hydration and pozzolanic reactivity within the concrete specimens. Hence, there is no evidence of any form of degradation in the concrete. Therefore, lending support to the argument by Ogbonna [6], that CESP and CSA blend result in an inorganic supplementary cementitious material, which is non-biodegradable because of the blended ash. Moreover, the optimum level of partial replacement was at 10%.

Objective three: To examine the microstructure of concrete with cement partially replaced with eggshell powder and coconut shell ash blend at the optimum level.

Scanning Electron Microscopy (SEM) and Energy-dispersive X-ray Spectroscopy (EDS) were used to analyze the microstructure of the concrete specimens. The focus was on the 0% and 10% optimum partial replacement specimens.

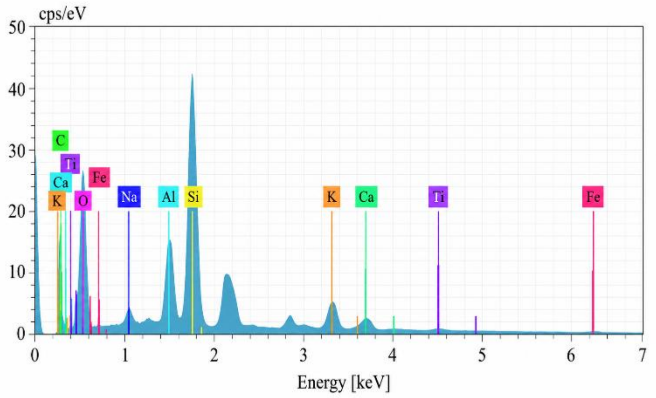

**Fig. 6 EDS elemental analysis of concrete with 0% CESP-CSA blend as a partial replacement of cement**

From Figure 6, the EDS elemental analysis confirmed that the concrete specimens for the control experiment comprised a typical cement–aggregate system, with cement hydration products (Si, Ca, Al, O, Fe) and aggregate phases (O, Si, Mg, Al) both clearly identifiable. The dominant elements appeared to be Ca and Fe. Calcium is associated with calcium **s**ilicate hydrates (C-S-H) and calcium hydroxide [1].

Likewise, from Figure 7, the EDS elemental analysis of the concrete specimen, revealed the presence of Carbon (C), Calcium (Ca), Oxygen (O), Iron (Fe), Magnesium (Mg), Aluminum (Al), and Silicon (Si) at varying concentration levels in the concrete specimens produced at optimal level of partial replacement (10%). The dominant elements appeared to be iron and calcium, as indicated by their prominent peaks at different energy levels. Calcium and iron are among the prominent elements in cement, in reference to BS EN 197-1:2000 [14]. The EDS spectrum indicated that the concrete specimen was composed of elements characteristic of cement (Ca, O, Si, Al, Fe) and aggregates (Si, O, Al, Mg) [37]. The relative heights of the peaks indicated the semi-quantitative elemental composition of the analyzed region.

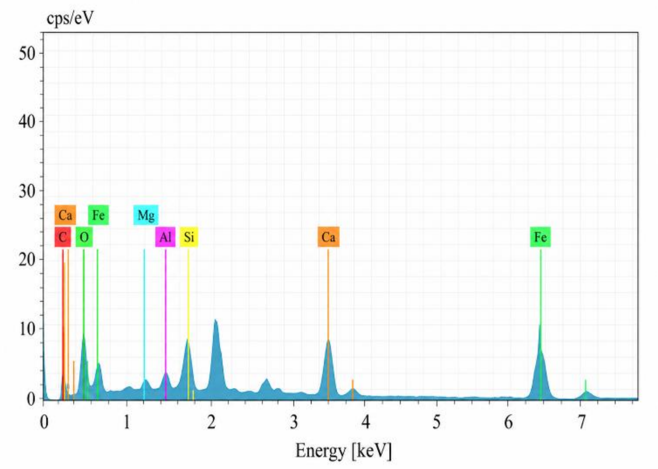

**Fig. 7 An EDS elemental analysis of concrete with 10% CESP-CSA blend as a partial replacement of cement**

From Table 7 (appendix), the (EDS) revealed the presence of Carbon (10.56%), Oxygen (44.90%), Sodium (1.10%), Aluminum (6.04%), Silicon (23.18%), Potassium (7.04), Calcium (4.18%), Titanium (1.05%), Iron (1.95%) In The Control Concrete (Cesp-Csa 0); And Carbon (10.13%), Oxygen (20.49%), Aluminum (3.95%), Silicon (10.63%), Calcium (19.30%), Iron (34.36%) And Magnesium (1.14%) in the (CESP-CSA 10).

This revealed the close resemblance in the elemental composition of the CESP-CSA blend with cement. Reference to BS EN 197-1:2000, the presence of elements like Silicon (Si), Aluminum (Al), Iron (Fe), And Magnesium (Mg) makes the CESP-CSA blend a supplementary cementitious material. These elements are present in clinker. The elements aid in concrete performances such as durability, sustainability, strength, hydration reaction, and setting time [1, 9].

Also, the CESP and CSA blend revealed a lower carbon mass (10.13%) in the concrete specimen at the optimal level of partial replacement compared to (10.56%) for the control specimen. Thus, suggesting the blend resulted in a lower carbon concrete specimen, which had a direct relationship with sustainability.

This is attributable to the presence of CESP and CSA blend, thereby affirming the view by Bhartiya and Dubey [7] and Ogbonna [6] that CESP and CSA blended concrete is a sustainable concrete option that lowers carbon emissions.

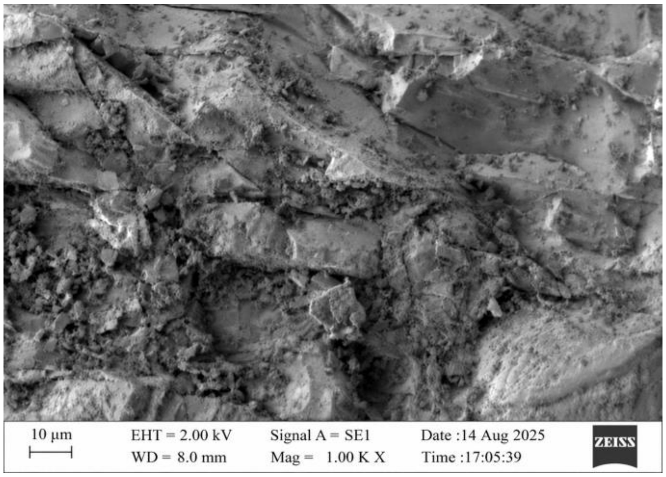

**Fig. 8 SEM analysis of the microstructure of a concrete specimen with 0% partial replacement**

Figure 8 presents an image of the microstructure of a concrete specimen with 0% CESP-CSA blend partially replacing cement. The SEM image revealed inconsistencies in the interaction between the phases of the materials. The larger distinct particles revealed the shape and integration of aggregates with their surrounding paste, thus affecting the bonding of aggregates and cement at the interzonal transition zone [1]. The dark and irregular spots revealed the presence of pores or voids in the concrete specimen [1]. This has the potential to impact the durability and permeability of the concrete specimen [1]. This is attributable to poor compaction during the specimen preparation process. The voids or the microcracks revealed the needle-like crystals of ettringite [1]. Also, the concrete specimen was embedded with pockets of Calcium Hydroxide (CH) (portlandites), and C-S-H gel, which are the main binding phases responsible for concrete's strength [1], and a few unreacted particles of cement or CESP-CSA blend at age 63 days.

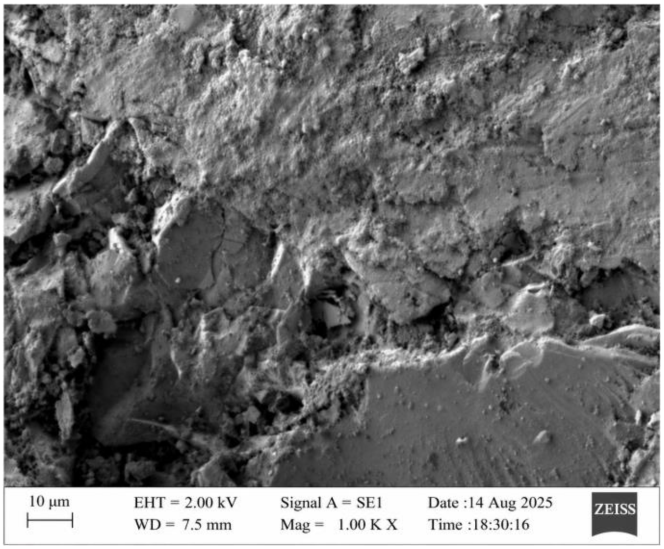

**Fig. 9 SEM analysis of the microstructure of a concrete specimen with 10% partial replacement**

Figure 9 revealed the microstructure and morphology of the blended concrete. It showed a heterogeneous mixture of particles with varying sizes and shapes. An indication of the likely presence of different components within the concrete matrix: cement, aggregates, chicken Eggshell Powder (ESP), and Coconut Shell Ash (CSA) [1]. The visible particles appeared irregular and angular. Indicating the presence of crushed chicken eggshell powder, coconut shell ash particles, and cement grains. The texture revealed a blend of coarse and fine aggregates [1]. The presence of Calcium Silicate Hydrate (C-S-H) gel and portlandites, which formed during cement hydration and pozzolanic reactions of CESP and CSA blend, is an indication of a binding matrix and filling pores according to Ranatunga et al. [1]. The dark spots were indicative of areas of pores and voids within the concrete [1]. This influenced the density and permeability of concrete. The image revealed the integration of CESP and CSA blend within the concrete matrix and their contribution to the overall integrity of the microstructure and strength performance of the concrete.

## 5. Conclusion

This study sought to evaluate the workability, microstructure, and mechanical performance of concrete with cement partially replaced with a blend of chicken eggshell powder and coconut shell ash. The study found that the CESP and CSA blend met the requirements for clinker, thus capable of being used as SCM. Workability of concrete decreased as the percentage of partially replacing cement with CESP and CSA blend increased. Compressive strength, tensile strength, and flexural strength of concrete progressively rose to 10% optimum replacement level, beyond which the dilution effect set in. The elemental analysis of the concrete specimens using the EDS revealed the inherent carbon in concrete specimens with CESP and CSA blend at 10% partial replacement level to be lower than the inherent carbon of the control specimen. Thus, the CESP and CSA blend contributed to carbon reduction in concrete. The SEM images of concrete specimens revealed the presence of calcium silicate hydrate (C-S-H) gel and portlandite in concrete specimens, an indication of a binding matrix. The study found alternative uses for chicken eggshells and coconut shells, otherwise waste materials polluting the physical environment, in concrete production, leveraging the properties of the CSA and CESP blend, which hitherto did not exist. Incorporating sustainability in concrete production has the potential to reduce the cost of concrete and reduce the carbon footprint of cement and concrete. Moreover, this study provides the basis for future studies on sustainable concrete production, most especially using a mixture of two SCMs. Empirically, it has established the chemical composition of CESP and CSA blend, which hitherto was not known, likewise the effect of CESP and CSA blend on workability, compressive strength, tensile strength, flexural strength, and microstructure of a concrete, and the comparative carbon reduction associated with the CESP and CSA blend. The study contributes to agricultural waste valorization as it finds value for agricultural waste in CESP and CSA blended concrete. It also contributes to combating climate change, Sustainable Development Goal 13: Climate Action [38], as it has demonstrated the low-carbon potential of CESP and CSA blended concrete.

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## Appendix

**Table 1. Mix design for C20 concrete with cement partially replaced with a blend of CESP and CSA.**

| Mix ID | CESP- CSA (Kg) | Cement (Kg) | Sand (Kg) | Crushed rock (Kg) | Water-cement ratio (0.58) (Kg) | Total $CO_2$ (kg) (Cradle-to-gate) | $CO_2$ Reduction compared to control (%) |
|---|---|---|---|---|---|---|---|
| **(CESP-CSA 0)** | 0 | 1.52 | 2.27 | 4.55 | 0.88 | 1.21 | 0.0 |
| **(CESP-CSA 5)** | 0.08 | 1.44 | 2.27 | 4.55 | 0.88 | 1.16 | -4.1 |
| **(CESP-CSA 10)** | 0.15 | 1.37 | 2.27 | 4.55 | 0.88 | 1.11 | -8.3 |
| **(CESP-CSA 15)** | 0.23 | 1.29 | 2.27 | 4.55 | 0.88 | 1.06 | -12.4 |
| **(CESP-CSA 20)** | 0.30 | 1.22 | 2.27 | 4.55 | 0.88 | 1.01 | -16.5 |

**Table 2. Properties of CESP and CSA blend**

| Material | chemical composition (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | CaO | $Al_2O_3$ | $Fe_2O_3$ | $SiO_2$ | $SO_3$ | MgO | $(CaO)/(SiO_2)$ |
| Cement | 51.5 | 5.94 | 3.8 | 25.5 | 4.00 | 3.98 | 2.02 |
| CESP-CSA | 92.0 | 1.10 | 0.20 | 0.71 | 1.21 | 1.82 | 129.6 |

**Table 3. Compressive strength performance of concretes**

| Percentage of partial replacement (%) | 7 days ($N/mm^2$) | 28 days ($N/mm^2$) | 63 days ($N/mm^2$) | One-way ANOVA | |
|---|---|---|---|---|---|
| | | | | F-statistics (2,12) | p-value less than 0.05 |
| (CESP-CSA 0) | 13.20 | 22.30 | 24.90 | 4.48 | 0.035 |
| (CESP-CSA 5) | 19.20 | 22.75 | 25.20 | | |
| (CESP-CSA 10) | 20.89 | 23.40 | 26.65 | | |
| (CESP-CSA 15) | 17.00 | 19.12 | 20.15 | | |
| (CESP-CSA 20) | 12.33 | 16.12 | 18.20 | | |

**Table 4. Models explain the compressive strength performance of concretes**

| Model | Equation | $R^2$ (goodness of fit) | Remarks |
|---|---|---|---|
| For 7-Day Strength ($y_7$) | $Y_7 = [-0.063x^2 + 1.25x + 13.20]$ | 0.96 | An indication that 96 % of the change in compressive strength of concrete at age 7 days can be predicted from the proportions of CESP and CSA blend — a very strong model fit. |
| For 28-Day Strength ($y_{28}$) | $Y_{28} = [-0.029x^2 + 0.31x + 22.30]$ | 0.88 | An indication that 88 % of the change in compressive strength of concrete at age 28 days can be predicted from the proportions of CESP and CSA blend — a very strong model fit. |
| For 63-Day Strength ($y_{63}$) | $Y_{63} = [-0.041x^2 + 0.54x + 24.90]$ | 0.93 | An indication that 93 % of the change in compressive strength of concrete at age 63 days can be predicted from the proportions of CESP and CSA blend — a very strong model fit. |

**Table 5. Flexural strength performance of concrete against the age of concrete**

| Percentage of partial replacement (%) | 7 days ($N/mm^2$) | 28 days ($N/mm^2$) | 63 days ($N/mm^2$) |
|---|---|---|---|
| 0%(CESP-CSA) | 2.24 | 2.90 | 3.14 |
| 5%(CESP-CSA) | 2.71 | 3.05 | 3.15 |
| 10% (CESP-CSA) | 2.80 | 3.85 | 3.25 |
| 15% (CESP-CSA) | 2.59 | 2.75 | 2.70 |
| 20% (CESP-CSA) | 2.16 | 2.52 | 2.63 |

**Table 6. Water absorption and long-term compressive strength of CESP and CSA blended concrete**

| Percentage of partial replacement | Water absorption after 140 days of soil burial (%) | Long-term compressive strength 140 days of soil burial ($N/mm^2$) | PH of soil | Moisture content (%) | Temperature ($^{o\,C}$) | Loss of ignition of soil (%) |
|---|---|---|---|---|---|---|
| (CESP -CSA 0) | 0.70 | 28.00 | 6.3 | 87 | 27 | 13 |
| (CESP -CSA 5) | 0.60 | 28.70 | | | | |
| (CESP-CSA 10) | 0.40 | 24.00 | | | | |
| (CESP-CSA 15) | 0.30 | 21.25 | | | | |
| (CESP -CSA 20) | 0.20 | 20.25 | | | | |

**Table 7. EDS elemental analysis of the concrete with cement partially replaced with 0% and 10% CESP and CSA blend**

| **Element** | **(CESP-CSA 0) Mass Norm. [%]** | **(CESP-CSA 10) Mass Norm. [%]** |
|---|---|---|
| Carbon | 10.56 | 10.13 |
| Oxygen | 44.9 | 20.49 |
| Sodium | 1.1 | - |
| Aluminum | 6.04 | 3.95 |
| Silicon | 23.18 | 10.63 |
| Potassium | 7.04 | - |
| Calcium | 4.18 | 19.30 |
| Titanium | 1.05 | - |
| Iron | 1.95 | 34.36 |
| Magnesium | - | 1.14 |
| Sum | 100.0 | 100 |