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Assessing the Effects of Coffee Husk Ash (CHA) and Eggshell Powder (ESP) as Partial Replacements for Cement and Spent Coffee Grounds (SCG) as Partial Replacement for Sand on the Compressive Strength of Concrete

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Abstract: *Sustainability is a global concern, with waste production and the carbon emissions from the construction industry contributing significantly. This study assesses the utilization of waste products as partial replacements for cement and sand. Coffee Husk Ash (CHA) and Eggshell Powder (ESP) for cement and Spent Coffee Grounds (SCG) for sand. In phase one, 50x50mm mortar samples with CHA and ESP in 5%, 10%, 15%, and 20% partial cement replacements were tested for compressive strength. The highest compressive strength after 28 days was observed in samples with 10% cement replacement containing (1) 75% ESP with 25% CHA and (2) 100% ESP. Phase two confirmed these results using 100x200mm concrete samples with water-cement ratios of 0.4 and 0.6 and adding 15% SCG as partial sand replacement. The highest compressive strength increase, 17.75%, occurred with a 0.4 W/C ratio and 10% cement replacement (75% ESP and 25% CHA) without sand replacement.*

Keywords: Sustainable Construction, Coffee Husk Ash (CHA), Eggshell Powder (ESP), Spent Coffee Grounds (SCG)

1. INTRODUCTION

The Philippines faces a significant waste generation and disposal issue. Metro Manila alone contributes to approximately 8,600 tons of waste daily. There is an urgent need for appropriate waste disposal solutions, with reusing and recycling being the most socially acceptable methods [4]; [15].

Concrete is the second most-consumed resource on earth besides water (Rodgers, 2018). However, the process by which these materials are obtained not only comes at the cost of depleting natural resources but also contributes significantly to carbon emissions and ecosystem disruption [9]. According to data from [7] on the global production volume of cement, an estimated 4.4 billion tons were manufactured in 2021. Additionally, this production simultaneously resulted in the emission of 1.7 billion metric tons of carbon dioxide, constituting a noteworthy 4.58% of the overall global carbon emissions [14].

There have been many previous studies of utilizing various material wastes as replacement materials in concrete. Alternative materials like coffee husk ash (CHA), eggshell powder (ESP), and spent coffee grounds (SCG) have shown promise as sustainable substitutes due to their availability as waste products and potential benefits in reducing the carbon footprint associated with concrete production.

While there are separate studies using coffee husk ash (CHA), eggshell powder (ESP), and spent coffee ground (SCG) as replacements for cement and sand, none have comprehensively used these materials and examined their combined effects in a single specimen to optimize compressive strength.

Coffee husk ash (CHA) is a by-product of coffee processing in which the encasing of the coffee beans is removed and burned. Spent coffee grounds (SCG) are the leftover grounds that remain after brewing coffee. The similarity of the texture and particle size of coffee grounds to sand was used as a main basis for possibly using it as a partial replacement [3]. On the other hand, coffee husks possess pozzolanic characteristics when added to cement due to their silica content.

Previous studies conducted by Gedefaw et. al. [1], Asfaw [11], Gashaahun [2], and Roychand et. al. [12], have shown that a replacement of a certain percentage of either CHA or SCG, increases the compressive strength. This study aimed to test the effectiveness of using CHA and SCG, in order to create a larger impact in reducing coffee waste.

Regarding eggshell wastes, around 661.39 thousand metric tons of eggs are produced each year in the Philippines. Researchers have explored the possibility of incorporating eggshell powder (ESP) into concrete as a partial replacement for cement. Multiple studies have proven that the inclusion of ESP to a certain percentage, usually up to 15%, increases the overall compressive strength of concrete and enhances its performance [5]; [6]; [13].

Coffee by-products generally contribute to environmental pollution. Since proper disposal of coffee wastes is not normally practiced, contamination of land and surface water is possible [8]. Further, eggshell wastes decompose and produce ammonia, hydrogen sulfide, and amine that negatively affect the surrounding environment [10].

The principle behind combining CHA and ESP as partial replacements for cement is based on the previous results of studies that explored CHA in concrete. It was found in the studies of [5]; [6]; [13], that an increase in the percentage of CHA replacement typically decreases the compressive strength of concrete. Studies conducted for ESP partial replacement found that an increase of around 15 to 20 percent leads to improved compressive strength [5]; [6]; [13]. Thus, ESP replacement is employed to remedy the quick decrease in strength to utilize more waste products.

Exploring possible sustainable alternatives for nonrenewable materials such as cement and sand will benefit the field. Thus, this research aims to fill this gap by investigating how these waste materials can be beneficial to the compressive strength of concrete when combined. In addition, this study seeks to establish novel insights into sustainable concrete.

2. OBJECTIVES

The researchers aim to evaluate the potential effects of incorporating coffee husk ashes and eggshell powder as partial replacements for cement and spent coffee grounds (SCG) as a partial replacement for sand in concrete. The specific objectives include the following:

a. To assess the effect of the mortar mixture composition of CHA and ESP partial replacement on the development of mortar compressive strength after 7 and 28 days. This is phase one of the research. Further, in this phase the maximum percentage of CHA and ESP that yields the highest compressive strength will be determined.
b. To evaluate the effect of SCG as a partial sand replacement in concrete with varying water-cement ratios, employing the maximum CHA and ESP mixture obtained from the mortar samples. This is phase two of the research.
c. To provide visual representation of the effect of these partial replacements through microstructural analysis using Scanning Electron Microscopy (SEM) on the sample that yielded with the best combination of CHA and ESP results from phase two.
d. To evaluate the cost-effectiveness of these alternative materials in concrete.

3. METHODS

3.1 Preparation of CHA

The coffee husks were exposed to sunlight and subsequently, ground into a powder using a grinder to achieve a texture like cement. The coffee husks were turned into ashes through the process of open fire burning. The materials were burned at approximately 400 degrees Celsius for three (3) hours and the ashes were sieved through a No. 100 sieve.

3.2 Preparation of ESP

The sourced eggshells were bought in powdered form. It was then air-dried for 24 hours before sieving through a No. 100 sieve. The crushed eggshells were subjected to heating at 100°C for twelve (12) hours in the oven.

3.3 Preparation of SCG

To practically convert the SCG into biochar, the sun-dried SCG was placed inside a large aluminum pan. The pan was covered with an aluminum sheet topped with soil, ensuring a tight seal and simulating an oxygen-restrictive environment. Using the scrap wood, the SCG from the pan was heated and burned at 400 degrees Celsius for three (3) hours. Finally, the heated SCG was sieved through a No. 4 Sieve.

3.4 Experimental Program

The mortar specimens, varying weights of combined CHA and ESP (0%, 5%, 10%, 15%, and 20% by mass) were used as partial replacements for cement to determine the optimal proportion yielding the highest compressive strength [1]; [13].

The concrete specimens, on the other hand, had a constant 15% SCG sand replacement (by volume) and various water-cement (W/C) ratios, specifically 40% and 60%.

For Phase 1, mortar specimens of 50 mm x 50 mm x 50 mm were tested. A total of 210 specimens were cast for mortar testing. Table 3.4.1. shows the number of mortar specimens for each partial replacement cases. These variations in the specimens were produced for both the 7-day and 28-day mortar batches, and subsequent curing processes were applied.

Table 3.4.1. Number of Mortar Specimens

	7- and 28-days Curing				
Cement Replacement (%)	**0%** CHA 100% ESP	**25%** CHA 75% ESP	**50%** CHA 50% ESP	**75%** CHA 25% ESP	**100%** CHA)% ESP 0% ESP
5	5	5	5	5	5
10	5	5	5	5	5
15	5	5	5	5	5
20	5	5	5	5	5
0			5		
Total			210		

For Phase 2, concrete specimens of 100 mm by 200 mm cylinder were casted. A total of 40 specimens were created, with variations including 40% and 60% water-cement (W/C) content. Table 3.4.2 shows the number of concrete specimens for each partial replacement cases. Each batch comprised of 5 specimens and cured for 28 days. Further, two mortar mixes that yielded the highest strengths were adapted, one comprising 25% CHA and 75% ESP, and the other consisting of 0% CHA and 100% ESP. These variations in mixes were subsequently modified to include a 15% partial replacement for sand with SCG.

Table 3.4.2. Number of Concrete Specimens

Mixture	**Water-Cement Ratio**	**28 days**	**Total**
C28	40%	5	5
	60%	5	5
C28-H25E75	40%	5	5
	60%	5	5
C28-H25E75-S	40%	5	5
	60%	5	5
C28-H0E100-S	40%	5	5
	60%	5	5
Total Specimen for Phase 2:			40

The samples were labeled accordingly: C28 represents the concrete sample that was cured for 28 days, H25 represents a CHA replacement of 25%, E75 represents an ESP replacement of 75%, and S indicates whether a 15% SCG sand replacement is in the mixture.
The rationale behind adapting the two proportions from phase 1 to phase 2 lies in the desire to carry forward the optimal blend of CHA and ESP identified in the mortar specimens to the concrete specimens. By doing so, the researchers assessed the performance of the identified optimal mixtures in a more practical and applicable setting, which is the concrete mix.

4. RESULTS AND DISCUSSION

A summary of the results obtained from the study conducted may be found in the succeeding chapter. The compressive test results of the mortar specimens may be found in Section 4.1 while the compressive test results of the concrete specimens may be found in Section 4.3.

4.1. Compressive Test Results of 7 Days Mortar Specimens

The coding system used in the table represents the mortar mix (M) with specific percentages of Coffee Husk Ash (H) and Eggshell Powder (E). For example, "M20-H100E0" indicated a mortar specimen with 20% cement replacement using 100% Coffee Husk Ash (H) and 0% Eggshell Powder (E). The results were compared to a control mortar mix (MC) with no cement replacement.

Table 4.1.1. **7**-Day Mortar Strength

% Cement Replacement	CODE H=CHA E=ESP	7-day Compressive Strength (MPa)	% Difference From Control
0	MC	12.6	0%
5	M5-H0E100	8.9	-29%
	M5-H25E75	14.9	-10%
	M5-H50E50	14.1	13%
	M5-H75E25	11.3	19%
	M5-H100E0	10.9	-14%
10	M10-H0E100	21.1	68%
	M10-H25E75	15.1	20%
	M10-H50E50	10.6	-16%
	M10-H75E25	11.6	-8%
	M10-H100E0	13.6	8%
15	M15-H0E100	13.1	4%
	M15-H25E75	13.0	3%
	M15-H50E50	5.8	-54%
	M15-H75E25	5.5	-57%
	M15-H100E0	4.4	-65%
20	M20-H0E100	9.0	-28%
	M20-H25E75	6.7	-47%
	M20-H50E50	5.2	-59%
	M20-H75E25	3.2	-74%
	M20-H100E0	2.5	-80%

At the 7 days curing point, the ordinary Portland cement was the primary source of the early hydration of the mortar samples. From this point, coffee husk ashes can start contributing to strength through interacting in the pozzolanic reactions with calcium hydroxide [1]. The ESP also acts as a filler to create a denser material in addition to the chemical pozzolanic reactions that it helps develop in early strength [5]. Naturally, the denser material with lesser porosity proved to be an important factor contributing to the increase in strength. The results verified that ESP is a great material for cement replacement alone. If it should be combined with CHA, a replacement of H25E75 should be adapted.
At the 5% to 15% cement replacement, the specimens showed varied results, with some combinations outperforming the control mix while others significantly underperforming. It was found that an increase in strength occurred for up to 10% cement replacement before substantial decreases in strength were observed. Previous studies that tested CHA as a partial replacement to cement received similar results in which the specimens that have shown an increase in strength typically range within the 5%-10% replacement of material. The primary reaction in mortar materials was the hydration of cement to form calcium silicate hydrate (C-S-H) gel, which is the main source of strength in the samples.
Further, a percent difference from the control specimen is found in the table above. The negative percentages represent a decrease in the compressive strength while the positive percentages represent an increase. The subsequent decline after peaking at 10% may be attributed to the water absorption of the material, where an increase in the ash material led to decrease in compressive strength. Among all specimens tested from the 7 days mortar batch, those with the highest compressive strength were specimens M10-H0E100 and M10-H25E75, with compressive strengths of 21.1 MPa and 15.1 MPa, respectively. Additionally, these resulted in the highest positive percent differences of 68% and 28%.

Table 4.1.2. 28-Day Mortar Strength

% Cement Replacement	CODE H=CHA E=ESP	7-day Compressive Strength (MPa)	% Difference From Control
0	MC	14.5	0%
5	M5-H0E100	17.0	17%
	M5-H25E75	17.0	17%
	M5-H50E50	11.0	-24%
	M5-H75E25	10.5	-28%
	M5-H100E0	10.2	-29%
10	M10-H0E100	23.9	65%
	M10-H25E75	18.2	25%
	M10-H50E50	12.7	-12%
	M10-H75E25	10.8	-25%
	M10-H100E0	10.8	-26%
15	M15-H0E100	14.8	2%

% Cement Replacement	CODE H=CHA E=ESP	7-day Compressive Strength (MPa)	% Difference From Control
	M15-H25E75	14.7	2%
	M15-H50E50	7.1	-51%
	M15-H75E25	9.0	-38%
	M15-H100E0	5.5	-62%
20	M20-H0E100	12.4	-14%
	M20-H25E75	8.7	-40%
	M20-H50E50	7.4	-49%
	M20-H75E25	3.6	-75%
	M20-H100E0	3.4	-76%

It was evident that these results mirror the pattern observed in the 7 Day Mortar specimens, wherein the highest compressive strength was attained at a 10% cement replacement rate, maintaining the same proportions of CHA and ESP. Specimens M10-H0E100 exhibited a strength of 23.9 MPa, whereas M10-H25E75 demonstrated a strength of 18.2 MPa.

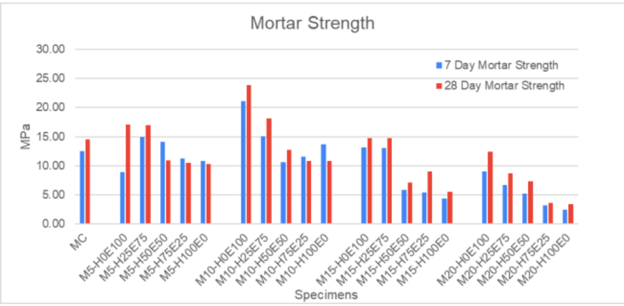

Fig. 4.1.1. Mortar Compressive Test Results

At the 28 days curing point, the pozzolanic reaction from the ESP was more prominent as proven in the increase in compressive strength. This demonstrated its capability to contribute to the formation of C-S-H gel, thereby enhancing the material. Additionally, the filler effect of ESP created a microstructure for a denser material that further strengthened the material. Generally, ESP performed better than CHA at lower replacement levels, particularly at the 10% replacement, where mixes with 100% ESP (M10-H0E100) exhibited a substantial increase in compressive strength. This supports the findings of Lejano et. al (2020), which indicated that the ESP can truly enhance strength of the mortar specimens. Overall, it can be observed that although CHA has pozzolanic properties that can contribute to strength development, the results obtained were not as effective as using ESP alone.

The purpose of selecting the two specimens with the highest compressive strengths, M10-H0E100 and M10-H25E75, was to investigate deeper into the effects of Coffee Husk Ash (CHA) on the compressive strength of concrete. If only the specimen with the highest strength had been chosen, it would have been the one with 100% ESP replacement where this could have prematurely terminated the exploration of CHA at Phase 1. Moreover, the consideration to the specimen with CHA is to re-evaluate the effectiveness of this alternative material to concrete specimens in Phase 2.

4.2. Response Surface Plot

To visualize the effect of the percent combinations of ESP and CHA on the strength of the mortar sample, 3D response plots were illustrated.

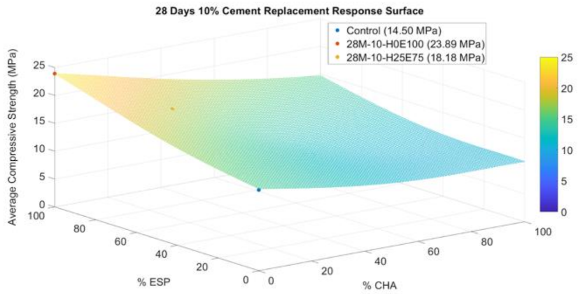

Fig. 4.2.1. Response Surface for Mortar at 28 Days Curing with 10% Cement Replacement

For instance, Figure 4.2.1 depicted the cement replacement with the highest strength results, being that of 10% cement replacement for 28 days of curing. The x-axis on the left represented the percentage of ESP while the x-axis on the right represented the percentage of CHA. The z-axis corresponded to the average compressive strength in MPa.

The control sample was denoted by the blue dot having a strength value of 14.50 MPa at ESP = 0% and CHA = 0%. The 28-M10-H0E100 Sample was located where ESP = 100% and CHA = 0%, shown by an orange dot, raised to a compressive strength of 23.89 MPa. This sample exhibited the highest strength in the plot, indicating that a high percentage of ESP (100%) significantly increases strength. The 28-M10-H25E75 sample was located at ESP=75 and CHA=25 by a yellow dot with a compressive strength of 18.18 MPa. This sample showed a moderate increase in strength in comparison to the control sample suggesting a beneficial effect from the combination of ESP and CHA.

The plot supported the trend in which a positive impact is made on the compressive strength of mortar with the addition of ESP. The surface gradient was steepest when moving along the ESP axis towards 100% ESP, indicating a rapid increase in compressive strength with ESP percentage. The surface gradually descended with the increase in CHA content. In regions where both ESP and CHA were present in moderate amounts, the gradient was gentler, reflecting a more balanced but less pronounced improvement in compressive strength. This interaction between ESP and CHA was observed to be beneficial up to a certain point, beyond which the addition of CHA does not prove to contribute positively to the compressive strength.

4.3. Compressive Test Results of Concrete Specimens

Each concrete specimen is denoted by a code representing the composition of materials used. "CC" stands for Control Concrete and S is for Spent Coffee Grounds (SCG), while the other codes maintain the same definitions as in phase 1.
Phase 2 involved re-evaluation of the results from phase 1 with the addition of investigating the effect of sand

replacement with SCG. Based on the data, it became evident that the role of SCG in the mix proportion was not effective. Despite the presence of CHA and ESP, the compressive strength of concrete decreased, as compared to the specimens without SCG exhibiting higher strengths.

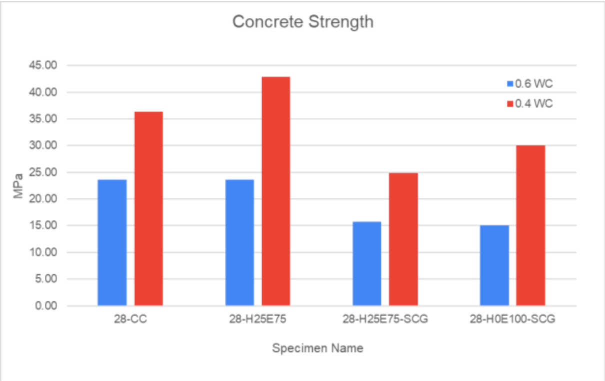

Fig. 4.3.1. Concrete Compressive Test Results

The concrete specimens with the highest compressive strength, regardless of the water-cement ratio, had a material proportion of C10-H25E75. At a 10% cement replacement, the compressive strengths reached 42.82 MPa and 23.66 MPa for the 0.4 and 0.6 water-cement ratios, respectively.

Table 4.3.1. 28-Day Concrete Strength

CODE H=CHA E=ESP	28 Days Compressive Strength (MPa)	% Difference from Control
0.4-CC	36.37	0.00%
0.4-C10-H25E75	42.82	17.75%
0.4-C10-H25E75-S	24.82	-31.75%
0.4-C10-H0E100-S	30.03	-17.43%
0.6-CC	23.58	0.00%
0.6-C10-H25E75	23.66	0.35%
0.6-C10-H25E75-S	15.68	-33.48%
0.6-C10-H0E100-S	15.06	-36.13%

It can be observed that the optimal 15% replacement of sand with SCG is not a viable option as it generally decreases the strength of the concrete material. The primary reason for this behavior is that SCG did not meet the expected properties of fine aggregates. Compared to sand, SCG has a lower fineness modulus (2.08) and specific gravity (0.76), indicating finer grains. This increases the surface area, necessitating more cement and water.
The difference in grain size was also observed during the visual inspection, revealing that the grain and texture of SCG appears to be ash-like. In addition, the particle size distribution showed that SCG does not conform to the standard curve for fine aggregates. The SCG curve falls outside the limits set by ASTM C33, with a median particle size of around 0.5 mm compared to 0.85 mm for sand.

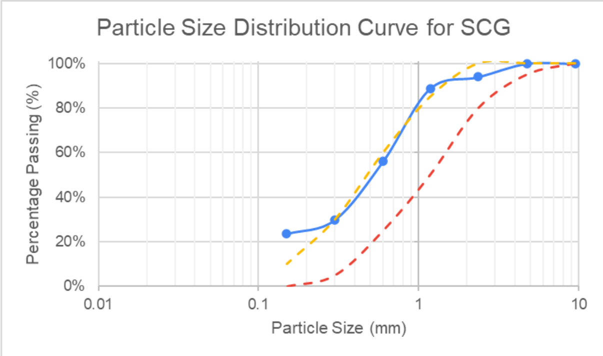

Fig. 4.3.2. Particle Size Distribution Curve for SCG

Thus, with the addition of SCG to the mixture, it increases the ash material while decreasing the sand material. As established in phase 1, a replacement material of cement greater than 10% would result in a reduction of strength. Furthermore, the decrease in strength made by SCG can also be attributed to the absorption of SCG considering that the absorption rate of SCG is very high with a value of 23.97% compared to sand which only has 2.15%. This means that the SCG can absorb a lot of water from the concrete mix leading to an increase in water demand. This reduces the effective water-to-cement ratio in the mix, potentially leading to insufficient hydration of the cement.
In terms of the percentage difference from the control, it can be observed that the specimens with CHA and SCG exhibited lower compressive strength values, with a decrease of around 31.75% to 33.48%. This decrease is due to the additional ash content from both CHA and SCG. In contrast, the 0.4-C10-H0E10-S specimen only showed a 17.43% decrease since despite the presence of the ash content from the SCG, the contribution of ESP is very significant in the strength development of concrete. However, this is not the case with the 0.6 water-cement ratio, where the sudden decrease in strength of the 0.6-C10-H0E100-S specimen, having a highest percentage difference of -36.13% is primarily due to the reduced cement content despite the same percentage content of ESP and SCG as the 0.4 water-cement ratio specimens.
Furthermore, despite prior knowledge of the material properties of SCG, the study proceeded based on the findings by [12], wherein a 30% increase in compressive strength was found at 15% fine aggregate replacement. Thus, the study wanted to verify whether this holds true while conducting an open-fire method, along with the cement replacements to make a more sustainable and economically viable improvement in concrete compressive strength.

4.4. SEM Analysis

The concrete sample that performed the best, namely, 0.4-C10-H25E75, with a compressive strength of 42.82 MPa was analyzed using a SEM machine. The figures above provided magnified illustration of the sample to further examine the structure of the material after the additions of the replacements. Figure 4.4.3. depicted a magnification of 10,000x where fiber-like structures are observed in some spaces of the material which are formed by the eggshell replacements. These fiber-like structures filled the voids in the sample, creating a denser material. No other distinct features of the coffee husk ashes were visibly apparent.

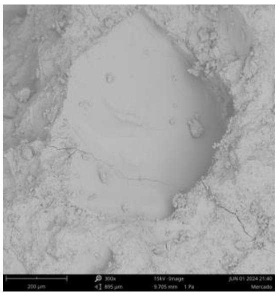

Fig. 4.4.1. SEM at 300x

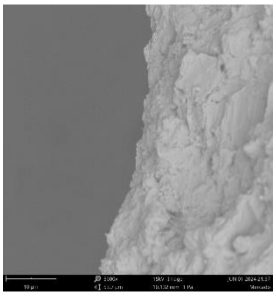

Fig. 4.4.2. SEM at 5000x

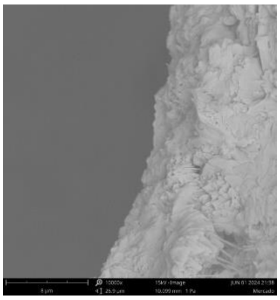

Fig. 4.4.3. SEM at 10000x

4.5. Cost Analysis

Table 4.5.1. showcased the cost analysis for each concrete specimen, where the cost per cubic meter is calculated by the amount of materials present in the cubic meter batch design mix multiplied by the unit cost of the respective materials used. Moreover, the cost efficiency column was derived by dividing the Cost/Volume column by the respective average strength of the specimen. It can be observed that the addition of the replacement materials was able to lower the cost in comparison to the control. However, the cost efficiency column indicated that only specimens of 0.4 W/C for 10% cement replacement of 25% coffee husks and 75% eggshell powder (0.4-C10-H25E75) were able to achieve a lower cost in terms of average compressive strength.

Table 4.5.1. Cost Analysis of Concrete

Specimen	Cost/Volume (Php/m^3)	Cost Efficiency (Php/MPa)
0.4-CC	5895.50	162.10
0.4-C10-H25E75	5812.70	135.75
0.4-C10-H25E75-S	5673.95	228.60
0.4-C10-H0E100-S	5698.65	189.77
0.6-CC	5122.95	217.26
0.6-C10-H25E75	5068.15	214.21
0.6-C10-H25E75-S	4881.30	311.31
0.6-C10-H0E100-S	4896.50	325.13

5. CONCLUSION

The evaluation of CHA and ESP as partial replacements in mortar revealed that for both 7 days and 28 days, the combination of 10% cement replacement with 25% CHA and 75% ESP (M10-H25E75) yielded a higher compressive strength compared to the control mix without replacements, making it the desired blend. CHA's pozzolanic reactions improved due to the calcium hydroxide found in ESP, contributing to strength development over time. Additionally, ESP further enhanced this process by also acting as a filler, resulting in a denser, less porous material that significantly improved compressive strength.

Moreover, the specimen with only eggshells (M10-H0E100) garnered a higher compressive strength than the control specimen for both 7 and 28 days supporting the results of Lejano et. al (2020). In addition, SEM analysis further revealed that the formation of fiber-like structures due to the ESP replacements contributed to the improvement of concrete strength.

In the second phase, the sample that performed the best was using a W/C ratio of 0.4 with 25% CHA and 75% ESP (C10-H25E75). The concrete with SCG yielded an overall decrease in strength in comparison to the control specimen. SCG proved ineffective as a sand replacement, leading to reduced compressive strength due to its lower fineness modulus, high water absorption, and non-compliance with fine aggregate standards.

On the other hand, the cost analysis displayed that specimens C10-H25E75 at 0.4 and 0.6 W/C ratio demonstrated the least cost per compressive strength in reference to the control deeming them the most economical and viable options for concrete production.

Overall, incorporating CHA and ESP as partial replacements increases the compressive strength of mortar and concrete. However, the inclusion of SCG as partial sand replacement in concrete specimens did not improve the compressive strength of concrete. This indicates that SCG is not effective as a fine aggregate replacement. Furthermore, the combination of CHA, ESP, and SCG in concrete did not improve the performance of the material in terms of enhancing compressive strength compared to traditional concrete.

6. RECOMMENDATIONS

In light of this research, the proponents recommend to further explore on the possibilities of SCG as a cement replacement given its material properties after conversion to ash as well as standardizing the pyrolysis process of it. Additionally, testing specific types of coffee husks may have an effect on the pozzolanic properties of the CHA. Further studies should consider focusing on a specific species (i.e. either purely arabica or liberica) to provide more precise insights.

Another recommendation would be to expand the research to include mechanical tests of flexural strength and split-tensile strength. Moreover, research on long-term durability of concrete utilizing CHA and ESP could be conducted to assess the performance of the concrete under various conditions in real life.

Furthermore, it is recommended to incorporate SEM analysis not only on the optimal mix specimen from Phase 2 but also on control specimens to compare differences and confirm structural changes. This would provide deeper insights into the effects of CHA, ESP, and SCG.

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