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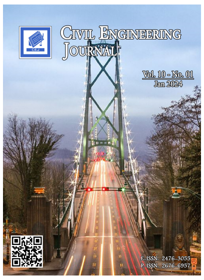

Recycling of Eggshell Powder and Wheat Straw Ash as Cement Replacement Materials in Mortar

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Abstract

Cement is among the important contributors to carbon dioxide emissions in modern society. Researchers are studying solutions to reduce the cement content in concrete to minimize the negative impact on the environment. Among these solutions is replacing cement with other materials, such as waste, which also poses environmental damage and requires landfill areas for disposal. Among these wastes are eggshell powder ash (ESPA) and wheat straw ash (WSA), which were utilized as cement substitutes in green mortar production. Thirteen mixtures were cast, one as a reference without replacement and twelve others that included replacing ESPA and WSA (single and combined) with cement in 2%, 4%, 6%, and 8% proportions of cement's weight. The mechanical (compressive and flexural strength), microstructural (SEM), and thermogravimetric analysis (TG/DTA) properties of all mixtures were examined. The results showed a remarkable improvement in mechanical properties, and the best improvement was recorded for the (4%ESPA+4%WSA) mixture, which reached 73.3% in compressive strength and 56% in flexural strength, superior to the reference mixture. Furthermore, SEM analyses showed a dense and compact microstructure for the ESPA and WSA-based mortars. Therefore, the WSA and ESPA wastes can be recycled and utilized as a substitute for cement to produce an eco-friendly binder that significantly improves the microstructural and mechanical characteristics of mortar. In addition, combining the two materials also presents a viable option for creating a sustainable ternary blended binder (with cement) that boasts superior properties compared to using the WSA or ESPA individually.

Keywords: Eggshell Powder Ash; Wheat Straw Ash; Mechanical Properties; SEM; Differential Thermal Analysis.

1. Introduction

Concrete is widely used in the construction industry because of its versatility, simplicity of obtaining raw materials, low cost, ease of execution, high mechanical strength, impermeability to water, and excellent durability [1, 2]. However, the production of concrete requires a significant amount of natural resources and releases greenhouse gases that contribute to climate change [3]. Cement, the main binding material in concrete, is responsible for about 7% of global CO_2 emissions. Therefore, using recycled or waste materials in the concrete industry is a means to promote alternatives to the current usage of concrete materials and contribute to the global objective of sustainable development [4, 5]. To promote sustainable development, research has focused on extending the service life of concrete structures and developing low-carbon concrete materials and systems [6]. Recycling or using waste materials in the concrete

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manufacturing process is one way to accomplish this. It is therefore feasible to lessen dependency on traditional concrete materials while also contributing to global environmental goals. Eggshell powder is one of these wastes [7, 8], as is wheat straw waste [9, 10]. These wastes are continuously produced locally, and most are disposed of in landfills without benefit. However, integrating these wastes into other industries, such as construction, can provide an excellent solution to minimize their harmful effects on the environment. Additionally, using these wastes as partial substitutes for cement in the construction industry can help reduce the damage caused by cement production.

Eggshells seem to have a significant chemical component in limestone, which is rich in calcium oxide, an essential chemical compound required for forming binder gel, namely calcium silicate hydrate, in cementitious materials. Introducing pulverized eggshell as a substitute cementitious ingredient can significantly decrease cement consumption in concrete production while also protecting natural lime and recycling solid waste products [11]. Several researchers in the literature have employed eggshell powder (ESP) as an alternative to cement. For instance, Pliya & Cree (2015) [12] explored the impact of replacing the cement with white and red eggshell powder (ESP) in proportions of 0 to 20% in a step of 5%. It was found that the flexural and compressive strengths of ESP-base mixtures were lower than those of the mixture without ESP. Tiong et al. (2020) [13] discovered that the incorporation of eggshell powder increased the compressive strength and ultrasonic pulse velocity (UPV) of the lightweight foamed concrete, and the optimal percentage of ESP was 7.5%. Nandhini & Karthikeyan (2022) [14] replaced cement with ESP in various proportions, namely 5%, 10%, 15%, and 20%. The findings revealed that the substitution of 10% ESP in mortar gave optimum compressive strength and enhanced the microstructure. Chen et al. (2022) [15] conducted a study on using ESP as cement filler in the percentages 0 and 15%. It was concluded that an ESP replacement level of around 5% provides the best performance.

On the other hand, wheat is the most widely produced grain crop globally [16]. It is possible to produce between 1.3 and 1.4 kilograms of wheat straw for every kilogram of wheat grain [17, 18]. Usually, the straw is utilized as animal feed or burned in open fields, which poses a significant environmental danger. Nevertheless, the ash was left behind after burning. Qudoos et al. (2018) found that wheat straw ash (WSA) enhanced the hydration reaction and improved the microstructure of the cement composites due to its pozzolanic and filler activity [18]. Thus, wheat straw ash (WSA) was utilized as a cement replacement material in many previous works. Amin et al. (2019) [19] examined how locally available wheat straw ash (WSA) can affect the mechanical strength and pozzolanic potential. They obtained WSA by burning wheat straw at a temperature of 550°C. To test its properties, the researchers replaced 15%, 20%, 25%, and 30% of cement in both mortar and concrete samples. The outcomes of their experiment showed that WSA can replace up to 20% of cement in normal-strength concrete, making it a sustainable option for common household building projects. The effect of replacing cement with WSA in varied percentages of 10%, 20%, and 30% on the properties of concrete was investigated by Khan et al. (2019) [20]. The results showed that the strength of concrete diminishes as the percentage of WSA increases. The 10% substitution was suitable for ordinary concrete. When WSA replaced 20% and 30% of the cement, the strength decreased. Hameed et al. (2021) [21] investigated the impact of utilizing WSA in concrete mixtures as a partial substitute for cement. The cement was replaced (by weight) with 0%, 10%, 15%, and 20% of WSA. The study revealed that when WSA was used as a substitute for cement, compressive strength decreased, while splitting tensile strength and modulus of rupture increased at 10% WSA content. Bheel et al. (2021) [22] investigated the impact of replacing cement with WSA within the 0 to 20% range. Their findings revealed that the optimal replacement ratio was 10% of the cement's weight, resulting in a 12% increase in compressive strength, an 11% increase in flexural strength, and a 10% increase in splitting tensile strength. Comparable results were also recorded by Katman et al. (2022) [23], which found that the optimum substitution rate of WSA was 10% by cement weight.

There have been limited studies in the literature that explored the possibility of using heat-treated eggshell waste as a substitute for cement. Moreover, there is a lack of research that has examined the potential of using eggshell powder ash and straw waste ash together as an alternative to cement. Furthermore, according to Paruthi et al. [24], the high calcium content of ESP makes it useful in various construction substances; however, there is still limited literature on the effects of incorporating eggshell powder in varying percentages on concrete properties. In addition, it is believed that this research is gaining importance locally to address problems related to these wastes due to their production locally in large quantities. Although produced locally in large quantities, there is no investment in reducing or reusing the waste, which creates a serious problem that requires appropriate solutions. Accordingly, this research aims to partially replace cement with percentages ranging from 0 to 8% with ESPA and WSA, individually or in combination. Thirteen mixtures were created, each with different replacement ratios. The experimental investigation encompassed the evaluation of mechanical properties, including compressive and flexural strengths, and the examination of microstructure, calcium hydroxide concentration, and differential thermal analysis (DTA) tests. It is thought that the results of this study are of environmental importance in terms of eliminating waste problems and their need for large areas for landfills on the one hand and, on the other hand, reducing the cement content, a primary contributor to greenhouse gas emissions.

2. Experimental Part

2.1. Materials

Ordinary Portland cement (OPC), natural sand, water, and superplasticizer were the main ingredients used in the production of the fresh mortar. The natural sand has complied with the requirements of EN 196-1 [25]. The sieve analysis of the sand is displayed in Table 1. OPC, as confirmed by the Iraqi Standard Specifications (No. 5) [26], was utilized as the main binding material. Table 2 shows the chemical compositions of cement, while the physical properties are presented in Table 3. The average particle size of cement (d50) is 17.99 µm. The cement particle size distribution is depicted in Figure 1. Superplasticizer type Glenium 54, which has a density of 1.08, Type F according to ASTM C494 [27], was used with all blends. Eggshell powder ash (ESPA) and wheat straw ash (WSA) were utilized as replacements for the cement. Table 2 presents the chemical composition of ESPA and WSA, which were determined using the XRF technique. The eggshell waste (ESP) used in this research was obtained from domestic waste produced locally (in Iraq). This waste was first cleaned and washed with tap water to remove the extra debris and unwanted material. Then, the ESP was air-dried and treated in the oven at 100 °C, then ground to powder and burned in an oven at 500 °C to form eggshell powder ash (ESPA). This preparation method was developed based on previous studies [28–30].

Straw is an agricultural waste in the form of dried leaves, stalks, and plant leaves. It was prepared by burning it in the oven at 650 °C to produce wheat straw ash. After that, the ash was ground to a powder before being used as a cement-replacing material. The ESPA and WSA (Figure 2) powders were passed through a 75 µm-opening sieve. Moreover, the particle size distribution of ESPA and WSA is displayed in Figure 1. The mean particle sizes (d50) of ESPA and WSA are 23.7 and 14.95, respectively.

Table 1. Sieve analysis of sand

Size (mm)	Passing %
2	100
1.6	95
1	65
0.8	33
0.16	8
0.08	0.5

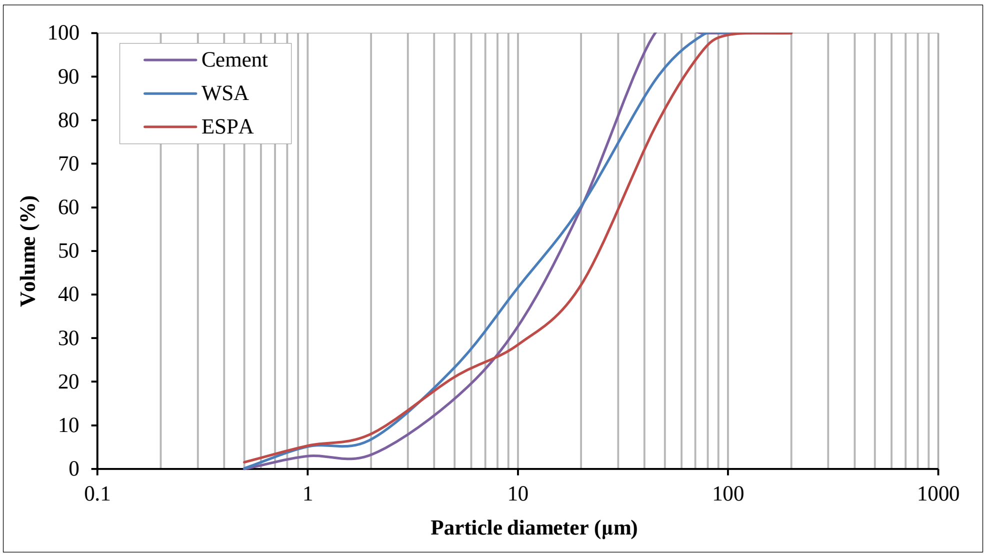

Figure 1. Particle size distribution of the cement, WSA and ESPA

Table 2. Chemical analysis of the cement, ESPA and WSA

Oxide	Content%		
	Cement	ESPA	WSA
CaO	63	82.9	19.8
SiO_2	24	3.1	48.7
Al_2O_3	4	1.8	2.1
Fe_2O_3	5	0.4	8.2
MgO	1.1	4.48	1.8
SO_3	1.64	3.2	0.5
K_2O	--	2.26	15
MnO	--	0.75	0.112
P_2O_5	--	1.6	0.31
L.O.I	3.38	--	--
C3A	3	--	--
C4AF	15	--	--

Table 3. Physical properties of cement

Property	Value
Compressive strength (MPa)	22
Compressive strength (MPa)	26
Initial setting time (hr:min)	1:20
Final setting time (hr:min)	3:05

(a) (b)

Figure 2. (a) Eggshell powder ash (b) Wheat straw ash

2.2. Mix Proportions, Mixing, Casting and Curing

Thirteen mixtures were designed and cast for this research. One control mixture was made without replacement, while twelve other mixtures were made by cast replacing cement with ESPA, WSA, or both. The cement-to-sand ratio was fixed at 1 to 2.75, while the water/binder ratio was 0.4. The mortar mix proportions are illustrated in Table 4. A pan-type mixer was used for mixing the mortar ingredients. The mixing procedure was as follows: First, all the dry materials, including cement, sand, and ESPA and WSA (if they were present), were put into the mixer and mixed for 2 minutes. Next, the water and superplasticizer that had been pre-mixed together were added. This mixture was then mixed for an additional 2 minutes. After stopping the mixer for half a minute, it was turned back on, and the wet materials were mixed for another minute. Once the mixing process was finished, the newly made mortar was placed in both standard cube and prism molds. After roughly 24 hours, the molds were taken out, and the samples were put in a basin of water and left to cure until it was time for examination. A summary of the experimental program is presented in Figure 3.

Table 4. Mix proportions details in grams for each mixture

Mix designation	Cement (g)	Sand (g)	Water (g)	ESPA (g)	WSA (g)	Superplasticizer (g)
C	800	2200	320	0	0	4
A2	784	2200	320	16	0	4
A4	768	2200	320	32	0	4
A6	752	2200	320	48	0	4
A8	736	2200	320	64	0	4
B2	784	2200	320	0	16	4
B4	768	2200	320	0	32	4
B6	752	2200	320	0	48	4
B8	736	2200	320	0	64	4
C2	784	2200	320	8	8	4
C4	768	2200	320	16	16	4
C6	752	2200	320	24	24	4
C8	736	2200	320	32	32	4

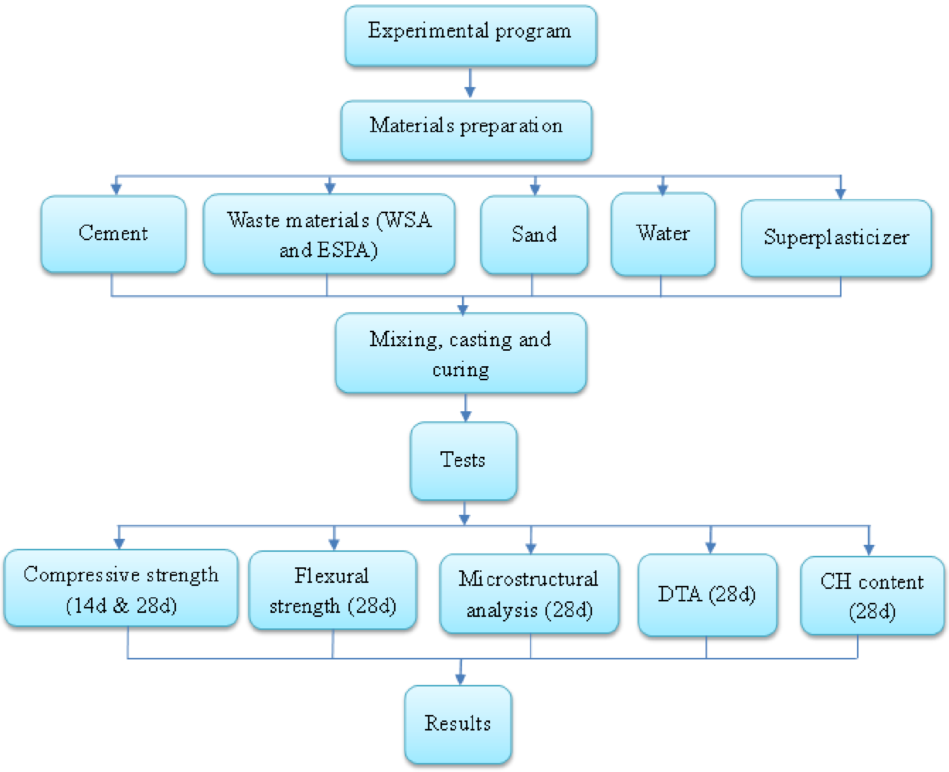

Figure 3. Flow chart diagram of the experimental program

2.3. Experimental Tests

2.3.1. Compressive Strength

The compressive strength test was performed using a cubic specimen with a dimension of 50×50×50 mm^3. The compressive strength, expressed in MPa, was determined by dividing the load that caused the specimen to fail, measured in N, by the specimen's cross-sectional area (mm^2). The test was conducted following ASTM C109 [31] on three samples, and the average value was determined. Figure 4 depicts the specimen under test. Two testing ages were considered: 14 and 28 days.

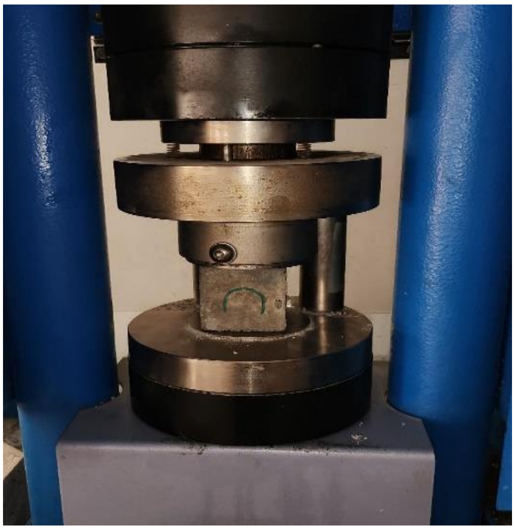

Figure 4. Compressive strength test

2.3.2. Flexural Strength

The flexural strength test for the mortar samples was carried out according to the BS EN 196-1 [25] standard; see Figure 5. A prism having a size of 40 mm × 40 mm × 160 mm was employed to perform the flexural strength test. An average of three prisms has been taken to determine the flexural strength. The flexural strength examination was conducted at 28 days.

Figure 5: Flexural strength test

2.3.3. Microstructural Analysis

Scanning electron microscopy (SEM) was adopted to observe the microstructure of the mortar specimens with and without ESPA and WSA. Small mortar pieces were used for this purpose and tested at 28 days.

2.3.4. DTA Analysis

Eleven samples were investigated using thermogravimetric analysis (TG/DTA). The powder samples have been embedded in a crucible made from ceramic and heated in a thermo-analyzer TG 209 (NETZSCH) at a rate of 10 °C/min under static conditions with nitrogen as a medium from ambient temperature to 1000 °C. The reference material utilized was alumina powder. Both TG and DTG were performed concurrently. Before TG/DTA analysis, all samples had been dried at 105 °C and chilled to room temperature.

3. Results and Discussion

3.1. Compressive Strength Results

Figures 6 to 8 illustrate the results of the mortar compressive strength of the ESPA, WSA, and (ESPA+WSA) mixtures, respectively, at 14 and 28 days. According to the research findings, it was discovered that after 14 days, all mixes incorporating waste as a cement replacement showed a considerable boost in compressive strength. The growth rate varied between 27.8 to 50% for ESPA-based mixes, 36.1 to 61.1% for WSA-based mixes, and 56.3 to 71.5% for ESPA+WSA-based combinations. It was also noted that the greater the replacement rate, the higher the increase in compressive strength. In other words, the mix with the highest replacement percentage (8%) recorded superior compressive strength compared to other mixes for each of the aforementioned replacement types. In the same context, the compressive strength results at 28 days old exhibited a pattern comparable to that at 7 days, but with a higher rate of increase due to the cement's sustained hydration and the wastes' pozzolanic reaction over time. Furthermore, the 8% replacement ratio yielded the highest compressive strength for all replacement types. The ESPA, WSA, and ESPA+WSA mixtures showed improvement rates of 57.3%, 70.7%, and 73.3%, respectively, at 8% content relative to the control mixture.

The improvement in compressive strength can be attributed to the pozzolanic activity of ESPA, which has a high percentage of calcium oxide [32, 33]. Similar results for eggshell powder were also found in previous works [34–36]. Besides, WSA contains silica, calcium oxide, and iron oxide that react with calcium hydroxide during cement hydration to form more C-S-H gel. [19, 37]. These findings are consistent with what has been documented in the literature [38]. Moreover, the compressive strength of blends with WSA increased at a higher rate than that of those with ESPA. This may be because WSA has smaller grains than WSPA, which helps in strengthening the filling effect and densification of the matrix, thus increasing the compressive strength.

Furthermore, the findings revealed that combining ESPA and WSA led to a more remarkable rise in compressive strength than using each material alone. This is because when both materials are present, the mortar matrix becomes abundant in CaO and SiO_2, which leads to the formation of a supplementary CSH gel through the pozzolanic reaction. Ultimately, this newly formed CSH gel enhances the density of the microstructure and strengthens it, leading finally to an increase the compressive strength.

Moreover, the results indicated that the compressive strength values of mixtures containing WSA are higher for a certain replacement ratio than those containing ESPA. This may be because WSA has a smaller particle size than ESPA (as presented in Section 2.1), which enhances the filling effect in WSA mixtures more than in mixtures containing ESPA, leading to an increase in compressive strength.

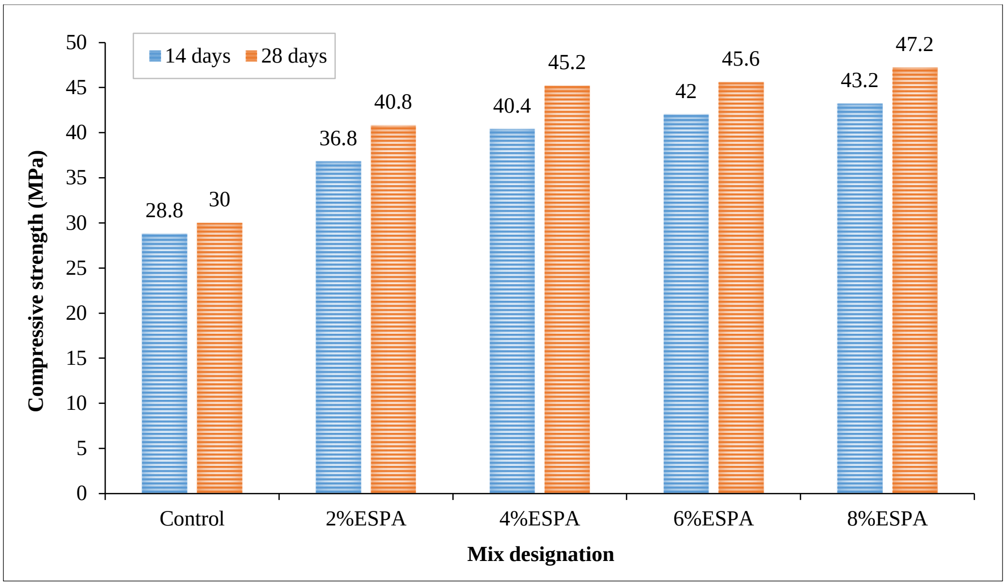

Figure 6. Results of compressive strength test of ESPA mixtures at 14 and 28 days

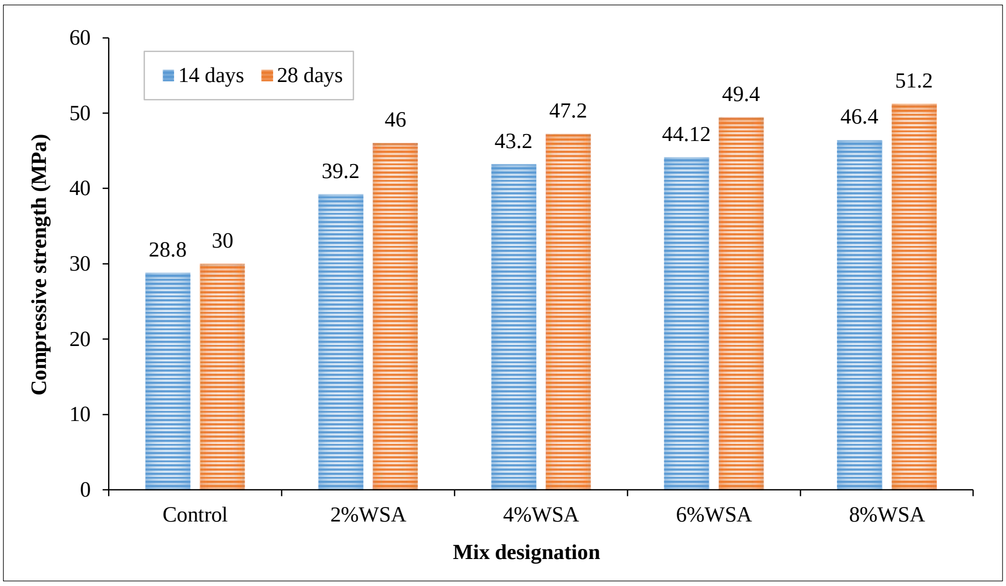

Figure 7. Results of compressive strength test of WSA mixtures at 14 and 28 days

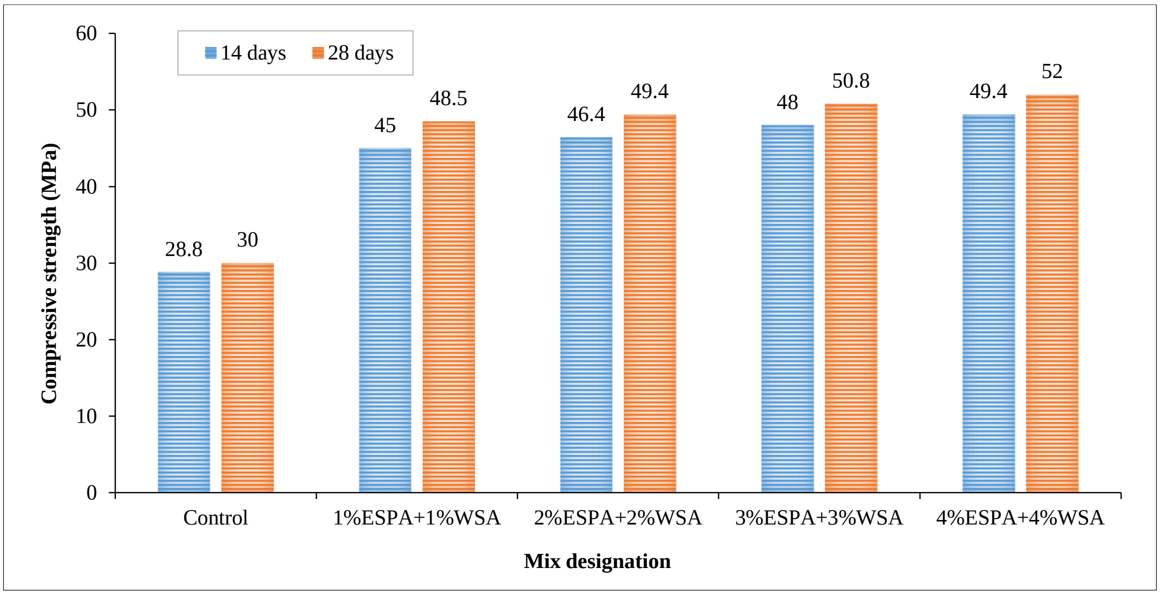

Figure 8. Results of compressive strength test of ESPA+WSA mixtures at 14 and 28 days

3.2. Flexural Strength Results

The flexural strength of concrete influences its deflection, shear strength, and brittleness [38]. As a result, flexural strength is an essential design feature. The effect of the partial substitution of ESPA and WHA by cement on the flexural strength of mortar after 28 days of curing is presented in Figures 9 to 11. Overall, the results revealed that substituting cement with waste material led to a noticeable enhancement in flexural strength, which became more significant as the waste content in the mixture increased. This improvement followed a similar trend to the 28-day compressive strength results. The enhancement rates ranged from 12.1 to 40% for ESPA mixtures, from 15.7 to 44.3% for WSA mixtures, and from 20 to 56% for ESPA+WSA mixtures. In other words, the highest flexural strength values were at an 8% replacement ratio, which were 9.8, 10.1, and 10.9 MPa for the ESPA, WSA, and ESPA+WSA mixes, respectively, compared to 7 MPa for the reference mix. This growth in flexural strength can be attributed to the inherent hydraulic effect and pozzolanic impact of the fine particles of the WSA, as well as to the densification of the microstructure [18, 23, 39]. Additionally, the small size of WSA particles in comparison to cement aids in filling micronized voids, leading to greater flexural strength. Moreover, improving the matrix structure due to the addition of ESPA increased flexural strength [40]. These results are consistent with the findings of earlier studies [41, 42].

Additionally, as in compressive strength, mixtures containing WSA exhibited higher flexural strength compared to those containing ESPA. This is because flexural strength is more influenced by the existence of gaps within the microstructure than compressive strength. The smaller particles of WSA, in contrast to ESPA, contribute to closing the pores within the mixture due to the packing effect, resulting in a greater enhancement in flexural strength.

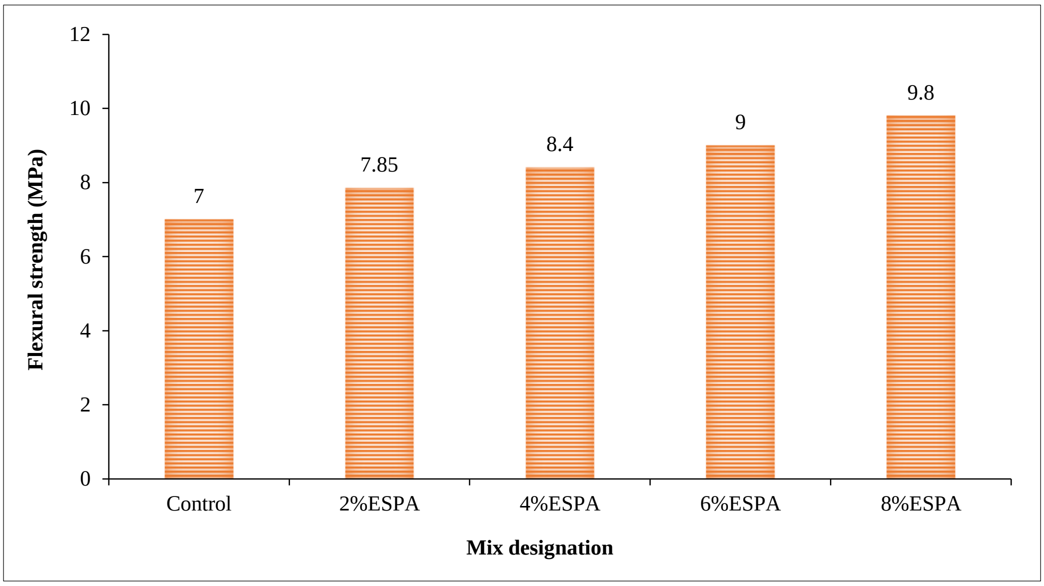

Figure 9. Results of flexural strength of ESPA mixtures at 28 days

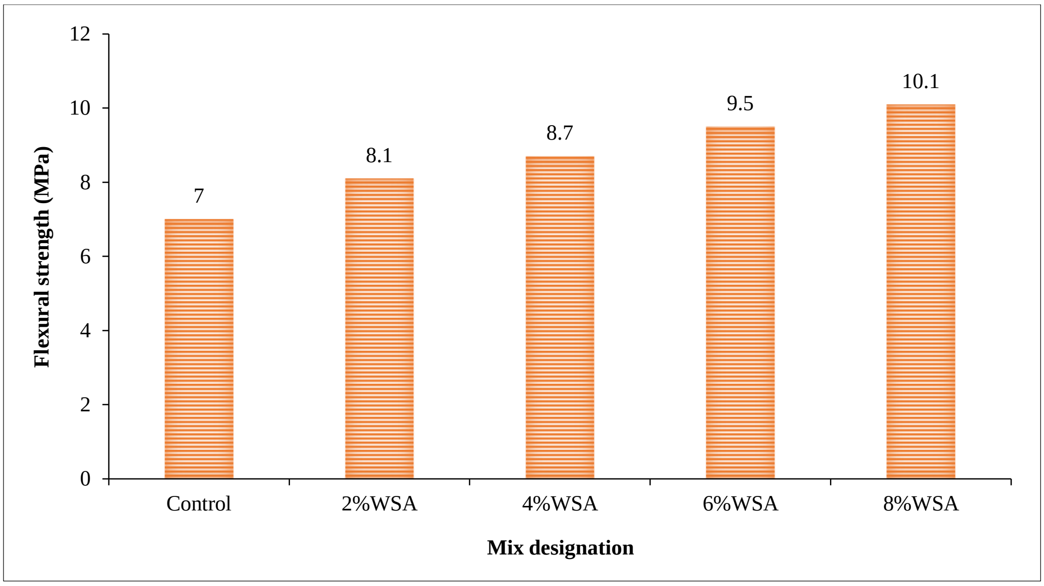

Figure 10. Results of flexural strength of WSA mixtures at 28 days

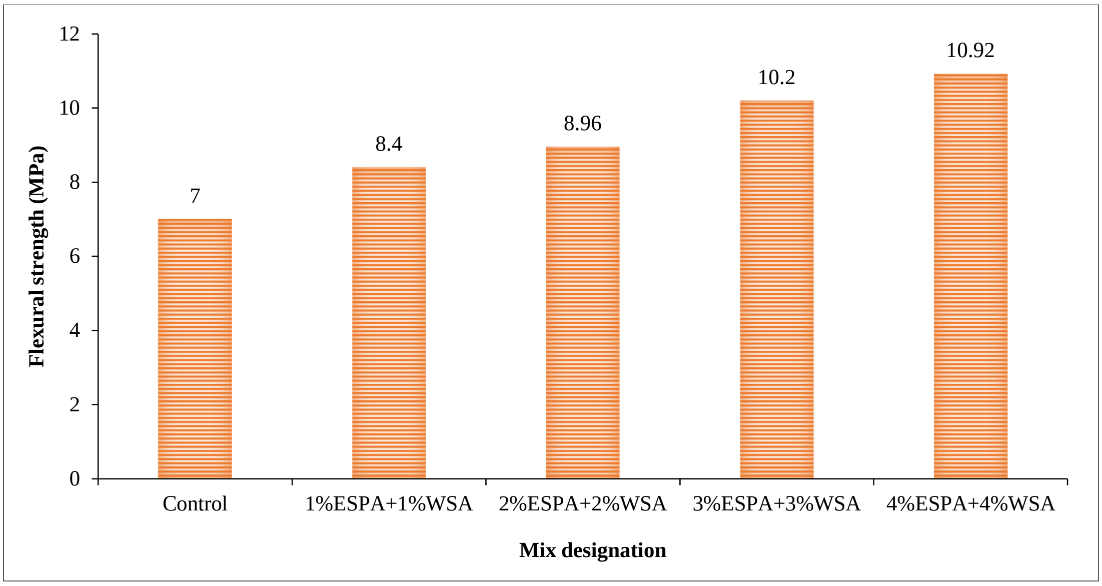

Figure 11. Results of flexural strength of ESPA-WSA mixtures at 28 days

In addition, a statistical correlation was established between the compressive and flexural strengths of ESPA, WSA, and ESPA-WSA mixtures. The relationships are shown in Figure 12, with a quadratic equation chosen for all of them based on the highest correlation factor value (R^2). The results indicate a strong relationship between compressive and flexural strength properties, with correlation factor values of 0.9362, 0.9936, and 0.996 for ESPA, WSA, and ESPA-WSA mixtures, respectively.

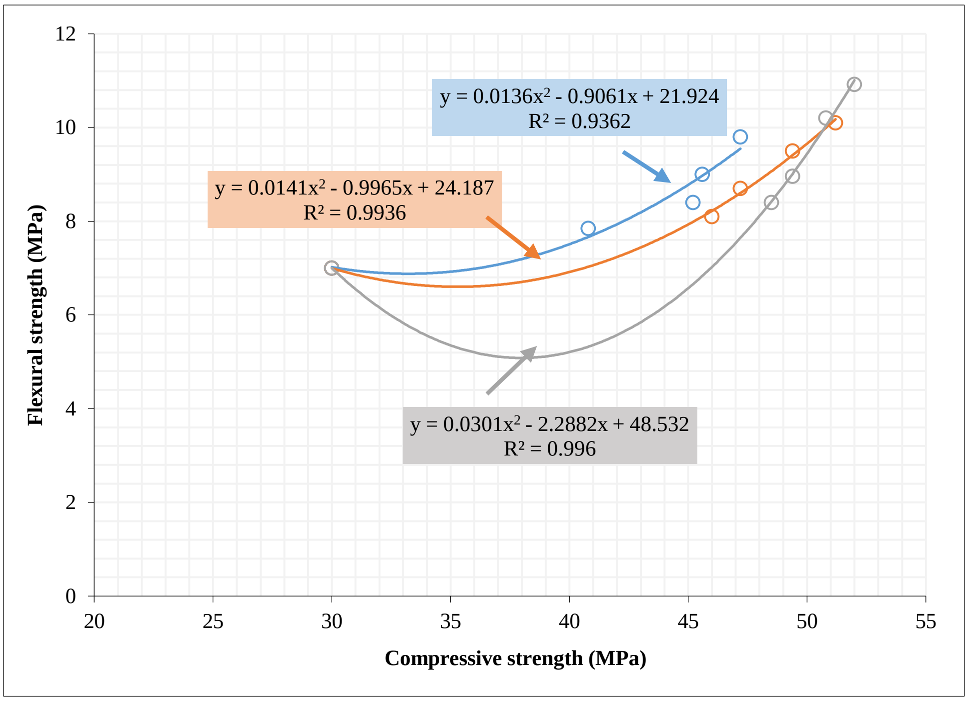

Figure 12. The compressive strength-flexural strength relationships of ESPA, WSA, and ESPA-WSA mixtures

3.3. Microstructure Analysis Results

The morphology of plain cement mortar and samples containing (ESPA), (WSA), and (ESP+WSA) are shown in Figures 13, 14, 15, and 16, respectively. For the plain mortar (Figure 13), it was found that portlandite (plate-like form) and C-S-H (sheet-like structure) were the predominant hydration products in all samples, and a needle-like structure was apparent, indicating the existence of ettringite, according to Li et al. [43]. In samples containing ESPA (Figure 14), ettringite had a rare appearance because of the existence of $CaCO_3$ in the sample, which made the stability of ettringite very low. Shiferaw et al. [44] also found the same results. Moreover, according to Shcherban et al. [34], when ESPA is added to cement paste, it reacts with the cement to form a large network of C-S-H. This results in a denser microstructure and a paste with high strength.

All mortar specimens exhibited abundant hydration products, including lumpy or stacked calcium hydroxide particles and flocculent C-S-H gels. In Figures 14 to 16, the SEM micrographs showed the distribution of C-S-H was nearly increased compared to plain mortar mix due to the cement replacement by ESPA and WSA. The results obtained are consistent with the findings reported in the literature [45, 46]. In these mixes, the range of development of CSH occurred due to the reaction between CH and micro-CaO from ESPA and SiO_2 from WSA to form additional CSH and ettringite. Thus, the explanation for the rise in the strength of the mortar when utilizing ESPA and WSA as partial replacements for cement can be evaluated and explained using the development of hydration products within the microstructure of mortar mixes. By comparing all figures, the formulation of other hydration outputs such as C-S-H and ettringite can be revealed, but in varying amounts depending on the replacement type.

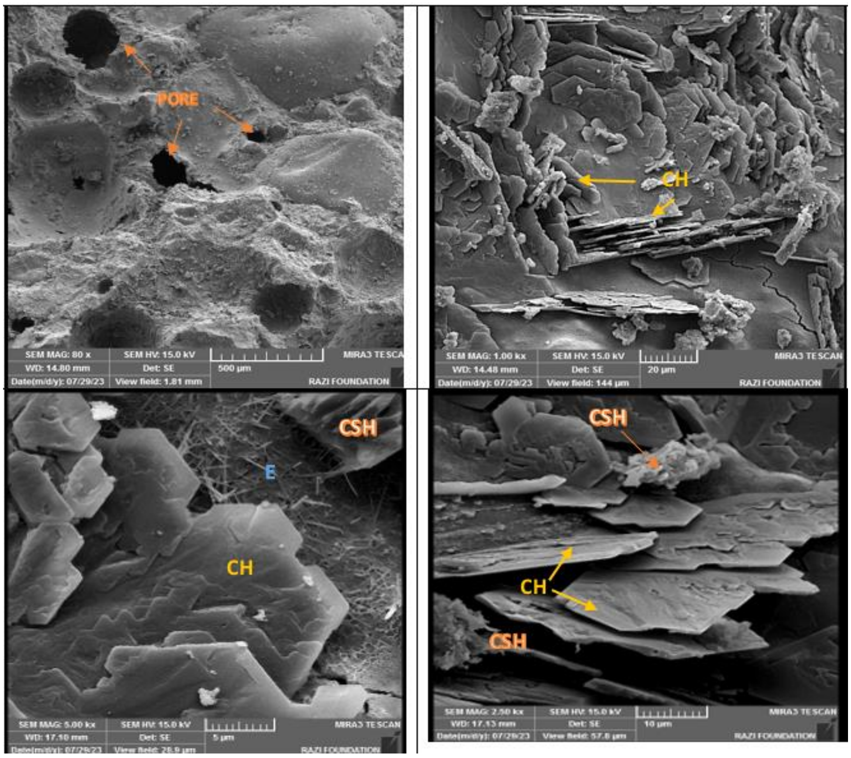

Figure 13. The SEM micrograph for the control mix

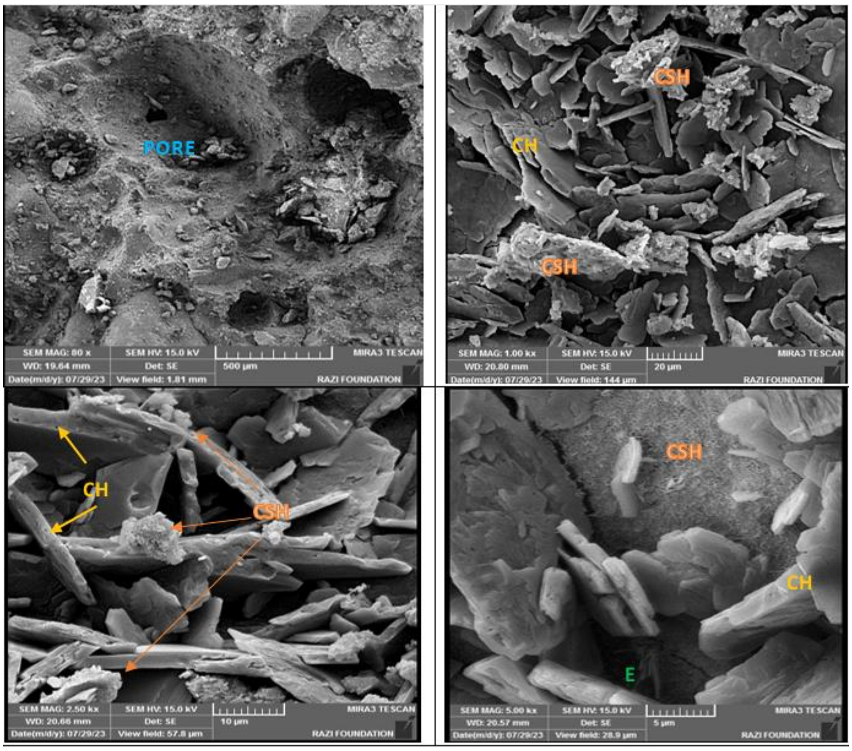

Figure 14. The SEM micrograph for the ESPA-based mortar

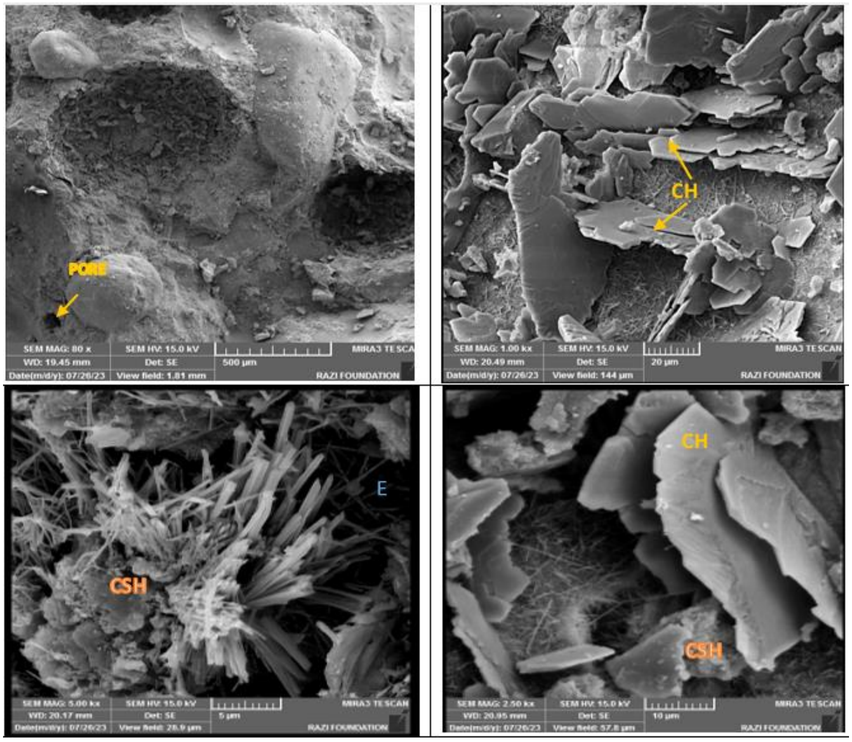

Figure 15. The SEM micrograph for the WSA-based mortar

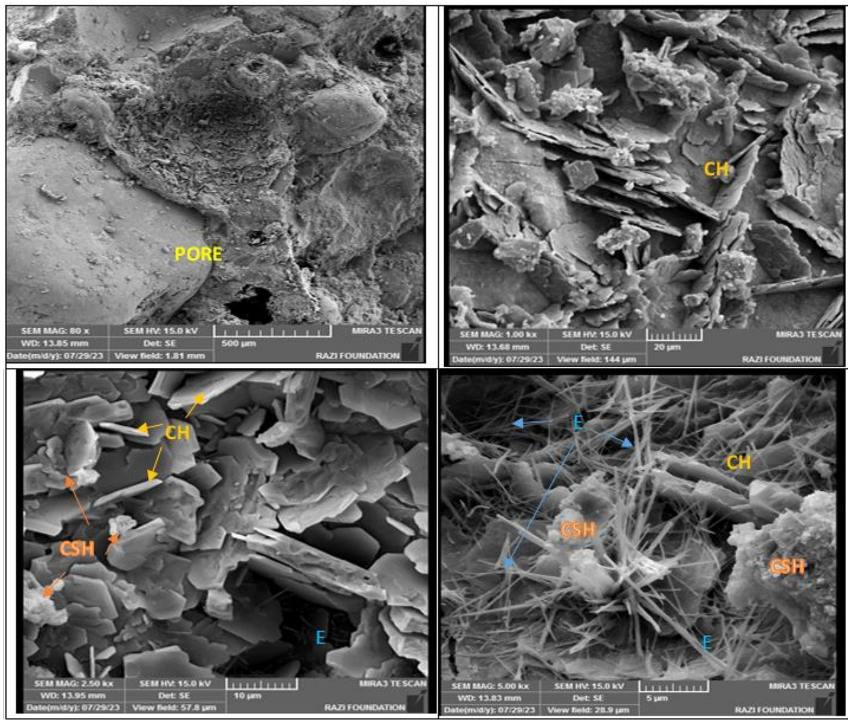

Figure 16. SEM Micrograph for mortar mix with (ESP+WSA)

3.4. Differential Thermal Analysis (DTA) Results

Despite being widely used in clay mineralogy, differential thermal analysis (DTA) has only lately been applied to other domains. The process involves tracking the heat changes caused by any physical or chemical changes as a substance is gradually heated. Thermal changes such as dehydration, crystalline transition, lattice breakdown, oxidation, and decomposition are frequently accompanied by a considerable temperature rise or fall and are suitable for DTA research.

The results of the thermal studies of the investigated samples are shown in Figures 17 to 20. In all DTA charts, the four distinct regions may be seen. The first effect has to do with the evaporation of water that was absorbed on the surface at 25 and 100 °C. This happened as a direct result of the samples absorbing moisture from the air after the cooling step to room temperature, and it happened again when the samples were dried at 104 °C. At temperatures ranging from 100 to 400 degrees Celsius, the second endothermic impact is brought on by the dehydration of CSH and ettringite. The proportion of CaO to SiO_2 in the hydrated cement mixture determines the temperature at which the individual components in the mix begin to lose water. The maximum temperatures of the third stage range from 430 to 460 °C. This leads one to believe that the $Ca(OH)_2$ created during the hydration process has been broken down, considering the subsequent reaction:

$$Ca(OH)_2\,(s) \rightarrow CaO\,(s) + H_2O\,(g) \tag{1}$$

The hydrated molecule is decarbonized by calcium carbonate in an endothermic reaction at around 790°C. The $CaCO_3$ was computed from the weight loss by assuming the following decarbonisation process [47].

$$CaCO_3\,(s) \rightarrow CaO\,(s) + CO_2\,(g) \tag{2}$$

In ESPA samples, $CaCO_3$ decomposition started at 740 °C, as shown in Figure 18, and the peaks illustrated an endothermic reaction compared with the control mix in Figure 17. The ESPA mix displayed higher intensity because of the higher levels of calcium carbonate in the mix. Figures 19 and 20 showed a higher intensity in peaks at temperatures between 420-450 °C, which indicates an additional reaction for consumption of CH; this impact can be related to the presence of additional silica and alumina from the WSA, which contributes to the occurrence of the pozzolanic reaction in a greater proportion in these mixtures [48].

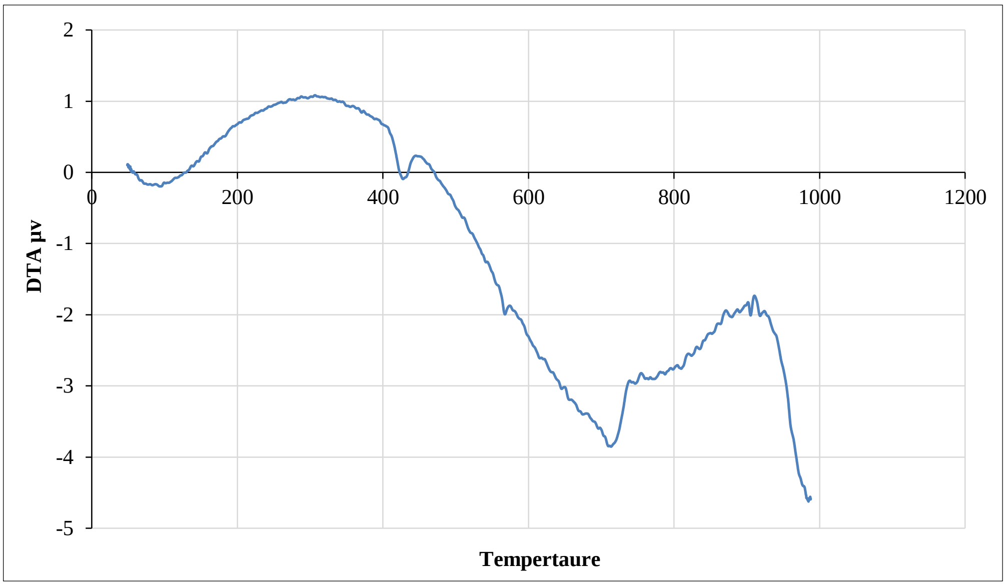

Figure 17. The DTA curve for the control mix

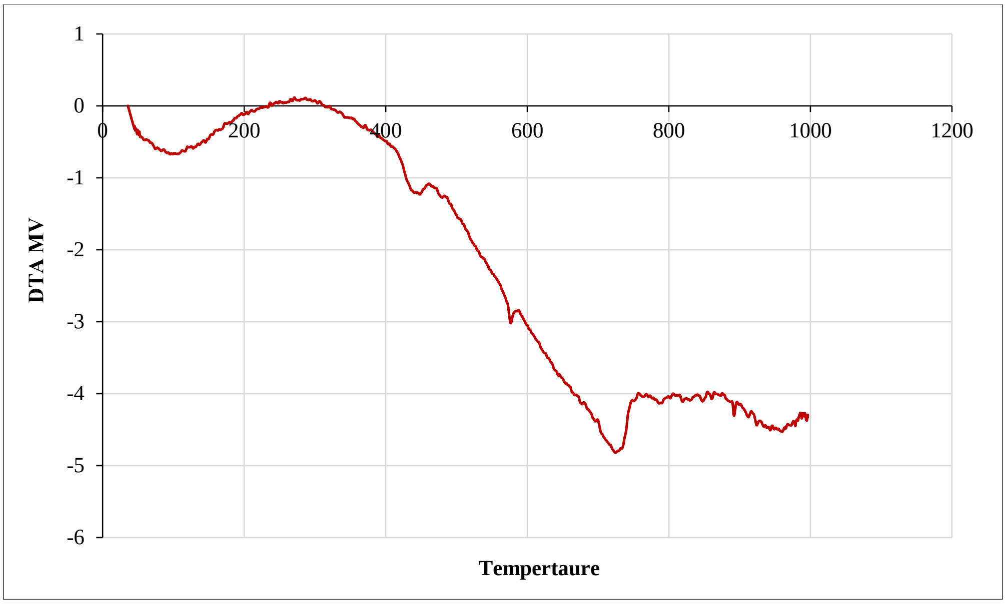

Figure 18. The DTA curve for the ESPA mix

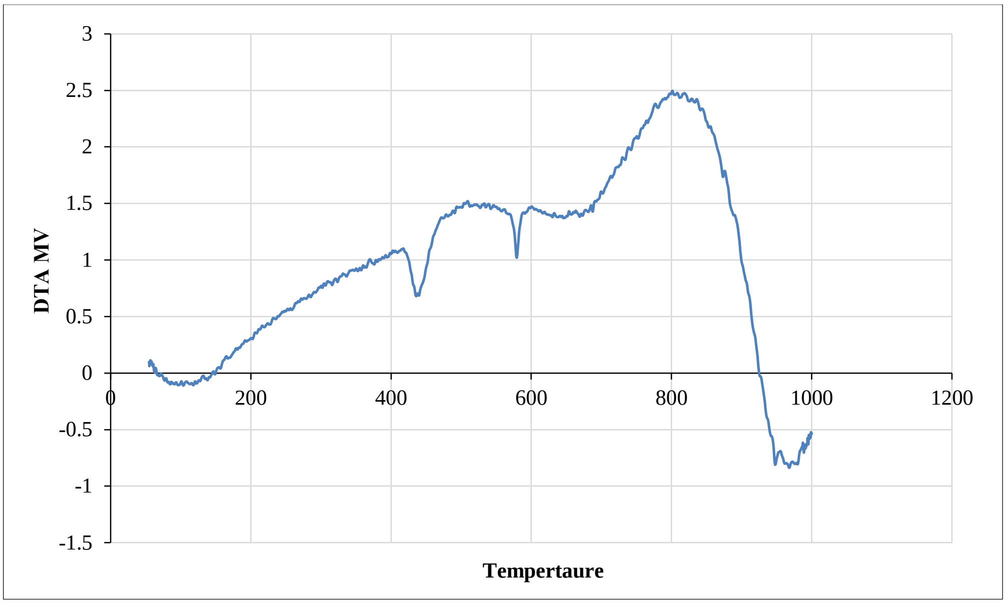

Figure 19. The DTA curve for the WSA mix

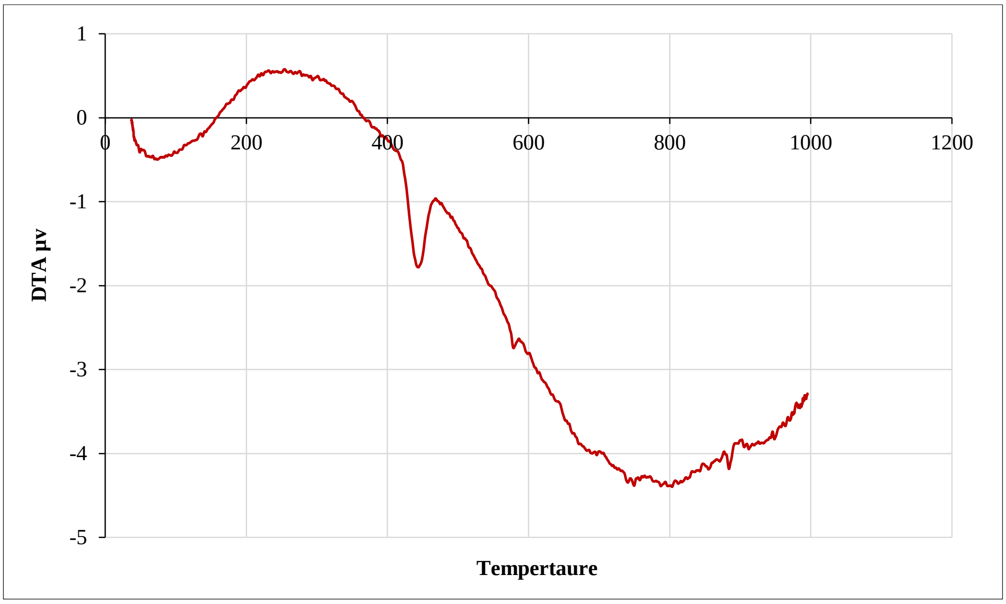

Figure 20. The DTA curve for the ESPA+WSA mix

3.5. CH Content Results

Determining CH levels in concrete samples helps monitor hydration over time. At a temperature range of 430-470°C, there is a significant endothermic reaction that causes the decomposition of CH, which was generated during the hydration stage. The amount of CH present can be determined by calculating the percentage of weight loss between the initial and final temperatures of the peak relevant to the reaction, as detected from the thermogravimetric analysis (TGA) curve:

$$Ca(OH)_2\ (s), \rightarrow CaO\ (s) + H_2O\ (g) \tag{3}$$

In addition, this analysis allows for estimating CH content from weight loss in paste samples. Taylor's formula was used to calculate the (CH) content [49].

$CH\% = WLCH\%\ (MWCH / MWH_2O)$

Where:

- MWH_2O = "molecular weight of H_2O= 18 g/mol".
- MWCH = "molecular weight of CH= 74 g/mol".
- WLCH = "weight loss during the dehydration of CH as a percentage of the ignited weight".

In Figure 21, the CH content of a control mortar mix and mixes with added ESPA, WSA, and (ESP+WSA) wastes is displayed. The figure shows that the use of ESPA and WSA in cement paste resulted in lower CH levels in all mortar mixes compared to the control mix. These results are compatible with the previous work [18]. The decrease in CH levels can be attributed to the reactivity of both WSA and ESPA in the cement paste, which consumed CH through the pozzolanic reaction. These findings were confirmed by the mechanical properties and microstructure characterization results, which demonstrated that ESPA and WSA effectively enhanced the mechanical properties and strengthened the internal structure of cement mortar. These materials are thus considered environmentally friendly supplementary cement materials.

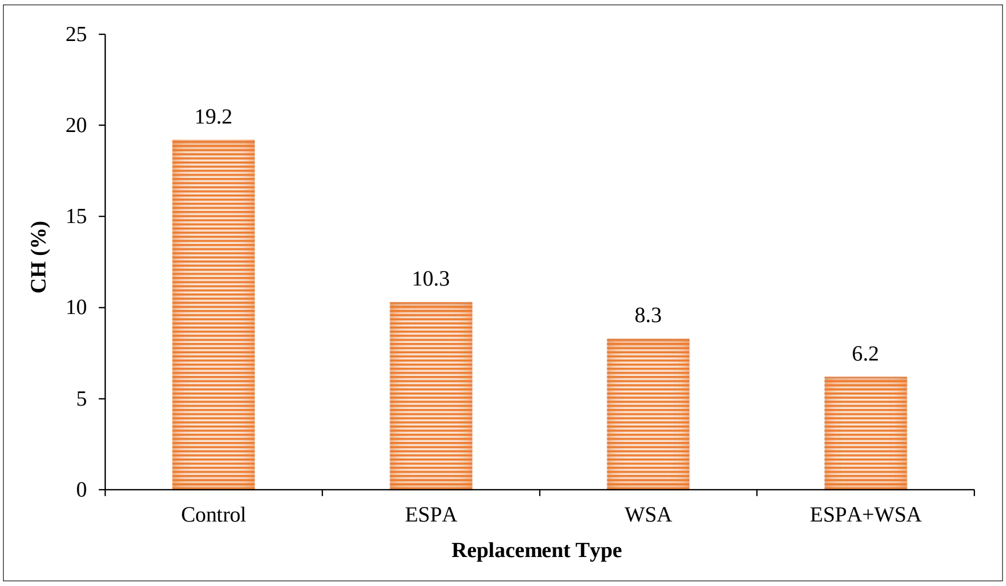

Figure 21. The CH content for the plain mortar and ESPA, WSA and WSPA+WSA mixtures

4. Conclusions

This research aims to develop an environmentally friendly mortar that can be made by replacing cement with waste materials like ESPA, WSA, and ESPA-WSA. 13 different combinations were made, using 0 to 8% of the waste materials in each mixture. The study examined the mechanical properties, thermal analysis, and calcium hydroxide content, and also analyzed the microstructure of the hardened mortar. After analyzing the results, the following conclusions are made:

- By replacing cement with ESPA and WSA wastes, it is possible to significantly improve the mechanical properties of the hardened mortar. The level of improvement increases with the amount of waste content added to the mixture. The best results were achieved when using a combination of ESPA and WSA. At an 8% replacement rate, the compressive strength values increased by 73.33% while the flexural strength increased by 56% for ESPA+WSA blends.
- Substituting ESPA and WSA for cement resulted in a denser and more refined mortar microstructure due to increased C-S-H gel production by the pozzolanic reaction, as evidenced by the SEM micrograph.
- According to the CH and DTA examinations, the use of ESPA or WSA as a substitute for cement resulted in a reduction of CH content. The lowest CH content was found in the ESPA+WSA mixture.
- In summary, it can be concluded that WSA and ESPA waste can be recycled and used as a substitute for cement to create an eco-friendly binder with a significant enhancement in both mechanical and microstructural properties. Furthermore, combining these materials is a promising solution for producing a sustainable ternary blend that possesses superior properties than if the wastes were utilized individually.

5. Declarations

5.1. Author Contributions

Conceptualization, A.O.H. and R.J.G.; methodology, A.O.H. and F.M.R.; validation, A.O.H., R.J.G., and Z.F.J.; formal analysis, Z.F.J.; investigation, A.O.H. and R.J.G.; resources, Z.F.J.; data curation, F.M.R.; writing—original draft preparation, A.O.H.; A.S., and M.S.N.; writing—review and editing, A.O.H., R.J.G., and Z.F.J.; visualization, F.M.R.; supervision, R.J.G. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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