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Orginal Article

Effect of Mixing Eggshell-Carrot Nanofibers on the Compressive Strength of a Mortar Cement

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Abstract

Background: *Eggshell powder (ESP) is a widely studied alternative to cement due to its chemical similarity to lime. Prior research has shown that up to 15% ESP replacement can improve compressive strength, and some findings show improvement even at 20% replacement levels.*

Methods: *This study used an experimental design approach was used. Mortar specimens were prepared with varying ESP and carrot nanofiber (CNF) proportions. The samples were cured under standard conditions and tested for compressive strength after 28 days.*

Results: *Among the tested combinations, the mix with 35% ESP and 0.30%-wt CNF achieved the highest compressive strength. However, this strength remained below the reference strength of the traditional control mix, which measured 7.5 MPa.*

Conclusion: *While the combination of ESP and CNF improved compressive strength relative to other experimental groups, it did not meet the performance of the traditional cement mix. Further research is required to refine the parameters and fully utilize the potential of these alternative materials in cement reduction.*

Keywords

cement, nanofibers, mortar cement, concrete, compressive strength, eggshells

INTRODUCTION

Industrialization and human development are directly proportional to one another. With the aim of different countries for development, industrialization is the way forward for every country. However, attributed to this aspiration, it has been identified that countries with Very High Human Development Index (HDI) produce the highest CO2 emission recorded, impacting the environmental welfare negatively (Borres et al., 2014). Over the last two centuries, the preference for cementing products has continuously increased. With their increased demand, the exhaustion of the environment's non-renewable resources has been a growing concern in the 21st (Mohamad et al., 2022). Limestone, among other aggregates, has been the primary non-renewable resource quarried and mined to produce Portland Cement (Soltanzadeh et al., 2018). Prolonged use of these resources will significantly raise concerns regarding biodiversity loss, environmental deterioration, global warming, etc. (Hussain et al., 2020). Further, the effect of cement on the environment also extends to the enormous energy consumption required to produce clinkers, the primary materials used for cement production (Mohamad et al., 2022). Thus, reducing even just a fraction of cement in the mix would significantly decrease the cement industry's negative environmental impact.

Mortar is a homogeneous mixture widely used in masonry works because of its versatility and easy production process. It can be defined as a composite material composed of a binder and a filler and obtains consistency by adding water. It is used in construction as a bonding, finishing, or decorative material. Mortar is categorized into different kinds, depending on the binder it uses. Because of their ability to achieve early strength, minimal required time setting, and high compressive strength, cement mortars were the most preferred in the 20th century (Gillot & Coutelas, 2018).

Over the years, several researchers have developed and studied sustainable alternatives, and waste materials have been the primary subject of this sustainable construction. Calcareous Shell or Eggshell in the form of Eggshell Powder (ESP) has been one of the observed waste materials highlighted in past research. The reason is that Eggshell has a chemical composition similar to lime. Eggshell is a bio waste that is 97% composed of Calcium Carbonate (CaCO), a chemical composition considered the leading cement component. Besides its similarity to lime's chemical composition, other research shows that its cellulosic structure contains amino acids, making it suitable for biosorption (Mohammed, 2015).

However, an expressly limited percentage ratio should be considered in the mix when ESP is added, mainly to maintain the optimal hydration process responsible for the strength development of concrete (Mohamad et al., 2016; Yerramala, 2014). Calcium Silicate Hydrate, the hydration process of cement, is where the strength development of any cementitious material depends (Liang, 2013). Despite many existing types of research, researchers have observed that the improvement of the design mix ratio of Eggshell has been limited due to its C-S-H property.

Daucus Carota, Sativus, or cultivated carrot, had been the subject of interest as a catalyst in maximizing cement's calcium-silicate-hydrate (CS-H). By maximizing C-S-H, cement's hydration process is enhanced in a significantly shorter period, demonstrating that the hydration process of cement is greater with carrot nanofibers than with the traditional concrete mix (Chi et al., 2020). A critical component that ESP-based mixture has the potential to complement. Allowing the researchers to hypothesize that deducting a portion of the usual cement ratio and combining the two organic materials will produce a mortar mix with lesser demand for cement while maintaining its optimal compressive strength. Thus creating a mixed design that is both economical and eco-friendly.

Process Framework

Cement is derived from a sedimentary rock called limestone. This material is principally composed of Calcium Carbonate ($CaCO3$) and then processed through heating and grinding in order to create calcium silicates, alite ($C3S$), and belite ($C2S$). These compounds are responsible for the activation of cement and its strength development. Arguably, cement is considered an environmental hazard due to the carbon emission during production and its demand for natural resources for its raw material.

Eggshell is a waste material that is mainly composed of Calcium Carbonate. As the material has been added in past studies, significant results present great potential for the material if the gap in its calcium hydrate can be addressed. Recently, Carrot Nanofibers have been discovered to be a suitable catalyst for maximizing calcium hydrates in cement, bridging the gap that eggshell-based mortar lacks. In this study, the researchers will add the two biomaterials in the mortar mix in different percentages and investigate the performance of the mix design.

This study aims to develop the optimal mortar concrete mix with less cement to produce an economical and environmentally friendly mortar mix by incorporating ESP and Carrot Nanofiber in ordinary portland cement (OPC) based on its compressive strength test result.

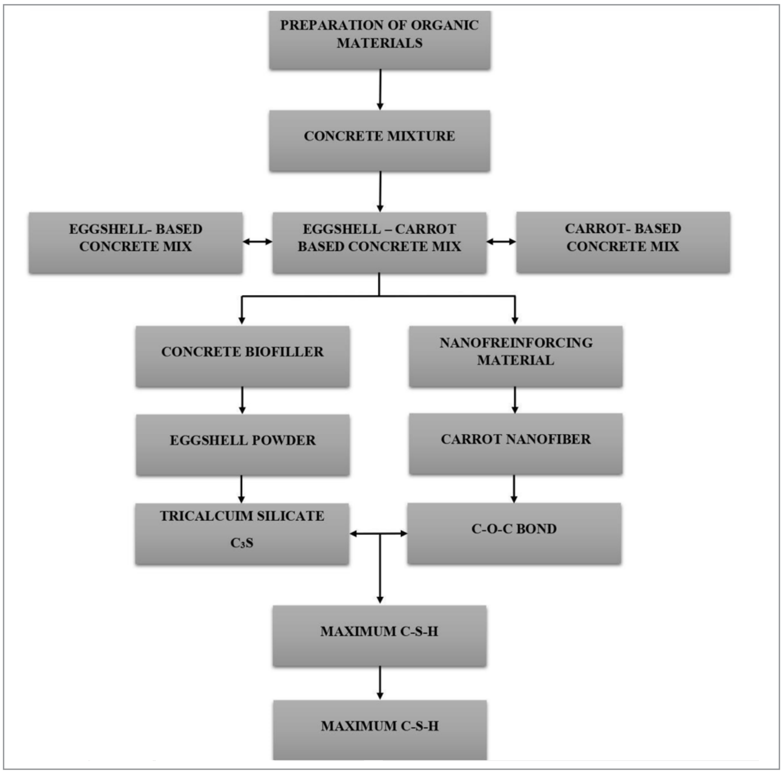

Figure 1. *Process Framework*

METHODS

This study followed an experimental research design to evaluate the influence of incorporating eggshell powder (ESP) and carrot nanofiber (CNF) on the compressive strength of mortar mixtures. A total of ninety (90) specimens were prepared for testing. The experimental design included three (3) control samples using a conventional mortar mix to establish a baseline for comparison.

The remaining samples were divided into three categories: four (4) groups with varying levels of ESP substitution, five (5) groups with different concentrations of CNF, and five (5) groups incorporating combinations of both ESP and CNF in different proportions. This structured grouping allowed for a systematic evaluation of the additives' individual and combined effects on the mechanical performance of the mortar.

All mixes were proportioned by weight, mixed uniformly, and cast into standard molds. After curing for 28 days under controlled conditions, compressive strength tests were performed following ASTM C109 standards.

Procedure

Preparation of Supplemental Materials

The preparation of the supplementary materials involved the following procedures:

Preparation of the Eggshell Powder

The treated eggshell powder (TESP) utilized in this study was prepared using a modified method adapted from Jaber et al. (2020). Chicken eggshells were collected from a local shop, thoroughly washed with clean water to remove surface impurities, and carefully stripped of their inner membranes to retain only the calciferous shell material. The cleaned shells were then air-dried at room temperature for five (5) days. After drying, the shells were partially crushed into coarse fragments and subjected to heat treatment at 250 °C for three (3) hours to eliminate any remaining organic matter and initiate calcination. Once cooled, the calcined shells were finely ground and sieved to obtain a powder with particle sizes passing through a 200 μm sieve.

Preparation of Carrot Nanofiber

The preparation of carrot nanofiber (CNF) in this study followed a modified procedure based on the method developed by Chi et al. (2021). Discarded carrot parts were sourced at a reduced cost from a local market. The carrots were thoroughly cleaned, cut into chunks, and processed using a juicer to separate the juice from the pulp. The extracted carrot pulp was then collected and diluted with water to achieve a solid content ranging from 0.1% to 10% by weight. A 0.5 M sodium hydroxide (NaOH) solution was added to the mixture to increase the pH to 14. The alkaline mixture was subsequently heated at 90°C for five (5) hours, followed by continuous stirring for one (1) hour. To attain the desired fineness and fiber dispersion, the mixture was homogenized using an agitator blade rotating at 30 m/s for five (5) minutes, effectively separating the cell walls from the middle lamella. A dispersing agent, Span 20, was added to prevent platelet aggregation. The final CNF product consisted of approximately 4% solids and 96% water, with a molecular composition corresponding to the stoichiometry of the deoxyglucose-sorbitol ($C_{12}H_{24}O_{10}$) disaccharide unit.

Figure 2. *Process Flow of Eggshell Powder*

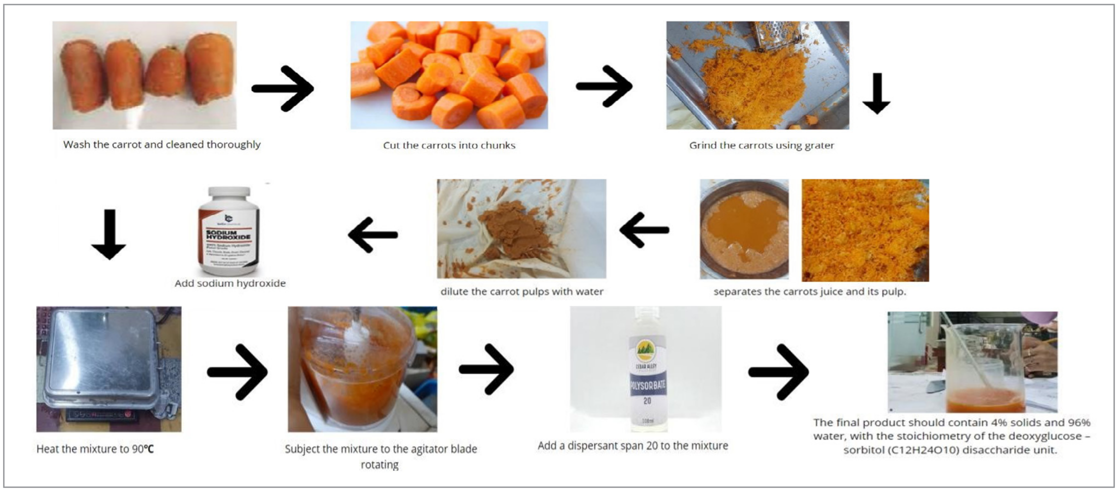

Figure 3. *Process Flow of Carrot Nanofiber*

Preparation of Mortar Mixture

The three settings of the experiment have utilized the standard way of mixing the mortar as indicated:

The mortar mix has been designed to follow the 1:4 ratio of a concrete mortar, with a constant water-cement ratio of 1.0. All have been converted to mass proportions, as stated in the literature (Dehghan et al., 2018). To calculate the exact mass proportions of the mix, the density of the sand used in the mortar mix is identified using the volume by geometry method (Krantz, 1991). The density gathered has been calculated using the formula to convert volume proportions to mass.

$$\rho := \frac{m}{v}$$

The dry ingredients, cement, and sand, were thoroughly mixed before the water was poured into the dry mixture.

Preparation of ESP-Controlled Mortar Sample

Following the mortar mixing stated above, instead of only comprising sand and cement for the dry ingredients, the ESP was added and was subjected to the rest of the procedure as indicated. The mixture ratio shall follow the 30%-45% range with a 5% increment, as identified in Table 1, and then be mixed manually.

Table 1. *Modified Mix Proportion with Eggshell Powder in Cube Mold*

No. of Specimen	Cement (g)	Sand (g)	Water (mL)	% Added	Eggshell (g)
12	806.4	4,608	1,152	30%	345.6
	748.8			35%	403.2
	691.2			40%	460.8
	573.6			45%	578.4

Preparation of Carrot-Based Mortar

Following the mortar mixing, instead of directly adding water to the dry ingredients, the water was combined with the carrot nanofiber with the ratios 0.2%-wt-0.6%-wt or as identified in Table 2. The aqueous solution was subsequently combined with the dry ingredients until thoroughly mixed.

Table 2. *Modified Mix Proportion with Carrot Nanofiber in Cube Mold*

No. of Specimen	Cement (g)	Sand (g)	Water (mL)	% Added	Carrot (mL)
15	1152	4,608	1,152	0.20%	11.52
				0.30%	17.28
				0.40%	23.04
				0.50%	28.8
				0.60%	34.56

Preparation of Eggshell Carrot-Based Mortar

By integrating the preparation procedures of egghshell-based and carrot-based mortar and its given parameter, the Eggshell Carrot-Based Mortar was created by combining the dry ingredients, sand, cement, and ESP with the identified mix ratio and was mixed for 1-2 minutes. Subsequently, the carrot nanofiber and water solution were thoroughly prepared and measured using the identified mix ratio. After both combinations of dry ingredients and preparation of the aqueous solution, it was mixed until thoroughly combined. Details of the mix ratios are referred to in Table 3.

Table 3. *Modified Mix Proportion with Eggshell Powder and Carrot Nanofiber in Cube Mold*

No. of Specimen	Cement (g)	Sand (g)	Water (mL)	% Added	Carrot (mL)	% Added	Eggshell (g)
15	807.26	4,608	1,152	0.20%	11.52	30%	344.74
				0.30%	17.28		
				0.40%	23.04		
				0.50%	28.8		
				0.60%	34.56		

Table 3. *continued*

No. of Specimen	Cement (g)	Sand (g)	Water (mL)	% Added	Carrot (mL)	% Added	Eggshell (g)
15	748.8	4,608	1,152	0.20%	11.52	35%	403.20
				0.30%	17.28		
				0.40%	23.04		
				0.50%	28.8		
				0.60%	34.56		
15	460.80	4,608	1,152	0.20%	11.52	40%	460.8
				0.30%	17.28		
				0.40%	23.04		
				0.50%	28.8		
				0.60%	34.56		
15	573.6	4,608	1,152	0.20%	11.52	45%	578.4
				0.30%	17.28		
				0.40%	23.04		
				0.50%	28.8		
				0.60%	34.56		

Preparation of Sample

The fresh mixture remained in the steel cube mold with a 10cm x 10cm dimension size for 24 hours and was removed after. The specimens are submerged in a standard water tank for 28 days of curing. After 28 days of water curing, the specimen was removed from the water and left to dry for 24 hours. The specimens are tested through a standard ASTM C109 compressive strength test for mortar.

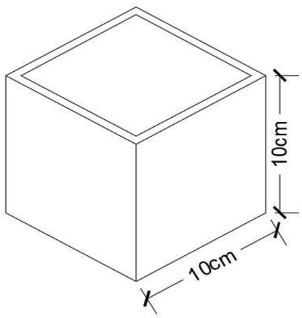

Figure 4. *Cube Mold*

Data Analysis

This study utilized descriptive statistics, analysis of variance (ANOVA), and analysis of covariance (ANCOVA) as the primary statistical methods to evaluate the results of laboratory tests conducted on various mortar mix compositions incorporating eggshell powder (ESP) and carrot nanofiber (CNF). Descriptive statistics summarized the compressive strength values and helped identify the overall trend among the different mix groups. ANOVA was used to assess whether there were statistically significant differences in compressive strength across the groups. At the same time, ANCOVA was employed to evaluate the individual and interactive effects of ESP and CNF, accounting for potential covariates. This analytical approach enabled more accurate comparisons by adjusting for baseline variations, thereby strengthening the reliability of the results. ANCOVA was conducted using JAMOVI software, with the significance level set at $p < 0.05$.

RESULTS AND DISCUSSION

Results were categorized into four (4) samples: Traditional Controlled Sample, CNF Controlled Sample, ESP Controlled Sample, and CNF-ESP Sample. The following show the results of the 90 specimens tested after the strength development of 28 days under submersion in water.

The traditional-controlled mortar specimens' compressive strength test result shows that the average compressive strength of the mixture is 7.53 MPa. With its proportioning and hardened property, the mortar produced has been identified to belong in the Type N category under the ASTM C270 specifications. As specified in the literature, Type N mortar is the most suitable type of mortar used in masonry construction. This data shall serve as the baseline value compared with the succeeding data presented as the controlled samples.

Table 4. *Compressive Strength of Traditional-Controlled Sample*

Sample	Peak Load (kN)	Compressive Strength (MPa)
1	73.45	7.35
2	72.09	7.21
3	80.4	8.04
Avg	**75.31**	**7.53**

Table 5 presents the result of the CNF-Controlled Sample. After 28 days of water curing, the specimens with the incorporations 0.2%-wt, 0.3%-wt, 0.4%-wt, 0.5%-wt, and 0.6%-wt averaged a compressive strength of 4.83 MPa, 6.98 MPa, 7.84 MPa, 6.50 MPa, and 6.82 MPa respectively.

Table 5. *Compressive Strength of Carrot Nanofiber Added to Mortar Mixture*

Add Percentage	Sample	Load Peak (kN)	Compressive Strength (MPA)
0.20%-wt	1	28.09	2.81
	2	69.03	6.90
	3	47.94	4.79
	Avg	48.35	4.83
0.30%-wt	1	84.8	8.48
	2	60.64	6.06
	3	64.09	6.41
	Avg	69.84	6.98
0.40%-wt	1	59.38	5.94
	2	92.25	9.23
	3	83.51	8.35
	Avg	78.38	7.84
0.50%-wt	1	59.56	5.96
	2	70.05	7.01
	3	65.29	6.53
	Avg	64.97	6.50
0.60%-wt	1	65.43	6.54
	2	80.28	8.03
	3	58.75	5.88
	Avg	68.15	6.82

Figure 5 presents the averaged compressive strength data for each sample set, indicating that the 0.4%-wt mixture yielded the highest strength among the tested combinations. Notably, this mixture achieved a compressive strength of 7.84 MPa, surpassing the baseline strength of 7.53 MPa observed in the traditional mortar mix. Mixtures with either lower or higher CNF content failed to exceed the performance of the conventional mix. This optimal incorporation level of 0.4%-wt is consistent with findings reported by Chi et al. (2021), who also identified it as the most effective concentration for enhancing compressive strength.

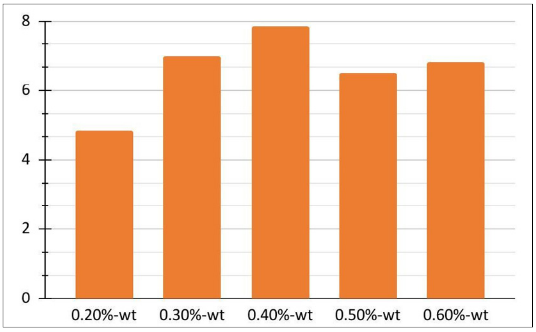

Figure 5. *Compressive Strength of Carrot Nanofiber Added to Mortar Mixture*

Table 6 shows the compressive strength test results of the ESP Controlled Sample after 28 days of submersion in water. The specimens with incorporation values of 30%, 35%, 40%, and 45% averaged a compressive strength test result of 2.32 MPa, 2.01 MPa, 1.98 MPa, and 1.54 MPa, respectively. Compared with the Traditional controlled Sample's compressive strength test result of 7.53 MPa, no eggshell incorporation percentage could surpass the baseline data.

Table 6. *Compressive Strength of Eggshell Added to Mortar Mixture*

Add Percentage	Sample	Load Peak (kN)	Compressive Strength (MPA)
30%	1	20.85	2.81
	2	18.03	1.80
	3	23.53	2.35
	Avg	20.8	2.32
35%	1	24.95	2.50
	2	13.78	1.38
	3	21.38	2.14
	Avg	20.04	2.01
40%	1	12.85	1.29
	2	26.85	1.38
	3	19.84	2.14
	Avg	19.85	1.99
45%	1	9.89	0.99
	2	17.39	1.74
	3	18.75	1.88
	Avg	15.34	1.54

Figure 6 shows a graph of the compressive strength test results gathered in the Sample. The graph suggests that the greater the value of the incorporation percentage, the lesser the compressive strength of the specimen (Ing & Choo, 2014). Following the reviewed literature, this result is expected as the maximum percentage of mixing that has presented a result surpassing the traditional mortar mix is limited to 20% of incorporation.

The optimal value most frequently reported in previous studies is limited to a maximum of 15%, as Ansari et al. (2016) noted. Compared with the standard ASTM mortar type, no eggshell incorporation percentage has reached the minimum compressive strength test to be classified.

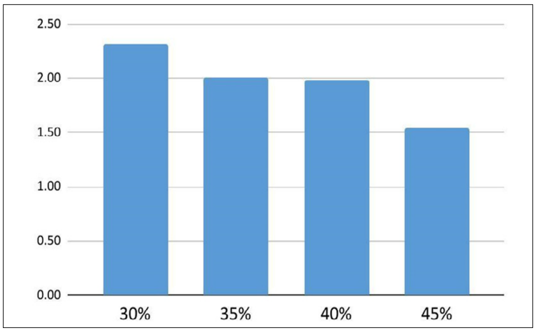

Figure 6. *Average Compressive Strength of Eggshell Added to Mortar Mixture*

Table 7 shows the compressive test results of the specimens added with CNF and ESP. The result shows that no mixing percentage has outperformed or equally performed compared to the Traditional-Controlled Sample, with a baseline compressive strength of 7.53 MPa. This data suggests that combining the supplemental materials in this incorporation percentage will not optimize the properties of mortar.

With this, the highest compressive strength achieved, 4.95 MPa, from 35% ESP and 0.3%-wt CNS, when compared with the ASTM type of mortars, the produced mortar mix can be classified as Type O. Further, Figure 7 shows that a mixture with relatively high compressive strength is within the mixtures containing 35% ESP with the CNF values.

Table 7. *Average Compressive Strength of Eggshell and Carrot Nanofiber Added to Mortar Mixture*

Carrot Nanofiber Percentage	Compressive Strength (MPa)			
	Eggshell Powder Percentage			
	30%	35%	40%	45%
0.20%-wt	3.45	4.76	1.79	1.96
0.30%-wt	2.76	4.95	3.63	2.78
0.40%-wt	2.38	4.85	3.05	2.22
0.50%-wt	2.39	3.35	1.71	1.61
0.60%-wt	2.29	3.92	1.30	1.32

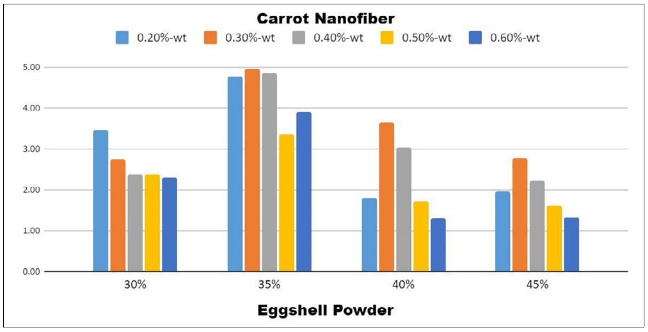

Figure 7. *Average Compressive Strength of Carrot Nanofiber and Eggshell Added to Mortar Mixture*

Table 8 shows a significant difference in the compressive strength among the different mix ratios of mortar by adding Eggshell as a key component in altering the design mix ratios of traditional mortar in its compressive strength. Similarly, there is a significant difference in the compressive strength among the different mix ratios of mortar by adding carrot as a key component in altering the design mix ratio of traditional mortar in its compressive strength. Furthermore, the combined incorporation of eggshell powder and carrot nanofiber produced statistically significant changes in compressive strength.

Figure 8 demonstrates that compressive strength increases with the addition of CNF, reaching a peak at approximately 0.4%, which is the optimal content. However, beyond this point, further increases in CNF lead to a reduction in compressive strength.

Figure 9, illustrates that the compressive strength initially increases with ESP content, reaching its peak at 30%, but begins to decline as the ESP percentage exceeds 35%. This indicates that adding more than 30% ESP negatively affects the strength of the mortar.

Table 8. *Two-Way Anova: Carrot Nanofiber and Eggshell Powder Mortar Mixture*

Source of Variation	S.S.	*df*	M.S.	*F*	P-value	F crit
Carrot Nanofiber	15.74421	4	3.936052	22.08288	1.10612E-09	2.605975
Eggshell Powder	51.02382	3	17.00794	95.42156	2.84325E-18	2.838745
ESP*CNF	8.56734	12	0.713945	4.005526	0.000442558	2.003459
Within	7.1296	40	0.17824			
Total	82.46497	59				

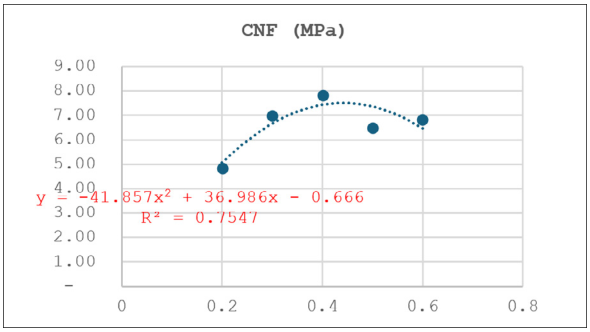

Figure 8. *CNF Nonlinear Regression Model*

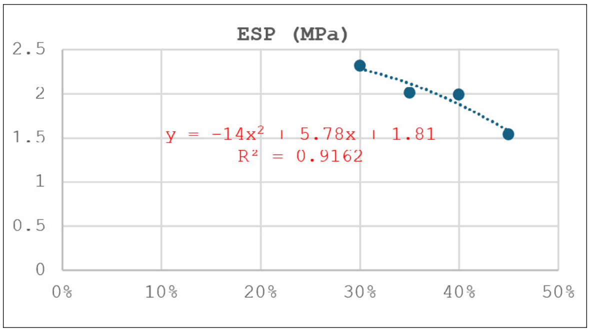

Figure 9. *ESP Nonlinear Regression Model*

$$Compressive \quad Strenght = 7.030 - 2.83CNF - 0.8196ESP$$

Table 9 illustrates that the coefficient of CNF is negative, indicating that an increase in CNF content tends to decrease the compressive strength of the mortar mix. Similarly, the negative coefficient of ESP suggests a slight reduction in compressive strength. The baseline compressive strength of the mortar mix, without CNF and ESP additives, is 7.030 MPa.

Table 9. *CNF and ESP Regression Results*

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	7.029	1.676547	4.192545	0.000611	3.491795	10.566205
CNF (%)	-2.83	1.613258	-1.754214	0.097401	-6.233677	0.573677
ESP (%)	-0.08196	0.040813	-2.008205	0.060782	-0.168067	0.004147

CONCLUSION

This study contributes to the growing body of research focused on sustainable and eco-friendly construction materials by exploring the potential of agricultural waste products—eggshell powder (ESP) and carrot nanofiber (CNF)—as partial cement replacements and additives in mortar mixtures. While the results indicated that the combination of ESP and CNF within the tested ranges did not enhance compressive strength compared to traditional mortar, the findings provide valuable insight into the limitations and behaviors of these materials in composite systems.

The study demonstrates that ESP has a slightly more pronounced effect on compressive strength than CNF, highlighting the need for precise optimization of material proportions to achieve desirable mechanical performance. This work lays the groundwork for further investigation into the synergistic effects of natural waste-based additives, including their behavior at different curing stages, their influence on durability, and their compatibility with other supplementary cementitious materials.

Author Contributions

B. R. Vosotros: Conceptualization, Methodology, Investigation, Visualization, Literature Review; **K. B. Mamugay:** Conceptualization, Methodology, Investigation, Formal Analysis, Literature Review; **N. E. Semense:** Investigation, Literature Review; **G. Intano III:** Investigation, Literature Review; & **E. Longos:** Writing – Review & Editing, Literature Review

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Ethical Approval

Not applicable.

Competing interest

The authors declare no conflicts of interest.

Data Availability

Data will be made available by the corresponding author on request.

Declaration of Artificial Intelligence Use

In this work, the authors utilized artificial intelligence (AI) tools and methodologies, specifically OpenAI's ChatGPT, to assist with paraphrasing, grammar refinement, and improving the clarity of written content. After using this tool, the authors carefully evaluated and revised the content as necessary and take full responsibility for the published content.

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