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Utilization of Eggshell Powder as a Green Mortar Material

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Recycling waste in cementitious materials promotes sustainable construction. It helps to prevent the depletion of natural resources while also reusing abundant recyclable wastes. Eggshells are one of these wastes that is being generated in large quantities because eggs are not expensive and have high nutritional value. On the other side, eggshell has a high content of calcium carbonate. It has a similar composition to the limestone powder used to produce Portland cement. This work investigates the effect of replacing a part of the cement with eggshell powder on mortar properties. The substitution rates were 5 %, 10 %, and 15 % of the cement's mass. The results were compared with those of an ordinary mortar for the following properties: workability, compressive strength, flexural tensile strength, density in the hardened state, water absorption by total immersion, porosity accessible to water, depth of water penetration under pressure and chemical attack by sulfuric acid. The experimental results show that adding eggshell powder as a partial cement substitute up to 10% improved workability, increased compressive strength by about 10 % and flexural tensile strength by about 20 %, reduced density, and produced a more durable mortar by reducing porosity, water absorption, and water penetration depth under pressure. On the other hand, it decreased resistance to chemical attack by sulfuric acid. Thus, eggshell powder could be used in future construction materials to reduce carbon dioxide emissions.

Keywords: cement, recycling, eggshells, mechanical properties, durability.

1. INTRODUCTION

Cement is the predominant construction material in terms of usage. Their production necessitates a substantial amount of energy, resulting in the emission of a considerable quantity of CO_2. Carbon dioxide (CO_2) is responsible for approximately 65% of the increase in global temperatures [1], and the cement industry is responsible for approximately 8 % of the total greenhouse gas emissions worldwide [2]. Currently, researchers are highly concerned with safeguarding the atmosphere and the environment. One proposed solution is to decrease cement production and repurpose by-products and waste materials [3]. Utilizing waste materials in the production of construction materials serves the dual purpose of diminishing clinker production, a crucial element in Portland cement, and effectively managing the substantial volumes of waste that accumulate in landfills. The accumulation of such waste poses significant health and environmental risks.

In light of this situation, researchers are currently focusing on developing novel cementitious composites using these waste materials. The primary objectives are to achieve economic benefits by reducing production costs, ecological benefits by eliminating these wastes from the environment, and technical benefits by enhancing the mechanical and physical properties of mortars or concretes [4]. Researchers have studied several wastes to incorporate them as a cement replacement in cementitious materials. For example, [5 – 7] report research on the substitution of part of the cement by brick waste. Other researchers [8, 9] were studying glass waste as a cement additive. [10] report on concrete waste as a substitution for Portland cement.

However, eggs are a primary source of dietary protein, and their global production and consumption are projected to rise by 50 % from 2015 to 2035 [11]. Global egg production in 2016 reached approximately 72 million tons, equivalent to nearly 1,360 billion eggs [12]. The National Association of Traders and Artisans (ANCA) reported that over 5 billion eggs were consumed in Algeria in 2017.

In addition, eggshells are classified as hazardous waste according to the regulations set by the European Commission. The primary environmental consequences associated with them include the potential for pathogen transmission, the release of noxious odours, and the generation of leachate in landfill sites. Consequently, recycling eggshells is an ideal environmental solution. Eggshells contain a high amount of calcium and are considered waste materials with a chemical composition that closely resembles limestone [13]. Utilizing eggshell waste as a partial replacement for cement in cementitious materials decreases the release of greenhouse gases and leads to the production of a cementitious material that is both non-polluting and environmentally sustainable.

Multiple studies have already investigated the impact of adding eggshell powder on the properties of cementitious materials, both when they are fresh and when they have hardened. In a study conducted by Mohd Arif et al. [14], the impact of incorporating eggshell powder, which was sieved using a 150 µm sieve at different proportions (5 %, 10 %, and 15 % of the cement mass) on the workability and

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compressive strength of concrete was investigated. The researchers discovered that incorporating eggshell powder as a replacement for cement, at a substitution rate of up to 10 %, resulted in a reduction in workability and an increase in compressive strength. Furthermore, after reaching a certain point, strength starts to diminish. Nandhini and Karthikeyan [15] observed that substituting cement with 10 % eggshell powder resulted in enhanced compressive strength of mortar. In addition, the studies by Eramma and Madhukaran [16] and Mukesh et al. [17] on adding eggshell powder to concrete and modifying its construction method supported the results obtained by Mohd Arif et al. [14]. The compressive strength, flexural tensile strength, and splitting tensile strength exhibit an upward trend as the substitution rate increases by 10%. However, once the substitution rate surpasses this threshold, the strengths begin to decline. Jhatial et al. [18] examined how the size of eggshell powder affects the workability and compressive strength of concrete. Their results showed that the higher the fineness, the greater the strength, but the lower the workability.

Previous studies [12, 19, 20] have also examined the impact of incorporating eggshell powder as a partial replacement for cement on both the workability and mechanical properties. The findings indicate that the workability and compressive strength of the material improved as the amount of eggshell powder used as a substitute for cement increased. Research on eggshell powder has consistently shown that adding this powder in limited amounts as a partial substitute for cement has a beneficial impact on the mechanical properties of cementitious materials. However, there have been limited studies conducted on the impact of adding this powder on the physico-chemical properties. This study aims to investigate the impact of incorporating hens' eggshells as a partial replacement for cement on the mechanical, physical, and chemical properties of the mortar.

2. METHODS AND MATERIALS

2.1. Materials

For the formulation of the mortars, we utilized rolled sand class 0/3, from the Tebessa region (Algeria), which possesses a density of 2.56 and a fineness modulus of 2.26. The cement utilized in all experiments is Portland cement CPJ-CEM II/42.5A, from the Hdjar Essoud factory in Skikda (Algeria), manufactured according to the Algerian standard NA 442-2008. The physical properties of the substance are as follows: a Blaine-specific surface area of 3550 cm²/g, bulk density of 1.09 g/cm^3 and specific gravity of 3.01. Table 1 displays the mean chemical composition, while Fig. 2 illustrates the particle size. The eggshells collected from the local fast food in Guelma (Algeria), were cleaned with tap water to eliminate impurities, and subsequently dehydrated in an oven for 24 h at a temperature of 105 °C. Subsequently, they were transformed into powder by grinding and sieving on a 63 µm sieve. The powder obtained had the following physical characteristics: a Blaine-specific surface area of 7243 cm²/g, a bulk density of 0.749 g/cm^3, and a density of 2.76. The average chemical composition is detailed in Table 1, while the particle size is illustrated in Fig. 2.

Table 1. Average chemical composition of cement and eggshell powder used

Components	Cement, %	Eggshell powder, %
CaO	58.6	54.64
SiO_2	24.92	0.09
MgO	1.21	0.62
$Al\ O_{23}$	6.58	0.1
$Fe\ O_{23}$	3.65	0.04
$Na\ O_2$	0.08	0.10
Cl^-	0.00	–
SO_3	2.17	0.03
PAF	1.70	–

Fig. 1. Powder obtained after grinding and sieving eggshells

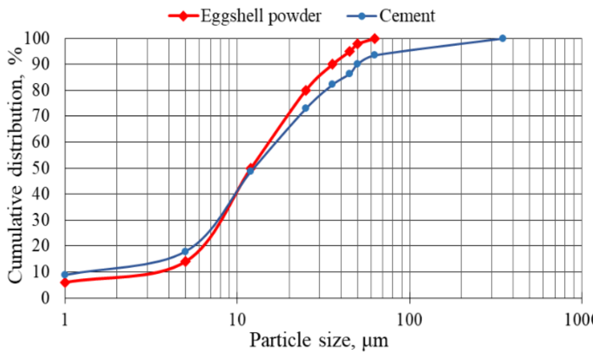

Fig. 2. Results of laser granulometry of cement and eggshell powder

2.2. Experimental methodology

Four different mortar formulations were prepared for this study: ordinary mortar (OM), when was formulated in accordance with the guidelines of EN 196-1, and three mortars of the eggshell powder (EPM5%), (EPM10%) and (EPM15%) with substitution rates of 5 %, 10 %, and 15 % respectively of the cement mass. The various mortar types are manufactured with a constant W/(C+A) ratio of 0.6. Table 2 provides a complete list of the different mortar compositions.

Table 2. Composition of the various mortars studied

	Sand, g	Cement, g	Eggshell powder, g	Water, ml
OM	1350	450	0	270
EPM5%	1350	427.5	22.5	270
EPMC10%	1350	405	45	270
EPM15%	1350	382.5	67.5	270

Several tests were carried out on the different mortar formulations: a workability test was carried out in accordance with standard NF EN 1015-6 (Fig. 3).

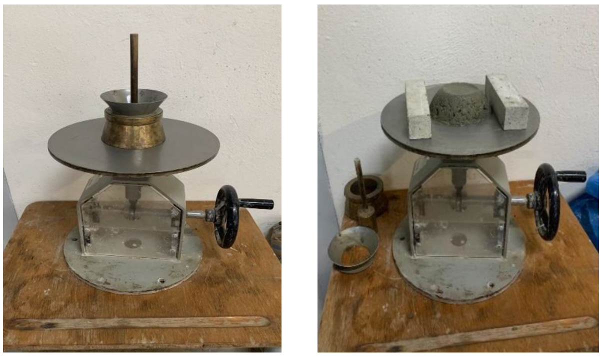

Fig. 3. Flow table test

The dry density test, the compression and flexural tension tests at 7 and 28 days, the water absorption test, and the porosity test are carried out on $(4 \times 4 \times 16)\ cm^3$ specimens (Fig. 4). These tests are carried out in accordance with standards: NBN EN 678, standard 196-1 (Fig. 5, Fig. 6), standard NBN B 15-215:1989, and NF EN 18-459, respectively. The water penetration depth under pressure test was carried out on $(15 \times 15 \times 15)\ cm^3$ specimens in accordance with standard NF EN 12390-8 (Fig. 7).

Fig. 4. Samples casting for $(4 \times 4 \times 16)\ cm^3$ specimens

Fig. 5. Compressive strength test

Fig. 6. Flexural tensile strength test

Fig. 7. samples casting for $(15 \times 15 \times 15)\ cm^3$ specimens

A chemical attack test was carried out with sulphuric acid (H_2SO_4) on $4 \times 4 \times 16\ cm^3$ specimens, which were immersed in water for 28 days. They were then immersed in a solution containing 5% H_2SO_4 in accordance with ASTM Standard C-267-97.

3. RESULTS AND DISCUSSION

3.1. Workability of mortar

Fig. 8 shows the results of the flow table test, which illustrated that replacing cement with eggshell powder improves the mortar's flow table workability. It rises from 16.9 cm for MO to 17 cm, 17.6 cm, and 19.2 cm for EPM5%, EPM10% and EPM15% mortars, respectively. Despite the increase, it is worth noting that the consistency for EPM5%, EPM10%, and EPM15% mortars ranges from 14 cm to 20 cm. According to NF EN 1015-3, these mortars are considered plastic. Eggshell powder has a lower water absorption capacity than cement, which accounts for the increasing the consistency of mortar. Both [12, 20, 21] reported consistent findings.

3.1. Compressive strength

The evolution of compressive strength was investigated after 7 and 28 days of water storage, and the results are shown in Fig. 9. The results indicate that the compressive strength of the four mortars studied increases steadily over time, with no drop-off. It can also be seen that substituting eggshell powder for a portion of the cement results in an increase in compressive strength up to a 10 % substitution rate, followed by a decrease at a 15 % substitution rate. At 28 days of age, the compressive strength of the reference mortar (OM) is 42.92 MPa, while the EPM5%, EPM10%, and EPM15% modified mortars have compressive strengths of 45.12, 47.03, and 39.43 MPa, respectively. The 5 % and 10% rates have increased by 5.13 % and 9.58 %, respectively.

Eggshell powder's high specific surface area (7243 cm²/g) makes mortar more compact and resistant. Furthermore, eggshell contains a high concentration of calcium oxide, which is a key component in improving the performance of cementitious materials [22]. Calcium oxide is known to improve cement paste hydration [23]. The compound reacts with the aluminous phase of cement to form carboaluminates and slows the conversion of ettringite to sulfoaluminates. It also increases the overall volume of the hydration product, resulting in a denser C-H-S gel that improves concrete microstructure by reducing voids and porosity [24]. When the percentage of eggshell powder exceeds 10 %, water demand increases, resulting in a higher water/cement ratio. The result is lower compressive strength [12, 25]. This pattern has been observed by [14, 16, 25, 26].

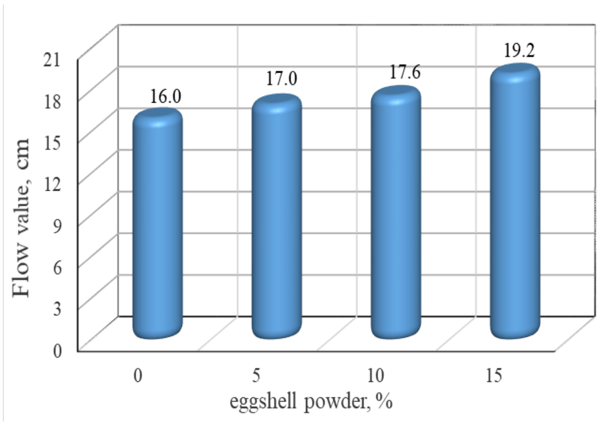

Fig. 8. Variation in workability as a function of substitution rate

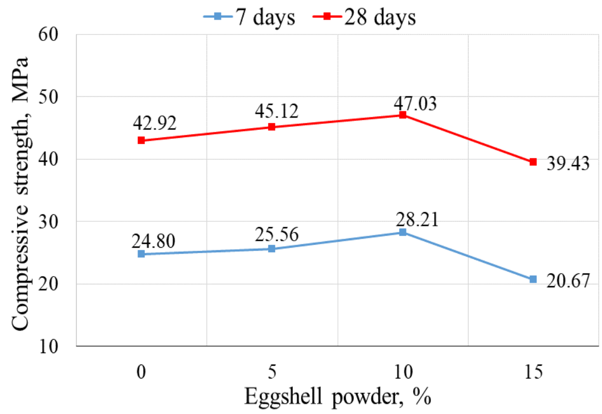

Fig. 9. Compressive strength values at 7 and 28 days of eggshell mortar

3.2. Flexural tensile strength

Fig. 10 shows the results for flexural tensile strength, with the same observation as for compressive strength: modified mortars have a 10 % higher flexural tensile strength than ordinary mortars. Above this point, tensile strength begins to decline. At 28 days, the ordinary mortar (OM) had a strength of 8.28 MPa, compared to a strength of 9.23 MPa for the EPM5% mortar, strength of 9.90 MPa for the EPM10% mortar, and strength of 7.41 MPa for the EPM15% mortar, i.e. an increase of 12.0 % and 20.1 % for the EPM5% and EPM10% mortars, respectively, and a decrease of 10.1 % for the EPM15% mortar. Both studies [16, 26] observed the same trend.

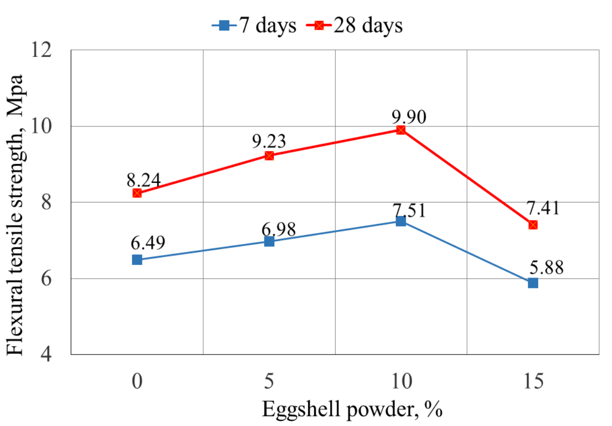

Fig. 10. Flexural tensile strength values at 7 and 28 days of eggshell mortar

3.3. Dry density

In terms of dry density, the results presented in Fig. 11 show that substituting eggshell powder for some of the cement results in a reduction in hardened mortar density. This decrease rises with the substitution rate. Compared to the OM control mortar, the density of EPM5% mortar decreased by 4.6 %, while that of EPM15% concrete decreased by 9.4 %. This decrease can be attributed to the substitute material's lower density when compared to cement. The same conclusion was reached by [13] in their investigation of lightweight concretes.

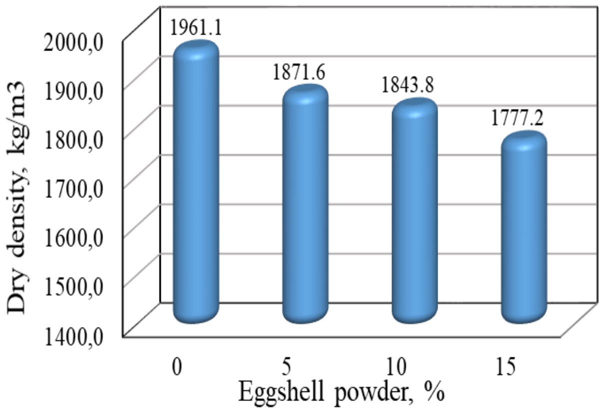

Fig. 11. Variation of dry density with % eggshell powder

3.4. Water absorption

From Fig. 12, it is observed that the water absorption by total immersion of ordinary mortar (OM) is greater than that of modified mortars, and it decreases with the increase of substitution rate. In comparison to ordinary mortar, we see a 4.3 % reduction in absorption for EPM5% and a 16.8 % reduction for EPM15% concrete. This decrease can be explained by the fact that eggshell powder fills the same role as fillers and adds calcium to produce more secondary C-S-H gel, which reduces voids [19]. These findings are consistent with those from [12] and [19].

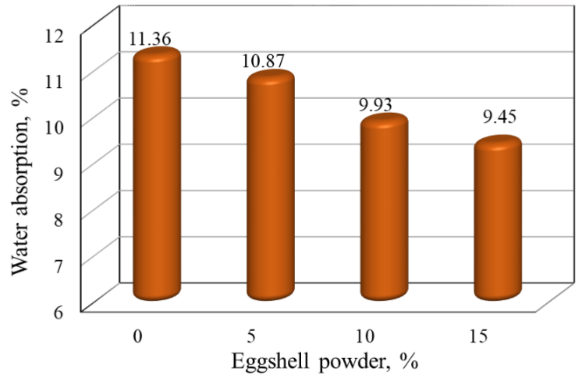

Fig. 12. Variation of water absorption with % eggshell powder

3.5. Water-accessible porosity

Fig. 13 shows that, compared to ordinary mortar (OM), the water-accessible porosity of the tested mortars decreases with the increase in the rate of substitution of cement by eggshell powder. The ordinary mortar had a porosity of 23.3 %, compared to 22.4 %, 22.2 %, and 22 % for the EPM5%, EPM10%, and EPM15% mortars respectively, representing decreases of 3.6 %, 4.5 %, and 5.4 % respectively. This reduction is due to the powder's filler effect, which compacts the mortar and reduces the pores and voids, and which makes the mortar more compact so fewer pores and fewer voids.

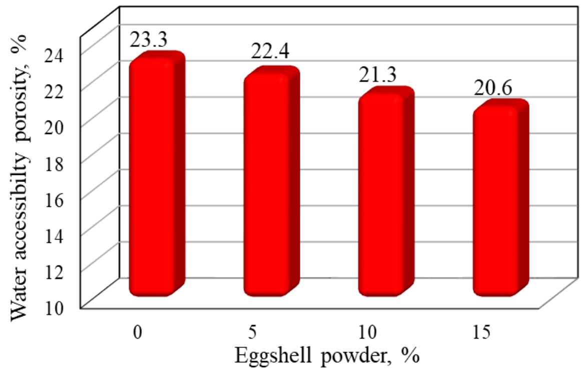

Fig. 13. Water-accessible porosity values of eggshell mortar

3.6. Water penetration depth under pressure

For the water penetration depth under pressure test (Fig. 14), the results presented in Fig. 15 shows that mortars containing eggshell powder have a lower water penetration depth than ordinary mortars and decrease as the substitution rate increases. It decreases from 15 cm for ordinary mortar to 14.5 cm, 11.9 cm, and 11.2 cm for EPM5%, EPM10%, and EPM15% mortars, respectively. When cement is replaced with 5 %, 10 %, or 15 % eggshell powder, the reduction rates are 3.2 %, 21 %, and 25.4 %, expressed as percentages. This decrease is due to modified mortars having a lower porosity than ordinary mortars.

3.7. Acid attack

Fig. 16 depicts the mass losses observed after 14, 28, and 56 days for all four compositions. The results of the mass loss test presented in Fig. 15 show that all four mortars studied experience mass loss. This loss is greater in modified mortars and increases with the increase in the substitution rate.

Fig. 14. Depth of water penetration test

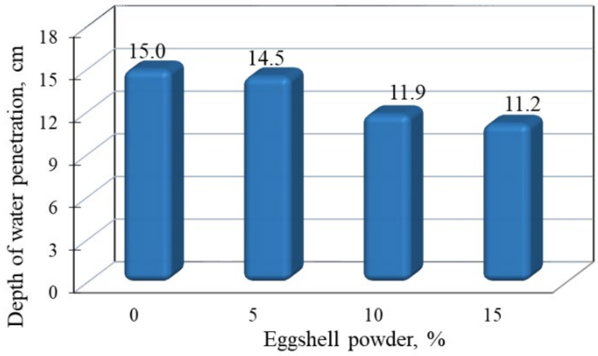

Fig. 15. Depth of water penetration of eggshell mortar

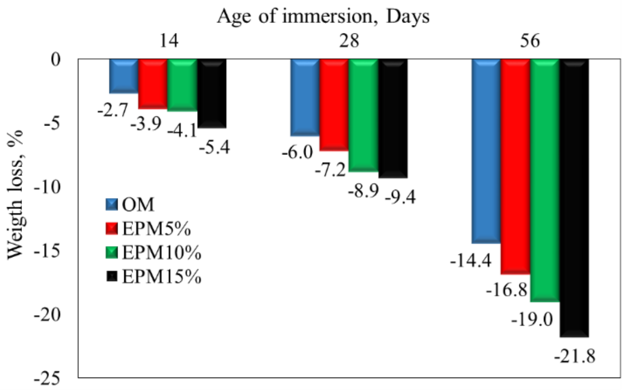

Fig. 16. Mortar mass variation as a function of immersion time in sulfuric acid

For example, after 28 days in the sulfuric acid solution, the OM mortar lost 6.03 % of its mass, whereas the EPM5%, EPM10%, and EPM15% mortars lost 7.21 %, 8.86 %, and 9.36 %, respectively. In terms of ratio, at 28 days, mass loss increases by 19.5 %, 46.9%, and 55.15 %

for EPM5%, EPM10%, and EPM15% mortars, respectively, compared to ordinary mortar (OM). This increase is due to the high calcium hydroxide content of eggshell powder, which is the element most susceptible to acid attack [19]. Furthermore, because replacing cement with eggshell powder increases the percentage of calcium hydroxide, the durability of eggshell mortar decreases as the amount of eggshell powder increases. Both studies [12] and [27] observed the same trend.

4. CONCLUSIONS

This study examined the impact of incorporating eggshell powder at different proportions (0 %, 5 %, 10 %, and 15 %) as a partial replacement for cement on the behavior of a cement mortar in a fresh and hardened state. The following findings have been established

1. The use of eggshell powder as a partial cement substitute improves the workability of mortar.
2. The dry density of eggshell mortars varies inversely; it decreases with increasing substitution rate. It should be noted that this decrease in density is due to the low density of eggshell powder.
3. The water absorption by total immersion, porosity, and depth of water penetration under pressure all decrease simultaneously with the increase in the rate substitution of powder of eggshells.
4. Incorporating eggshell powder at concentrations of up to 10% enhances compressive strength by about 10% and flexural tensile strength by about 20 %.
5. Incorporating eggshell powder decreases the mortar's resistance to chemical attack caused by sulfuric acid and leads to an increase in mass loss, therefore a decrease in durability.

This study showed that 10 % of eggshell powder is the optimal percentage for partial replacement of cement. Thus, eggshell powder could potentially be used in the future in construction materials to reduce carbon dioxide emissions.

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