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Limestone derived eggshell powder as a replacement in Portland cement mortar

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HIGHLIGHTS

- Chicken eggshell waste used as a limestone filler in Portland cement mortar.
- A larger than laboratory scale method was used to crush raw eggshells into fine powders.
- White and brown eggshells were evaluated for their mechanical performance.
- Eggshell based limestone mortars had lower properties compared to natural limestone.

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ABSTRACT

In recent years, a general trend exists to reduce usage of natural resources and re-use waste materials. This work aimed to study the performance of ground white and brown chicken eggshell waste powders as potential replacements of conventional quarried limestone in Portland cement mortars. A processing method to produce large quantities of eggshells was developed. Limestone amounts of 0%, 5%, 10%, 15% and 20% by weight were added as Portland cement replacements. Chemical composition, elevated temperature degradation and eggshell particle morphology were investigated. Compression and flexural strength measurements were carried out on mortar specimens. The results showed eggshells contain mostly calcite with small amounts of organic membrane and matrix. The powdered eggshell particles appeared to have an irregular morphology due to the grinding process utilized. The strength of the mortars were affected by the addition of various limestone materials. In conclusion, white and brown eggshells derived limestone powder were found to have inferior properties compared to natural conventional limestone even with 5 wt.% Portland cement replacements.

1. Introduction

Mortar and concrete materials are extensively used in the building and construction industries. One of the main ingredients, Portland cement (PC) is generally expensive and yields carbon dioxide (CO_2) emissions during its production (approximately 1 tonne of CO_2 greenhouse gasses are generated for making 1 tonne of PC) and consumes a lot of energy in its manufacturing process. Social and environmental issue of sustainability and energy conservation are assisting in changing the PC industry by lowering and partially replacing its cement production with supplementary cementing materials (SCMs). SCMs are industrial waste by-products such as; fly ash, blast furnace slag and silica fume which have pozzolanic properties (blended cements). More recently, in an added effort to reduce the use of cement, limestone (LS) has been added to PC as a filler or as a partial cement replacement as permitted by European Standard EN 197-1-2011 [1], American Standard ASTM C150-12 [2] and Canadian Standards CSA A3001-08 [3]. This can be viewed as a cost reduction and a lower carbon foot-print strategy.

Current sources of limestone are derived from crushing quarried limestone rocks, chalk and sea shells. LS is considered an inert material and does not have cementing pozzolanic properties since it does not produce calcium silicate hydrates (C–S–H). The recommended limestone powder additions do not affect the properties of the concrete at certain replacement amounts while benefiting the environment (e.g. lower embodied energy). For example, limestone powder is used as a partial PC replacement or filler in three areas; conventional PC (<5% by weight of LS), in Portland-limestone cement (PLC) (<15% by weight of LS) or as filler in self-compacting concrete (SCC) (>15% by weight of LS).

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In the past decade recycled materials have been added to concrete in an effort to reduce post-consumer wastes and industrial by-products entering the landfills [4]. One of these materials could be waste chicken eggshells which contain a very pure form of calcium carbonate or limestone frequently called calcite ($CaCO_3$). Re-use of limestone based eggshells would promote recycling of farm waste and prevent its diversion to landfills. Consumption of eggs in restaurants and households are minor compared to the majority of eggs utilized in egg breaking plants for mass production of liquid eggs for use in food and non-food related products. The annual amount of eggs sent to breaking plants in France and Canada is approximately 1 billion [5] and 2.3 billion [6], respectively. The weight of an average egg is about 60 g, while the empty shell corresponds to 11 wt.% [7]. Correspondingly, 1 billion eggs would produce 6600 tonnes of limestone powder. Although these amounts would not support the concrete industry in total it could be used as partial supplements. Farm hatcheries and/or egg breaking plants are positioned all over the country resulting in transportation issues for obtaining the raw waste product. However, if certain locations are targeted where viable amounts can be produced, the technology [8] is available to make small local onsite or regionally centralized reclamation facilities.

A limited number of studies have been conducted on the re-use of eggshell waste as an alternative material. Eggshells have been investigated in the form of limestone or lime in civil engineering applications. For example, Freire and Holanda [9,10] added 0–15 wt.% eggshell powder to 70 wt.% red plastic clay, 15 wt.% commercial quartz and 0–15 wt.% calcareous materials to produce ceramic wall tiles. The mixture was dried and sintered at 1150 °C for 1 h. The wall tiles exhibited flexural strengths on average of 16 MPa with 5–10 wt.% and 15 MPa with 15 wt.% eggshell powder additions. The results were in compliance with local ceramic tile standards which indicated this material could be used as an alternative to current wall tiles. Similarly, Amaral et al. [11] investigated soil bricks containing partial PC replacements of 0–30 wt.% eggshell powder. Bricks containing 10–20 wt.% eggshell powder increased in compression strength by 12% and 7%, respectively as compared to the reference bricks without eggshell. However, when 30 wt.% eggshell powder was added compression strength decreased by only 2%. The results showed up to 30 wt.% eggshell waste powder can be added to bricks made of soil and Portland cement.

Heating limestone to elevated temperature produces lime (CaO) or often referred to as eggshell ash. Beck et al. [5] prepared lime based cement mortars with fine tuffeau aggregates containing eggshell lime (ESL) and commercial lime (CL) for restoration purposes. The crushed eggshell based limestone was initially heated to elevated temperature to create lime or quicklime and further reacted with water in a process known as slaking to generate slaked lime or aerial lime-calcium hydroxide ($Ca(OH)_2$). Adding fine aggregates produced the lime-based mortars. The authors observed ESL was purer and whiter than the CL with calcium hydroxide contents of 97.1% and 92.2%, respectively. This was explained by a higher content of impurities in the limestone based calcareous stone. Both ESL and CL based mortars were observed to behave identically in mechanical properties. The compressive and flexural strengths were highest with values of 3.9 MPa and 2.4 MPa, respectively when 15 wt.% lime binder was added. In another study, Mtallib and Rabiu [12] evaluated the setting time of PC paste consisting of different amounts of eggshell ash. The cement paste with the greatest eggshell content of 2.5 wt.% had the optimum accelerating effect. The authors' determined eggshell ash could be used to decrease the setting time in cement paste as the ash contained CaO which accelerates the hydration rate. Moreover, Jayasankar et al. [13] conducted tests on concrete containing fly ash, rice husk ash and eggshell ash as a partial supplement to PC. The highest compressive strengths were obtained when 5 wt.% eggshell ash were added to the concrete mix but decreased with higher additions. The authors found the new concrete mix containing the three ash ingredients to be equivalent in compressive strength as the control concrete. Okonkwo et al. [14] added various amounts of eggshell ash to PC and lateritic reddish-brown soil to study the strength properties. Compared to the control sample without eggshell ash, the research determined the compressive strength increased by 35% for specimens containing mixture of 8 wt.% cement and 10 wt.% eggshell ash.

In general eggshell quality can be affected by several factors such as; type of hen strain/breed/genetics, age, nutritional diet, and stress related to population density [15]. Brown eggs are larger, heavier and have thicker shells than white eggs; however, the shell color is not an indication of the internal quality of an egg since brown eggs are not healthier than white eggs [16]. In one study, the percentage of calcium carbonate in brown eggs was found to be 96–97 wt.% and 3–4 wt.% organic matter [5,17] while in other investigations white eggs were found to have 94 wt.% calcium carbonate content with 6 wt.% organic matter and other minor compounds [7,14]. Based on these findings, the calcium carbonate content of white and brown eggs can be considered equivalent.

This study evaluated the performance of crushed and ground white and brown chicken eggshell waste for use in PC mortar as a replacement of natural quarried limestone. A preparation method for transforming as-received raw eggshells into a large quantity of fine powder was developed and presented herein as opposed to small laboratory samples (e.g. grams versus kg). For instance, approximately 15 kg of both white and brown eggshell powders were produced and will be used in other related or non-related research. The eggshell based limestone powders were investigated using X-ray diffraction (XRD), thermal gravimetric analysis (TGA), differential thermal analysis (DTA) and secondary electron microscope (SEM) imaging. To study the effects of mortar and offset the behavior of fine and coarse aggregates, PC was partially replaced with eggshell limestone powder and measured against conventional natural quarried limestone powder. Mortars were evaluated for compression strength and flexural strength at 7, 14 and 28 days.

2. Experimental program

2.1. Materials

White and brown raw eggshells were obtained from two locations. White eggshells from an egg breaking plant were obtained pre-compacted, semi-crushed in a ten liter plastic pale as shown in Fig. 1(a), while brown eggs from a local hatchery arrived in trash bags as presented in Fig. 1(b). Both eggshell wastes were processed into powders using an identical procedure. In separate batches, the eggshells were first dry-crushed in a steel drum containing eleven steel balls with diameters of 47.62 mm for one hour as shown in Fig. 2. In a second step, the crushed eggshells were quickly agitated in water using an electric drill with stirrer and continuously rinsed with clean water until a clear liquid was visible as given in Fig. 3(a) and (b), respectively. Eggshells contain a thin inner membrane which were removed. In an industrial process, wastewater generated from the rinsing step could be filtered and re-used as suggested by Oliveira et al. [18]. For instance, recirculating the water in a continuous loop could consume minimal water. The wastewater could also be used for agricultural irrigation. In addition, the filtered medium consists of the thin inner eggshell membranes and could be recuperated, processed and purified for its high valued collagen content (10%) [18]. A third step consisted of drying the finely crushed material at 105 °C for 24 h as presented in Fig. 4(a) and (b). For finer powder, a second grinding stage was required. The powders were then sieved to three different sizes and mixed to a final fineness according to the French standard requirements NF P 18-508 [19] as shown in Fig. 4(c).

2.2. Mixtures

Mortar specimens were produced with and without limestone fillers as PC replacements. Three batches of mortars were fabricated and were referred to as: the reference mortar without limestone (M), mortar with normal or