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Performance evaluation of eco-friendly mortar made with natural and artificial pozzolans; red clay and glass powder.

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Abstract: To reduce the environmental impact associated with Portland cement (PC) manufacturing, the use of supplementary cementitious (pozzolanic materials) materials in the development of cement-based materials such as concrete and mortar, has gained great attention in recent years. For this reason, this research study investigates the effect of using two types of pozzolanic material (natural and industrial pozzolan), represented by red clay (RC) and glass powder (GP), as a partial substitution for Portland cement in the preparation of cement-based mortar. The methodology of this study involved the design of seven mortar mix compositions and evaluating them in terms of workability and unconfined compression strength (UCS). Accordingly, the results showed that the addition of glass powder as a cement substitution yielded a gradual workability improvement, whereas the incorporation of red clay as a cement substitution induces a gradual workability reduction. In contrast, the unconfined compression strength revealed that the optimum glass powder content for strength performance was 5%, whereas no strength improvement was observed in this study using red clay, thus indicating the superiority of glass powder in enhancing the mechanical properties of mortar. Therefore, the outcome of this study suggests the possibility of improving both the fresh and hardened mortar properties using glass powder, as a partial replacement for cement.

Keywords: (Mortar, pozzolanic materials, red clay, glass powder)

Introduction

Global warming is one of the considerable concerns for the future of human civilization, indicating the importance of developing sustainable engineering construction strategies [1]. Commonly, cement-based materials such as concrete and mortar are characterized as widely versatile construction materials, probably due to their ability to be moulded into different forms, and raw material availability, along with their cost efficiency [2]. Cement-based materials are also rated as the second most utilized material worldwide, following water [3], with an estimated concrete usage of 30 million tons yearly [1]. In addition, Mortar is typically composed of binder, fine aggregates (sand), and water, of which Portland cement is the conventional binder used for binding the mortar matrix. However, there are some negative issues associated with Portland cement manufacturing including; 1) the consumption of huge quantities of natural raw materials such as limestone and clay (2.8 tons of raw materials per ton of Portland cement) [4]; 2) the enormous energy consumption (5000 MJ per one ton) [5]; and 3) the higher carbon dioxide emissions released to the atmosphere (a ton of CO_2 per ton of Portland cement)[6]. Apart from that, the use of cement in concrete technology also shows limited proficiency in the attendance of sulphate, inducing problematic issues such as crack formation, expansion, and deterioration, due to the nucleation and growth of gypsum and ettringite [7]. Ettringite is a hydrous calcium aluminate sulfate crystalline, which forms due to the reaction between the hydrated compounds (from cement hydration), and sulfate (from cement or the surrounding soil and seawater), in the presence of water [8]. This mineral has a higher water absorption capacity [9,10], adsorbing water, thus its volume increases significantly, thereby causing cracks, expansion and softening of the cement-based material. Consequently, the utilization of supplementary cementitious materials such as industrial pozzolanic materials and waste materials (including rice husk ash, ground granulated blast-furnace slag, glass powder, natural clay soil and pulverized fly ash), as a part of Portland cement in cement-based materials (mortar and concrete) has been encouraged [11]. This is because of their efficiency in enhancing the performance of cement-based products through their pozzolanic reactions, along with their positive effects on minimizing the environmental impacts of cement manufacturing [12].

In the literature, Yan et al., 2019 [7], utilized GGBS as a partial replacement (0, 25, 50, and 75%) of Portland cement, and reported that 75% was the optimum replacement amount in terms of the sulfate resistance of concrete immersed in 5% sodium sulfate. Cercel et al., (2021) [13] investigated the physicomechanical properties of mortar made by activation of both ground granulated blast-furnace slag and glass powder with a binary combination of sodium carbonate and quicklime and concluded that the produced mortars are a viable replacement for the traditional Portland cement. Hwang and Cortes, (20121) [14] studied the effect of co-utilization of fly ash and glass powder as a partial substation of Portland cement and reported the enhancement of the ratio and unconfined compressive strength development of mortar and previous concrete, thus suggesting the feasibility of producing a sustainable and green infrastructure pervious concrete by the co-utilization of fly ash and glass powder as a part of Portland cement. Nahi et al., (2020) [14] examine the incorporation of powdered soda lime glass powder as a 0, 10, 25, 35, and 60% replacement of Portland cement in mortar, and reported a reduction in the flowability of the mortar when more than 25% cement replacement was introduced.

Given the above-mentioned literature, it is obvious that the use of pozzolanic materials in cement-based materials is encouraged, to improve the physico-mechanical properties and reduce the environmental concerns of cement manufacturing. Therefore, this study aimed to explore the effect of using red clay and glass powder as a partial replacement (0, 5, 10, 15%) of cement in mortar, of which the former was activated by 3 wt% of quicklime to accelerate the dissolution of clay particles and the release of silica and alumina within the system. To this end, seven mortar mixes were designed and evaluated in terms of workability and compressive strength. Accordingly, the results suggested the feasibility of developing a sustainable mortar using glass powder.

Methodology

1- Materials

The raw materials used in this study included: 1) four cementitious materials (Portland cement-PC, quicklime-L, glass powder-GP, red clay-RC); 2) one fine aggregate (Sand-S); and 3) water. **Table 1** shows the oxide compositions of the Portland cement, lime, red clay, and glass powder, whereas **Table 2** and **Table 3** represent some physical properties.

Table 1: Oxide compositions of Portland cement, lime, glass powder and red clay.

Oxides	PC	L	RC	GP
SiO_2	20.13	0.67	71.84	72
Al_2O_3	4.49	0.07	12.71	3.52
Fe_2O_3	4.26	0.05	3.51	1.77
CaO	63.24	71.6	0.39	10.59
MgO	2.42	0.58	0.95	1.56
Na_2O	0.02	0.02	0.54	10.46
P_2O_5	0.1	0.03	-	-
Mn_2O_3	0.05	0.02	-	-
K_2O	0.57	0.01	-	0.89
TiO_2	0.26	0.01	-	-
V_2O_5	0.06	0.02	-	-
BaO	0.05	0.01	-	-
SO_3	1.12	0.19	-	-
LOI	4.3	27.4	19.9	-

Table 2: Physical properties of Portland cement (PC) and Lime (L), red clay (RC) and glass powder (GP).

Oxides	PC	Lime	RC	GP
Density (kg/m^3)	1400	-	-	1200
Specific gravity (Mg/m^3)	3.15	2.82	-	2.5
Fineness (m^2/kg)	365	750	-	-
pH	13.41	12	7	-
Colour	Grey	white	Brown	white
Form	Powder	powder	Powder	powder

The PC used was a commercially available Portland cement (CEM-II) in the form of grey fine powder. It was manufactured in compliance with the Libyan standard specifications No. 340 of 2009 and obtained from the Arab Union Cement Company in Zliten, Libya, through a local supplier. The characterization tests conducted on the as-received product indicated that the PC has a softness of 3575, initial setting time of 135 minutes, final setting time of 225 minutes, 3-days compressive strength of 22.3 N/mm^2 and 7 days- unconfined compressive strength of 49.3 N/mm^2. The red clay (RC) was a natural clay with oxide compositions as outlined previously in **Table 1**, with a liquid limit of 56%, plastic limit of 33% and plasticity index of 23%. It was collected from the valley of Souf al-Jeen in the city of Bani Waleed, Libya.

The glass powder (GP) was prepared by grinding various types of glass bottles in the laboratory, after being dried and washed. The grounded powder was then sieved through a 0.063 mm sieve size and the particles passing the prescribed sieve, which has oxide compositions as outlined in **Table 1**, were used. The fine aggregate used in the experimentations was natural sand with particle size distribution results as shown in **Fig. 1** and some physical properties as outlined in **Table 3**. The sand was brought from Zliten through a local quarry and supplied by a local contractor. The water used in this study was potable water with chemical compositions as outlined in **Table 4,** which was obtained through a commercial service by a local company. By comparing the oxide compositions with those outlined in Libyan specifications No. 294, it was observed that the water used was suitable for use.

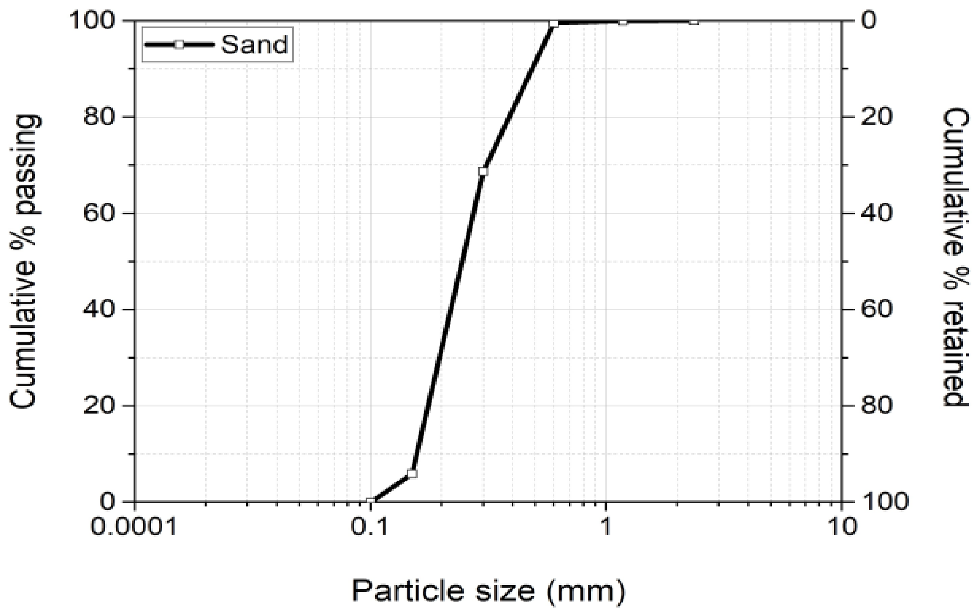

Fig. 1: Particle size distribution of sand.

Table 3: Some properties of sand

Physical properties	Sand
Specific Weight	2.58
Density	1736
Absorption Rate %	1.25
Fine Material Content %	0.15
Chloride Content %	0.75
Colour	White
Sulfate Content %	0.165

Table 4: Chemical compositions of water.

Chemical compositions	Quantity (mg/litter)
CO_3	57.97
HCO_3	104.12
CI	216.29
Na	120.62
Mg	5.43
Ca	3.32
K	62.18
$CaCO_3$	30.84
Dissolved solids	698.0
Conductivity	1.21
pH	9

2- Mix design

The mortar mix compositions assessed through the laboratory experimentations were designed using, 1) a fixed binder: sand proportion of 1:3; 2) a constant water/cement ratio of 0.55, and 3) seven various binder combinations. These binders (see **Table 5**) were made of; 1) 100% of PC (as a control mix); 2) M2-5%GP, representing 5% cement replacement with glass powder; 3) M3-10%GP, representing 10% cement replacement with glass powder; 4) M4-15%GP, representing 15% cement replacement with glass powder; 5) M5-5%RC, representing 5% cement replacement with red clay; 6) M6-10%RC, representing 10% cement replacement with red clay; and 7) M7-15%RC, representing 15% cement replacement with red clay. However, it should be noted that 3% of the total amount of red clay was a quicklime to enhance the dissolution of clay particles. As for the purpose of designing such mixes, this was to obtain an eco-friendly mortar, with equivalent characteristics to the control mix.

Table 5: Proportions of Binder combination.

Mix Design	PC	GP	RC
M1 (100 % PC)	100	-	-
M2 (5 % GP)	95	5	-
M3 (10 % GP)	90	10	-
M4 (15 % GP)	85	15	-
M5 (5 % RC)	95	-	5
M6 (10 % RC)	90	-	10
M7 (15 % RC)	85	-	15

3- Sample preparation and testing

A total of six cubical specimens with dimensions of 50 mm × 50 mm × 50 mm were prepared for each mix composition, in accordance with [17-21]. For each mix, the dry ingredients (PC, L, RC and GP) were firstly mixed in a mixer for 3 minutes, before the water was introduced and the mixing continued for further 3 minutes. Subsequently, the consistency of fresh mortar was measured by slump test, in accordance with BS EN 12350-2:2019 [20]. The semi-paste mixture was afterwards poured into the pre-oiled moulds and vibrated for 1 minute to remove air voids. Afterwards, the mortar-filled moulds were stored at 20±5 ℃ to be de-moulded after 24 hours, preparing for the curing. Finally, six cubes were cured in a water tank at 20±5 ℃, preparing for the unconfined compressive strength test at 7 and 28 days of moist curing. Finally, the unconfined compressive strength was conducted using a compressive machine at a load speed ratio of 1.4 kN/sec, in accordance with BS EN 12350-3 2019 [21].

Results and discussions

1- Slump test

The slump value of mortars made with glass powder and red clay is presented in **Fig.2**, alongside the slump value of Portland cement-based mortar as a benchmark.

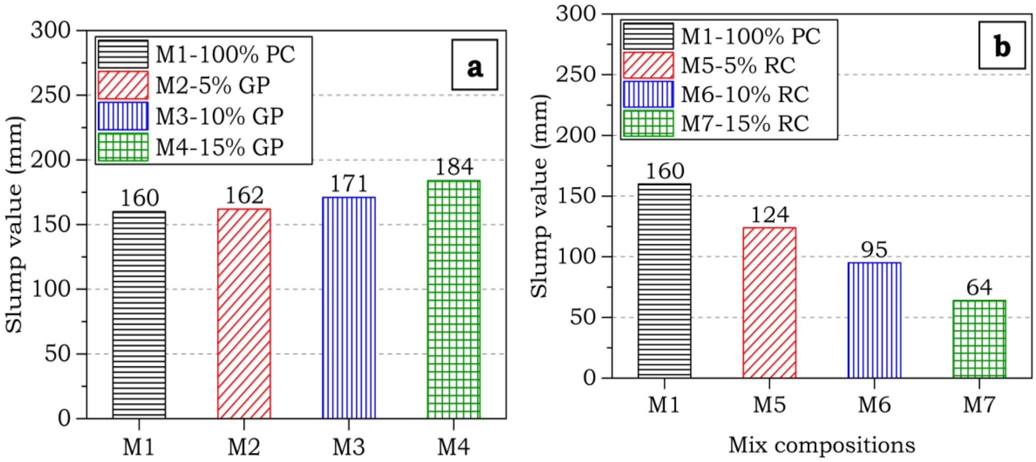

Fig. 2: Slump values of mortars made with; **a)** glass powder, and **b)** red clay.

As seen in **Fig.2**, the observations revealed a gradual increase in the slump value, as the quantity of glass powder increased, where the control mortar mix (M1-100%PC) displayed the lowest slump value of 160 mm, relative to that of 162 mm, 171 mm, and 184 mm for the case of M2-5%GP, M3-10%GP and M4-15%GP, respectively. This trend, however, was in reverse order in the case of cement substitution with red clay (see **Fig. 2b**), where the slump value was reduced gradually from 160 mm to 124 mm, 95 mm, and 64 mm for the mortar mix composition of M5-5%RC, M6-10%RC and M7-15%RC, respectively. The increase in slump value in the case of using glass powder as a partial cement substitution, therefore, suggests the possibility of reducing the water demand and improvement of the pumpability of the mortar, whereas the reduction in slump in the case of red clay indicates the needs for using lubricants such as superplasticizer if higher workable mortar is required.

The gradual enhancement in the slump value induced by using glass powder as a replacement for cement, which was in line with the outcomes of the slump value of concrete made with glass powder reported in [22], can be attributed to the glassy (smoothness) of glass powder surface, the lower water absorption capability of glass powder relative to Portland cement, and the coarser texture of glass powder, all of which ease the slumping of the mortar mixture. As for the gradual reduction induced by the application of lime-activated red clay is probably because of several reasons: 1) the high-water absorption capability of clay due to its negatively charged particle surface; 2) the substantial heat induced by the extremely high exothermic hydration reaction of quicklime which causes the evaporation of water; and 3) the fineness of the clay particles [22-27].

2- Unconfined compressive strength (UCS)

The unconfined compressive strength (UCS) development of mortar fabricated using different glass powder and red clay contents as a partial replacement of Portland cement is plotted in **Fig. 3**, alongside the UCS of the Portland cement-based mortar (M1) as a benchmark.

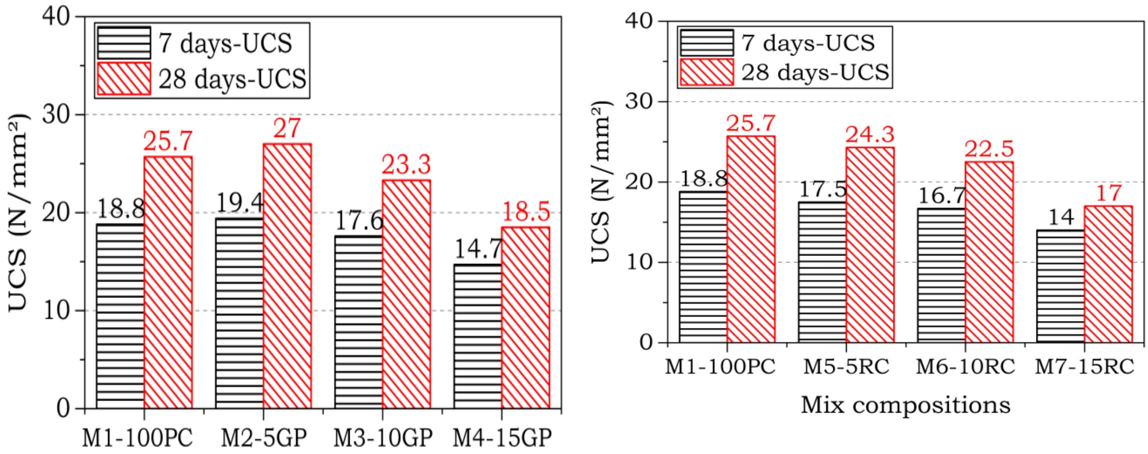

Fig. 3: The UCS evolution of mortars made with; **a)** glass powder, and **b)** red clay, at 7 and 28 days of curing age.

Generally, there was a steady increasing development in the UCS as the curing age increases from 7 to 28 days for all the mortars cured in water. This, therefore, demonstrates the formation of new hydrates and confirms that the strength of cubical mortars followed the general trend of UCS evolution of cement-based materials. This strength development is owing to the initial hydration of cement components with water to produce hydrated products such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH), which are responsible for the densification of the concrete system and the interlocking of the mixture [2].

The effect of the incorporation of glass powder observed in M2, M3 and M4 showed that the unconfined compressive strength was increased as the quantity of glass powder increases to 10%, beyond which further increase induces a compromise on the UCS. As an instance, the 28 days-UCS was increased from 25.7 N/mm^2 for M1-100%PC to 27 N/mm^2 for M2-5%GP, and then reduced to 23.3 N/mm^2 for M3-10%GP, and 18.5 N/mm^2 for M4-15%GP, indicating that 5% cement replacement with glass powder is the optimum substitution level in terms of the UCS. This unconfined compressive strength trend was also in agreement with the unconfined compressive strength trend of another researcher [22], who reported that 5% and 10% cement substitution is the optimum replacement level for concrete grade 33MPa and 45MPa, respectively.

The improvement of unconfined compressive strength induced by the incorporation of glass powder at a 5% cement replacement level, is probably due to the reaction between the glass powder and the calcium hydroxide produced during the hydration of Portland cement, which facilitates the formation of further calcium silicate hydrate (C-S-H). These hydrates crystalline with time, densifying the mortar matrix, reducing the porosity, and inducing better bonding, all of which enhance the UCS performance. As for the reduction in UCS induced by the higher replacement level, this can be credited to the reduction in the quantity of cement, which induces a compromise on the needed oxides for the formation of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H).

On the application of red clay soil as a part of Portland cement, however, the observation revealed a gradual compromise on the unconfined compressive strength as the quantity of red clay soil was increased. In this context, the 28 days-UCS was reduced from 25.7 N/mm^2 for M1-100%PC to 24.3 N/mm^2 for M5-5%RC, 22.5 N/mm^2 for M6-10%RC, and 17 N/mm^2 for M7-15%RC, indicating the negative impact of red clay on the strength development of mortar. This strength trend was not in line with the observation of the finding reported in [22], where the strength was increased corresponding to the addition of calcined clay, the difference of which can be assigned to the reactivity and the calcination of the clay used. For this reason, research studies considering the effect of heating the red clay at elevated temperatures are encouraged for future work, to select the appropriate calcination temperature for this particular clay (red clay) and to enhance the application of red clay as a partial replacement of cement.

Conclusions

The feasibility of developing an eco-friendly mortar by using both glass powder and red clay as a partial Portland cement substitution has been investigated under this study in terms of the workability and the unconfined compressive strength, and the main conclusions emerged from the results of the experimentations can be drawn as follows:

The utilization of glass powder as a partial replacement of Portland cement in mortar mixture improves the workability (slump value) as the cement substitution level increases, due to its glassy surface (smoothness), its lower water absorption capability, and the coarser texture of the glass powder, relative to that of the Portland cement.

The incorporation of red clay soil as a cement substitution in mortar reduces the workability of mortar, due to the high-water absorption capability and the fineness of the clay particles.

The unconfined compressive strength of mortar increases as the quantity of glass powder increases up to a 10% cement substitution level, beyond which the strength exhibited a gradual reduction. The enhanced strength at a 5% cement replacement level is due to the pozzolanic reaction between the glass powder and the calcium hydroxide, enabling the formation of further calcium silicate hydrate, thus densifying the matrix, and inducing better interlocking. As for the reduction in UCS beyond 5% replacement, this could be due to the reduction in the cement content, which induces a compromise on the needed oxides for the formation of hydrates responsible for strength development.

The application of red clay in mortar as a cement substitution yielded a gradual compromise on the unconfined compressive strength, as the amount of red clay increased. This is probably due to the lower reactivity of the clay used.

The limitations of this study, which can have an impact on the authenticity of the experimentation findings are the use of clay without calcination, which is anticipated the main reason for the reduction of strength. Therefore, studies considering the heating of clay at elevated temperatures and investigating the effect of calcination temperature on the ability of clay with respect to the mechanical performance of mortar are recommended for future work. In the process of heating, the silica content of the clay is improved and became more active, which in turn induces an enhanced mechanical property of the mortar matrix.

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