Nasr, MS, Shubbar, AAF, Abed, ZA-AR and Ibrahim, MS

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Article

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Properties of Eco-Friendly Cement Mortar Contained Recycled Materials from Different Sources

Mohammed Salah Nasr [1,*], Ali Abdulhussein Shubbar [2,3], Zain Al-Abideen Raed Abed [4], Mohammed Sami Ibrahim [3]

[1] Babylon Technical Institute, Al-Furat Al-Awsat Technical University, 51015 Babylon, Iraq.

[2] Department of Civil Engineering, Liverpool John Moores University, Henry Cotton Building, Webster Street, Liverpool L3 2ET, UK.

[3] Department of Civil Engineering, College of Engineering, University of Babylon, Babylon, Iraq.

[4] Department of Architecture Engineering, College of Engineering, University of Babylon, Babylon, Iraq.

* Corresponding author: E-mail: msn_alamar@yahoo.com, dw.moh1@atu.edu.iq

Abstract

Building materials such as sand, cement, bricks, and steel are usually the main components of the construction sector. All these materials are produced from existing natural resources and they will cause substantial damage to the environment as a result of their continuous depletion. Moreover, during the manufacture of various building materials, especially cement, a high concentration of carbon dioxide is constantly emitted into the atmosphere. Therefore, to reduce this environmental damage as well as to save natural resources, this study was performed to recycle the wastes of some of building materials such as marble, granite and porcelain tiles and clay brick through using them as cement and aggregate replacement materials in cement mortar. Sixteen mixtures were cast for this study. In addition to the control, the mortar mixes were divided into five groups, three mixes in each group. In four of the five groups, cement was replaced in three proportions (5%, 10%, 15% by weight) with each of marble, granite, porcelain and clay brick waste powders (passing through 150-micron sieve). The fifth group included 100% replacing (by weight) of the natural sand with the marble, granite and porcelain tiles wastes (with a comparable gradation). The influence of these wastes on flow rate, compressive strength, flexural strength, bulk density, ultrasonic pulse velocity (UPV) and water absorption tests were observed. Results showed that it is possible to produce an eco-friendly mortar made with 100% recycled marble or porcelain aggregate with a significant improvement in the mechanical and durability properties in comparison with natural aggregate mortar.

Keywords: building materials waste, cement replacement, aggregate replacement, eco-friendly mortar.

1. Introduction

Conventional materials such as clay, sand, gravel, cement, bricks, wood and steel usually represent the main components of the construction sector. Generally, concrete that consist of cement and natural fine and coarse aggregate is considered one of the main consumer of natural resources and will cause substantial damage to the environment as a result of their continuous depletion [1–3]. For example, the extensive usage of natural (fine and course) aggregate is one of the main reasons for the scarcity of natural aggregates in many countries around the world [4]. Furthermore, the cement industry consumes high energy as well as emits a high amount of CO_2 into the atmosphere [5–10]. The cement industry contributes about 7% of carbon dioxide production worldwide [11–15]. Moreover, the cement cost represents about 20% of the concrete cost [16]. Therefore, there has been a need to find alternatives to cement and natural aggregate from the economical and environmental viewpoint [17,18]. Extensive research has been done over the past years to find sustainable alternative to natural aggregate and cement. For example, the coarse aggregate was replaced by lightweight aggregate that produced from various sources such as palm oil [19], expanded clay [20] and lava [2,21]. Fine aggregate was replaced by Tyre Rubber [22], Copper Slag [23] and Mica [24]. One the other hand, the cement was replaced by GGBS [14], CKD [25], Fly ash [26], rice husk ash [27] and bottom ash [28].

One of the most used construction materials in Iraq is the clay brick, which is considered as the main element in the construction of the horizontal housing units. Additionally, the common materials used for flooring in the Iraqi housing units are marble, granite and porcelain tiles. Because that the Iraqi people (especially at the middle and south of Iraq) tend to build their housing units with bearing walls (using clay bricks) rather than structural construction (concrete beams and columns), thus clay bricks are used extensively and will result in large residues that need to be treated. The situation is similar for floor materials.

The impact of the clay brick, marble, granite and porcelain waste on different concrete or mortar properties was discussed previously by several studies.

Hasan et al [29] reported that substitution sand with 10% or 20% marble powder had a negative impact on mortar mechanical properties especially at later ages (56 days). Bacarji et al [30] found that, when replacing the cement with 5% to 15% of marble residue, the marble residue might act as a filler in concrete. Tayeh [31] reported that the compressive strength was reduced after using marble powder (passing through sieve #200) as cement replacement in proportions of 10% to 30%. However, according to Ergün [32], replacing cement with 5% waste marble powder improved the flexural and compressive strength compared to the conventional concrete (without replacement). Moreover, Ashish [33] found that replacing sand with 15% marble powder increased the 28-days compressive strength by 4.5%.

Li et al [34] used the granite powder as cement replacement to enhance the dimensional stability and durability of mortar. Results indicated that the compressive strength and water resistance were improved. Additionally, the cement content was reduced by 25%. On the other hand, the SP demand was increased. According to Bacarji et al [30], the granite residue act as a non-reactive material and using it as cement alternative caused a reduction in compressive strength and increasing in water absorption.

Patel and Shah [35] made an experimental study to investigate the durability and the mechanical performance of high performance-concrete (HPC) made with porcelain waste powder as cement replacement. The cement was replaced by 5%, 10%, 15% and 20% of porcelain waste with water/binder ratio of 0.33. Results revealed that 15%

porcelain waste folded better performance compared to the control mix in terms of compressive and flexural strength, sorptivity, corrosion and chloride penetration as well as achieved major environmental benefits. Similar findings were recorded by Hasan et al [29] when replacing the sand with 20% porcelain waste.

Aliabdo et al [36] performed a study to explore the effect of the crushed clay brick on phyisco-mechanical properties of paste, mortar and concrete (concrete masonry units). The clay brick was crushed and classified as recycled aggregates and powder. Results indicated that the incorporating of crushed clay powder by 25% reduced the pore size of the cement paste. The utilizing of the crushed clay brick as recycled aggregate in the concrete masonry units led to a decrease in the compressive strength, unit weight and increased the thermal resistance and water absorption related to the reference units. Additionally, the splitting tensile strength, modulus of elasticity and the porosity of concrete were affected negatively by the high content of the crushed clay brick. On the other hand, Olofinnade et al [37] investigated the properties of concrete made from ground clay brick waste (powder) as a partial replacement of cement in the percentage 10%, 20%, 30% and 40%. Results indicated that the 10% substitution of the powder caused a significant increase in compressive and splitting tensile strength. After that percentage, the strength was decreased. It was recommended that the ground clay brick waste should not be exceeded by 15% in the production of concrete.

Based on the literature above, it is clear that there is no specific pathway for the effect of building material waste on the properties of concrete or mortar. There are conflicting results in terms of positive and negative impacts on different characteristics. Moreover, for marble, porcelain and granite, wastes used in the concrete or mortar production for most previous works were come from cutting or polishing of these materials (industrial waste). Limited studies addressed the crushed tiles waste. Additionally, limited studies used comparable grading with the natural aggregate. Furthermore, limited studies dealt with the use of the Iraqi building materials waste as cement or aggregate replacing materials. Additionally, according to the authors' knowledge, in Iraq, there is no study found to replace the sand totally by such wastes. Furthermore, it is believed that the inclusion of building materials waste in the concrete or mortar as cement or aggregate replacement is a good solution in terms of improving the environment and reducing the depletion of natural resources. Thus, this study was performed to recycle the wastes of some of the locally available building materials such as marble, granite, and porcelain tiles and clay brick through using them as a cement or aggregate replacement in cement mortar.

2. Research objectives

This study aims to achieve the following objectives:

1. Explore the influence of using locally (produced or available) building materials (such as marble, granite and porcelain tiles and clay brick) wastes as a substitute for cement or natural aggregates on some mechanical and durability properties of cement mortar.
2. Improve the environment by integrating such wastes into the concrete industry in addition to reducing the depletion of natural resources.
3. Investigate the possibility of producing an eco-friendly mortar using these wastes without a significant negative effect on its different characteristics.

3. Experimental work

3.1 Materials

The materials used in this study to manufacture the cement mortar were cement, natural sand, building material wastes, superplasticizer and water. Lime cement (CEM II 42.5R L-A) conforms to the Iraqi specification IQS No. 5 [38] was used. The chemical composition of cement is shown in Table 1. The natural sand was graduated according to the Iraqi specification IQS No. 45 [39], as shown in Figure 1. To investigate their effect on different mortar properties, building material (such as marble, granite, and porcelain tiles and yellow-clay brick) wastes were utilized as cement or aggregate replacement (see Figure 2). These wastes were obtained by crushing of large broken portions of tiles into small particles, then they were either ground to a powder to be used as cement replacing material or graduated to be used as an alternative to the natural aggregate. The granite, marble and bricks wastes that were used as aggregate replacing materials were crushed to small particles using hand crusher then they sieved on sieves ranged between 1.18 to 0.15 mm. Then the retained materials on each sieve were separated and weighed. To achieve comparable grading, the crushed materials were proportioned as that for the natural sand used which is tested previously (conformed to the Iraqi specification IQS No. 45 [39]). Thereafter, the proportioned materials for each granite, marble and bricks were mixed together using a mechanical mixer to ensure homogeneity. Thus, the adopted particle size was similar to that for the natural sand used which is originally conformed to the Iraqi specification IQS No. 45 [39]. The powder which was passed through 150-micron sieve was used as cement replacement. The chemical composition of these waste is presented in Table 1. To make a good comparison between them, the materials wastes that used as an aggregate replacement were graduated as for natural aggregate (0.15 – 1.18 mm in size), see Figure 1. Glenium

54 superplasticizer, which conforms to ASTM C494 Type A and F [40], was added to the mixing water to adjust the workability of the mortar mixtures. Tap water was used as mixing water for all mixtures.

Table 1: The chemical composition of cement and building materials waste.

Oxides	**Cement**	**Marble**	**Granite**	**Porcelain**	**Clay brick**
CaO	62.1	51.82	1.46	3.4	28.11
SiO_2	22.1	1.97	72.37	65.49	40.59
Al_2O_3	4.2	0.38	8.1	19.38	12.01
Fe_2O_3	3.9	0.55	1.94	2.71	4.92
MgO	3.3	1.69	0.38	1.93	5.15
SO_3	1.9	0.22	---	---	5.3
Na_2O	---	0.11	3.65	1.94	1.29
K_2O	---	0.05	3.91	2.37	0.86
Free lime	0.7	---	---	---	---
L.S.F.	0.86	---	---	---	---
Insoluble residue	1.1	---	---	---	---

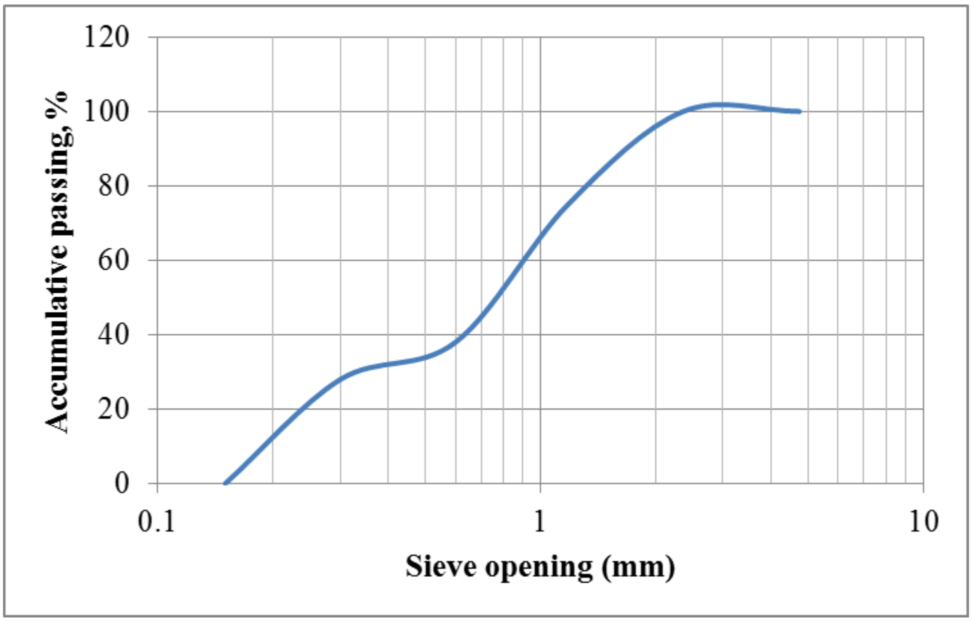

Figure 1: The grading of the sand and its replacing materials (marble, granite, and porcelain tiles waste).

3.2 Mortar mixtures

Sixteen mixtures were carried out in this study. One reference mix (without addition), twelve mixes containing a weighed replacement of cement with marble (M), granite (G), porcelain (P) and clay brick (B) powders (three substitutions: 5%, 10% and 15% for each material) and three mixtures included full replacing (100% by weight) of natural aggregate with marble, granite and porcelain tiles waste. The adopted mix proportions for all mixes were 1:2.75 (binder: sand). In order to observe the influence of the used materials on fresh mortar flow, the superplasticizer and water/ binder ratio were fixed for all mixes as 0.4% (by weight of cement) and 0.485, respectively. The mix proportion details for mortar mixes are illustrated in Table 2.

Figure 2: Materials used in this study.

Table 2: Mix proportion details for the mortar mixes (as a part of the binder weight).*

Mix No.	Replacement type	Mix designation	Cement	MP	GP	PP	BP	Sa	Ma	Ga	Pa	WW	SP
1	None	Con	1	0	0	0	0	2.75	0	0	0		
2		M5	0.95	0.05	0	0	0	2.75	0	0	0		
3		M10	0.9	0.1	0	0	0	2.75	0	0	0		
4		M15	0.85	0.15	0	0	0	2.75	0	0	0		
5		G5	0.95	0	0.05	0	0	2.75	0	0	0		
6		G10	0.9	0	0.1	0	0	2.75	0	0	0		
7	Cement replacing mixtures	G15	0.85	0	0.15	0	0	2.75	0	0	0		
8		P5	0.95	0	0	0.05	0	2.75	0	0	0	0.485	0.004
9		P10	0.9	0	0	0.1	0	2.75	0	0	0		
10		P15	0.85	0	0	0.15	0	2.75	0	0	0		
11		B5	0.95	0	0	0	0.05	2.75	0	0	0		
12		B10	0.9	0	0	0	0.1	2.75	0	0	0		
13		B15	0.85	0	0	0	0.15	2.75	0	0	0		
14		MA	1	0	0	0	0	0	2.75	0	0		
15	Sand replacing mixtures	GA	1	0	0	0	0	0	0	2.75	0		
16		PA	1	0	0	0	0	0	0	0	2.75		

* MP: marble powder; GP: granite powder; PP: porcelain powder; BP: brick powder; Sa: sand aggregate; Ma: marble aggregate; Ga: granite aggregate; Pa: porcelain aggregate; WW: water; SP: superplasticizer

3.3 Mixing

The mixing process was done using a mechanical mixer according to the following procedure:

- All dry materials were placed in the mixer and mixed for 1 min at a slow speed (140 rpm).
- The mixer was stopped and the water and the superplasticizer (which were mixed previously) were added to the dry materials and the mixer was operated for 1 min at a slow speed.
- The mixer was stopped for 1 minute during which the speed was converted to the medium speed (285 rpm).
- Then all materials were mixed final mixing for 2 minutes.

3.4 Casting and curing

Before casting, molds were cleaned and lubricated with a light layer of oil to facilitate their lifting after hardening. After mixing, the flesh mortar was poured in standard cubic (50×50×50 mm) and prismatic (40×40×160 mm) molds and compacted using an electrical vibrator. After about 20 to 24 hours of casting, the specimens were de-molded and immersed in water at a temperature of 20± 2 °C until the time of the test.

3.5 Tests

Different tests were carried out to monitor the effect of the used materials on the properties of the fresh and hardened mortar. Flow test according to ASTM C1437 [41] was performed for fresh mortar. For hardened mortar, compressive strength, flexural strength, ultrasonic pulse velocity (UPV) and water absorption tests were executed. One test age (at 28 days) was depended for all hardened tests. Cubic 50 mm specimens were used for compressive and UPV tests, while 40×40×160 mm prisms were accounted for the flexural strength test. The latter was calculated using the following equation [42]:

$$F = \frac{1.5\ P\ L}{b^3} \qquad (1)$$

Where; F is the flexural strength (MPa), P is the ultimate load (N), L is the distance between supports (mm) and b is the cross-section dimension of the prism.

After breaking the flexural strength prisms in the machine into two halves, the prisms portions (the two halves) were used to perform the water absorption test. The procedure described in ASTM C642 [43] was followed for determining the water absorption of hardened mortar. The method included drying the samples in the oven at 100-110 ºC and weighing them every 24 hours until the constant mass (the mass difference between any two successive values is ≤ 0.5%). After cooling, the specimens were immersed in water and weighed every 24 hours until the constant mass. Then the water absorption can be calculated using the following equation:

$$W = \frac{A-B}{B} \times 100 \qquad (2)$$

Where; W is the water absorption (%), A is the mass of the wet specimens and B is the mass of the oven-dried specimens.

The dry bulk density was determined by dividing the measured mass (oven-dried) of the prismatic specimens (40×40×160 mm) by their volume [44]. Average of three readings were considered for each of the compressive and flexural strengths and bulk density tests, while an average of six readings was taken into account for UPV (two readings from each cube) and water absorption (two readings from each broken prism) tests.

4. Results and discussions

4.1 Flow test results

The flow test results of all mixtures are presented in Figure 3. For cement replacement mixes, results indicated that marble mixes showed comparable flow at 5% and 10% substitution related to the control sample. However, the flow rate was increased at 15% substitution. The lower specific gravity of marble powder than the cement resulting in increasing the volume of paste compared to Portland cement and leading to enhance the flowability which is more pronounced at 15% content of marble powder [45]. Moreover, the flow rate of granite mixes was equal to that for the control mixture. On the other hand, clay brick powder decreased the flow rate. The higher the substitution of the clay brick powder, the lower was the flow rate. These results differed from what Tayeh et al [28] found, as they reported that using pottery powder as a partial substitute for cement improved the workability of mortar. The reason for this difference may be due to the fact that the method of production of pottery and the degree of its burning in addition to surface characteristics of its particles might differ from that for building bricks, and therefore these properties can affect its water demand. The reduction in flow rate can be attributed to the ability of the clay brick powder to absorb water, the roughness of its surface and the angularity [46] which led to the loss of a part of the mixing water and thus reduced the flow rate. For porcelain powder mixtures, the results showed a slight improvement in flow rate for all used ratios in comparison with the control mix. Furthermore, for aggregate replacement mixes, results revealed that the flow rate was enhanced in the presence of marble aggregate by about 5% which can be interpreted by the favoring the rheology of mortar as a result of the low porosity and water absorption of crushed marble waste [47–49]. However, it was reduced for granite and porcelain aggregate by 13% and 49% respectively.

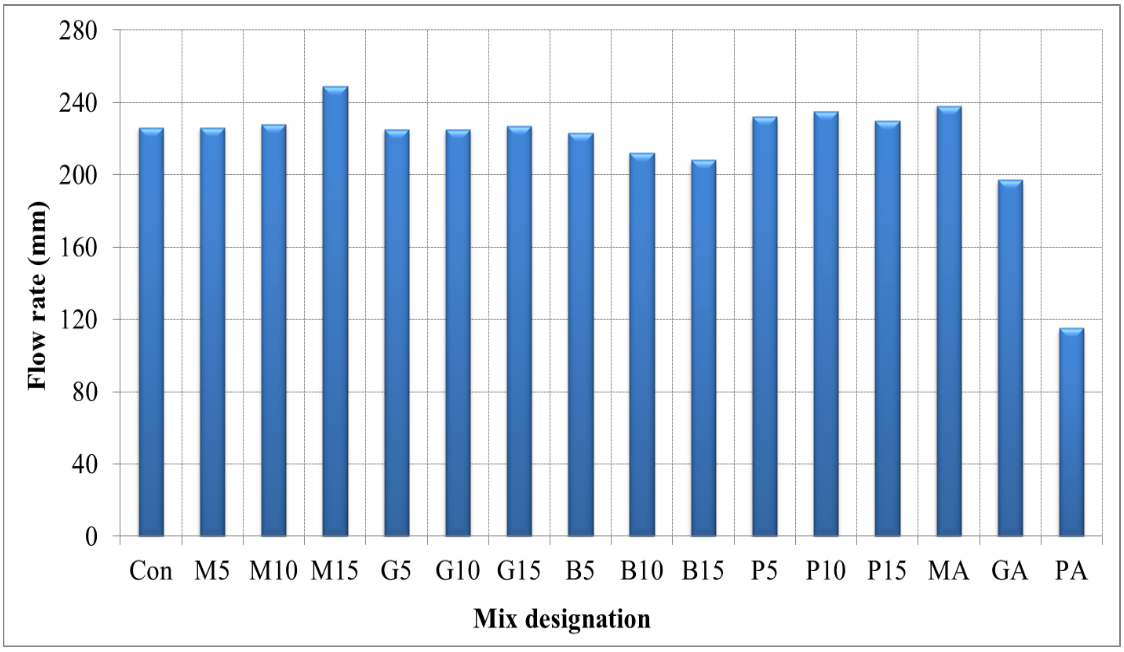

Figure 3: Flow rate results of fresh mortars.

4.2 Compressive strength results

Results of the compressive strength test for mortar mixes are illuminated in Figure 4. Results indicated that all mixes containing building materials waste as cement replacement reduced the compressive strength in comparison to the reference mixture. For marble, granite and porcelain mixes, the reduction rate was increased with the increase of the powder substitution. The reduction rates for clay brick mixes were 18%, 29% and 23% respectively. These results are in agreement with previous work [36]. Compared to the control sample, the minimizing rate (62%) was obtained for 15% substitution of granite powder. This reduction in compressive strength regardless of waste type can be attributed to the low reactivity of these waste [46] and the dilution of the silicates (C_3S and C_2S) which represent the main components for hydration process and in charge of concrete strength [50–52] as well as the decrease in C_3A content [53]. For aggregate replacing mixes, it was found that the replacement of sand with marble and porcelain tiles waste improved the compressive strength by 4% (for both) compared to the reference mix. This increment is a result of aggregate characteristics such as good granulometric distribution, surface texture that leads to enhance the composite quality [47,54–56]. Contrary, the granite aggregate reduced the compressive strength by 16%. This reduction in compressive strength of granite aggregate can be interpreted according to Jain et al [57] who reported that the replacing of fine aggregate with high level (more than 60%) of granite cutting waste reduced the compressive strength of concrete due to the increase in the porosity causing revoking in the pore filling effect. The UPV results (as presented in the following sections) support this claim.

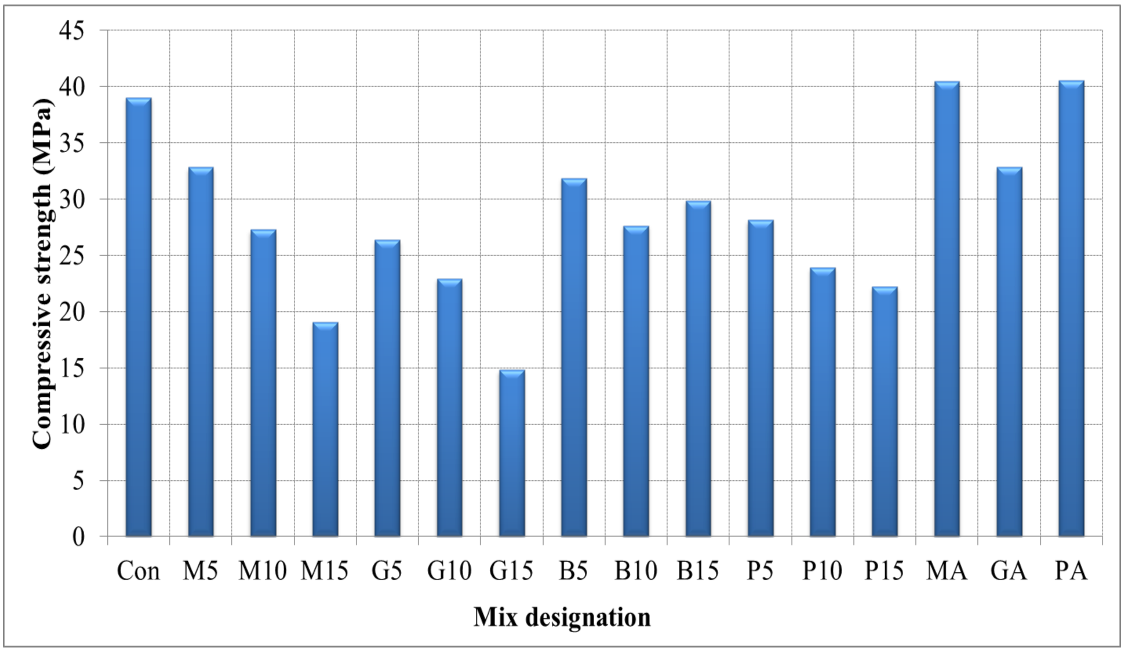

Figure 4: Compressive strength results of the mortar mixtures.

4.3 Flexural strength results

Figure 5 shows the results of the flexural strength test. As in compressive strength, all cement substitution mixtures showed lesser flexural strength values than the reference mixture. Additionally, the higher the substitution percent, the higher the reduction rate for marble, granite and porcelain mixes were recorded. The possible reason for that is the poor interlocking between the waste powder and aggregate [58]. The greatest reduction in flexural strength (67%) was given by 15% substitution of granite powder, however, the least reduction (11%) was found at 5% replacement with marble powder. The reduction rates of clay brick powder mixtures were 17%, 36% and 25% for B5, B10 and B15 respectively. Similar findings for clay brick were recorded by Zhu et al [59] who reported that the flexural strength was reduced at 3 days and 28 days, respectively, by 27% and 18% when the powder increased from 9% to 27%. The authors attributed that reduction to the lower pozzolanic activity of clay brick powder compared to cement. For natural sand replacement mixes, a significant improvement was observed for marble aggregate (about 7%) compared to the natural sand. The highest enhancement was recorded for the porcelain aggregate mix, about 156%. The enhancement in flexural strength for porcelain aggregate was more pronounced than that in compressive strength. The reason for that may be returned to that flexural strength is affected by the pore structure and the interfacial transition zone (ITZ) between the aggregate and cement more than the compressive strength [60]. In contrast, the flexural strength was reduced by about 6% for the granite aggregate mix. As explained in compressive strength, the increase of voids within the mortar matrix may cause the flexural strength to be decreased. Similar results for the high replacement levels (> 40%) of aggregate with granite waste were recorded by Singh et al [61].

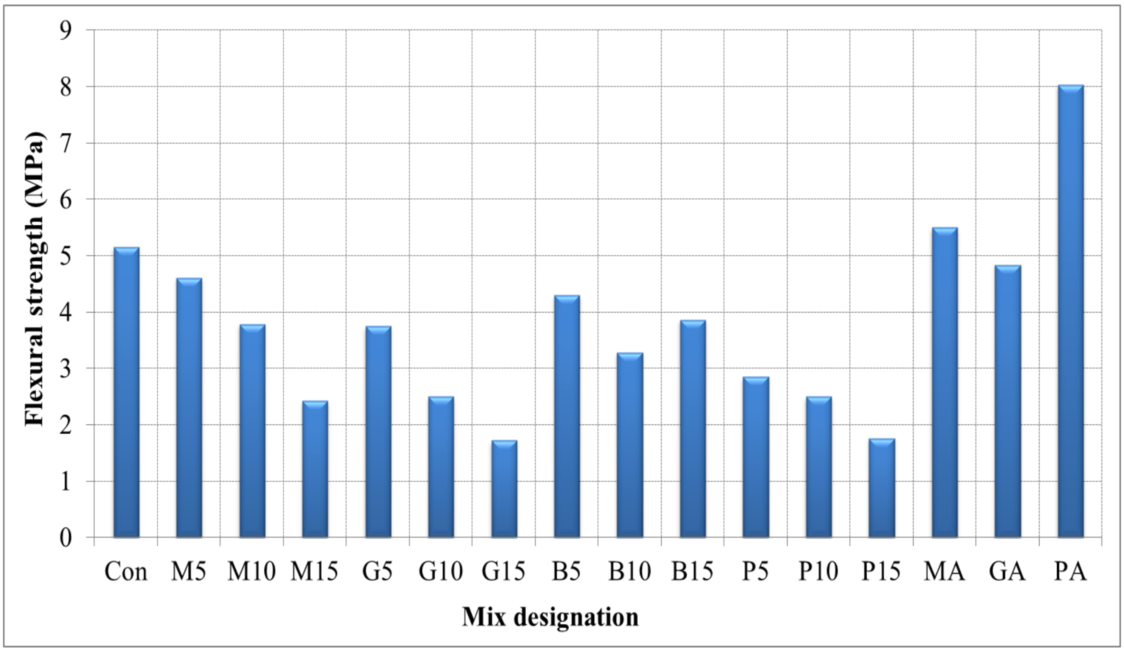

Figure 5: Flexural strength results of the mortar mixtures.

4.4 Water absorption results

Figure 6 displays the results of the absorption test for all mixtures used in this study. The results showed that all mixtures containing building material wastes as substitutes of cement in different percentages gave higher absorption values than the reference mix, except for the 5% clay brick mix, which showed equal absorption to the reference sample. The 5% marble powder showed a negligible increase in the absorption rate, about 1% related to the control specimen. The absorption rate ranges were (11.55 to 18.22%), (11.86 to 12.52%), (11.45 to 12.32%) and (11.99 to 12.31%) for marble, granite, clay brick and porcelain powder-based mixtures, respectively compared to 11.45% for control mixture. This increase in water absorption rates of waste powder mixtures refers to the increase in the porous volume of mortar mixtures [62]. These findings are in agreement with what was reported in previous works [62,63]. Conversely, all aggregate substitution mixtures showed lower absorption rates than the reference mix. Maximum enhancement in absorption rate (17%) compared to the reference mixture was given by the marble aggregate mixture. The water absorption of granite and porcelain was lower than that for the control mix by 4% and 9%, respectively. This improvement in water absorption resistance might be due to better packing (which results from the good interlocking with the cement paste) between the cement matrix and the recycled aggregate [57].

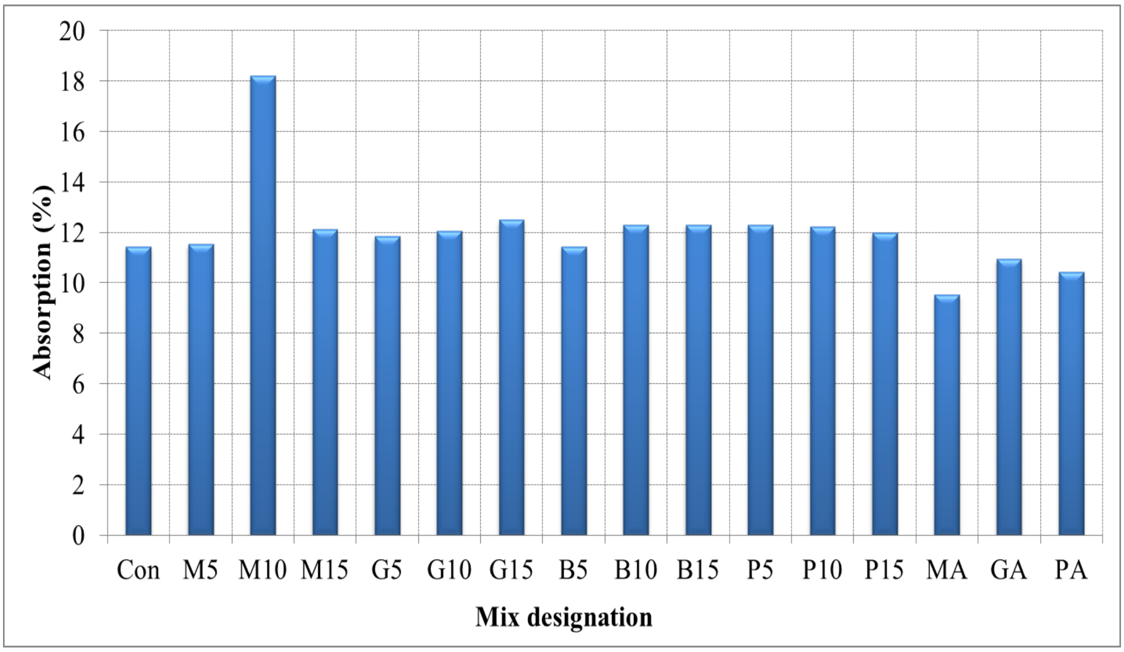

Figure 6: Water absorption results of the mortar mixtures.

4.5 Ultrasonic pulse velocity results

The results of the ultrasonic pulse velocity values of mortar mixtures are shown in Figure 7. Ultrasonic pulse velocity test is used to evaluate the quality of concrete, the existence of voids, and to assess the effectiveness of cracks repair [64]. This examination has also been extended to include a large range of concrete properties, including durability [65]. For this study, it was revealed that the cement substitution mixtures with building material wastes as cement replacement resulted in a reduction in the ultrasonic velocity values in comparison to the control mixture. In general, the UPV values of all mortars ranged between 3420 km/s (for G15 mixture) and 4080 km/s (for control mixture). The highest reduction in the velocity (16%) was found when the cement was replaced with 15% granite powder. For aggregate substitution mixtures, it was noticed that the marble aggregate improved the velocity by about 3% while the granite reduced it by 2%. The porcelain aggregate showed a pulse velocity equal to that for natural sand. Except for G15 mix, it can be observed that there is no significant change in UPV results after replacing cement or sand with building materials waste. This behavior is owing to that the UPV is proportioned to the fourth root of compressive strength [52,66,67].

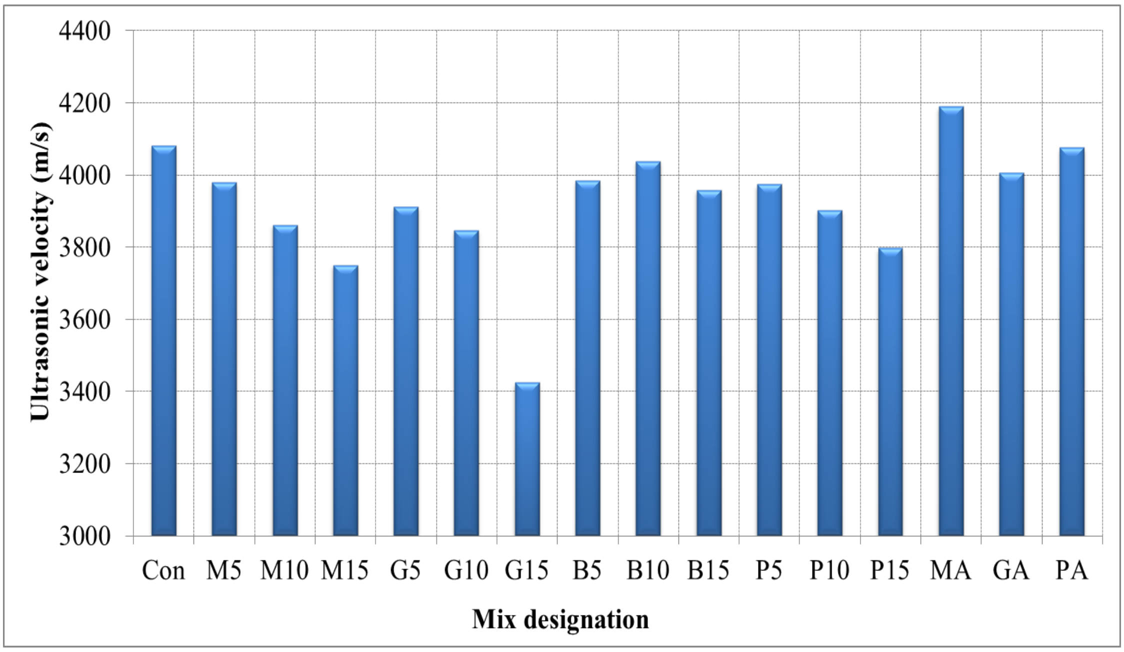

Figure 7: Ultrasonic pulse velocity results of the mortar mixtures.

4.6 Bulk density results

The results of the dry bulk density of the hardened mortars are shown in Figure 8. In general, the density values for all mixtures containing building waste materials as cement or fine aggregate replacements indicated lower values than the control sample except for M5 mixture which folded approximately comparable density (the reduction rate was less than 1%) to that for the reference mix. Moreover, for cement replacement mixtures, in most replacement types, the higher the replacement rate the lower density values were recorded. This can be attributed to the increase of the porosity of the mortars as a result of increasing the water to cement ratio [68] as well as to the lower specific gravity of these waste compared to the cement [69]. The reduction rates were (0.3 to 3.8%), (7 to 17.1%), (2.4 to 5%), (10.3 to 15%) for marble, granite, clay brick and porcelain powder containing mixtures respectively. Results of sand-replacing mixtures indicated that the dry bulk density was declined by 7.9% for marble, 13.3% for granite and 8.9% for porcelain mixtures in comparison to the control specimen. This reduction in bulk density is owing to the lower density of these waste compared to the natural fine aggregate (sand) [44]. Similar trends were recorded by Gameiro et al [70].

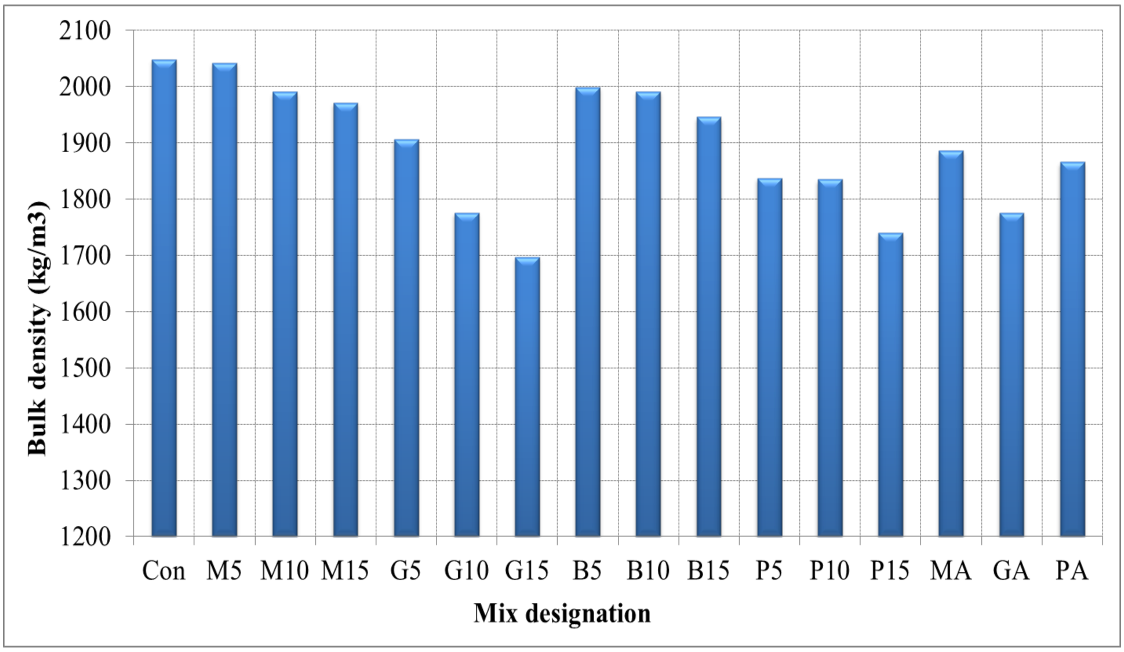

Figure 8: Bulk density results of the mortar mixtures.

5. Conclusion

According to the findings obtained in this study, the following points can be deduced:

1. Replacing the cement with marble and porcelain powder can enhance the flow rate of the cement mortar, while the clay brick powder reduces it compared to the control sample. Using marble wastes as aggregate increases the mortar flow by about 5%, however, the granite and porcelain aggregate reduces the flow by 13% and 49%, respectively in comparison to the natural sand.
2. Using marble, granite, porcelain and clay brick wastes as cement replacement have a negative impact on the mechanical properties of the cement mortar. The maximum reduction percentages in compressive and flexural strength (62% and 67% respectively) were obtained at 15% substitution of granite powder.
3. The replacing of natural aggregate with marble and porcelain wastes improves the compressive strength (by 4% for both) and flexural strength (by 7% and 56%, respectively) of the cement mortar. On the other hand, for granite aggregate mortar, compressive and flexural strengths are reduced by 16% and 6% respectively.
4. For water absorption, all cement replacement mixtures show higher absorption rates, except for 5% substitution of clay brick powder which indicates a comparable absorption rate, related to the control mix. For aggregate replacing mixes, using marble, granite and porcelain enhance the water absorption resistance by 17%, 4% and 9%, respectively.
5. The ultrasonic pulse velocity values are reduced in different rates for cement replacement mixtures. The substitution of cement with 15% granite powder wastes reduces the UPV by 16%, which represents the maximum reduction rate, compared to the reference sample. For aggregate replacement mixtures, the velocity is increased by 3% for marble mortar, while it decreases by 2% for granite. The porcelain aggregate mortar reveals comparable velocity values with the control specimens.

6. Using building materials waste as cement or aggregate replacement reduces the bulk density of the hardened mortars. The decreasing rates increased as the replacement level was increased for cement substitution mixtures.
7. It can be concluded from this study that it is possible to produce an eco-friendly cement mortar made with 100% of recycled marble or porcelain tiles as fine aggregate with a significant improvement in mechanical and durability properties compared to the mortar made with the natural aggregate. Moreover, among all mixtures performed in the current study, the best performance was achieved for mixture contained 100% recycled marble as fine aggregate.

Conflict of interest

None

Acknowledgments

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