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Journal of Engineering Science and Technology
Vol. 16, No. 1 (2021) 136 - 151

PERFORMANCE OF GREEN MORTAR MADE FROM LOCALLY AVAILABLE WASTE TILES AND SILICA FUME

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Abstract

The continuous depletion of natural resources used in concrete require vital replacement materials to reduce the consumptions of the natural resources. Moreover, the growth in the population increases the construction of new houses to accommodate the population, which increases the demand concrete and other construction materials. The replacement of the existing building materials with the newly materials proceed from recycling the waste materials for example, flooring tiles, which is usually disposed of in landfills without any benefit in Iraq. Therefore, this study aims to recycle locally available floor tiles waste by using it as a total alternative to fine aggregate to enhance the sustainability by reducing the depletion of natural aggregates. Three types of waste tiles were used in this research, which are marble, granite, and porcelain. Four mortar mixtures were designed, casted and tested in the research. One control mixture made from natural sand aggregate and three mixtures in which the sand was fully replaced with each of marble, granite, and porcelain waste tiles with comparable grading as that for sand. The cement was partially replaced with a 10% silica fume (SF) in all mixtures. The flowability, mechanical and durability tests of mortar mixtures were investigated. The results indicated that the combination of porcelain waste tiles aggregates with 10% silica fume imparted superior performance compared to all other mixtures with improvements of 99% in the compressive strength, 53% in the flexural strength and 17% in the water absorption resistance.

Keywords: Aggregate replacement, Green mortar, Silica fume, Tiles waste.

1. Introduction

Concrete is one of the widespread construction materials. Concrete consumes a large amount from natural sources every year [1, 2]. Thus, to save resources such as natural aggregate, it is important to find alternatives such as recycled waste materials [2-5]. For example, the materials widely used in flooring in Iraq are marble, granite and porcelain tiles [6, 7]. So, when demolished, large quantities of waste materials are generated. Most construction materials wastes are difficult to get rid of over time, so it is buried in landfills without use, and thus will cause environmental damage and requires high management costs [8-10]. Therefore, the reuse of these materials is considered a worthy solution in terms of improving the environment and towards developing sustainability.

The utilizing of marble [11], granite [11, 12] or porcelain [13, 14] waste as aggregate replacement in the production of concrete or mortar was addressed previously by many researchers. In general, most of the results of these studies indicated that the use of construction materials waste represents a good solution in the field of environmental sustainability, but these studies differed in the optimum ratios for replacing each material with aggregate and the reason for this may be due to the difference in the source of the waste in addition to the differences in the granular size distribution and other physical characteristics [15-19]. Moreover, most of these studies used waste materials as powder and not graded, as well as the results were fluctuating in their impact on the various properties of mortar or concrete [20-22]. Tavakoli et al. [23] replaced the aggregate with ceramic tiles waste to investigate their effect on concrete properties. The coarse aggregate was replaced with 0 to 40% while the sand was replaced with 0 to 100% with ceramic tiles waste. The results indicated that the optimum replacement levels of sand and coarse aggregate were 25 to 50% and 10 to 20% respectively. At these percentages, the compressive strength was improved, and the unit weight was reduced.

Elçi [24] utilized crushed tiles waste as aggregate replacement in concrete production. The replacement level was 25% of the aggregate weight. The results were compared with limestone aggregate concrete. The results of this study showed that the floor tiles aggregate imparted comparable mechanical properties as that for limestone aggregate.

Elçi [24] investigated the effect of using marble and porcelain waste as sand replacement on the properties of recycled aggregate concrete. The marble waste was used in a proportion of 5% while the porcelain waste was used in a proportion of 10% by weight of sand for each replacement. The results of this study indicated that these wastes enhanced the tensile strength and modulus of rupture of concrete while the workability was reduced. The marble wastes increased the compressive strength by 5% whereas the compressive strength values were comparable to that for reference mixture in the presence of porcelain waste.

On the other hand, cement (the main binder materials in the concrete) consumes high energy during its production as well as a high amount of carbon dioxide (CO_2) is emitted into the atmosphere (represents about 7% of CO_2 produced worldwide) [25, 26], which is responsible for many environmental problems, such as climate change [27-34], global warming that causes water shortages [35-39], and water pollution [40-49]. This means that there is an urgent need to find alternatives to cement to reduce the cement content in concrete or mortar so as to reduce the environmental damage resulting from its manufacture. For example, sludge of wastewater treatment plants and industrial by-products were used to develop cementations materials [50-55]. Therefore, supplementary cementitious materials (SCMs) were used as cement replacement to reduce these impacts [56-58]. Silica fume (SF) is one of the SCMs used due to its high pozzolanic activity and its role in improving different concrete/mortar properties [59, 60]. Although SF is more expensive than cement, according to Meddah et al. [61] the long term benefits derived from its use, such as extending the service life of the structure and reducing carbon dioxide emissions (by reducing the cement content), may overcome the initial increase in its cost.

According to the above, most of the previous research has partially replaced aggregate with construction waste, and studies that have replaced 100% natural aggregate were very limited. In addition, limited studies have used a gradation of waste tiles similar to that in natural aggregates. Moreover, limited studies have examined the waste produced in Iraq and its impact on the various properties of the mortar with the presence of silica fume as a partial alternative to cement. Thus, this study aimed to investigate the 100% replacement of natural aggregate with locally available waste tiles in cement mortar with similar sieve grading to make a good comparison between them in the presence of silica fume as partial replacement of cement. The main aim of this experimental study is reducing the environmental impact of these wastes through recycling and reusing them in the construction sector as well as saving natural resources. According to Samadi et al. [62] work, it is possible to produce mortar using crushed waste (ceramic) as an alternative to cement and fine aggregate at low construction cost and environmentally friendly. Furthermore, Silva et al. [63] reported that using recycled fine aggregate (from demolishing and construction waste) is cost-effective and technically feasible. The other aim of this study is reducing the CO_2 emission and energy-consuming that associated with the cement industry by reducing the cement content in the mix by replacing it with 10% silica fume. As a summary, it is believed that if the low-cost natural sand is not available or the available one has no acceptable properties or it is required to produce high-performance mortars, then producing mortar using building materials waste can be considered as a promising solution.

2. Materials and Methodology

This phase of the investigation focuses on the explanation and validation of the used procedures, methods, tests, and tools.

2.1. Materials

2.1.1. Cement

Limestone cement (CEM II/A-L-42.5R) was utilized in the production of mortar mixtures. This type of cement is manufactured with 6-20% limestone addition. The cement is conforming to the Iraqi standards No. 5. The chemical composition and physical properties of cement are shown in Tables 1 and 2, respectively.

Table 1. The fineness and chemical composition of cement.

Oxide	Cement	Iraqi Standard limit
CaO %	62.1	-
SiO_2 %	22.1	-
Al_2O_3 %	4.2	-
Fe_2O_3 %	3.9	-
MgO %	3.3	<5
SO_3 %	1.9	<2.8
L.O.I.	3.1	0.66-1.02
Blaine Fineness (m^2/kg)	3600	-

Table 2. The physical specification of cement.

Property	Value
Initial setting time (min)	105
Final setting time (min)	150
Fineness (m^2/kg)	370
Specific Gravity (kg/Litter)	3.1
Bulk Density (kg/m^3)	1.369

2.1.2. Sand

Locally available sand with a size range of (0.15 to 1.18 mm) was used as fine aggregate. The grading of sand, as presented in Fig. 1, is identical to the Iraqi standards No. 45.

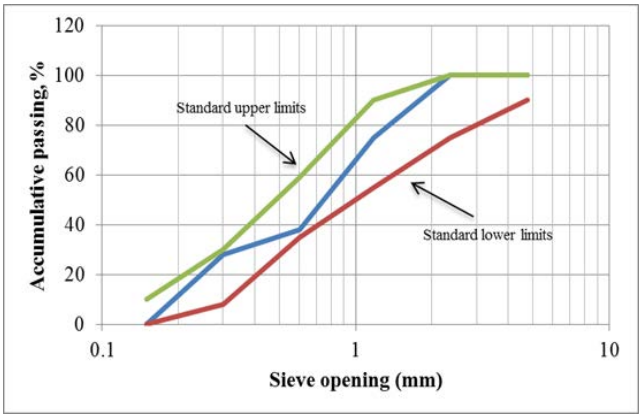

Fig. 1. The particle size distribution of the sand and the floor tile wastes (identical to sand).

2.1.3. Silica fume

Silica fume (SF) purchased from BASF (Baden Aniline and Soda Factory) company was used as a cement replacing material. The chemical composition of SF is displayed in Table 3.

Table 3. The physical and chemical properties of silica fume*.

Oxide	Cement
SiO_2	90.2
Al_2O_3	0.24
Fe_2O_3	2.4
CaO	0.65
MgO	0.41
SO_3	0.4
K_2O	1.26
Na_2O	0.16
TiO_2	0.02
L.O.I.	3.33
Fineness (m_2/kg)	21000
Chloride content (%)	< 1%
Activity index (%)	123

* The properties of silica fume are adopted from [64]. The same material used in this study.

2.1.4. Waste tiles

Three types of waste flooring tiles (marble, granite, and porcelain) were used in this study. The large pieces of each tile type were crushed and graduated to be used as sand replacement. The crushed waste was graded as that for sand, see Fig. 1. The tiles wastes were graded identically as to sand by weighing the residue on each sieve and isolating it and then it was proportioned according to the corresponding percentage in each sand sieve.

2.1.5. Superplasticizer

Glenium 54 (G54) superplasticizer purchased from BASF company was used as a workability adjuster for all mortar mixtures. G54 is complying with ASTM C494 Type A and F.

2.1.6. Water

Tap water was used for mixing and curing of mortar mixtures.

2.2. Methodology

Four mixtures were cast for this study. One control mixture made from natural sand and three other mixtures included full replacement of sand with either of marble, granite, or porcelain waste tiles. The cement in all mixtures was partially replaced with a fixed percentage of SF (10% by cement weight). The mix proportion of mortars was 1:2.75 (total binder: fine aggregate) and water/binder was 0.485 [59]. The superplasticizer content was fixed constantly in all mixtures to study the influence of these wastes on the workability of the fresh mortars. The details of mortar mixtures are presented in Table 4.

Table 4. Mix proportion details of mortar mixtures (kg/m^3)*.

Mix	Fine aggregate type	Cement	SF	Aggregate amount	Water	Super-plasticizer
Control	Sand	425	47	1298	229	1.89
MASF10	Marble	425	47	1298	229	1.89
GASF10	Granite	425	47	1298	229	1.89
PASF10	Porcelain	425	47	1298	229	1.89

* The designations of waste-based mixtures consisted of two parts, the first part refers the type of waste (MA: marble aggregate, GA: granite aggregate and PA: porcelain aggregate) while the other part (SF10) refers to use 10% SF.

The fresh mortars were mixed using a mechanical mixer according to the following procedure [59]: The dry materials were fed into the mixer, and mixed at 140 rpm speed rate for one minute. Then, the water and G54 superplasticizer mixed and they added to the dry materials. Thereafter, all materials were mixed at 140 rpm speed rate for one minute. After that, the mixer was stopped for one-half minutes. Finally, the whole materials were mixed at 285 rpm speed rate for two minutes.

After mixing completing, the fresh mortars were cast into metallic standard moulds in two layers. Cubic (50 mm) and prismatic (40×40×160 mm) moulds were used. A total of 12 cubes and 12 prisms were cast, three specimens for each mix. An electrical vibrator was used for fresh mortar damping. After 20-24 hours, the hardened specimens were lifted and immersed in a water tank at 20 ± 2 °C until the test day.

The flow rate, compressive and flexural strengths (see Fig. 2), bulk density, water absorption, and ultrasonic pulse velocity (UPV) tests were performed to investigate the waste tiles impact on different characteristics of mortar. The flow rate was measured using the flow table according to ASTM C1437. The compressive strength and UPV tests were measured using 50 mm specimens. The flexural strength was determined using 40×40×160 mm prismatic specimens using Eq. (1):

$$F = \frac{1.5\, P\, L}{b^3} \tag{1}$$

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.

The bulk density was determined by measuring the mass of the 40×40×160 mm specimens and divided by its dimensions. The prismatic specimens halves which were broken under flexural test machine were depended to determine the water absorption of the hardened mortars following the procedure described in ASTM C642 using the following Eq. (2):

$$W = \frac{A-B}{B} \times 100 \tag{2}$$

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

Average of six readings was considered for UPV and water absorption tests and an average of three readings were taken into account for the compressive strength, flexural strength, and bulk density tests.

Fig. 2. (a) Flow rate, (b) Compressive strength, (c) Flexural strength, and (d) Ultrasonic pulse velocity tests.

3. Results and Discussions

3.1. Flow rate results

The results of flow rates of fresh mortars are illustrated in Fig. 3. The results of this study revealed that the flowability of the fresh mortar was enhanced by 6% and 2% after substitution of sand with marble and granite waste tiles, respectively. This may be due to the smooth surface texture and lower water absorption of the crushed marble and granite compared to the natural aggregate (sand). Contrary, the flow rate of the porcelain waste mixture was lower than that for the natural aggregate by 12%. Porcelain tiles have a high surface hardness. Thus, this reduction in the flow rate can be attributed to the high angularity of the crushed porcelain tiles which led to decrease workability by increasing the friction with the cement paste. Where, the higher the rough surface and the angularity, the higher the water required (increased the water demand) to produce workable concrete [36]. By observing the results above, the flow of mixtures containing waste materials as a sand replacement has been reduced or improved slightly. When considering that the ratios of superplasticizer and SF content are constant for all mixtures as well as the fact that the grading is identical, it can be concluded that the waste materials characteristics might have the greatest role in affecting the workability of fresh mortar.

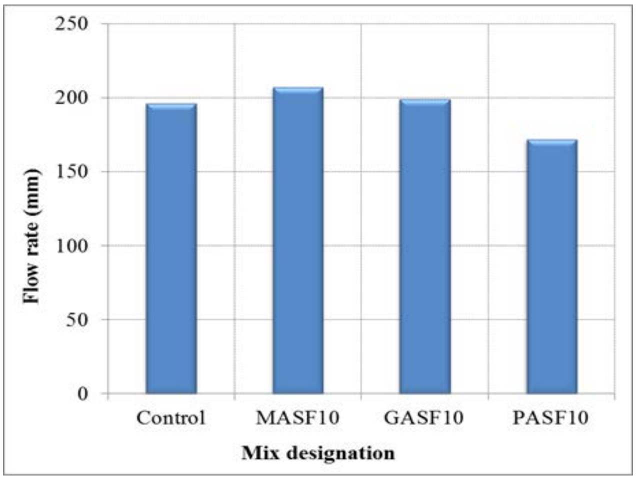

Fig. 3. Flow rate results of mortar mixtures.

3.2. Compressive strength

Figure 4 presents the compressive strength of mortar mixtures. As explained in the figure above, the results of this study indicated that though that SF is used as a cement replacement, the presence of the marble and granite waste tiles led to a decrease in the compressive strength of mortar mixtures by 7% and 11% respectively compared to the natural aggregate mix. This reduction is owing to the poorer interfacial bond between the cement paste and the recycled aggregate [37]. However, the compressive strength was improved significantly in the presence of porcelain waste, about 99% higher than that for the reference mixture. This improvement can be attributed to the bonding enhancement between the porcelain waste aggregate and the cement paste as well as to the higher compressive strength of porcelain tiles than natural aggregate which is come from the higher pressure that applied during the manufacture of the porcelain tiles [9]. Furthermore, the pozzolanic reaction of SF together with the rough surface of porcelain tiles waste improved the interfacial transition zone and thus increased the compressive strength.

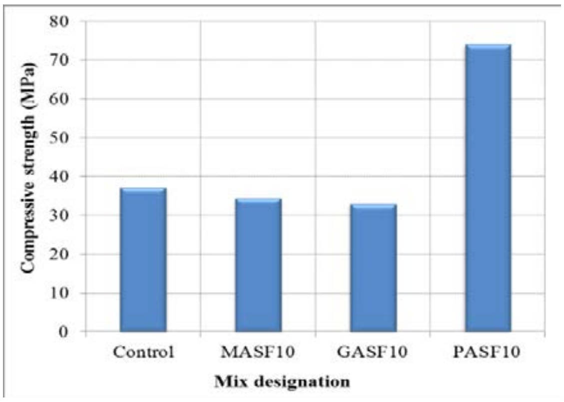

Fig. 4. Compressive strength results of mortar mixtures.

3.3. Flexural strength results

The flexural strength results of mortars are shown in Fig. 5. As presented in the figure above, it can be seen that, as for compressive strength, the flexural strength values were declined when the sand was fully replaced by marble and granite waste tiles while it was increased by replacing it with porcelain aggregate. The change percentages were -10%, -15% and +53% for marble, granites and porcelain-based mixtures respectively compared to the control specimen. As described in compressive strength, the reduction of flexural strength of marble and granite-based mixtures might be due to the poor interlocking between the aggregate and the cement paste [38]. On the other hand, the higher flexural strength of porcelain tiles compared to the natural aggregate interpreted this enhancement in the flexural strength of the porcelain waste-based mixture [9].

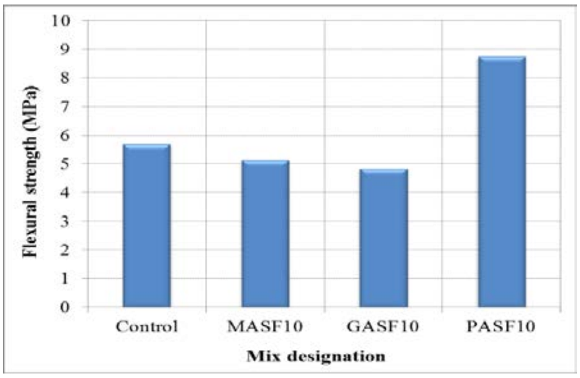

Fig. 5. Flexural strength results of mortar mixtures.

3.4. Water absorption results

Figure 6 displays the water absorption results of the control and waste tiles-based mixtures. The results presented in the figure above indicated that substitution of sand with waste tiles in the presence of silica fume improved the water absorption resistance of the hardened mortars. Compared to the reference mix, the improvements were 13%, 13% and 17% for marble, granite, porcelain waste tiles, respectively. The porcelain waste gave the best water absorption resistance compared to all other mixtures. This may be attributed to the decrease in the porosity of the porcelain-based mixture compared to all other mixtures. This claim is supported by UPV results where the porcelain mixes folded higher UPV values than all other mixtures. The pore refinement, as well as the densifying of the interfacial transition zone (a small region between cement and aggregate) provided by the pozzolanic reaction of SF together with the rough surface of the crushed porcelain, might have an important role in the enhancement of the water absorption resistance.

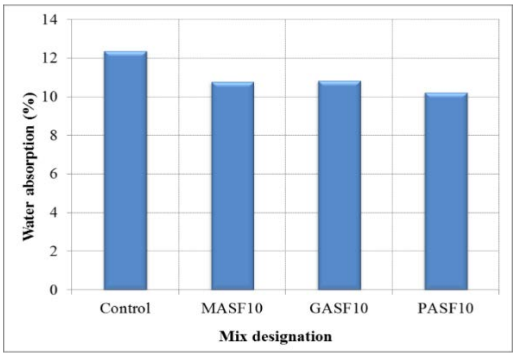

Fig. 6. Water absorption results of mortar mixtures.

3.5. Bulk density results

The dried bulk density results of all mixtures are presented in Fig. 7. As show in the figure above the results indicated that using the waste tiles as aggregate replacement reduced the bulk density of the hardened mortars.

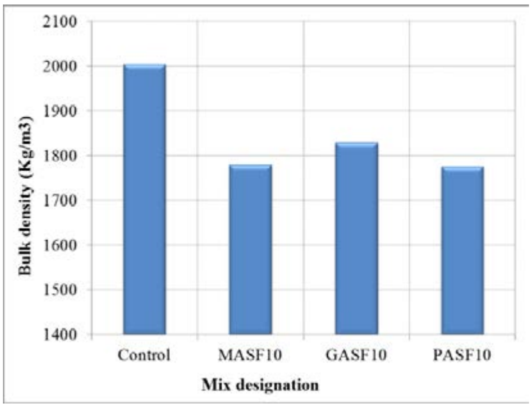

Fig. 7. Bulk density results of mortar mixtures.

Related to that for the sand-based mixture, the reduction rates were 11%, 9% and 11% for marble, granite, porcelain waste tiles mixtures, respectively. This reduction in bulk density can be attributed to that the bulk densities of these waste are lower than that for sand [40].

3.6. UPV results

The UPV test is usually used to assess the quality of concrete. The pulse velocity is affected by the medium through which it travels. The results of the UPV of all mixtures are shown in Fig. 8. Results demonstrated that the ultrasonic velocity values of the marble and granite waste aggregate were lower than that for sand aggregate by 8% and 2% respectively, which could be attributed to the higher porosity of mixtures incorporated these waste compared to the sand-based mortar [24]. On the other hand, the porcelain waste aggregate enhanced the pulse velocity by 5%. The dense microstructure as a result of better interlocking at the interfacial transition zone between the crushed aggregate and cement paste might reduce the porosity and thus increased the speed of the transmitting wave.

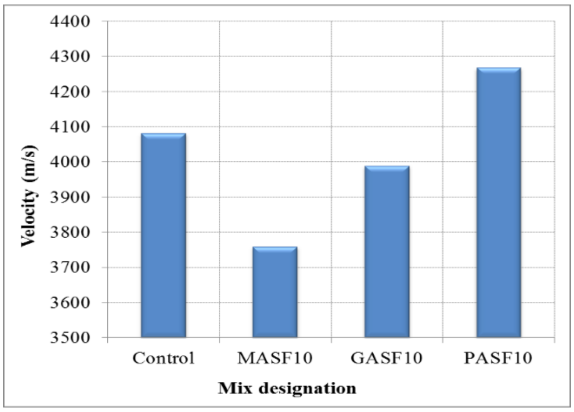

Fig. 8. Ultrasonic pulse velocity results of mortar mixtures.

4. Conclusions

The following experimental facts were observed during the course of this study:

- The substitution of natural aggregate with marble and granite waste enhanced the flowability of the fresh mortar by 6% and 2% respectively while the flow rate was decreased by 12% in the presence of porcelain waste.
- The porcelain waste tiles increased the compressive and flexural strengths of the hardened mortar by 99% and 53%. The marble and granite waste tiles had reduced the mechanical properties of mortar. However, the reduction rates were no more than 15% in compressive strength and flexural strength tests.
- The substitution of natural aggregate with waste tiles improved the water absorption resistance of the hardened mortar. The best improvement (17%) was given by the porcelain waste-based mixture.
- Replacing sand with waste tiles reduced the hardened density by 9%-11% related to the natural aggregate specimen.

- The UPV values were reduced by 8% and 2% respectively after substation of sand with marble and granite waste. On the other hand, the velocity of the transmitting wave was increased by 5% in the presence of porcelain waste.
- Regarding all tests considered in this study, it can be concluded that by replacing sand with porcelain waste tiles, it is possible to produce a sustainable mortar with superior durability and mechanical performance.
- An extensive study is recommended to be made to compare the cost of using such waste as an alternative to sand, taking into account the cost of grinding as well as the overall long-term benefits of using these wastes in concrete (or mortar) production.

Abbreviations

RAC	Recycled aggregate concrete
SCM	Supplementary cementitious materials
SF	Silica fume
SP	Superplasticizer
UPV	Ultrasonic pulse velocity

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