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Recycling of stone cutting sludge in formulations of bricks and terrazzo tiles

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This study examines the possibility for enhancing the use of stone cutting sludge waste in the production of building bricks and terrazzo tiles, which would reduce both the environmental impact and the production costs. Stone cutting wastes in the form of sludge is currently generated at several factories in Jordan. At the Samara factory, incorporation of the sludge in the batch formulations of bricks and terrazzo tiles was examined. The physicochemical and mineralogical characteristics of the sludge were analyzed to identify the major components. Results indicated that the sludge generated from stone cutting could be used in producing concrete bricks. Mixtures of aggregates with added amounts of sludge were used successfully to produce non-load bearing bricks. Sludge was also used to produce terrazzo tiles and the results indicate that the transverse strength, water absorption and tile measurements, for all the taken samples, comply with Jordanian standards. The transverse strength decreased while water absorption increased as the sludge ratio increased.

Keywords: sludge, stone cutting waste, terrazzo tiles, building bricks, slurry, recycle, clean, Jordan

Introduction

In recent decades, the growing consumption and the consequent increase of industrial production has led to a fast decrease of the available natural resources such as raw materials and energy sources. On the other hand, large volumes of production rejects or sub-products are generated, which are not recycled (Ferreira *et al*. 2004). As a result of a chronic shortage of building materials, civil engineers have been challenged to convert such industrial wastes to useful building and construction materials (Turgut & Algin 2007).

Stone-cutting industries produce large amounts of solid waste world-wide, which are expected to increase further as world production by the stone and marble industries increases annually at high rates. At present, stone-cutting factories generate high quantities of sludge, which increase the operation costs and decrease profits. The generated sludge from stone-cutting factories is prohibited from being discharged to the public sanitary system (Ammary 2007). The factories currently hold the generated sludge in open or closed basins for 2–3 weeks based on the quantity of sludge and the volume of basins. During holding, the sludge loses significant amounts of water by evaporation especially during hot seasons. At the same time, the suspended particles settle and condense in the bottom of the basin, which increase the sludge density. The sludge in the settling basins eventually has to be transported by trucks and disposed off in a sanitary landfill. In order to hold a high quantity of sludge, the factories are forced to construct larger volume of basins, which increase the capital cost of the factory. The sludge produced through the cutting and working of stone is still considered an inert waste product. Once it has satisfied the required criteria for acceptance, it is given to authorized waste dump (Colombo *et al*. 2008).

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As a result of environmental and economical parameters, recycling sludge in construction sectors is the focus of much on-going study. For utilizing waste stone and stone powder sludge generated from quarry and cutting processes, the Korea Institute of Geology has developed manufacturing technologies for artificial stone plate as a building material with firing method and hydrothermal synthesis (Park & Chung 1996).

Use of textile effluent treatment plant sludge has been suggested in many building materials such as hollow bricks, solid bricks, cement concrete flooring tiles and pavement blocks (Balasubramanian *et al*. 1995). Weng *et al*. (2003) investigated the possibility of producing bricks from dried sludge collected from an industrial wastewater treatment plant and found that the sludge proportion and the firing temperature were the two key factors determining the brick quality. Several researchers studied the possibility of using sludge generated from municipal wastewater treatment plant in producing clay bricks. They obtained good results concerning strength and water absorption, but the main problem is the presence of biodegradable material in the sludge, which may cause voids and weight loss in bricks (Valls *et al*. 2004, Abdul *et al*. 2004, Lin & Weng 2001, Slim & Wakefield 1991, Tay 1986, Alleman & Berman 1984).

Stone-cutting sludge has been used to improve the characteristics of agricultural soils enriching them with potassium, magnesium, phosphorous and a number of micro-elements, which are useful for vegetable production (Carrao & Castelli 2008). Ferreira *et al*. (2004) have shown that the physicochemical characteristics of granite sludge match well the requirements needed in brick and roof tile formulations. Thus, the incorporation results in negligible changes in the properties of the final products (Torres *et al*. 2004). Menezes *et al*. (2002) extensively reported the production of bricks and tiles using granite sludge (Torres *et al*. 2004). Alzboon & Mahasneh (2009) used stone-cutting sludge waste in concrete production and obtained good results regarding compression strength and slump characteristics of concrete.

The main objective of this study was to evaluate an alternative final destination for the growing production of sludge from stone-cutting processes. The proposed procedure includes recycling the sludge for use in producing building bricks and terrazzo tiles. Based on this, the stone cutting sludge can be transformed from an environmental problem to valuable material.

Bricks are available in Jordan markets in many sizes such as 40 × 20 × 10, 40 × 20 × 11, 40 × 15 × 10 and 40 × 20 × 20 cm. Bricks could be solid (voids ≤ 25%), or hollow (voids ≥ 40%). Bricks with thickness of 10 cm are used for non-load bearing walls and partitions, whereas bricks with thickness of 15 cm and 20 cm are used for load-bearing and external walls. Terrazzo tiles are widely used with dimensions of 30 × 30 × 3, 25 × 25 × 2.5 and 20 × 20 × 2 cm. The tiles consist of two layers – the upper and bottom layer. Marble and quartz in addition to the cement, aggregate and colours are used in the production of the upper layer; in the bottom layer, quartz, marble and colours are not used. The thickness of the upper layer is determined according to the Jordanian standards (> 7 mm), while the thickness of the bottom layer ranges from 2–3 cm depending on the tile's dimensions (MPWH, 1985).

The strength of bricks and tiles vary from region to region and depends on the nature of the available soil, size of aggregate, strength and shape of raw materials. Strength also varies between factories based on the technique adopted for mouldings. Type of mortar and mix proportion is another important factor, which determines the strength. Jordanian specifications state that the amount of cement used to produce bricks and tiles should be not less than 200 kg m^{-3}. The minimum required strength for load and non-load bearing concrete bricks should not be less than 35 kg cm^{-2} and 70 kg cm^{-2}, respectively. The minimum transverse strength for terrazzo tiles is 30 kg cm^{-2} (MPWH, 1985).

Materials and methods

Sludge characteristics

In order to understand the influence of the incorporation of stone cutting sludge as a raw material for bricks and terrazzo tile production, samples of sludge were collected and analyzed for general characterization. Analyzed characteristics included water content for slurry sludge, sieve analysis, density, total solid (TS), total volatile solid (TVS), silica oxide (SiO_2), calcium oxide (CaO), aluminium oxide (Al_2O_3), ferric oxide (Fe_2O_3), magnesium oxide (MgO), chloride (Cl), potassium oxide (K_2O), phosphorus oxide (P_2O_3), sodium ratio (SR), aluminium ratio (AR) and lime saturation factor (LSF) have been performed and examined.

Typical drying method for 24 h at 105°C was used to determine water content, total solid and density of sludge. Four samples were burned at 550°C to determine the total volatile solid. Other chemical components have been determined using X-ray diffraction. Sample analyses were repeated in triplicate at different laboratories in order to achieve satisfactory accuracy in the results.

Fabrication of concrete bricks

To determine the best sludge–sand mixing ratio, the sludge was mixed with sand in different proportions. The two semi-dry components (sludge and sand) were mixed with a constant amount of Portland cement according to the Jordanian standards (> 200 kg m^{-3}). Water was gradually added to make the mixture plastic. Cement and water proportions in the mixes were taken as constant to exclude the effect of these parameters on the results. A mechanical mixer was used to produce a homogeneous mixture, which was achieved after 3–5 min of mixing.

After mixing, concrete bricks were fabricated in a steel mould with internal dimensions of 400 mm in length, 100 mm in width, and 200 mm in depth. In order to achieve standard measurement of bricks and sufficient compression force, a new standard brick mould was used to produce the prototype samples. The mixed materials were put into the mould and a

Table 1: Specifications of the modified brick samples.

Sample reference label	Size of discarded materials (μm)	Discarded material (%) = Substituted material	Average bricks dimensions (cm)	Density (g cm^{-3})	Relative strength= Strength/(strength of M_R) %	Voids (%)
M_1	<149	11.3	40.2 × 20.2 × 10.1	2.25	97%	32.4
M_2	<500	28.8	40.2 × 20.1 × 10.1	2.20	82%	32.2
M_3	<841	45.1	40.1 × 20.1 × 10.1	2.18	65%	32.2
M_R	–	0	40.1 × 20.1 × 10.1	2.33	100%	32.4

compression force with vibration was applied for about 30 s. Then, the formed bricks were removed from the moulds and labelled B_1, B_2, B_3, and B_4 which corresponding to the sludge ratio in the mixture of 100%, 75%, 50%, 25%, respectively; the symbol B_R refers to the reference sample (free of sludge). Eighteen samples of bricks were taken for each mixing ratio. Samples were left for 24 h for drying and then sprinkled with water for another 3 days in the same location. The samples were transported to the storage area and sprinkled with water for an additional 4 days. This production and curing procedure complies with Jordanian standards item 603/2 (MPWH, 1985).

After 28 days, the brick samples were analyzed in accordance with Jordanian standards. Visual inspection, dimensions, compression strength, and water absorption were determined. The dry compressive strength of brick samples is determined using a servocontrolled compression test machine with a maximum capacity of 1560 kN and loading it at a uniform slow rate. The maximum crushing force for each sample was recorded. The crushing strength (compressive strength, F) was found by dividing the force needed to cause the brick to fail (P) by the cross-sectional area (A) of the brick in contact with the bearing plate of the machine $F = P/A$. Before the bricks were tested, the dimensions of brick's face in contact with the bearing plate were measured.

Modification of the brick samples

The results of sieve analysis of sludge samples showed that most of the particles pass through sieve number 100 (150 μm); therefore, classified as a fine material. In order to avoid the segregation phenomenon, disturbance or unbalance in particle size gradation, additional experiments was performed to keep the ratio of the fine material in the mixture within the applicable limit when the sludge was used instead of fine sand. The same aggregate was used in the fabrication of three new sets of mixes. However, part of the fine material was replaced by sludge (Table 1). Twelve samples for each type (M_1, M_2, M_3, M_R) were prepared, fabricated, and tested following the typical brick production method.

Fabrication of terrazzo tiles

Sieve analysis of sludge samples showed that all particles have sizes ≤ 160 μm, representing finer gradation of aggregates used to produce terrazzo tiles. The Jordanian standard for civil works allows use of fine aggregate with particle sizes 150 μm and 300 μm in the production of terrazzo tiles with percentages up to 10% and 30%, respectively. Based on this limitation, sludge is used in the production of terrazzo tiles. Because the face (upper layer) of the tile contains specified materials (quartz and marble), the sludge is used only in the preparation of the back layer (bottom part). Sludge was added to the standard mixture with different ratios. Samples were labelled as T_1, T_2, T_3, and T_4 which refers to the sludge ratio in the mixture (100%, 75%, 50%, 25%), respectively; the symbol T_R refers to the reference samples (free of sludge).

Mixes were prepared according to the Jordanian standards (item 803/6) where the face layer consists of cement and aggregate (1:3), fraction of marble or quartz and colours. The back layer consists of cement and graded aggregates (1:3). First, all components were mixed appropriately in a dry phase to become well mixed, then water was added and mixed. After homogeneity was achieved, terrazzo tiles were fabricated in a steel mould with internal dimensions of 30 × 30 × 3 cm. A compression force of 14 N mm^{-2} with vibration was applied to achieve the optimum density and compression strength. Twelve samples for each type (T_1, T_2, T_3, T_4, T_R) were prepared. Then, the formed tiles were removed from the moulds and left for 48 h in humid conditions. Samples were submerged in a water tank for 3 days and stored again in the humid environment for 23 days. After the curing period (28 days) was completed, samples were analyzed according to the Jordanian standards. Visual inspection, tile dimensions, thickness of face layer, transverse strength, and water absorption were assessed.

Results and discussion

Characteristics of sludge

Physical and chemical characteristics

Table 2 shows the average physical and chemical composition of sludge samples generated from the stone-cutting processes. The results show that there is a great compositional difference in sludge derived from different cutting processes. The variation in mineralogical and chemical composition of the sludge depends on the type and origin of rocks. The water content in the slurry samples ranged from 95–99.5%, making it a significant source of water which can be utilized for different production processes. Dried sludge contains a high quantity of calcium oxide (54%) but undetectable Cl and K_2O. In addition, small amounts of silica, ferric oxide, aluminium oxide and volatile solids were detected.

Table 2: Chemical and physical properties of the sludge samples.

Parameter	Unit	Ranges	Average
Water content	by wt%	95.7–98.2	97.3
TS*	mg l^{-1}	24300–27500	26000
TVS*	mg l^{-1}	1.3–1.4	1.3
SiO_2**	wt %	0.75–0.91	0.83
CaO**	wt %	48.4–61.2	54.72
Al_2O_3**	wt %	0.18–0.24	0.21
Fe_2O_3**	wt %	0.09–0.13	0.11
MgO**	wt %	0.86–0.95	0.91
Cl**	wt %	BDL	BDL
K_2O**	wt %	BDL	BDL
SO_3**	wt %	0.09–0.12	0.11
LSF**	–	1.85–2.34	2.06
SR**	–	2.41–2.65	2.53
AR**	–	1.84–1.91	1.88

(*Slurry samples, **dried samples, BDL, below detection limit.

Sieve analysis of sludge samples

In order to obtain accurate results, 32 sieves with diameters ranging from 0.5–300 µm were used to determine the sludge particles size distribution. Figure 1 shows the sieve analysis of the dried sludge and the differential particle size distribution. The average particle size, D_{50}, is about 9.1 µm, while D_{10}, D_{16}, D_{84} and D µm are about 1.3 µm, 1.8 µm, 30 µm and 37 µm, respectively. Sieve analysis was also done for the standard aggregates used for brick and terrazzo tile production and shown in Figure 1. For aggregate samples, the average particle size, D µm, is about 1.1 mm, while D_{10}, D_{16}, D_{84} and D_{90} are about 0.15 mm, 0.25 mm, 5.2 mm and 5.9 mm, respectively. Results of sieve analysis indicated that around 11.8% of the volume of the aggregates has a particle size less than the maximum size of sludge particles (160 µm). This means that the sludge is suitable, as a fine material, for being directly incorporated into brick-type formulations and terrazzo tiles.

Specifications of the conventional brick samples

Visual inspection

Each brick was inspected visually and all B_2, B_3, B_4, B_R samples were found solid and free of defect which would interfere with proper placing of the unit or affect its strength. The samples show flat surface and uniform shape with perpendicular and straight edges. The samples have no intrinsic cracks or damage resulting from manufacturing or handling. Grade B_1 samples show irregular and variable dimensions as a result of the brick slumping during de-moulding. This slumping also caused swelling and deformation in the shape of bricks. B_2-, B_3- and B_4-type bricks have the same dimensions as the reference bricks (B_R) with no significant variation in the density and the percentage of voids. The dimensions of bricks of type B_1 gave height ranges of 15–18.5 cm, whereas the thickness ranged from 10–14 cm in the upper to the bottom sides, respectively. Except for bricks op type B_1, all other types have voids within the permissible limits. The Jordanian specification classifies the bricks according to their density as following: normal bricks (density ≥ 2 t m^{-3}), medium (density 1.7–2 t m^{-3}) and light (density ≤ 1.7 t m^{-3}), which means that all the produced samples can be classified as normal bricks (Table 3). The results indicate that the bulk density of the bricks decreased as the sludge content increased.

Compression strength and water absorption

The compressive strength is the most important engineering quality index for building materials. Figure 2 shows the results of the compression strength values for all samples. The obtained results were compared with Jordanian standards for non-load and load bearing bricks. Results show that the compression strength of bricks type B_3, B_4, B_R comply with Jordanian standards for non-load bearing bricks, while all samples of bricks type B_1 have smaller values in comparison with the standards. Bricks of type B_1 had only one-third of the compression strength of the reference sample (B_R). Three samples of bricks of type B_2 failed to achieve the required strength. All types of bricks failed to achieve the required

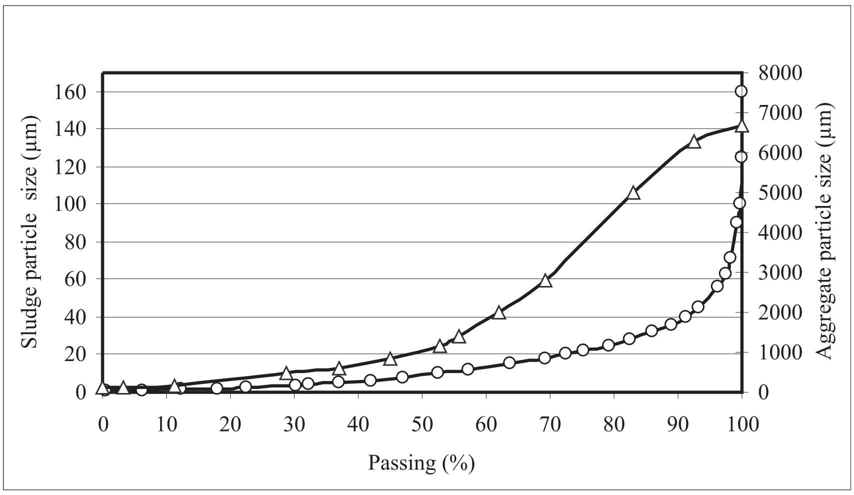

Fig. 1: Sludge and aggregate size distribution: aggregate particle size (triangles), sludge particle size (circles).

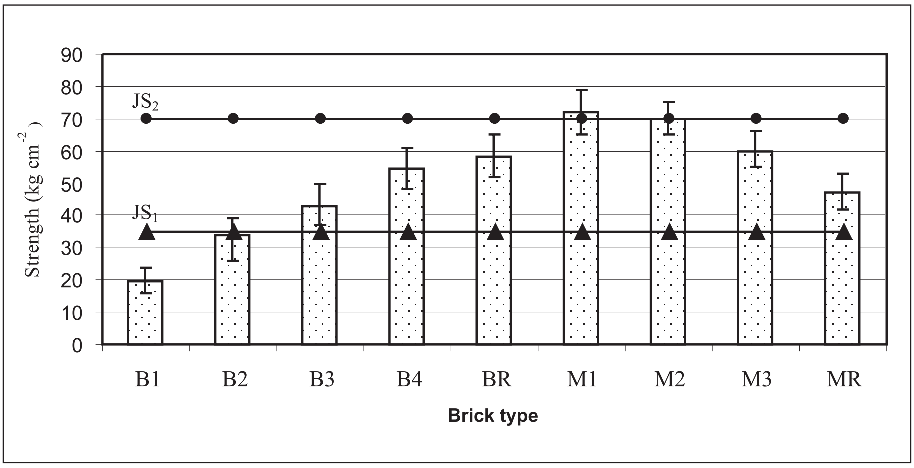

Fig. 2: Compression strength of the conventional and modified bricks B, conventional samples; M, modified samples; JS_1, JS_2, Jordanian standards for non-load and load-bearing bricks, respectively. The error bars in the figure represent the range of values.

Table 3: Specifications of the conventional brick samples.

Sample reference label	Average brick dimensions (cm)	Density (g cm$^{-3)}$	Voids (%)	Relative strength = (Strength)/(strength of B_R)
B_1	40.40 × 17.3 × 11.35	2.1	34.1	33%
B_2	40.25 × 20.20 × 10.15	2.11	31.4	58%
B_3	40.20 × 20.20 × 10.15	2.13	32.2	74%
B_4	40.15 × 20.25 × 10.10	2.17	32	93%
B_R	40.15 × 20.20 × 10.10	2.19	32	100%

strength for load-bearing bricks. It is worth mentioning that these bricks with of dimensions 40 × 20 × 10 cm dimension are used only for non-load bearing walls and internal partitions. The compression strength is inversely proportional to the percentage of sludge added to the mixture (Figure 2). Regarding compression strength and water absorption, a mixture of aggregates with 50% of sludge could be used successfully to produce non-load bearing bricks. This result indicates that the sludge waste could be re-used in brick production, which would reduce material consumption, increase profit, and conserve the environment. There is insignificant variation in the water absorption for all the samples. The values for B_1, B_2, B_3, B_4 and B_R were 12.1%, 11.95%, 11.8%, 11.65% and 11.6%, respectively.

Specifications of the modified brick samples

Visual inspection

Modified brick samples were fabricated in order to improve the mixtures by grading the aggregate. These samples were produced, cured and tested as for the conventional samples. All fabricated samples had a uniform shape, were free of deformation, cracks, damage and swelling, and there was no visible variation between the modified and the reference samples. The void ratios of all samples were within allowable limits (Table 1). The density of all samples was the same as a normal brick where densities are more than 2 t m^{-3}. The reference sample (M_R) had the highest density while M_3 had the lowest. Water absorption was 10.5%, 10.6%, 10.6%, and 10.5% for M_1, M_2, M_3, and M_R samples, respectively.

Compression strength

Figure 2 shows the average compression strength for different categories of the modified samples. The compression strengths of all M samples (M_1, M_2, M_3, M_R) complied with Jordanian standards for non-load bearing bricks, while 23% of the B samples (B_1, B_2, B_3, B_4) failed to achieve such standards. The modified samples gave better result than the conventional B samples. In the case of B samples, sludge was added to the mixtures which increased the percentage of fine materials and decreased the strength. In the modified method, the sludge was substituted in the mixture and the same amount of fine materials was discarded from the mixture, which keeps the ratio of the fine materials approximately constant. Bricks of types M_1 and M_R succeeded in achieving the standard limit for load-bearing bricks while types M_2 and M_3 failed to achieve the required limit. The discarding of the fine material from aggregate (pass from No. 100) and substituting with sludge had insignificant effects on brick quality; therefore, this is recommended in the fabrication of bricks. The compression strength is inversely proportional to the percentage of sludge substituted in the mixture (Figure 2). Results indicate that the sludge could be added to the coarse aggregate instead of the fine material. This method may be applied by producing aggregate without fine material with

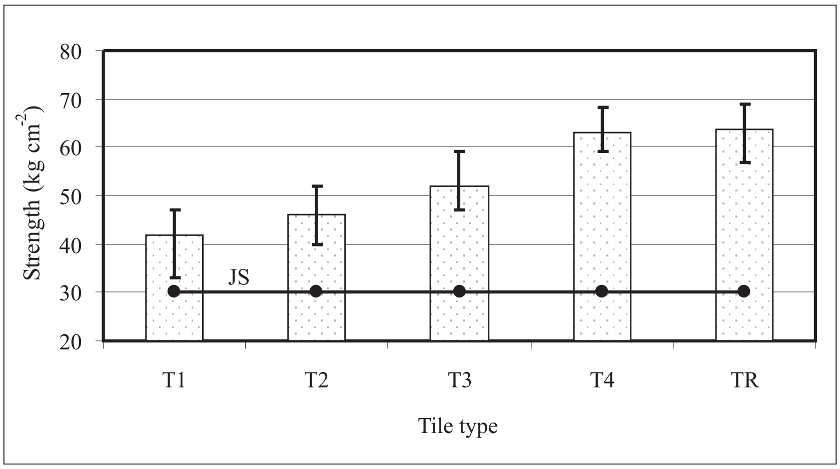

Fig. 3: Transverse strength of tile samples (JS. Jordanian standard for transverse strength of tiles). The error bars in the figure represent the range of values.

Table 4: Specifications of the terrazzo tile samples.

Sample reference label	Average dimensions (cm)	Average total thickness (mm)	Average thickness of the face layer (mm)	Relative strength= Strength/(strength of T_R)	Absorption (%)
T_1	30 × 30	32.2	10	66%	5.41
T_2	30 × 30	32.6	11	72%	5.31
T_3	30 × 30	33	10	82%	4.86
T_4	30 × 30	32.6	10	99%	4.77
T_R	30 × 30	32	11	100%	4.71

the sludge added later to the mix. This application will conserve natural materials and solve the environmental and economical problems caused by sludge accumulation.

Specifications of the terrazzo tile samples

Physical specifications

Many physical properties of the fabricated samples were tested such as dimension, visual inspection and thickness of the face layer. No deformation cracks or deflection were noticed for any of the samples. Table 4 shows the dimensions, total thickness, and thickness of the face layer for each type of sample. All samples complied with Jordanian standards in terms of total thickness (≥ 30 mm), and thickness of the face layer (≥ 7 mm). In spite of using the same mould, the thickness of the produced tiles varied as a result of the variation in the applied hydraulic load and the loading period.

Transverse strength

Figure 3 shows the average of transverse strength values for all samples. The obtained results indicate that the average transverse strength for all tested samples is more than that required by Jordanian standards (30 kg cm^{-2}). The transverse strength decreased as the ratio of the added sludge increased. The strength values for all tested samples ranges from 28–71 kg cm^{-2} and only one sample (type T_1) failed to achieve the required strength. All samples had the same amount of cement and the same thickness and components of the face layer, which explains the high strength value for all samples. The values of transverse strength for tiles types T_4 and T_R are comparable, which indicates that the use of sludge in the mixture at a 25% ratio did not affect the strength. These results indicate that sludge waste could be re-used, at high percentage, in the bottom layer of terrazzo tiles. The bottom layer represents about 75% of the tile's volume, so using sludge in this layer with 25%, 50%, 75% and 100% ratios will conserve used materials by 19%, 38%, 56% and 75%, respectively.

Water absorption of tiles

Water absorption was determined by a similar method to that of the brick samples. All samples had absorption ratios much less than the required limit by Jordanian standards (8%) as shown in Table 4. All samples ranged from 3.9–6.4% indicating that all values are better than the standard limit. Because of the fineness of sludge, it absorbs more water than the coarse aggregate, so the water absorption increased as the sludge ratio increased.

Conclusions

Utilization of sludge waste from stone cutting is essential in order to minimize waste and environmental considerations. Moreover, it is an effective use of a limited natural resources.

The results presented and discussed show that sludge generated from stone-cutting processes can be regarded as a novel raw material for the production of building bricks and terrazzo tiles. Based on this study, it is concluded that the use of sludge generated from stone cutting up to a maximum of 50% of the aggregate volume can be used in the manufacture of non-load bearing bricks. Sludge was also used successfully in the fabrication of terrazzo tiles. The use of sludge in these applications could serve as an alternative solution to disposal.

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