The use of aluminum slag waste in the preparation of roof tiles

M M Ahmed ∗, M F Abadir, Ayman Yousef and K A M El-Naggar
1 Department of Mathematics and Physics Engineering, Faculty of Engineering at Mataria, Helwan University, Cairo 11718, Egypt
2 Department of Chemical Engineering, Faculty of Engineering, Cairo University, Cairo, Egypt
3 Department of Chemical Engineering, Egyptian Academy for Engineering and Advanced Technology, Cairo, Egypt

∗ Author to whom any correspondence should be addressed.

E-mail: marwa_elnagar77@yahoo.com and aymanyousef84@gmail.com

Keywords: clay roof tiles, aluminum slag, cold water absorption, saturation coefficient, mechanical strength

Abstract
Aluminum slag waste generated from the smelting process of bauxite was used to prepare roof tiles samples. Clay was substituted by slag waste in percentages reaching 40% in the basic mix and the plasticity of the obtained mud was determined. This was followed by pressing the mud in steel molds and drying. The effect of waste addition on drying shrinkage was subsequently assessed. Firing of the green bodies was carried out at three temperatures (900, 1000 and 1100 °C) and hour soaking at each temperature. Fired roof tile properties improved on increasing the percentage of alumina sludge and firing temperature possibly because of the presence of high amounts of fluxing oxides in aluminum slag. This caused a drop in porosity that increased the mechanical strength of tiles. The results showed that the substitution of clay by 40% waste and firing at 1100 °C resulted in products conforming to ASTM C-1167 for clay type roof tiles. Cold water absorption dropped to 12%, below the maximum permissible limit of 15%, the value of Saturation Coefficient was 0.83, below the 0.86 limit and the obtained breaking strength of 3370N significantly exceeded the minimum requirement of 890N.

1. Introduction

The increasing demand for building materials due to the continuous population growth necessitated the search for cheaper manufacturing sources. Ever since asbestos has been abolished for use in roof making, cement or clay-based roof tiles have been commonly used [1]. In this respect, clay tiles are usually preferred over cement types because of their lighter weight and lower water absorption [2].

Clay roof tiles bricks are manufactured from clay based materials mixed with water, shaped by extrusion or pressing, then dried and fired at temperatures between 900 to 1100 °C [3, 4]. The addition of diverse waste materials to the clay mix offers clear environmental and economic advantages; in this contest, the literature abounds research devoted to the use of such wastes in the production of roof tiles.

Dondi et al [5] used glass waste from panels as an additive to roof clays in order to promote the formation of a vitreous phase. Its addition decreased plasticity and drying shrinkage at all addition levels. The fired bodies exhibited reasonable strength for 2 to 4% addition ranging although some volatilization of lead was observed. A similar attempt was later made by Costa et al [6] who recycled broken glass flak waste in the preparation of roof tiles in proportions reaching 10%. Firing was carried out at temperatures ranging between 800 and 1200 °C. They observed that firing shrinkage and flexural strength both increased for waste addition exceeding 8% and at firing temperatures above 900 °C.

Torres et al [7] incorporated wastes from rock cutting and polishing into the production of roof tiles. Different proportions of waste were used and their effect on plasticity, drying properties and firing behavior was investigated. Minimal water absorption and maximum flexural strength were observed on using 10% granite waste. A similar approach was undertaken by Sultana et al [8] who used hard rock dust as an addition to clay in roof tile production. The extent of dust addition ranged from 0 to 50% whereas firing temperatures ranged between 850 and 1100 °C. They recommended the use of 20 to 30% rock dust and firing at 900 °C to obtain reasonable properties. However, the the strength test performed was not specified.
The use of rubber and plastic waste in the preparation of roof tiles was investigated by Gaggino et al. [9] who used crushed rubber and LDPE pellets as admixtures to clay. They compared the properties of the fired bricks with those prepared using ceramics and concrete. However, the extent of waste addition and the conditions of firing were not indicated. Datta [10] also utilized plastic waste for the preparation of roof tiles. Waste plastics were gathered, shredded, melted and mixed with sand and crushed stones and high strength blocks with acceptable compressive strength and reasonable thermal properties were obtained at the different addition levels.

A study was carried out by Figen et al. [11] in which a mixture of tile waste and coal fly ash was used as additive. Tile waste levels were varied from 0 to 20% while the percent of fly ash was fixed at 5%. Increased percentages of tile waste caused a decrease in drying shrinkage owing to their non-plastic nature. Firing was carried out at temperatures ranging from 900 to 1100 °C. They reported that neither firing shrinkage nor water absorption were affected by the firing temperature. The results for flexural strength, though an essential standard requirement, were not reported.

Sharma et al. [12] reviewed the use of industrial waste generated from diverse sources such as natural fibers, food waste along with coal industry refuse that could be used for roof tiles manufacturing. They concluded that the most suitable materials to use in the preparation of roof tiles were organic fibers and sand aggregate. The testing procedures used for roof tiles were also discussed.

Recently, Ercioglu et al. [13] used glass waste to prepare porous ceramic products. The incorporation of the waste resulted in a 25% decrease in energy consumption on firing.

Wastes of metallic nature have also been used in the preparation of low cost roof tiles, although the reported research work is relatively scarce. Dondi et al. [14] used PC and glass waste as additive to clay roof tiles. A reduction in plasticity of the raw pastes and an improvement in sintering characteristics upon firing were noticed. They recommended using no more than 4% waste with particle size less than 1mm. On the other hand, Al Hamati et al. [15] added the waste produced from alum manufacture to a clay mix in proportions reaching 30%. Firing was carried out at 1000 °C. They reported a breaking strength of 743N which is lower than the permissible value of 890N required by ASTM1167-03 [16]. Viera et al. [17] reviewed the possibility of adding iron slag waste to fired clay structural components including roof tiles. They concluded that the maximum allowed percent to be used was limited by the adherence of the produced bricks or tiles to standards. They also established that the presence of coke from the iron making process represented an economic advantage by releasing heat during combustion, thus saving energy during firing.

The reason that has triggered carrying out this work is the large amounts of solid waste originating from the local aluminum industry in Egypt. According to recent data from the World Bureau of Metal Statistics, the annual production of aluminum in Egypt is about 258 thousand metric tons [18]. The OECD Environment Directorate listed different types of waste generated from the aluminum industry [19]. These are produced throughout the production process starting from bauxite tailings and ending with aluminum slag. As the local production of aluminum uses high grade bauxite, the presence of low amounts of iron oxides does not produce much red mud. The main solid waste produced from the smelting process is the quenched slag waste, which has been used in the present work as additive to clay in the preparation of roof tiles.

2. Material and methods

2.1. Raw materials

2.1.1. Raw materials used

Two types of raw materials were used: Kaolin clay form Aswan area in Upper Egypt and crushed aluminum smelting waste kindly supplied by the Egyptian Aluminum Company (Egyptalum) located in Nag Hammadi in Upper Egypt.

2.1.2. Characterization of raw materials

Both raw materials were characterized for the following properties:

2.1.2.1. Chemical composition

This was determined using x-ray fluorescence (AXIOS, panalytical 2005, Wavelength Dispersive WD–XRF Sequential Spectrometer) was used to determine the chemical analysis of both materials as shown in table 1.

Table 1 reveals that while alumina represents the main component present in the waste, the clay used mainly consists of silica and alumina. This is evident by the x-ray pattern presented in figure 2. The loss on ignition of clay is mainly due to the dehydroxylation of kaolin [20].
2.1.2.2. Metallurgical composition

The mineralogical composition of both materials was determined by x-ray diffraction (XRD) (Brukur D8 advanced computerized x-ray diffractometer apparatus with mono-chromatized CuKα radiation) at 40 kV and 40 mA. Figures 1 and 2 display the XRD patterns of both materials used in this work.

The waste consisted of hexagonal alumina (H: Al₂O₃), cryolite (C: Na₃AlF₆), corundum (c: Al₂O₃) and goethite (G: FeO(OH)). On the other hand, clay was composed of kaolinite (K: Al₂Si₂O₅(OH)₂) and quartz (Q: SiO₂).

2.1.2.3. Particle size distribution

The mean particle size was determined using the standard sieve analysis procedure described in ASTM C136 [21].

Figure 3 displays the particle size distribution of both raw materials. It appears that the waste material is slightly coarser than clay as evidenced by the differences in their median sizes \(D_{50}\) as it equals 0.22mm for waste and 0.2mm for clay. Their Sauter particle size, defined by the following expression, is a better measure for fineness [22].

\[
\frac{1}{D_{50}} = \int_{0}^{1} \frac{d\varphi}{D_p}
\]

Where, \(D_p\) is the screen opening that retains a fraction \(\varphi\) of solids.

| Component | Clay wt% | Waste wt% |
|-----------|----------|-----------|
| Al₂O₃     | 32.906   | 64.5      |
| SiO₂      | 48.931   | 2.62      |
| Na₂O      | 0.094    | 4.29      |
| K₂O       | 0.014    | 3.61      |
| CaO       | 0.505    | 0.47      |
| MgO       | 0.09     | 8.31      |
| TiO₂      | 5.918    | 0.13      |
| Fe₂O₃     | 1.193    | 0.46      |
| SO₂       | 0.291    | 0.42      |
| F         | —        | 2.24      |
| Cl        | 0.011    | 9.82      |
| Cr₂O₃     | 0.138    | 0.01      |
| ZrO₂      | 0.465    | 0.034     |
| LOI       | 9.2      | 2.74      |
| TOTAL     | 99.756   | 99.654    |
These values were calculated to be 0.266mm and 0.352mm respectively for clay and paste powder respectively, as emphasized by the shift of the particle size distribution curve of clay to the left of that of waste powder.

2.2. Samples preparation
Alumina waste was dried at 110 °C in a drying oven for 24 h before being finely ground in a laboratory ball mill. The waste and clay were mixed with different weight percentages (0, 10, 20, 30 and 40). The mixtures were blended with 18% water then molded and semi-dry pressed in rectangular molds with dimensions (150 × 30 × 30 mm³) under a uniaxial pressure of 10MPa. The samples were left to dry at room temperature for 24 h, then dried overnight at 110 °C in a drying oven. These were then fired in a muffle furnace to different firing temperatures (900, 1000 and 1100 °C) at a heating rate of 10 °C min⁻¹ with a soaking time of 1 h.
2.3. Testing procedures

The plasticity of the raw mixtures was determined using the Pfefferkorn Plasticity technique \[23\] while the linear shrinkage of green and fired samples was determined according to ASTM C 326 \[24\]. Water absorption, bulk density and apparent porosity of fired samples were determined according to ASTM C 373 18 \[25\]. The powder density was determined using the pycnometer method ASTM D 5695 19 \[26\]. The total porosity \( p \) was subsequently calculated from the relation:

\[
\rho_B = \rho_p (1 - p)
\]  

Where, \( \rho_B \) is the bulk density and \( \rho_p \) the particle density.

Finally, both breaking and flexural strength were determined in accordance to ASTM C 648 20 \[27\].

3. Results and discussions

3.1. Effect of waste addition on pfefferkorn plasticity number

As the percent waste was increased, the plasticity of the mix decreased up to 20% addition, after which the values fluctuated about some fixed figure. This behavior is attributed to the non—plastic nature of the waste. As the percent waste exceeds 20%, it seems that the high flowability of the waste caused the plasticity values to stabilize as shown in figure 4.

An attempt was also made to follow up the effect of particle size of waste on plasticity. Sieved portions of the waste having the particle sizes shown in table 2 were added to clay and the Pfeffrkorn plasticity was then determined.

Figure 5 displays the results obtained for the effect of average particle size of waste on plasticity for a mix containing 40% waste. It shows that an increase in waste particle size slightly reduces plasticity as the coarse size of particles impedes their motion through finer clay particles.

| Minimum size mm | Maximum size mm | Average size mm |
|-----------------|-----------------|----------------|
| 0.075           | 0.15            | 0.113          |
| 0.15            | 0.3             | 0.225          |
| 0.3             | 0.71            | 0.505          |
| 0.71            | 1.4             | 1.055          |
| 1.4             | 3.35            | 2.375          |
| 3.35            | 6.7             | 5.025          |
3.2. Effect of waste addition on linear drying shrinkage (LDS)

Figure 6 clearly shows that the average linear drying shrinkage, as measured for 3—specimen samples, linearly decreases with the increase in waste addition level. This is presumably due to the non—plastic character of the waste. It is also interesting to note that the percent LDS is directly connected to the plasticity as both decrease with waste addition.

The different size fractions illustrated in table 2 were added in 40% level to clay and mixed with water and the corresponding drying shrinkage determined. Figure 7 emphasizes the fact that the effect of the particle size of waste on LDS is similar to its effect on plasticity. That is, LDS decreases with the increased coarseness of added waste. This behavior has been previously reported for different clay mixes [28, 29].

4. Effect of waste addition on fired properties

4.1. Powder density of fired samples

Neither the substitution of clay by aluminum slag waste nor firing temperature seem to affect the powder density of fired samples to any appreciable extent. The powder densities, as determined by the pycnometer method, resulted in values in the range 2.49 to 2.51 g.cm$^{-3}$. An average value of 2.5 g.cm$^{-3}$ was used to calculate the total porosity of fired samples.
4.2. Properties of fired samples

Three—specimen samples of the mixes, consisting of waste substituted clay in percentages ranging from 0 to 40% (by weight), were fired at 900, 1000 and 1100 °C. They were held at the firing temperature for one hour after which the following properties were determined as function of both firing temperature and percent waste: Percent linear firing shrinkage, percent water absorption (Cold and Boiling), saturation coefficient, bulk density and apparent and total porosities. The results will be discussed in the following sections:

4.2.1. Cold water absorption (CWA%)

Figure 8 presents the effect of percent waste on the percent CWA for samples fired at different temperatures. In order to avoid crowding in this figure, table 3 was included to display the standard deviation and standard error of the 3—specimen sample readings at 1100 °C.

| % Waste | Mean | St. dev. | St. error |
|---------|------|---------|-----------|
| 0       | 14.22| 0.2178  | 0.0662    |
| 10      | 14.54| 0.5652  | 0.1719    |
| 20      | 16.31| 0.397   | 0.1207    |
| 30      | 15.06| 0.1537  | 0.0467    |
| 40      | 14.43| 0.2458  | 0.0747    |

Figure 8. Effect of waste addition on percent CWA.

Figure 7. Effect of particle size of waste on LDS (40% slag mix).
It is clear that the extent of waste used did not play any major role in assessing the cold water absorption values. On the other hand, it appears that the firing temperature has had a direct effect on decreasing the amount of water absorbed by sealing off some of the available pores at the surface. The individual correlation coefficients revealing the dependence of percent CWA on firing temperature and percent waste were determined using the EXCEL function 'Correlation' and were found to equal — 0.925 and — 0.145 respectively, revealing the much stronger dependence of CWA on temperature. According to ASTM C-1167 [16], this value should not exceed 15% for normal duty tiles. This entails firing at 1100 °C regardless of the percent waste used.

4.2.2. Boiling water absorption (BWA%)

Figure 9 shows that there is a general decrease in water absorption values with increased waste addition despite noticing some slight irregularity in that trend. It is important to note that ASTM C1167 [16] sets no maximum value for boiling water absorption. It is clear from the figure that the values of BWA starts decreasing on firing when a substitution level of 30% is reached. This can be interpreted in light of the chemical composition of the waste which reveals that the percent fluxing alkali oxides (Na₂O + K₂O) is about 8%. It is known that the presence of alkali oxides, in particular, causes a serious drop in the melting temperatures of clay based ceramic bodies, which explains the observed decrease in water absorption associated with increased waste addition presumably caused by partial vitrification [30].

The increase in BWA up to about 20% waste may be due to the presence of the coarser particles of wastes which would create more pores. As the percent waste exceeds 20%, it seems that the fluxing effect of alkalis overcomes that of its particle size resulting in decreased absorption. This interpretation can be explain the behavior of the total porosity curves displayed in figure 10, which show that the figures of porosity tend to decrease after a certain amount of waste has been added.

![Figure 9. Effect of waste addition on percent BWA.](image)

![Figure 10. Effect of waste addition on percent total Porosity.](image)
4.2.3. Saturation coefficient (SC)

Saturation coefficient denotes the ratio between cold and boiling water absorption and generally increases with an increase in pore size. According to ASTM C1167 [16] this value should not exceed 0.86 for normal duty tiles. This can only be secured by firing at 1100 °C with at least 30% waste substitution as seen in figure 11. Table 4 displays the values of standard deviation and standard error of saturation coefficient reading for samples fired at 1100 °C.

| % Waste | Mean  | St. dev. | St. error |
|---------|-------|----------|-----------|
| 0       | 0.943 | 0.01345  | 0.0409    |
| 10      | 0.931 | 0.01646  | 0.0500    |
| 20      | 0.883 | 0.00404  | 0.0129    |
| 30      | 0.848 | 0.0095   | 0.0289    |
| 40      | 0.832 | 0.00513  | 0.0156    |

4.2.4. Percent linear firing shrinkage

Figure 12 represents the variation of percent linear firing shrinkage (LSF) with percent waste and firing temperature. In general, the higher the firing temperature the more pronounced is the firing shrinkage. At
900 °C, no appreciable shrinkage takes place owing to the absence of any appreciable sintering. The extent of waste addition plays little role in assessing shrinkage values.

At 1000 °C, there is no serious variation in shrinkage percentages up to 20% waste addition. The elevated level of alkali oxides present in the waste decreases the melting temperature of the mixture, resulting in the appearance of little amounts of viscous liquid that promote liquid phase sintering [30]. This helps increasing the observed values of shrinkage.

At 1100 °C, the coarser nature of the waste causing an increase in porosity delays the appearance of the effect of fluxing alkalis. This is due to the negative effect of an increase in particle size on the sintering behavior. This is a well—documented effect outlined by the general equation relating the relative linear shrinkage \( \frac{\Delta L}{L_0} \) to sintering time \( t \) and particle size \( D \), that takes the following form [31]:

\[
\frac{\Delta L}{L_0} = k \frac{t^m}{D^n}
\]

Where, \( k, m \) and \( n \) are empirical constants, depending on the sintering mechanism involved.

Above 20% waste addition, the values of shrinkage start increasing resulting in a maximum value of 3.4% at 40% waste due to enhanced vitrification.

This situation can be explained, using a rough approximation, by assuming that dry kaolin mainly consists of alumina and silica, while the waste mainly consists of alumina, fluxing oxides and silica. This latter assumption corresponds to a percentage of the strongest fluxing oxides (K\(_2\)O and Na\(_2\)O) of about 9.4%. As a first approximation, the SiO\(_2\)—Al\(_2\)O\(_3\)—Na\(_2\)O diagram was considered and the fluxing oxides were assumed to be represented on that diagram by Na\(_2\)O. The original kaolin (assumed to consist solely of alumina and silica) shows as point A on figure 13 [32], while the waste mix is given by B. On the AB line, adding 40% waste corresponds to the composition represented by point C. Whereas the original binary mix (A) possesses an initial melting temperature of 1590 °C and a final melting temperature of 1890 °C [32], the composition C lies within the tie triangle Silica—Mullite—Albite that exhibits a eutectic at 1068 °C. This means that partial vitrification is expected to take place at 1100 °C, a fact corroborated by the SEM micrograph (b) in figure 14 displaying a low porosity and the presence of a liquid phase.
Figure 14. SEM Micrographs (2500 ×): a-Specimen with 0% waste fired at 1100 °C. b-Specimen with 40% waste fired at 900 °C. c-Specimen with 0% waste fired at 1100 °C.

Figure 15. Effect of waste addition on bulk density.

Figure 14 (a) represents the SEM micrographs for a specimen consisting of pure clay fired at 1100 °C which shows that vitrification has started. The micrographs of two specimens containing each 40% waste fired at 900 °C and 1100 °C are also shown in figures 14(b) and (c) respectively. While no liquid phase could be observed
in the first case, the second specimen clearly showed vitrification behavior, as predicted from the results obtained in figure 11. Large pores appear for the specimen fired at 900 °C, practically disappearing in the second specimen fired at 1100 °C.

4.2.5. Bulk density
The variation of bulk density with both firing temperature and percent waste is shown in figure 15. The rise in porosity for samples fired at 1100 °C at waste additions between 20% and 30% reflects on the values of bulk density (shown in figure 9). However, the density tends to increase at higher levels of waste addition reaching its highest level for samples fired at 1100 °C and 40% waste.

4.2.6. Mechanical strength
The mechanical strength of fired tiles was determined in two ways: first, by calculating the average breaking strength for each three specimen sample and second, by calculating the bending strength (MOR). Figure 16 indicates that there is a general increase in breaking strength following an increase in waste level and firing temperature. According to ASTM C1167 [16], a minimum breaking strength of 890N is required. The figure shows that all investigated samples fired at least at 1000 °C conformed to this requirement with strength figures at 1100 °C largely exceeding the minimum value. Table 5 presents the standard deviation and standard error of breaking strength readings for sampled fired at 1100 °C.

It is interesting to note that the strength is essentially affected by the total porosity of the sample as can be seen from figure 17 which reveals a progressive decrease in strength following an increase in porosity. The calculated determination coefficient for that correlation (R²) is about 0.68, meaning that variations in porosity account for about 68% of the variation in strength. This dependence has been largely discussed in the literature and several empirical equations were proposed to relate these two variables. A comprehensive review concerning that matter was presented by Salvini et al [33].

Finally, the bending strength (Modulus of Rupture) was calculated and plotted against the percent waste for the three firing temperatures. The trend of variation is less regular than that of breaking strength although a maximum value of MOR has also been obtained on firing at 1100 °C of samples containing 40% waste (9.8MPa). Although there are no standard requirements for MOR, figure 18 shows the results obtained.

| % Waste | Mean  | St. dev. | St. error |
|---------|-------|----------|-----------|
| 0       | 2234.33 | 99.1077  | 301.388   |
| 10      | 3363   | 62.6498  | 190.519   |
| 20      | 2408   | 197.987  | 602.083   |
| 30      | 2994.67| 52.3482  | 159.192   |
| 40      | 3369.67| 52.7289  | 160.349   |

Figure 16. Effect of waste addition on Breaking Strength.

Table 5. Standard error of strength readings (Level of significance = 0.05).
5. Conclusion

Aluminum slag was used to partly substitute clay in the preparation of fired roof tile samples up to 40% replacement. The samples were mixed with the amount of water that produced the highest plasticity. The pastes formed were then molded, dried and fired to temperatures varying from 900 to 1100 °C for one hour. The following results were obtained for the fired bodies:

- Cold Water Absorption (CWA) was not greatly affected by the percent waste added but rather by firing temperature. Only samples fired at 1100 °C produced CWA values below the maximum allowable value of 15%.
- The Saturation coefficient (SC) values for all samples fired at 1000 and 1100 °C were below the maximum allowable value of 0.86.
- The Breaking Strength (BS) of most samples largely exceeded the minimum standard requirement of 890N, generally increasing by slag addition. This is presumably due to enhanced sintering and vitrification, particularly for samples fired at 1000 and 1100 °C.

Based on the above results, it seems reasonable to make use of aluminum slag waste in a percentage of 40% in samples to be fired at 1100 °C. This guarantees a cold water absorption of 12%, less than the maximum allowable value of 15%, a saturation coefficient of 0.83 less than the maximum value of 0.86 and a breaking strength...
significantly exceeding the minimum requisite of 890N (3370N). Thus a dual environmental and economic viability as 40% of the original clay material can be replaced by an environmentally hazardous valueless waste.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Ayman Yousef  https://orcid.org/0000-0002-2372-5261

References

[1] Hazmat C 2021 Roofing materials containing asbestos Victoria, BC: VRZ3.3L
[2] Liu Y, Yang W M and Hao M F 2009 Research on mechanical performance of roof tiles made of tire powder and waste plastic Adv. Mater. Res. 87–88 329–32
[3] Akbari H, Levinson R and Berdahl P 2003 A review of methods of manufacturing residential roofing materials Report prepared for California Energy commission PIER Program 113–4
[4] Necker I Jr, Prette A L G, Alarcon O E and Fredel M C 2008 Developing of ceramic roof tiles process by powder pressing and Firing in Roller kiln Mater. Sci. Forum 591–593 521–5
[5] Dondi M, Guarini G, Raimondo M and Zanelli C 2009 Recycling PC-TV waste glass in clay bricks and roof tiles Waste Manage. (Oxford) 29 1945–51
[6] Costa F B, Teixeira S R, Souza A E and Santos G T A 2014 Recycling of glass cullet as aggregate for clays used to produce roof tiles’ Revista Matéria 14 1146–53
[7] Torres P, Fernandes H R, Olhero S and Ferreira J M F 2009 Incorporation of wastes from granite rock cutting and polishing industries to produce roof tiles’ J. Eur. Ceram. Soc. 29 23–30
[8] Sultana S, Ahmed AN, Zaman MN and Rahman A 2015 Utilization of hard rock dust with red clay to produce roof tiles Journal of Asian Ceramic Societies 3 23–6
[9] Gaggino R, Positieri M J, Irico P, Kreiker J, Arguello R and Sánchez M P A 2013 Ecological roofing roof tiles made with rubber and plastic wastes Advanced Materials Research 844 458–61
[10] Datta T 2020 Recycling plastic waste as pavement/roof tiles International Research Journal of Engineering and Technology 7 111–4
[11] Figen A K, Orçanay U and Piğın S 2017 Manufacturing and characterization of roof tiles, a mixture of tile waste and fly ash Journal of Nature and Applied Science 21 224–9 online version, (10.19113)
[12] Sharma A K, Baredar P and Dubey A K 2018 A review on preparation of roof tiles using industrial waste and fibers’ International Journal of Civil Engineering and Technology 21 224–9 (https://dergipark.org.tr/en/pub/sdlfenbed/iissue/30898/334433)
[13] Ercioglu N and Ubay E 2020 An environmentally friendly process for preparing commercial ceramic foam composites based on frit/ glass wastes Int. J. Appl. Ceram. Technol. 18 850–61
[14] Dondi M, Raimondo M and Chiara Z Recycling PC 2009 and TV waste glass in clay brick and roof tiles Waste Manage. 29 1945–51
[15] AL Hamati M F and Faris F G 2014 Reuse of alum sludge in clay roof tiles manufacturing Int. Conf. Eng., Inform. Tech. Sci. (ICEITS 2014) (Kuala Lumpur, Malaysia)
[16] ASTM C 1667—03 2013 Standard Specifications of Clay Roof Tiles
[17] Viera C M, Amaral F L and Monteiro S N 2017 Recycling of steel making plants wastes in clay bricks Chapter in ‘Current topics in the utilization of clay in industrial and medical applications’ (https://doi.org/10.5772/intechopen.74431)
[18] Galal S 2021 Production of aluminum in Egypt: 2010—2019 STATISTICA A 2 2010–2019 (https://www.statista.com/statistics/1037375/egypt-aluminum-production/)
[19] OECD Global forum on environment 2010 Sustainable Material Management (Belgium: Mechelen)
[20] Gasparini E, Tarantino N, Ghigna P, Riccardi M P, Cedillo-Gonzalez E C, Siliardi C and Zema M 2013 Thermal dehydroxylation of kaolinite under isothermal conditions Appl. Clay Sci. 80 417–25
[21] ASTM C136 / C136M—19 2019 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates
[22] Kowalczyk P B and Drzymala G 2015 Physical meaning of the Sauter mean diameter of spherical particulate matter Part. Sci. Tech. 34 645–7
[23] De Andrade F O, Al-Qureshi H L and Hotza D 2010 Measuring and modelling the plasticity of clays Mater. Res. 13 395–9
[24] ASTM C 326—09 2009 Standard Method for Drying and Firing Shrinkages of Ceramic Whiteware Clays
[25] ASTM C 373—18 2018 Standard Test Methods for Determination of Water Absorption and Associated Properties
[26] ASTM D 5695—19 2019 Standard Test Methods for testing of Coating Powders
[27] ASTM C 648—20 2020 Standard Test Method for breaking Strength of Ceramic Tiles
[28] Kingery W D and Frand J 1954 Fundamental study of clay: XIII, drying behavior and plastic properties J. Am. Ceram. Soc. 37 596–602
[29] Oummad S 2019 Drying behaviour of ceramic green bodies: experimental characterization and numerical modeling France University of Limoges PhD Thesis
[30] Ozturk Z B and Ay N 2012 An investigation of the effect of alkaline oxides on porcelain tiles using factorial design J. Ceram. Proc. Res. 13 635–40
[31] Leriche A, Cambier F and Hampshire S 2021 Sintering of Ceramics: An overview Encyclopédia Mater. 1 233–48
[32] Schaifer J F and Bowen N L 1956 The system Na2O—Al2O3—SiO2 Am. J. Sci. 254 129–95
[33] Salvini V C, Pandolfelli V C and Spinelli D 2018 Mechanical properties of porous ceramics Recent advances in porous ceramics ed U B Al Naib (Malaysia: Univ. Tech.) (https://doi.org/10.5772/intechopen.71612)