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ASSESSMENT ON THE PHYSICAL, MECHANICAL PROPERTIES AND LEACHING BEHAVIOUR OF FIRED CLAY BRICK INCORPORATED WITH STEEL MILL SLUDGE

The disposal of industrial steel mill sludge in landfills has frequently received significant concern as the sludge has a very notable potential to contaminate soil surface and groundwater in the long run. Recently, the incorporation of industrial steel mill sludge into fired clay brick has become one of the promising alternative methods as it could produce a lightweight product while minimizing the environmental impact of the waste used. In this study, fired clay bricks as the most common building material were incorporated with 0%, 5%, 10% and 15% of steel mill sludge and fired at 1050°C (heating rate of 1°C/min). The manufactured bricks were subjected to physical and mechanical properties such as firing shrinkage, dry density, and compressive strength while the Toxicity Characteristic Leaching Procedure (TCLP) was conducted to analyze leaching behavior from the manufactured bricks. The results demonstrated that incorporation up to 15% of steel mill sludge reduces the properties up to 27.3% of firing shrinkage, 8.1% of dry density and 67.3% of compressive strength. The leaching behavior of Zn and Cu from steel mill sludge was reduced up to 100% from 7414 to 9.22 ppm (Zn) and 16436 to 4.654 ppm (Cu) after 15% of sludge incorporation. It was observed that high temperature during the firing process would improve the properties of bricks while immobilizing the heavy metals from the waste. Therefore, recycling steel mill sludge into construction building materials could not only alleviate the disposal problems but also promote alternative new raw materials in building industries.

Keywords: building materials; leachability; fired clay brick; steel mill sludge; brick properties

1. Introduction

With the rapid development in industrial activity, the demand for steel production to meet the winding of flat products continues to increase. Due to the high demand for the product, a large amount of industrial waste has been generated. There is no denying that industrial waste is the largest contributor to solid waste generation in landfills.

Over the past few decades, the contamination of heavy metal has become a worldwide issue due to its toxic characteristics and abundant production especially from the industry [1]. The major concern is on the heavy metal components in the wastewater and sludge due to their harmful potential of being released to the surrounding [2]. For instance, the steel industry contributed a large amount of heavy metal sludge. In particular, 0.90 tons of steel mill sludge is generated for every 1000 tons of rolling steel production [3]. To make it worse, a high level of oil presence in the steel mill sludge has minimized the ability of the heavy metal in the sludge to be recycled through the sintering process. This situation has resulted in the only option left for the steel mill sludge is to be treated and disposed of at the designated landfill site [4]. The hazardous metal present in the sludge could have an adverse impact on the environment especially if it is being disposed of. Other viable options for the management of steel sludge must therefore be critically investigated.

Furthermore sustainable development has promoted the recycling or reuse of sludge to maintain environmental safety. One of the alternatives for the recycling of sludge, which offers enormous potential, is the recycling of sludge into building materials, namely clay brick, ceramic and concrete [5]. This method provides a long-term approach to sludge disposal for economic and environmental sustainability. A few studies have produced a positive result on the use of heavy metal sludge in

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ceramics [6,7]. Another study that has extensively examined the possible encapsulation of heavy metal in the fired clay brick, found that the temperature increase associated with the firing of bricks could prevent heavy metals from leaking to the surrounding area [8].

The wide usage and versatility of bricks in the building industry as well as the structural composition of bricks provide a distinctive alternative for sludge recycling [9,10]. The type of industrial mill sludge that has been incorporated in bricks includes wastewater treatment sludge [5], sewage sludge [11], mosaic sludge [12], paper sludge [13] and electroplating sludge [14], with varying sludge composition. The varying composition of clay and sludge as raw materials showed that bricks can accept the introduction of high sludge percentage and still maintain to be a viable construction option [15]. The physical and mechanical properties of these bricks were analyzed, and the findings revealed that the sludge content used in the brick manufacturing plays a crucial role in influencing the brick quality.

This study presents the influence of steel mill sludge as a partial replacement of clay soil as a raw material of brick on the physical and mechanical characteristics of fired clay bricks as well as their leaching behaviour. The amount of steel mill sludge incorporated into fired clay brick is 0%, 5%, 10% and 15%.

2. Materials and methods

The methodology involved in this study is mainly divided into three stages which are the manufacturing process, physical and mechanical properties testing and leaching behavior of steel mill sludge-brick (SMSB).

2.1. Raw materials preparation

Raw materials for SMSB which are clay soil and steel mill sludge were collected from the industry located at Sedenak and Kluang, respectively. Upon arrival, both raw materials were oven-dried for a day at 105°C. After the drying process, the raw materials were crushed and sieved to ensure that the particle size of the materials is less than 500 µm. This step is crucial to make certain of the homogeneity of the sample size for the brick manufacturing process. Apart from that, X-Ray Fluorescence (XRF) analysis was done to determine the chemical elements present in the raw material. Four percentages (0%, 5%, 10% and 15%) of steel mill sludge were used as a clay replacement and mixed with a predetermined amount of water, as per shown in Table 1. Next, the brick mixture was compacted into the mould (210 mm × 102 mm × 65 mm) at pressure 2000 kPa. The brick was then removed and dried in the oven for 24 hours before being fired in the furnace at 1050°C with a firing rate of 1°C/min. Then, the fired brick samples were left cooled for at least a day at room temperature before being tested for physical, mechanical and leaching tests.

TABLE 1

Mixture amount of raw material for SMSB production

Percentage of steel mill sludge (%)	Amount of clay soil (kg)	Amount of steel mill sludge (kg)	Total mixture amount	Amount of water (mL)
0	3.00	0.00	3.00	450
5	2.85	0.15	3.00	480
10	2.70	0.30	3.00	510
15	2.55	0.45	3.00	540

2.2. Physical and mechanical testing

The physical and mechanical properties of bricks that were tested in this study are firing shrinkage, dry density, initial rate of suction and compressive strength. The procedures of testing were carried out following BS 3921:1985 [16]. In each testing, three brick samples for each percentage were used and the properties value was obtained from an average value.

2.3. Toxicity characteristic leaching procedure testing

The mobility of inorganic contaminants present in a brick sample was tested using the Toxicity Characteristic Leaching Procedure (TCLP) based on USEPA Test Method 1311. This procedure is essential for the understanding of the leaching behavior and also for the verification of whether the generated leachate from brick would classify the material as hazardous. The crushed samples from the previous compressive strength test were collected and sieved through 9.5 mm sieve. About 20 g of the sieved sample was placed in a 500 mL high-density polyethylene plastic bottle with 400 mL of predetermined extraction fluid. The sample was agitated in a rotatory end-to-end at 30 rpm for 18 ± 2 hours (at 22 to 24°C). Then, the sample was filtered through a 0.7 µm glass fiber filter and sent for metals analysis using atomic absorption spectrometry (AAS) analysis.

3. Result and discussion

In this section, chemical characteristics of clay soil and steel mill sludge were discussed. Besides, the results of physical, mechanical properties and leaching tests were also elaborated and compared to the standard brick.

3.1. Chemical composition of raw materials

Table 2 summarized the chemical composition of raw materials obtained from the XRF analysis. From Table 2, clay soil in this study mainly consists of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3) with minor content of sodium oxide (Na_2O) and calcium oxide (CaO). High silica content in the raw material is beneficial to increase the strength of brick after the firing process. Meanwhile, the presence of a significant amount of iron oxide influences the reddish colour of the brick, giving an aesthetic value to the brick. Table 2 also shows that steel mill sludge contains a high amount of iron oxides and magnesium oxides. The significant content of iron oxides in steel mill sludge is related to the main materials used to make steel bar products.

TABLE 2

Chemical composition of raw material

Chemical	Concentration (%)	
	Clay soil	Steel mill sludge
Metal content as oxides, dry basis (wt.%)		
Silicon oxide (SiO_2)	60.7	3.2
Aluminium oxide (Al_2O_3)	24.4	0.68
Iron oxide (Fe_2O_3)	4.46	70.9
Sodium oxide (Na_2O_3)	0.3	5.2
Magnesium oxide (MgO)	1.2	4.28
Manganese oxide (MnO)	0.05	0.57
Calcium oxide (CaO)	0.25	1.59
Titanium oxide (TiO)	0.09	0.15
Lead oxide (PbO)	0.04	0.28
Heavy metal, dry basis (ppm)		
Chromium (Cr)	19.5	345.5
Scandium (Sc)	14.5	5.0
Vanadium (V)	67.0	33.5
Cobalt (Co)	5.5	11.0
Nickel (Ni)	6.0	102.0
Copper (Cu)	15.0	6932.5
Zinc (Zn)	97.5	15654
Gallium (Ga)	20.0	23.5
Arsenic (As)	15.0	—
Rubidium (Rb)	108.5	35
Strontium (Sr)	47.5	63.5
Yitrium (Y)	57.5	16.5
Zirconium (Zr)	344.5	130.5
Niobium (Nb)	14	6.0
Molybdenum (Mo)	1	9.0
Tin (Sn)	7.5	615.5
Antimony (Sb)	2.50	—
Caesium (Cs)	11.5	10.5
Barium (Ba)	293	195.0
Lanthanum (La)	37.5	28.0
Cerium (Ce)	80.5	5.0
Lead (Pb)	20.5	4121.5
Thorium (Th)	26	75.0
Uranium (U)	6.5	3.0

In addition, when comparing the concentration of heavy metals in clay soil and steel mill sludge, the concentration of heavy metals in steel mill sludge is much higher. The elements present in steel mill sludge arranged in descending order are as follows: Zn (16436 mg/L), Cu (7414 mg/L), Pb (4391 mg/L), Sn (657 mg/L), Cr (351 mg/L) and Ni (104 mg/L).

3.2. Firing shrinkage of SMSB

Firing shrinkage is related to the expansion or shrinkage of a hardened mixture due to the loss of moisture content throughout the firing stage [17]. In the case of brick, several parameters affect its shrinkage, such as the characteristics and ratio of the brick components, the method of mixing and the moisture content of the surroundings. The effect of the amount of steel mill sludge incorporated into fired clay brick on the firing shrinkage is exhibited in Figure 1. From the trend, it can be observed that the firing shrinkage was decreased with the increasing addition of steel mill sludge. The control brick has the highest shrinkage value with 2.56% followed by 5% SMSB with 2.37%.

Meanwhile, the shrinkage value for both 10% and 15% SMSB is 1.86%. The shrinkage value for all percentages is far below the standard which is 8%. Apart from that, the result shows that the addition of steel mill sludge has increased the ability of the brick to comply with the standard brick size. Thus, the introduction of steel mill sludge into fired clay brick could enhance the shrinkage value while producing brick with excellent properties.

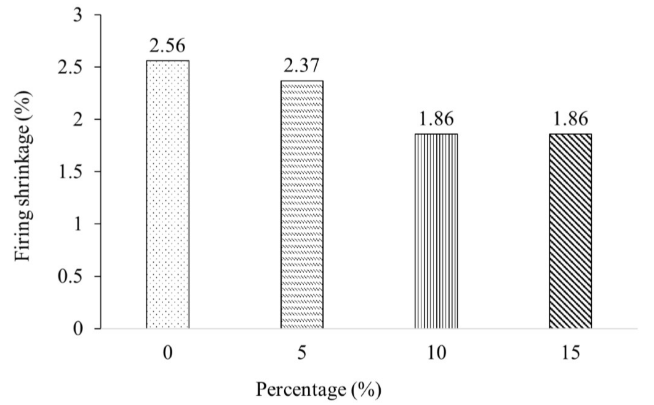

Fig. 1. Firing shrinkage of steel sludge mill-brick

3.3. Dry density of SMSB

Dry density of brick refers to the ratio between the mass and volume after the drying and firing process. Dry density value of SMSB is presented in Figure 2. From the figure, it should be noted that the dry density is inversely proportional to the amount of steel mill sludge added during manufacturing process. The control brick was found to have the highest density value of 1935 kg/m^3 followed by 5% SMSB with a density value of 1890 kg/m^3 while the dry density value of 10% SMSB is 1823 kg/m^3. The lowest density value of brick was obtained by the addition of 15% steel mill sludge (1779 kg/m^3). The addition of more than 15% of steel mill sludge has resulted in lower dry density due to the presence of porosity in brick. The relationship between the dry density and sludge percentage acquired from this study manifested the same agreement with the outcome obtained from the previous study [18,19].

In general, the dry density values of brick must be between 1500 kg/m^3 to 2000 kg/m^3 [9]. Therefore, it was found that both control brick and SMSB were complying with the average density value of common brick. Furthermore, it has also appeared that the incorporation of steel mills sludge has produced a lightweight brick which could minimize the cost of transporting the brick.

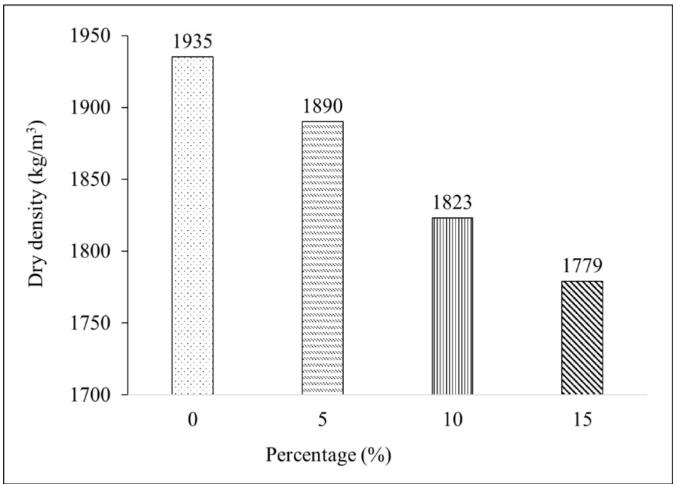

Fig. 2. Dry density of steel sludge mill-brick

3.4. Initial rate of suction of SMSB

By referring to the results obtained in Figure 3, the control brick was found to have the lowest value of the initial rate of suction (IRS) with an average value of 3.12 g/mm^2, followed by 5% of SMSB with an average value of 3.80 g/mm^2. Meanwhile, the value of IRS for 10% of SMSB is 5.04 g/mm^2. It was also determined that 15% of SMSB dominates the highest value of IRS with an average value of 7.12 g/mm^2. The result showed that the IRS of each brick sample was much lower than the standard IRS value. The addition of steel mill sludge has literally modified the clay characteristic. The results collected in this study are relatively close to the previous study in which the increase of waste content into clay bricks will potentially increase the suction rate (Kizinievič et al., 2018). Based on the brick specification set out in British Standard 3921:1985, the low value of the SMSB-possessed IRS allowed it to be classified as a damp-proof brick [16].

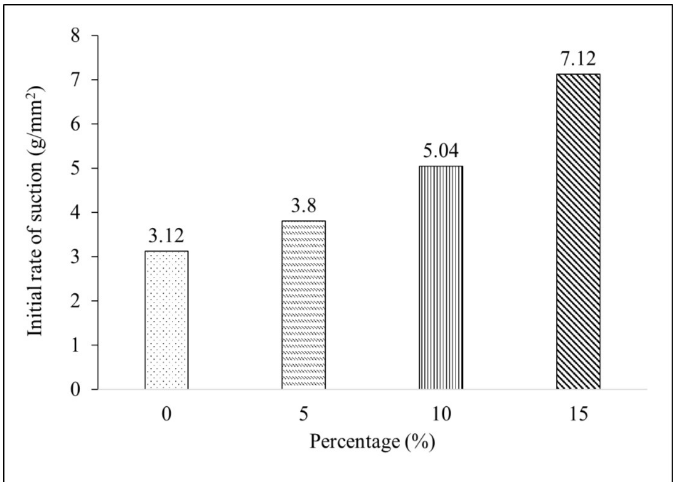

Fig. 3. Initial rate of suction of steel sludge mill-brick

3.5. Compressive strength of SMSB

Compressive strength is one of the important properties to ensure the engineering quality of bricks to withstand loads. Based on Figure 4, 15% of SMSB has the lowest compressive strength value, 7.43 N/mm², followed by 10% of SMSB with the strength value of 11.45 N/mm². Meanwhile, control brick has the highest value of compressive strength (22.72 N/mm²), followed by 5% of SMSB with the value of 16.8 N/mm². It shows that the compressive strength was reduced by the increasing amount of steel mill sludge incorporated into the brick. The presence of porosity due to the complete combustion of organic matter in clay soil has resulted in a lower compressive of brick.

This finding is identical to the previous study results, which implied that higher addition of sludge had reduced the compressive strength value [20]. It was determined from the compressive strength test that all measured bricks complied with the BS 3921:1985 standard ranging from 7 N/mm² to 100 N/mm², however not strong enough to be classified as Engineering Brick A or Engineering Brick B [16].

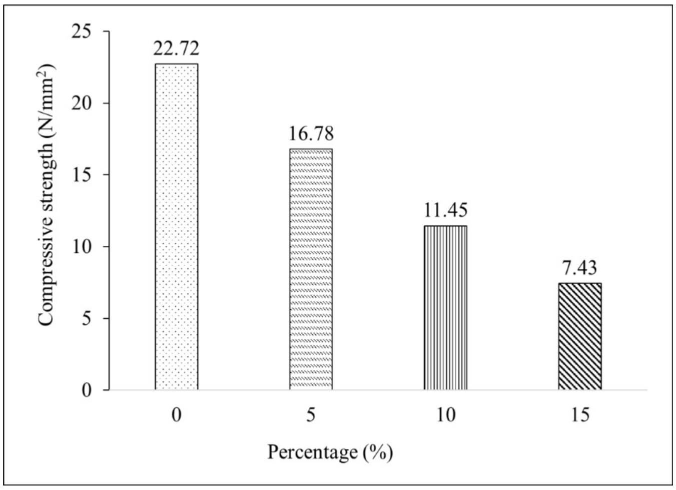

Fig. 4. Compressive strength of steel sludge mill-brick

3.6. Leachability of Heavy Metals

The results in Table 2 show that the concentration of heavy metals in steel mill sludge is much higher than the concentration of heavy metals in clay soil. Therefore, the leachability of fired clay bricks with steel mill sludge would also be studied. In this analysis, two of the most critical heavy metals, Zn and Cu, are chosen.

3.6.1. Zn concentration in leachate

Figure 5 shows the results of the leaching behavior of Zn contained in the extraction fluid of the sludge brick. From the result, the concentration of Zn in all specimens is consistent with the standard set by USEPA which is limited to less than 500 mg/L. It is shown that the increments in steel mill sludge in the brick cause the Zn leaching. This showed that the leachate concentration of Zn is increasing as the amount of steel mill sludge that is added to the production of clay brick.

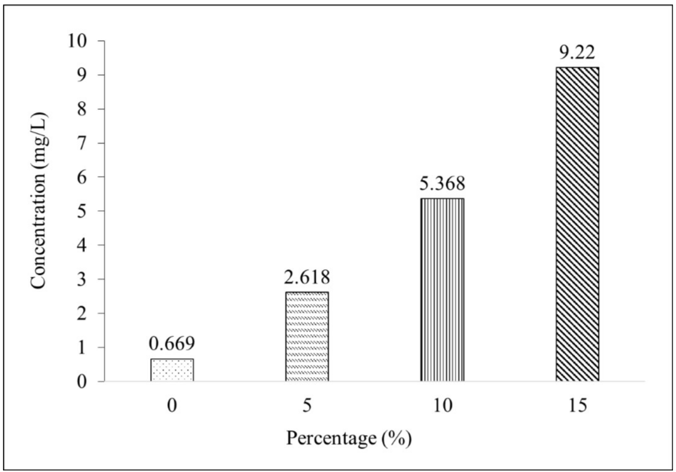

Fig. 5. Leachate concentration of Zn

3.6.2. Cu concentration in leachate

Figure 6 shows the results of the leaching behavior of Cu contained in the sludge brick extraction fluid. Based on the figure, the increase in steel sludge had an impact on the leaching behavior of Cu in brick where leachate concentration increased from 0.034 mg/L to 4.654 mg/L. Furthermore, the Cu was found below the permissible limit set by USEPA which is below 100 mg/L.

The level of heavy metals leached from the manufactured bricks is strongly influenced by the increase of steel mill sludge during the manufacturing process. This is because the heavy metals contained in the steel mill sludge were found to be high during the chemical characterization. It is also explained that, due to the re-dissolution of Zn at a strong base condition, the concentration of Zn will increase due to the increasing sludge content. Meanwhile, Cu is a low-activity element that is comparatively difficult to vaporize and easy to accumulate in the sludge.

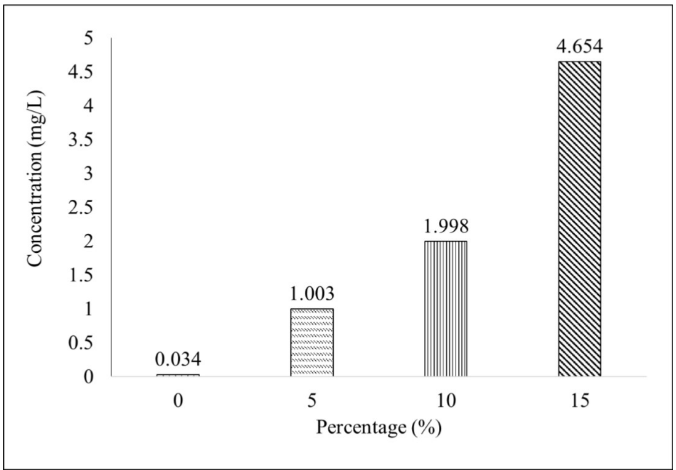

Fig. 6. Leachate concentration of Cu

The leachability study resulted in an acceptable value, although Zn and Cu showed the highest heavy metals concentration contained in steel mill sludge. Therefore, the incorporation of steel mill sludge up to 15% into fired clay brick would produce an acceptable amount of leachate and secure to be used as a building material.

4. Conclusion

Overall, it can be inferred that the corresponding chemical composition of steel mill sludge to the clay soil has great potential to be used as a raw material replacement for brick production. The optimum percentage of steel mill sludge incorporated into fired clay brick is limited up to 5%. The results show that the brick with the suggestion percentage has the highest compressive strength and low initial rate of suction.

The study also identified that all specimens produced leachate concentrations of heavy metals below the permissible limit that USEPA has regulated. For Zn and Cu case focused on this research, which is the higher concentrations in the XRF results, their concentrations in the leachate of all specimens are not a concern as their value is still below the permissible limit of USEPA.

The results from the physical and mechanical properties evaluation deduced that the recycling of steel mill sludge into fired clay brick could serve as a desirable alternative to replace the disposal method of the sludge while producing good quality brick.

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