

POSSIBLE RECYCLING OPTIONS OF WASTE MATERIALS IN MANUFACTURING CERAMIC TILES

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ABSTRACT: Throughout the world, the generation of wastes is increasing in quantity and diversity at a rapid rate. Effective and efficient methods must be developed to correctly dispose and recycle the wastes produced. It is also necessary to reduce the non-renewable resources used and lower the impact on our environment. In 2017, over 13.5 million square meters of tiles were produced globally, and the demand for ceramic tiles has escalated along with social development. There has been an increasing incentive to recycle waste materials in ceramic tiles due to the high heterogeneity of the raw materials, and the matrix for creating ceramics being flexibly interchangeable. The objective of this paper is to review and discuss the various recycling options of waste materials in the production of ceramic tiles. Past experimentation includes the addition of glass, coal ash, municipal solid waste ash, sewage sludge, and mining and ore wastes in ceramic tiles. They were used as an additive or substitute for the key components of the ceramic tiles. The results show a general enhancement to the physical and mechanical properties of the tiles with minor adverse effects on the aesthetics. Furthermore, when recycled with toxic wastes, the heavy metals were found to be immobilised during the firing process of the tiles. Therefore, the addition of wastes in tiles offers a sustainable solution to a growing pollution problem, in addition to decreasing the consumption of natural resources utilised in the manufacturing of tiles. However, further research and developments are essential.

Keywords: Waste Materials; Ceramic Tiles; Recycling; Sustainability; Geomaterials

1. INTRODUCTION

From the beginning of the industrialisation period and to the continuing expansion in world population, the issue relative to waste generation has become a constantly growing environmental issue [1]. In 2016, the annual global municipal solid waste generation reached 2.01 billion tonnes, and it will rise to 3.40 billion tonnes by 2050 if all conditions remain the same. The same report from the World Bank also indicates that more than 33% of waste is mismanaged, and only 13.5 % of waste has been recycled globally [2]. Moreover, the erroneous disposal methods adopted by developing countries in handling wastes can potentially cause severe heavy metal pollution to the ecosystem and result in adverse health impacts on the urban and aquatic life [3]. Additionally, waste materials vary greatly, and the subsequent impact of each type of waste on environmental toxicity requires a case by case investigation. As natural resources are depleting and climate change by gas emissions and environmental contaminations are increasing, many researchers are focusing on recycling waste materials in construction materials with promising results.

Ceramic tiles are considered to be a heterogeneous product that can be manufactured with the addition of waste materials. Technological innovations in the ceramic tile manufacturing

industry involve the development of novel ceramic products, one being porcelain tiles. The development of unique ceramic products has significant advancements in technical performance and aesthetic appearance [4]. Research confirmed the modern ceramic products exhibit high tolerance in its composition, suggesting the potential to recycle waste materials without compensating for the overall quality and even encapsulate heavy metals through sintering process where different particles fused together to become a new piece [5]. In addition, a study reported that over 13.552 million m² of ceramic tiles were produced in 2017, with a compound annual growth rate of 5.2 % [6]. Therefore, the ceramic tiles industry has the capability to recycle large quantities of waste material while reducing the usage of natural raw materials. Utilising waste materials in the manufacturing process of ceramic tiles can be a sustainable solution to ease the pressure on waste management.

2. USE OF WASTE MATERIALS

The objective of this paper is to review and discuss all major research studies on recycling wastes in the production of ceramic tiles. The wastes materials studied include waste glass, coal fly ash, coal bottom ash, municipal solid waste incineration (MSWI) fly ash, MSWI bottom ash,

sewage sludge, incinerated sewage sludge ash, granite cutting sludge, iron ore tailings and waste clay from placer gold mining.

2.1 Glass Waste

Glass is one of the most common materials in our life. Despite the superior properties of glass products, the popularity is because of its high recyclability, where recycled glass products have no apparent loss in purity and quality [7]. Due to the different chemical compositions of different types of glass, it is essential to categorise glass wastes before the recycling process. Most glass wastes are soda-lime-silicate (SLS) glass, which can be found in containers and flat glass. Other common types of waste glass that have been studied for recycling products include alkali-barium silicate from cathode ray tubes, sodium borosilicate from liquid crystal display and Pyrex, lead glass from crystal glassware and cathode-ray tubes, and aluminoborosilicate from glass fibres [8]. It is critical to categorise all glass wastes, as glass is being used in electrical and electronic applications and, therefore, may potentially contain hazardous chemicals and heavy metals. However, recent studies have shown that special treatment, such as washing with acid, can increase the recovery rate of glass wastes [8, 9].

Incorporating high amounts (>60 wt.%) of end of life fluorescent lamp glass (FLG) and waste packing glass (PWG) into ceramic tiles have received promising experimental results (Table 1). The final products achieve comparable mechanical properties to traditional ceramic tiles. Furthermore, FLG (<400 µm) tile passes the tile requirement of EN ISO 10545 for BIa group with low water absorption (<0.5 %) and high bending strength (>35 MPa), which is equivalent to high sintered floor tiles. It is to be noted that these two types of glasses are close to typical SLS glass but contain different impurities and varying ratios of chemical components. The differences in the composition of these two glass wastes cause different characteristic temperatures, which further affect the properties of the final tiles. Moreover, the consolidation stage of waste glass tiles requires a lower temperature than the temperature of glass melting and highly sintered ceramic tile, which demonstrates lesser energy will be used during the firing process and ability of reduction in production time that commensurate to the time of industrial fast firing cycles. Unfortunately, this experiment did not carry out a control sample ceramic tile and PLG (<100 µm) tile, so we can only assume from the results on Table 1, that the finer particle size of PGW results in better performance, and the tiles with different waste glasses can have noticeable performance gap. Reformulation of the clay bodies of the tile and the glazes are necessary in order to utilise the high

Table 1 Properties of ceramic tiles with waste fluorescent lamp glass and waste packing glass (reproduce from Andreola et al. [10]).

Sample type	Linear shrinkage (LS %)	Water absorption (WA %)	Bending strength (MPa)
PGW (<400µm)	4.87	1.83	23.37
PGW (<100µm)	5.46	0.29	30.6
FLG (<400µm)	8.79	0.02	40.93

Note: Results are under the same manufacturing processes. Sintering 60 min at 1000 °C, and formed by pressing (40 MPa).

amount of glass waste in the production of tiles [10].

Another comprehensive review paper compared multiple research studies on recycling different types of glass into ceramic tiles. Overall, waste glass has the potential to be recycled into ceramic tiles while enhancing some properties. Water absorption will decrease with the increase of glass content regardless of the types of glass waste, and bending strength will generally improve with a high amount of glass content and higher firing temperatures [8]. It is worth mentioning that multiple studies have found that firing temperature is critical to the performance of ceramic tiles. Firing shrinkage is found to increase with increasing firing temperature [11], but it will decrease if the firing temperature is beyond a certain range [12]. Similarly, flexural strength also improves at higher firing temperatures [13], but another study found flexural strength will start to decrease if firing temperature rises beyond the optimal temperature, i.e., the flexural strength of waste glass tiles keep improving until firing temperature exceed the optimal range of 1120 °C to 1160 °C in their experiment [14]. Additionally, waste glass can increase the hardness of tile, but there is some controversy about the effects on abrasion resistance [11, 15].

Heavy metals and hazardous chemicals of waste materials are another important consideration when recycling into new products. Studies found that unfired ceramic tiles with waste glass contain a high content of heavy metals; however, the leachate of heavy metals decreases after the firing process [16, 17]. Therefore, it can be considered safe to recycle hazardous glass waste in the production of ceramic tiles as the firing process can potentially immobilise toxic organic compounds and encapsulated hazardous contaminants. Furthermore, by recycling waste glass in ceramic tiles, the need for natural resources will decrease, the time required for mixing will lessen, and the energy consumption

during firing will reduce. Most importantly, recycling waste glass in tiles may offer a solution to the glass waste issue [8, 10].

2.2 Coal Ash

Despite there are many power generation methods and the trend of transitioning to renewable energy, coal combustion is still the primary power generation method in most countries. The unburned solid residues are known as ash, and they can be classified as fly ash or bottom ash according to the location where it was captured [18]. Due to the enormous amount of coal ashes and potential impact on the ecosystem, such as leaching toxic or chemical substances and accumulation throughout the food chain [19], researchers put lots of effort into utilising coal ash [20]

2.2.1 Coal fly ash

Zimmer and Bergmann trialed 20 – 80 wt.% of coal fly ash in their experiment of ceramic tile production. They have found 60 wt.% of fly ash in ceramic tile is the maximum amount that satisfied the minimum flexural strength (green) requirement of handling under industrial conditions. The ceramic tile with 60 wt.% fly ash passed the technical properties requirement with a flexural strength of 30 MPa, water absorption of 12 %, and shrinkage of 7.5 %. Moreover, to increase the plasticity of coal fly ash tile as fly ash is non-plastic material, they investigated the effects of adding limestone and feldspar separately. The addition of limestone can reduce shrinkage and increase green flexural strength for unfired tiles. However, it impairs the properties of flexural strength, water absorption and porosity. The addition of 30 wt.% feldspar into fly ash tiles can significantly reduce porosity (~5%) and water absorption (2%), and increase flexural strength (>35 MPa) greatly. The only downside of adding feldspar is the linear shrinkage will increase. Therefore, the amount of feldspar used in coal fly ash tile is critical to improving the tile performance without causing deformation defects [21]. Another research team achieved promising results on recycling coal fly ash with borax solid waste to replace part of the potassium feldspar in the formula of ceramic wall tiles. The 10% fly ash tile showed an increase in flexural strength with other properties that comparable to the control wall tiles. Moreover, the 10 % coal fly ash and 5 % borax waste tile have significant improvements on its flexural strength and water absorption but slightly impaired its firing shrinkage [22]. In the northwest of China, researchers incorporated 70 wt.% high alumina coal fly ash into the recipe of ceramic tile. The fly ash tile achieves 67 MPa flexural strength and apparent porosity of 0.13 % [23], which have a massive

potential for the ceramic industry and to reduce coal fly ash wastes. Nevertheless, it is worth mentioning coal fly ash may contain toxic heavy metals, such as Pb, Cd, and Cr, and radioactive elements (^{238}U , ^{232}Th , ^{226}Ra , ^{40}K , etc.) [24]. It is recommended that researchers conduct further studies to ensure tiles containing coal fly ash will not be an environmental issue.

2.2.2 Coal bottom ash

Coal bottom ash also can be used as a raw material for ceramic tiles. Namkane et al. [25] incorporated 20 - 80 wt.% of bottom coal ash into the clay bodies of tiles, and they have found all sample tiles can be classified as BIb group according to the ISO rules of water absorption under firing at 1175 °C. The optimal bottom ash tile comprises 40 wt.% of bottom ash and 60 wt.% of clay as they have the lowest linear shrinkage with the smallest deformation, and the flexural strength can reach 24.8 MPa, which is feasible for ceramic tiles but lower than commercial products. Moreover, they also discovered that tiles containing coal bottom ash are sensitive to firing temperatures and will easily affect the aesthetic aspects of planarity and darken the colour of ceramic tiles (Fig 1). Subsequently, Namakane et al. [26] continued their research with the addition of sand and leonardite, which are common wastes from coal mining, to enhance the plasticity of tiles, as bottom ash is a non-plastic material. The highest amount of waste content that achieved the properties required can reach up to 42.8 wt.% (21.4 wt.% of bottom coal ash and 21.4 wt.% of leonardite). Additionally, this tile can be used as floor tiles, as it satisfies the BIIa group of flexural strength (22-30 MPa), and the chemical aggression resistance reaches unglazed Class A tile which means that it is suitable to be used under the environment of household chemicals and swimming pool salts [26]; and further proved the possibility to recycle coal bottom ash in ceramic tiles.

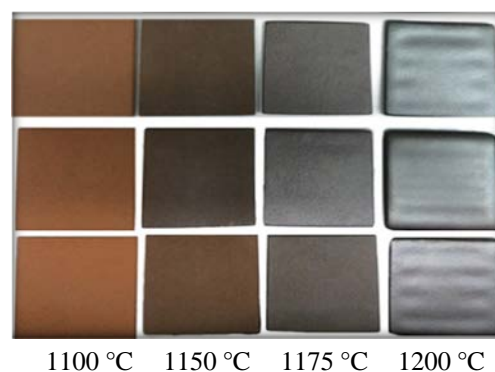


Fig. 1 Coal bottom ash tiles (10 cm × 10 cm × 0.8 cm) after firing at different temperatures [25].

2.3 Municipal Solid Waste Incineration Ash

Municipal solid waste, commonly called by the term trash and garbage, it is a highly inhomogeneous mixture that comes from every sector of our life. Municipal solid waste incineration (MSWI) is the process that can effectively reduce the mass by around 80 % and destroys pathogens and toxins in the waste that may come from places like hospitals and factories. As part of the toxins and heavy metals that may still exist after the incineration, MSWI ash is considered as a type of hazardous waste. Therefore, more recycling options are needed in order to balance out the substantial quantities of waste produced every day in the world.

2.3.1 MSWI fly ash

Researchers in China studied the recycling of untreated MSWI fly ash into ceramic tiles. In their experiment [27], they found that incorporating 20 wt.% of MSWI fly ash is an ideal ratio for recycling the maximum amount of waste and creating ceramic tiles that are within the Chinese standards. With the addition of 20 % MSWI fly ash by weight in tiles, a compressive strength of 18.6 MPa and a water absorption of 7.4 % was achieved at a firing temperature of 960 °C. Also, it was found for a firing temperature above 1000 °C, the heavy metals in the ceramic tile were immobilised. However, Cd, Hg, Pb, and Zn are still exceeding the limit when the leachability analysis was conducted on an unglazed tile. In contrast, researchers also found that the reduction in porosity by glazing a ceramic tile surface can effectively reduce the amount of heavy metals leaching, even below the detection limit for the instruments they used. Another research also discovered that glazing could prominently encapsulate and stabilise the fly ash tiles; however, a highly acidic environment may lead to the leachate of heavy metals [28].

2.3.2 MSWI bottom ash

A group of researchers attempted to produce porcelainised tiles by adding 3 – 15 wt.% untreated MSWI bottom ash and vitrified bottom ash (50 % MSWI bottom ash + 50 % glass cullet). In the results [29], all tile samples with untreated or vitrified bottom ash meet the requirements for floor tiles. The water absorption was found to be below 0.1 %, bending strength between 45 to 53 MPa, and improvement on linear shrinkage was detected. The vitrified bottom ash tile demonstrated better physical properties compared to the untreated bottom ash tile. However, incorporating bottom ash in ceramic tile can cause aesthetic issues, such as dark colour and noticeable deformation on the planarity. Hence, consideration should be given to the amount of bottom ash used or maybe reformulate the recipe for better performance.

In another study [30], researchers utilised 2 – 5 wt.% untreated bottom ash and 5 – 10 wt.% vitrified bottom ash (with glass) to replace part of Na-feldspar sand in the matrix, and test the possibilities of making monopors tile and porcelain tiles. The result shows that MSWI bottom ash is technically feasible for ceramic tile making. For porous single firing tile, the addition of 5 wt.% untreated bottom ash does not have many impacts on water absorption and linear shrinkage. Vitrified bottom ash is not tested due to its not cost-effective to put in production. For porcelain tiles, vitrified bottom ash tiles exhibit clear improvement on water absorption and linear shrinkage compared with the control tile at a firing temperature above 1160 °C. MSWI bottom ash releases heavy metals and solubilisation of alkaline metals. Therefore, a leachability test was conducted to check if it is suitable to be recycled in tiles. The result shows all fired tiles still release a small amount of leachate, but they are below the limit value for inert waste. As shown in Table 2, the results indicate that post-treated bottom ash does not have significant

Table 2 Leaching results of post-treated bottom ash (PTBA) and fine & coarse ground PTBA ceramic samples compares to Italian limits (adapted from Andreola et al. [31]).

Metals/ Anions	Post-treated Bottom Ash	Fine ground PTBA ceramic	Coarse ground PTBA ceramic	Non-hazardous waste (mg/L)	Inert waste (mg/L)
Cu	0.48	0.276	0.212	5	0.2
Zn	0.191	0.289	0.181	5	0.4
Ni	0.05	0.041	0.011	1	0.04
As	<0.05	<0.05	<0.05	0.2	0.05
Cd	0.008	0	0	0.02	0.004
Cr total	<0.001	<0.001	<0.001	1	0.05
Pb	0.53	0.142	0.042	1	0.05
Cl ⁻	200	12	9	1500	80
SO ₄ ²⁻	375	< 0.2	5	2000	100
pH	10.68	8.1	7.16	5–12	5–12

Note: Fine ground & coarse ground sample fired at 1210 °C and 1190 °C, respectively.

ecotoxicity impacts on the environment. This is due to the process of sintering and vitrification can immobilise heavy metals, alkali, and anions [31]. Thus, MSWI bottom ash has the potential to be recycled in ceramic tiles.

2.4 Sewage Sludge

Sewage sludge is another high volume solid waste generated by human activities from wastewater treatment plants. Zhou et al. [32] used 50 - 65 wt.% untreated sewage sludge to replace the kaolin in the raw materials of tiles. The XRD pattern reveals the composition of sewage sludge is like natural clayey material, mainly composed of quartz, kaolinite, and a small amount of illite and albite. Hence, it would be a viable alternative to traditional raw materials. Furthermore, tiles with up to 60 % of sewage sludge by weight can achieve tile requirements. Tiles with 60 wt.% of sewage sludge have water absorption of 1.14 %, bending strength of 25.5 MPa, and linear sintering shrinkage around 12 % under firing temperature at 1210 °C. To sum up the key findings, tiles with a high content (> 60 wt.%) of sewage sludge and under high firing temperature (> 1210 °C) are more likely to have severe deformation defects. Tiles containing less than or equal to 60 wt.% sewage sludge satisfied the requirements of split tiles (bending strength > 23 MPa & water absorption < 3 %). The leachability of sewage sludge tiles reduced drastically once fired, and the leaching of heavy metals is far below the regulatory limit. However, in another research, the results are almost entirely different. Jordán et al. [33] tested the effects of adding 0 - 10 wt.% of three sources of sewage sludges into two types of ceramic clays in their experiments. The overall results show the amount of sewage sludge has no impacts to linear shrinkage (before and after firing); porosity and water absorption will increase with the increases in sewage sludge content, and bending strength will decrease while sewage sludge increases. As shown in Fig. 2, Zhou et al. [32] revealed the flowchart of their preparation process for sewage sludge tile, while Jordán et al. [33] did not mention in their paper.

2.4.1 Incinerated sewage sludge ash

Sewage sludge is also often incinerated, as this process can significantly reduce the mass, volume and hazardous components. In a comprehensive review paper written by Lynn et al. [34], they reviewed and summarised the main findings of various research studies. In general, recycling sewage sludge ash into glazed and unglazed tiles is a possible solution with no significant production issues. The water absorption of unglazed ceramic tiles often exceeds the required limit; however, it

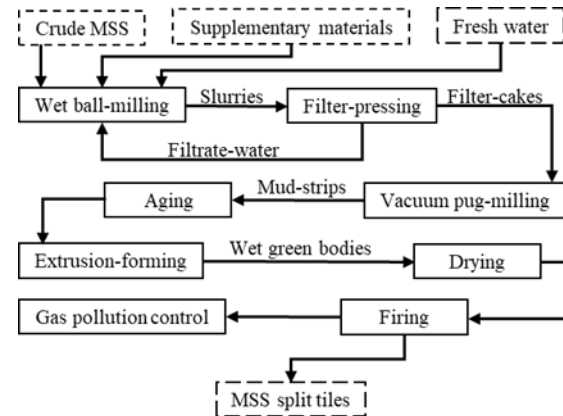


Fig. 2 Flowchart of the preparation process for municipal sludge (MSS) tile (adapted from Zhou et al. [32]).

only has minor impacts on low ash content tiles, and the application of glazing can effectively reduce water absorption. Bending strength and abrasion limit fulfils the standards, but they will decrease with increasing the content of sewage sludge ash in tiles. Moreover, there is no impact on chemical resistance, no significant effects on firing shrinkage, and there is a reduction of loss on ignition due to organic matter having been burned off prior to the tile firing process [34]. Subsequently, research shows that the overall performance can be improved by adding nano-SiO₂ additive into the sewage sludge ash tile [35]. Thereupon, more in-depth studies on the manufacturing formula and processes need to be undertaken in order to recycle sewage sludge ash with high efficiency and high quality.

2.5 Mining And Ore Waste

2.5.1 Granite cutting sludge

Industrial waste is a huge part of the waste stream, and it is often neglected during considerations of recycling priorities. In Europe, the average amount of waste generated through the production stages of ornamental stone can exceed 80% of the total raw material used [36]. Torres et al. [37] incorporated granite cutting sludge into the formula of porcelain tiles. The results show that adding up to 50 wt.% of granite sludge in ceramic tiles can reduce water absorption (<0.25 %) and increase bending strength (>55 MPa) compared with typical commercial porcelain tile. The optimal extruded porcelain sample satisfy the water absorption BI group of the ISO standards, and granite cutting sludge shows negligible effects on other properties. Nonetheless, it is essential to realise that different source of materials may have a visible difference in composition, and the selection of firing temperature may affect the final properties significantly.

Therefore, they continued their studies on

recycling sludge from the production of ornamental stone. In the subsequent studies [38], they have categorised the sludges into granite cutting and polishing sludge (GS) and white sludge (WS) from the process of silica sand-washing. The composition shows GS contains a large amount on iron and CaO, which are the residue from the abrasive shot operation and marble stone that the supplier also processes in their site. WS are mostly kaolinite and close to common clay materials. The optimal ratios are tile with 20 wt.% of sludge (10 wt.% of WS & 10 wt.% of GS) and tile with 30 wt.% of WS, these tiles have a significant increase in bending strength (~38 MPa), and lower water absorption (~6 %) compared with a commercial ceramic sample. Furthermore, the optimal samples are aesthetically superior to the commercial sample, with smoother surface texture.

Related studies on marble and granite rejects were also carried out by Segadães et al. [39]. The final tile with 30 wt.% of marble and granite rejects achieves the IIb grade water absorption of the ISO standard, lower water absorption and comparable mechanical properties to the control sample. More impressively, the tile with below 30 wt.% of granite rejects has poorer performance than the tile with 30 wt.%. The 10 wt.% granite rejects ceramic tile sample has the worst overall performance in all sample tiles, but with increasing the waste content that the properties will be enhanced. Besides, the tile with 30 wt.% of marble and granite rejects can sinter at a lower firing temperature with better performance than the control tile, which indicates the possibilities to reduce the production cost and energy used on firing [39].

2.5.2 Iron ore tailings

Iron ore tailing also has been trialled in the manufacturing process of ceramic tiles. Das et al. [40] incorporated 30 – 40 wt.% of tailings samples in the ceramic bodies with different formula ratios. The tile with 40 wt.% of tailings has the optimal results under 1200 °C firing temperature, it has superior abrasion hardness and bending strength than commercial tiles, and the properties pass most of the requirements of EN standards (except the straightness of sides, surface quality and water absorption are slightly inferior). Water absorption can further reduce from 3 % to 0.5 % if the firing temperature is increased by 50 °C. However, adverse effects may occur to the other properties, such as firing shrinkage will increase with increasing firing temperature. Hence, the recycling formula needs to be optimised to achieve balanced performance in the future, in order to take the advantage to reduce the expenditure and protect mineral resources with saving 30% of raw materials in a conservative estimation [40].

2.5.3 Waste clay from placer gold mining

In Turkey, white-firing clays are nearly exhausted in reserves due to popular demand in the ceramic tile and sanitaryware industry. Therefore, Özkan et al. [41] tried to use waste clay from a placer gold mine to replace part of the Istanbul clay to make ceramic floor tiles. Results show the floor tile with 10 wt.% of waste clay not only qualified the performance but also enhanced water absorption and bending strength compared with commercial floor tiles. Besides, waste clay tiles fired at 1160 °C can achieve comparable physical properties to commercial floor tiles fired at 1180 °C, which by estimation, can save around 10 % of firing energy. However, waste clay does not have enough viscosity during the slurry process. Therefore, extra water is required to obtain the fluidity, which will cost more energy to vaporise water out and lose some of the density [41]. Overall, waste clay can be used in ceramic floor tile to provide satisfactory performance and save energy and resources

3. DISCUSSION AND CONCLUSION

As shown above, recycling of different wastes in ceramic tiles shows the ability to enhance some properties of ceramic tiles. Still, at the same time, the other properties might be compensated due to the addition of wastes. In addition, most studies did not apply glazing or use fluxing agents like feldspar as they are commonly used in the industry and have shown the ability to improve the performance further. Moreover, many journal articles did not reveal the process of manufacture or did not set a control ceramic tile to compare with experimental tiles. This brought some difficulty to compared with the properties of commercial tiles directly as the formula may not be able to produce qualified tiles.

Many research studies have discovered that some factors can influence the properties critically. One is the firing temperature; many studies show that waste sample tiles appear to have better performance when firing at a higher temperature of the selected firing temperature range. However, if the temperature is over or below the optimal temperature range, inferior performance will occur. A suitable range of firing temperature needs to be determined, such as using XRD to determine the composition of waste material. The second factor is the differences in materials. Waste materials or raw materials of ceramic tile may have different chemical or mineralogical compositions if the acquired location is different. Therefore, it is necessary to determine the composition of materials and test them locally before they are included in the manufacturing process. The third one is the variations in manufacturing techniques. Since there are many commercial methods for producing ceramic tiles, the experimental methods may not be

suitable, and the results may be different. Hence, a suitable method in production needs to be selected and tested in trials under production conditions.

Ceramic tiles have proven their strong tolerance for recycling waste materials. The high heterogeneity and versatile uses create the possibility to use various wastes to make the most widely used products. Plus, tiles used for different purposes have different product standards, which further expand the feasibility of recycling. For future development, the tiles with waste need to achieve a balanced performance by finding the optimal formula ratio and production techniques. As most of the studies did not apply glazing, use fluxing agents, or such techniques, more in-depth experiments are required to test their effects on performance and properties. In the future, researchers can study the recycling of more different types of waste materials into ceramic tiles and create a more sustainable society.

4. ACKNOWLEDGMENTS

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5. REFERENCES

- [1] Nwachukwu M.A., Ronald M., and Feng H. Global capacity, potentials and trends of solid waste research and management, *Waste Management & Research*. 2017, 35(9), 923-934.
- [2] Kaza S., Yao L., Bhada-Tata P., and Van Woerden F. What a Waste 2.0: A Global Snapshot of Solid Waste Management To 2050, World Bank Publications, Washington, D. C., UNITED STATES, 2018, <<http://ebookcentral.proquest.com/lib/rmit/detail.action?docID=5614550>>.
- [3] Ferronato N. and Torretta V. Waste Mismanagement in Developing Countries: A Review of Global Issues, *International journal of environmental research and public health*. 2019, 16(6), 1060.
- [4] Dondi M., Raimondo M., and Zanelli C. Clays and bodies for ceramic tiles: Reappraisal and technological classification, *Applied Clay Science*. 2014, 96, 91-109.
- [5] Rahaman M.N. Ceramic Processing, CRC Press LLC, Milton, UNITED KINGDOM, 2017, <<http://ebookcentral.proquest.com/lib/rmit/detail.action?docID=5477211>>.
- [6] World production and consumption of ceramic tiles, 2018. Viewed 28/04/2020, <http://www.mec-studies.com/filealbum/740_0.pdf>.
- [7] GPI. 'Benefits of Glass Packaging', 2020. Viewed 30/04, <<https://www.gpi.org/benefits-of-glass-packaging>>.
- [8] Silva R.V., de Brito J., Lye C.Q., and Dhir R.K. The role of glass waste in the production of ceramic-based products and other applications: A review, *Journal of Cleaner Production*. 2017, 167, 346-364.
- [9] Ling T.-C. and Poon C.-S. Utilisation of recycled glass derived from cathode ray tube glass as fine aggregate in cement mortar, *Journal of Hazardous Materials*. 2011, 192(2), 451-456.
- [10] Andreola F., Barbieri L., Lancellotti I., Leonelli C., and Manfredini T. Recycling of industrial wastes in ceramic manufacturing: State of art and glass case studies, *Ceramics International*. 2016, 42(12), 13333-13338.
- [11] Lin K.L. Use of thin film transistor liquid crystal display (TFT-LCD) waste glass in the production of ceramic tiles, *Journal of Hazardous Materials*. 2007, 148(1-2), 91-97.
- [12] Hwang J.-Y., Huang X., Garkida A., and Hein, A. Waste colored glasses as sintering aid in ceramic tiles production, *JMMCE*. 2006, 5(5), 119-129.
- [13] Youssef N.F., Abadir M.F., and Shater M.A.O. Utilisation of soda glass (cullet) in the manufacture of wall and floor tiles, *Journal of the European Ceramic Society*. 1998, 18(12), 1721-1727.
- [14] Matteucci F., Dondi M., and Guarini G. Effect of soda-lime glass on sintering and technological properties of porcelain stoneware tiles, *Ceramics International*. 2002, 28(8), 873-880.
- [15] Lin K.-L., Lee T.-C., and Hwang C.-L. Effects of sintering temperature on the characteristics of solar panel waste glass in the production of ceramic tiles, *Journal of Material Cycles and Waste Management*. 2015, 17(1), 194-200.
- [16] Raimondo M., Zanelli C., Matteucci F., Guarini G., Dondi M., and Labrincha J.A. Effect of waste glass (TV/PC cathodic tube and screen) on technological properties and sintering behaviour of porcelain stoneware tiles, *Ceramics International*. 2007, 33(4), 615-623.
- [17] Dondi M., Guarini G., Raimondo M., and Zanelli C. Recycling PC and TV waste glass in clay bricks and roof tiles, *Waste Management*. 2009, 29(6), 1945-1951.
- [18] Benavidez E., Grasselli C., and Quaranta N. Densification of ashes from a thermal power

- plant, *Ceramics International*. 2003, 29(1), 61-68.
- [19] Carlson C.L. and Adriano D.C. Environmental impacts of coal combustion residues, *Journal of Environmental quality*. 1993, 22(2), 227-247.
- [20] Ahmaruzzaman M. A review on the utilisation of fly ash, *Progress in Energy and Combustion Science*. 2010, 36(3), 327-363.
- [21] Zimmer A. and Bergmann C.P. Fly ash of mineral coal as ceramic tiles raw material, *Waste Management*. 2007, 27(1), 59-68.
- [22] Olgun A., Erdogan Y., Ayhan Y., and Zeybek B. Development of ceramic tiles from coal fly ash and tincal ore waste, *Ceramics International*. 2005, 31(1), 153-158.
- [23] Wang H., Zhu M., Sun, Y., Ji R., Liu L., and Wang X. Synthesis of a ceramic tile base based on high-alumina fly ash, *Construction and Building Materials*. 2017, 155, 930-938.
- [24] Wang N., Sun X., Zhao Q., Yang Y., and Wang P. Leachability and adverse effects of coal fly ash: A review, *Journal of Hazardous Materials*. 2020, 396, 122725.
- [25] Namkane K., Naksata W., Thiansem S., Sooksamiti P., and Arqueropanyo O.-a. Utilisation of coal bottom ash as raw material for production of ceramic floor tiles, *Environmental Earth Sciences*. 2016, 75(5), 386.
- [26] Namkane K., Naksata W., Thiansem S., Sooksamiti P., and Arqueropanyo, O.-a. Utilisation of leonardite and coal bottom ash for production of ceramic floor tiles, *Environmental Earth Sciences*. 2017, 76(17), 628.
- [27] Haiying Z., Youcai Z., and Jingyu Q. Study on use of MSWI fly ash in ceramic tile, *Journal of Hazardous Materials*. 2007, 141(1), 106-114.
- [28] Zhipeng T., Bingru Z., Chengjun H., Rongzhi T., Huangpu Z., and Fengting L. The physiochemical properties and heavy metal pollution of fly ash from municipal solid waste incineration, *Process Safety and Environmental Protection*. 2015, 98, 333-341.
- [29] Barbieri L., Corradi A., Lancellotti I., and Manfredini T. Use of municipal incinerator bottom ash as sintering promoter in industrial ceramics, *Waste Management*. 2002, 22(8), 859-863.
- [30] Rambaldi E., Esposito L., Andreola F., Barbieri L., Lancellotti I., and Vassura, I. The recycling of MSWI bottom ash in silicate based ceramic, *Ceramics International*. 2010, 36(8), 2469-2476.
- [31] Andreola F., Barbieri L., Queiroz Soares B., Karamanov A., Schabbach L.M., Bernardin A.M., and Pich C.T. Toxicological analysis of ceramic building materials – Tiles and glasses – Obtained from post-treated bottom ashes, *Waste Management*. 2019, 98, 50-57.
- [32] Zhou J., Li, T., Zhang Q., Wang Y., and Shu Z. Direct-utilization of sewage sludge to prepare split tiles, *Ceramics International*. 2013, 39(8), 9179-9186.
- [33] Jordán M.M., Almendro-Candel M.B., Romero M., and Rincón J.M. Application of sewage sludge in the manufacturing of ceramic tile bodies, *Applied Clay Science*. 2005, 30(3), 219-224.
- [34] C. J. Lynn, R. K. Dhir, and G. S. Ghataora, Sewage sludge ash characteristics and potential for use in bricks, tiles and glass ceramics, *Water Science and Technology*, 2016, 74(1), 17-29.
- [35] Chen L. and Lin D.F. Applications of sewage sludge ash and nano-SiO₂ to manufacture tile as construction material, *Construction and Building Materials*. 2009, 23(11), 3312-3320.
- [36] da Silva A. and Almeida I. Towards INDUSTRY 4.0 | a case STUDY in ornamental stone sector, *Resources Policy*. 2020, 67, 101672.
- [37] Torres P., Fernandes H.R., Agathopoulos S., Tulyaganov D.U., and Ferreira J.M.F. Incorporation of granite cutting sludge in industrial porcelain tile formulations, *Journal of the European Ceramic Society*. 2004, 24(10), 3177-3185.
- [38] Torres P., Fernandes H.R., Olhero S., and Ferreira J.M.F. Incorporation of wastes from granite rock cutting and polishing industries to produce roof tiles, *Journal of the European Ceramic Society*. 2009, 29(1), 23-30.
- [39] Segadães, A.M., Carvalho, M.A., and Acchar, W. Using marble and granite rejects to enhance the processing of clay products, *Applied Clay Science*. 2005, 30(1), 42-52.
- [40] Das S.K., Kumar S., and Ramachandrarao P. Exploitation of iron ore tailing for the development of ceramic tiles, *Waste Management*. 2000, 20(8), 725-729.
- [41] Özkan İ., Çolak M., and Oyman R.E. Characterization of waste clay from the Sardes (Salihli) placer gold mine and its utilisation in floor-tile manufacture, *Applied Clay Science*. 2010, 49(4), 420-425.