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Upcycling Ceramic Waste for Sustainable Tile Production

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Abstract

The conventional method of manufacturing ceramic tiles generates a significant volume of scrap that are largely disposed of as waste leading to unsustainable practices and a loss of both money and natural resources. This research work aimed to explore the feasibility of utilizing scrap tiles from ceramic industries for manufacturing tiles to reduce resource consumption, lower production costs and decrease the carbon footprint of ceramic production. In this process, test samples were prepared by substituting varying percentages (3%, 5%, 10%, 15%) of traditional raw materials with waste tiles. The samples were then subjected to a series of tests to measure their properties, including density, modulus of rupture (MOR), loss on ignition, shrinkage, water absorption, and thermal expansion, and were compared with a standard sample. The results showed that the inclusion of waste material improved the mentioned parameter of floor tiles up to a certain substitution level. Previous research has primarily focused on enhancing specific tile properties (e.g., flexural strength, water absorption). Comprehensive evaluations, including long-term durability, shrinkage, thermal expansion, and environmental impact, have not been extensively studied when substituting traditional materials with waste tiles. The primary objective of this research is to investigate the feasibility of recycling waste ceramic tiles, Material Substitution Analysis, Performance Assessment, Optimization of Substitution levels, Industrial applicability.This approach opens a new possibility for eco-friendly and cost-efficient tile production while maintaining or improving performance.

Keywords: Waste, Recycling, Sustainability, Eco-Friendly.

1. Introduction

Traditionally ceramic tiles are made from naturally occurring raw materials such as clay, feldspar, quartz, etc[1] and this process is energy-intensive. With the increasing demand for tiles, the expanded extraction of geomaterials is putting substantial pressure on the ecological balance[2]. On the other hand, rapid industrialization has led to global issues such as the depletion of natural resources and the generation of vast amounts of waste from construction and demolition activities[3]. The construction sector has a significant impact on environmental costs; this part of human activity contributes almost 36% to the generated waste[4]. Waste tiles, a type of construction waste, come mainly from the ceramic tiles industry, surplus materials from construction projects, and debris from the destruction of older buildings[1][3]. A typical floor tile formula has a firing temperature of 1180° C and contains roughly 50% clay, 40% feldspar, and 10% quartz[5]. Significant manufacturing losses in the ceramic tile sector are a result of off-standard tile manufacture[6]. The main causes of these losses include size inconsistencies, glazing flaws, cracks, and over- or under-firing, and these wastes are not recycled during the manufacturing process. Around 7% of the firms' total manufacturing capacity is thought to be made up of these non-standard tiles[7].The management and storage of these waste tiles is becoming a serious environmental problem due to its contribution to increasing pollution. As a sustainable and eco-friendly solution, recycling offers an efficient way to manage this waste, and way to conserve natural resources, lower raw material costs, and mitigate pollution.[8][9]. Since the late 1990s, research has examined the recycling of various waste materials in ceramic tile production. Several studies have focused on exploring alternative raw materials and utilizing industrial waste in porcelain tile manufacturing. Consequently, in recent years, traditional ceramics have adopted environmentally friendly practices by substituting natural raw materials with waste.

Torres et al[10] observed enhanced flexural strength and reduced water absorption in ceramic floor tiles by incorporating granite and quartzite sludges into their composition. Gennaro et al. also demonstrated some technological advances[11] in utilizing Zeolite-Feldspar epiclastic rocks as an alternative for flux materials in ceramic tile manufacturing. However, the high slip viscosity, poor powder compressibility, and increased color darkening associated with higher iron oxide in zeolite feldspar epiclastic rocks make them unsuitable for industrial production. Current research is focused on using waste ceramic tiles, such as leftover tiles from factories or tiles from demolished buildings, as a substitute for natural raw materials in ceramic floor tile production. This research aims to explore the feasibility of recycling waste ceramic tiles as substitutes for natural raw materials in floor tile production, addressing both environmental and economic concerns. It evaluates the effects of replacing traditional components like clay, feldspar, and quartz with varying percentages (3%, 5%, 10%, 15%) of waste tiles, analyzing key tile properties such as density, modulus of rupture (MOR), water absorption, shrinkage, thermal expansion, and loss on ignition. The study seeks to determine the optimal substitution level that maintains or improves tile performance. Additionally, it examines the sustainability of this approach by assessing resource conservation, waste management, and carbon footprint reduction. Finally, the research addresses the industrial applicability of this method, considering challenges such as waste variability and ensuring compatibility with existing production processes. The ultimate goal is to establish a sustainable, eco-friendly, and cost-effective manufacturing alternative in the ceramic tile industry. Additionally, it will explore potential future improvements to enhance this sustainable practice, addressing any challenges to encourage broader use in the tile industry.

2. Materials and Methodology

The manufacturing of ceramic tiles generates waste at different stages of the production process. A significant percentage of this waste is recycled into the current ceramic products and processes. A large bulk of broken ceramic tiles change into wastage. This experimental study deals with the investigation of the possibility of using this waste broken tiles in the manufacturing process of ceramic tiles. At first, a tiles sample was Prepared without adding any wastage in body composition that was used as a reference to continue the rest of the experiment. Then broken tiles were used in the body composition as the substitute for stone material such as Thai soda with 3, 5, 10, and 15 percent. Finally, a comparison was made between the flexural strength, shrinkage, and water absorption, of the reference samples and waste added samples.

2.1 Raw materials

The raw materials used in this research were Malaysian Plastic clay, Malaysian Semi Plastic clay, Sylhet clay, Chitka clay, Soda feldspar, Potash feldspar and waste floor tiles. The chemical composition of raw materials was also determined using X-ray fluorescence spectrometry. Thermal expansion and contraction properties were determined using Dilatometer in raw materials using model Q500 a heating rate equal to 7 ◦C/min at a temperature range of 25–900 ◦C.

2.2 Characterization

2.2.1 Instrumental Details:

Pot Mill:
Pot Mill is an ideal equipment for achieving analytically pure and contamination free micro milling of ceramic as well as metallic powders. The equipment accepts dry samples as well as samples in suspension form. Samples as large as 200 micron particle size can be reduced to materials of extreme fineness (less than 1 micron).Micro Milling is carried out by rolling of the balls on material as well as frequent ball impact within milling media.The sample is fed in the pot along with balls of suitable material and the pot is made to rotate on P.U. coated support rollers. The pot rotational speed can be varied in the range of 20 to 200 rpm. Pot rotates about its axis, while the balls inside the pot spin about their own axis in the same direction, the material gets trapped between the inner wall of bowl & balls and gets rolled over by weight of balls .

Screener:
Screeners sort raw materials into different particle sizes, ensuring that only particles of a specific size range are used in the tile production process. A screener in the tiles industry laboratory is a device used to separate and classify materials, such as powders or granules, based on their particle size.

Pressing Machine

The hydraulic press replaced the old, labor-intensive methods of shaping ceramics. One of the main advantages of using a hydraulic press in ceramic production is its ability to apply uniform pressure. Once the ceramic material is loaded into the moulding chamber, hydraulic pressure is applied to the hydraulic cylinders. The hydraulic cylinders exert force on a platen or piston, which presses down on the ceramic material inside the moulding chamber. After the pressing operation is complete and the ceramic material has been formed, the hydraulic pressure is released from the hydraulic cylinders.

Dryer:

Tiles sample were arranged on trays with enough space between them to allow uniform heat distribution. Then the tray were placed in a dryer at 200°C for 2hours. The drying process was carefully monitored to prevent too rapid moisture loss, which could cause cracking. The main goal of drying was to remove the residual moisture from the pressed tile samples, which was necessary to prevent defects during the firing process.

Spray Dryer:

The aqueous suspension of raw material resulting from wet ball milling (solids content ~ 60 to 70 %) is sprayed under pressure to produce fine droplets which contact a stream of hot air. Drying of the droplets produces highly uniform, more or less spherical hollow granules (with a moisture content of typically 5.5 to 7 %).

Tunnel Dryer:

These are essentially a long tunnel structure through which a line of dryer cars loaded with the green ceramic ware is pushed. High temperature air is fed into the tunnel at the discharge end, and this is induced to flow towards the entry end by one or more fans. As the airflows down the dryer, it transfers heat to the product and its humidity content increases.

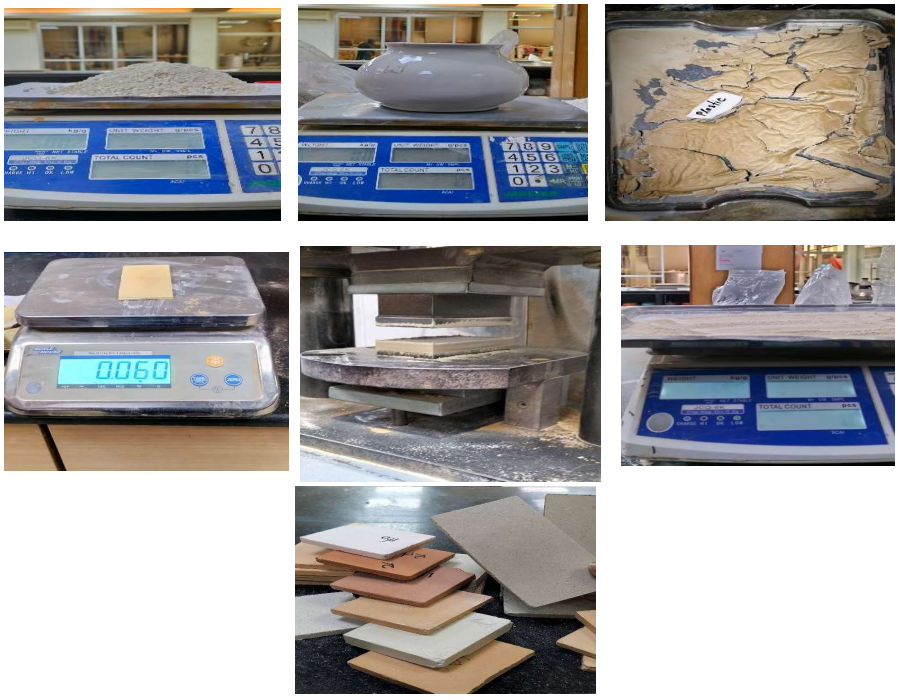


Fig 1 : Experimental Set Up

2.3 Preparation of the Sample

The procedure for manufacturing ceramic tiles involves several key steps. Initially, batching entails mixing various raw materials in precise ratios based on the composition enlisted in Table 1. This process includes batch calculations to determine the appropriate amounts of each material, leading to the preparation of five sample tiles, with one serving as a reference. Subsequently, the weighed raw materials were transferred to a milling jar and grinding was done for several hours. After reaching the desired fineness, the slurry is filtered to separate fine particles from the grinding media. The slurry undergoes initial drying in an oven set to 200°C for 30 minutes, ensuring complete moisture removal. After drying, the slurry is crushed using a hand roller or blender, followed by sieving to ensure desired fineness and uniform particle size distribution of the raw materials. Then pellet shaped samples were prepared by pressing method using 100 to 500 MPa pressure. The as-prepared tile samples are then arranged on trays with adequate spacing and subjected to drying in a 200°C oven for two hours, with monitoring to prevent rapid moisture loss that could lead to cracking. Finally, the dried tile samples are placed on kiln shelves, ensuring they are arranged flat and stable to prevent warping or sticking. The kiln is initially heated to 200°C and gradually elevated to a peak temperature of 1200°C to 1300°C, maintained for two to three hours, before slowly reducing to room temperature. Once cooled, the tile samples are carefully removed and prepared for testing.

Table1: Composition of prepared tiles samples.

Sample No	Malaysian Plastic	alaysian Semi Plastic	Sylhet Clay	Chitka Clay	Thai Soda	Potash Feldspar	Binder	Wastage
01	10	15	5	5	60	5	0.45	Nill
02	10	15	5	5	57	5	0.45	3
03	10	15	5	5	55	5	0.45	5
04	10	15	5	5	50	5	0.45	10
05	10	15	5	5	45	5	0.45	15

RESULTS AND DISCUSSION:

3. Characterization of tiles raw materials

3.1 Characterization of raw materials

3.1.1.Chemical composition

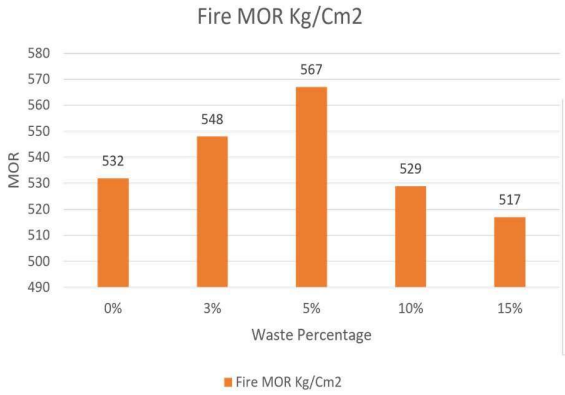
The chemical composition of raw materials was determined using XRF as shown in Table 2.

Table 2. Chemical composition of raw materials XRF

Main Components	Plastic Clay	Semi Plastic Clay	Soda Feldspar	Potash Feldspar Chips	Chitka Clay	Sylhet Clay
SiO_2	<68.0%	≤54.0	67.98	67.20	65.61	70.86
Al_2O_3	>20.0%	≥33.0	15.06	18.35	20.37	19.82
TiO_2	<1.0%	≤1.0	0.55	1.25	1.02	0.98
Fe_2O_3	<2.3	≤1.3	1.47	NIL	7.44	4.11
CaO	<0.5	≤0.5	3.06	0.50	0.74	0.32
MgO	>0.8	≤0.5	1.29	0.02	0.72	0.56
K_2O	>1.4	≥1.2	2.62	8.05	2.80	2.62
Na_2O	<0.5	≤0.2	7.45	0.65	0.63	0.40
Li_2O			<0.1			

MnO			<0.01	0.11	0.04
P_2O_5				0.15	0.09
Cr_2O_3				0.02	0.02
ZrO_2				0.06	0.06
SrO				0.01	0.004
ZnO				0.04	0.02
SO_3				0.28	0.11
LOI at 950℃	<10.5	≤15.0	0.53		
MOR (kg/cm^2)	>45	>18			
CR (63μm)	<6.0%	≤10.0			
FS @1200℃	7-11 %	8.0-12.0			
WA @1200 ℃	<6.0%	≤11.0			
FC@1200℃	>73.0 point				
WI@1200℃	>25 point				
Moisture	Max 35.0%				

The trash-broken floor tile's composition, as determined by XRF analysis, is mostly composed of silica (SiO_2) and alumina (Al_2O_3), two prevalent ingredients in ceramics[14]. A large percentage of silica indicates that the tiles are in a glassy or vitreous phase, and alumina adds to their overall strength and longevity. Iron (Fe_2O_3), titanium (TiO_2), potassium (K_2O), sodium (Na_2O), magnesium (MgO), calcium (CaO), and loss on ignition (LOI) are some of the other minor components that have been found like general floor tiles broken raw materials[15][16][17]. The presence of volatile compounds, such as carbonates or organic materials, which may have been introduced during the manufacturing process or by weathering, is indicated by the LOI value. Additionally, the investigation shows that the burnt tiles had a relatively low water absorption rate, which is advantageous for ceramic materials because it improves resistance to moisture-related damage. The comparatively high whiteness index indicates that the tiles are light in color, which is frequently desired for flooring applications.Overall, the XRF results point to the broken floor tile debris as a viable raw material for ceramic products, especially those that need to be strong, long-lasting, and water-absorbent-low. However, additional research and testing would be required to ascertain its particular applicability for various applications and to improve the processing conditions.



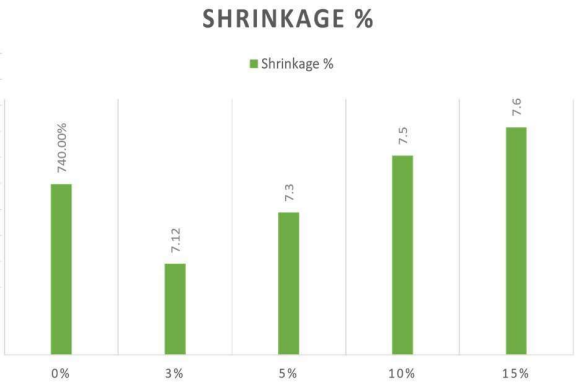
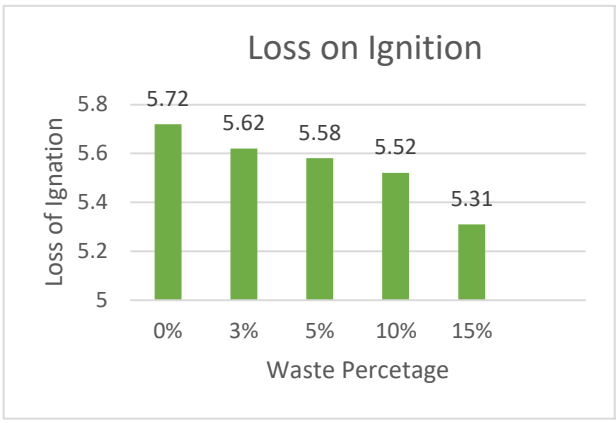


Fig.2. Comparison of strength (MOR) of the samples.

Fig.3. Comparison of Shrinkage of waste added sample



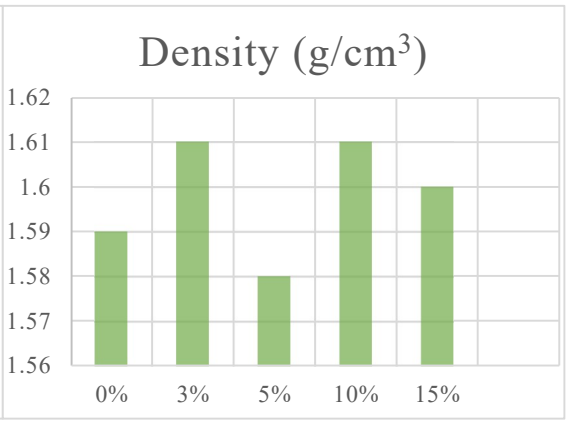
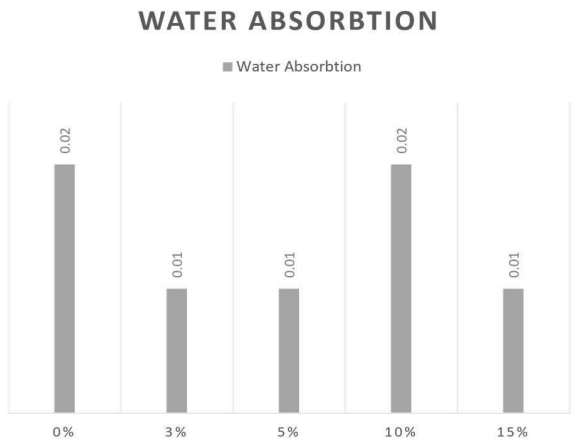


Fig.4. Comparison of Loss on Ignition of samples

Fig.5 Comparison of Density of waste added sample



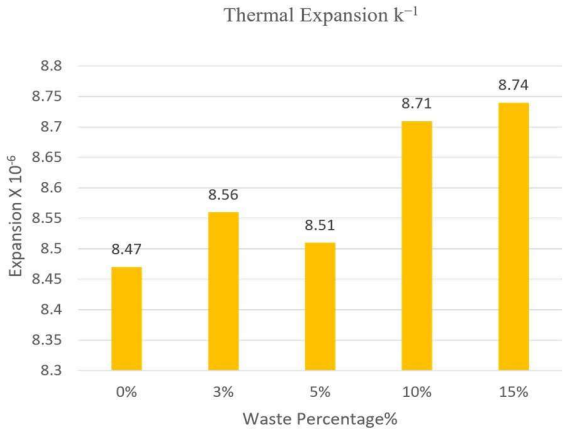


Fig.6. Comparison of Water Absorption samples

Fig.7. Comparison of Thermal expansion of samples

Modulus of Rupture (MOR):

MOR increases with increasing temperatures and waste addition. The modulus of rupture (MOR) of samples with different waste contents is compared in figure 2. The material's bending strength, or MOR, was evaluated for samples containing 0%, 3%, 5%, 10%, and 15% waste. 0% waste carrying sample tiles(generic tiles) has MOR value of 532 kg/cm^2 .As the waste percentage increases to 5%, the fire MOR initially increases from 532 kg/cm^2 to 567 kg/cm^2, where as from 5% to 15%, the fire MOR gradually decreases from 567 kg/cm^2 to 517 kg/cm^2. . In contrast, MOR has slightly increased between 0% and 3% of waste content. The results indicated that increasing the waste addition causes an increase in strength due to the improvement of densification rate when increasing the firing temperature and waste addition. Increasing firing temperature is preferred to produce a liquid phase due to the fusion of particle waste that forms a boundary with the basic mixture of floor tiles.[16] The following equation shows the calculation of MOR respectively.

$$MOR = \frac{3FL}{2bh^2}$$

Where F is the breaking load (N), L is the span between the supporting rods (mm), b is the width of the tile at the broken edge (mm) and h is the minimum thickness of the tile (mm). According to the International Standard (ISO 13006), the mechanical properties of ceramic tiles depend on the values of breaking strength and modulus of rupture. The minimum values of breaking strength and modulus of rupture depend on the thickness of the ceramic tile. Figure 2 shows the modulus of rupture for specimens containing different percentages of floor. Commercial floor tiles have an average modulus of rupture of greater than 580 kg/cm2 . It is accurate to state that the inclusion of ceramic waste results in an increase in the rupture modulus required for floor tiles. According to ISO 13006, floor tiles must achieve an MOR greater than 560-580 kg/cm^2. While the study demonstrates improvement with waste incorporation, one of the samples met the commercial threshold, suggesting further optimization is required.Waste addition between **3%-5%** provides the best trade-off between sustainability and mechanical performance. Overall, it reveals a nonlinear relationship between waste percentage and fire MOR. While a moderate amount of waste can improve resistance, excessive waste can diminish it. This suggests that there is an optimal waste percentage that maximizes the fire MOR of floor tiles.

Shrinkage:

The linear firing shrinkage (LFS) is determined according to ASTM C326-03 using the following equation:[12]

$$\text{LFS\%} = \frac{L_d - L_f}{L_d} \text{ X } 100$$

Where L_d and L_f are dried and fired specimens respectively .0% waste carrying sample tiles(generic tiles) has Shrinkage value of 7.40% .The shrinkage percentage initially drops from 7.40% to 7.12% as the waste percentage rises from 0% to 3%. But although the waste percentage keeps going up from 3% to 15%, the shrinkage percentage goes up from 7.12% to 7.6% with time. With a shrinkage percentage of 7.4%, the sample that had no trash added had the lowest. Shrinkage values ranging between 7% and 10 % are the best for the production of medium-to-high tension porcelain and medium-grade earthenware.[17] There is some non-linearity in the exact relationship between waste addition and shrinkage, fig- 3 generally indicates that adding waste to the samples causes more shrinkage. This implies that a tiny amount of waste can be added to lessen the material's shrinkage[18] also the shrinkage properties of the material may be adversely affected by the addition of excessive trash.

Water absorption :

Water absorption (WA%) has been calculated according to ASTM C373[13] using the following equation

$$\text{WA\%} = \frac{M_w - M_f}{M_f} \text{ X } 100$$

Where M_f and M_w are the mass of the absorbed water by the fired specimens and the mass of fired specimens respectively. 0% waste carrying sample tiles(generic tiles) has WA value of 0.01 .The water absorption is comparatively steady, averaging 0.01 when the waste percentage rises above 3%. This suggests that the water absorption characteristics remain mostly unaffected by the addition of additional trash In comparison to the lower percentages, there is a modest increase in water absorption at 10% waste. The results of our experiment show that the water absorption value is just 0.01–0.02 kg/m^3, illustrated in figure 6 indicating that ceramic waste can produce significantly denser tiles. The average water absorption value for waste used in wall tiles is less than 0.22 wt% of total body weight[16].Changes in the material's microstructure or the creation of new pores could be the cause of this. This experiment demonstrates that adding a small quantity of trash to floor tiles can boost their water resistance. Raising the waste percentage, however, does not provide any further advantage beyond a certain point and may even slightly increase water absorption.

Density:

The density of 0% waste carrying sample tiles (generic tiles) is 1.59 which first rises to 1.61 as the waste percentage increases from 0% to 4% and falls from 1.61 to 1.60 when the waste percentage rises from 4% to 16%. This implies that the density of the material can be raised by adding a tiny quantity of waste whereas adding too much waste may have a detrimental effect on the material's density characteristics. The sample's density increases as the amount of ceramic waste added rises from 0% to 3%. This might be explained by elements like structural alterations in the material or cavities created by adding ceramic debris also the leftover ceramic material has a higher density than the original. The density progressively rises from 5% to 15% of ceramic waste adding. Figure 5, in summary, demonstrates a non-linear relationship between density and the addition of ceramic waste .This suggests that although the effect is not as great as it was initially, the volume of ceramic debris is still influencing the sample's overall density. The physical properties of the tiles are comparatively good with the addition of ceramic waste. After adding ceramic waste, the pattern becomes more complex, with both increases and drops in density. Comparison says A waste addition between **3%-5%** strikes a balance, enhancing density without causing structural compromises . Evaluating recycled aggregates in tile production, this study found that low waste content densified the material matrix, while high waste levels introduced porosity and reduced overall density(Gonzalez-Corrochano et al.) Aligns with the nonlinear relationship observed, emphasizing the balance between waste addition and structural integrity.

Loss on Ignition (LOI):

The higher LOI values in the waste-added tiles suggest a higher organic content or the presence of other volatile materials in the waste. Adding floor tile waste to normal tile composition leads to a significant increase in Loss on Ignition (LOI).When a sample is heated to a particular temperature, the proportion of volatile stuff that is lost is known as the loss on ignition (LOI). It is evident from the graph that: "0%" indicates that containing no waste sample has the highest LOI. This indicates that its volatile matter content is the highest. Sample "15%" is the one with the lowest LOI. Its low volatile matter percentage is indicated by this. As the label gets thinner, the samples' LOI goes up. This indicates a higher percentage of volatile materials in the samples with lower labels. Figure 4, taken as a whole, indicates that the LOI of the various waste samples differs significantly. When using recycled construction materials, LOI values decreased with waste addition due to the pre-processed or pre-heated nature of waste components. Aligns with the observed trend in this study, reinforcing the idea that pre-fired or stabilized waste materials contribute to reduced LOI. (Gonzalez-Corrochano et al).

Thermal Expansion :

Thermal expansion increases in tandem with the waste percentage, which rises from 0%(containing no waste) to 15%. In other words, materials with greater waste percentages expand more than those with lower waste percentages when heated. For instance, the drop in waste between 0% and 3% is more noteworthy than the drop in waste between 10% and 15%. Particular values at 0% Waste expansion coefficient of $8.47\times10^{-6}k^{-1}$, coefficient of expansion $\approx 8.565\times10^{-6}\,k^{-1}$ at waste 3% and expansion coefficient is $8.51\times10^{-6}\,k^{-1}$ at 5% waste, Coefficient of expansion is $8.71\times10^{-6}\,k^{-1}$ at 10% waste: Coefficient of expansion $\approx 8.74\times10^{-6}\ k^{-1}$ at 15% waste. For the manufacturing of tiles, the typical thermal expansion coefficient ranges from $7.3\times10^{-6}\ k^{-1}$ to $8.7\times10^{-6}\ k^{-1}$ [18]. The thermal expansion coefficient typically decreases as the waste percentage rises shown in figure 7. This indicates that, in comparison to samples with lower waste content, samples with higher waste content often

expand less when heated. Thermal expansion does not decrease linearly. For various waste percentages, the rate of decline varies. We can state that the inclusion of ceramic waste does not affect the thermal qualities of the tile product because the thermal expansion coefficient value is within the standard range. Figure 7 indicates that the samples' ability to expand thermally can be decreased by adding wastage to them. Research on tile production using fly ash showed that the thermal expansion coefficients increased due to the waste material's composition, yet remained within the acceptable range of 7.0×10^{-6} K^{-1} to 8.7×10^{-6} K^{-1}. (Karaman et al0 The findings corroborate the current study, suggesting that waste content slightly modifies thermal expansion without compromising thermal performance

4.Conclusion

In this study, we investigated the feasibility of incorporating recycled floor tile waste into the production of new tiles. The XRF and other analyses of the waste material revealed that it primarily comprised silica (SiO2) and alumina (Al2O3), along with minor quantities of other oxides. By incorporating varying percentages of floor tile waste into the tile production process, we were able to addition of 3-5% of waste product to showcase maximum strength, durability, water absorption, etc. mechanical properties. These findings suggest that recycled floor tile waste has the potential to be a viable and sustainable alternative to virgin raw materials in tile production. However, further research is warranted to investigate the effects of different processing parameters, such as firing temperature, cooling rate, and particle size distribution, on the physical and mechanical properties of the resulting tiles. Additionally, exploring the use of additives or binders to enhance the compatibility between the recycled waste and the other raw materials could improve the overall quality and performance of the produced tiles. Furthermore, it would be beneficial to conduct life cycle assessments (LCAs) to evaluate the environmental impact of using recycled floor tile waste in comparison to traditional ceramic tile production methods. This would provide valuable insights into the sustainability benefits of incorporating waste materials into the manufacturing process.

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