International Journal of Engineering Trends and Technology
ISSN: 2231 – 5381 / https://doi.org/10.14445/22315381/IJETT-V70I4P237
Volume 70 Issue 4, 433-456, April 2022

Original Article

Fabrication and Property Characterization of Expanded Perlite-Based Tile

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Received: 15 March 2022 Revised: 05 April 2022 Accepted: 06 April 2022 Published: 30 April 2022

Abstract - *Conventionally, wall tiles are made up of earthenware clay manufactured by baking or firing for decoration and indoor applications only not exposed to weather elements as it cannot resist the ill effects of wind, rain, and direct sunlight; thus, cannot be used for outside installation and wall protection. Considering the intense heat, moisture, wind, pollution, and rain brought about by climate change, and wall protection is necessary through wall cladding installation. However, a functional substitute for traditional tile composition and manufacturing is essential for a sound and quality wall cladding material. In this paper, an expanded perlite-based tile was fabricated and evaluated its properties. An optimum mixture proportion was designed by combining 7 grams of fine expanded perlite aggregates, 100grams of Portland cement, 4 grams of sodium silicate, and 50grams of water, all by mass, which yields the maximum compressive strength for the production of expanded perlite-based tiles for wall cladding system with a dimension of 610mm x 305mm x12.7mm. The physical and mechanical properties of the expanded perlite-based tile were evaluated based on ASTM standards. Results indicated that the tile is non-vitreous and suitable for wall cladding, and water absorption value can be controlled through glazing. The expanded perlite-based tile is lighter than conventional tiles, has high breaking strength when glazed, and has low thermal conductivity. Finally, the cost of one unit of expanded perlite-based tile amounted to Php108.38.*

Keywords - *Expanded Perlite, Expanded Perlite-Based Tile, Mortar Tile, Sodium Silicate.*

1. Introduction

Tiles are no longer considered new in the art world due to their aesthetic worth and qualities. Tiles have been employed for aesthetic purposes in temples and other structures since around 4000 BC when the Assyrians and Babylonians used them. Tiles have been used in many different places worldwide over the years. Ceramic tile, also known as non-porcelain tile or porcelain tile, is a type of burned clay tile used for interior and exterior decorating. Since they were initially introduced and used, both the process and the materials used to make tiles have substantially advanced. Ceramic tiles that have been glazed and vitrified are made by firing a particular white clay at 1200°C before applying the glaze. Previous studies have revealed various methods for making ceramic tiles for interior and exterior decorative purposes by baking or firing them. For example, by firing a glass composition, Barattini, Bertocchi, Burzacchini, and Neri (2003) constructed a ceramic tile and glazed it for use on it. The firing procedure is used in this traditional method of making ceramic tiles. The ceramic tile's porous body of the baked or burned earthenware clay component was still treated with a glazing substance to achieve a fine ornamental surface. Minerals, plant life, and animals from the ground are pulverized by water pressure in regions where streams or rivers historically ran to make earthenware clay. Because most clays are appropriate for agriculture, earthenware clay is difficult to come by nowadays, making it expensive. And, to save money, clay cannot be converted into ceramic tiles for indoor or outdoor use without batch firing or hot pressing. Carbo, Hacker, Byers, and Cimaglio (2016) produced an acoustical tile with a core and surface treatment by heat exposure, but this technique resulted in quantifiable formaldehyde emissions.

Furthermore, patent number CN1094115C is an acoustic tile and panel for roofs made of expanded perlite, cellulosic fibre, and optionally mineral wool produced by a water-felting technique. This acoustical tile is intended for indoor use only; despite its low weight, it should not be exposed to the outdoors as it is quickly damaged.

With time, tile wall cladding has evolved into an important aspect of architecture and engineering, notably structural design. When ceramic facades became popular in the early twentieth century, the Babylonians utilized the first tile wall covering constructed of ceramics in nearly 2600 years. The cladding has withstood fluctuations in temperature and atmospheric attack for over a century. The EP2279309B1 patent covers a technique of cladding with tiles for floors, walls, ceilings, and other types of flat, undulated, or mixed surfaces that are horizontal, vertical, or inclinations for interior use. Because tile wall cladding does not require as much cutting as other wall cladding. A nonporous vitreous wall cladding tile with an integral peripheral undercut attachment flange is produced by vacuum forming the tile to the desired shape from molten or plastic sheet and then trimming the article to form an inwardly-extending peripheral flange providing a locking undercut recess of reverse angle, according to patent number 3528791. This tile can be used indoors and outdoors; however, it should not be exposed to the sun or rain.

In terms of the materials used, production methods, and installation methods, wall cladding as a building wall protection has evolved globally over the centuries. According to Grand View Research, Inc. (PRNewswire, 2017), the worldwide cladding industry is expected to reach USD 111.1 billion by 2025, as demand for greater moisture conservation and energy efficiency of building exteriors develops. The building industry has a significant demand (Wall Cladding Solutions, n.d.). Indeed, with an annual average wind speed of 4 km/h, mean annual precipitation of 244.42 mm (www.climatestotravel.com), mean annual rainfall of 978mm (bagongpag-asa.dost.gov.ph/information/climate-Philippines), and the highest temperature of 42.2oC recorded on April 21, 2019, exterior wall cladding exposed to the elements is an important consideration in building construction in the Philippines (CNN Philippines Staff, 2019). More tropical cyclones (TCs) enter the Philippine Area of Responsibility (PAR) than anyplace else in the globe, according to the Department of Science and Technology's Philippine Atmospheric Geophysical and Astronomical Services Administration (2019). An average of 20 tropical cyclones per year reach the PAR, with roughly 8 or 9 passing over the Philippines. The typhoon season peak from July to October, when roughly 70% of all typhoons form. Typhoon Mangkhut was the most powerful, with sustained winds of more than 165 mph and gustiness of nearly 200 mph, making it the equivalent of a Category 5 hurricane (Cappucci, 2018). Walls exposed to a lot of wind-driven rain, such as during typhoons, need to be covered with wall cladding. It protects walls from the heat, moisture, wind, pollution, and rain brought on by climate change, all of which have a negative impact on the building's exterior wall. As an outer finishing layer, it optimizes thermal and environmental performance while keeping undesired outdoor elements at bay, according to Radhi (2014).

Thus, regardless of today's wall cladding system trends for modernism, lightweight tile wall cladding made from natural raw minerals remains appealing to homeowners. The researcher was inspired by previous research on perlite-sodium silicate technology to investigate the possibility of developing a tile for wall cladding made from a mortar of expanded perlite aggregates, Portland cement, sodium silicate, and water reinforced with wire mesh for indoor and outdoor installations with improved water-resistance, durability, and functionality without the need to be heated.

In this light, the researcher saw the potential of utilizing the perlite ore in the Bicol Region. According to Torres et al. (2015), one of the country's regions with rich mineral reserves of perlite is the Bicol Region. Its unique geological setting characterized by the number of volcanoes on the mainland contributes to its abundance of mineral deposits. Sixty-nine per cent of the perlite reserve in the region can be found in Baao, Camarines Sur, and the remaining reserves can be found in Legazpi City. The active perlite mines are being operated by UBS Marketing Corporation (276.23 hectares) in Legazpi City and Orophil Stonecraft, Inc. (205.27 hectares) in Baao and Iriga City Camarines Sur. Through environmental protection, proper management, and the goal of reducing waste, there could be the sustainability of perlite ore in the quarry owned by the Orophil Stonecraft, Inc. in Antipolo, Baao Camarines Sur. Since its first year of operation in 2006, the company has maintained an established mining system geared toward sustainable production of perlite. Based on DENR Mines and Geosciences Bureau (2019), Orophil Stonecraft, Inc. has 141.1418 hectares of perlite, bentonite, and other associated mineral deposits in the quarry for mining.

2. Methodology

This study employed an experimental research design to characterize the expanded perlite-based tiles' physical and mechanical properties. The experimental method attempts to maintain control over all independent and dependent variables that may affect the result of the experiment by attempting to determine or predict what may occur (Leedy, 1997). This method is also aimed at tracing any relationship between the two variables. In this case, the physical properties of the expanded perlite and Portland cement were characterized, physical and mechanical properties of the expanded perlite-based tiles were also determined.

2.1 Project Development

The flow diagram of the fabrication and property characterization of the expanded perlite-based tiles is shown in Figure 1. The materials to be used were gathered in the preparation phase, and the needed particle size of expanded perlite aggregates was selected.

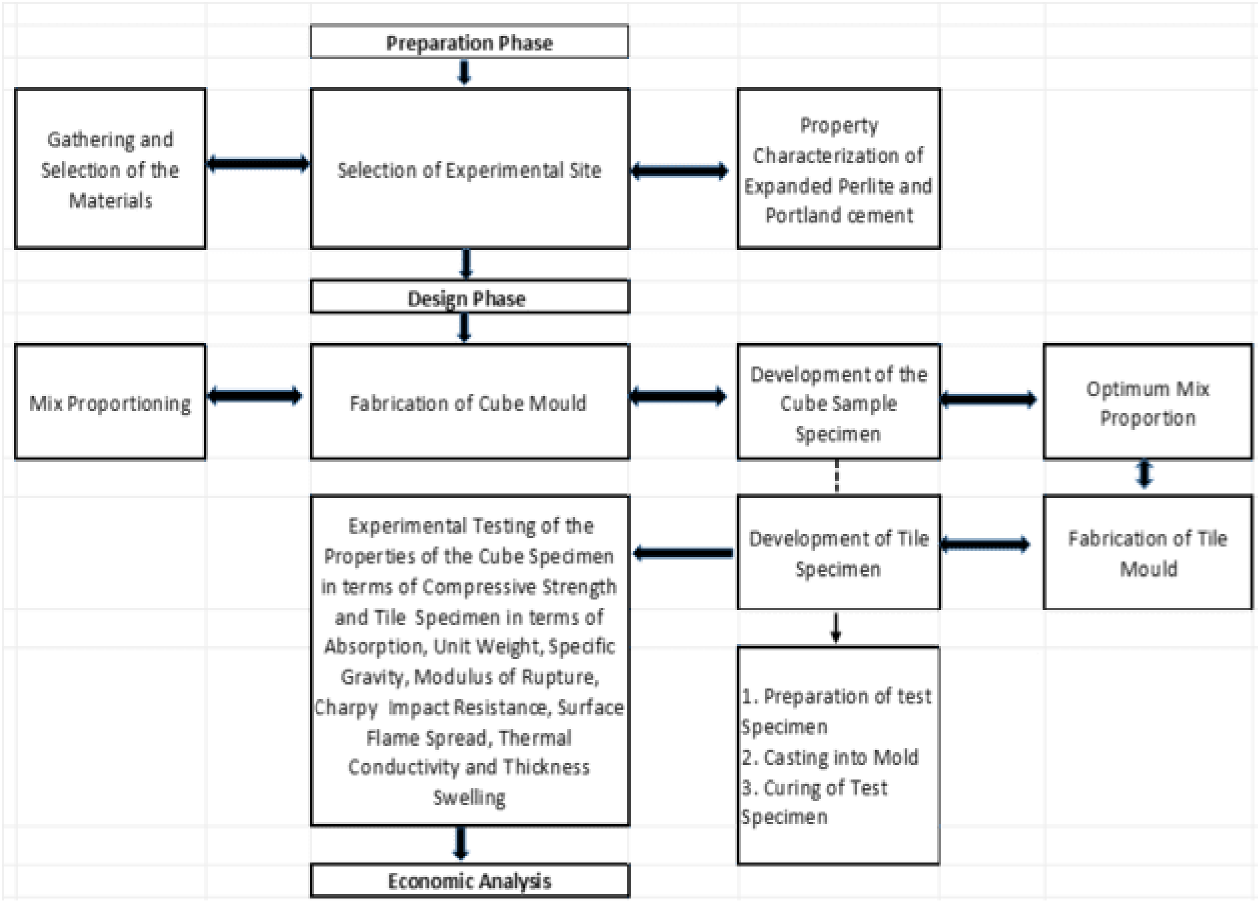


Fig. 1 Flow diagram of the fabrication and property characterization of expanded perlite-based tile

Tools, apparatuses, and equipment were also prepared, ideal sites for experiments were selected, and expanded perlite and Portland cement property characterization were conducted. In the design phase, trial mix proportioning of mortar was done to determine the optimum design mixture. The 50mm cube mould was also fabricated, and cube sample specimens were cast into the mould. After a 7, 14, and 28 days curing period, the compressive strength test of the cube specimen was conducted to determine which among the trial mix proportions yields the highest compressive strength for the fabrication of tiles. Then, the tile mould fabrication and the tile specimen's development were conducted. In the experimental phase, the physical and mechanical properties of the tile specimen were tested for water absorption, unit weight, specific gravity, impact resistance and modulus of rupture, surface flame spread, thermal conductivity, and thickness swelling.

2.2 Mix Proportioning

Fine and medium-sized expanded perlite aggregates without sand aggregates were tested for the initial phase of the experiment, as provided in Table 1a. Also, fine and medium-sized expanded perlite aggregates with sand were tested in the second phase of the experiment, as provided in Table 1b. In the initial phase of the experiment, three cube sample specimens were made for each mixture proportion of sodium silicate/cement (SS/C) ratio of 0.04, 0.05 and 0.06 to determine the average compressive strength with a total of nine (9) cube specimens for each expanded perlite/cement (EPA/C) ratio of 0.07, 0.08 and 0.09. Twenty-seven (27) cube sample specimens were made using fine-sized expanded perlite aggregates for the trial mixture proportions without fine sand aggregates. Twenty-seven (27) cube sample specimens were made using medium-sized expanded perlite aggregates.

The SS/C ratio and the EPA/C ratio in Table 1a were based on the following related studies. From the study conducted by Wang, Sun, Zhang, and Wang (2018) on the effect of sodium silicate on Portland cement, calcium aluminate cement, and gypsum rich-water, it has resulted that if the content of sodium silicate is above 3%, the early strength of rich-water materials increases and there was long term strength retrogression. This was confirmed by the study of Kubba, Hewayde, Huseien, Sam, and Asaad (2019) that the compressive, tensile, and flexural strengths of multi-blend geopolymer mortars increase with the increase of sodium silicate.

In the study of Ali (2019) on the effect of aqueous sodium silicate on the properties of recycled aggregate mortar, it was concluded that the recycled aggregate mortar with 2-3% sodium silicate shows 4-9% higher compressive strength than the natural aggregate mortar and if it has 2-4% sodium silicate content shows acid attack resistance. The researcher adopted this; 4%, 5%, and 6%

sodium silicate by mass of Portland cement content in the mixture were used. The water-cement ratio in this study was based on Singh and Thammishetti's (2015) study on the effect of water/cement ratio on the mechanical properties such as compressive and split tensile strength of cement mortar cylinder and cube experimentally for 28 days. In their study, the increase in water/cement ratio decreased cement mortar's compressive and split tensile strength. Moreover, it was observed that the minimum water-cement ratio required to make the cement mortar workable is 0.5. This was adopted in this study, and a constant water-cement ratio of 0.5 was used.

Table 1.a. Mixture Proportions of Samples Using Fine and Medium-Sized Expanded Perlite Aggregates Without Fine Sand Aggregates

Mixture	**EPA/C**	**W/C**	Ordinary Portland Cement (g)	**Expanded Perlite Aggregates (g)**	**Sodium Silicate (g)**	**Water (g)**
Fine-sized Expanded Perlite Aggregates						
Mix 1 F		0.05	100	7	4	50
Mix 2 F	0.07	0.05	100	7	5	50
Mix 3 F		0.05	100	7	6	50
Mix 4 F		0.05	100	8	4	50
Mix 5 F	0.08	0.05	100	8	5	50
Mix 6 F		0.05	100	8	6	50
Mix 7 F		0.05	100	9	4	50
Mix 8 F	0.09	0.05	100	9	5	50
Mix 9 F		0.05	100	9	6	50
Medium-sized Expanded Perlite Aggregates						
Mix 10 M		0.05	100	7	4	50
Mix 12 M	0.07	0.05	100	7	5	50
Mix 13 M		0.05	100	7	6	50
Mix 14 M		0.05	100	8	4	50
Mix 15 M	0.08	0.05	100	8	5	50
Mix 16 M		0.05	100	8	6	50
Mix 17 M		0.05	100	9	4	50
Mix 18 M	0.09	0.05	100	9	5	50
Mix 19 M		0.05	100	94	6	50

The laboratory experiments conducted by the researcher using various percentages of expanded perlite aggregates showed that the mixture with 8% of expanded perlite aggregates produced the highest compressive strength. And so, 7%, 8%, and 9% expanded perlite by mass of Portland cement were adopted. A constant of 100 grams of Portland cement was used to produce trial mixture proportions. The mass of water is 50grams computed based on the water-cement ratio of 0.50. Various percentages of expanded perlite and Portland cement were mixed using mechanical mixing until a uniform colour was achieved. Half of the computed amount of water was added and mixed thoroughly for about 3 minutes using a mechanical mixer. Another half of the water was then added and mixed thoroughly for about 5 minutes before adding sodium silicate. Then mix again for about 4 minutes.

In the second phase of the experiment, as provided in Table 1. b, the same amount of Portland cement and sodium silicate content was used. However, a Portland cement- aggregates ratio of 1:1 for each mixture proportion was used. For every 100 grams of Portland cement, 100 grams of fine and medium-sized sand and expanded perlite aggregates were also used. And so, 5%, 10%, and 15% of expanded perlite aggregates and 95%, 90%, and 85% of fine sand aggregates, respectively, were used in the mixture. The total amount of water used was based on the study of Ali (2019), in which the initial amount of water was based on 50% of Portland cement mass, then added with the amount of water depending on the fine aggregates' absorption capacity. The fine aggregates used are fine sand and expanded perlite.

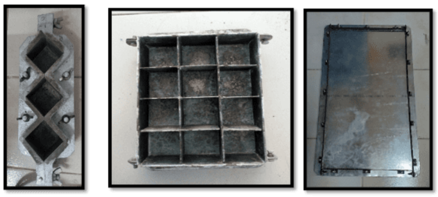
Table 1.b. Mixture Proportions of Samples Using Fine and Medium-Sized Expanded Perlite Aggregates With Fine Sand Aggregates

Mixture	Ordinary Portland Cement (g)	**Fine Sand Aggregates (g)**	**Expanded Perlite Aggregates (g)**	**Sodium Silicate (g)**	**Water (g)**
Fine-sized Expanded Perlite Aggregates					
Mix 1 F	100	90	10	40	82
Mix 2 F	100	90	10	50	81
Mix 3 F	100	90	10	60	81
Mix 4 F	100	95	5	40	72
Mix 5 F	100	95	5	50	72
Mix 6 F	100	95	5	60	71
Mix 7 F	100	85	15	40	91
Mix 8 F	100	85	15	50	91
Mix 9 F	100	85	15	60	90
Medium-sized Expanded Perlite Aggregates					
Mix 10 M	100	90	10	40	71
Mix 12 M	100	90	10	50	70
Mix 13 M	100	90	10	60	70
Mix 14 M	100	95	5	40	67
Mix 15 M	100	95	5	50	66
Mix 16 M	100	95	5	60	66
Mix 17 M	100	85	15	40	74
Mix 18 M	100	85	15	50	75
Mix 19 M	100	85	15	60	73

Water absorption of fine and medium-sized expanded perlite aggregates was determined first. Fine-sized expanded perlite aggregates have higher water absorption capacity than medium-sized expanded perlite aggregates. This resulted in a large amount of water added to the mixture proportions with fine expanded perlite aggregates compared to the medium-sized expanded perlite aggregates. Twenty-seven (27) cube specimens were made using fine-sized expanded perlite aggregates for the trial mixtures. Twenty (27) cube specimens were also used for trial mixtures, using medium-sized expanded perlite aggregates with fine sand. The cube specimens were tested for compressive strength after 28 days of curing by soaking in water to produce expanded perlite-based tiles for the wall cladding system.

2.3 Fabrication of Cube and Tile Mold

Cubical metal moulds measuring 50mm on each side were fabricated and used for the sample specimen in the compressive strength test shown in Figure 2a following ASTM C348. The moulds were fabricated using a plain GI sheet and flat bars welded together and fastened by bolts to form a cube. The dimension is 12 inches by 24 inches by 1/2 inch thick for the tile mould. A fabricated plain GI sheet with flat bars and bolts is used as a mould, shown in Figure 2b for the tiles.



(a) (b)

Fig. 2. (a) 12-50mm cube mould made up of welded plain GI sheet; (b) 12 in. x 24 in. x 1/2 in. metal mould for wall cladding tiles

2.4 Development of the Sample Cube Specimen

Fifty-four (54) cube specimens were fabricated for the trial mixtures without fine sand utilizing fine and medium-sized expanded perlite aggregates for each curing period of 7, 14, and 28 days. And also, fifty-four (54) cube specimens for the trial mixtures with fine sand utilizing fine and medium-sized expanded perlite aggregates were prepared for a 7, 14, and 28 days curing period with 324 cube specimens. After applying oil to the inner surfaces of the cube mould, the fresh mortar was cast into the mould shown in Figure 3a. The procedure follows ASTM C109 "Standard Test Method for the Compressive Strength of Hydraulic Cement Mortar (Using 2-in. or [50mm] Cube Specimens)". The cube specimens were removed from the mould after 24 hours and allowed to cure by submerging in water for 7, 14, and 28 days shown in Figure 3b.

(a) (b)
Fig. 3 (a) Casting of Cube Specimen (b) Curing of cube specimen by soaking in water

Compressive Strength. Compressive strength is an important property of wall cladding tile to determine its durability and resistance to impact due to environmental factors as it will expose to the building exterior. This test was conducted following ASTM C109. Three 50mm cube specimens were fabricated for each of the thirty-six (36) mixture proportions utilizing fine and medium-sized expanded perlite aggregates with sand and without sand aggregates, respectively, for the three curing periods of 7, 14, and 28 days. Fine-sized expanded perlite aggregates ranged from 0.074 to 0.420mm, and medium-sized expanded perlite aggregates ranged from 0.420 to 2.00mm. Fine-sized sand aggregates similar to fine-sized expanded perlite aggregates were used as well. A total of 324 cube specimens, as shown in Figure 4a, were subjected to compression testing using the Compression machine shown in Figure 4b at the Department of Public Works and Highways (DPWH) 5th Engineering District Camarines Sur. The actual load was recorded at the sample break in kilonewton (kN) and the compressive strength in megapascal (MPa). The compressive strength in megapascal was computed using the formula for stress in Strength of Materials (Pytel & Singer, 1987):

$$S=F/A \tag{1}$$

where S is the compressive strength in Pascal,
F is the force in Newton applied perpendicular to the cross area, A, in square millimetres.

The compressive strength results were recorded, and the mean compressive strength for each trial mix was computed using the formula:

$$MCS = \frac{\sum compressive strength of 3 specimen}{3} \tag{2}$$

The mean compressive strengths were analyzed and compared. The mixture proportion with the highest compressive strength was considered the optimum design mix for producing expanded perlite-based tiles for the wall cladding system.

(a) (b)
Fig. 4 (a) Cube specimen of 7, 14, and 28 days curing, (b) Compression testing of cube specimen

2.5 Development of Sample Tile Specimen

The optimum design mixture was adopted to prepare tile mortar for the different property tests of the expanded perlite-based tiles. The mould was cleaned and wrapped with a plastic cover so that the fresh mortar would not stick to the mould and the tile would have a glass-like surface. Corners of the mould were pasted with artificial clay so that the water would not leak. After mixing the expanded perlite, Portland cement, sodium silicate, and water thoroughly, the mixed mortar was put half-filled in a tile mould and tamped with a rubber mallet for about 5 minutes to settle the mixture. Wire mesh was laid to provide the needed strength of the wall tiles before adding again with half of the fresh mortar and tamped. Bubbles on top were pricked to remove the voids. After about 5 minutes, the tile's surface was tapped with plastic mesh with a 1-inch square hole. The room temperature was about 25 degrees Celsius, as indicated in Figure 5.

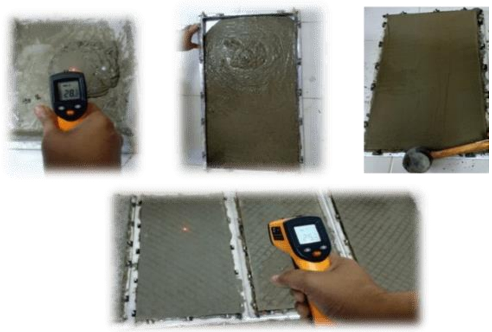


Fig. 5 Casting of expanded perlite-based mortar into tile mould and taking the temperature of the specimen

The specimens were allowed to dry overnight and stripped off from the moulds 24 hours after casting. The specimens were put in the curing tank shown in Figure 6 and submerged for 7, 14, and 28 days. The curing of the specimen is based on ASTM C 192 “Methods of Making and Curing Concrete Test Specimens” in the laboratory.

Fig. 6 The curing of tile specimens by soaking in water

2.6 Physical and Mechanical Property Determination of the Sample Tile Specimen

The tile specimens were subjected to different physical and mechanical property tests to determine their performance, such as water absorption, unit weight, and specific gravity. Charpy impact resistance, modulus of rupture, surface flame spread, and thickness swelling were tested after 28 days of curing. These tests were conducted following the British Standard 476 Part 7 and ASTM standards for materials testing.

2.6.1 Water Absorption

Water absorption is the measurement of a product's density, porosity, and specific gravity. It is used as a tool for identifying the structural properties of the body of the tile, which may be required to determine its use in an application. Tiles are classified according to water absorption percentages shown in Table 3. This test was conducted following ASTM C373 or the Standard Test Method for Determination of Water Absorption of Ceramic Tile to determine the percentage of water absorbed by the tile body in a saturated condition. Five (5) cylindrical representative specimens from the tile mixture with a total measured mass of 250 grams were subjected to a water absorption test. It was subjected to up to 150o C in an oven for 24 hours. It was removed from the oven after 24 hours and allowed to cool. The representative specimens were boiled using a pot while saturated with water for 5 hours to replace air bubbles from the open pores. After 5 hours, the fire was off and immersed in water for 24 hours, then damped with cloth, and the mass was measured again. The water absorption in per cent was calculated using the equation:

$$WA\ (\%) = \frac{m_2 - m_1}{m_1} x100 \qquad (3)$$

where WA is the water absorption in percent;
m2 is the wet mass in gram;
m1 is the dry mass in gram.

Water absorption capacity based on ASTM C373 is summarized in Table 2. The absorption of glazed ceramic wall tile often exceeds 15 per cent, so it is normally non-vitreous. For glazed ceramic floor tile, the water absorption is between 2.0 and 6.0, and so it is normally vitreous or semi-vitreous (Interceramic, n.d.).

Table 2. Water Absorption Classification

Ceramic Tile Body	Water Absorption (%)
Impervious	0.5 or less
Vitreous	More the 0.5 – not more than 3.0
Semi-vitreous	More the 3.0 – not more than 7.0
Non-vitreous	More the 7.0 – not more than 20

(Source: Interceramic, n.d.)

Unglazed ceramic wall tiles with lower absorption rates are easier to maintain because of their resistance to staining. It will not readily absorb grease, food and beverage spills, and other staining agents.

2.6.2 Unit Weight

Unit weight or density determination of expanded-perlite- based tile mortar was conducted using the cylindrical mould. This test follows the ASTM Standards for Unit Weight Determination of Tile Mortar.

The unit weight was calculated using the equation:

$$Unit\ weight = \frac{MMS - MM}{V} \qquad (4)$$

Where the unit weight is in kg/m3;
MMS is the mass of mould and the sample;
MM is the mass of the mould only in kg.

The volume and mass of the cylindrical mould were measured as shown in Figure 7a. After mixing the proportion of Portland cement, expanded perlite, sodium silicate, and water, the fresh mortar was cast into a cylindrical mould, weighed, and recorded the mass. Figure 7b shows the cylindrical mould filled with mortar for the unit weight determination.

(a) (b)

Fig. 7 (a) Weighing the empty cylinder mould and (b) weighing the mould filled with expanded perlite-based mortar for unit weight determination.

2.6.3 Specific Gravity

Specific gravity is the ratio of the mass (or weight in air) of a unit volume of the expanded perlite-based tile to the mass of the same volume of water at room temperature. The specific gravity plays an important role in the weight proportions of concrete mortar and is used to measure the strength and quality of the tile for the cladding system. The unit weight is expressed in kilo Newton per cubic meter computed from the formula

$$\gamma = mg/V \qquad (5)$$

Where γ is the unit weight,
m is the mass of the tile specimen in kilogram,
g is the acceleration due to the gravity constant, which is 9.81 meters per second square and
V is the volume of the tile specimen in a cubic meter

2.6.4 Charpy Impact Resistance

There is no standard for this test of expanded perlite tile specimen. However, based on the study of Thomas and Sorensen (2018) on the Charpy impact test methods for cementitious composites, the minimum dimension of impact test specimens for ceramic fibre-reinforced composite is 10 x 20 x 80mm. In this study, the Charpy pendulum impact machine was also used in the conduct of the test. Four (4) tile specimens, two of which are glazed and two are unglazed, were used in this test. Nine (9) representative cuts of sample specimens from each tile specimen were sawn, measuring 12.7 x 40 x 70mm. There were three (3) horizontally cut sample specimens from the top corner of the tile, three (3) vertically cut sample specimens from the bottom, and three (3) horizontally cut sample specimens from the centre of the tile. A total of thirty-six (36) representative cuts of sample specimens shown in Figure 8a were subjected to the Charpy impact resistance test. Figure 8b shows the Charpy impact testing of representative cut sample specimen placed horizontally across the testing machine. The sample specimen was laid horizontally. The loading was applied through a 26.11 kg pendulum with a distance of 0.6345 meters from the axis to the centre of gravity swung from a given height with swung angle β and lifting angle α. The energy required to break the sample specimen was calculated using the formula:

$$E = PD\,(\cos\alpha - \cos\beta) \quad (6)$$

where E is in J/m2; P is the weight of the pendulum, 26.11 kgs; D is the distance from the axis to the centre of gravity =0.6345 meters; α is the hammer lifting-up angle and
β is the hammer swing-up angle.

(a) (b)

Figure 8. (a) Representative cut sample specimen and (b) Set up of Charpy impact testing

2.6.5 Modulus of Rupture

This test is conducted following ASTM C648-98 or the Standard Test Method for Determination of Breaking Strength and Modulus of Rupture of Ceramic Tiles and Glass Tiles by Three-Point Loading. Breaking strength is measured by applying force to an unsupported tile portion until breakage occurs. This test covers the determination of the breaking strength of glazed and unglazed porcelain and ceramic wall tile. Ceramic tiles used for floors and walls must withstand the expected load-bearing capacity of various installations and must meet greater than 250 pounds of force per square inch (1.72369 MPa) to be considered suitable for use. Four (4) tiles were used in this test, two (2) of which are unglazed and two (2) are glazed. Three (3) representative sample specimens were sawn from each tile, measuring 50mm x 170mm x 12.7 mm totalling twelve (12) cut sample specimens shown in Figure 9a. Three (3) representatives cut specimens from the horizontal corner of the tile, three (3) from the vertical corner, and three (3) from the centre. A manual Compression machine of the TUP Manila IRTC Materials and Testing laboratory was used in this test, as shown in Figure 8b. The specimen was laid horizontally into three-point supports 150 mm apart. The load was applied directly to the centre of the tile specimen at a constant rate until it broke. Figure 9b shows the assembly of the tile onto the machine.

(a) (b)

Fig. 9 (a) Representative cut specimens and (b) Modulus of Rupture test using Manual Compression machine.

The Modulus of Rupture was calculated using the formula:

$$\text{MOR} = \frac{3P\max L}{2bd^2} \quad (7)$$

where P is the maximum load in Newton,
L is the length of span in mm,
b is the width of the specimen in mm and
d is the thickness of the specimen in mm.

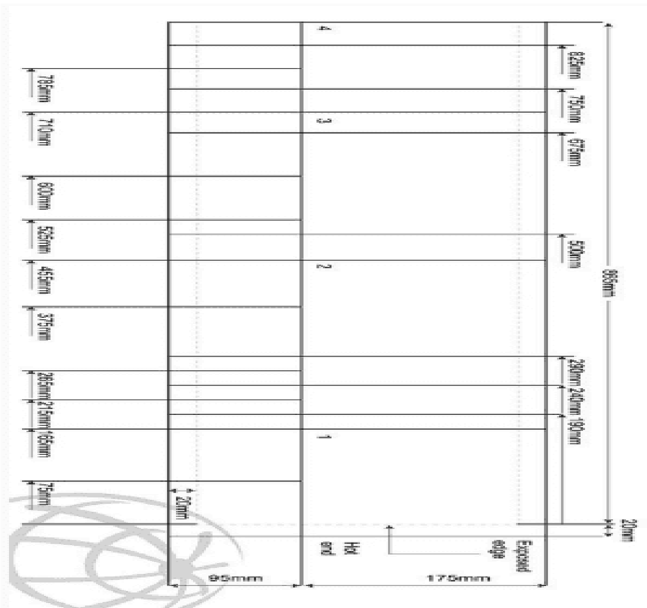
The average energy at the break of the three representative cut specimens was computed and recorded.

2.6.6 Surface Flame Spread

This test was conducted following the standards and procedures in British Standard 476 Part 7 of 1997 or the Fire Test on Building Materials and Structures which is a method or test to determine the classification of the surface spread of flame of products wherein the lateral spread of flame along the surface of the specimen in vertical position is measured.

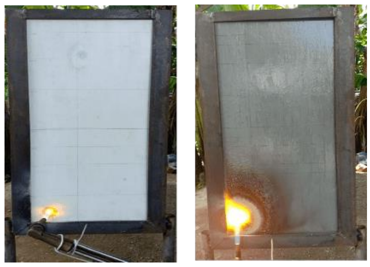
The classification system is based on the rate and extent of flame spread. This fire test method was applied to the tile, which is used for wall cladding, considering that there is no other available suitable testing equipment in the region. This test requires six (6) sample specimens for each type of tile properly removed from the mould after 28 days or more curing period. Six (6) glazed and six (6) unglazed tile sample specimens of size 305mm x 610mm x 12.7 mm were marked vertically on the fair surface with the reference lines of 75mm, 165mm, 190mm, 215mm, 240mm up to 675mm using a visible pen marker after fitting onto the metal holder. As shown in Figure 10, the reference lines were based on armacell.com (https://local.armacell.com/en/armacell-india/know-how/armacell-bs476-part7/) used in testing glass-reinforced panel insulation board. Then, the tile was inserted vertically into a fabricated metal tile holder with a 600mm high stand. The reference lines are the distances on the fair face of tile that the surface flame can reach. Class 1 classification has a flame spread below the 165mm reference line in Figure 10 after the flame stopped at 1.5 and 10 minutes.

A cutting torch connected to the oxy-acetylene tank was used in the tests, as shown in Figure 11. The cutting torch was ignited to a temperature ranging from 255-550oC, and the nozzle was focused on the external fair face of the tile 75mm at a right angle from the tile surface. After 1.5 minutes, the flame was extinguished, and the time and the maximum extent of flame spread vertically were measured and recorded. Then the cutting torch was again ignited to a temperature ranging from 255-550oC, and the nozzle was again focused on the same point on the tile, and the flame was extinguished after 10 minutes. The time and the maximum extent of flame spread vertically on the external fair face of the tile were measured and recorded. The temperature at the back of the tile was also measured and recorded using an infrared thermometer which ranges from 75-100oC.



(Source: https://local.armacell.com/en/armacell-india/know-how/armacell-bs476-part7/)

Fig. 10 Reference lines on the external fair face of the tile specimen



(a) (b)

Fig. 11 (a) The unglazed tile specimen in the tile holder with ignited cutting torch focused on the external fair surface lower left edge, and (b) the glazed tile specimen in the tile holder with ignited cutting torch focused on the external fair surface lower left edge of the tile

This was repeated for the number of tile specimens. The flame spread after 1.5 minutes and 10 minutes was compared with the standard class limits as shown in Table 3, and the classification was assigned.

Table 3. Class Limits of the Surface Flame Spread of the Wall Cladding Tiles

Classification	Class Limits	
	Surface Flame Spread at 1.5 min. (mm)	Final Surface Flame Spread (mm)
Class 1	165 (+25)	165 (+25)
Class 2	215 (+25)	455 (+25)
Class 3	265 (+25)	710 (+25)
Class 4	Exceeding Class 3 Limits	

2.6.7 Thermal Conductivity

This test was conducted to determine the thermophysical property of the expanded perlite-based tile for the wall cladding system following Fourier's law for the one-dimensional steady-state conduction method. The thermophysical property is characterized by the material's capability to store or transfer heat energy. Www.EngineeringToolbox.com defines thermal conductivity as "the quantity of heat transmitted through a unit thickness of a material- in a direction normal to a surface of the unit area- due to a unit temperature gradient under steady-state conditions". A lower thermal conductivity value means lower heat energy conducted by the building material. Glazed and unglazed tiles were prepared for the thermal conductivity test. Three (3) incandescent light bulbs of 50W were used as heat sources. The 50W bulb was first used for the 50W heat energy, followed by the two (2) bulbs and three (3) bulbs for the 100W and 150W energy, respectively. The temperature inside the aluminium-glass chamber was first measured using the infrared thermometer shown in Figure 12a. Then the bulb was lighted inside through the 220-240 current-voltage connection. The tile specimen was sandwiched between the heat source and the heat sink inside the closed aluminium-glass chamber, as shown in Figure 12b allowing the heat flow to exist perpendicular to the surface of the specimen from the hot face to the cold one. The closed aluminium-glass chamber was insulated to ensure that no heat would escape from the chamber. The temperature of the glazed and unglazed tile specimen at the heat source and heat sink was measured after 5 minutes for 1 hour each and recorded. Similarly, the same procedures were done for 100W and 150W heat energy, as shown in Figure 12c and Figure 12d, respectively. The thermal conductivity of the tile specimens was calculated using the equation,

$$K = QL/(A(t_h - t_c)) \quad (8)$$

Where: k = material's thermal conductivity in W/m.K

L = thickness of specimen at test temperature in m.

A = cross-sectional area of specimen in sq.m.

th = temperature of the tile specimen in contact with the hot bulb in °C.

tc = temperature of the tile specimen in the heat sink/cold surface in °C.

Q = amount of heat flowing through the tile specimen assumed to be the same as the heat output from the bulb in W/m2.

(a) (b)

(a) (b)

Fig. 17 (a) The unglazed tile specimen in the tile holder with ignited cutting torch focused on the external fair surface lower left edge, and (b) the glazed tile specimen in the tile holder with ignited cutting torch focused on the external fair surface lower left edge of the tile.

Then the mean or average thermal conductivity was calculated to describe the expanded perlite-based tile's thermophysical property compared to the thermal conductivity of some selected materials for the wall cladding system presented in Table 4 from www.EngineeringToolbox.com.

Table 4. Thermal Conductivity of Common Materials for Wall Cladding System

Material	Thermal Conductivity, K (W/m.K)
Aluminum Brass	121
Brick dense	1.31
Brick, fire	0.47
Brick, Insulating	0.15
Cement, mortar	1.73
Concrete, dense	1.0-1.8
Concrete, store	1.7
Fire-clay brick 500°C	1.4
Glass	1.05
Granite	1.7-4.0
Plastic, foamed (insulation materials)	0.03
Porcelain	1.5
Styrofoam	0.033
Timber, oak	0.17

Source: (www.EngineeringToolbox.com)

2.6.8 Thickness Swelling

This test was conducted following ASTM D570-98 or the Standard Test Methods for Water Absorption of Plastics. This method was also applicable to use in evaluating composites. And so, this method was applied in evaluating the thickness swell of expanded perlite-based tiles as also belonging to composites. Five (5) unglazed tile specimens of size 12 inches x 24 inches were used for the thickness swelling test to determine if the water absorbed by the tile causes shrinkage and affects the thickness of the tile. The thickness of the tile specimens was measured at four points midway along each side using a Vernier calliper. Then, it was submerged in clean water for 24 hours at room temperature. After 24 hours, the water was drained, and the specimens were damped with a cloth to remove the surface water. The mass was measured using the digital balance, and the thickness was also measured. The average of the four thickness measurements was computed and used to compute thickness swelling. The thickness swelling was calculated using the equation:

$$TS = \frac{T_f - T_i}{T_i} x100 \quad (9)$$

Where: TS is the thickness swelling in per cent;

TF is the final thickness (average of four midway thickness in mm);

TI is the initial thickness (average of four midway thickness in mm)

3. Results and Discussion

3.1 Physical Properties of Expanded Perlite Aggregates and Portland Cement

The physical properties of the materials that were considered are as follows: fineness modulus and water absorption of fine and medium-sized expanded perlite aggregates and specific gravity of fine-sized expanded perlite aggregate only, and percentage fineness of Portland cement.

Presented in Table 5 are the fineness modulus test results for the samples of fine and medium-sized expanded perlite aggregates. The fineness modulus of the fine-sized expanded perlite aggregate is 2.36, while the medium-sized expanded perlite aggregate is 2.71.

Table 5. Physical Properties of Expanded Perlite and Portland Cement

Expanded Perlite					Portland Cement
Fineness Modulus		Specific Gravity	Water Absorption		Percentage Fineness (Fresh Cement)
Fine-Sized Aggregates	Medium-Sized Aggregates		Fine-Sized Aggregates	Medium-Sized Aggregates	
2.36	2.71	2.30	204.72%	90.46%	99.57%

In a study conducted by Purwandito, Suria and Usman (n.d.) in determining the effect of the fineness modulus of fine sand aggregates from different quarries on concrete compressive strength, it was found that sand fineness modulus did not significantly affect the concrete compressive strength. However, Chang, Lin, Lin and Lin (2001) determined the effects of various fineness moduli of fine aggregates on the engineering properties of high-performance concrete. They found out that the fine aggregate with the highest fineness modulus has a better positive effect on the properties of the fresh and hardened high-performance concrete.

Compressive strength is an important tile property as a wall cladding component. A compressive strength quality test was conducted to determine the strength capacity of the tile to withstand the load subjected to it. Wall cladding tile for exterior applications requires sufficient strength to resist various system stress such as rapid changes in temperature, earthquake, wind loads and moisture shrinkage and expansion, which in turn affect the durability and performance of the cladding system. The wall cladding tile comprises masonry mortar composed of Portland cement, fine expanded perlite aggregates in replacement to sand, sodium silicate and water. The minimum compressive strength of mortar for unit masonry based on ASTM C270 for external non-load bearing classified as Type N is 5.2MPa or equivalent to 750psi.

3.2 Compressive Strength of Mixture Proportions Using Fine and Medium-Sized Expanded Perlite Aggregates Without Sand Aggregates

The variations in the average compressive strengths after 7 days, 14 days and 28 days of curing in the sample cube specimens with fine and medium-sized expanded perlite aggregates without fine sand aggregates are presented in Table 6. M1 to M9 is the identification number for mixture proportions with fine expanded perlite aggregates, and M10 to M18 are the identification number of mixture proportions with medium-sized expanded perlite aggregates. For the mixture proportions with fine-sized expanded perlite aggregates, M4 has the highest compressive strength of 13.94 MPa for 7 days, M1 has the highest compressive strength of 18.22MPa for 14 days, and mixture M1 again has the highest compressive strength of 21.62MPa for 28 days curing.

Mixture Without Sand	Average Compressive Strength (MPa)			Mixture Without Sand	Average Compressive Strength (MPa)		
	7 Days	14 Days	28 Days		7 Days	14 Days	28 Days
Fine-sized Expanded Perlite Aggregates				Medium-sized Expanded Perlite Aggregates			
M1F	12.83	18.22	21.62	**M10 M**	10.03	15.43	17.42
M2 F	12.32	15.66	18.20	**M11 M**	7.10	10.90	12.04
M3 F	11.64	12.95	14.31	**M12 M**	6.21	8.60	10.30
M4 F	13.94	16.18	19.02	**M13 M**	14.54	15.43	16.81
M5 F	13.91	14.47	17.99	**M14 M**	8.60	12.33	13.93
M6 F	5.49	14.27	17.84	**M15 M**	7.32	9.48	11.22
M7 F	8.27	15.87	16.91	**M16 M**	8.71	10.84	12.17
M8 F	7.92	13.04	16.01	**M17 M**	7.78	10.07	11.64
M9 F	6.45	10.83	13.47	**M18 M**	7.48	9.07	10.82

Table 6. Compressive Strengths of 50mm Cube Specimens Without Sand Aggregates with w/c = 0.5

On the other hand, for mixture proportions with medium-sized expanded perlite aggregates, mixture M13 has the highest mean compressive strength of 14.54MPa for 7 days of curing, mixtures M10 and M13 have the highest mean compressive strength of 15.43 MPa for 14 days curing and mixture M10 has the highest mean compressive strength of 17.42 MPa for 28 days curing period. It can be observed that after the 14-day curing, there is a maximum increase of 160% on the average compressive strength while only a 25% increase after 28 days of curing in the specimen using fine-sized expanded perlite aggregates. At the same time, there is only a 54% maximum increase after 14 days of curing and a 21% maximum increase after 28 days of curing period in the specimen using medium-sized expanded perlite aggregates. Additionally, it can be observed that the mixtures with 4g of sodium silicate content in the EPA/C ratios of 0.07, 0.08 and 0.09 have the highest compressive strengths.

Considering the data in Table 6, the compression test results of sample cube specimen with mixture proportions using fine-sized expanded perlite aggregates without fine sand aggregates were analyzed using two-way ANOVA and illustrated in Figure 13. At the top of each bar, the error bar values are the standard deviation errors of the three (3) sample specimens for each mixture proportion. The figure shows the compressive strengths of M6F with 6g of sodium silicate and 8g of fine expanded perlite aggregates and M7F with 4g sodium silicate and 9g fine expanded perlite aggregates dominate the mixtures with 40.39 and 22.25 standard deviation error value, respectively.

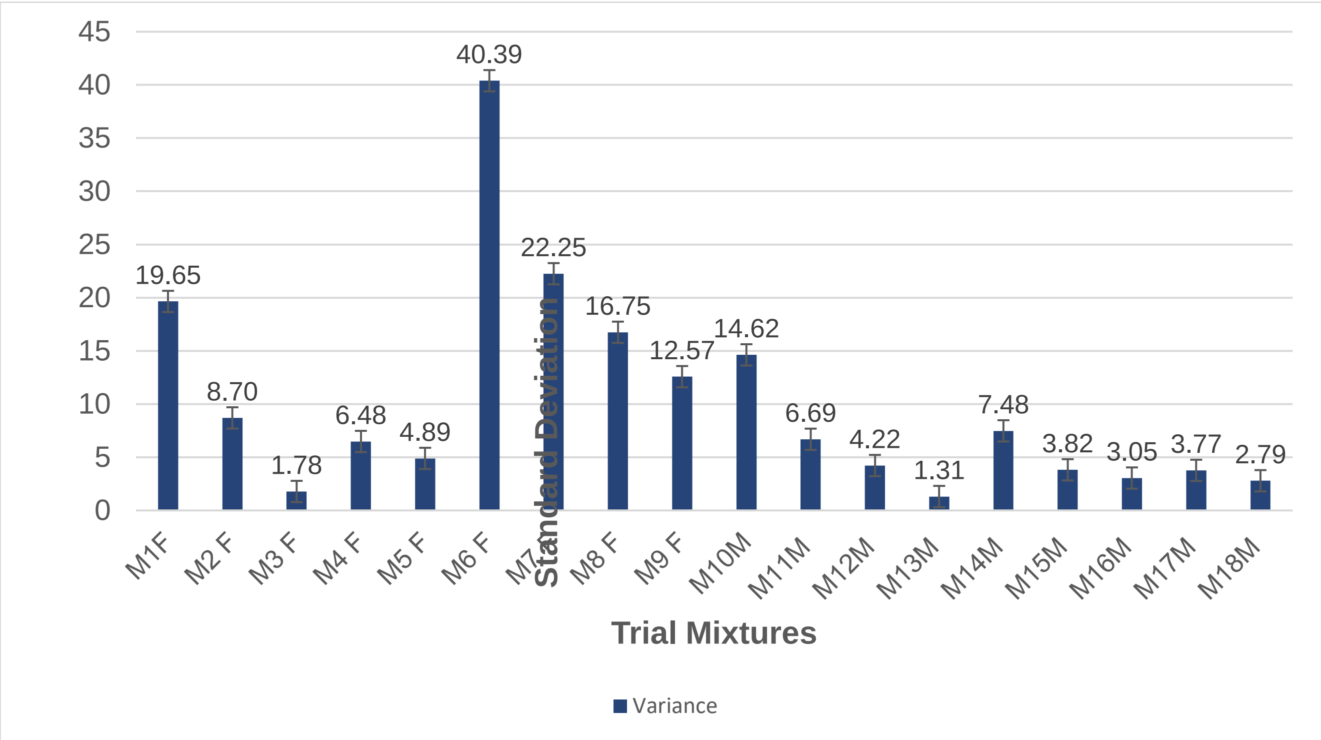


Fig. 13 Standard Deviation Error of Compressive Strengths of Sample Cube Specimens Using Fine and Medium-Sized Expanded Perlite Aggregates Without Sand Aggregates

Table 7 shows the result of the ANOVA test on the compressive strengths of sample cube specimens using fine-sized and medium-sized expanded perlite aggregates without sand aggregates. There is a significant difference in the compressive strengths of sample specimens after 7 days, 14 days and 28 days of curing. This can be attributed to the binding property of the sodium silicate to the fine-expanded perlite aggregates and Portland cement and its accelerating effect on the hydration of Portland cement, as stated by Wang, Sun, Zhang and Wang (2018) and Kubba, Hewayde, Huseien, Sam and Asaad (2019). Additionally, there is also a significant difference in the compressive strengths of the samples using 4g, 5g and 6g of sodium silicate and 7g, 8g and 9g of fine expanded perlite aggregates. The variations in the increasing contents of sodium silicate and fine expanded perlite aggregates affect the compressive strengths of the tiles and their behaviour for 7 days, 14 days and 28 days curing periods with constant w/c = 0.05 as reported by Singh and Thammishetti (2015).

Table 7. Analysis of Variance of Compressive Strengths of the Sample Cube Specimens Using Fine and Medium-Sized Expanded Perlite Aggregates Without Sand Aggregates

Source of Variation	SS	df	MS	F	P-value	F crit	Significance
Rows	127.613	8	15.952	5.655	0.00163	2.5911	Not Significant
Columns	221.787	2	110.89	39.31	6.7E-07	3.6337	Not Significant
Error	45.1319	16	2.8207				
Total	394.532	26					

3.3 Compressive Strength of Mixture Proportions Using Fine and Medium-Sized Expanded Perlite with Sand Aggregates

Presented in Table 8 are the compressive strengths of the sample cube specimens at 7-day, 14-day and 28-day curing periods with mixture proportion using fine and medium-sized expanded perlite aggregates with sand aggregates. The same designation of mixtures was used in this group.

Table 8. Compressive Strengths of 50mm Cube Specimens Using Fine and medium-Sized Expanded Perlite Aggregates with Fine Sand Aggregates

Mixture With Fine Sand Aggregates	Average Compressive Strength (MPa)			Mixture With Fine Sand Aggregates	Average Compressive Strength (MPa)		
	7 Days	14 Days	28 Days		7 Days	14 Days	28 Days
Fine-sized Expanded Perlite Aggregates				Medium-sized Expanded Perlite Aggregates			
M1F	6.24	10.49	14.41	**M10 M**	9.21	10.64	12.27
M2 F	6.12	8.26	11.15	**M11 M**	7.85	9.23	10.77
M3 F	4.98	7.16	8.52	**M12 M**	6.15	6.45	8.23
M4 F	8.35	9.94	13.91	**M13 M**	8.41	10.74	13.57
M5 F	7.92	9.82	13.54	**M14 M**	7.40	9.11	11.74
M6 F	5.85	9.64	10.34	**M15 M**	5.81	8.57	11.11
M7 F	4.58	9.40	13.39	**M16 M**	2.64	6.87	11.30
M8 F	4.45	6.56	10.32	**M17 M**	1.96	6.25	8.16
M9 F	2.26	5.68	8.45	**M18 M**	1.83	2.16	6.41

For the specimen using fine-sized expanded perlite aggregates, M4 has the highest average compressive strength of 8.35MPa after 7 days of curing, and M1 has 10.49MPa for 14 days of curing 14.41MPa for a 28-day curing period. For sample cube specimen using medium-sized expanded perlite aggregates, M10 has the highest average compressive strength of 9.21MPa after 7 days of curing, and M13 has 10.74MPa after 14 days of curing 13.57MPa after 28 days curing period.

It can be observed in Table 8 that these mixture proportions with sand aggregates using fine-sized expanded perlite aggregates reached a maximum of 105% increase on the average compressive strength after 14 days of curing and only 57% maximum increase after 28 days of curing period. While for mixture proportions using medium-sized expanded perlite aggregates, there was a 219% maximum increase in the average compressive strength after 14 days of curing and a 197% maximum increase after 28 days of curing period. However, these mixture proportions' compressive strengths were lower than those of the mixture proportions without fine sand aggregates.

Considering the data in Table 8, the compressive strengths of sample cube specimens with fine sand aggregates were analyzed using a two-way ANOVA without replication, and the result with standard deviation errors as illustrated in Figure 13. The standard deviation error of the three (3) sample specimens for each mixture proportion is on the top of each bar in the figure. From the figure, the compressive strengths of M7F with 40g of sodium silicate, 15g of fine-sized expanded perlite aggregates, 100g Portland cement, 91g water and 85g fine sand aggregates, and M16M with 40g sodium silicate, 15g medium-sized expanded perlite aggregates, 100g Portland cement, 74g water and 85g fine sand aggregates dominate the mixtures with 19.46 and 18.75 standard deviation error value, respectively.

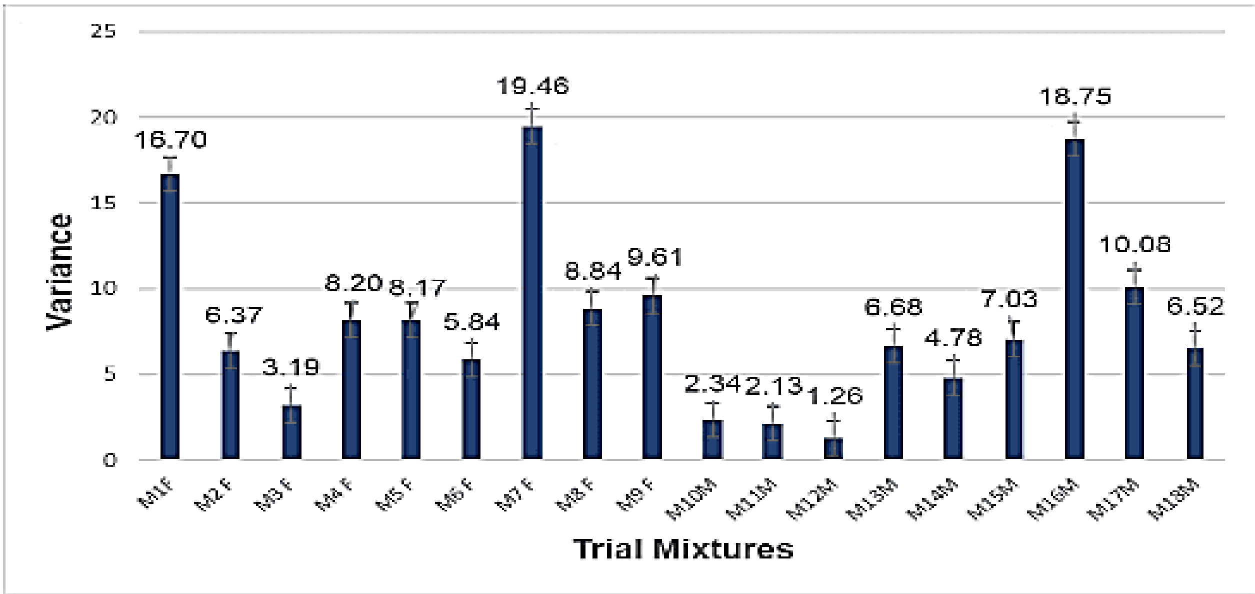


Figure 14. Standard Deviation Error of Compressive Strengths of Sample Cube Specimens Using Fine-Sized and Medium-Sized Expanded Perlite Aggregates with Sand Aggregates

Based on the result of the ANOVA test on the compressive strengths of sample cube specimens using fine-sized and medium-sized expanded perlite aggregates without sand aggregates, as presented in Table 9, it appears that there is a significant difference in the compressive strengths of the sample specimens after 7 days, 14 days and 28 days of curing. This can also be attributed due to the binding property of the sodium silicate to the fine-expanded perlite aggregates and Portland cement and its accelerating effect on the hydration of Portland cement, as stated by Wang, Sun, Zhang and Wang (2018) and Kubba, Hewayde, Huseien, Sam and Asaad (2019). Also, there is a significant difference found in the compressive strengths of the sample specimens on the use of 5%, 10% and 15% of fine expanded perlite aggregates by mass of Portland cement, the 95%, 90% and 85% of fine sand aggregates used and the 50% of Portland cement mass water content added with the amount depending on the absorption capacity of the sand and fine expanded perlite aggregates. The variations in the increasing contents of sodium silicate and decreasing content of fine sand aggregates with a specific amount of water affect the compressive strengths of the tiles and their behaviour for 7 days, 14 days and 28 days curing periods. This conforms to the statement of Ali (2019).

Table 9. Analysis of Variance of Compressive Strengths of the Sample Cube Specimens Using Fine-Sized and Medium-Sized Expanded Perlite Aggregates with Sand Aggregates

Source of Variation	Sum of Squares	df	Mean Squares	F	P-value	F crit	Significance
Rows	231.05	17	13.59	12.2	7E-10	1.933	Significant
Columns	254.06	2	127	114	8E-16	3.276	Significant
Error	37.872	34	1.114				

As reflected in the average compressive strength results for 7 days, 14 days and 28 days of curing, the average compressive strengths yielded for cube specimens with fine sand aggregates were much higher than that of the compressive strengths of cube specimens without fine sand aggregates.

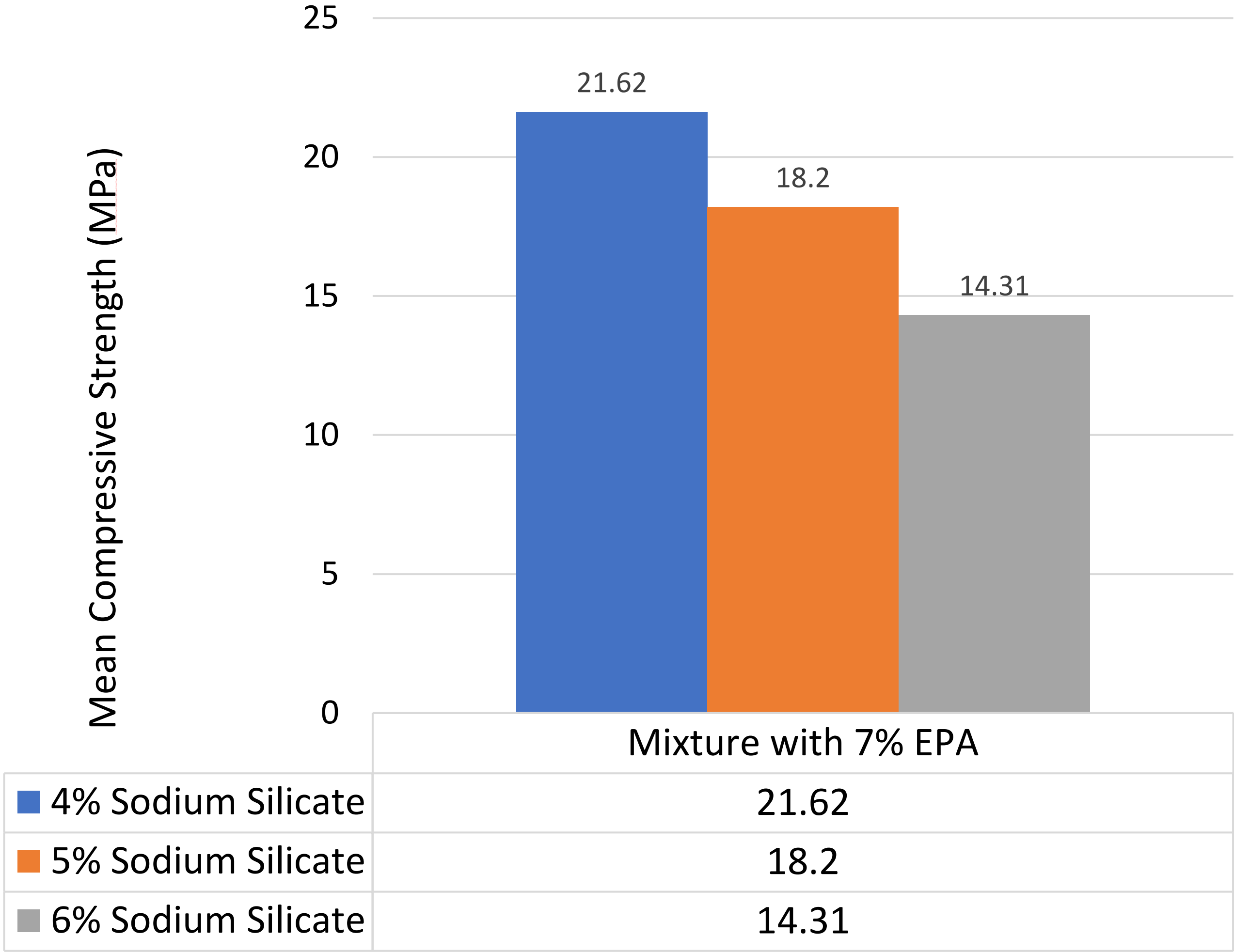


Fig. 15 Average Compressive Strengths of Mixtures with 7% Expanded Perlite Aggregates (EPA) and with 4%, 5% and 6% Sodium Silicate for 28 days of curing

The results only show that the fine-sized expanded perlite aggregates could be used in mixtures and as a replacement for fine-sand aggregates. This also confirms the positive effect of using sodium silicate content above 3% on increasing compressive strength, as Wang et al. (2018) reported. Indeed, a water-cement ratio of 0.5 is an ideal proportion to have a workable cement mortar.

Table 10 shows the result of the analysis of variance (ANOVA) test on the compressive strengths of the specimens with 4%, 5% and 6% sodium silicate with a constant composition of 7% of fine-sized expanded perlite aggregates. There is no significant difference between the compositions in terms of the compressive strengths of the three mixture proportions during the 7-day curing period, as indicated by the F-value of 2.30 (p-value= 5.14). However, there are significant differences in the compositions in terms of compressive strengths between the sample mixture proportions during the 14 days and 28 days curing periods with the F-value of 625.20 (p-value =5.14) and F-value of 501.63 (p-value =5.14), respectively. The results only show that with that composition of expanded perlite aggregates and sodium silicate, the compressive strengths increased with longer curing periods.

Table 10. Analysis of Variance of Compressive Strengths of the Tile Specimens Using 7g Fine-Sized Expanded Perlite Aggregates with 4g, 5g and 6g Sodium Silicate for 7 Days, 14 Dyas and 28 Days Curing

	Sources of Variation	df	Sum of Squares	Mean Squares	F		Significance
					Computed	Tabular	
7 days	Between Groups	2	2.15	1.08	2.30	5.14	Not Significant
	Within Groups	6	2.80	0.47			
	Total	8	4.95				
14 days	Between Groups	2	41.68	20.84	625.20	5.14	Significant
	Within Groups	6	0.20	0.03			
	Total	8	41.88				
28 days	Between Groups	2	80.26	40.13	501.63	5.14	Significant
	Within Groups	6	0.47	0.08			
	Total	8	80.73				

Statistically, the size of expanded perlite aggregates, the proportion of sodium silicate and the reinforcing material affect the compressive strength of the wall cladding tile.

The optimum mixture proportion normally yields the highest average compressive strength. This study used this as the basis for the fabrication and production of expanded perlite-based tiles for the wall cladding system. Table 11 shows the mixture proportion of the mixture M1F using fine-sized expanded perlite aggregates without aggregates that exhibited the highest mean compressive strength at 28 days of curing. The mixture contains 100 grams of Portland cement, 7 grams of expanded perlite aggregates, 4 grams of sodium silicate and 50 grams of water. The expanded perlite aggregate cement ratio is 0.07, and the water-cement ratio is 0.5.

Table 11. Optimum Mixture Proportion

Material	Quantity (1:0.07:0.04:0.5)
Portland Cement (g)	100
Fine Expanded Perlite Aggregate (g)	7
Sodium Silicate (g)	4
Water (g)	50
Aggregate-Cement Ratio	0.07
Water-Cement Ratio	0.5

3.4 Physical and Mechanical Properties of Expanded Perlite-Based Tiles As Wall Cladding System

Physical properties of expanded perlite-based tiles considered are water absorption, unit weight and specific gravity. Mechanical properties are Charpy impact resistance, modulus of rupture, surface flame spread and thickness swelling.

The water absorption test was conducted in accordance with ASTM C373, as shown in Table 12. The water absorption for each of the five (5) unglazed sample tile specimens is 17.54%, 16.95%, 14.96%, 16.41% and 14.54%, with an average water absorption 16.08%. This value is classified as non-vitreous or permeable. However, glazing could be applied on the wall cladding tile or impermeable tile surfaces. Compared to glazed ceramic wall tile, the water absorption value is already high, which is limited for indoor application only to avoid exposure to rain and moisture because it tends to become a breeding ground for bacteria under wet conditions.

The unit weight test was conducted as it describes the structure and characterizes the quality of the material. It is used interchangeably with density. The unit weight calculation of fresh mortar is presented in Table 12. The mass of the cylindrical mould is 4.10 kgs with a volume of 1.334x10-3m3. The mass of the fresh mortar of expanded perlite-based tile and the mass of the mould is 6.39 kgs giving a density of 1716.64 kg/m3. Compared to the density of cement mortar with sand which is 2162 kg/m3, expanded perlite-based tile is lighter than the masonry mortar. This is attributed to the expanded perlite aggregates used, which are lightweight.

Table 12 shows the result of the specific gravity of the expanded perlite-based tile specimen based on its unit weight. The unit weight of tile mortar is 1716.64 kg/m3 and has a specific gravity of 1.72. The value indicates that the tile is considered lightweight because it is almost twice the unit weight of water.

Table 12. Physical Properties of Expanded Perlite-Based Tiles

Physical Property	Value	Remark
Water Absorption	16.08%	Non-vitreous
Unit Weight	1716.64 kg/m^3	Lightweight
Specific Gravity	1.72	Lightweight

Presented in Table 13 is the result of the Charpy impact resistance test for the horizontal, vertical and centre representative of glazed and unglazed tile. This was conducted to determine the total impact energy on the representative cut tiles specimen. A total of thirty-six (36) representative cut sample specimens from two unglazed and two glazed tiles were subjected to an impact resistance test. For unglazed tile 1, the horizontal, vertical and centre representative cut sample specimens have an average energy of 1.33J, 3.33J and 3.17J, respectively. For unglazed tile 2, the horizontal, vertical and centre representative cut sample specimen have an average energy of 3.79J, 3.36J and 4.10J, respectively. For glazed tile 3, the horizontal, vertical and centre representative cut sample specimens have an average energy of 3.32J, 3.79J and 3.32J, respectively. For glazed tile 4, the horizontal, vertical and centre representative cut sample specimens have an average energy of 3.53J, 2.86J and 4.13J, respectively.

Table 13. Charpy Impact Resistance

Tile Representative Cut Specimen	Average Energy (J)		Total Average Energy (J)
	Sample 1	Sample 2	
Unglazed			
Horizontal	1.33	3.79	2.56
Vertical	3.33	3.36	3.35
Center	3.17	4.10	3.64
Glazed			
Horizontal	3.32	3.53	3.43
Vertical	3.79	2.86	3.33
Center	3.32	4.13	3.73

It can be observed in Figure 36 that for unglazed tiles, the horizontal cut has mean energy of 2.55J, the vertical cut has 3.35J, and the centre cut has 3.64J. For glazed tiles, the horizontal cut has 3.43J, the vertical cut has 3.33J, and the centre cut has 3.73J. Getting the means, the glazed tiles are more resistant to impact than the unglazed tiles. Glazing not just protects the wall cladding tiles but also increases the impact resistance. In addition, the centre cut gets the highest mean energy among the three cuts. This may be attributed to the thickness of the centre cut sample specimen.

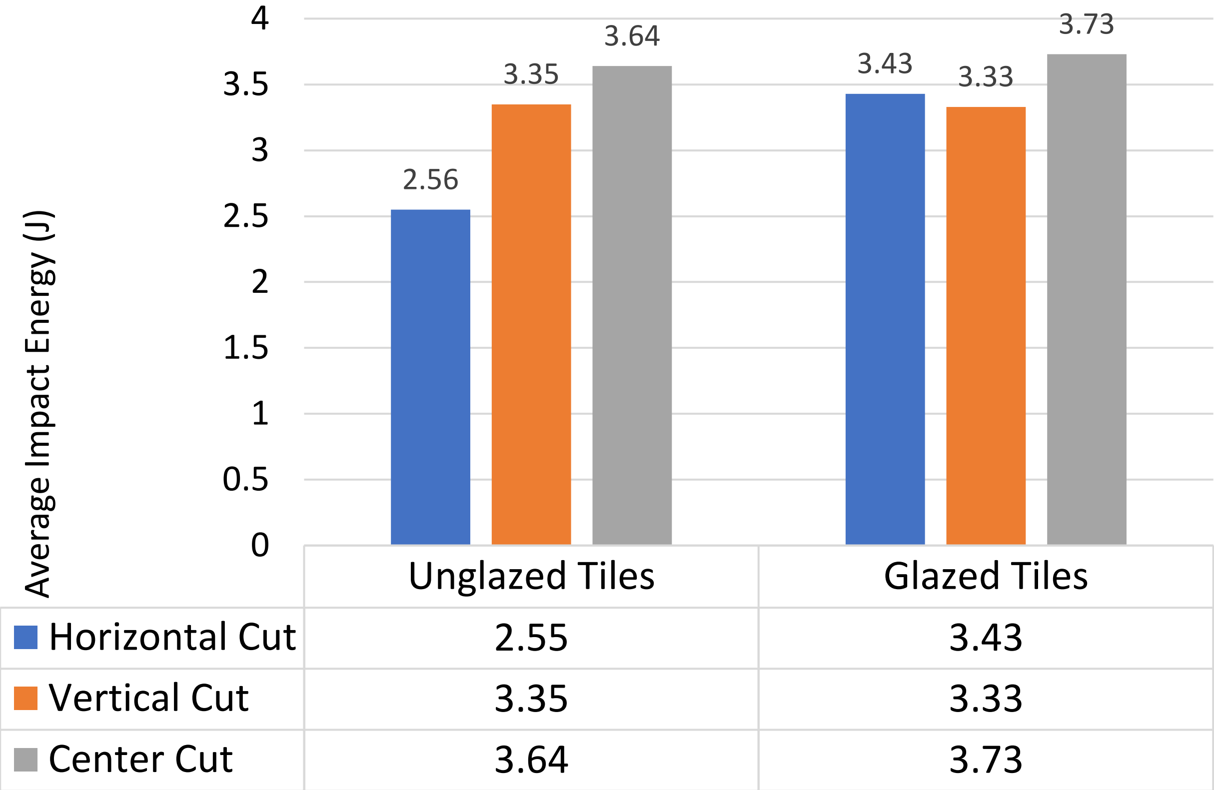


Fig. 16 Comparison of Impact Energy at Break of Unglazed and Glazed Wall Cladding Tiles

Table 14 shows the independent samples t-test of the Charpy impact resistance of the horizontal, vertical, and centre cut of the glazed and unglazed wall cladding tiles. The results show no significant difference in the compositions of the sample tile specimen in terms of Charpy impact resistance between the glazed and unglazed tiles in the horizontal, vertical and centre cuts as indicated with their means. Glazing did not affect the Charpy impact resistance of the tile. However, the higher impact resistance energy of the centre cuts can be attributed to the wire mesh reinforcement, which was properly secured at the centre of the tile.

Table 14. Independent Samples t-test of Charpy Impact Resistance for Horizontal Cut, Vertical Cut and Center Cut of Glazed and Unglazed Tiles

	Tiles	N	Mean	Std. Deviation	Std. Error Mean
Energy (J) of Horizontal Cut	Glazed	6	3.4267	0.26128	0.10667
	Unglazed	6	2.5600	1.63971	0.66941
Energy (J) of Vertical Cut	Glazed	6	3.3233	1.78220	0.72758
	Unglazed	6	3.3450	1.14332	0.46676
Energy (J) of Center Cut	Glazed	6	3.7233	0.82252	0.33579
	Unglazed	6	3.6333	0.56592	0.23104

Modulus of rupture was tested to determine its impact resistance at service. Floor tiles are more prone to impact damage than wall tiles. Impact damage of floor tile is caused by the uneven distribution of substrates or probably because the tile is not perfectly flat and breaks when the static load is applied. On the other hand, with the installed wall cladding tile using the adhered method, impact damage is possibly caused by uneven adhesive distribution since no static load is applied. This is why this test method is not appropriate for wall cladding tile (Harrison and Brough, n.d.). The results of the modulus of rupture test or the static bending test are presented in Table 15.

Out of the four (4) tiles, two of which are unglazed, and the other two were glazed. The width and thickness of the three (3) cut representative specimens were measured at three different points for every tile. The average width and thickness were computed, and the force at the break to compute the modulus of rupture in each specimen. For the unglazed tile specimen, Specimen 2 has the highest modulus of rupture value (6.10MPa). In contrast, Specimen 4 has the lowest modulus of rupture (4.34MPa), and the average modulus of rupture for the unglazed tile specimen was 5.20MPa. Specimen 5 exhibited the highest modulus of rupture (7.17MPa) for the glazed tile specimens, and Specimen 3 exhibited the lowest modulus of rupture (3.36MPa). The average modulus of rupture for the glazed tile specimens is 5.60MPa. Comparing the two tiles, glazed tiles are more resistant to impact damage than unglazed tiles. Glazing increases the resistance of the wall cladding tiles to breaking at impact.

Table 15. Modulus of Rupture of Expanded Perlite-Based Tiles

SPECIMEN	Average Modules of Rupture (MPa)
Unglazed	5.20
Glazed	5.60

3.5 Surface Flame Spread

The result of the fire performance test based on the British Standard BS 476 Part 7 of 1997 is presented in Table 16. This test provides the fire performance of tiles used for wall cladding. The data show that after 1.5 minutes that the burning torch was stopped, the flame in the unglazed tile extinguished after 1.76 minutes, while in the glazed tile, the flame extinguished after 1.74 minutes. The smoke was extinguished after 1.94 minutes in the unglazed tile and 2.28 minutes in the glazed tile. The flame height was 102.50mm in unglazed and 105mm in the glazed tile, which is consistent with the rate at which the tile burned and stopped the flame after 10 minutes, where the unglazed tile self-extinguished the flame after 1.65 minutes and the glazed tile after 1.63 minutes.

Table 16. Average Surface Flame Spread of Expanded Perlite-Based Tiles

	Class Limits	Unglazed Tile	Glazed Tile
	Flame Self Extinguished (min.)	1.76	1.74
Flame Stoppage after 1.5min.	Smoke Self-Extinguished (min.)	1.94	2.28
	Flame Spread Height (mm)	102.50	105.00
	Flame Self Extinguished (min.)	1.65	1.63
Flame Stoppage after 10min.	Smoke Self Extinguished (min)	1.84	2.30
	Flame Spread Height (mm)	112.50	116.67
Result	Tested specimens are classified as Class 1 where the flame does not spread, smoke easily extinguished and only the focus of the fire nozzle is burnt.		

The smoke self-extinguished after 1.84 minutes in unglazed and after 2.30 minutes in glazed tile, and the flame spread height is 112.50mm in unglazed and 116.67 mm in glazed tile. During the fire tests, the flame spread heights did not reach the 165mm reference line; the tile could be classified as Class 1 based on the British standard.

The result shows that for the glazed tile, the flame self-extinguished earlier than it did in the unglazed tile. The smoke self-extinguished longer when the flame was spread higher in the glazed than it was in unglazed tile.

In any building, fire is inevitable. One factor influencing the spread of fire within and outside the building is influenced by the finished material, such as in walls. As such, the fire performance of building materials through the flame spread test method considering the ignition temperature and smoke toxicity is evaluated and regulated by the standard requirements for fire safety. The standards define the equipment and test method used to describe the flame spread rating of the material, just like the American Society for Testing and Materials (ASTM) Standard Test Method 84 or the Tunnel test, which describes the surface burning characteristics of interior building materials.

For exterior finish materials, the most applicable fire testing for tiles to be used for wall cladding is the National Test Standard of England and Wales BS 476: Part 7 or the British standard with classifications of surface flame spread as non-combustible, limited combustibility, 0, 1 & 2, 3 and 4. The classification or rating indicates a relative rate at which flame will spread over the surface of a material, compared with the flame spread on asbestos board which is zero and on red oak, which is 100. The rating in which the flame will not spread along the surface and not an indicator of a material's fire resistance (https://www.acousticalsurfaces.com).

Thermal Conductivity. The results of the thermal conductivity test using Fourier's law of steady-state one-dimensional conduction method are presented in Table 17. The data show the mean thermal conductivity values for each 50W, 100W and 150W heat energies for glazed and unglazed tile specimens recorded every 5 minutes for one (1) hour. The temperature of the hot face of the glazed tile specimen varies from 29.2oC to 35.5oC for 50W, 34.6 oC to 47.2 oC for 100W and 41.5 oC to 53.4 oC for 150W heat energy. The recorded temperature in the cold surface varies from 27.8 oC to 32.5 oC for 50W, 31.7 oC to 43.0 oC for 100W and 33.2 oC to 43.6 oC for 150W. Similarly, for the unglazed tile specimen, the recorded temperature on the hot surface varies from 32.9 oC to 36.5 oC for 50W, 35.7 oC to 44.2 oC for 100W and 41.2 oC to 53.2 oC for 150W. While in the cold surface varies from 30.6 oC to 33.1 oC for 50W, 41.5 oC to 38.2 oC for 100W and 33.1 oC to 43.5 oC for 150W. Given the temperatures in the hot and cold surfaces of the tile specimens, the area of 0.18605 square meters and thickness of 0.0127 meters, the thermal conductivity was calculated. The average thermal conductivity for glazed tile specimens were 1.34, 1.16 and 1.12 for 50W, 100W and 150W, respectively. While for unglazed tile specimens are 1.22, 1.21 and 1.19 for 50W, 100W and 150W, respectively. As indicated in the plotted bar graph of the average thermal conductivity values in Figure 17, there is an abrupt reduction in the glazed tile specimens while only a gradual drop in values in unglazed tile specimens.

Table 17. Thermal Conductivity (k) Test Results (for 1 Hour) of the Glazed and Unglazed Expanded Perlite-Based Tile for 50W, 100W and 150W Heat Energy

Time (min.)	Mean Thermal Conductivity, k (W/m.K)					
	Glazed Tile			Unglazed Tile		
	50W	100W	150W	50W	100W	150W
0	-	-	-	-	-	-
5	2.44	2.35	1.23	1.46	1.29	1.26
10	2.13	1.02	1.08	1.10	1.10	1.14
15	1.22	0.88	1.16	1.18	1.31	1.19
20	1.18	0.98	1.13	1.31	1.31	1.22
25	1.14	1.14	1.09	1.42	1.29	1.28
30	1.10	0.99	1.09	1.42	1.22	1.31
35	1.18	0.88	1.19	1.37	1.07	1.16
40	1.10	1.00	1.19	1.22	1.37	1.22
45	1.14	1.05	1.08	1.10	1.08	1.19
50	1.18	1.22	1.06	1.03	1.16	1.16
55	1.14	0.81	1.11	1.03	1.18	1.04
60	1.14	1.63	1.07	1.00	1.14	1.06
Average k	**1.34**	**1.16**	**1.12**	**1.22**	**1.21**	**1.19**
		1.21			**1.21**	
REMARKS: The value is within the thermal conductivity range of dense concrete which is 1.0 to 1.6, lower than the thermal conductivity of dense brick which is 1.31, fireclay brick of 1.4 and porcelain of 1.5.						

However, getting further, the mean of both the glazed and unglazed tile their thermal conductivity is 1.21, which is within the range of the dense concrete (1.0-1.8), lower than the thermal conductivity of dense brick (1.31), fire-clay brick (1.4) and porcelain (1.5).

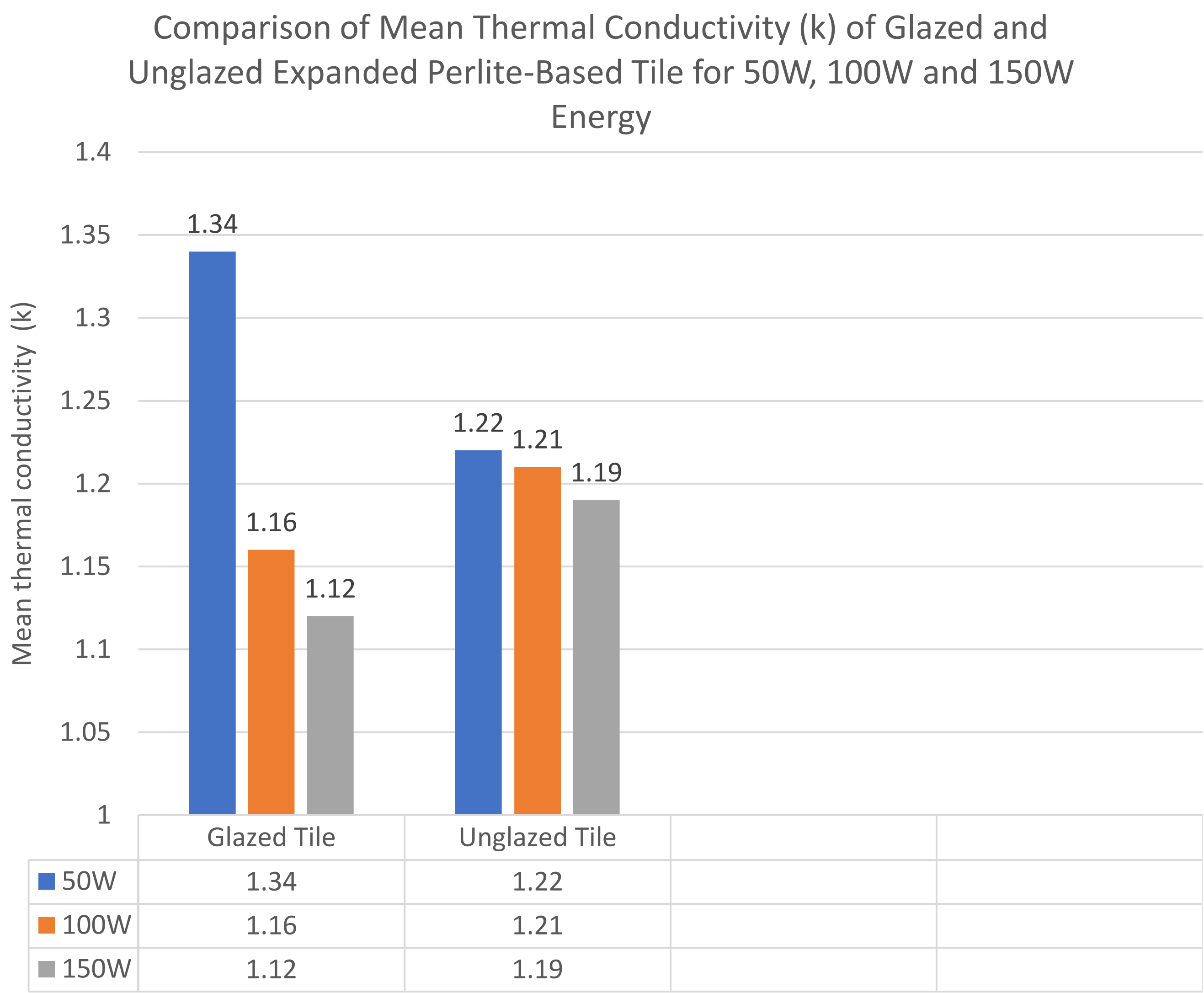


Figure 17. Mean Thermal Conductivity (k) (for 1 Hour Duration) of Glazed and Unglazed Expanded Perlite-Based Tile for 50W, 100W and 150W Heat Energy

Table 18 shows the independent samples t-test of the thermal conductivity (k) of the glazed and unglazed tiles for 50W, 100W and 150W energy. Based on the results shown in the table, there is no significant difference in the thermal conductivity between the glazed and unglazed tiles. The expanded perlite-based tile has low thermal conductivity. This can be attributed to the insulative property of expanded perlite aggregates and the sodium silicate used. Similarly, both the glazed and unglazed tiles attained higher thermal conductivity at 50W energy but gradually decreased with the increase of energy from 100W to 150W. Statistically, the thermal conductivity of the tile is not affected by the glazing or the surface coating applied on the tile.

Table 18. Independent Samples t-test of Thermal Conductivity (k) for 50W, 100W and 150W Energy

	Tiles	N	Mean	Std. Deviation	Std. Error Mean
Thermal Conductivity (k) of 50W Energy	Glazed Unglazed	12 12	1.3408 1.2217	0.44726 0.17299	0.12911 0.04994
Thermal Conductivity (k) of 100W Energy	Glazed Unglazed	12 12	1.1625 1.2100	0.43052 0.10243	0.12428 0.02957
Thermal Conductivity (k) of 150W Energy	Glazed Unglazed	12 12	1.1233 1.1858	0.05614 0.08129	0.01621 0.02347

3.6 Thickness Swelling

Presented in Table 16 is the result of the thickness swelling test for the expanded perlite-based tile specimen. Five (5) unglazed tile specimens were subjected to a thickness swelling test by soaking them in water for 24 hours. They were soaked in water after measuring the four-midway thickness of dried tiles. The average of the four-midway thickness of each tile before soaking in water was computed as the initial average thickness. Hence, the average of the four-midway thickness of each tile after soaking in water was computed as the final average thickness. The change in the final average thickness is the thickness swelling of the tile. For specimen 1, the average initial thickness is 12.59mm. For specimen 2, the average initial thickness is 12.91mm. For specimen 3, it is 12.42; for specimen 4, it is 13.39; and for specimen 5, it is 12.44. The final average thickness of specimens 1, 2, 3, 4 and 5 is 12.59mm, 12.91mm, 12.42mm, 13.39mm and 12.44 mm, respectively.

It could be observed that the initial and final thickness values remained the same after the test. This could be explained that although the expanded perlite component of the tile was high water absorbent, the surfaces of the tile were smooth without any visible voids. The tile structure was not porous; no water uptake took place in the tile specimen. Generally, the thickness swelling test is conducted in some studies if the composite utilizes cellulosic natural fibres. In the study of Chiang, Osman and Hamdan (2014) on the water absorption and thickness swelling behaviour of sago particles on urea-formaldehyde particleboard, the high value of thickness swelling obtained was attributed to the high percentage of absorbent particles in the panel. Also, it could be attributed to the porosity of the structure that more water was absorbed, causing it to swell, which led to the increased thickness swelling value.

Table 19 summarises the results of the mechanical properties of the expanded perlite-based tiles for the wall cladding system. The glazed centre-cut tile is more resistant to Charpy impact energy of 3.73J than the unglazed centre-cut tile with 3.64J. Glazing could enhance the impact resistance. Similarly, glazing also improves its impact resistance at a break of 5.60MPa for glazed over 5.20MPa for unglazed tile. Surface flame spread is classified as Class 1, where the flame does not spread over 165 mm for 10 minutes; the smoke is easily extinguished and burnt only the portion of the tile focused by the flame nozzle. There is no thickness swelling because the surface is not porous, with water resistance.

Table 19. Summary of the Results of the Mechanical Properties of Expanded Perlite-Based Tiles for Wall Cladding System

Mechanical Property	Value		Remarks
	Glazed	Unglazed	
Charpy Impact Resistance	3.73J (center cut)	3.64J (center cut)	Glazed center cut tile is more resistant to impact energy. Glazing increases the impact resistance of the tiles.
Modulus of Rupture (MPa)	5.60	5.20	Glazed tiles are more resistant to impact at break.
Surface Flame Spread	Class 1		Flame does not spread over 165mm for 10min, smoke easily extinguished and only the focus of the fire nozzle is burnt.
Thermal Conductivity (W/(m.K)	1.21	1.21	Belongs to dense concrete with k ranges from 1.0 to 1.8, the thermal conductivity of dense brick (1.31), fire-clay brick (1.4) and porcelain (1.5).
Thickness Swelling	No thickness swelling		No water uptake took place in the tile specimen; high water resistant.

4. Conclusion

The following are the conclusions derived from the results of the study:

- The fineness modulus of expanded perlite aggregates positively affected the compressive strength of the expanded perlite-based tile after 7, 14 and 28 days of curing. The specific gravity of expanded perlite was smaller than the specific gravity of sand aggregates; therefore, for lightweight masonry mortar, it is advisable to use expanded perlite aggregates. Although expanded perlite aggregates are hydrophilic, the water hydration was accelerated with sodium silicate. Thus, it positively affects the early compressive strength development in the expanded perlite-based tile. The higher the value of the percentage fineness of cement, the fresher the cement. Fresh cement reacts quickly with water resulting in accelerated hydration and early strength of the mortar paste. Utilizing the developed expanded perlite-based tile in wall cladding installation is economical. One can save up to 60% due to the less energy cost of production and less expensive raw materials.
- The optimum mix proportion used to produce the expanded perlite-based tile proves to be the most suitable mix design. It attained its maximum early strength after 14 days of curing, thus, conforming with ASTM C109/ C109M.
- The fabricated expanded perlite-based tile exhibited a satisfactory water absorption, making it suitable for wall cladding tiles. However, as a non-vitreous tile, glazing is important to make it more waterproof. Expanded perlite aggregates could be used in making lightweight mortar or concrete. Similarly, the specific gravity of the expanded perlite-based tile mortar is lower than the specific gravity of mortar with sand aggregates because its mass is just almost twice the mass of water. Glazed tiles have higher impact resistance than unglazed tiles. The centre cut of the developed expanded perlite-based tile had the highest impact energy to break as it was thicker than the other parts. This part was also fully reinforced with the wire mesh, which enhanced its impact strength.
- Moreover, glazed tiles have a higher modulus of rupture value using the three-point horizontal impact loading. The fabricated tile belongs to Class 1 surface flame spread where the flame does not spread; only the point of flame is burnt and with smoke easily extinguished. Similarly, the thermal conductivity of the fabricated tile is inversely proportional to the temperature, equivalent to dense concrete but superior to brick and porcelain. Also, it does not swell or expands in water. The sodium silicate and Portland cement served as a coating for the expanded perlite particles making the mortar water-resistant.

5. Recommendations

Based on the conclusions made, the following are highly recommended:

- To improve the strength properties of the expanded perlite-based tile by making it more lightweight, using smaller sizes of expanded perlite aggregates having smaller fineness modulus.
- To improve the compressive strength and other properties of the tile by using hot sodium silicate with optimum mixture proportion in the production of expanded perlite-based tile for the wall cladding system.
- To enhance the physical and mechanical properties of the fabricated expanded perlite-based tile for wall cladding system specifically for indoor and outdoor applications without baking and heating. Tests for thermal expansion, moisture expansion, sound absorption, surface abrasion, deep abrasion, chemical and stain resistance and thermal shock resistance must be considered.
- To develop an expanded perlite-based tile wall cladding system that is more durable by enhancing its aesthetics and its resistance to weather elements. Furthermore, to test the bond strength of the wall cladding system installed on concrete masonry wall surfaces using pure structural adhesives.
- To utilize the developed expanded perlite-based tile for wall cladding system application.

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