A COMPARISON BETWEEN THE INFLUENCE OF THREE DIFFERENT SIZES OF EXFOLIATED VERMICULITE ON THE THERMAL AND MECHANICAL PROPERTIES OF CEMENT CONSTRUCTION BRICKS

Pieter Adrian Huysamen,Western CAPE / STELLENBOSCH,Jan Van Riebeeck High School, adrian.huysamen@janvanriebeeck.org

ARTICLE INFO

Gold medalist in BUCA IMSEF 2022

Mrs Milandré Bezuidenthout(Advisor)

Awarded by Ariaian Young Innovative Minds Institute , AYIMI

http://www.ayimi.org ,info@ayimi.org

ABSTRACT

A study was embarked on to determine what influence replacing increasing proportions of sand with exfoliated vermiculite will have on a cement brick's strength and insulation properties. These bricks, with various ratios of sand and exfoliated vermiculite, were compared to control sample bricks, made according to the industry standard formula of a ratio of 8:1 by volume of sand and cement. The study also investigated if the size of exfoliated vermiculite would influence the results. The study conclusively proved that exfoliated vermiculite is a viable filler in cement brick making.

Keywords : *Bricks,Cement , Exfoliated Vermiculite*

1. Introduction

South Africa has a backlog of affordable housing for its growing population. An in-depth review of all the alternative building materials currently available on the market and available skilled labour needs to be undertaken.

Due to the lack of skills to build with alternative materials such as wood or panel boards, a high demand remains for houses built with conventional bricks and mortar. Such buildings are perceived to be reliable and strong, but costly and take more time to construct. Building with bricks and mortar requires a strong, skilled labourer as it is strenuous work laying on average 500 - 600 bricks per day. This together with the declining artisanship in the building industry is worrying as shown by Doku (2009).

According to the quarterly report published by The Construction Industry Development Board in October 2018, there are around 89% males and 11% females in the construction industry. This problem can substantially be addressed by introducing lightweight construction bricks to this industry.

Buildings are considered to be an open system, and therefore interact with the environment. Thermal energy transfer take place between a building and its immediate environment. 25% - 30% of all the energy consumed in the world. 80% of the energy used by a building is due to heating or cooling(How is heat transferred? Conduction -- Convection -- Radiation, 2022), Hence, by ensuring these lightweight bricks have superior insulation properties it will assist in reducing the energy consumption of homeowners across the country. This will in turn reduce the threat to climate change, environmental pollution and human health by reducing emissions from coal-fired power stations which are South Africa's main source of electrical energy.

There are also other disadvantages of the common cement construction brick. Firstly, it is very heavy and some configurations cumbersome thus extending construction time and increasing construction cost. The accumulative mass of dwellings or residential property structures constructed with cement bricks requires substantial foundations. Secondly, the common cement brick is not very fire resistant meaning it loses much of its structural strength during a fire. Finally, these bricks have poor insulation properties and as mentioned, do little to reduce the electrical energy demand on the power grid in South Africa.

Drawing on the excellent thermal properties of exfoliated vermiculite and its resilience to fire, such an addition to cement brick making could revolutionize the building industry. Lighter bricks would require lesser foundations and the improvement of insulation properties would reduce residential energy consumption used for heating and cool dramatically. This would reduce the demand on the electricity grid as well as reduce the volume of harmful greenhouse gasses released by conventional coal-fired power stations.

Vermiculite is a naturally occurring mineral that takes the form of glossy flakes, varying in colour from dark grey to sandy brown. These flakes, a hydrated magnesium iron aluminium silicate mineral, are easily exfoliated by a heat source or microwaves and in so doing expand on average ten times in volume forming wormlike particles.

Exfoliated vermiculite is a light, non-toxic, sterile material and is pH neutral. It is commonly used in passive fire protection plaster mixtures, as loose media in insulation applications, as conveyors of minerals in animal feed and as a growing medium in the agriculture industry. Its name comes from the Latin word "vermiculare," which means "to breed worms," and the English suffix "ite," which means "mineral" or "rock".

To be noted is that this study was embarked on not to redesign a building brick, but to rather investigate if exfoliated vermiculite could be a suitable additive to common cement bricks. All sample bricks were produced following a set procedure to ensure batch conformity. By replacing part of the sand in the cement brick with exfoliated vermiculite it is believed that such bricks would retain enough strength rendering them suitable for the construction industry. To form a definitive view, three size ratios of exfoliated vermiculite were used in the study to determine if one is more suitable than the other.

Two more variables were introduced as both were deemed relevant. The first variable was fire, whereby influence of fire on the strength of bricks was investigated, and secondly the insulation properties of the bricks. The purpose of the study was to find the perfect size of exfoliated vermiculite and the ratio of an aggregate mix

mix (building sand to exfoliated vermiculite) that would render a strong yet lightweight brick with improved insulation properties.

2. Literature Review

Developing lighter building material with better insulation properties has been a topic of many research papers, such as, Köksal, DiazGencel and Rabanal (2013), Georgiev, Yoleva, Djambazov, Dimitrov, Ivanova (2017) and Beal, Selby, Atwater, James, Viens, Almquist (2019). The benefit of such materials ranges from energy savings due to reduced heating and/or cooling required to cost savings as less structural materials are required e.g. lesser foundations. Lightweight houses are specifically beneficial in parts of the world where ground subsidence is common as these types of dwelling place less pressure on the ground beneath the house or structure.

Much research has been done on lightweight building bricks such as, Dimitrov, Ivanova (2017) and Beal, Selby, Atwater, James, Viens, Almquist (2019). These studies reviewed the relationship between lightweight fillers to normal aggregate in construction bricks. In these studies, mixtures were varied to create an optimal recipe that not only reduces the mass of the brick but also ensured that sufficient strength or structural integrity was retained.

Köksal, DiazGencel and Rabanal (2013), investigated the properties of the cement mortar modified with styrene-acrylic ester copolymer. were investigated. Exfoliated vermiculite as a lightweight aggregate was used for making the polymer-modified mortar test specimens. Tests showed that the bulk density and thermal conductivity of the specimens decreased, whereas the water absorption and porosity increased. Conversely, flexural and compressive strengths decreased with increases in the percentage of exfoliated vermiculite in the mortar mixture. The study also found that the thermal conductivity measured in W/mK of cement bricks reduced as the volume of exfoliated vermiculite increased.

The research was also done on how to improve the thermal insulation properties of cement brick. Better thermal insulation properties were achieved by increasing the porosity of the cement bricks by introducing pore-forming additives to the cement. Georgiev, Yoleva, Djambazov, Dimitrov, Ivanova (2017), used exfoliated vermiculite and exfoliated perlite was selected as pore formers. Both materials have very low density and good thermal insulation properties. The results showed an increase in water absorption and apparent porosity compared to fired pure clay bricks, but more importantly lower thermal conductivity.

In an additional paper Beal, Selby, Atwater, James, Viens, Almquist (2019), studied the thermal and mechanical properties of fired clay bricks were. Clay bricks containing three different pore-forming additives were investigated. The additives included three types: inorganic (vermiculite), organic (sawdust), and ash (wood ash). In this study, the trends in bulk density, porosity, water absorption, compressive strength, and thermal conductivity were investigated. The study found that vermiculite as an additive decreased thermal conductivity.

All of the research conducted on porous additives in brick making came to the same conclusion, namley that the use of exfoliated vermiculite in building bricks reduced the bulk density, reduced the thermal conductivity and decreased the compressive strength of the building brick. In the literature review, no published research on the various commercially available sizes of exfoliated vermiculite nor the structural integrity of such brick when exposed to fire could be found indicating a gap in the research.

This report will draw from some of the methods used in the studies cited to conduct tests on bricks with different ratios of exfoliated vermiculite to sand. As a variation, batches of cement bricks will also contain three different sizes of exfoliated vermiculite: micron, super fine and fine. The particle size distribution (PSD) of micron grade range between 0.18 to 1mm, super fine between 0.355 and 2mm and a fine between 0.355 and 2.8mm.

3. Problem Statement

Due to the mass of the common cement bricks used in the building industry, there are many more male than female brick-layers. To create equal opportunities for women one of the main hurdles to overcome is the mass of the cement brick. A bricklayer lays up to 500 bricks a day each weighing 2.3 kg. In other words, a bricklayer will pick up and place 1.15t bricks per day.

Once a dwelling (house) is completed, the brick gives structural integrity, but limited insulation to the outside environment as interior spaces require either heating in winter and/or cooling in summer.

Home fires are therefore common in winter months as open flame heaters such as paraffin heaters or fireplaces are used to warm the interiors of such dwellings. These heating methods frequently lead to home fires and the subsequent structural damage to building bricks in such fires requires that most fire-damaged walls be demolished and rebuilt with new bricks.

To find the perfect ratio of an aggregate made up of a mixture of exfoliated vermiculite and building sand that will render a strong yet lightweight brick even after fire damage. In addition, three different sizes of exfoliated vermiculite will be used to see if this influences the result.

Research Question and Hypothesis:What is the perfect ratio of three common sizes of exfoliated vermiculite each to sand, to make a lightweight brick that is still suitable for the construction industry? To be suitable the mixture must render a brick that retains sufficient strength, retains its structural integrity after exposure to an open flame, has good insulating properties and must weigh less than a standard cement brick (Fig. 1) .

Fig. 1: (Left to Right) Grades of exfoliated vermiculite fine, super fine and micron (Picture: P.A. Huysamen)

The perfect ratio for a suitable lightweight brick is such that exfoliated vermiculite will replace 50% of the volume of coarse sand used in a standard 8:1 (sand to cement) ratio cement brick. The compression strength-to-mass value of this lightweight brick will be as good as that of normal cement brick, but its mass will be significantly less, have better insulation properties, and its compression strength-to-mass value will be greater than that of a standard cement brick after both have been exposed to a simulated fire (Figs. 2 and 3).

Fig.2: Sample brick M5/3 -1: five volume portions exfoliated micron grade vermiculite, three-volume portions sand and one volume portion cement (Picture: P.A. Huysamen)

Fig. 3: Control sample brick C -1: eight volume portions sand and one volume portion cement (Picture: P.A. Huysamen)

4. Materials and Method

4.1. Mass

Variables:

- Independent variable: Sample bricks with various sizes and volume ratios of exfoliated vermiculite.
- Dependent variable: The mass of the sample bricks.
- Constant variable: The dimensions of the sample bricks.

Materials

- Digital scale with a measurement scale in milligrams
- A sheet of paper
- Pencil

Procedure :

1. Place a sample brick on a scale that has been set to zero.
2. Allow the digital display to stabilise.
3. Record the mass of the sample brick on a tabled sheet.
4. Repeat the proses until all 30 sample bricks are weighed.

4.2. Strength

Variables:

- Independent variable: The downward pressure applied to the sample brick.
- Dependent variable: The downward pressure at which the brick falls.
- Constant variable: The dimensions of the sample bricks and placement position on the hydraulic press. The rate at which the force on the press plate is increased.

4.3. Materials

- A workshop hydraulic press with gauge
- Flat steel press plate
- Flat base plate with markings
- Cellular phone with video capability
- A sheet of paper
- Pencil

Procedure:

1. Place the sample brick on the base plate with the top face facing upwards.
2. Ensure the sample brick is placed within the predetermined markers on the fixed base plate.
3. Place a steel press plate on top of the sample brick to ensure the applied pressure is evenly spread across the top face of the sample brick.
4. Start a recording of the pressure gauge.
5. Apply an increasing load onto the press plate increasing it at a steady rate until the sample brick fails.
6. Stop the recording.
7. Review the video footage in slow motion and record the pressure at which the pressure suddenly reduced (this is the point where the brick failed).
8. Repeat the proses until all 20 sample bricks are tested (Figs. 4 and 5).

4.4. Open Flame Structural Integrity Test

Variables:

- Independent variable: The downward force applied to the flame exposed sample brick.
- Dependent variable: The downward force at which the brick fails.
- Constant variable: Exposure time of the sample brick to the flame of a butane torch. Position at which the flame makes contact with the sample brick surface.

Fig. 4: An example of a crushed sample brick (Picture: P.A. Huysamen)

Fig. 5: A typical workshop hydraulic press Picture: (RP-20T, n.d)

4.4.1 Materials

- Non-flammable tile or paver
- Butane torch
- Ruler
- Stopwatch
- A workshop hydraulic press
- Flat base plate
- Press plate
- Cellular phone with video capability
- A sheet of paper
- Pencil

Procedure :

1. Place a sample brick onto the non-flammable surface i.e. tile or paver.
2. Ignite the butane torch.
3. Place the butane torch a set distance away from the sample brick at which the open flame contacts the sample brick at a predetermined position.
4. Allow the flame to stay in contact with the brick for 2 minutes.
5. Remove the flame from the brick and extinguish the flame.
6. Allow the brick to cool for 20 minutes.
7. Place the sample brick on the base plate with the top face facing upwards.
8. Ensure the sample brick is placed within the predetermined markers on the fixed base plate.
9. Place a steel press plate on top of the sample brick to ensure the applied pressure is evenly spread across the top face of the sample brick.
10. Start a recording of the pressure gauge.

11.Apply an increasing load onto the press plate increasing it at a steady rate until the sample brick fails.
12.Stop the recording.
13.Review the video footage in slow motion and record the pressure at which the pressure suddenly reduced (this is the point where the brick failed).
14.Repeat the proses until all 10 sample bricks are tested (Fig. 6).

Fig. 6: Sample brick after being exposed to a butane torch flame for 2 minutes (Picture: P.A. Huysamen)

4.5. Insulation

Variables:
-Independent variable: Sample bricks with various sizes and volume ratios of Vermiculite.
-Dependent variable: The temperature of the exposed side of the sample brick.
-Constant variable: Exposure temperature, time and sample brick dimensions.
Materials
-Non-flammable tile or paver
-Butane torch
-Ruler
-Carpenters Pencil
-Stopwatch
-A sheet of paper
-Infrared electronic temperature gauge
-Pencil
Procedure:
1.Using a pencil draw two well-defined crosses on the bottom face of the sample brick 3cm apart.
2.Place a sample brick onto the non-flammable surface i.e. tile or paver.
3.Turn the sample brick on its side with the crosses facing the side of the butane torch.
4.Ignite the butane torch.
5.Place the butane torch a set distance away from the sample brick ensuring the flame strikes one of the marked crosses.
6.Allow the flame to heat the brick until the temperature at the unheated cross reaches 400 ºC as measured with an infrared temperature gauge.
7.Remove the flame from the brick and extinguish the flame.
8.Continue to take surface temperature readings at the second cross position at 10-seconds intervals for 60 seconds.
9.Record the temperature readings in a set table format.
10.Repeat the process until all 10 sample bricks are tested (Figs. 7 and 8).

Fig. 7: Picture 7: Two crosses 3cm apart in the centre of the bottom brick face (Picture: P.A. Huysamen)

Fig. 8: Surface temperature readings were taken 3cm from the flame impact point (Picture: P.A. Huysamen)

5. Results

All the sample bricks were weighed, and the average mass of each mixture was calculated. This was done to determine the mass of each mixing ratio required to calculate the average compression strength-to-mass ratio of each mixing ratio and for the mass, comparison stated in the hypothesis. The volume of exfoliated vermiculite in the different sample bricks was found to be directly correlated to the mass of the brick. The mass of the sample bricks containing exfoliated vermiculite was found to be on average 31.3% lower than the control cement brick (C) made from sand and cement at a volume ratio of 8:1. The relationship of all the specimens to the control brick can be seen in table (1), figures (9 and 10). Even the mass of the heaviest brick was 26.6% lower than the control. This is in accordance with the hypothesis.It is clear that the control sample bricks C (1-3) were on average the heaviest. Sample bricks M 6/2 (1-3) were on average the lightest. Also apparent is that sample bricks containing exfoliated vermiculite were all lighter than the batch average of control sample bricks C.

Table 1: Individual and batch average mass in kg of the different sample bricks

Different Sample Bricks	Mass (kg)	Sample Brick Batches	Batch Average Mass (kg)
C-1	0.196	C	0.195
C-2	0.197		
C-3	0.191		
M 4/4-1	0.140	M 4/4	0.140
M 4/4-2	0.137		
M 4/4-3	0.143		
M 5/3-1	0.126	M 5/3	0.126
M 5/3-2	0.123		
M 5/3-3	0.128		
M 6/2-1	0.104	M 6/2	0.106
M 6/2-2	0.108		
M 6/2-3	0.105		
SF 4/4-1	0.140	SF 4/4	0.141
SF 4/4-2	0.140		
SF 4/4-3	0.144		
SF 5/3-1	0.124	SF 5/3	0.125
SF 5/3-2	0.127		
SF 5/3-3	0.123		
SF 6/2-1	0.110	SF 6/2	0.108
SF 6/2-2	0.106		
SF 6/2-3	0.109		
F 4/4-1	0.141	F 4/4	0.143
F 4/4-2	0.143		
F 4/4-3	0.145		
F 5/3-1	0.134	F 5/3	0.135
F 5/3-2	0.132		
F 5/3-3	0.138		
F 6/2-1	0.120	F 6/2	0.119
F 6/2-2	0.122		
F 6/2-3	0.116		

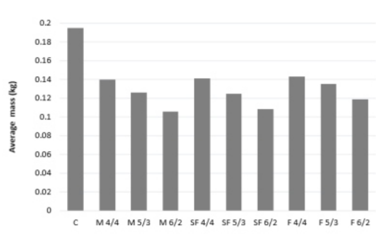

Fig. 9: Average mass in kg of the different sample bricks

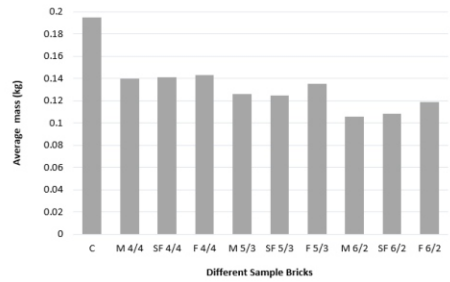

Fig.10: The average mass of the similar mix ratio sample bricks in kg

To determine the compression strength-to-mass value of the sample bricks each sample was crushed in a hydraulic press. This test was performed to assess the hypothesis that the compression strength-to-mass value of bricks will not be significant compromised by replacing a volume portion of the sand in a cement brick with exfoliated vermiculite. The volume ratio of exfoliated vermiculite to sand in the different sample bricks was found to have a direct correlation to the compression strength-to-mass value of the bricks. The compression strength of bricks containing vermiculite was on average 35.7% lower than the control brick made from sand and cement. The impact different volume ratio mixtures had on the compression strength of the sample brick can be seen in Table (2) and Figure (11). Dividing the batch average maximum compression strength of the sample bricks by the same batch average mass presented a different outcome (Table 3 and Fig. 12).

Table 2: The pressure at which the sample bricks failed

Individual Sample Bricks	Press Gauge Readings (kPa) at Failure	Press Force (N) at failure	Pressure on Brick (Pa) at failure	Sample Brick Batches	Ave Batch Pressure (Pa) at failure
C-1	970	1,627	4,089,692	C	4,026,450
C-2	940	1,576	3,963,207		
M 4/4-1	700	1,174	2,951,324	M 4/4	2,909,163
M 4/4-2	680	1,140	2,867,001		
M 5/3-1	700	1,174	2,951,324	M 5/3	3,035,648
M 5/3-2	740	1,241	3,119,972		
M 6/2-1	560	939	2,361,060	M 6/2	2,403,221
M 6/2-2	580	973	2,445,383		
SF 4/4-1	580	973	2,445,383	SF 4/4	2,656,192
SF 4/4-2	680	1,140	2,867,001		
SF 5/3-1	680	1,140	2,867,001	SF 5/3	2,909,163
SF 5/3-2	700	1,174	2,951,324		
SF 6/2-1	600	1,006	2,529,707	SF 6/2	2,487,545
SF 6/2-2	580	973	2,445,383		
F 4/4-1	460	771	1,939,442	F 4/4	1,981,604
F 4/4-2	480	805	2,023,765		
F 5/3-1	640	1,073	2,698,354	F 5/3	2,677,273
F 5/3-2	630	1,057	2,656,192		
F 6/2-1	580	973	2,445,383	F 6/2	2,234,574
F 6/2-2	480	805	2,023,765		

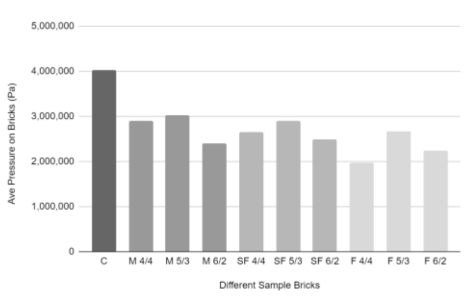

Fig. 11: The average pressure (Pa) on the different sample brick batches at failure

The average compression strength-to-mass value of sample bricks containing exfoliated vermiculite was on average 0.6% lower than the value of the control brick. It can therefore be argued that the results are aligned with the hypothesis.

This average was affected by the size of exfoliated vermiculite used to replace volumes of sand. The average compression strength-to-mass value of bricks containing fine grade exfoliated vermiculite (three different mixing ratios) was 15.5% lower than the value of the control brick. In contrast, the average compression strength-to-mass value of super fine and micron grade ratios respectively 4.9% and 9.1% greater than that of the control brick. These two ratios are then as stated in the hypothesis, as good as the normal cement brick. Table (2) and figure (11) show that the control cement bricks C 1-2 are on average the strongest and sample bricks F4/4 1-2 on average the weakest. It also shows that sample bricks containing vermiculite are substantially weaker.

Table 3: The average compression strength-to-mass ratio of different brick batches

Sample Brick Bathes	Ave Pressure on Brick (Pa) at failure	Average mass (kg)	Compression Strength-to-mass ratio (Pa/kg)
C	4,026,450	0.195	20,683,817
M 4/4	2,909,163	0.140	20,779,733
M 5/3	3,035,648	0.126	24,156,350
M 6/2	2,403,221	0.106	22,743,420
SF 4/4	2,656,192	0.141	18,793,811
SF 5/3	2,909,163	0.125	23,335,529
SF 6/2	2,487,545	0.108	22,961,953
F 4/4	1,981,604	0.143	13,857,368
F 5/3	2,677,273	0.135	19,880,739
F 6/2	2,234,574	0.119	18,725,482

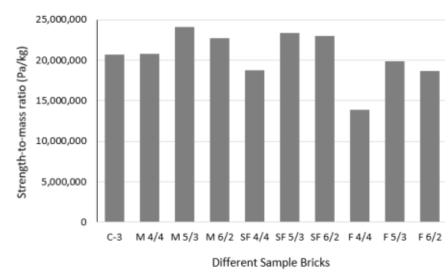

Fig 12: The compression strength-to-mass ratio of different sample brick batches

Table (3) and figure (12) show that the average of the sample brick batch M 5/3 has the highest compression strength-to-mass ratio. The average batch sample bricks with the lowest compression strength-to-mass ratio were F4/4.The average of the batch control sample brick's compression strength-to-mass ratio was the sixth highest.

All the different sample bricks were exposed to a butane flame for 2 minutes and then crushed with the use of a hydraulic press. This was done to simulate the loss of structural integrity or reduction in maximum compression strength after brick is exposed to fire.

The results of this test were as expected. The compression strength-to-mass value of the cement control brick was reduced by 21% (20.7 MPa to 16.3 MPa) after it was exposed to the butane flame. In comparison, the average compression strength-to-mass value of bricks containing exfoliated vermiculite was reduced by 10.6% (20.6 MPa to 18.4 MPa) only. The average compression strength-to-mass value of all sample bricks containing exfoliated vermiculite, after its exposure to a butane flame, was 12.6% (18.4 MPa versus 16.3 MPa) higher than that of the control brick (Table 4 and Fig.13). The hypothesis was confirmed, the sample bricks containing exfoliated vermiculite were substantially stronger than the cement and sand sample bricks. It shows that the control sample brick C-3 after it was exposed to a butane torch flame, weakened the most if compared to the average of the control C. In comparison sample brick F6/2 -3 weekend the least when compared to the average of the sample bricks F6/2. Sample bricks

bricks containing vermiculite weakened by the lowest margin after it was exposed to a butane torch flame.

Table 4: The compression strength-to-mass ratio of burnt and unburnt sample bricks

Burnt Sample Bricks		Unburnt Sample Bricks	
Sample Brick Batches	**Compression Strength-to-mass ratio (Pa/kg)**	**Sample Brick Batches**	**Compression Strength-to-mass ratio (Pa/kg)**
C-3	16,334,932	**C**	20,683,817
M 4/4-3	17,395,420	**M 4/4**	20,779,733
M 5/3-3	21,410,281	**M 5/3**	24,156,350
M 6/2-3	22,005,410	**M 6/2**	22,743,420
SF 4/4-3	15,517,875	**SF 4/4**	18,793,811
SF 5/3-3	20,223,943	**SF 5/3**	23,335,529
SF 6/2-3	22,047,899	**SF 6/2**	22,961,953
F 4/4-3	13,084,690	**F 4/4**	13,857,368
F 5/3-3	15,276,007	**F 5/3**	19,880,739
F 6/2-3	18,536,647	**F 6/2**	18,725,482

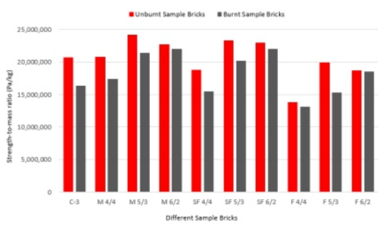

Fig. 13: The compression strength-to-mass ratio of burnt and unburnt sample bricks

A single specimen of each sample size batch was exposed to a butane torch flame until the surface temperature 3cm away from the flame centre reached 400°C. The flame was then removed, and the temperature was measured over 60 seconds at 10-second intervals. The rate at which the temperature reduced was used to test the hypothesis that bricks containing exfoliated vermiculite will have better insulation properties than normal cement brick.

The use of exfoliated vermiculite in the different sample bricks was found to be directly correlated to the length of time it took for the brick to cool down. The temperature of the sample bricks containing vermiculite was on average 34.7% cooler than the control cement sample bricks after 50 seconds. Some sample bricks were more than 40% cooler after 50 seconds (Table 5 and Fig. 14). The data illustrate that the bricks containing exfoliated vermiculite did not absorb as much heat (the core of the sample brick did not heat up as much) and were able to dissipate the little heat build-up at a higher rate. This confirms the hypothesis that bricks containing exfoliated vermiculite will have better insulation properties.

Table 5: The temperature (°C) of the different sample bricks was measured over 60 seconds

Different Sample Bricks	**Temp (°C) - 0 sec**	**Temp (°C) - 10 sec**	**Temp (°C) - 20 sec**	**Temp (°C) - 30 sec**	**Temp (°C) - 40 sec**	**Temp (°C) - 50 sec**	**Temp (°C) - 60 sec**
C-3	400	210.6	152.8	125.9	114.5	105	89.8
M 4/4-3	400	173.3	124.1	99.1	89.5	77.8	72.3
M 5/3-3	400	142	104.7	82.9	71.2	61.7	58.2
M 6/2-3	400	119.5	91.6	76.6	65.2	56.9	54.1
SF 4/4-3	400	169	125.8	105.2	87.6	76.9	69.9
SF 5/3-3	400	174.3	127.8	105.5	94.6	84.7	75.3
SF 6/2-3	400	154.1	110.1	91	75.2	66	64.1
F 4/4-3	400	170.9	118.1	100.4	79.4	67	62.9
F 5/3-3	400	191	109.9	86.3	74.9	65.1	62.7
F 6/2-3	400	146.3	98.4	77.9	65.5	60.8	56.4

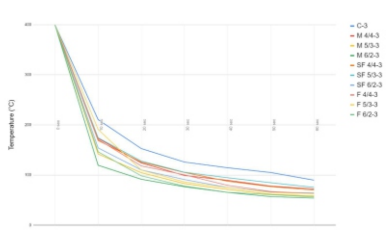

Fig. 14: The temperature (°C) of the different sample bricks was measured over 60 seconds

It shows that the control sample brick C-3 took the longest time to cool down after being exposed to a butane torch flame. Sample brick M6/2 -3 with the highest content of exfoliated vermiculite cooled down the fastest. All sample bricks containing exfoliated vermiculite cooled down at a more rapid rate than the control sample brick C-3.

6. Discussion

This study was undertaken to find the perfect ratio of three common sizes of exfoliated vermiculite each to sand. The aim was to develop a lightweight brick that is still suitable for the construction industry. To be suitable the mixture must render a brick that retains sufficient strength, retains its structural integrity after exposure to an open flame, has good insulating properties and must weigh less than a standard cement brick.

Weighing each sample brick revealed that the sample bricks containing six volume portions of micron grade exfoliated vermiculite had the lowest mass. In other words, six of the eight sand volume portions were replaced by micron-grade exfoliated vermiculite. The average mass of the M 6/2 sample brick batch was 0.106 kg, 42.0% lighter than the average of the control sample brick batch C. The average mass of the control sample brick batch was 0.195 kg and contained eight volume portions of sand. All the sample bricks containing exfoliated vermiculite weighed significantly lighter than any of the control sample bricks C 1-3. The heaviest sample bricks with exfoliated vermiculite contained 50% fine grade exfoliated vermiculite and 50% sand. The average mass of this batch labelled F 4/4 was 0.143 kg. The latter was 24.7% lighter than the average sample brick batch C.

A clear trend was identified in that the lightest group sample bricks all contained six volume portions of exfoliated vermiculite and two volume portions of sand. The second lightest group sample brick contained five volume portions of exfoliated vermiculite and three-volume portions of sand. The heaviest group sample brick contained equal volume portions of sand and exfoliated vermiculite. This highlights the trend that the mass of the sample bricks is related to the volume content of exfoliated vermiculite. Analyzing the sample bricks made with micron exfoliated vermiculite revealed that the reduction in mass is not directly proportional to the volume increase of exfoliated vermiculite. As the volume of exfoliated vermiculite increases by 13% from sample M 4/4 to M 6/2, the average sample brick mass reduced by 10.0% and 5.9%. These results echo those achieved in the research done by Köksal , Coz Diaz , Gencel and Rabanal (2013). Theyfound that by increasing the exfoliated vermiculite to sand ratio in a mixture containing 10% cement the dry bulk density decreased. Increasing the exfoliated vermiculite to sand ratio from 3:1 to 6:1 dry bulk density reduced by 22.8%. Increasing the mixture ratio from 6:1 to 9:1 reduced the bulk density further, this time by 12.4%.

A trend was noticed during the mass tests. Comparing the same ratio mixtures it was clear that the finest grade in a specific ratio blend was the lightest and the largest grade the heaviest. This could not be explained against the bulk density of each grade as the bulk density increases as the exfoliated vermiculite size decreases. Typically, the bulk density of micron and super fine grades exfoliated vermiculite is 125 g/l and that of fine grade exfoliated vermiculite 112 g/l. The only plausible explanation is that a measured volume of micron grade vermiculite contained more particles than the coarser grades of exfoliated vermiculite. This is supported by the Particle size distribution (PSD) analysis mentioned earlier in the report. And because the ratio blends were done per volume measure the finest grade displace more sand particles.

A pure strength test revealed that sample bricks containing vermiculite were on average 35.7% weaker than the average of the control sample bricks C, as shown in Table 2. The strongest sample brick was as expected the control cement brick C-1. The strongest sample brick containing exfoliated vermiculite contained five volume portions of micron exfoliated vermiculite and three-volume portions of sand and is labelled M 5/3 -2 .

The weakest sample brick labelled F 4/4 -1 contained 4 volume portions fine grade exfoliated vermiculite to 4 volume portions of sand. This unexpected trend was also noticed in other blend sizes. It was thought that this ratio would be the strongest. It was thought that the higher volume of sand in the sample bricks will increase their strength.

A trend was identified showing that the 5:3 ratio (five volume portions of exfoliated vermiculite to three volume portions of sand) was consistently the strongest ratio of each exfoliated vermiculite size range . The strength of the sample bricks also gradually decreased as the exfoliated vermiculite used in the mixtures increased in size and volume, from micron (finest) to fine (coarsest) grade and from a mix ratio of 5:3 to 6:2. These results are built on past research done by Georgiev, Yoleva, Djambazo\v, Dimitrov, Ivanova (2017). The researchers found that baked clay bricks with exfoliated vermiculite as an additive affected the strength of clay bricks as the volume percentage of vermiculite increased. The compression strength of baked clay bricks was on average 24 MPa and reduced to 17 MPa, 15 MPA and 12 MPa as the percentage of exfoliated vermiculite in the mixture increased from 3% to 5% and 8%. This trend was also evident in this research and compression strength was reduced when the mix ratio, vermiculite to sand increased from 5:3 to 6:2. The compression strength of the micron mixture was reduced by 20.8%, super fine by 14.5% and fine by 16.5%.

The trend was reversed when a compression strength-to-mass analysis was done. Reviewing the compression strength-to-mass analyses the strongest average sample brick by mass was the M 5/3 sample bricks. Of all the sample bricks tested, the batch average of the control sample bricks, labelled C, rated sixth. As with the strength analyses, the 5:3 ratio sample bricks were the strongest in each exfoliated vermiculite size category, followed by the 6:2 ratio, placing the 4:4 ratio last again. The sample bricks containing micron exfoliated vermiculite were again stronger by mass than the sample bricks containing super fine exfoliated vermiculite, which in turn was stronger than the sample bricks containing fine (largest size) exfoliated vermiculite. This analysis provides new insight into the strength review of bricks containing exfoliated vermiculite as it would suggest that taller structures could be built with these bricks. A quick calculation reveals that 9,291 control sample bricks C having a 0.0045m² area of compression can be stacked one on top of the other before the bottom sample brick reaches its failure compression strength of 4.026 MPa. In comparison a staggering 10,841 (M 5/3) sample bricks can be stacked one on top of the other before the bottom sample brick reaches its failure compression strength of 3.035 MPa.

The open flame structural integrity test results showed a significant reduction in structural integrity after a sample brick was exposed to a 1,400°C butane flame. Noticeable was that the strength of all sample bricks containing exfoliated vermiculite was less affected by the open flame test. The compression strength-to-mass of sample brick C - 3 was reduced by 21.0% compared to an average reduction of the vermiculite samples of only 10.6%. Sample bricks containing 5 volume portions of exfoliated vermiculite to 3 volume portions of sand were on average the strongest before the burn test. Once exposed to the butane flame burn test its average compression strength-to-mass value was below that of the 6:2 ratio sample bricks. The compression strength-to-mass value of the 6:2 sample bricks was reduced by the lowest average percentage of 2.7% compared to 16.0% of the 5:3 mix ratio and 13.9% of the 4:4 mix ratio sample bricks. This can be explained by its high exfoliated vermiculite concentration as it benefited from the insulation properties of this material.

The experiment provides new insight into the use of exfoliated vermiculite in construction. No research articles were found in which the structural integrity of bricks containing exfoliated vermiculite was studied after it was exposed to fire. In the insulation test, the volume of exfoliated vermiculite used in the different sample bricks influenced the rate of heat loss. The results from heating each brick till the measuring point reached 400°C and then letting it cool down in a room at 20°C are summarized .

After 50 seconds the surface temperature of the exfoliated vermiculite sample was on average 34.7% cooler than the control sample brick C-3. The highest variance after 50 seconds compared to the sample brick C-3 a was 48.1°C. The test result highlighted a clear trend, the bricks containing vermiculite cooled down faster. This trend further increased as the volume ratio of exfoliated vermiculite increased in the sample bricks. The cooling down tempo relates to how much heat energy was stored in the sample brick. Therefore, a sample brick that cooled down faster stored less heat energy and therefore had better insulation properties. This view is supported by D Green, R Perry (2015).

Sample brick M 6/2 -3 had the best insulation properties and it coincided with the largest volume ratio of exfoliated vermiculite. This sample brick also contained the smallest size of exfoliated vermiculite which in theory replaced the largest amount of sand particles. These findings build on existing evidence of research done by Betty Beal, Audriana Selby, Colin Atwater, Christina James, Christopher Viens, and Catherine Almquist (2019). The study found that at a 25% concentration of the mass fraction made up of exfoliated vermiculite in clay bricks, the thermal conductivity decreased by 20%.

This was also the finding in the paper, by Köksal , Coz Diaz , Gencel and Rabanal (2013), The study found that the thermal conductivity measured in W/mK of a cement brick reduced as the volume of exfoliated vermiculite increased. At a fixed 10% cement by total volume the exfoliated vermiculite volume ratio to sand was increased from 3:1, 6:1 and 9:1. Thermal conductivity reduced from 0.536 W/mK to 0.514 W/mK and then 0.377 W/mk respectively. This study found a similar trend, the heat loss measured in degrees Celsius over the first 10 seconds was the greatest with a mix ratio of 6:2 followed by 5:3 and then 4:4. The temperature reading reduced respectively by 65.0%, 57.7% and 57.2%.

Having analysed all the test results, it can be seen that there is no one, clear way to choose the best performing sample brick. A statistical scoring system was therefore devised and presented in Table (6). In this table, a score of 10 was assigned to the best performing sample brick and a score of 1 to the worst performing sample brick. This was done for each test and subsequent derivative. To maintain consistency, the control sample brick made from sand and cement only was included in the scoring system.

Table 6: Statistical Scorecard

Sample Bricks Batches	Mass Test	Compression Strength-to-mass ratio Unburnt	Compression Strength-to-mass ratio Burnt	Insulation Test	Total
C	1	5	4	1	11
M 4/4	4	6	5	3	18
M 5/3	6	10	8	8	32
M 6/2	10	7	9	10	36
SF 4/4	3	3	3	4	13
SF 5/3	7	9	7	2	25
SF 6/2	9	8	10	6	33
F 4/4	2	1	1	9	13
F 5/3	5	4	2	5	16
F 6/2	8	2	6	7	23

As can be seen from the above table the sample brick batch M 6/2 reflected the highest score. This sample brick scored the highest in two categories, namely mass and insulation and performed the second best in the compression strength-to-mass test after the sample bricks were exposed to a butane flame. It can therefore be deduced that based on this scorecard the sample bricks M 6/2 were on average the best performing brick.

7. Limitations and Errors

Some limitations in the testing equipment were identified the greatest of which was the hydraulic press. The fact that it was a manual, hand pump version, resulted in an uneven pressure increase. Ideally, a hydraulic press with a hydraulic pump would have been preferred as such a unit would have resulted in an even pressure gradient increase.

There were also pressure gauge limitations on the unit, the dial scale of the gauge was almost three times the range required meaning sighting errors crept in as it was necessary to estimate values when the pointer was between markings on the dial. A lower pressure gauge would have resulted in more exact readings.

8. Recommendations for Future Research

To better understand why a 50:50 (exfoliated vermiculite to sand) ratio sample brick was weaker than the 5:3 and 6:2 ratio (exfoliated vermiculite to sand) bricks, more studies could be done to confirm or refute this finding.

A more conclusive insulation test should be performed to test the insulation properties of bricks containing exfoliated vermiculite. Linking to this test a real fire simulation under controlled conditions would confirm if bricks containing exfoliated vermiculite are indeed more structural intact after a fire as this research project concluded.

9. Conclusion

The research aimed to prove a hypothesis. The perfect ratio for a suitable lightweight brick is such that exfoliated vermiculite will replace 50% of the volume of coarse sand used in a standard 8:1 (sand to cement) ratio cement brick. The compression strength-to-mass value of this lightweight brick will be as good as that of normal cement brick, but its mass will be significantly less, have better insulation properties, and its compression strength-to-mass value will be greater than that of a standard cement brick after both have been exposed to a simulated fire, and the series of tests did exactly that. The original hypothesis was generally correct.

It was found that the best performing batch of sample bricks, M 6/2 replaced 75% sand with exfoliated vermiculite. The hypothesis predicted 50%. The sample bricks containing exfoliated vermiculite were substantially weaker than the control sample brick batch C when reviewing the compression strength data only. However, when the failure pressure was reworked as a function of mass, sample brick batch M 6/2 was 9.96% stronger than the control batch C.

The tested mix ratios increased beyond the hypothesis which would strictly nullify the winning batch M 6/2 which weighed 45.8% less than the control batch C. To compensate for this, 50% ratios as per the hypothesis was analysed and it was determined that the average mass of the batch containing 50% exfoliated vermiculite still weighed 27.5% less than the standard batch C. This is again in line with the hypothesis.

The compression strength-to-mass value of the best performing batch M 6/2 was 9.96% above that of the control batch C. The compression strength-to-mass value of control brick C-3 was reduced by 21.0% after the simulated fire test compared to a mere 3.2% reduction of sample brick M 6/2 -3. It is therefore deduced that bricks filled with expanded vermiculite will be stronger per mass than normal cement brinks even after it has been exposed to a fire. This deduction is also in line with the hypothesis.

The research illustrated that a fine, exfoliated vermiculite is a better filler material than a coarser grade if used as a filler to reduce the mass of standard cement brick. More importantly, the study demonstrated that when the replacement volume ratio of sand exceeds 60% the bricks are stronger by mass than a standard cement brick. The significance of this was mentioned in the report. Due to the lightness and relative strength of the bricks, regulatory brick layer height can be achieved therefore such bricks have no limiting factor in normal wall construction. The significant mass saving would then also assist in drawing more women into this male-dominated market which will empower women and transfer skills to a new social grouping.

Acknowledgements

Throughout the writing of this report, I have received a great deal of support and assistance. I would first like to thank my teacher, Mrs Milandré Bezuidenthout, whose expertise was invaluable in formulating the research questions and methodology. Her insightful feedback pushed me to sharpen my thinking and brought my work to a higher level. I would also like to thank André Huysamen and Tanya Huysamen, my parents, for their wise counsel, a sympathetic ear, and assistance in writing, designing and editing this report.

References

[1] Alberternst, R., 2020. How many bricks can a bricklayer lay in a day?. [online] Findanyanswer.com. Available at: <https://findanyanswer.com/how-many-bricks-can-a-bricklayer-lay-in-a-day> [Accessed 7 March 2021].

[2] Beal, B., Selby, A., Atwater, C., James, C., Viens, C. and Almquist, C., 2019. A comparison of thermal and mechanical properties of clay bricks prepared with three different Pore-Forming additives: Vermiculite, wood ash, and sawdust. Environmental Progress & Sustainable Energy, 38(6), p.13150.

[3] Georgiev, A., Yoleva, A., Djambazov, S., Dimitrov, D. and Ivanova, V., 2018. Effect of exfoliated vermiculite and exfoliated perlite as pore forming additives on the physical properties and thermal conductivity of porous clay bricks.

. J. Chem. Technol. Metall, 53(2), pp.275-280.

[4] Grant, A., 2021. Gardening With Vermiculite - Vermiculite Uses And Information. [online] Gardening Know How. Available at: <https://www.gardeningknowhow.com/garden-how-to/soil-fertilizers/vermiculite-growing-medium.htm> [Accessed 2 July 2021].

[5] Grunert, J., 2021. [online] Garden.lovetoknow.com. Available at: <https://garden.lovetoknow.com/wiki/Vermiculite_for_Gardening> [Accessed 14 June 2021].

[6] Koksal, F., del Coz Diaz, J.J., Gencel, O. and Alvarez Rabanal, F.P., 2013. Experimental and numerical analysis of new bricks made up of polymer modified-cement using exfoliated vermiculite. Computers and Concrete, 12(3), pp.19-36.

[7] Mandovalvermiculite. 2021. Mandoval | Passive Fire Protection Products. [online] Available at: <https://www.mandovalvermiculite.co.za/> [Accessed 5 July 2021].

[8] McMahon, M., 2021. What is Vermiculite? (with pictures). [online] All Things Nature. Available at: <https://www.allthingsnature.org/what-is-vermiculite.htm> [Accessed 10 June 2021].

[9] Rabello, L.G. and da Conceição Ribeiro, R.C., 2021. A novel vermiculite/vegetable polyurethane resin-composite for thermal insulation eco-brick production. Composites Part B: Engineering, p.109035.

[10] Rashad, A.M., 2016. Vermiculite as a construction material–A short guide for Civil Engineer. Construction and Building Materials, 125, pp.53-62.

[11] Shiffler, A., 2021. Vermiculite: Uses for growing plants, safety, and comparison to Perlite. [online] Herbs at Home. Available at: <https://herbsathome.co/what-is-vermiculite/> [Accessed 2 July 2021].

[12] Sutcu, M., 2015. Influence of exfoliated vermiculite on physical properties and thermal conductivity of clay bricks. Ceramics International, 41(2), pp.2819-2827.

[13] The Editors of Encyclopaedia Britannica, 2021. Vermiculite | mineral. [online] Encyclopedia Britannica. Available at: <https://www.britannica.com/science/vermiculite> [Accessed 4 April 2021].