

Compressive Strength, Water Absorption and Thermal Performance of One-part Geopolymer Concrete-based Alternative Masonry Units

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Abstract

The reliance on conventional clay and cement-based masonry units in South Africa has demonstrated unfavourable environmental impacts while failing to meet the country's affordable housing (AH) demands. The need for alternative building technologies is critical to addressing the current delivery backlog of AH and achieving sustainability. This work explored the development of an alternative solid maxi concrete block through one-part geopolymer chemistry. The fly ash-blast furnace slag (FABS) and the fly ash-metakaolin (FAMK) based one-part geopolymer concrete alternative masonry unit (AMU), activated by solid sodium hydroxide, powdered calcium hydroxide and solid sodium metasilicate pentahydrate, were developed and evaluated for compressive strength, water absorption, initial rate of absorption (IRA), and thermal performance. A 28-day compressive strength of 18.4 MPa and 6.1 MPa is obtained for the FABS and FAMK units, respectively. Furthermore, a 5.4% and 9.6% cold water absorption, 8.3% and 10% boiled water absorption, 0.2 kg/m²/min and 0.3 kg/m²/min IRA, and thermal resistance (R-value) of 0.11 m²°C/W and 0.13 m²°C/W are found for the FABS and FAMK unit, respectively. These results show that both AMUs have the potential to be used in achieving sustainable construction.

Keywords: Compressive strength, One-part geopolymer concrete alternative masonry unit, Thermal performance, Water absorption.

1. Introduction

For many years, Masonry has served as a valuable construction material in developing human settlements. However, producing conventional clay and concrete-based masonry has brought challenges against sustainable development, primarily due to the high carbon footprint associated with the clay firing and the limestone calcination operations. In addition to the adverse environmental impacts associated with conventional masonry, its application in affordable housing (AH) schemes has created a housing delivery backlog that is concerning due to both material and land prices. The development of low-carbon alternative masonry units (AMUs) incorporating alternative masonry materials should be considered to address both environmental concerns and inadequate AH delivery targets. Such a candidate, which is considered in this work, is the geopolymer.

Geopolymers are formed through the synthesis of rich aluminosilicate materials by high alkaline reagents whereby a three-dimensional aluminosilicate network structure is formed, having great potential to replace cement as they possess high mechanical strength, good thermal properties, and excellent durability (Cong & Cheng, 2021). Geopolymer cement entails the alkali activation of rich aluminosilicate materials such as typical industry wastes comprising fly ash (FA), ground granulated blast furnace slag (GGBFS) and metakaolin (MK). Such supplementary cementitious materials (SCMs) have been used in partial cement replacement to reduce conventional cement production and minimise global industry waste disposal. Also, geopolymer cement is frequently produced using the non-user-friendly and prolonged two-part preparation approach. In contrast, the more user-friendly and quicker one-part preparation approach is used less. Furthermore, geopolymers containing FA and MK are predominantly heat-cured instead of ambient cured like the FA and GGBFS blend.

Hence, this work was limited to the exploration of the one-part preparation approach utilising solid alkali reagents comprising solid sodium hydroxide, powdered calcium hydroxide and solid sodium silicate pentahydrate in the development of the fly ash-ground granulated blast furnace slag (FABS) based and the fly ash-metakaolin (FAMK) based geopolymer concrete masonry unit cured under ambient condition. Specifically, the 290 mm long X 240 mm wide X 90 mm high maxi concrete brick



alternative was only evaluated for compressive strength, water absorption and thermal performance.

2. Literature Review

2.1. Overview of Affordable Housing in South Africa

The presence of informal settlements in South Africa has been of major concern. Previous reports have indicated that as of 2022, over 2700 informal settlements were present in South Africa (Human Settlements | South African Government, 2024). More recent reports show that 12% of South African households reside in informal dwellings, with these informal dwellings mainly concentrated in Gauteng and Western Cape (Human Settlements | South African Government, 2024). In terms of the Constitution of the Republic of South Africa of 1996, the Department of Human Settlements is mandated to establish a sustainable national housing development process with a focus on creating integrated and transformed human settlements, upgrading informal settlements, and providing AH units (Human Settlements | South African Government, 2024).

AH units are typically constructed as Category 1 single-storey buildings. Category 1 buildings were introduced in South Africa to regulate the requirements of buildings in low-income communities so that the health and safety risks associated with unregulated informal settlements are addressed. These buildings are generally smaller in size and occupancy and have lower performance level allowances relating to serviceability than non-Category 1 buildings (De Villiers, 2019).

However, many South Africans who have qualified for state subsidised housing are still without the adequate housing as initially promised to them. Despite a steady increase in government subsidised housing, the main factors affecting AH delivery encompass high building and material costs, lack of suitable land, and increased land prices (Kota-Fredericks, 2013). Kota-Fredericks (2013) encourages the implementation of alternative development strategies so that these challenges may be addressed. Further investigations into alternative building materials, such as developing alternative masonry units (AMUs), may pave the way for reducing materials costs and increasing AH delivery.

2.2. Environmental Impact of Conventional Masonry

In the context of affordable housing (AH) in South Africa, the two common masonry units used for its construction comprise either the solid maxi concrete block, with dimensions of 290 mm long X 140 mm wide X 90 mm high, or the hollow concrete block, with dimensions 390 mm long X 140 mm wide X 190 mm high (De Villiers, 2019). The 222 mm long X 106 mm X wide 73 mm high imperial clay brick is also used. However, clay bricks contribute heavily to carbon dioxide (CO₂) emissions, particularly during their firing stage, whereby the clay material is heated at high temperatures and pressures. The greenhouse gas (GHG) emissions contributing to the environmental burden created by the clay brick industry thus primarily stem from intensive energy consumption through the utilisation of fossil fuels (Kumbhar et al., 2014). Moreover, the production line of concrete masonry units (CMUs) also encompasses significant greenhouse gas emissions attributed to Ordinary Portland cement (OPC) production, which contributes approximately 8% toward global anthropogenic CO₂ emissions primarily due to the calcination of limestone (Hajimohammadi & van Deventer, 2017). The need for AMUs to comply with prescribed performance standards is thus pertinent to the problem.

2.3. Performance Requirements of Masonry Units

2.3.1. Compressive Strength

As per SANS 10400-K (2011), the average compressive strength of solid masonry units for use in a single-storey or the upper-storey of a double-storey building should be at least 4 MPa.

2.3.2. Water Absorption

Water absorption characteristics influence the long-term durability of masonry units. As per IS 2185-1 (2005), a maximum water absorption limit of 10% is stipulated for concrete masonry units. Additionally, SANS 10164-1 (1980) stipulates an IRA between 0.7 and 1.8 kg/m²/min for adequate mortar and unit bonding.

2.3.3. Thermal Performance

In addition to the thermal conductivity (K-value), the most important thermal property for masonry walling systems is its thermal resistance (R-value), as it describes the



ability of the material to resist the transmission of heat flow through the material. This is an essential property during extreme hot and cold periods where sufficient insulation is required for thermal comfort. As per Table 6 and Table 7 in SANS 10400-XA (2021), a minimum R-value is required for walls with a surface density equal to and greater than 270 kg/m^2 or less than 270 kg/m^2 , respectively, depending on the energy zone in which the building is located. However, these R-values only apply to non-Category 1 buildings but may be used for comparison.

3. Research Methods

3.1. Materials

The aluminosilicate precursors used in this work comprise Class F FA, GGBFS and MK. The FA, GGBFS, and MK were sourced from Lafarge Pty (Ltd), Western Cape, Meyerton PPC factory, Gauteng, and Kaolin Group Pty (Ltd), Cape Town, respectively. The aggregates comprising natural fine Malmsbury sand and 13 mm Greywacke stone were sourced from GH Building Supplies, Stellenbosch, Western Cape, South Africa. The chemical composition of each precursor was characterised at the Central Analytical Facility (CAF) of Stellenbosch University using X-ray fluorescence (XRF) analysis and is shown in Fig. 1. The XRF results show an abundance of silica and alumina in FA and MK. In contrast, GGBFS shows richness in silica, alumina, and calcium. The chosen solid alkali activators were solid NaOH pellets, powdered ($\text{Ca}(\text{OH})_2$) and solid $\text{Na}_2\text{SiO}_3 \cdot 5\text{H}_2\text{O}$, sourced from KIMIX Chemical and Laboratory Supplies, Cape Town, South Africa.

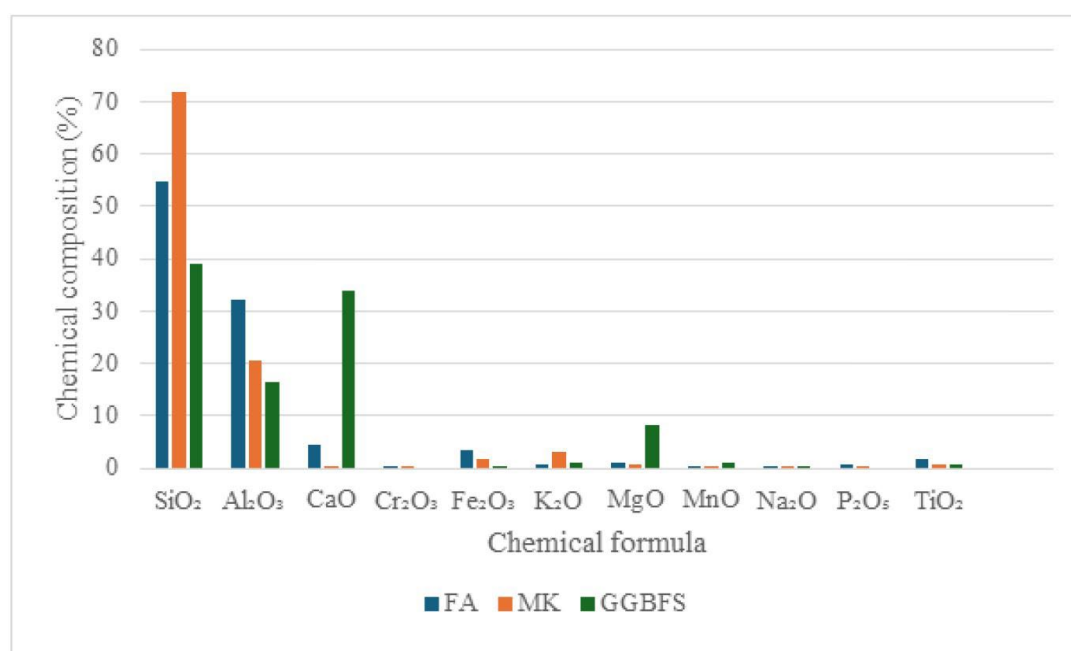


Figure 1: Percent chemical composition of materials

3.2. Experimental Methods

3.2.1. Mixing, Casting, and Curing

The final mix proportions for both units are shown in Table 1. The one-part mixing procedure, otherwise known as the “just add water” method, was followed during the making of both the FABS and FAMK units. This specific procedure reduces the risks of handling large quantities of alkaline reagents. For the production of both combinations, dry ingredients comprising the selected precursors, solid alkali activators of powdered $\text{Ca}(\text{OH})_2$ and solid $\text{Na}_2\text{SiO}_3 \cdot 5\text{H}_2\text{O}$, natural fine Malmesbury sand (a relatively coarse natural sand) and 13 mm Greywacke stone were mixed for 2 minutes. The solid NaOH pellets could not be added to the dry ingredients without first dissolving the pellets in water, as this would result in wasted and unreacted NaOH, with subsequent limited precursor dissolution during mixing. Therefore, the water for mixing constituents was used to dissolve the NaOH pellets and added to the dry ingredients. Afterwards, the wet ingredients were mixed for an additional 2 minutes. The aggregate-to-binder ratios used in the formulations were chosen to maximise the use of South Africa’s industrial waste products.

Additionally, the activator dosages and ratios were arrived at based on the precursor requirement, requiring a higher dosage for the FAMK unit than the FABS unit, as MK typically contains more reactive species. Furthermore, as the FAMK combination is low in calcium, a higher $\text{Ca}(\text{OH})_2$ dosage was required for reactivity. After mixing, the wet geopolymer concrete mixes were cast in 290 mm long X 140 mm wide X 90 mm high prismatic wooden moulds whilst undergoing compaction on a vibrating table. The units were thereafter left to cure in a climate-controlled room under ambient temperature conditions of 23 ± 2 °C to the desired curing age.

Table 1: Mix proportions for the two masonry unit types

Constituents (kg/m^3)	FABS	FAMK
Water	206	240
Fly ash	321	200
Ground granulated blast furnace slag	214	-
Metakaolin	-	200
Malmsbury fine sand	963	961
13 mm Greywacke stone	642	641
Superplasticizer	3	4
Powdered calcium hydroxide	12	58
Solid sodium hydroxide pellets	12	7
Solid sodium metasilicate pentahydrate	29	15
Total	2402	2326

FABS: Fly ash and ground granulated blast furnace slag-based unit.

FAMK: Fly ash and metakaolin-based unit.

3.2.2. Compressive Strength

The 290 mm long × 140 mm wide × 90 mm units were tested for compressive strength on their bed face, chosen to simulate loading in the orientation in which they will be erected during construction. Six units were tested at 7 and 28 days in accordance with BS EN 772-1 (2011) on a 2-meganeutron Instron testing machine with steel plates

placed above and beneath the unit, as shown in Figure 2. A 1 mm/min loading rate was used so that the maximum load could not be reached within 1 minute of testing.



Figure 2: Compressive strength test

3.2.3. Water Absorption

The water susceptibility of each unit was characterised by testing the water absorption in both cold water and boiled water submerged conditions. Additionally, the IRA for both units was measured. Six units were tested for the FABS and FAMK units. The water absorption in cold water temperature conditions, as shown in Fig. 3a, was carried out to determine the water content mass expressed as a percentage of initially dry units after a 24-hour submersion test in accordance with IS 2185-1 (2005). The water absorption in boiled water temperature condition, as shown in Fig. 3b, was carried out to determine the water content mass expressed as a percentage of initially dry units after 5 hours of submersion in boiled water, which was followed by 19 hours of submersion in the same water that was allowed to cool to room temperature by natural loss of heat, totalling a 24-hour testing duration, tested in accordance with BS EN 772-2 (1998). The IRA test, as shown in Figure 3c, was carried out to measure the initial rate of capillary suction of the masonry units by submersing the units at a depth of 5 mm over a submersion time of 1 minute tested in accordance with (BS EN 772-11), (2011).



Figure 3: Water absorption tests. (a) cold water, (b) boiled water, (c) IRA

3.2.4. Thermal Performance

The thermal properties investigated in this work comprise the K-value and the R-value of a 1 m X 1 m wall for both the FABS and FAMK units. As shown in Figure 4, a guarded hotbox set-up, designed and tested according to the requirements of ASTM C1363-11 (2011), was used whereby the wall specimen was enclosed in the middle compartment by the metering chamber on the left (set to a temperature of 30 °C) and the climatic chamber on the right (set to a temperature of 5 °C). These temperatures were selected to simulate a high-temperature gradient and, therefore, investigate the insulation capability of the AMUs in such environments. The test was run for about 2 hours, with thermocouples connected around the apparatus and on either side of the specimen, which recorded the steady state temperatures throughout the test. From these readings, the K-value and R-value are determined.



Figure 4: Guarded Hotbox set-up

4. Findings and Discussion

4.1. Compressive Strength

The 7 and 28-day compressive strength for both units is presented in Figure 5. The 7-day strength for the FABS unit is 11.7 MPa, and the 28-day strength is 18.4 MPa. A high gain in strength of 58% is thus observed for the unit between its 7 and 28-day age. This is similar to studies in the literature, which have reported a strength gain ranging between 57 and 83% between the 7 and 28-day age for an FA-slag-based geopolymer concrete blend (Deb et al., 2013). The rate of development of strength gain is attributed to the presence of the slag and its calcium bearing compounds, which subsequently contribute to the development of the calcium silicate hydrate (CSH) gel in combination with the geopolymeric gel (Qin et al., 2022).

Moreover, the 7-day and 28-day strength of the FAMK unit is 5.69 MPa and 6.07 MPa, respectively, thus showing no considerable increase in strength between each age. The FAMK unit is a low calcium blend, so elevated curing is typically needed to accelerate the geopolymerisation process and gain strength. However, the calcium content from the $\text{Ca}(\text{OH})_2$ assists in the strength development of low-calcium blends (Qin et al., 2022). Hence, both units comply with the minimum required compressive strength of 4 MPa for solid masonry units in single-storey buildings, thus showcasing its potential as an AMU in applying Category 1 single-storey buildings for AH.

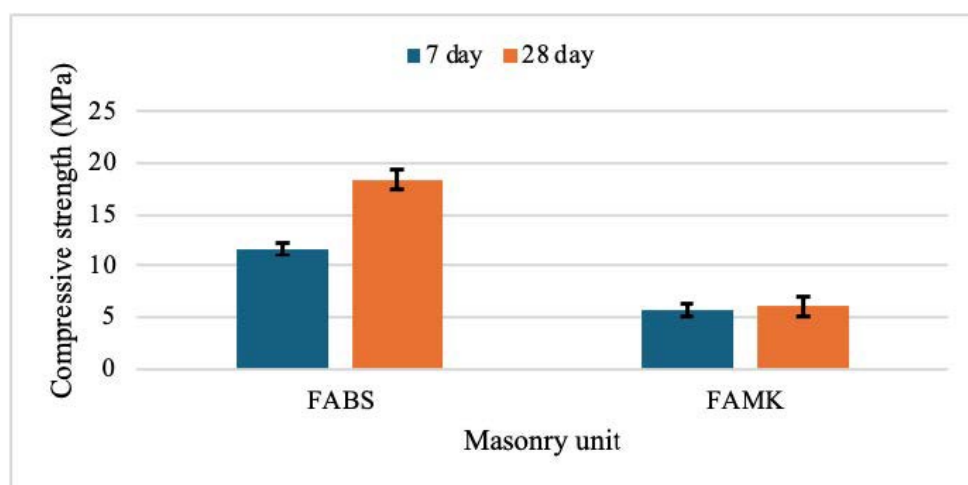


Figure 5: Compressive strength results. FABS: Fly ash-ground granulated blast furnace slag-based unit, FAMK: Fly ash-metakaolin-based unit

4.2. Water Absorption

The water absorption in cold and boiled conditions is presented in **Table 2**. The FABS unit showed a cold and boiled water absorption of 5.4% and 8.3%, respectively. The cold-water absorption result is comparable to those obtained in the literature, where studies have reported values between 1.0 and 3.25% for FA-slag-based geopolymer blends (Bellum et al., 2022). They attribute the low water absorption to the reduced porosity of the matrix due to the crystalline binding phases developed from the slag. Similarly, for the FAMK unit, a cold water absorption of 9.6% was attained, which can be primarily attributed to the calcium content from the $\text{Ca}(\text{OH})_2$. Additionally, the higher boiled water absorption results of 8.3% and 10% for the FABS and FAMK units, respectively, are understandable as hotter fluids are thinner and have more particle kinetic energy to propagate through the voids. These results, however, are acceptable for concrete masonry units as the water absorption does not exceed 10%. The IRA for the FABS and FAMK units was 0.2 $\text{kg/m}^2/\text{min}$ and 0.3 $\text{kg/m}^2/\text{min}$, respectively. The IRA is an important property of masonry units that indicates the rate of capillary suction within the initial stages in wet environments. This property is important when considering the masonry unit and mortar joint interface. A high IRA indicates high suction of the masonry unit from the adjacent mortar joint, subsequently affecting the mortar joint hydration process and thus weakening the bond. As per SANS 10164-1 (1980), an acceptable IRA for masonry units should fall between 0.7 and 1.8 $\text{kg/m}^2/\text{min}$. The IRA obtained for both units in this work is thus lower than the specified range. However, this is still favourable as it is low enough not to influence the bond between the unit and mortar. Hence, these results showcase promising serviceability and durability against external factors when applying Category AH units.

Table 2: Water Absorption and IRA Results

Masonry unit	FABS	FAMK
Cold water absorption (%)	5.4	9.6
Boiled water absorption (%)	8.3	10.0
IRA ($\text{kg/m}^2/\text{min}$)	0.2	0.3

4.3. Thermal Performance

The K-value and the R-value of each FABS and FAMK 1m X 1m wall are presented in Table 3. Additionally, the dry density of both units is also given. The FABS unit obtained 1.31 W/m°C and 0.11 m²C/W for thermal conductivity and thermal resistance, respectively. The FAMK unit obtained 1.04 W/m°C and 0.13 m²C/W for thermal conductivity and thermal resistance, respectively. Moreover, heat conductance through a material is directly linked to its density, as denser materials have more particle interaction, increasing heat transmission through the material. Given that the FABS unit exhibits a higher density, it has a higher K-value and lower R-value. Conversely, the FAMK unit, with its lower density, exhibits a correspondingly lower K-value and a higher R-value.

As per Table 3 in SANS 10400-XA (2021), the minimum required R-value for walls having a surface density equal to or greater than 270 kg/m² should be either 0.4 m²C/W or 0.6 m²C/W, depending on the energy zone. Similarly, Table 7 in SANS 10400-XA (2021) stipulates a minimum required R-value of either 1.9 m²C/W or 2.2 m²C/W for walls with a surface density less than 270 kg/m², depending on the energy zone. Considering the geometry of the wall specimen in this study, the recorded dry densities of the units and the dry density of a standard masonry mortar mix obtained from Thamboo et al. (2019), the surface density for each wall, as presented in Table 3, was obtained. These surface densities thus classify both walls under Table 6 in SANS 10400-XA (2021).

The results, however, exhibit unsatisfactory R-values for both units, not meeting the minimum requirement of either 0.4 m²C/W or 0.6 m²C/W for walls situated in the different energy zones of South Africa. These minimum required R-values, however, are specifically for non-Category 1 buildings. The only requirement for single-leaf walls of Category 1 buildings is the minimum thickness requirement of 140 mm. Hence, there is no minimum required R-value set for Category 1 buildings.

However, in comparison to conventional masonry units in South Africa, as given in Table 4, the hollow concrete block, the solid clay brick and the solid concrete brick possess a K-value of 0.98 W/m°C, 0.82 W/m°C and 1.4 W/m°C, respectively (Aerated

Autoclaved Concrete Blocks Cape Town South Africa | Aertec, 2024). Additionally, the hollow concrete block, the solid clay brick and the solid concrete brick possess an R-value of $0.09 \text{ m}^2\text{C/W}$, $0.13 \text{ m}^2\text{C/W}$ and $0.08 \text{ m}^2\text{C/W}$, respectively (Aerated Autoclaved Concrete Blocks Cape Town South Africa | Aertec, 2024). The R-value of $0.11 \text{ m}^2\text{C/W}$ for the FABS unit is similar to the imperial clay brick and better than the imperial concrete brick and hollow concrete block. In comparison, an R-value of $0.13 \text{ m}^2\text{C/W}$ for the FAMK unit is identical to the imperial clay brick and better than the imperial concrete brick and hollow concrete block. Hence, these results showcase the potential of these AMUs to achieve adequate thermal comfort for occupants in AH units. However, it should be noted that the thermal properties depend on the material's thickness. Hence, despite an improvement in R-value, it may still not indicate an improvement over conventional masonry as the walls tested in this study had their units orientated on their bed face as erected in construction, thus having a wall thickness of 90 mm. In contrast, the thickness of the conventional masonry units in Table 4 are slightly different.

Table 3: Dry density of wall components and thermal properties of walls

Masonry wall component	Dry density of component (kg/m^3)	Constructed wall surface density, including mortar (kg/m^2)	Wall K-value ($\text{W/m}^2\text{C}$)	Wall R-value ($\text{m}^2\text{C/W}$)
FABS unit	2017.81	465.8	1.31	0.11
FAMK unit	1903.46	455.7	1.04	0.13
Mortar	2022.0 (Thamboo et al., 2019)	-	-	-

Table 4: Thermal properties of conventional masonry (Aerated Autoclaved Concrete Blocks Cape Town South Africa | Aertec, 2024).

Conventional masonry unit	Thickness (mm)	K-value ($\text{W/m}^2\text{C}$)	R-value ($\text{m}^2\text{C/W}$)
Hollow concrete block	140	0.98	0.09
Imperial clay brick	106	0.82	0.13
Imperial concrete brick	106	1.4	0.08

5. Conclusion

The FABS and FAMK-based geopolymer concrete AMU, activated by solid NaOH, powdered $\text{Ca}(\text{OH})_2$ and solid $\text{Na}_2\text{SiO}_3 \cdot 5\text{H}_2\text{O}$, was developed in this work and tested for its compressive strength, water absorption, and thermal performance. After investigation, the following conclusions are drawn.

1. Both units comply with the minimum required compressive strength of 4 MPa for solid masonry units intended for single-storey masonry structures.
2. Both units showcase acceptable water absorption characteristics.
3. The walling systems comprising each AMU type do not meet the required R-value for adequate energy efficiency in buildings. However, the AMUs produced in this work still show promising results when compared to conventional clay and concrete masonry units with an improvement in R-value.

While conventional clay—and cement-based masonry units may meet performance requirements in Category 1 buildings, their contribution to environmental issues and delays in AH delivery is of concern. Alternatives such as the FABS and FAMK units produced in this work are promising as they can satisfy strength, durability, and thermal requirements, thus potentially replacing conventional masonry materials and mitigating environmental impacts and AH delivery shortages.

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