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Design and production of sustainable lightweight concrete precast sandwich panels for non-load bearing partition walls

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Abstract: The trend for utilizing sustainable products is becoming increasingly important in the construction industry. Precast concrete sandwich systems containing expanded polystyrene (EPS) is gradually replacing the conventional blockwork systems due to its lightweight, enhanced insulation properties and rapid installation. Accordingly, there is a need to optimize the design and production of this system to provide superior insulation, durability and rapid installation while ensuring adequate bonding, strength and mechanical properties to sufficiently fit its purpose. Research has shown that the system’s technical properties are highly dependent on the mix design and the production and installation methods. This study involved the design and production of a sustainable lightweight precast concrete sandwich panel for non-load bearing partition wall systems. An experimental program was developed to identify the optimum mixture proportions for the EPS concrete core. Practical procedures for system production and installation were proposed. Physical and mechanical properties for the proposed EPS concrete system were determined based on experimental testing and calculations. A relationship between the plastic density of fresh EPS concrete and its compressive strength was established to ensure quality control before concrete is cast. Results revealed a high degree of correlation of 0.97 between the core density and compressive strength.

ABOUT THE AUTHOR
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PUBLIC INTEREST STATEMENT
The trend for utilizing sustainable products is becoming increasingly important in the construction industry. Precast concrete sandwich systems containing expanded polystyrene (EPS) is gradually replacing the conventional blockwork systems due to its lightweight, enhanced insulation properties and rapid installation. Research has shown that the system’s technical properties are highly dependent on the mix design and the production and installation methods. This study involves the design and production of a sustainable lightweight precast concrete sandwich panel for non-load bearing partition wall systems. Practical procedures for system production and installation are proposed. An experimental program is developed and property relationships are established to ensure quality control. Technical properties comparison reveal that the proposed system is superior in comparison to the conventional lightweight blockwork system. Furthermore, the installation time for the proposed wall system is compared with the conventional block work system and results reveal significant faster installation and reduction in the total cost.
Technical comparison revealed that the proposed system is superior in comparison to the conventional lightweight blockwork system. Furthermore, the installation time for the proposed partition wall system was 3 times faster in comparison with the conventional block work system, which would lead to significant reduction in the total cost.

Subjects: Composites; Concrete & Cement; Structural Engineering

Keywords: Expanded polystyrene (EPS); EPS concrete; sandwich panels; non-load bearing; partition walls; precast walls

1. Introduction

Energy consumption for structures is increasing mainly due to cooling and heating requirements to provide thermal comfort that accounts to 25–40% of total energy consumption (Robinson et al., 2017). Therefore, many government agencies around the world have set certain targets and guidelines to reduce the energy towards near zero energy buildings (ZEBs). The most sustainable way to reduce energy consumption is by controlling mass thermal transfers through building components. Energy sustainability in buildings is best achieved by introducing an insulation material into the building (Gervásio et al., 2010).

Precast Concrete Sandwich Panel (PCSP) is a structural system consisting of a low-density core and high strength facing materials that act integrally as one unit to resist applied loads. These structures are strong, yet light in nature. The facing materials may be composed of concrete, steel, aluminum, carbon fiber material, calcium silicate, magnesia, or fiber cement, etc. (Benayoune et al., 2006; Jeom et al., 1999; Lee & Pessiki, 2006; Liew & Sohel, 2009; Rice et al., 2006). The core often consists of lightweight concrete, fiber reinforced composite, or foam (Jeom et al., 1999; Liew & Sohel, 2009; Scudamore & Cantwell, 2002; Stoll et al., 2004). These materials can be combined to form composite sandwich panels that can have many advantages. Wall sandwich panels may be used for cladding and bearing, non-bearing, or shear walls. A neoteric, growing interest has been observed in the use of precast sandwich panels for non-load bearing partition walls because of their high quality, lightweight, rapid installation, insulation and aesthetic properties. For the lightweight concrete core, the main aim is to select a sustainable material with low weight, excellent thermal insulation properties and high technical performances in term of hydropobicity and low water absorption. Unlike conventional cement composites that are characterized by porosity and hydrophilicity, hydrophobic composites offer enhanced durability properties (Neto et al., 2016; Weisheit et al., 2016).

Polystyrene is a vinyl polymer, which is a long hydrocarbon chain with a phenyl group attached to every other carbon atom (Bischoff et al., 1990). Expanded Polystyrene (EPS) lightweight concrete is being increasingly utilized in the construction industry in various applications, mainly due to its lightweight qualities, excellent heat preservation and sound insulation (Bhatta et al., 2011; Herki & Khatib, 2016). To utilize these properties, sandwich partition walls can be produced by filling the core with a lightweight EPS concrete mixture. In many building applications, EPS is the most used insulator in precast concrete sandwich panels (Bida et al., 2018). This is mainly due to its low cost, low density, low water absorption, excellent insulation properties and availability. The system can consist of an EPS concrete core enclosed within fiber cement boards. The fiber cement boards are used as outer sheathing to the EPS concrete core and provide the system with enhanced properties that include strength, durability, thermal insulation, acoustic insulation, moisture proof, and fire insulation.

Several studies have been made on lightweight sandwich panels to propose efficient insulation materials and optimization of location and thickness of these materials. This plays a vital role in reduce energy consumption in buildings. Bolattürk (2006) reported a suitable thicknesses for
expanded polystyrene material ranging from 20 to 170 mm with about 22 to 79% energy savings. Ucar and Balo (2009) recommended optimum thicknesses for extruded polystyrene ranging from 10.6 to 76.4 mm. Ekici et al. (2012) conducted an investigation on the insulation thickness of expanded polystyrene, extruded polystyrene, Fiberglass, and foamed polyurethane materials in several wall assemblies and recommended an insulation thickness ranging from 20 to 186 mm for best performance. Yu et al. (2009) reported that an appropriate selection of the type of insulation material and thickness is of vital importance in concrete sandwich panel systems and revealed that expanded polystyrene is the most efficient insulation material when compared to extruded polystyrene, foamed polyurethane and perlite in terms of overall performance and cost, and recommended thicknesses of 53 to 236 mm. EPS concrete sandwich panels can be used for various types of structures such as houses, towers, hotels, warehouses, and industrial and commercial buildings. Table 1 shows some of the advantages of utilizing an EPS concrete sandwich system.

Although the hydrophobic nature and very low-density of EPS beads is advantageous in terms of offering lighter and more durable structural elements, EPS concretes are more prone to segregation and poor bonding in comparison with normal weight concretes (Chen & Liu, 2004). Consequently, because of the low bond between the EPS and the cement paste, and hydrophobic nature and low mechanical strength of EPS beads, there is a significant decrease in the compressive strength of EPS concretes (Perry et al., 1991). Research has also shown that the compressive strength of EPS concrete is governed by the quantity of EPS beads, followed by the water to cement ratio (Xu et al., 2012). Studies have revealed that incorporating silica fume to replace part of the cement can gives mixtures that are more cohesive and less prone to floating of the EPS beads (Babu & Babu, 2003; Moutassem, 2020). Research has also shown that the use of bonding agents such as latex-based bonding agents can improve the bonding between the EPS beads and the cement paste (Moutassem, 2020; Sayadi et al., 2016). In addition, following a proper mixing process can significantly improve its quality, homogeneity, bonding, stability, and avoid floating of the EPS beads (Moutassem, 2020). A proper mixing procedure should require wetting of the EPS beads with part of the mixing water and bonding agent to ensure proper bonding with the rest of the materials (Moutassem, 2020). Research has shown that replacing normal aggregates with EPS beads offers better resistance against corrosion and chemical attacks due to the EPS inert characteristics (Sayadi et al., 2016). Although virgin EPS is more commonly used in building systems in comparison with recycled EPS, few studies investigated its use and determined that recycled EPS improves the mechanical properties slightly but lowers the thermal insulation properties (Tittarelli et al., 2016). Othman (2010) investigated the effect of adding different insulation materials to building blocks and concluded that the amount of energy consumption can be drastically reduced.

Although the sandwich panel system provides numerous advantages due to its lightweight and insulation properties, its application comes with challenges such as bonding issues and low strength. With the increased focus on sustainability and use of sustainable products, there is a need to optimize the design and production of quality lightweight partition wall systems to provide superior insulation, durability and rapid installation in comparison with conventional blocks while ensuring adequate bonding, strength and mechanical properties to sufficiently fit its purpose. This study involves the design and production of a lightweight precast concrete sandwich panel for a non-load bearing partition wall system, utilizing EPS concrete for the inner core. The optimum mixture proportions will be identified and proposed. Practical procedures for EPS concrete panel production and installation will be examined and proposed in this study. An experimental program will be developed to determine the physical and mechanical properties for the proposed EPS concrete wall system. In addition, technical and installation time comparisons between building a wall using conventional blocks as opposed to using the EPS concrete precast partition wall system will be drawn.
Table 1. Advantages of using an EPS concrete partition wall sandwich system (Moutassem, 2019)

| Advantages        | Description                                                                 |
|-------------------|-----------------------------------------------------------------------------|
| Cost Efficient    | • Lightweight system brings about a reduction in the superimposed loads. This results in a reduction in slab thickness and all other supporting structural elements, which reduces the cost of the structure.  
• Easy installation and elimination of plastering.  
• Easy installation of doors, windows and conduits.  
• Fewer labor hours and thus reduced labor related costs.  
• Transport efficiency.  
• Minimum on-site wastage. |
| Time Saving       | • Easy handling and rapid installation. An economical system with ready finished surface. Effectively avoiding the need for plastering and ensuring significantly shorter construction cycles.  
• MEP embedded into the wall before concrete casting, which avoids post installation cuttings. |
| Quality           | • Flat and straight (no ripples).  
• High quality materials from reputed suppliers. |
| Sustainability    | • Superior thermal insulation and heat preservation. EPS beads in the core act as an air and vapor barrier allowing temperatures to be maintained for longer periods, offering an energy efficient and air tight building providing significant savings in heating and cooling costs.  
• Minimal wastage. MEP embedded in the wall prior to core casting, minimizes cutting and wastage.  
• High durability and moisture resistance. |
| Acoustic Insulation| • Dampening of sound between rooms and in corridors, making this system idyllic for residential units, schools, hotels and office partitions. |
| Safety            | • Fire rating exceeding 2 hours and no spread of fire.  
• Non-toxic fumes released. |
| Handling          | • No plastering required.  
• Ready to paint.  
• Lightweight.  
• Simple installation. |

2. Materials, methods and experimental testing

2.1. Core materials and mixture proportions

The materials used to produce the lightweight EPS concrete core consist of EPS beads, Ordinary Portland Cement (OPC), densified Silica Fume, bonding and foaming agents and a superplasticizer. In this study, ASTM Type I OPC was used. Grey colored spherical EPS beads (NEOPOR F 5300) produced by BASF were used in this study. EPS bead sizes ranged from 2.5–3.5 mm and bulk density ranged from 15–20 kg/m³. The main advantages of EPS include low density, heat insulation/preservation, impact resistance, fire resistance, environmental protection, good process ability, and safety (Bhutta et al., 2011; Herki & Khatib, 2016). Silica fume (SF) was used in a few mixtures to replace part of the cement. Utilizing SF enhances the strength, durability, and stability...
of the EPS concrete mix (Babu & Babu, 2003). Condensed silica fume (ELKEM 920D) with a 28-day compressive strength of 56 MPa was used in this study. A latex type bonding agent (Planicrete SP) was used as an additive to enhance bonding between the EPS beads and the cement paste (Moutassem, 2020), as well as improving the tensile and flexural strength of the partition wall system. The amount of bonding agent used was 4 kg/m³ for all mixtures. A foaming agent (FA) was used to entrain air by providing a uniform network of stable air bubbles that can sustain themselves and do not burst easily ensuring a mix which is low in density and does not collapse after placement. The air content was determined following ASTM C 138 (2017). A Polycarboxilate-based Superplasticizer was used as an additive to significantly improve the workability of the mix and reduce water demand, resulting in an increase in strength, durability and flowability. Concrete slump was determined following ASTM C143 (2020). Accordingly, six different mix designs were investigated in order to identify the optimum core mixture that is most suitable for the precast partition wall system. Details of the mixture proportions are given in Table 2. Since there is no mixture proportioning standard for EPS concrete, these 6 mixture designs were selected based on literature, specifically based on the extensive study conducted by Moutassem (2020). The amount of EPS beads occupy volumes in the range of 56–62% of the concrete mixtures and thus significantly reducing the total weight of each concrete mixture, as shown in Table 2.

### Table 2. Core mixture proportions

| Mix # | w/c   | EPS (%) | EPS (kg/m³) | OPC (kg/m³) | SF (kg/m³) | Water (kg/m³) | HRWR (kg/m³) | Air Agent (kg/m³) | Bonding Agent (kg/m³) | Mixture Weight (kg/m³) |
|-------|-------|---------|-------------|-------------|------------|---------------|--------------|-------------------|------------------------|-------------------------|
| 1     | 0.24  | 58      | 13.8        | 744         | 0          | 179           | 4.10         | 0.0               | 4.0                    | 945                     |
| 2     | 0.25  | 58      | 14.0        | 550         | 0          | 138           | 9.60         | 3.0               | 4.0                    | 718                     |
| 3     | 0.30  | 62      | 14.8        | 450         | 0          | 135           | 1.80         | 3.0               | 4.0                    | 609                     |
| 4     | 0.30  | 57      | 13.7        | 407         | 23         | 129           | 5.00         | 3.0               | 4.0                    | 585                     |
| 5     | 0.30  | 58      | 13.8        | 407         | 23         | 129           | 2.15         | 2.5               | 4.0                    | 581                     |
| 6     | 0.32  | 56      | 13.5        | 325         | 30         | 114           | 2.20         | 1.5               | 4.0                    | 490                     |

2.2. Precast system description

The system consists of an EPS core sheathed with fiber cement boards that are used as outer sheathing and provide the system with enhanced properties. Each precast panel has dimensions of 0.6 m x 3.0 m x 100 mm (width x length x minimum thickness), are connected together along the length via an adhesive material, and are supported by the bottom and top floor slabs using adhesive material and channels or angles. Each lightweight panel can be lifted and handled physically without the need for cranes and heavy machinery. A sample cut of an EPS concrete sandwich panel is shown in Figure 1. Cross-sectional details and dimensions of the interlocking joints are provided in Figure 2. The given dimensions of the interlocking joint were selected to ensure a continuous connectivity between the individual wall panels to form a rigid wall system.

2.3. Proposed methods for system production and installation

Production of EPS concrete sandwich panels can be made using an automated system or a partially automated system. Installation on the other hand is usually done manually. The following section presents the proposed methods for the production and installation of a high quality non-load bearing partition wall system.

2.4. Proposed production and mixing procedure

(1) Cut the fiber cement boards to desired dimensions.

(2) Apply the bonding agent twice on the inside rough surfaces of the fiber cement boards.
Figure 1. Sample cut from an EPS concrete sandwich panel.

Figure 2. Cross-sectional details for an EPS concrete sandwich panel.
(3) Measure the quantities required for all approved production materials as per the EPS concrete mix design.

(4) Clean the mould and apply a mould release agent.

(5) Insert and fix the fiber cement boards in the mould.

(6) Mix the EPS concrete materials following a quality mixing procedure to ensure homogeneity, stability, proper bonding and avoid floating of the EPS beads. Accordingly, the following mixing procedure which was proposed by Moutassem (2020) was adopted and applied in this study:

- Pour the EPS beads into the mixer.
- Mix the bonding agent with 1/3 of the water, pour them into the mixer and mix for 3 minutes.
- Pour the cementing materials and mix for 4 minutes.
- Pour the foaming agent into the remaining water, mix them together for 1 minute and then slowly pour it into to the mixer and mix for 2 minutes.
- Slowly pour the water reducer into the mixer and mix for 1.5 minutes.
- Check the slump (or spread) and proceed with casting.

(7) Pour the concrete immediately into the mould (in 2 layers). Vibrate the first layer for 10 seconds using a table vibrator. Pour the second layer and vibrate for 15 seconds.

(8) Finish the top surface for smoothness.

(9) Strip the wall from the mould within 24 hours.

(10) Cure the concrete to ensure hydration continues to take place until it has gained sufficient strength.

2.5. Proposed installation procedure

(1) Measure the location and/or position of the partition wall on the floor using a snap chalk line or profile to mark the outline on the floor. Do not forget to mark door openings as necessary. Use a level and a straight edge to mark the outlines of the partition wall and ceiling.

(2) Fix channels or angles to the floor and ceiling along the marked outline.

(3) Plant two or three layers of dowels using chemical anchors and a threaded bar (10 mm or 12 mm as per design requirements) along each panel joint.

(4) Apply polymer adhesive equally on the sides of the partition wall element (interlocking joints)

(5) Carry the partition wall element to the installation place and slide the panel tightly into position, forcing the polymer adhesive out at the male/female joints.

(6) Repeat the same procedure for all partition elements until the wall is fully completed.

(7) Fill any small gaps between every two sheets using a suitable sealant.

(8) Allow the adhesive and sealant to cure for 24 hours.

(9) Paint the walls as required.

Figure 3 presents photos of system installation carried out in this study to divide a large room into 2 separate rooms.

2.6. System experimental testing and calculation

Precast sandwich panels were constructed using an identified optimum core mixture following the procedure outlined above. Consequently, testing was carried out to determine the technical properties of the precast sandwich panel system. These properties include density, compressive strength, flexural strength, fire rating and thermal insulation value. These technical properties
were determined for both 100 mm and 150 mm thick sandwich panels. Additionally, installation time was monitored for each stage. The density of hardened EPS concrete was conducted in accordance with ASTM C567 (2019) at 28 days. For the compressive strength, EPS concrete cube specimens, with attached fiber cement boards, were cut out of the sandwich panel, cured in a water tank, and tested at 28 days. The flexural strength at 28 days was determined by subjecting the sandwich panel to an increasing uniform load until fracture. The service load deflection was determined by subjecting the panel to a uniform service load of 250 kg for 24 hours. The fire test for the EPS concrete wall system was conducted following ASTM E119 (2020) to determine the fire resistance of a complete assembly. This test evaluates the duration (fire rating) for which the building system contain fire, retain their structural integrity, or exhibit both properties during a predetermined test exposure. The fire test for the EPS concrete product was conducted following ASTM E84 (2020) to determine both flame spread and smoke development indices. The flame spread index is a numerical reference that measures how fast and far a flame spreads during a certain time duration. The smoke development index measures the concentration of smoke a materials emits as it burns for a certain time duration. Thermal insulation property was determined by calculating the U-value for the sandwich panel system. The U-value was calculated by considering the thermal conductivity values (K-values) for each material in the identified mixture. Accordingly, the thermal resistance values (R-values) for the volume fractions of wall components i.e. EPS, fiber cement boards and concrete, were calculated. The U-value for the system is then determined by finding the reciprocal of the summation of the R-values.
3. Results and discussion

3.1. Core mixtures experimental results

Table 3 presents the experimental results of the EPS concrete core mixtures. These results include values for the slump, air content, fresh plastic density, hardened density, and compressive strength at 28 days ($f'_{C28d}$). Previous studies have shown that the density of hardened lightweight concrete is the most significant property that influences its compressive strength (Babu & Babu, 2003; Babu et al., 2006; Perry et al., 1991; Sabaa & Ravindrarajah, 1999). Figure 4(a) shows the relationship between the hardened density of the EPS concrete core and the core compressive strength. The high degree of correlation, $R^2$ of 0.97, confirms the high significance of this property in terms of compressive strength. Moreover, to ensure quality control before concrete is cast, a relationship between the plastic core density of fresh concrete and the compressive strength of hardened concrete was established as shown in Figure 4(b). These results are consistent with past studies where an increase in EPS concrete density leads to an increase in the compressive strength (Babu & Babu, 2003; Babu et al., 2006; Perry et al., 1991; Sabaa & Ravindrarajah, 1999).

Certain criteria are set for the proposed precast wall system to be regarded as an optimum core mixture. These criteria include: i) achieving high flow for rapid placement, ii) density lower than 550 kg/m$^3$ to ensure that the system is light enough to allow manual installation; iii) 28-day compressive strength exceeding 2 MPa to ensure sufficient strength during handling; iv) good surface finish to ensure sufficient contact area for proper bonding to the fiber cement boards. Subsequently, mix number 5 was identified as the optimum mixture, effectively meeting all necessary criteria. Therefore, based on the identified mixture proportions, the water-to-cement ratio and amounts of OPC, condensed silica fume, EPS beads, bonding agent, foaming admixture and superplasticizer are 0.30, 407 kg/m$^3$, 23 kg/m$^3$, 13.8 kg/m$^3$, 4 kg/m$^3$, 2.5 kg/m$^3$ and 2.15 kg/m$^3$, respectively. If a higher strength is required, mixtures such as 1 or 2 can be used, depending on the strength requirement. However, the higher density may require additional workmanship or use of machinery during the installation process.

3.2. Sandwich panel system experimental results

Following the proposed production procedure and the identified optimum core mixture, panels were produced and testing was done to determine their technical properties. Table 4 presents the results for the technical properties. The following sections will discuss these results and provide technical and time comparisons between the 100 mm thick EPS concrete sandwich panel considered in this study, and the conventional blocks system.

3.3. Panel density

The target design density for the sandwich panels was lower than 600 kg/m$^3$ to ensure that the panels are light enough for handling and installing without the aid of machinery. As shown in Table

### Table 3. Core mixtures experimental results

| Mix | Slump (mm) | Air (%) | Fresh Density (kg/m$^3$) | Hardened Density (kg/m$^3$) | $f'_{C28d}$ (MPa) |
|-----|------------|---------|--------------------------|-----------------------------|-------------------|
| 1   | 70         | -       | 978                      | 996                         | 7.79              |
| 2   | 40         | 6       | 788                      | 794                         | 5.16              |
| 3   | 240        | 20      | 527                      | 554                         | 2.83              |
| 4   | 220        | 11      | 661                      | 706                         | 3.51              |
| 5   | 245        | 20      | 509                      | 509                         | 2.21              |
| 6   | 240        | 22      | 470                      | 473                         | 1.91              |
the densities obtained for the 100 and 150 mm thick sandwich panels were 598 and 567 kg/m$^3$, respectively. Density is a very important perimeter for lightweight concrete as it controls many physical and mechanical properties. The density of EPS concrete is dominated by the porosity of the specimen, which is mainly controlled by the volume fraction of air (entrapped and entrained), capillary porosity (which depends on the water to cementing materials ratio), and the volume fraction of the EPS beads (which are of negligible density and strength). Previous studies have shown that an increase in the density of lightweight concrete results in improved mechanical properties (Babu & Babu, 2003; Babu et al., 2006; Perry et al., 1991; Sabaa & Ravindrarajah, 1999). As shown in Table 3, the higher density of the 100 mm thick sandwich panel resulted in higher compressive and flexural strengths, which is consistent with past studies (Babu & Babu, 2003; Babu et al., 2006; Perry et al., 1991; Sabaa & Ravindrarajah, 1999). It should be noted that although both sandwich panels used the same materials and mixture proportions, the density of the 150 mm thick panel is lower than that of the 100 mm because the increase in thickness is based on the low density core whereas the higher density fiber cement boards are fixed in thickness.

### 3.4. Panel strength and deflection

The non-load bearing sandwich panel was designed to achieve a target compressive strength exceeding 3 MPa to ensure that the panels have sufficient strength to sustain their own weight and weight of any attached materials, as well as resist forces during handling and installation. The flexural strength of the 100 mm thick EPS concrete precast sandwich system was determined to be 2.7 MPa, which is considerably higher in comparison with similar non-load bearing partition walls systems such as hollow blocks and AAC blocks (Prakash et al., 2013; Raghunath et al., 2012). The 3-meter panel was subjected to a uniform service load of 250 kg for 24 hours and then subjected

| Property                        | EPS Concrete Sandwich Panel (100 mm thick) | EPS Concrete Sandwich Panel (150 mm thick) |
|---------------------------------|------------------------------------------|------------------------------------------|
| Density (kg/m$^3$)              | 598                                      | 567                                      |
| Compressive Strength (MPa)      | 3.2                                      | 3.0                                      |
| Flexural Strength (MPa)         | 2.7                                      | 2.3                                      |
| Thermal Insulation—U (W/m$^2$K) | 0.66                                     | 0.42                                     |
| Fire Rating—System (Hours)      | 2                                       | 2                                        |
| Flame Spread Index              | 0                                        | 0                                        |
| Smoke Developed Index           | 0                                        | 0                                        |
to additional loads in order to determine the breaking load. Load versus mid-span deflection is shown in Figure 5. Results revealed that the total service load deflection was only 6 mm, which is considerably low compared with the limits set in different codes and standards. Results also revealed that the EPS concrete sandwich panel can sustain a breaking load of 750 kg, making it a considerably strong panel in comparison with other non-load bearing partition wall systems. This is mainly due to the higher flexural strength of the bonded fiber cement boards, as shown in Figure 2, which significantly increases the flexural strength of the sandwich panel.

3.5. Panel fire rating and thermal insulation

As shown in Table 4, the EPS concrete sandwich system successfully passed the 2-hour fire rating test conducted following ASTM E119 (2020). Moreover, the EPS concrete sandwich system successfully passed the flame spread and smoke development tests conducted following ASTM E84 (2020). As per ASTM E84, Class A corresponds to a flame spread index of 0–25 and smoke developed index of less 0–450. Based on the index values of 0 determined for the flame spread and smoke development as shown in Table 4, the EPS concrete product classification falls under Class A. These results were anticipated because bonding the EPS beads to concrete significantly improves its performance against fire, flame spread and smoke development. As shown in Table 4, the thermal insulation, U-values, determined for the 100 mm and 150 mm-thick EPS concrete sandwich panels were 0.66 and 0.42, respectively. These low values are consistent with past studies (Shi et al., 2019; Xu et al., 2016). As such, it is recommended to use the 150 mm-thick panel system for exterior walls due to its lower U-value i.e. higher thermal insulation. Use of special finishing materials can further reduce the U-values.

3.6. System comparison

Table 5 provides a technical comparison between the EPS concrete sandwich system (100 mm thick) considered in this study and the conventional lightweight blocks system. Density and strength values for the conventional blocks system are based on ASTM C129 (2017) requirements. Comparison between these systems reveals that overall the EPS concrete sandwich system is superior to the conventional blocks system.

Table 6 presents the installation time comparison between building a 16 square meter wall using conventional blocks, versus using the EPS concrete precast partition wall system. As shown, the total amount of time it takes to build a 16 square meter wall using the EPS concrete precast system is approximately 30.5 hours. However, the total amount of time it takes to build a 16 square meter wall using block work is approximately 102.5 hours. Therefore, the installation time
for the EPS concrete system is reduced by 70%. This will give rise to a significant reduction in total cost, which includes labor, machinery, etc.

4. Conclusions
This study involved the design and manufacturing of a sustainable lightweight precast concrete sandwich panel for a non-load bearing partition wall system. Based on experimental testing, the optimum mixture proportions for the EPS concrete core were identified and proposed. Practical procedures for production and installation of high quality EPS concrete panels were proposed and implemented. The technical properties for the proposed EPS concrete precast partition wall system were determined based on experimental testing and calculations. Technical and time comparisons were made between the EPS concrete sandwich panel considered in this study and the conventional lightweight blockwork system. This study revealed the following main conclusions.

- A high degree of correlation between the core fresh and hardened densities and the core compressive strength. The degree of correlation ($R^2$) was 0.97.
- A relationship between the plastic density of fresh EPS concrete and its compressive strength was established to ensure quality control before concrete is cast and left to set.

| Steps                          | Time (hours) | Steps                           | Time (hours) |
|-------------------------------|--------------|---------------------------------|--------------|
| Marking Locations             | 0.5          | Marking Locations               | 0.5          |
| Installation of bottom & top  | 1.5          | Mortar mixing and setting it    | 1.0          |
| channels or angles            |              | out                             |              |
| Installation of first panel    | 0.5          | Laying of blocks                | 48           |
| using dowel bars              |              |                                 |              |
| Installation of all panels     | 2.0          | Rigid scaffolding required at 1.5|              |
| into position                  |              | height                          |              |
| Closing of joints             | 1.0          | Curing                          | 24           |
| Finishing of joints           | 1.0          | Manual Plastering               | 5            |
| Curing                        | 24           | Curing                          | 24           |
| Total Time                    | 30.5         | Total Time                      | 102.5        |

Notes:
- Panels have no height restrictions.
- Mobile scaffolding can be used if needed.

Table 6. Installation time comparison

| Table 5. System technical comparison |
|-------------------------------------|
| Description                        | EPS Concrete Sandwich Panel | Lightweight Blocks |
| Density (kg/m$^3$)                 | < 600                       | < 1680             |
| Compressive Strength (MPa)         | 3.2                         | > 3.45             |
| Flexural Strength (MPa)            | 2.7                         | N/A                |
| Fire Rating (hours)                | > 2                         | Varies             |
| Thermal Insulation                 | High                        | Low                |
| Energy Efficiency                  | High                        | Low                |
| Plastering                         | Not required                | Required           |
| Painting                           | 2 coats                     | 4 coats            |
| Wastage                            | None                        | High               |
| Installation Time                  | Rapid                       | Slow               |
The EPS concrete partition wall system was deemed superior in comparison to the conventional lightweight blockwork system. The technical properties values determined include density, compressive strength, flexural strength, fire insulation and thermal insulation.

Installation time for the proposed EPS concrete partition wall system is less than 30% in comparison with the block work system, which would lead to significant reduction in the total cost.

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