Developing of lightweight concrete sandwich wall panels with good thermal insulation properties for sustainable buildings

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Abstract. This research study aims at developing and investigating the mechanical and thermal properties of lightweight sandwich wall panels with good thermal insulation properties to reduce electric power for cooling of buildings. Within this study, several thermal insulation sandwich wall panels with two outer lightweight concrete layers and inner expanded polystyrene layer were developed and tested. Test parameters included the type of the outer concrete layers and the effect of using glass fiber reinforced polymer (GFRP) shear ties to connect the outer layers. Different ratios of polystyrene beads and vermiculite aggregates (53, 68 and 84% by volume of the natural coarse aggregates) were used to replace the natural coarse aggregates in the two outer concrete layers for better insulation properties and to develop lighter panels. Test results showed that using the GFRP shear ties was effective to connect the two outer layers of the panels. The results also revealed that increasing the amount of the polystyrene beads and the vermiculite aggregates decreased the thermal conductivity, the density, and the compressive strength of the panels. These values ranged from 0.41 to 0.25 W/m.K, 596 to 486 kg/m³, and 4.21 to 2.02 MPa respectively, for the panels with polystyrene beads. For the panels with vermiculite aggregates, these values were 0.46 to 0.34 W/m.K, 646 to 626 kg/m³, and 3.14 to 1.96 MPa, respectively.

The results showed that the panels with polystyrene beads were stronger, lighter, and had better thermal properties. Using the developed panels will help to reduce the self-weight of buildings resulting in smaller structural elements. In addition, the excellent thermal properties of the developed panels are expected to reduce power consumption and develop more sustainable buildings.

1. Introduction

High temperature levels in the Arabian Gulf region during summer consumes enormous electric power for cooling of buildings. Most of the residential buildings in the region are made of single skin walls using hollow or solid concrete blocks that have poor thermal insulation properties. There is a limited use of cavity walls and insulation materials due to their high cost [1]. Several researchers tried to develop concrete blocks with good thermal insulation properties. Pierzchlewicz [2] developed and tested several concrete hollow blocks with staggered and aligned holes. The test results showed that the thermal conductivity of the blocks with staggered holes ranged between 0.57 and 0.68 W/mK, while it ranged between 0.87 and 0.92 W/mK for the blocks with aligned holes. In another study [3] blocks with very low thermal conductivity made with lightweight leeka aggregates and silt were developed. The study concluded that the low thermal conductivity of the blocks (0.375 W/mK) satisfies the target thermal design requirements for a comfortable interior temperature without the need of mechanical air-conditioning. Al-Jabri et al. [1] developed two types of hollow blocks with densities of 798 and 1168
kg/m³ and compressive strengths of 2.2 and 3.3 MPa, using vermiculite and expanded polystyrene (EPS) beads, respectively. They concluded that the developed blocks satisfy the Omani standard [4] for compressive strength requirements for non-load bearing masonry. The thermal conductivity of the blocks was about 0.62 W/mK. However, the recorded temperatures inside rooms built from these blocks reached 38°C after only about 100 hours. This might be related to the mortar layers used to connect the blocks, which worked as thermal bridges in the walls and reduced the insulation efficiency.

Sandwich wall panels that consist of two outer thin concrete layers (wythes) and inner lightweight core have also been used as walls in buildings. They have fewer thermal bridges and better thermal insulation properties compared to regular concrete blocks [5]. O’Hegarty et al. [6] investigated the thermal transmittance of thin lightweight precast sandwich cladding panels. The tested panels achieved an average thermal transmittance of 0.324 Wm⁻²K⁻¹. They concluded that the major source of heat loss in thin wall design is the thermal bridging, which account for up to 71% of the total thermal transmittance of the tested thin sandwich panel. Fernando et al. [7] investigated the structural feasibility of an EPS based lightweight concrete full scale sandwich wall panel, which achieved a failure stress of 3.89 N/mm². Ridha et al. [8] studied the compressive and flexural behavior of composite panels made of lightly profiles steel skins and lightweight concrete, which showed good ductility in flexure. Hou et al. [9] studied the flexural behavior of four sandwich panels with reinforced concrete wythes (connected with diagonal steel bars) and inner flat or ribbed EPS layer. They concluded that the flat or ribbed EPS did not affect the behavior of the sandwich wall panels as all panels showed bi-linear load deflection response. O’Hegarty et al. [10] also investigated the flexural behavior of four precast concrete sandwich panels made of fiber reinforced concrete outer layers and foam insulations. Carbon fiber reinforced polymer (CFRP) bars were used to connect the outer concrete layers. They concluded that all panels showed a ductile failure. In addition, the capacity of the panel increased as the outer layer thickness increased.

In sandwich wall panels, shear ties or connectors are important to connect the outer concrete layers of the panels to increase their capacity. Steel connectors can form thermal bridges that allows the temperature to move from one side of the wall to the other side. Glass fiber reinforced polymer (GFRP) bars are composite materials, which are known with their high tensile strength, corrosion resistance, and low thermal conductivity. They have been widely used in several structural applications including the rehabilitation of existing structures [11-13] and as internal reinforcement in new structures (Benmokrane et al. 2008, Thébeau et al. 2010, El-Gamal et al. 2010, 2007) [14-17]. Due to their low thermal conductivity, several research studies have investigated their use as shear ties or connectors in sandwich wall panels. Naito et al. [18] tested fourteen different types of shear ties. They concluded that determining the most suitable shear ties type depends on their shear strength, tensile strength, stiffness, thermal conductivity, installation effort required, and cost. Woltman et al. [19] investigated different types, sizes, and cross-sectional dimensions of GFRP connectors. They concluded that the cross sections shape, sizes, and spacing had insignificant effects on the shear strength. However, they concluded that the end treatment of the connectors can lead to a better shear strength of the GFRP connectors. Hou et al. [20] studied the performance of four different types of GFRP shear connectors in sandwich panels. Test results shows that all the GFRP connectors had approximately similar response. However, GFRP shear connector with solid webs was found to increase the ultimate resistance of the panel slightly more than the other types of connectors.

2. Research Objectives

The main objective of this research study is to develop and investigate the mechanical and thermal properties of sandwich wall panels with two outer lightweight concrete layers and inner EPS insulation sheet. Vermiculite aggregates and EPS beads are used as partially replacement of the natural coarse aggregates in the outer concrete layers of the panels. The effect of using GFRP ties to connect the two outer layers of the panels is also investigated.
3. Test Specimens and Materials Used

3.1. Outer Concrete Layers
Normal and lightweight concrete mixes were used in the outer concrete layers of the sandwich panels. The normal weight concrete had a target compressive strength of 50 MPa and its mix proportions are listed in Table 1. In addition to the normal concrete mix, several lightweight concrete mixes were produced by partially replacing the natural coarse aggregate in the normal weight concrete mix with EPS beads or vermiculite aggregates. Figure 1 shows photos of the polystyrene beads and the vermiculite aggregates used in this study.

Table 1. Mix proportions for normal weight concrete.

| Materials                        | Content (kg/m$^3$) |
|----------------------------------|--------------------|
| Cement                           | 430                |
| Coarse Aggregate (10 mm)         | 990                |
| Sand                             | 660                |
| Water                            | 215                |

Figure 1. Polystyrene beads and vermiculite aggregates.

3.2. Expanded Polystyrene Plates (Inner Layer)
EPS sheets were used as the inner layer in the sandwich panels. The dimensions of the EPS sheets were 500 mm length $\times$ 500 mm width $\times$ 140 mm thickness. The density of the EPS sheets was 10.5 kg/m$^3$. Figure 2 shows a photo of the EPS sheets used in this study.

3.3. GFRP Shear Ties
GFRP bars were used as shear ties in the developed sandwich panels. For each panel, four ribbed GFRP bars of 6 mm diameter were used to connect the two outer concrete layers of the panels. The GFRP bars were 200 mm length and were machined at both ends as shown in Figure 3 to connect the outer concrete layers of the sandwich panels.

3.4. Sandwich Panels
Several panels of 500 x 500 x 200 mm each, composed of an inner ESP layer and two outer concrete layers were constructed. The thickness of the inner ESP layer was 140 mm while the thickness of each outer concrete layer was 30 mm. Four GFRP bars spaced at 40 cm were used as shear ties to connect the outer concrete layers. The cross section of the panel is shown in Figure 4.
3.5. Test Parameters

Two parameters were investigated in this study. The first parameter was the effect of using GFRP shear ties to connect the outer concrete layers of the panels. This parameter was investigated in eight panels with normal concrete mixes (Ref. panels). Four panels were prepared with grooves in the polystyrene inner layer (Ref-Grooves) and other four panels were prepared with GFRP shear ties (Ref-Ties). The second parameter was the effect of using polystyrene beads and vermiculite in the outer concrete layers of the panels as partially replacement of the natural coarse aggregates. To investigate this parameter, 20 sandwich panels were constructed (4 for each set). The replacement ratios were 53, 68 and 84% by volume of the natural coarse aggregates. A summary of the experimental program is listed in table 2.

| Name     | Lightweight Aggregate | Coarse Aggregate Replacement ratio (%) | No. of Panels | Notes                   |
|----------|-----------------------|----------------------------------------|---------------|-------------------------|
| Ref-Grooves | -                     | -                                      | 4             | Without shear ties      |
| Ref-Ties  | -                     | -                                      | 4             |                         |
| Poly-53%  | Polystyrene           | 53                                     | 4             |                         |
| Poly-68%  | Polystyrene           | 68                                     | 4             |                         |
| Poly-84%  | Polystyrene           | 84                                     | 4             | With GFRP shear ties    |
| Ver-53%   | Vermiculite           | 53                                     | 4             |                         |
| Ver-84%   | Vermiculite           | 84                                     | 4             |                         |
3.6. Testing and Instruments

From each set of sandwich panels, three panels were tested in compression after curing for 28 days and the fourth panel was used for thermal conductivity measurements. A 4000 kN capacity hydraulic testing machine was used to test the sandwich panels under compression at a loading rate of 1 mm/min. Figure 5 shows one panel during testing in the hydraulic testing machine. Hot Disk M1 Machine was used to measure the thermal conductivity for each layer of the sandwich panel. Eq. (1) was used to calculate the effective thermal conductivity of the multi-layer sandwich panel. Figure 6 shows Hot Disk M1 Machine.

\[ k = \frac{k_1A_1+k_2A_2+k_3A_3}{A_{\text{total}}} \tag{1} \]

where: \( k_1, k_2, k_3 \) is the thermal conductivity of each layer, \( A_1, A_2, A_3 \) is the cross-sectional area of each layer.

![Figure 5. Hydraulic testing machine](image1)

![Figure 6. Hot disk M1 machine](image2)

4. Test Results and Discussion

4.1. Summary of Test Results

Table 3 summarizes the main results of the tested panels. It can be noticed that the average weight of the panels ranged between 37.9 kg in the Ref-Grooves panels to 24.3 kg in the Poly-84% panels. This resulted in average densities of 758 and 486 kg/m\(^3\), respectively. The average capacities ranged between 1289 kN in the Ref-Ties panels to 196 kN in the Ver-84% panels, which resulted in compressive strengths of 12.8 and 1.96 MPa, respectively. Regarding the thermal conductivity of the panels, the maximum thermal conductivity were measured in the two reference panels (Ref-Grooves and Ref-Ties) with a thermal conductivity of 0.69 and 0.68 W/m.K, respectively. The minimum thermal conductivity (0.25 W/m.K) was recorded in the Poly-84% panels (with 84% replacement ratio of polystyrene beads).

| Panel         | Weight (kg) | Density (kg/m\(^3\)) | Maximum load (kN) | Compressive Strength (MPa) | Displacement at maximum load (mm) | Thermal conductivity (W/m.K) | Panel |
|---------------|-------------|-----------------------|-------------------|-----------------------------|-----------------------------------|-------------------------------|-------|
| Ref-Grooves   | 37.9        | 758                   | 1131              | 11.3                        | 2.28                              | 2.22                          | 0.69  |
| Ref-Ties      | 37.1        | 741                   | 1280              | 12.8                        | 2.83                              | 2.21                          | 0.68  |
| Poly-53%      | 29.81       | 596                   | 420.96            | 4.21                        | 2.19                              | 1.28                          | 0.41  |
| Poly-68%      | 27.53       | 551                   | 325.23            | 3.25                        | 3.39                              | 0.93                          | 0.03  |
| Poly-84%      | 24.31       | 486                   | 202.11            | 2.02                        | 3.73                              | 0.76                          | 0.25  |
| Ver-53%       | 32.31       | 646                   | 313.9             | 3.14                        | 2.78                              | 1.47                          | 0.46  |
| Ver-84%       | 31.30       | 626                   | 196.35            | 1.96                        | 3.28                              | 1.06                          | 0.34  |

4.2. Effect of using GFRP Shear Ties

Figure 7 shows a comparison between the density, compressive strength, and thermal conductivity of the two reference specimens with grooves and with shear ties. It can be noticed that both sets of panels
have similar average density and thermal conductivity as they are made from the same concrete mix. However, the Ref-Ties specimens (with GFRP ties) show higher compressive strength (13% more) compared to the specimens with grooves. In addition, the Ref-Ties panels show higher axial displacement at maximum load than the panels with grooves. This indicates that the presence of the GFRP shear ties delayed the failure and enhanced the axial capacity and the corresponding axial displacement. The GFRP shear ties connected the two outer concrete layers together as seen in figure 8a, which enhanced the capacity of the panels. However, in the Ref-Groove panels. Figure 8b shows that the outer concrete layers were separated from the inner polystyrene insulation layer, which resulted in a lower axial capacity at a lower axial displacement compared to the REF-Ties panels. Therefore, in all panels with lightweight aggregates, it was decided to use GFRP shear ties in all panels. It is worth mentioning that the compressive strength of both types of panels are higher than the concrete compressive strength of the commercially available concrete hollow blocks (5 to 10 MPa) but they show much lower thermal conductivities (0.68 W/m.K compared to 1.6 W/m.K).

![Figure 7. Comparison between Ref-Grooves and Ref-Ties panels](image)

![Figure 8. Typical failure mode of the Reference panels](image)

4.3. Effect of Lightweight Aggregates Replacement Ratio

Figures 9 and 10 show the relation between the polystyrene and vermiculite replacement ratios and the density, the compressive strength, and the thermal conductivity of the panels. Figures 9a and 10a show that as the polystyrene and vermiculite replacement ratios increase, the density of the panels decrease. The densities of the panels with polystyrene beads were 596, 551, and 486 kg/m³ for the replacement ratios of 53, 68, and 84%, respectively. These densities were less than the density of the Ref-Ties panels by about 19.6, 24.6, and 34.4%, respectively. For the panels with vermiculite aggregates, the densities were 646 and 626 kg/m³ for the 53 and 84% replacement ratios, respectively, which were less than the density of the Ref-Ties panels by about 12.8 and 15.5%. It is worth mentioning that the densities of the developed panels are much lower than the density of commercially available concrete hollow blocks.
(1193 kg/m³). In addition, they are less than the densities of lightweight concrete blocks developed by Al-Jabri et al. [1] (798 and 1168 kg/m³). Furthermore, they are much lower than the density of the commercially available blocks with thermal insulation layer (1418 kg/m³). The lower weight and densities of the panels developed in this study is expected to reduce the self-weigh of the walls in buildings. This will result in smaller structural elements.

Figures 9b and 10b show that as the polystyrene and vermiculite replacement ratios increase, the compressive strengths decrease. The compressive strengths of the panels with 53, 68, and 84% replacement ratios of polystyrene beads were 4.21, 3.25, and 2.02 kg/m³, respectively. These values were less than the compressive strength of the Ref-Ties panels by about 67.1, 74.6, and 78.6%, respectively. The compressive strengths of the panels with 53 and 84% replacement ratios of vermiculite aggregates were 3.14 and 1.96 kg/m³, respectively. These values were less than the compressive strength of the Ref-Ties specimen by about 75.5 and 84.7%, respectively. It is worth mentioning that the compressive strength of the panels with different polystyrene beads replacement ratios are comparable to the results in [1] (2.2 and 3.3 MPa). In addition, the panels with 53 and 68% replacement ratios are satisfying the Omani standards [4] requirements for non-load bearing walls.

Figures 9c and 10c show that as the polystyrene and vermiculite replacement ratios increase, the thermal conductivity of the panels decrease. Figure 9c shows that the thermal conductivities of the panels with polystyrene beads were 0.41, 0.30, and 0.25 W/m.K for the replacement ratios of 53, 68, and 84%, respectively. These values were less than the thermal conductivity of the Ref-Ties panels by about 39.7, 55.9, and 63.2%, respectively. The thermal conductivities in the panels with vermiculite aggregates were 0.46 and 0.34 W/m.K for the 53 and 84% replacement ratios, respectively (Figure 10c), which were less than the thermal conductivity of the Ref-Ties specimen by about 32.4 and 50%, respectively. Compared to commercially available concrete hollow blocks, the thermal conductivities of all panels with lightweight aggregates are much lower than their thermal conductivity (1.6 W/m.K). They were also lower than the results in [1, 2] but were comparable with the results in [3]. These lower thermal conductivity values obtained in this research study will result in better thermal insulation in buildings and is expected to reduce the electric power consumption required for cooling of buildings.
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4.4. Effect of Lightweight Aggregate Replacement Material

Figure 11 shows a comparison between the densities, compressive strengths, and thermal conductivities of panels with polystyrene bead and vermiculite aggregates. It can be noticed that the panels with vermiculite aggregates have higher densities and thermal conductivities than similar panels with polystyrene beads. The increase in the density of the panels with vermiculite aggregates was about 18% on average compared to the panels with polystyrene beads. The average increase in the thermal conductivity values of the panels with vermiculite aggregates was about 24.1% compared to the panels with polystyrene beads. This indicates that the panels with polystyrene bead have better thermal insulation properties than those with vermiculite aggregates.

On the other hand, the panels with vermiculite aggregates have lower compressive strength than similar panels with polystyrene beads. The compressive strengths of the panels with polystyrene beads were about 35.5 and 55% greater than the compressive strengths of the panels with vermiculite aggregates at replacement ratios of 53 and 84%, respectively. The results show that panels with polystyrene beads are better than the panels with vermiculite as they gave lower densities, better compressive strengths, and better thermal insulation properties.

Figure 11. Effect of the type of the lightweight material
5. Conclusions

Based on the test result of this research study, the following conclusions can be derived:

- The developed sandwich panels with natural aggregates (reference panels) showed lower densities and higher compressive strengths than the commercially concrete hollow blocks and thermal insulation blocks available in Oman.
- The average thermal conductivity of the developed reference panels was about 42% of the thermal conductivity of the commercially available concrete hollow blocks and it was comparable to the thermal conductivity of the local available thermal insulation blocks.
- Using GFRP shear ties was more effective than using grooves. The GFRP ties delayed the failure and enhanced the capacity of the panels by about 13% compared to the panels with grooves.
- As the polystyrene and vermiculite replacement ratios increased, the density, compressive strength, and thermal conductivity of the sandwich panels decreased.
- The densities of the panels with lightweight aggregates ranged between 486 and 646 kg/m$^3$. These densities were lower than the density of the reference panels by about 12.8 to 34.4%. There were also much lower than the densities of the commercially available concrete hollow blocks and concrete thermal insulation blocks.
- The compressive strengths of the panels with polystyrene beads ranged between 4.21 and 2.02 kg/m$^3$ and ranged between 3.14 and 1.96 kg/m$^3$ for the panels with vermiculite. The developed panels with 53 and 68% lightweight aggregates can be used for non-load bearing walls.
- The thermal conductivities of the panels with polystyrene beads and vermiculite aggregates ranged from 0.41 to 0.25 W/m.K and from 0.46 to 0.34 W/m.K, respectively. These values were lower than the thermal conductivities of all commercially concrete blocks available in Oman. The lower thermal conductivity values of the developed lightweight panels is expected to result in a better thermal insulation in buildings and is expected to reduce the electric power consumption.
- The results show that the panels with polystyrene beads are better than the panels with vermiculite as they gave lower densities, higher compressive strengths, and lower thermal conductivities.

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