Thermal Performance of Precast Concrete Sandwich Panel (PCSP) Design for Sustainable Built Environment

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Abstract: Malaysia's awareness of performance criteria in construction industry towards a sustainable built environment with the use of precast concrete sandwich panel (PCSP) system is applied in the building's wall to study the structural behaviour. However, very limited studies are conducted on the thermal insulation of exterior and interior panels in PCSP design. In hot countries such as Malaysia, proper designs of panel are important to obtain better thermal insulation for building. This study is based on thermal performance of precast concrete sandwich panel design for sustainable built environment in Malaysia. In this research, three full specimens, which are control specimen (C), foamed concrete (FC) panels and concrete panels with added palm oil fuel ash (FC+ POFA), where FC and FC+POFA sandwiched with gypsum board (G) were produced to investigate their thermal performance. Temperature difference of exterior and interior surface of specimen was used as indicators of thermal-insulating performance of PCSP design. Heat transfer test by halogen lamp was carried out on three specimens where the exterior surface of specimens was exposed to the halogen lamp. The temperature reading of exterior and interior surface for three specimens were recorded with the help of thermocouple. Other factors also studied the workability, compressive strength and axial compressive strength of the specimens. This study has shown that FC + POFA specimen has the strength nearer to normal specimen (C + FC specimen). Meanwhile, the heat transfer results show that the FC+POFA has better thermal insulation performance compared to C and FC specimens with the highest temperature difference, 3.4°C compared to other specimens. The results from this research are useful to be implemented in construction due to its benefits such as reduction of energy consumption in air-conditioning, reduction of construction periods and eco-friendly materials.

1. Introduction

Sustainability in construction industry involves issues such as designing a new building, which are combined with term such as "green building", "sustainable built environment" and "environmental friendliness" [4]. Construction industries in Malaysia also have progressed due to the awareness of sustainability of build environment from conventional on-site construction methods to green building approaches and because of possibility that something unpleasant or unwelcome damages to the environmental might happen, this method was however previously criticised [1, 5]. Therefore, PCSP system can be perceived as an alternative approach in creating and maintaining the sustainable built environment, hence can also maximise benefits from integrated strategies, which focus on all of the building's materials and systems, as well as the way they interact [2, 4].

In hot countries such as Malaysia, the building's wall should be able to retain heat of the day and release the heat during the night. Hence, the PCSP applied in the building's wall should have the suitable thermal performance in order to save the energy thermal capacity that required maintaining the internal temperature by help of air-conditioning system [6]. It should be noticed that an appropriate design of thermal insulation of exterior and interior panels in PCSP can significantly reduce the consumption of energy for space heating and cooling and eventually reduce the degradation of energy-quality and caused carbon dioxide (CO2) emissions, which is in line with the concept of sustainable building [3].

Despite the fact that energy demand is increasing, we still have many waste resources that can be developed and used for heat insulating materials [26]. The waste resources which can be used for heat insulating materials include EPS, FA, POFA, gypsum and others. Usage of the waste materials in construction can help in reducing the pollution and degradation of resources. On the other hand, many waste materials such as POFA are unutilised and cause land and air pollution in the vicinity of palm oil factories [27]. The use of palm oil fuel ash (POFA) is one of the possibilities to produce a good thermal performance in wall panel of PCSP. To encourage usage of POFA in foamed concrete (FC) there is a need to know the thermal performance of POFA concrete panel in PCSP design.

In order to develop and construct PCSP design with a good thermal insulation, an experimental work which includes three full-scaled specimens, control specimen (C), foamed concrete specimen (FC) and foamed concrete with added 30% of palm oil fuel ash (POFA) with similar size (300mm x 200 mm x 120mm) was conducted to study the thermal performance for each different design of mix proportion. The temperature variations of the exterior and interior layer of panels were recorded to investigate the temperature difference for the three different panels and to compare the thermal performance between FC and FC+POFA panels with C panel. Meanwhile, the cube from these three types of specimens also been produced in order to observe the workability and compressive strength development. Different mixes proportions of foamed concrete in PCSP were used to study the effect of the proportion of the properties of the panels, especially in thermal properties.

2. Literature Review

This section briefly discusses the precast concrete sandwich panel (PCSP) and the previous research on the foamed concrete (FC) mixture and thermal behaviour of different materials in the sandwich panels.

2.1 Precast Concrete Sandwich Panel (PCSP)

PCSP is commonly classified as a prefabricated concrete system, which is used for building envelopes. It is known as a structurally and thermally efficient system that is used for the exterior walls in the building construction. PCSP is currently used as the curtain walls with a little modification and it can function as loading bearing elements [7, 28]. Another study stated that the thermal efficient systems of PCSP can save nearly 20% in energy cost compared to framed works [9].

This type of sandwich panel is light in weight and had also been used widely in construction projects, but still maintaining adequate strength, good durability, good thermal insulation and good sound insulation [6]. Not only that, the use of sandwich panels in the construction projects can allow the workers work in clean and safe environment [7]. The period of a project will be shorter compared to the conventional construction method due to pre-casting of wall panels which also can be produced everyday including rainy day. Due to reduction of workers in fabricating the PCSP, the cost will also decrease [9].

However, there is limited implementation of PCSP system in construction of Malaysia due to the barriers such as is higher initial capital investment and higher cost of transportation and extra cost needed to train the existing semi-skilled labour to be highly skilled labour [10]. Hence, this sandwich panels system still needs a lot of time and efforts to make it suitable in construction industry of Malaysia. Every sector should realise that high energy consumption in construction industry will lead to environmental issues.

2.2 Foamed concrete (FC) with palm oil fuel ash (POFA) as additives

Foamed Concrete (FC) is still considered as a new construction material compared to the conservation concrete. FC is one of the lightweight concrete which consists of Portland cement, fine aggregates (sand), water, foaming agent and compressed air [9]. There are clear differences between the normal concrete and FC, where FC requires a higher proportion of ultra-fine materials and the incorporation of chemical admixtures, particularly high range of water [10]. But generally, FC possesses the characteristics such as low in density, high workability [9], high thermal insulation [11], high fire resistance [12] and high strength compared to conventional concrete.

Thus, it could be concluded that FC is a more sustainable choice compared to conventional concrete due to its characteristics. Hence, it is encouraged to apply FC in the wall system construction and the study of new additives such as POFA waste should be conducted to reduce the waste generation and in the same time create a sustainable built environment. POFA is an agro-waste ash from palm oil residue, which burnt at temperatures of about 800˚C –1000 ˚C in biomass thermal power plants. However, due to its high high-strength properties and fewer impacts to environment in concrete specimens, the construction industries has seriously been motivated [13]. Application of 15% to 30% POFA in construction industry can increase the strength of concrete. Use of POFA as the cementing materials in construction industry will also reduce the environmental problems associated without disposing it in landfill [15].

2.3 Study of Gypsum Board on Thermal Performance of PCSP Design

Gypsum board is an eco-friendly material, which possesses a low environment impact and provides good thermal performance. A group of researchers [3] carried out an experimental work which involved a series of heat test on three different design of PCSP. The three specimens include conventional concrete sandwiched layer (C), specimen having a solid gypsum sandwich layer (G) and specimen having a gypsum layer with voids (GV). The results of experiment showed that sandwiched gypsum layer can effectively retard the heat transfer possess in the PCSP and the gypsum layer with voids possess higher thermal insulating among the specimens. The thermal performance of the GV specimens can be considered as the better one compared to others [3].

The gypsum board can achieve the strength similar to normal foamed concrete [15]. Therefore, the gypsum board is potentially viable in the wall system of construction building if the mechanical properties of gypsum paste are improved in future.

3. Methodology

3.1 Step 1: Preparation of Materials

In order to produce 1000kg/m^3 of foamed concrete with higher strength, selection of the material must base on quality, economical and good performance. Materials used in this study are water, Ordinary Portland Cement (OPC), sand, POFA, foaming agent and gypsum powder. The sand used was passed through 600 µm and water used in this study is tap water. Meanwhile, the source of POFA was from palm oil industry in Kahang which classified as Class F Fly Ash in accordance with ASTM C618 (2008). Foaming agent used is Sika AER 50/50 and it was diluted with water by 1 proportion of foaming agent to 20 proportions of water. Gypsum board was used as the sandwiched layer in the PCSP design. Gypsum powder used for moulding of gypsum board will be gypsum casting powder. This powder was obtained from Chip Seng Ceiling Plaster Trading, Batu Pahat, Johor.

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3.2 Step 2: Fresh Concrete Mixture

Mix Proportions

There is no standard method for proportioning foamed concrete, so the mix proportion of the foamed concrete incorporated with POFA was determined by previous study. The ratio of cement-sand and water-cement ratio used in this study is constant throughout whole experimental work which is 1:2 and 0.5 [16]. The mix proportions used for different samples are shown in Table 1. Meanwhile, Table 2 shows the details of layer used in the test.

Table 1: Mix proportions of different samples

Samples	Target Dry Density (kg/m^3)	Cement: Sand	Cement: POFA
C	1000 ± 50	1:2	100:0
FC	1000 ± 50	1:2	100:0
FC + POFA	1000 ± 50	1:2	70:30

Table 2: Details of layer used in the tests

Samples	Exterior Layer	Sandwiched Layer	Interior Layer	Dimension (mm)
C	-	-	-	300 x 200 x 120
FC	FC	Gypsum	FC	300 x 200 x 40 each layer
FC + POFA	FC + POFA	Gypsum	FC + POFA	300 x 200 x 40 each layer

Preparation of mixing procedure of foamed concrete was based on previous study of researchers. The mixing procedures of foamed concrete in laboratory are as follows.

The target density of foamed concrete was determined and materials of required quantity were prepared. OPC, sand and POFA were weighted and mixed in a concrete mixer until uniformly mixed. Thereafter, water was added mixed until uniformly mixed. The mixer stopped for volume reading. After taken the volume reading, while the mixer still in motion, foam is added to the mix through the foam generator.

Preparation of Batching of Gypsum Mixture and flow test

The composition for mixture of gypsum powder and water was applied as in [17]. Flow test was conducted by using a slump cone and flat base plate as complied with ASTM C 995 (2001).

Air Curing

A result from the previous study where air curing was used showed that air curing can lead to higher compressive strength [18]. Figure 1 shows the condition of air curing in the room. For this study, 6 cubes and the PCSP panels of each type of specimens were placed in moulds and left to dry in the room with the temperature of 30 °C ± 2 °C until the time of testing which are 7 and 28 days respectively as shown in Figure 1 PSCP panels only test after 28 days.

3.3 Step 3: Assembly of PCSP

The Figure 1 shows the assembly of three full-scaled panels which used to underwent axial compressive test and heat transfer test.

Control Panel, (C) | Foamed Concrete Panel, (FC) | Foamed Concrete with added POFA Panel, (FC+POFA)

Figure 1: Assembly of three full-scaled panels

3.4 Step 4: Concrete Test

Cube Test and Axial Compressive Test

Cube Test was performed in accordance with BS EN 12390-3 (2002). An axial compressive load with specific rate of loading is applied to the cubes until failure occurred. Mean value will be obtained from the three cubes and then taken as compressive strength for each foamed concrete mix. The same procedures of cube test were applied on the axial compressive test of specimens in panel size. The failure of cube and panel applied by specified load were noted thereafter.

Consistency and Stability

The fresh density and hardened density of the specimens were used to check the stability and consistency of the mix [19]. The consistency and stability of the specimens is determined by the Equation (1) and Equation (2) [19]. Consistency Fresh Density Designated Density

$$\text{Consistency} = \frac{\text{Fresh Density}}{\text{Designated Density}} \quad (1) \qquad \text{Stability} = \frac{\text{Fresh Density}}{\text{Hardened Density}} \quad (2)$$

3.5 Step 5: Heat Transfer Test

After 28 days, the panels underwent the heat transfer test where temperature variations across the wall thickness over time in different specimens were recorded in order to observe the thermal insulation performance. In heat transfer test, a halogen lamp was used as a heat source for 8 hours [3] and was placed 250 mm away from the exterior concrete, as demonstrated in Figure 2.

The heat conduction from exterior concrete surface to interior concrete surface is the primary concern in this study. The panels were wrapped with aluminium foil around the sample to reduce the heat loss to surrounding and to minimize the radiation from the halogen lamp reaching the sides of panels during the experiment, and also to ensure one dimensional heat transfer. Thermocouple is used to measure the temperature of exterior and interior surface of specimens for every 30 minutes. Also, Figure 2 shows the experimental setup before and after panel covered with aluminium foil.

Figure 2: A schematic diagram showing the specimen, heat source and experimental setup before and after covered with aluminium foil

To simplify the heat transfer analysis, there are some assumptions that need to be introduced. The assumptions included:
(a) The panels have the same effective density
(b) There is no convective heat transfer at sides of the panels, as the panels are wrapped by aluminium foil and the experiment will take place inside a controlled environment.
(c) The radiation from halogen lamp reaching to the sides of panels were prevented by aluminium foil, hence radiation can be negligible.
The temperature difference will be calculated after 8 hours radiation. The temperature differences for two layers are calculated based on Equation (3). The higher the temperature differences between the two layers, the more the heat is been insulated and the better the thermal performance of the PCSP design.

$$\text{Temperature Difference} = T_1 - T_2 \tag{3}$$

where
T_1 = Temperature of exterior surface of concrete
T_2 = Temperature of interior surface of concrete

4. Results and Discussions

Workability, Consistency and Stability of Specimens

The fresh concrete properties are shown in Table 3. All the specimens show good result in workability, consistency and stability.

Table 3 shows that the spread value of FC+POFA specimen range from 430 mm to 450 mm is lower than the C and FC specimen range from 520 to 540mm. In other words, the addition of POFA in the mixture makes the concrete less workable compared to the C and FC specimens. The finding which was agreed by [19] and [20] found that the replacement of POFA will cause a reduction in spread value and workability compared to other specimens due to the shape of the pozzolan particles in the POFA.

High consistency of the C and FC specimens mean the specimens are wetter compared to FC+POFA specimens, and wetter mixtures are more workable than the drier mixtures. Hence, the addition of POFA in the foamed concrete mixture will cause the mixture to have lower workability and consistency.

Table 3: Spread value, consistency and stability of various types of specimens

Specimens	Cube Detail	Sand: POFA	Spread (mm)	Consistency	Stability
C and FC	C_1	100:0	520-540	1.10	1.05
	C_2			1.09	1.05
	C_3			1.10	1.05
	C_4			1.08	1.03
	C_5			1.10	1.04
	C_6			1.09	1.05
FC + POFA	FC_1	70:30	430-450	1.05	1.02
	FC_2			1.06	1.02
	FC_3			1.04	1.02
	FC_4			1.05	1.03
	FC_5			1.05	1.02
	FC_6			1.06	1.02

Meanwhile, the values of stability for the FC+POFA specimens are nearer to 1.00 compared to C and FC specimens. This might be due to the high content of silicon dioxide (SiO_2) in POFA which will produce more C-S-H gel compound from the pozzolanic reaction that will help in improving the interfacial bonding between the aggregates and mixtures at later ages [20]. Thus, addition of the POFA in the foamed concrete will provide higher stability compared to the control specimens.

<u>Cube Test and Axial Compression Test Results</u>

All the specimens were tested for compressive strength at day 7 and day 28. Generally, Figure 3 reveals the compressive strength of the specimens increased from 7 days to 28 days.

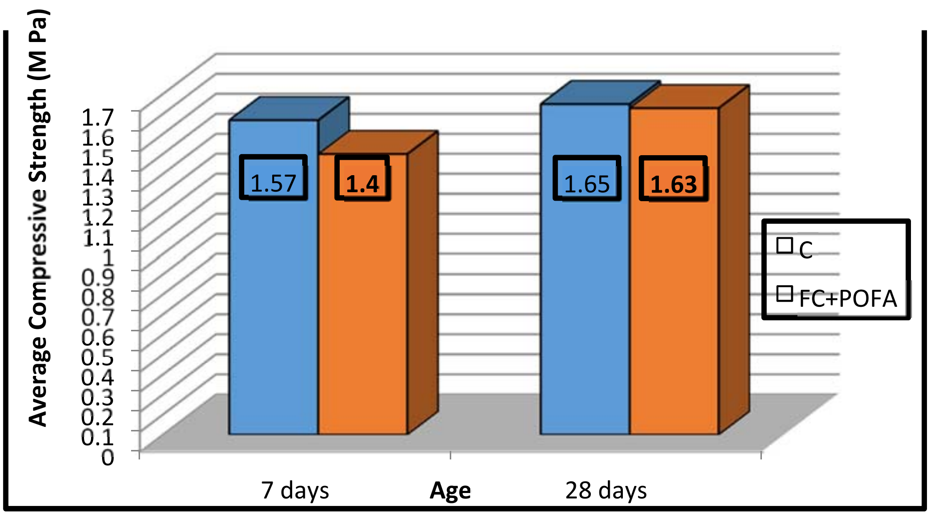

Figure 3: Compressive strength of various types of specimens at day 7 and day 28

Figure 3 shows that the compressive strength of C specimen at day 7 is 1.57 MPa which is higher than the FC+POFA specimen which is 1.4 MPa. Similar study had also shown the same situation where addition of POFA in concrete will cause low compressive strength on day 7 [21]. This may be due to the pozzolanic characteristic that is possessed by POFA which cause the compressive strength to develop slowly at early age as compared to the control specimen (C).

However, the compressive strength of FC+POFA specimen at day 28 showed an increase to 1.63 MPa, nearer to the compressive strength of normal specimen. The result of compressive strength in this study shows some differences compared to other researches that the addition of 30% of POFA in the concrete mixture can improve the compressive strength compared to the normal concrete. This situation may be due to the different physical and chemical properties of POFA used in the experiment work [22]. The concentration of SiO_2 in the POFA used in this experiment may be relatively smaller than the previous researches conducted [22]. Hence, the present study is able to conclude that POFA has the potential to be used as the partial cement replacement in producing foamed concrete as the strength possessed by FC+POFA specimen is near to a normal concrete.

The axial compressive strength for the three specimens which were air cured for 28 days are shown in Figure 4. The results show that the FC+POFA panel has the highest strength of 3.3 MPa compared to other panels. Meanwhile, C panel's strength is the lowest which is 1.9 MPa. The FC and FC+POFA panels have higher strength compared to the C panel which may be due to the existence of gypsum layer as the sandwich layer in these two panels. The gypsum layers also possess high strength when applied to axial load. The gypsum cube achieved a high strength when it underwent cube test [17]. Hence, the existence of the gypsum layer will also affect the axial compressive strength of the panels.

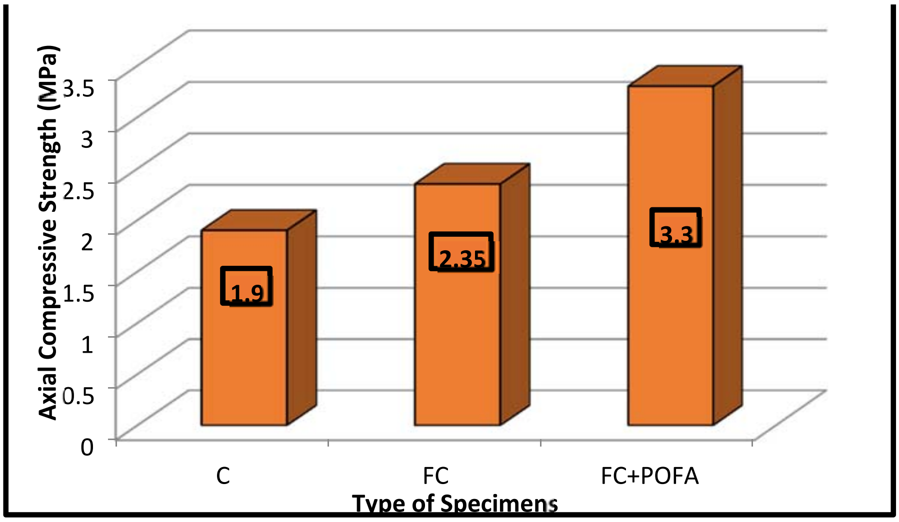

Figure 4: Axial compressive strength for various types of panels at 28 days

Heat Transfer Test Results

Table 4: Temperature difference of exterior and interior surface of specimens after 8 hours radiation

Specimens	Average Temperature (°C)		
	Exterior Surface	Interior Surface	Difference
C	88.3	43.7	44.6
FC	88.6	41.4	47.2
FC + POFA	88.7	40.7	48.0

In order to clearly observe and compare the value of temperature difference for the three specimens, Table 4 had summarized the results of heat transfer test. This later exposed the specimens under halogen lamp for 8 hours. The temperature of the interior surface for the three specimens show significant difference; FC+POFA specimen has the greatest temperature difference of 48.0°C compared to the other specimens. The temperature difference for FC+POFA is 3.4°C and 0.8°C higher than the C specimen and FC specimen respectively. Since the temperature difference indicates the thermal-insulating performance of the PCSP design, hence FC+POFA specimen has the better thermal insulation performance compared to C and FC specimens.

The temperature difference of FC specimen is 2.6°C higher than C specimen which may be due to the existence of gypsum layer at the middle of PCSP design. The inclusion of gypsum layer in the PCSP design can efficiently reduce the heat transfer to interior surface of wall and so improve the thermal insulation performance in a building [3]. On the other hand, the temperature difference FC+POFA specimen is 0.8°C higher than the FC specimen which may due to the addition of POFA in the concrete mixture. This result implies that addition of 30% of POFA in concrete mixture can improve the thermal insulation performance of a building.

Based on the experimental results, the FC+POFA specimen can improve the thermal insulation performance of the wall system. The 3.4°C drop of temperature in FC+POFA design compared to the normal wall design can lead to a significant reduction of the electricity consumption in the air-conditioning system. The significance of temperature drop on the energy saving proved that small drop of temperature can lead to great reduction of energy [3].

5. Conclusions and Recommendations

Based on the laboratory results, the following conclusions can be drawn:

a) The addition of 30% of POFA in the foamed concrete decrease the workability and consistency but increased the stability and also the compressive strength of the concrete.
b) The temperature difference between the exterior and interior surface of C specimen after 8 hours exposed to halogen lamp is 44.6°C.
c) A temperature difference of exterior and interior surface for FC panel after 8 hours is 47.2°C.
d) A temperature difference of exterior and interior surface for FC panel after 8 hours is 48.0°C.
e) In this study, temperature difference indicates the thermal-insulating performance of the PCSP designs. From this study, the results had shown that temperature difference of FC+POFA specimen is the highest and is 3.4°C higher than the C specimen.

Meanwhile, FC specimen is 2.6°C higher than the C specimen. Hence, in this study, FC+POFA specimen has the highest thermal-insulating performance and follow by FC specimen. . The 3.4°C and 2.6°C drop of temperature in FC+POFA specimen and FC specimen compared to the normal wall design can lead to a significant reduction of the electricity consumption in the air-conditioning system.

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