Proceedings of the 7th International Conference on Civil Structural and Transportation Engineering (ICCSTE'22)
Niagara Falls, Canada – June 05-07, 2022
Paper No. 188
DOI: 10.11159/iccste22.188

Experimental Study on the Thermal Characterization of PTF Concrete

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Abstract **-** In this paper, the thermal properties of concrete mix prepared with Palm Tree Fiber (PTF) are presented. The objective of the study is to investigate the effect of adding waste from agriculture to concrete on its thermal conductivity. The final goal is to reduce the buildings energy consumption by enhancing the insulation properties of structural concrete without compromise the integrity of the structure. Therefore, the research has also investigated the effect of adding the natural PTF fiber on the mechanical properties of concrete. This paper presents the thermal insulation research outcome of the PTF concrete. The testing protocol involved two methods: the thermal conductivity for small concrete cylinders and thermography of concrete slab using IR camera. Five families of concrete were prepared with increased amount of added PTF. It was found that adding PTF to concrete has enhanced the thermal insulation properties of concrete. Thermal conductivity test results as well as thermography test indicate that PTF can be used to increase the thermal resistance of concrete. The main disadvantage though is the high-water absorption of the fiber which detrimentally influences the mechanical properties of concrete. It is suggested that that the percentage of added fiber to structural concrete to be limited to 3% and to 4% for non-structural applications.

Keywords**:** Thermal conductivity of concrete, insulation, PTF, Thermal diffusion, Global Warming

1. Introduction

The issue of global warming has grown increasingly prominent in recent years. Temperature records are being set all around the world, both for highs and lows. Global warming will be exacerbated by the usage of hydrofluorocarbons (HFCs) in cooling equipment, as well as CO_2 and black carbon emissions from the largely fossil fuel-based energy that now powers cooling. The consumption rates of electrical energy are directly proportional to the changes in the climate [1]. The use of electricity in hot harsh climates is steadily increasing due to the excessive use of air conditioning. Every air-conditioned house in the United States is expected to emit two tons of carbon dioxide each year. The thermal insulation performance of the building envelope has a direct impact on the thermal stability and comfort of the internal environment, and it plays a critical role in lowering the building's operational energy consumption [2] and [3]. It is thought that by installing superior insulation systems in our homes, particularly in the GCC, the use of air conditioners may be improved to consume less electricity. The major goal of this study is to see how adding an environmentally friendly natural fibre like PTF to concrete affects both structural and mechanical properties.

2. Material and Methods

The concrete mix was prepared as per the ASTM standard guidelines [4, p. 31]. The mix design for grade 40 MPa was reached after a trial-and-error comprehensive benchmark study and shown in Table 1. The ultimate strength of concrete was evaluated at curing ages of 7 and 28 days using the compressive strength test on cylindrical 100mm × 200 mm samples. The PTF was added to the mix and replace by sand volume in five different ratios of 0%, 1%, 2%, 3% and 4%. A series of destructive and non-destructive tests were conducted in order to check the effect of adding the PTF on the mechanical, physical and thermal properties of concrete. A total of 215 of 100 mm×200 mm and 20 of 150 mm×300 mm cylindrical shaped samples plus ten (200 mm×200 mm×30mm) and ten (200 mm×200 mm×50mm) concrete slabs were casted and tested during this phase of the project.

The effect of adding the PTF on the mechanical and physical properties of concrete grade 40 MPa will be reported in a separate document. The 20 concrete slabs were used for the thermal tests which are presented here. The compressive strength of the pure concrete cylinders from the benchmark study are shown in Table 2.

Table 1: Mix Design for 40 MPa concrete Grade

Cement (kg)	**Water (kg)**	**Sand (kg)**	**Agg (3/4″) (kg)**	**Agg (1/2″) (kg)**	**Agg (3/8″) (kg)**	**Admixture (ℓ)**
320	180	695.00	610.0	230.0	325.0	4.5

Table 2: Compressive Strength Results of 40 MPa grade

Sample Name	**Weight (g)**	**Curing Age (days)**	**Load (kN)**	**Compressive Strength (MPa)**	**Average Strength (MPa)**
Mix-40-1	3765.87	7	281.1	35.13	33.55
Mix-40-2	3861.78		233.9	29.79	
Mix-40-3	3871.00		272.9	34.92	
Mix-40-4	3802.72		283.4	34.37	
Mix-40-5	3782.85	28	383.5	46.36	43.79
Mix-40-6	3846.28		340.7	42.92	
Mix-40-7	3880.53		353.2	44.05	
Mix-40-8	3818.48		340.3	41.81	

Two approaches were followed in this study for measuring the thermal conductivity of the PTF concrete. In the first approach, a FLIR C2 infrared camera, was utilized to perform thermography test on saturated and dried samples. In the second approach, concrete cylinders core cuts were tested using the G.U.N.T Hamburg WL 420 Heat Conduction apparatus, Fig. 7 and WL420 v12 acquisition software Fig. 8. The small cylinders (10 mm ×50mm) were extracted from the 50 mm-thick slabs using powerful waterjet machine that uses a high-pressure of 3800 bar water jet. The concrete slabs and small cylinders are shown in Figures 1and 2. In each sample two Φ1mm – 40 mm apart holes were drilled carefully at the top and bottom of the sample as shown in Fig. 3. The holes were used to insert the two thermocouples with Peltier element concealed as presented in Fig. 7.

Four samples were tested using the Hamburg machine in two phases. In the first phase the samples were saturated in water for 24 hours prior to the testing. In the second phase the samples were dried in the oven under 110 °C. Then they were tested using the same machine. These two extreme conditions represent the maximum and minimum water content limits in the concrete which influences its thermal conductivity reading. The average thermal conductivity of each set was calculated for the wet and dry conditions and reported here.

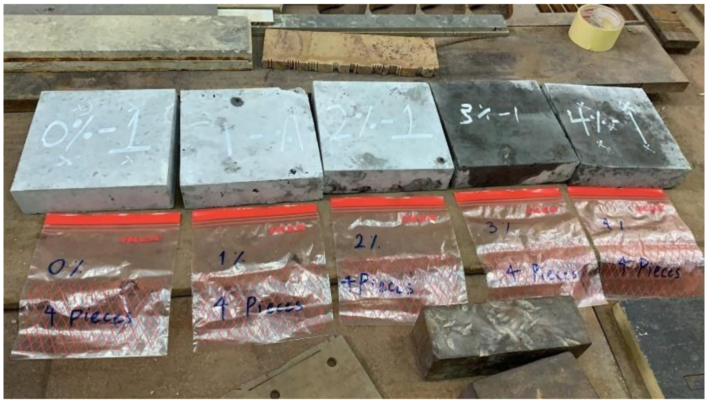

Fig. 1: 50 mm-thick slabs before cutting

Fig. 2: 50 mm-thick slabs after waterjet cutting

Fig. 3: Sample preparation for thermal conductivity test

Fig. 4: Extracted cylindrical core samples – from left to right 0%,1%, 2%, 3% and 4%

Thermography testing was conducted using the methodology reported in ref. [3] and shown in Fig. 6. The thermal conductivity of the PTF-concrete was investigated by means of measuring the surface temperature gradient using infrared thermal imaging camera FLIR C2 (FLIR system Taby, Sweden) Fig. 5. FLIR Tools software (FLIR systems, USA) was used to view and post-process the thermographic results. Four square specimens (30mm and 50mm think) of each family were prepared and cured at room temperature of 28 days prior to testing. The room temperature of ~ 26 ˚C was considered as an initial temperature for the test. Each sample was placed in an XPS insulation board (Qatami Insulation Materials®, Kuwait), and was exposed to a heat source of 275W as shown in the Fig. 6. The thermal distribution of the specimen was examined for 30 min and was stored at 10 minutes intervals.

Fig. 5: FLIR C2 infrared camera

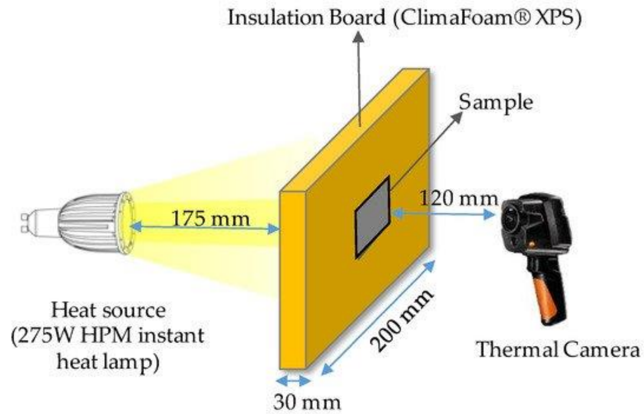

Fig. 6:Thermography test setup [3]

The thermal conductivity of the small cylinders was measured using Equ.(1) utilizing the G.U.N.T Hamburg WL 420 Heat Conduction apparatus.

$$\dot{Q} = \lambda \cdot \frac{A}{L} \cdot (T_1 - T_2) \tag{1}$$

In which:

$\dot{Q} =$ Heat Flux
$\lambda =$ Thermal Conductivity
$A =$ Cross-sectional area
$L =$ Length
T_1 *and* T_2= Temperatures at the hot surface and cool surface respectively

Although heat conduction is spatial, in the previous equation, the heat conduction in the specimen is assumed to stick to linear flow in one direction for simplicity. This assumption is considered to be acceptable given that the heating and cooling plates overlaps the entire top and bottom faces of the specimen. Hence, the transvers thermal gradient will be uniform at every section along the sample. This means no heat fluxes in the transverse direction to the flow. Furthermore, the higher the thermal conductivity of a material, the lower is the temperature difference at the same heat flux [5].

Concrete consists of several ingredients including mortar paste (resulting from the hydration reaction of cement and water), aggregates of several sizes, sand, free water content and air voids. The concrete grade, mix standard, source and quality of the constituents and quality of mixing and casting of concrete significantly influence the mechanical, physical, and thermal properties of concrete [6]. Pure cement mix, i.e. mortar, was reported to have very low thermal conductivity comparing to that of gravel and sand. Therefore, in the case of the sand and gravel concrete mixtures, there is practically no difference in thermal conductivity due to the relative "richness" or "leanness" in cement of a mixture, at any rate for the range of temperature of 100 °C to 200 °C [7].

The concrete is considered as heterogeneous material having variable characteristics due to the different composition within the material itself [8]. Therefore, and for practical reasons, the tested sample, i.e., the cut, shall be perpendicular to the expected heat flow. Nevertheless, the sampling shall be taken randomly from variant places in the large element in order to obtain representative samples.

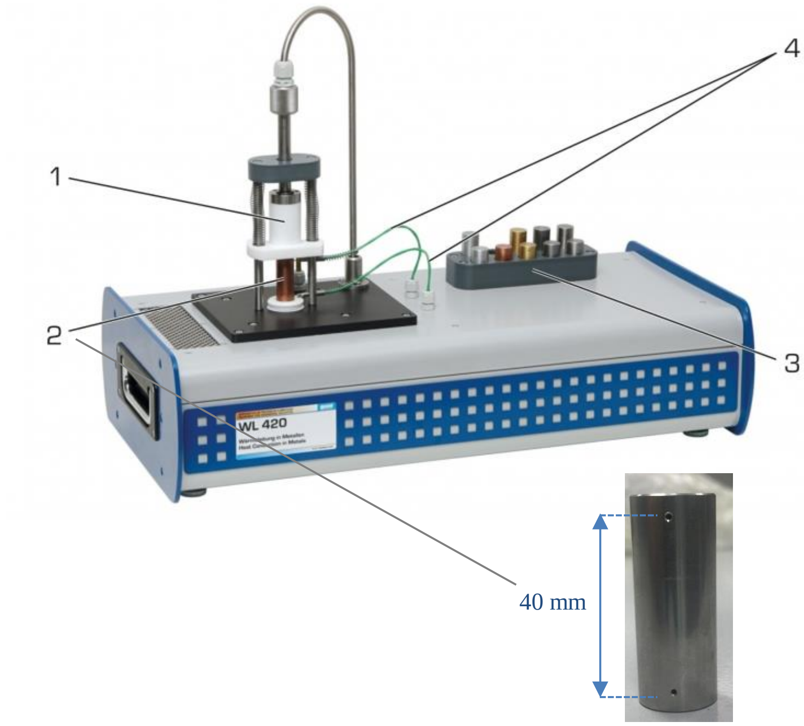

Fig. 7: The G.U.N.T Hamburg WL 420 Heat Conduction apparatus
1.Heater, 2. Sample 3. Storage for samples, 4. Thermocouple

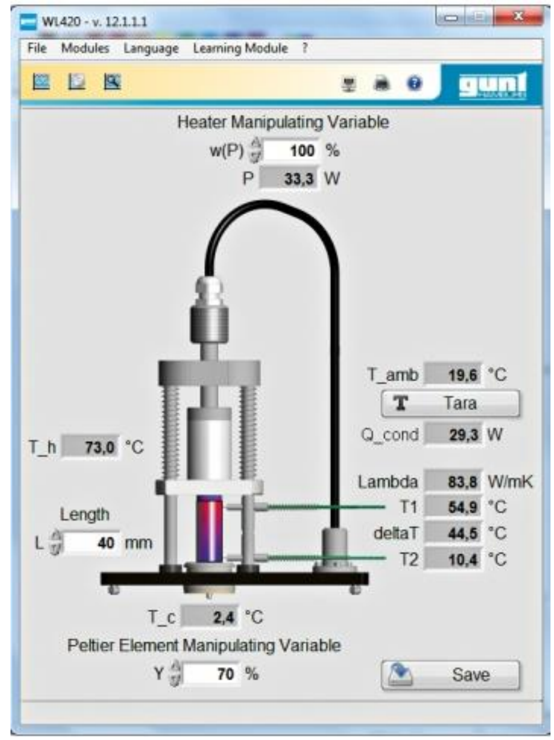

Fig. 8: WL 420 Heat Conduction Data Acquisition Interface

3. Results

In this part the thermal conductivity results from the two approaches described above are presented. Although, the results do not match perfectly due to several reasons such as the different size of the tested samples, the representativity of the sample cut with waterjet and the variation in the testing protocols, the results agree on the fact that thermal resistance is improved with the addition of the PTF.

3.1. Thermography Test Results

Thermographic images of the surface temperature distribution of the samples were captured by the infrared camera at different heating duration (i.e., 0 min, 10 min, 20 min, and 30 min) as shown in Fig. 9. Thermographic images significantly demonstrated different thermal colour images. The highest average recorded surface temperature after 30 min was 38.30 ˚C for neat concrete, and the lowest average surface temperature was 34.10 ˚C for 4% PTF/concrete, respectively. The average temperature of the samples at each family was recorded with respect of time Fig. 10.

3.2. Thermal Conductivity Test

The average thermal conductivity λ_{avg} (W/mk) from four samples per family was calculated and drawn versus the ratio of PTF as shown in Fig. 11. The λ_{avg} value was calculated for wet and dry conditions. It can be noticed from the figure, that the conductivity is increased with the increase of the water content in the concrete. Which is consistent with the higher conductivity of the water comparing with the conductivity of the air voids in concrete (in the dry conditions). This difference appears clearly with high percentages of PTF due to the hight water absorption of the natural fiber.

It worth mentioning here that in some cases the core cut resulted in high percentage of PTF and subsequently to a higher conductivity comparing to the normal concrete or samples with lower percentages of PTF. This might be due to the small size of the core relative to the slab. The core sample might be taken from a location in the slab at which PTF amount does not represent the actual overall percentage of fibre in the slab. Another reason could be the possibility of the cut passing through large aggregate which has higher conductivity than the cementitious mortar. For these reasons, it is recommended that the thermal conductivity to be measured using the hot plate method on large concrete areas.

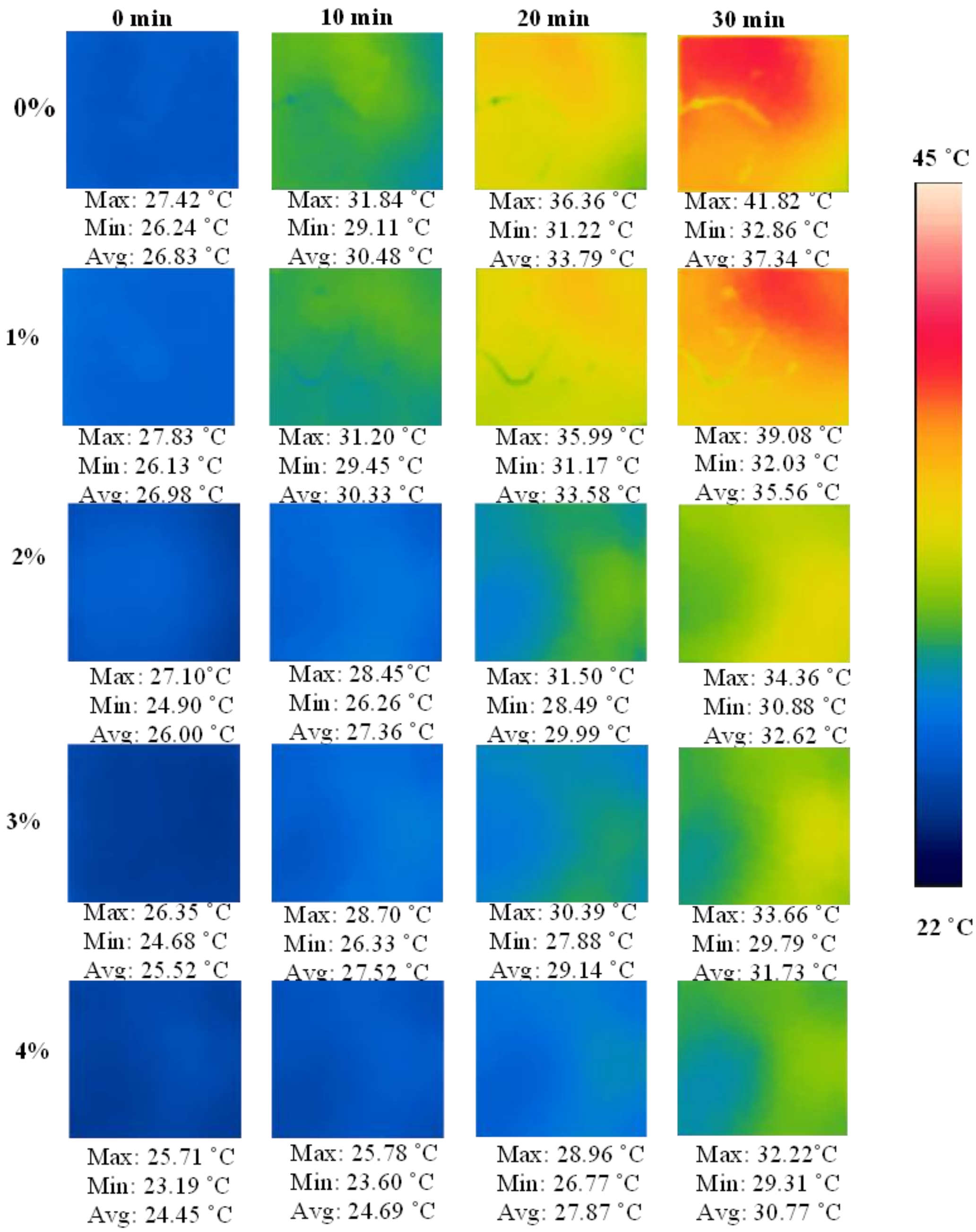

Fig. 9: Surface temperature distribution for the PTF-concrete measured at 10-minute time intervals

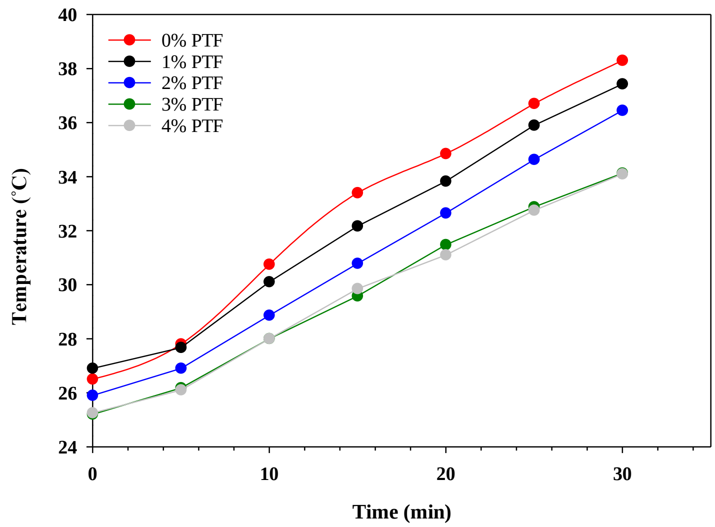

Fig. 10: Surface temperature verses time of 0%, 1%, 2%, 3% and 4% PTF in concrete

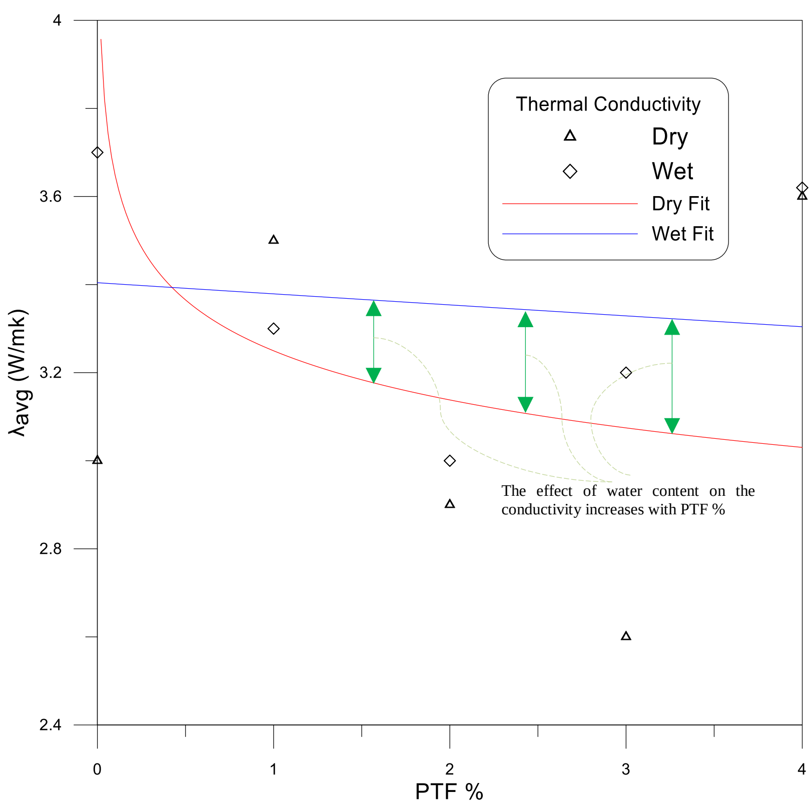

Fig. 11: Thermal conductivity of saturated and dry samples vs the PTF %

4. Conclusion

This experiential work was carried out at the Civil Lab in the Australian University in order to explore the effect of adding natural fiber such as PTF on the thermal properties of concrete. The results from the thermography illustrated a notable reduction in heat-transferring rate and thermal conductivity of the material with increasing of PTF content in the concrete. The lowest recorded average temperature of a heating time of 30 min was 34.10 ˚C for 4% PTF/cement. It was noticed thatintroducing PTF to the concrete matrix, has remarkably reduced the thermal conductivity by up to ~ 13% compared to plain concrete.

The thermal conductivity test reveals that the thermal resistance is enhanced by increasing the percentage of PTF in concrete. The conductivity is also influenced by the percentage of water content in the concrete samples. The effect of the water content on the conductivity is pronounced clearly in mixes with hight PTF percentage. This can be contributed to the increase in water absorption of concrete due to the increase in the amount of PTF introduced to the mix. The location and size of the concrete sample, with respect to the larger concrete specimen from which it was cored, influences the determining the representative thermal characteristics of the PTF concrete. It is recommended to conduct the thermal conductivity test on large cylindrical or 2D plate or slab samples , in order to obtain representative measurements.

Acknowledgements

The authors acknowledge the financial support of the Kuwait foundation for the Advancement of sciences (KFAS) for this funded project with Grant# CN-20-35EM-04 and PN20-35EV-02.

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