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HEATING APPLICATION OF CARBON FIBER FILAMENT IN LOW TEMPERATURE ENVIRONMENT

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Abstract

In this study, an electrical resistance heating method using carbon fiber filament was investigated. Nine carbon fiber filaments each of length 22.5 cm were arranged in parallel connection as the heat panel. A concrete block with the dimension of 30 cm by 25 cm by 8 cm was fabricated. The heat panel was embedded inside the concrete block at 6 cm depth. Three k-type thermocouples were positioned inside the concrete slab, one at the center and the other two at the edges. Three different power densities of $7.4\,W/m^2$, $15\,W/m^2$ *and* $30\,W/m^2$ *were considered. The experiments were carried out at room temperature during winter in a cold region (Kayseri, Turkey). The experimental results revealed that increasing the power density, accelerate the temperature changes. And the temperatures recorded by thermocouple at the center (*Tc_1*) of the slab were higher than those recorded by the other two thermocouples at the edges (*Tc_2 *and* Tc_3*). Moreover, carbon fiber filament resistance heating can be a practicable solution for heating buildings, deicing of bridge decks, driveways and aircraft.*

Keywords: carbon fiber filament, heating, concrete slab.

Introduction

Continuous carbon fiber is predominantly attractive as a structural material due to its high strength, low density, high stiffness, high thermal conductivity, good fatigue and creep resistance, toughness and damage tolerance (Alvaro et al, 2009). With regard to most functional properties, carbon fibers are exceptional compared to the other fiber types .In contrast to the non-conducting nature of polymer and ceramic matrices, carbon fibers are electrically and thermally conductive. They can serve not only as reinforcement but also as an additive for improving the electrical or thermal conductivity. Moreover, carbon fibers have almost zero coefficient of thermal expansion, thus they can also be used as an additive to lower the thermal expansion. Also, the combination of low thermal expansion and high thermal conductivity makes carbon fiber useful for heat sinks in electronics and space structures that require dimensional stability. (Alvaro et al, 2009).

Even though steel fibers are conductive, their typical diameter (≥ 60 μm) is much larger than the diameter of a typical carbon fiber(≥ 7 μm).The combination of electrical conductivity and small diameter makes carbon fibers attractive for use in composite functional property tailoring. Commercial and industrial applications are mainly related to aerospace, rocket nozzles, aircraft brakes, heat exchangers, prosthetic devices and space structures. Biomedical applications comprise of hips and heart valves implants, surgical and diagnostic devices, pacemakers, and pharmaceutical packaging (P.K. Mallick 2007).

Previous study revealed that carbon based products especially carbon fiber filament and carbon woven fabrics can be used for heat transfer and deicing applications. Electrical conductivity is achieved by adding steel fiber and steel shavings to the concrete (Tuan et al. 2008). They reported that, the volume fraction of the conductive components determine the level of electrical conductivity. However, increased amount of conductive components might impair the surface quality and mechanical strength of the concrete. Study conducted over six years showed that, the heating system was successful for deicing and snow melting. The cost of operation was not very expensive. Moreover, no electric shock was reported to harm any pedestrians and vehicles. (Quantao et al. 2010) manufactured electrically conductive porous asphalt concrete by adding steel fibers and wools in it. The steel fibers improved the strength of the concrete, while the steel wools played an important role in electrical conductivity. When the volume fraction of steel wool was 10%, desired mechanical strength and electrical conductivity was achieved. In conductive concrete applications; it should be assured that the surface current should not jeopardize pedestrians. (Alvaro, et al. 2009) also reported that carbon fiber provide better conductivity compared to other conductive materials. They also reported that when insufficient bitumen used in asphalt concrete, the conductive elements were not distributed evenly and conductivity of concrete decreased.

(Shaopeng Wu, et al., 2005) investigated the best conductive component for concrete. It was revealed that carbon fiber is more efficient compared to graphite, carbon black and others. Beside carbon based materials, nickel was also used for manufacturing conductive concrete and successful deicing was achieved (Kun, et al., 2011).Using ground-source pipes heat was transferred from 33 feet to the surface of the bridge. This heating was sufficient to prevent freezing and provided some snow melting (Lee et al. 1984). Infrared heating (Cress et al. 1995), and conductive concrete (Xie et al. 1995) have also been tried. Concrete is brittle material and electrically nonconductive. When some conductive and semi-conductive materials are added and dispersed, conductivity can be achieved to a certain degree.

Zhao used carbon fiber cables in concrete, and carried out heating experiments on small concrete specimens. The field application revealed that carbon fiber cable can be used for heating. Possible thermal stresses and degradations of steel reinforcement during this operation were not studied (Hong-Ming, et al., 2010). They also used finite element analysis for optimizing the cable positions and intervals for the best heating performance (Hongming, et al., 2011). (Xiao-min, et al., 2012) studied the heating performance of carbon nano fiber papers. The nano fiber papers were attached to the concrete and a rapid respond of the temperature increment was observed. In similar study, carbon nano fiber polymer was used in place of carbon nano fiber paper (Hui, et al., 2013).(Taejin and Chung, 2003) measured the thermal performance of chopped carbon fiber mat. The carbon fiber mat was coated with metal and heating performance was tested. However, the metal coating did not contribute in favor of the heating. A comprehensive study was conducted by Yang in this field (Yang, et al., 2012). They have manufactured a heating system using woven carbon fiber fabric. The fabrics were cut into eight long strips and insulated electrically, and were embedded into concrete with the dimensions of180 × 120 cm. They conducted 16 tests and concluded that woven fabrics can be used for electrical heating.

Methodology

Materials Used

The materials used in this research were carbon fiber filaments, thermocouples, concrete slab, DC power supply and copper wire.

Specimen preparations

The insulated carbon fiber filaments were embedded in a concrete slab of dimension 30 cm by 25 cm by 8 cm. The fiber filaments were positioned in parallel arrangement whereby, copper wires were attached at the two parallel ends as shown in Fig. 1(b). Eight carbon fiber filaments of length 22.5 cm were attached to the copper wires. Furthermore, small piece of the insulated rubber at the two ends of each carbon fiber filaments were pull off and cord – end terminals were cramped at both ends. The cord-end terminals were pushed inside the T – Tap terminals, and then cramped to the copper wire. The copper wires served as the power supply medium. The frame or heat panel was placed at 6 cm depth inside the concrete slab.

(a) (b)

Fig. 1: (a) Continuous carbon fiber and (b) parallel arrangement of the fiber filaments as the heat panel

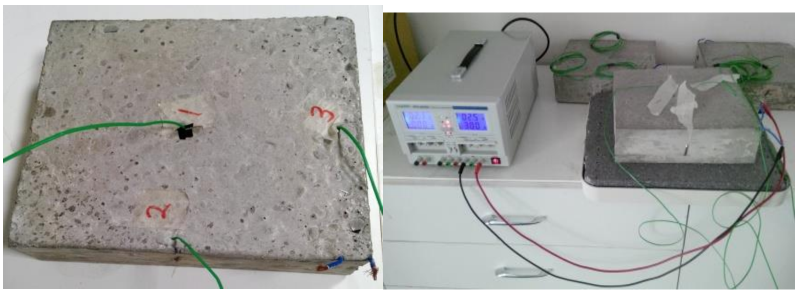
Three k-type thermocouples were positioned inside the concrete slab; one at the center and the other two at the edges at 1.5 cm depth from the top as depicted in Fig. 2. Tests were carried out at room temperature using three different power densities of $7.4\,\mathrm{W/m^2}$, $15\,\mathrm{W/m^2}$ and $30\,\mathrm{W/m^2}$ respectively. The electric power P generated, due to the flow of current I as a result of voltage difference V is governed by the equation

$$\mathrm{P} = \mathrm{IV} \tag{1}$$

This power is dissipated as heat, consequently allowing a form of heating known as resistance heating. The electrical resistance was approximately found to be1.0 Ω. Also, the heat generated that crosses the boundary of the concrete slab by virtue of a temperature difference to its surrounding as illustrated in Fig. 3 is governed by one-dimensional steady state Fourier – Biot equation (Kakac, 1993).Since the bottom and four sides of the concrete slab are cautiously insulated with Styrofoam, only heat in the vertical direction (y-axis) can be dissipated.

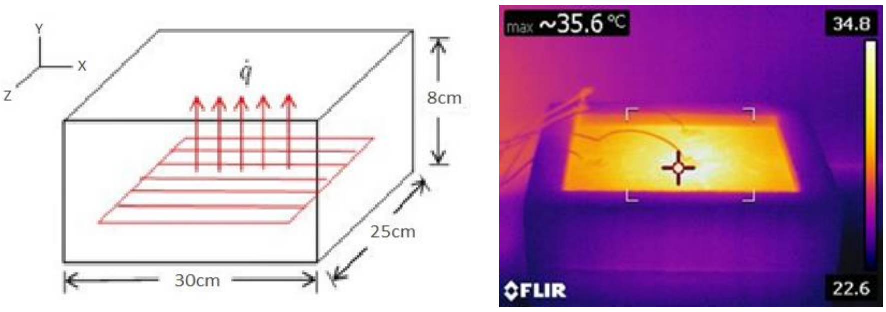
$$T(y) = \frac{\dot{q}L^2}{2K}\left[1-\left(\frac{y}{L}\right)^2\right] + \frac{\dot{q}L}{h} + T_\infty \tag{2}$$

Where $\dot{q}$ is the heat flux [W/m²],K is the thermal conductivity [W/mK],h is the film coefficient [W/m²K], y is the depth or height from the heat source to the surface of the block [m], $L$is the height of the concrete block [m] and T_∞ is the ambient temperature [K].The temperature rises during the experiments were recorded using the data acquisition through the thermocouples embedded inside the concrete slab. Conductivity of the concrete differs depending on the environmental effects and no heat generation can be observed unless the applied current exceeds the threshold value. (Alvaro et al, 2009)



(a) (b)

***Fig. 2**: (a) Thermocouples at three different locations and (b) carrying out experiment at room temperature*



(a) (b)

Fig. 3:Heat dissipated along the vertical direction (a) sketch and (b) IR image

Results and Discussion

The experiments were conducted at Erciyes University (Meliksah coordinate) during winter at room temperature. The effects of power density changes were respectively considered. Fig. 4 shows a graph of temperature variation with time for 7.4 W/m² power density. The temperature rise proficiently as the current was applied and reached 30°C in 103 minutes. Moreover, a declination of the curves observed as Fig. 4 illustrated due to the turning off of the power supply. Tc_1, Tc_2 and Tc_3indicate the thermocouple 1, 2 and 3 respectively.

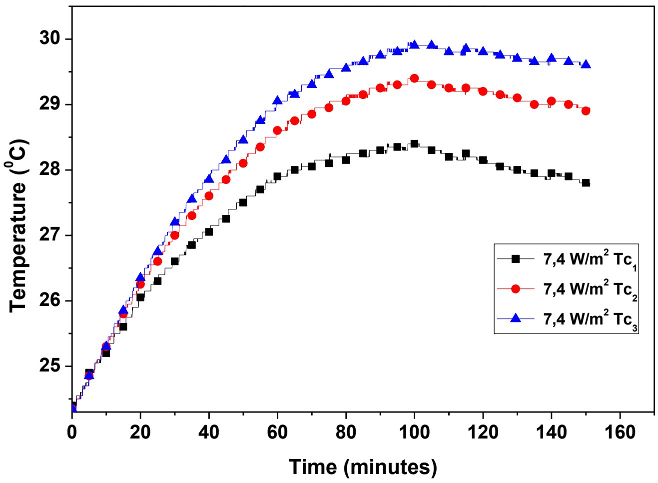
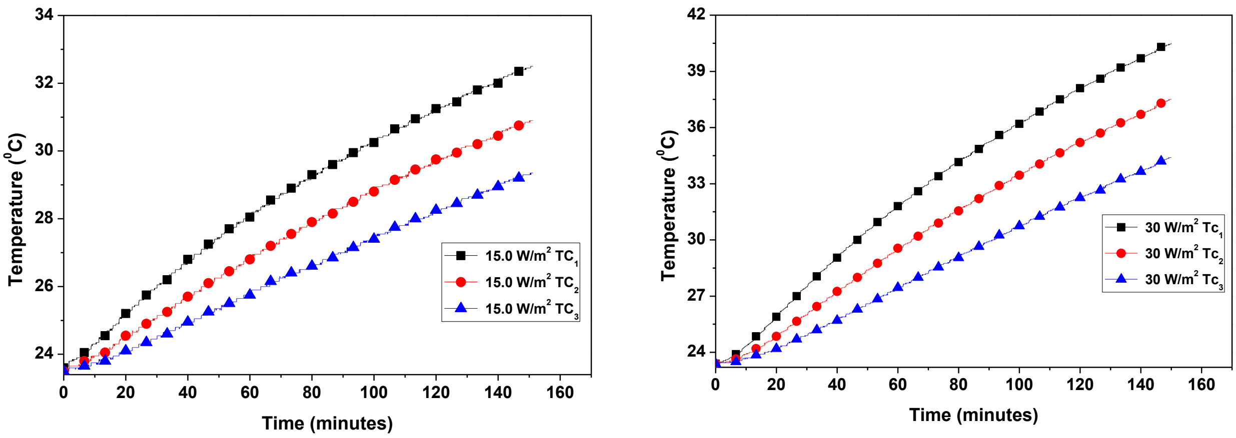


***Fig. 4**:Temperature versus time graph of 7.4W/m² power density*

The Temperature against time graphs of 15W/m² and 30W/m² are shown in Fig. 5.Itis obvious that increasing the power density accelerate the temperature changes. For 2.5 hours power supplied, the temperature elevated to 33°C and 41°C for 15W/m² and 30W/m² respectively. Consequently, higher power densities should be selected for applications that require a rapid temperature rise and deicing operation. However, if time is not a major concern, lower power densities can also be used as long as they are capable of increasing the surface temperature above 0°C. Fig. 6 shows a combine graph of temperatures recorded by $Tc_1$of 15W/m² and 30W/m² power densities. The Tc_1 positioned at the center of the concrete block recorded higher temperature values compared to the Tc_2 and Tc_3. This is due to the electrical resistance that depends on the geometry of the carbon fiber filament which is proportional to the length and inversely proportional to the cross-sectional area(Chung, 2010).



(a) (b)

***Fig. 5**: Temperature changes of (a) 15W/m² and (b) 30W/m² power density*

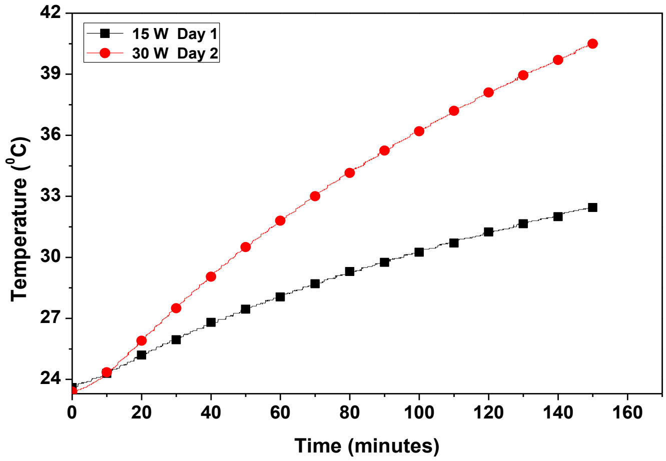


***Fig. 6:** Temperature variation with time for 15W/m² and 30W/m²*

Conclusions

Carbon fiber filament resistance heating can be a practicable solution for heating buildings, deicing of bridge decks, driveways and aircraft. It offers lower installment and material cost compared to other heating systems. The construction of the heat panel is easy and provides a consistent heating. Furthermore, the experimental results disclosed that the higher the power density, the rapid respond of temperature changes can be achieved. Higher temperature values were observed at the center of the block as Tc_1 exemplified. Selection of the power density depends on the applications one desired and should be carefully determined by considering possible ambient temperature. Also, positioning of the heat panel can be studied in the future work.

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