Self-heating structural materials

D D L Chung

Composite Materials Research Laboratory, University at Buffalo,
State University of New York, Buffalo, NY 14260-4400, USA

Abstract

Self-heating structural materials, being useful for deicing and space heating, are reviewed. They include cement–matrix and polymer–matrix composites that are rendered self-heating through enhancing their effectiveness for resistance heating. The enhancement is attained by the use of electrically conductive fibers (continuous or discontinuous) and interlayers. The interlaminar interface between continuous carbon fiber laminae provides a two-dimensional array of heating elements. Power up to 6.5 W, maximum temperature up to 134 °C and time to reach half of the maximum temperature rise down to 14 s have been attained.

1. Introduction

Heating is useful for structures for the purpose of deicing, healthy living, hazard mitigation and industrial processing. Deicing is needed for aircraft driveways, airport runways, highways, bridges and other structures. The alternative method of snow removal, say by shoveling, is labor-intensive, expensive and time-consuming. Heating is essential for buildings in cold regions. The space heating of buildings accounts for much of the energy consumed in the USA.

The heating of structures is conventionally accomplished by the use of functional materials (e.g. metal coils—the coil configuration is necessitated by the requirement of a long length of metal wire due to the low resistivity of metals) that are not structural materials, or the use of systems (e.g. forced air heating systems) that are outside the structural materials. For the purpose of spatially uniform heating, design simplification, implementation convenience and energy efficiency, it is desirable to use structural materials themselves for heating, i.e. structural materials that heat themselves through the conversion of energy (e.g. electrical energy) to heat. Such structural materials are said to be self-heating.

The dominant structural materials are cement–matrix composites (for buildings) and continuous fiber polymer–matrix composites (for lightweight structures such as aircraft). This paper reviews the attainment of self-heating in both types of structural composites.

Electrical heating includes resistance heating (i.e. Joule heating) and induction heating, in addition to heating by the use of electric heat pumps, plasmas and lasers [1, 2]. It has to be distinguished from solar heating [3–7] and the use of fossil fuels such as coal, fuel oil and natural gas [2]. Due to the environmental problems associated with the use of fossil fuels and due to the high cost of solar heating, electrical heating is increasingly important. Although electric heat pumps are widely used for the electrical heating of buildings, resistance heating is a complementary method which is receiving increasing attention. Resistance heating is the focus of this paper.

Resistance heating involves passing an electric current through a resistor, which is the heating element. In relation to the heating of buildings, resistance heating typically involves the embedding of heating elements in the structural material, such as concrete [8–10]. The materials of heating elements cannot be too low in electrical resistivity, as this would result in the resistance of the heating element being too low and a high current would be needed to reach a certain power. The materials of heating elements cannot be too high in resistivity either, as this would result in the current in the heating element being too low (unless the voltage is very high). Materials for heating elements include metal alloys (such as nichrome), ceramics (such as silicon carbide [11]), graphite [12, 13], polymer–matrix composites [14–18], carbon–carbon composites [19], asphalt [20] and concrete [21].

Resistance heating is not only useful for the heating of buildings, it is also useful for the deicing of bridge decks [22], driveways and aircraft [14], plastic welding [23] and for the demolition of concrete structures [24, 25]. On the other hand, electrical self-heating is undesirable for the performance and reliability of electrical interconnections [26, 27], bolometers [28], superconductors [29], transistors [30], diodes [31] and other semiconductor devices [32].
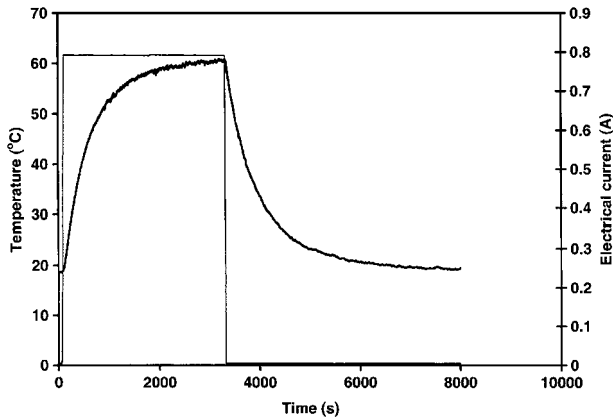
Figure 1. Temperature variation during heating (current on) and subsequent cooling (current off), using steel fiber (8 μm-diameter) cement as the resistance heating element. Thick curve: temperature. Thin curve: current [44].

2. Self-heating cement–matrix composites

Conventional concrete is electrically conductive, but the resistivity is too high for resistance heating to be effective. The resistivity of concrete can be reduced by the use of electrically conductive admixtures or aggregates, such as discontinuous carbon fibers [33–37], discontinuous steel fibers or shavings [22, 38–40] and graphite or carbon particles [41–43]. It can also be reduced by the use of an alkaline slag binder [21]. However, the most effective method of decreasing the resistivity is to use a conductive admixture at a volume fraction beyond the percolation threshold [35]. Percolation means the attainment of a continuous conductive path due to the touching of adjacent conductive fibers or particles. The objective of this section is to comparatively evaluate the effectiveness of conductive cement–matrix composites for resistance heating. These composites are lower in resistivity than cement itself by orders of magnitude, due to the attainment of percolation of the conductive admixtures.

Due to the exceptionally low electrical resistivity (0.85 Ω cm) attained by the use of 8 μm-diameter steel fibers in cement [44], the effectiveness for heating is exceptionally high for cement with these steel fibers, as described below. A DC electrical power input of 5.6 W (7.1 V, 0.79 A) resulted in a maximum temperature of 60 °C (initial temperature = 19 °C) and a time of 6 min to reach half of the maximum temperature rise (figure 1). The efficiency of energy conversion [44] increased with time of heating, reaching 100% after 50 min (figure 2). The heat power output per unit area attained by steel fiber cement was 750 W m^{-2}, compared to 340 W m^{-2} for a metal wire having the same resistance. Due to the presence of steel fibers, the structural properties are superior to those of conventional cement-based materials.

In contrast, for carbon fiber (1.0 vol%) cement of electrical resistivity 104 Ω cm, an electrical power input of 1.8 W (28 V, 0.065 A) results in a maximum temperature of 56 °C (initial temperature = 19 °C) and a time of 256 s to reach half of the maximum temperature rise. The high voltage (28 V, compared to 7 V in the case of steel fiber cement) is undesirable due to the voltage limitation of typical power supplies. The performance is even worse for graphite particle (37 vol%) cement paste of resistivity 407 Ω cm.

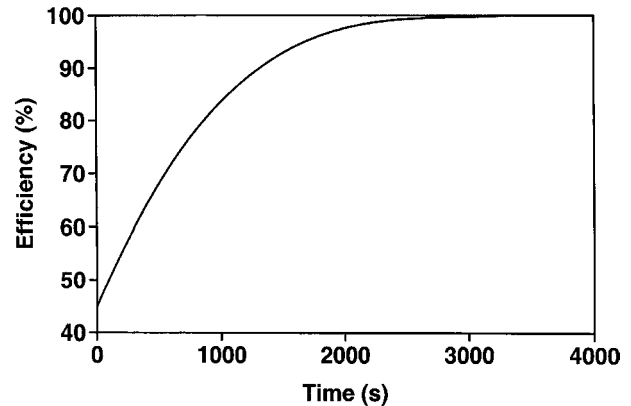**Figure 2.** Efficiency versus time during heating of steel fiber (8 μm-diameter) cement at a current of 0.48 A [44].

The steel fibers mentioned above are only 8 μm in diameter. Steel fibers of larger diameter (e.g. 60 μm) are much less effective in reducing the electrical resistivity of cement-based materials [39] and are therefore less effective for self-heating. For example, steel fibers of 8 μm diameter at 0.54 vol% gave a cement paste of resistivity 23 Ω cm, whereas steel fibers of 60 μm diameter at 0.50 vol% gave a cement paste of resistivity 1.4 × 10^3 Ω cm; steel fibers of 8 μm diameter at 0.36 vol% gave a cement paste of resistivity 57 Ω cm, whereas steel fibers of 60 μm diameter at 0.40 vol% gave a cement paste of resistivity 1.7 × 10^3 Ω cm.

An alternate concrete technology involves using steel shavings (0.15–4.75 mm particle size) as the conductive aggregate, in conjunction with low-carbon steel fibers as the conductive admixture [22, 40]. The use of 20 vol% steel shavings together with 1.5 vol% steel fibers resulted in an electrical resistivity of 75–100 Ω cm [22]. The resistivity increased with time, reaching 350 Ω cm in 6 months [22], presumably due to corrosion of the steel shavings and fibers. The high resistivity and the increase in resistivity with time are undesirable. In contrast, stainless steel fibers (8 μm diameter, 0.7 vol%) cement have a low resistivity of 0.85 Ω cm and the resistivity is stable over time. Furthermore, it does not require any special mixing equipment or procedures and does not require any special aggregate.

3. Self-heating polymer–matrix composites

Self-heating in continuous fiber polymer–matrix composites can be attained by using the following methods:

(a) embedding a low resistivity interlayer (e.g. a carbon fiber mat) between adjacent laminae during composite fabrication and the use of the interlayer as a heating element,

(b) use of conductive reinforcing fibers (e.g. continuous carbon fibers) to render the composite conductive and the use of the overall composite as a heating element, and

(c) use of the interlaminar interface between adjacent laminae of conductive reinforcing fibers (e.g. continuous carbon fibers) as a heating element.

Method (a) is most common, as it is applicable to a broad range of composites, whether the reinforcing fibers are
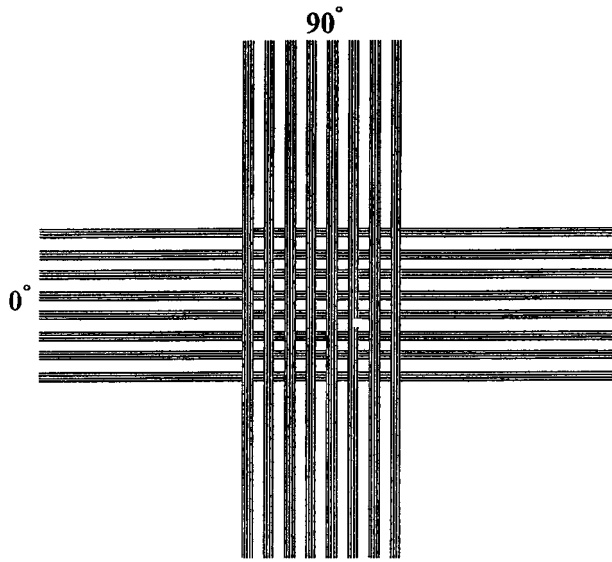
563

90°

0°

Figure 3. Sensor array in the form of a carbon fiber polymer–matrix composite comprising two crossply laminae [46].

conductive or not. Method (b) is not common, due to the need for using carbon fibers of relatively low resistivity and such fibers are relatively expensive. Method (c) involves an innovative concept in which the contact resistance associated with the interlaminar interface between laminae of conductive fibers allows the interface to serve as a heating element. The interface between two crossply laminae can be subdivided to provide a two-dimensional array of heating elements, in addition to an $x–y$ grid of electrical interconnections, thereby allowing spatially distributed heating (figure 3) and a very small thermal mass for each heating element.

An example in relation to method (a) involves the use of a porous mat comprising short carbon fibers and a small proportion of an organic binder as the interlayer. The fibers in a mat are randomly oriented in two dimensions. The mats are made by wet-forming, as in papermaking. A mat comprising bare short carbon fibers and exhibiting a volume electrical resistivity of 0.11 Ω cm and thermal stability up to 205 °C has been shown to be effective as a resistive heating element [45]. It provides temperatures up to 134 °C (initial temperature = 19 °C) at a power of up to 6.5 W, with a time up to 106 s to reach half of the maximum temperature rise. The electrical energy input to heat by 1 °C during the initial period of rapid temperature rise (5 s) is up to 3.8 J. The efficiency is nearly 1.00 even in the first 5 s of heating. A mat comprising metal (Ni/Cu/Ni tri-layer)-coated short carbon fibers and exhibiting a volume electrical resistivity of 0.07 Ω cm provides lower temperatures (up to 79 °C) but a faster response (up to 14 s to reach half of the maximum temperature rise) [45].

An example in relation to method (c) involves the use of the interface between two crossply laminae of a continuous carbon fiber epoxy–matrix composite [46]. For an interface of area 5 mm × 5 mm and resistance 0.067 Ω, a DC electrical power input of 0.59 W (3.0 A, 0.20 V) results in a maximum temperature of 89 °C (initial temperature = 19 °C). The time to reach half of the maximum temperature is up to 16 s. The efficiency of energy conversion reaches 100% after about 55 s of heating, when the heat power output is up to 4×10^4 W m^{-2} of the interlaminar interface.

4. Comparison of self-heating structural materials

Table 1 shows a comparison of the effectiveness of various materials for self-heating, as similarly evaluated in the laboratory of the author [44–47]. The carbon fiber epoxy–matrix interlaminar interface (no 6 in table 1) [46] and the Ni/Cu/Ni-coated carbon fiber mat (no 5 in table 1) [45] are exceptional in their ability to provide a fast and significant temperature response, though the power capacity is low. A carbon fiber mat (no 4 in table 1) [45] is exceptional in its ability to deliver high power and a significant temperature rise; it is superior to the cement–matrix composites (nos 1–3 in table 1) in power capacity, temperature capacity and fast response. On the other hand, it is much inferior to flexible graphite (not a structural material, no 7 in table 1) [47] in all three attributes.

Comparison of the volume electrical resistivity of the various materials in table 1 shows that a low resistivity tends to be associated with good self-heating performance, although there are exceptions. The outstanding performance of flexible graphite is attributed to the outstandingly low resistivity.

The maximum temperature is limited by the ability of the material to withstand high temperatures. Flexible graphite is outstanding in this ability. However, the maximum temperature is also determined by the ability of the material to sustain current. A low resistivity greatly helps this ability, as shown by comparing the performance of the three cement-based materials (nos 1–3 in table 1).

The time to reach half of the maximum temperature rise increases with the maximum temperature rise, as shown by comparing the response time at different input powers for the same material [44–47]. This time is expected to be reduced by a decrease in thermal mass (which relates to the mass and the specific heat) or an increase in thermal conductivity. The fast response of the carbon fiber epoxy–matrix interlaminar interface is attributed mainly to its low thermal mass, which is due to the microscopic thickness of the interface. The fast response of the Ni/Cu/Ni-coated carbon fiber mat and the flexible graphite is attributed mainly to the high thermal conductivity.

The power in table 1 is the electrical power input, which is essentially equal to the heat power output after an initial period in which the material itself is being heated. The power is governed by the ability of the material to sustain current and voltage. This ability is enhanced by a decrease in resistivity.

Although the resistivity is not the only criterion that governs the effectiveness of a material for self-heating, it is the dominant criterion, particularly in relation to the power and the maximum temperature. In general, the selection of a self-heating structural material depends on the requirements concerning the maximum temperature, power response time and the mechanical properties. For cement-based structures, steel fiber cement (no 1 in table 1) is recommended. For a continuous fiber polymer–matrix composite, a carbon fiber mat (no 4 in table 1) is recommended for use as an interlayer. For spatially distributed heating, the carbon fiber epoxy–matrix interlaminar interface is recommended.

Flexible graphite cannot be incorporated in a structural composite, due to its mechanical weakness and impermeability to the resin. However, it can be placed on a structural material and its flexibility allows it to conform to the topography of the structural material.

Table 1. Effectiveness of self-heating from a temperature of 19 °C.

	Material	Maximum temperature (°C)	Time to reach half of the maximum temperature rise	Power (W)	Volume resistivity (Ω cm)	Reference
1	Steel fiber (0.7 vol%) cement	60	6 min	5.6	0.85	[44]
2	Carbon fiber (1.0 vol%) cement	56	4 min	1.8	100	[44]
3	Graphite particle (37 vol%) cement	24	4 min	0.27	410	[44]
4	Carbon fiber (uncoated) mat	134	2 min	6.5	0.11	[45]
5	Ni/Cu/Ni-coated carbon fiber mat	79	14 s	3.0	0.07	[45]
6	Carbon fiber epoxy–matrix interlaminar interface	89	16 s	0.59	[b]	[46]
7	Flexible graphite[a]	980	4 s	94	7.5×10^{-4}	[47]

[a] Not a structural material.

[b] The relevant quantity is the contact resistivity rather than the volume resistivity.

5. Conclusion

Self-heating structural materials in the form of cement–matrix and polymer–matrix composites have been engineered by the use of electrically conductive fibers (continuous or discontinuous) and interlayers. Both the volume of the composite and the interlaminar interface can be used as heating elements. The interlaminar interface between continuous carbon fiber laminae is attractive in its amenability to providing a two-dimensional array of heating elements. A cement–matrix composite containing 0.7 vol% steel fibers (8 μm diameter) and a mat of discontinuous uncoated carbon fibers for use as an interlayer are effective for self-heating. However, the effectiveness is low compared to flexible graphite, which is not a structural material.

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