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Cement-based thermocouples

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Abstract

A cement-based thermocouple in the form of a junction between dissimilar cement pastes and exhibiting thermocouple sensitivity 70 ± 7 μV/°C is provided. The dissimilar cement pastes are steel fiber cement paste (n-type) and carbon-fiber silica-fume cement paste (p-type). The junction is made by pouring the cement pastes side by side.

Keywords: Physical properties; Electrical properties; Cement paste; Fiber reinforcement; Thermoelectric

1. Introduction

A thermocouple is a thermometric device that involves a junction of two materials that are dissimilar in the thermoelectric power, which is a material property that describes the extent of the Seebeck effect in that material. The thermocouple measures the temperature at the junction by giving the voltage difference between the free ends of two materials making up the junction.

The Seebeck effect has been observed in cement pastes [1–4]. The effect is largest in cement pastes containing short steel fibers due to the free electrons provided by the steel fibers [4]. In contrast to steel fibers, carbon fibers provide holes [1–3]. Hence, n-type and p-type cement pastes can be obtained by the use of appropriate fibers. Plain cement paste is weakly n-type [3].

Although the Seebeck effect has been observed in cement-based materials, thermocouples have not been made previously by using cement-based materials. This paper provides cement-based thermocouples, including their fabrication and properties. These thermocouples are attractive in that they render a concrete structure an inherent ability to sense temperature.

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2. Experimental methods

The steel fibers used to provide strongly n-type cement paste were made of stainless steel No. 434, as obtained from International Steel Wool (Springfield, OH). The fibers were cut into pieces of length 5 mm prior to use in the cement paste in the amount of 0.5% by mass of cement (i.e., 0.10 vol.%). The properties of the steel fibers are shown in Table 1 of Ref. [4]. The mechanical properties of mortars containing these fibers are described in Ref. [5]. However, no aggregate, whether coarse or fine, was used in this work.

The carbon fibers used to provide p-type cement paste were isotropic pitch based, unsized, and of length ~5 mm, as obtained from Ashland Petroleum (Ashland, KY). They were used in the amount of either 0.5% or 1.0% by mass of cement (i.e., either 0.48 or 0.96 vol.% in the case of cement paste with silica fume, and either 0.41 or 0.82 vol.% in the case of cement paste with latex). The fiber properties are shown in Table 1 of Ref. [3]. No aggregate (fine or course) was used. The cement paste with carbon fibers in the amount of 1.0% by mass of cement was p-type, whereas that with carbon fibers in the amount of 0.5% by mass of cement was slightly n-type, as shown by thermoelectric power measurement [3].

The cement used in all cases was Portland cement (Type I) from Lafarge (Southfield, MI). Silica fume (Elkem Materials, Pittsburgh, PA, EMS 965) was used in the amount of 15% by mass of cement. The methylcellulose, used in the amount of 0.4% by mass of cement, was Dow Chemical, Midland, MI, Methocel A15-LV. The defoamer (Colloids, Marietta, GA, 1010) used whenever

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Table 1
Absolute thermoelectric power (μV/°C)

Cement paste	Volume fraction fibers	μV/°C	Type	Reference
(i) Plain	0	1.99 ± 0.03	weakly n	[3]
(ii) S_f (0.5*)	0.10%	53.3 ± 4.8	strongly n	[4]
(iii) C_f (0.5*) + SF	0.48%	0.89 ± 0.09	weakly n	[3]
(iv) C_f (1.0*) + SF	0.95%	− 0.48 ± 0.11	p	[3]
(v) C_f (0.5*) + L	0.41%	1.14 ± 0.05	weakly n	[3]

SF = silica fume; L = latex; S_f = steel fibers; C_f = carbon fibers.

methylcellulose was used was in the amount of 0.13 vol.%. The latex, used in the amount of 20% by mass of cement, was a styrene butadiene copolymer (Dow Chemical, 460NA) with the polymer making up about 48% for the dispersion and with the styrene and butadiene having a mass ratio of 66:34. The latex was used along with an antifoaming agent (Dow Corning, Midland, MI, No. 2410, 0.5% by mass of latex).

A rotary mixer with a flat beater was used for mixing. Methylcellulose (if applicable) was dissolved in water and then the defoamer was added and stirred by hand for about 2 min. Latex (if applicable) was mixed with the antifoam by hand for about 1 min. Then the methylcellulose mixture (if applicable), the latex mixture (if applicable), cement, water, silica fume (if applicable), carbon fibers (if applicable) and steel fibers (if applicable) were mixed in the mixer for 5 min.

A junction between any two types of cement mix was made by pouring the two different mixes into a rectangular mold (160 × 40 × 40 mm) separately, such that the time between the two pours was 10–15 min. The two mixes were poured into two side-by-side compartments of the mold and the paper (2 mm thick, without oil on it) separating the compartments was removed immediately after the completion of the two pours. Each compartment was roughly half the length of the entire mold.

After pouring into oiled molds, an external electrical vibrator was used to facilitate compaction and decrease the amount of air bubbles. The resulting junction could be seen visually, due to the color difference between the two halves of a sample. The samples were demolded after 1 day and cured in air at room temperature (relative humidity = 100%) for 28 days.

Five types of cement paste were prepared, namely, (i) plain cement paste (weakly n-type, consisting of just cement and water), (ii) steel fiber cement paste (strongly n-type, consisting of cement, water and steel fibers), (iii) carbon-fiber silica-fume cement paste (very weakly n-type, consisting of cement, water, silica fume, methylcellulose, defoamer and carbon fibers in the amount of 0.5% by mass of cement), (iv) carbon-fiber silica-fume cement paste (p-type, consisting of cement, water, silica fume, methylcellulose, defoamer and carbon fibers in the amount of 1.0% by mass of cement) and (v) carbon-fiber latex cement paste (very weakly n-type, consisting of cement, water, latex and carbon fibers). The water/cement ratio was 0.45 for pastes (i), (ii), (iii) and (iv), and was 0.23 for paste (v). The absolute thermoelectric power of each paste is shown in Table 1.

Four pairs of cement paste were used to make junctions, as described in Table 2. Three specimens were tested for each pair.

Thermocouple testing was conducted by heating the junction by resistance heating, which was provided by nichrome heating wire (wound around the whole perimeter of the sample over a width of 10 mm that was centered at the junction), a transformer and a temperature controller. The voltage difference between the two ends of a sample was measured by using electrical contacts in the form of copper wire wound around the whole perimeter of the sample at each end of the sample. Silver paint was present between the copper wire and the sample surface under the wire. The copper wires from the two ends were fed to a Keithley 2001 multimeter for voltage measurement. A T-type thermocouple was positioned to almost touch the heating wire at the junction. Another T-type thermocouple was attached to one of the two ends of the sample (at essentially room temperature). The difference in temperature between these two locations governs the voltage. Voltage and temperature measurements were done simultaneously using the multimeter, while the junction temperature was

Table 2
Cement junctions

Junction	Pastes involved	Junction type	Thermocouple sensitivity (μV/°C)	
			Heating	Cooling
(a)	(iv) and (ii)	pn	70 ± 7	70 ± 7
(b)	(iii) and (ii)	nn^+	65 ± 5	65 ± 6
(c)	(v) and (ii)	nn^+	59 ± 7	58 ± 5
(d)	(i) and (ii)	nn^+	28 ± 4	/

nn^+ refers to a junction between a weakly n-type material and a strongly n-type material.

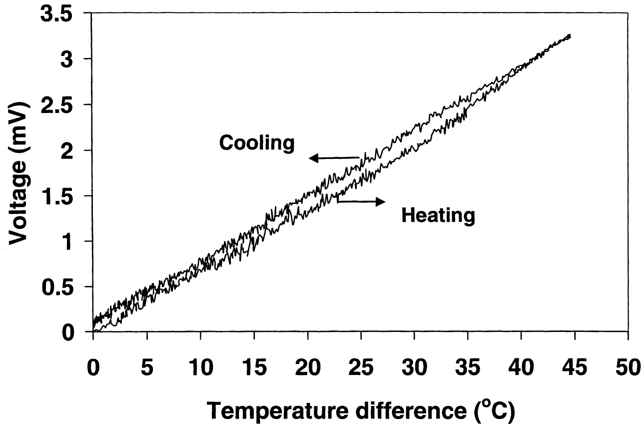

Fig. 1. Variation of the cement-based thermocouple voltage with temperature difference during heating and then cooling for junction (a).

varied through resistance heating. The voltage difference divided by the temperature difference yielded the thermocouple sensitivity.

3. Results and discussion

Figs. 1–4 show plots of the thermocouple voltage vs. the temperature difference (relative to essentially room temperature) for junctions (a), (b), (c) and (d), respectively. The thermocouple voltage increases monotonically and reversibly with increasing temperature difference for all junctions except junction (d), which involves plain cement paste on one side of the junction. Among junctions (a), (b) and (c), which have carbon fibers on one side and steel fibers on the other side of each junction, the thermocouple voltage noise decreases and the thermocouple sensitivity (Table 2) and reversibility increase in the order: (c), (b) and (a). The highest thermocouple sensitivity is 70 ± 7 μV/°C, as attained by junction (a) both during heating and cooling. This value approaches that of commercial thermocouples. Junction (a) gives the best thermocouple behavior (in terms of sensitivity, linearity, reversibility and signal-to-noise ratio) is due to the greatest degree of dissimilarity between the materials that make up the junction. The linearity of the plot of thermocouple voltage vs. temperature difference is better during cooling than during heating for junction (a). That the thermocouple voltage increases and then decreases upon cooling in Fig. 4 for junction (d) is not understood.

The values of the thermocouple sensitivity (Table 2) are higher than (theoretically equal to) the difference in the absolute thermoelectric power of the corresponding two cement pastes that make up the junction (Table 1). For example, for junction (a), the difference in the absolute thermoelectric power of pastes (iv) and (ii) is 54 μV/°C, but the thermocouple sensitivity is 70 μV/°C. The reason for this is unclear. Nevertheless, a higher thermocouple sensitivity does correlate with a greater difference in the absolute thermoelectric power.

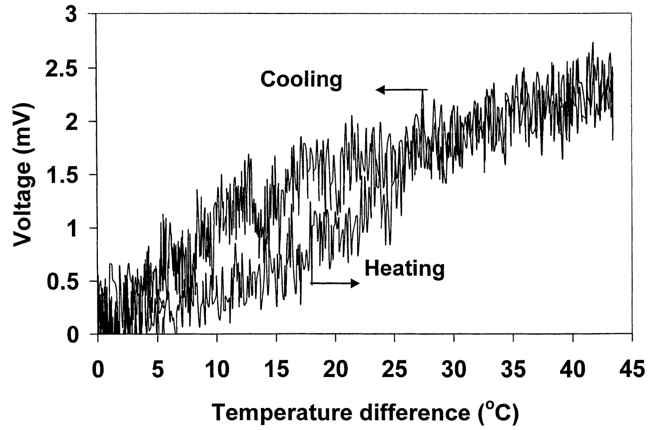

Fig. 3. Variation of the cement-based thermocouple voltage with temperature difference during heating and then cooling for junction (c).

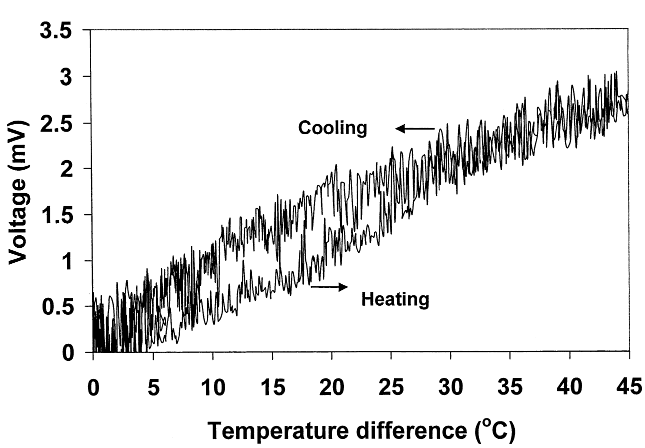

Fig. 2. Variation of the cement-based thermocouple voltage with temperature difference during heating and then cooling for junction (b).

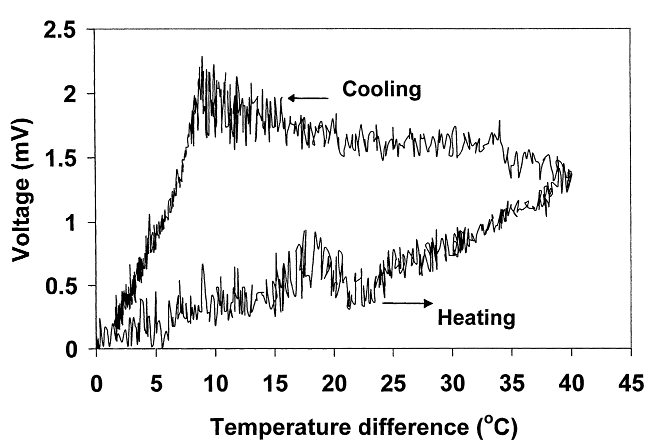

Fig. 4. Variation of the cement-based thermocouple voltage with temperature difference during heating and then cooling for junction (d).

4. Conclusion

Cement-based thermocouples with sensitivity up to 70 μV/°C have been achieved by using junctions made by pouring dissimilar cement pastes side by side. The pastes are preferably carbon fiber cement paste (p-type) and steel fiber cement paste (n-type).

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