ACI MATERIALS JOURNAL TECHNICAL PAPER
Title no. 96-M57

Effect of Admixtures on Thermal and Thermomechanical Behavior of Cement Paste

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A comparative study was conducted on the thermal and thermomechanical behavior of cement pastes containing various additives (silica fume, latex, methylcellulose, and short carbon fibers). The thermal conductivity was decreased by silica fume, methylcellulose, or latex by up to 46 percent. It was not increased by carbon fibers. The specific heat was increased by silica fume, latex, methylcellulose, or carbon fibers by up to 9 percent. The flexural storage modulus decreased reversibly with increasing temperature from 30 to 150 C, whereas the weight loss upon heating was irreversible. Silica fume gave higher modulus than methylcellulose or latex, which in turn gave higher modulus than the absence of any additive. The creep rate was lower for silica fume than methylcellulose or latex, for which the creep rate was lower than the absence of any additive. The apparent coefficient of thermal expansion was reduced by silica fume (but still positive), but was negative for methylcellulose or latex.

Keywords: admixtures; cement pastes; thermal properties.

INTRODUCTION

The thermal behavior (i.e., thermal conductivity, specific heat, and thermal expansion) and thermomechanical behavior (i.e., mechanical behavior upon heating and creep) of concrete are relevant to any use of concrete, especially in relation to structures that require thermal insulation (low thermal conductivity desired), dissipation of heat from embedded heaters (high thermal conductivity desired), temperature stability (high specific heat desired), dimensional stability (low thermal expansion and creep resistance desired), and stiffness in a hot environment and in a fire (little or no decrease of stiffness upon heating desired). Although much work has been done on the mechanical properties of concrete at room temperature, relatively little work has been done on the thermal or thermomechanical behavior.[1-25]

The degradation of concrete upon heating can be in the form of weight loss (mass loss due to spalling and moisture loss),[1,5-7,15,25] porosity increase,[1,5] and decreases in strength and modulus.[1,2,5,7-15] The fractional loss in weight is larger when silica fume is present.[5,6] The temperature for the onset of mechanical weakening is decreased when a polymer (latex or methylcellulose) is present.[23]

The thermal conductivity of concrete increases with increasing moisture content.[15,17,18] It is also increased by using aggregate of a higher thermal conductivity.[15] With the exception of lightweight aggregates, the cement paste has a lower thermal conductivity than the aggregate, so lean mixes tend to give higher conductivity; in the case of lightweight aggregates, the opposite holds true.[15] Steel fibers (50-mm long) increase the thermal conductivity of concrete at 30 C from 1.4 to 2.0 W/m.K.[4] Welded wire mesh placed along the direction of heat flow increases the thermal conductivity of mortar from 1.0 to 1.5 W/m.K for the case of five mesh layers, and to 6.9 W/m.K for the case of 15 mesh layers.[19] Both thermal diffusivity and specific heat decrease during curing of concrete.[21]

Admixtures, such as polymers (e.g., latex and methylcellulose), silica fume, and short fibers, are used in concrete for improving the mechanical properties, decreasing the drying shrinkage, or decreasing the permeability. However, their effects on the thermal or thermomechanical properties have received little attention.

RESEARCH SIGNIFICANCE

This paper provides a comparative study of the thermal and thermomechanical properties of cement pastes containing various additives (polymers, silica fume, and short carbon fibers). The properties include the thermal conductivity and specific heat at room temperature and the dynamic flexural modulus, dimension, and weight during heating (up to 200 C) and cooling. Additives for decreasing the thermal conductivity, increasing the specific heat, decreasing the creep rate, and decreasing the thermal expansion have been identified. The decrease in the modulus of elasticity upon heating has been found to be reversible, in spite of the irreversibility of the weight loss upon heating.

EXPERIMENTAL

Materials

Cement paste made from portland cement (Type I) was used for the cementitious material. The admixtures used include: 1) latex, a styrene butadiene copolymer with the polymer making up about 48 percent of the dispersion and with styrene and butadiene in the weight ratio 66:34, such that the latex (20, 25, or 30 percent by weight of cement) was used along with an antifoam (0.5 percent by weight of latex); 2) methylcellulose (0.4 percent by weight of cement), which was used along with a defoamer (0.13 volume percent); 3) silica fume (15 percent by weight of cement); and 4) carbon fibers, which were isotropic pitch-based and unsized, with length = 5 mm and diameter = 15 μm, used in the amount of 0.5 or 1.0 percent by weight of cement (corresponding to a fiber volume fraction of 0.53 or 1.1 percent, respectively). The water-reducing agent was a sodium salt of a condensed naphthalenesulfonic acid used in amounts as shown in Table 1 for the various mixes. Table 1 also shows the water-cement (w/c) ratio for each mix. The amounts in Table 1 were chosen to maintain the slump at around 170 mm. No aggregate (whether fine or coarse) was used.

A Hobart mixer with a flat beater was used for mixing. For the case of cement pastes containing latex, the latex and antifoam were first mixed by hand for about 1 min. Then, this mix, cement, and water were mixed in the Hobart mixer for 5 min. For the case of pastes containing methylcellulose, methylcellulose was dissolved in water, and then fibers (if applicable) and

ACI Materials Journal, V. 96, No. 4, July-August 1999.
Received November 6, 1997, and reviewed under Institute publication policies. Pertinent discussion will be published in the May-June 2000 *ACI Materials Journal* if received by February 1, 2000.

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Table 1—Amounts of water and water-reducing agent (WR) for each mix

	Water-cement* ratio	WR-cement* ratio, percent
Plain	0.45	0
+ methylcellulose	0.32	1
+ latex	0.23	0
+ silica fume	0.35	3
+silica fume + methylcellulose	0.35	3
+ methylcellulose + fibers	0.35	3
+ silica fume + methylcellulose + fibers	0.35	3

*Cement—not cementitious material.

the defoamer were added and stirred by hand for about 2 min. Then this mix, cement, and water were mixed in the Hobart mixer for 5 min. After pouring the mix into oiled molds, an external vibrator was used to decrease the amount of air bubbles. The specimens were demolded after 1 day and then allowed to cure at room temperature in air (relative humidity = 40 percent) for 28 days. Testing was performed at 28 days.

Testing procedure

The thermal conductivity (in W/m.K) was given by the product of the thermal diffusivity (in cm^2/s), specific heat (in J/g.K) and density (in g/cm^3). For measuring the thermal diffusivity, the laser flash method was used. In this method, a pulsed laser and a computer were used. The specimen was in the form of a disc, with a diameter of 13 mm and a thickness of 2 mm. Sample preparation for laser diffusivity measurement involved: 1) polishing both sides of the sample; 2) coating both sides of the sample with gold for thermal contacts; and 3) coating one of the sides (the side on which the laser beam would hit) with carbon to avoid reflection of the laser beam, since carbon is black. The temperature of the specimen at the side without the carbon coating was measured after the laser flash as a function of time by using a thermocouple. From the temperature-versus-time curve, the thermal diffusivity was calculated by using an equation in Reference 26. Six specimens of each type were tested. A differential scanning calorimeter and disc-shaped specimens 6-mm in diameter and 1-mm-thick were used for measuring the specific heat. A three-curve analysis method was used; it involved obtaining a sample, baseline, and reference material data. Sapphire was selected as a reference material. Six specimens of each type were tested.

Dynamic mechanical testing (ASTM D 4065-94) at controlled frequencies (0.20, 1.00, and 2.00 Hz) and temperatures (25 to 150 C) were conducted under flexure using a dynamic mechanical analyzer. Measurement of the storage modulus (dynamic elastic modulus given by the real part of the complex modulus) was made as a function of temperature at a constant frequency of 1.0 Hz. The heating rate was 2 C/min, which was selected to prevent any artificial damping peaks that may be caused by higher heating rates. The specimens were in the form of beams (24 x 8 x 3 mm) under three-point bending, such that the span was 20 mm. The loads used were all large enough so that the amplitude of the specimen deflection was always over the minimum value of 5 μm, required by the equipment for accurate results. The loads were set so that each different type of specimen was always tested at its appropriate stress level. Six specimens of each type were tested.

The change in thickness of a disc-shaped specimen (6 mm in diameter, 0.8 to 3.4-mm thick) was measured as the temperature was increased from room temperature to 200 C at a heating rate of 2 C/min, and as the temperature was subsequently decreased to room temperature at 2 C/min. In a different experiment, the change in dimension was measured during heating from room temperature to 200 C at 20 C/min, holding at 200 C for 471.25 min, and subsequent cooling to room temperature at 20 C/min. The former experiment was for studying the thermal expansion behavior, whereas the latter experiment was for measuring the creep rate at 200 C. In both experiments, a thermal mechanical analyzer with probe diameter of 3.4 mm was used. The probe force was 200 mN, which corresponded to 1560 Pa acting on the top face of the specimen. The dimension measured was in the force direction.

For compressive testing according to ASTM C 109-80, specimens were prepared by using a 2 x 2 x 2-in. (5.1 x 5.1 x 5.1-cm) mold. Compression testing was performed using a hydraulic material testing system (MTS). The cross head speed was 1.27 mm/min. Six specimens of each type were tested.

RESULTS AND DISCUSSION

Thermal conductivity and specific heat

Table 2 shows the thermal diffusivity, specific heat, density, thermal conductivity, and air-void content of various cement pastes at room temperature. The thermal conductivity decreased significantly and monotonically with increasing latex content, even though the air-void content decreased monotonically, and the specific heat increased monotonically. This is because both the thermal diffusivity and the density decreased with increasing latex content. The thermal diffusivity decreasing with increasing latex content is due to the insulating nature of latex. The specific heat increased with latex content due to the high specific heat of the latex and the decrease in air-void content.

Methylcellulose (0.6 percent by weight of cement) was as effective as latex (20 percent by weight of cement) for decreasing the thermal conductivity, mainly because the former gave lower thermal diffusivity, but higher specific heat, than the latter. For the same reason, methylcellulose (0.8 percent by weight of cement) was as effective as latex (25 percent by weight of cement) for decreasing the thermal conductivity. The air-void content was higher for the former than the latter (in each comparison), but the density was about the same.

Silica fume (15 percent by weight of cement) was as effective as latex (between 20 and 25 percent by weight of cement) and methylcellulose (between 0.6 and 0.8 percent by weight of cement) for decreasing the thermal conductivity, mainly because the former gave lower density, but higher specific heat, than the latter. The low density of the cement paste with silica fume is related to the high air-void content.

The combined use of silica fume (15 percent by weight of cement) and methylcellulose (0.4 percent by weight of cement) gave lower thermal conductivity than the use of silica fume alone, mainly because the former gave lower thermal diffusivity, but higher specific heat, and lower density than the latter. In spite of the low density for the former, the air-void content was lower for the former.

Silica fume (15 percent by weight of cement) was more effective than methylcellulose (0.4 to 0.8 percent by weight of cement) in increasing the specific heat. Methylcellulose (0.6 to 0.8 percent by weight of cement) was more effective than latex (20 to 30 percent by weight of cement) in increasing the specific heat. The high effectiveness of silica fume is due to the interface

Table 2—Thermal diffusivity, specific heat, density, and thermal conductivity of cement pastes at room temperature

Cement paste	Thermal diffusivity, mm^2/s, ±0.03	Specific heat, J/g.K, ±0.001	Density, g/cm^3, ±0.02	Thermal conductivity, W/m.K, ±0.03	Air void content,* percent, ±0.02
Plain	0.37	0.703	1.99	0.52	2.32
+ latex, 20 percent by weight of cement	0.29	0.712	1.83	0.38	1.53
+ latex, 25 percent by weight of cement	0.25	0.723	1.79	0.32	1.25
+ latex, 30 percent by weight of cement	0.22	0.736	1.76	0.28	1.10
+ methylcellulose, 0.4 percent by weight of cement	0.31	0.732	1.86	0.42	2.12
+ methylcellulose, 0.6 percent by weight of cement	0.28	0.737	1.84	0.38	2.10
+ methylcellulose, 0.8 percent by weight of cement	0.24	0.742	1.81	0.32	2.07
+ silica fume	0.27	0.765	1.72	0.36	3.14
+ silica fume + methylcellulose†	0.25	0.771	1.69	0.33	2.97
+ methylcellulose† + fibers, 0.5 percent by weight of cement	0.33	0.761	1.73	0.44	3.33
+ methylcellulose† + fibers, 1.0 percent by weight of cement	0.26	0.792	1.66	0.34	3.97
+ silica fume + methylcellulose† + fibers, 0.5 percent by weight of cement	0.22	0.789	1.62	0.28	4.36

*Measured using ASTM C 185-91a.
†0.4 percent by weight of cement.

between silica fume and the cement matrix, as silica fume itself is not high in specific heat. The high effectiveness of methylcellulose, even at a low concentration, is probably due to the liquid solution form of methylcellulose added to the mix, in contrast to the solid dispersion form of latex added to the mix. The solution probably allowed more uniform distribution in the mix than the dispersion. Due to the high effectiveness of both silica fume and methylcellulose, their combined use resulted in a particularly large specific heat.

In spite of the relatively high thermal conductivity of carbon fibers, the addition of carbon fibers to cement paste with methylcellulose (whether with or without silica fume) was not effective for increasing the thermal conductivity. This is because of the increase in air-void content (decrease in density) with increasing fiber content. In the absence of silica fume, with fibers at 0.5 percent by weight of cement, the thermal conductivity was essentially the same as that without fibers (but with methylcellulose); with fibers at 1.0 percent by weight of cement, the thermal conductivity was lower than without fibers. In contrast, the electrical resistivity decreases monotonically with increasing carbon fiber content, even beyond a fiber content of 1 percent by weight of cement.[27] The apparent contradiction between the electrical resistivity and thermal conductivity in their variation with fiber content is because carbon fibers are more electrically conductive than concrete by 10 orders of magnitude, whereas they are more thermally conductive than concrete by only 1 to 2 orders. As a result, voids are more detrimental to the thermal conductivity than to the electrical conductivity.

Whether with or without silica fume, the specific heat was increased by adding fibers. The specific heat also increased with increasing fiber content. This effect is due to the vibration in the form of slippage at the fiber-matrix interface, since the specific heat of graphite is not high. In spite of the specific heat increase, the thermal conductivity failed to increase upon fiber addition.

In the presence of silica fume, the thermal conductivity was decreased by fibers in the amount of just 0.5 percent by weight of cement, because the air-void content was higher when silica fume was present. The cement paste with silica fume, methylcellulose (0.4 percent by weight of cement), and fibers (0.5 percent by weight of cement) gave: 1) one of the lowest thermal diffusivities and one of the lowest thermal conductivities (same as the paste with latex in the amount of 30 percent by weight of cement) among all the pastes investigated; 2) the second highest specific heat (just lower than that of the paste with methylcellulose and fibers in the amount of 1.0 percent by weight of cement) among all the pastes investigated; and 3) the lowest density (the highest air void content) among all the pastes investigated. Because latex (20 to 30 percent by weight of cement) is more expensive than fibers (0.5 percent by weight of cement), methylcellulose (0.4 to 0.8 percent by weight of cement) or silica fume (15 percent by weight of cement), the paste with silica fume, methylcellulose, and fibers is less expensive than that with latex (30 percent by weight of cement), and thus it is recommended for use in attaining low thermal conductivity or low thermal diffusivity. Because fibers are more expensive than silica fume, the paste with silica fume, methylcellulose, and fibers (0.5 percent by weight of cement) is less expensive than that with methylcellulose and fibers (1.0 percent by weight of cement), and thus it is recommended for use in attaining high specific heat. This paste also exhibited high tensile strength (1.88 MPa, compared with 0.88 MPa for plain cement paste), high tensile ductility (0.0173 percent, compared with 0.004 percent for plain cement paste), and high tensile modulus (14 GPa, compared with 10.9 GPa for plain cement paste); the high tensile strength and tensile ductility are mainly due to the fibers, while the high tensile modulus is mainly due to the silica fume.[27]

Modulus during heating

Fig. 1 gives the storage modulus (± 0.02 GPa) as a function of temperature for seven cement pastes. The addition of latex, methylcellulose, or silica fume increased the storage modulus. The highest storage modulus value was attained by silica fume at all temperatures studied. Methylcellulose was less effective than silica fume, but more effective than latex, for enhancing the storage modulus, even though methylcellulose was used in a much smaller quantity than latex. The greater the latex-cement ratio, the higher the modulus. This means that polymer addition is not as effective as silica fume addition for enhancing the modulus, but the type of polymer is more important than the quantity of polymer in affecting the modulus. The greater effectiveness of methylcellulose than latex is probably related to the liquid form of methylcellulose and the solid particle dispersion form of latex, and the consequent superior dispersion of methylcellulose than latex in the cement paste. The storage modulus decreased with increasing temperature for all seven pastes. Fig. 2 shows the fractional decrease in storage modulus as a function of temperature for the seven pastes. The addition of silica fume or methylcellulose increased this fraction relative to the value for plain cement paste at all temperatures studied. The addition of latex

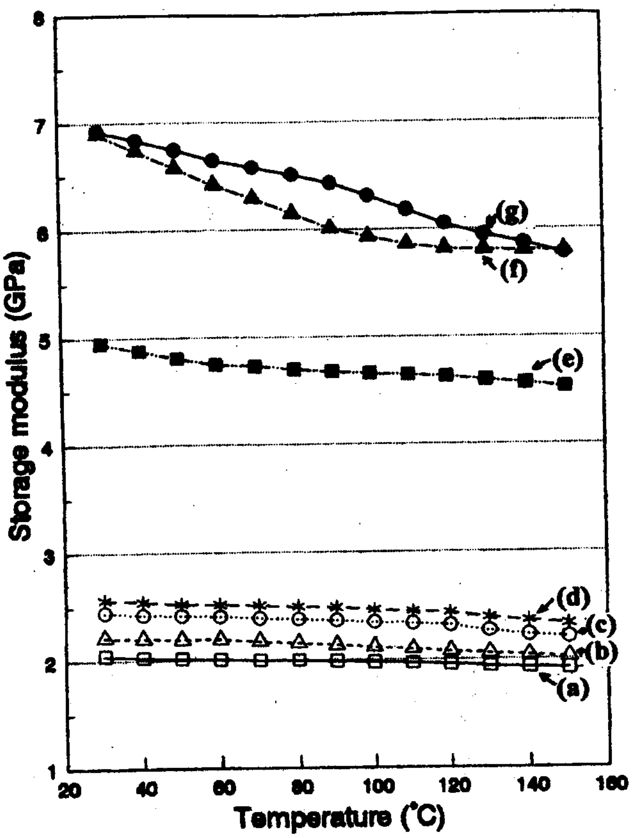

Fig. 1—Variation of flexural storage modulus with temperature during heating for: (a) plain cement paste; (b) cement paste with latex (20 percent by weight of cement); (c) cement paste with latex (25 percent by weight of cement); (d) cement paste with latex (30 percent by weight of cement); (e) cement paste with methylcellulose; (f) cement paste with methylcellulose and silica fume; and (g) cement paste with silica fume.

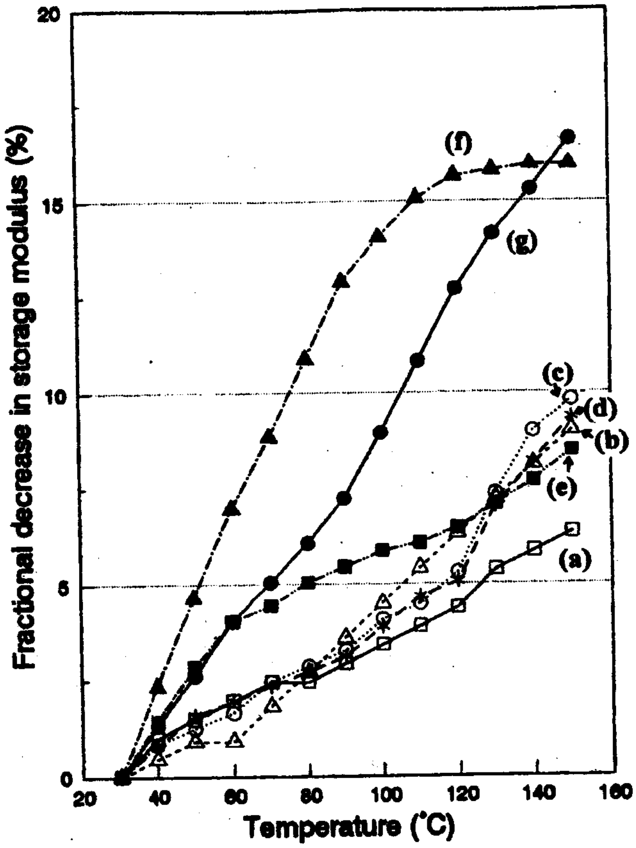

Fig. 2— Fractional decrease in flexural storage modulus as function of temperature during heating for: (a) plain cement paste; (b) cement paste with latex (20 percent by weight of cement); (c) cement paste with latex (25 percent by weight of cement); (d) cement paste with latex (30 percent by weight of cement); (e) cement paste with methylcellulose; (f) cement paste with methylcellulose and silica fume; and (g) cement paste with silica fume.

increased this fraction relative to the value for plain cement paste only at 80 C or above. The greatest value of this fraction was attained by the addition of methylcellulose plus silica fume. This fraction was higher for silica fume addition than any of the polymer additions.

Although the silica fume addition gave a high storage modulus, it also gave a large fractional decrease of the storage modulus upon heating. Although plain cement had a low storage modulus, it had a small fractional decrease of the modulus upon heating.

Modulus and weight during heating and cooling

The effect of heating on the storage modulus (Fig. 1) was reversible, as observed upon cooling at 2 C/min immediately after the heating. However, thermogravimetric analysis (TGA) using the thermal/mechanical analyzer during heating at 10 C/min and subsequent cooling at 10 C/min showed that all cement pastes exhibited totally irreversible weight loss (presumably due to moisture loss), primarily from 70 to 100 C during heating. Fig. 3 and 4 show the storage modulus and relative weight, respectively, during both heating and subsequent cooling, for the case of cement paste with silica fume. After heating to 350 C at a heating rate of 10 C/min, the fractional loss in weight was 9.0, 7.5, and 2.8 percent for plain cement paste, cement paste with silica fume, and cement paste with latex, respectively. Although silica fume cement paste gave a smaller fractional loss in weight than plain cement paste, it gave a larger fractional decrease in modulus than plain cement paste. In spite of the irreversible weight loss (Fig. 4), the decrease in

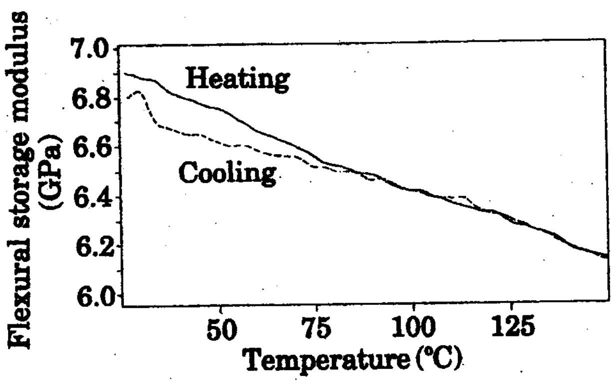

Fig. 3—Variation of flexural storage modulus (1Hz) with temperature during heating (solid curve) and cooling (dashed curve) for cement paste with silica fume. Static stress was 1.84 MPa; dynamic stress was 0.703 MPa; and flexural strength (ASTM C 348-80) was 2.75 MPa.

storage modulus upon heating was reversible (Fig. 3). This means that the moisture loss had a negligible effect on the modulus. It also means that the decrease in modulus upon heating was not due to moisture loss, but was probably due to the softening of the solid network itself. This interpretation is consistent with the fact that the modulus decreased gradually with increasing temperature from 30 to 150 C, whereas the weight loss occurred abruptly at 70 to 100 C. It is supported by the observation that the room temperature compressive strength of

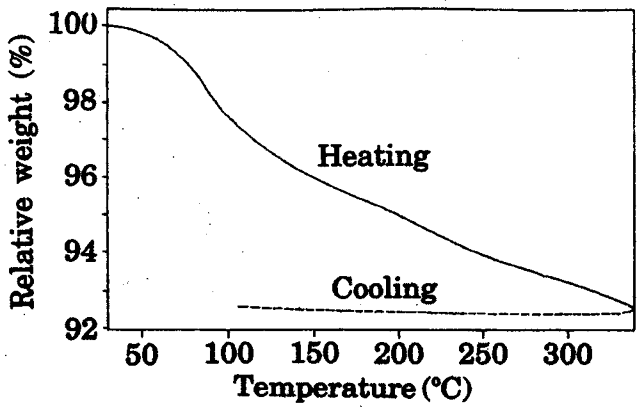

Fig. 4—Variation of relative weight with temperature during heating (solid curve) and cooling (dashed curve) for cement paste with silica fume. Initial sample weight was 63.966 mg.

Table 3—Compressive strength* of cement pastes†

Cement paste	30 C	60 C	90 C	120 C	150 C
With latex	47.2 ± 1.2 percent	48.5 ± 2.2 percent	49.7 ± 1.3 percent	50.4 ± 1.8 percent	51.7 ± 2.2 percent
With silica fume	44.6 ± 2.1 percent	45.5 ± 1.8 percent	46.2 ± 1.5 percent	47.6 ± 2.1 percent	48.9 ± 1.2 percent

*In MPa.
†At room temperature after heating at temperatures up to 150 C for 2 hr.

cement paste with silica fume or that with latex did not decrease after heating at up to 150 C for 2 hr, as shown in Table 3. (The compressive strength even increased slightly after heating, probably due to more complete pozzolanic reactions.) It is also consistent with the observation that sealing had no significant effect on the modulus at various temperatures from 50 to 240 C.[8] The reversible modulus decrease is in contrast to the irreversible modulus decrease reported by previous workers.[9-13] The apparent discrepancy is partly due to the difference in measurement method. The ASTM D 4065-94 method used in this work had not been used in previous work. Furthermore, most previous work addressed the static modulus rather than the dynamic modulus (measurement of the dynamic modulus is more nondestructive than that of the static modulus due to the small strain variation in the former), and most previous work addressed the effect of heating rather than the effects of both heating and cooling.

Dimension during heating and cooling

Fig. 5 to 8 show the fractional change in dimension in the compressive stress (1560 Pa) direction during heating and subsequently cooling for plain cement paste (initial dimension = 1.98 mm), cement paste with methylcellulose (initial dimension = 0.84 mm), cement paste with latex (initial dimension = 0.95 mm), and cement paste with silica fume (initial dimension = 3.42 mm), respectively.

Plain cement paste (Fig. 5) expanded upon heating so that the apparent coefficient of thermal expansion (CTE) near room temperature was 8.1×10^{-6} C^{-1}. At 61 C, the expansion started to deviate negatively from linearity, so that the apparent CTE decreased. At 113 C, the dimension began to decrease so that the apparent CTE became negative. Upon subsequent cooling from 150 C, the dimension continued to decrease. This means that the dimensional decrease upon heating beyond 113 C was irreversible. Both the dimensional decrease and the decrease in apparent CTE upon heating are attributed to the softening of the cement paste (Fig. 2). During cooling below 84 C, the dimension decreased linearly with decreasing temperature, with

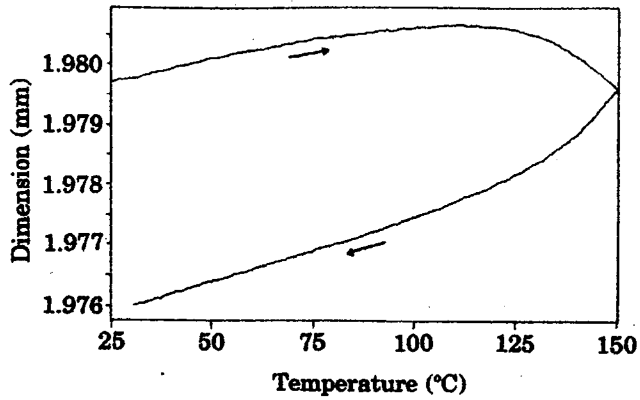

Fig. 5—Effect of heating and cooling, both at 2 C/min, on dimension of plain cement paste.

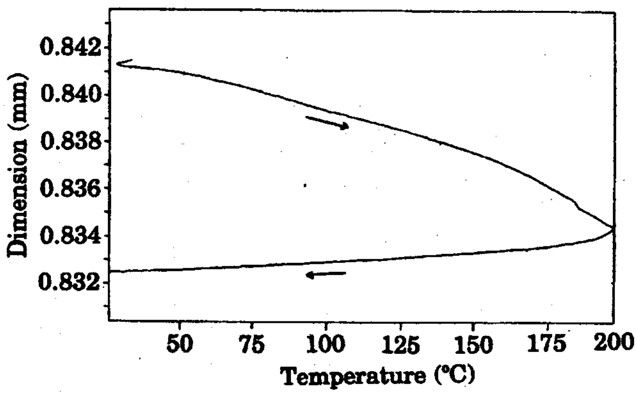

Fig. 6—Effect of heating and cooling, both at 2 C/min, on the dimension of cement paste with methylcellulose.

the apparent CTE 9.5×10^{-6} deg C^{-1}. That the apparent CTE during cooling was higher than that during heating is because of the time-dependent nature of the dimensional decrease, which is partly due to creep.

Cement paste with methylcellulose (Fig. 6) contracted upon heating, essentially from room temperature onward, so that the apparent CTE was negative and became more negative as the temperature increased, as previously reported.[23] Contraction continued upon subsequent cooling from 200 C. Similar behavior was observed for cement paste with latex (Fig. 7).

Cement paste with silica fume (Fig. 8) exhibited an apparent CTE of 5.1×10^{-6} deg C^{-1} upon heating up to 200 C. No contraction was observed during heating up to 200 C, in contrast to the contraction observed for the pastes in Fig. 5 to 7. The absence of contraction in the paste with silica fume is consistent with the high storage modulus at any temperature, compared with the other pastes (Fig. 1). Upon subsequent cooling, the paste with silica fume contracted such that the apparent CTE was higher than that during heating. This difference in apparent CTE between heating and cooling is attributed to creep. The apparent CTE was lower for cement paste with silica fume than plain cement paste. This is consistent with the high storage modulus of the former.

Creep

The creep rate at 200 C was taken as the strain rate in the 471.25-min period in which the temperature was constant at 200 C. As shown in Table 4, it was reduced by the presence of methylcellulose, latex, or silica fume so that silica fume gave the greatest reduction. Latex and methylcellulose gave similar reductions. The low creep rate of the paste with silica fume is consistent with the high storage modulus (Fig. 1). Relative to plain

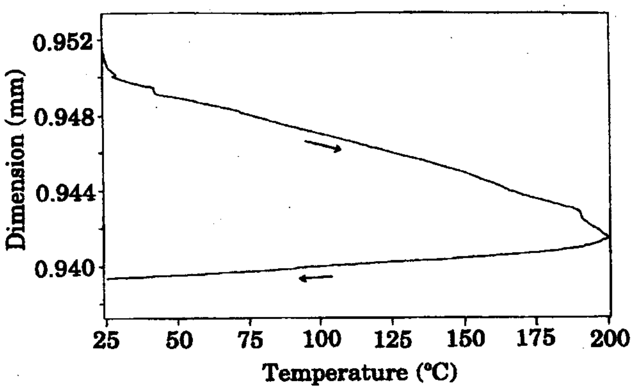

Fig. 7— Effect of heating and cooling, both at 2 C/min, on dimension of cement paste with latex.

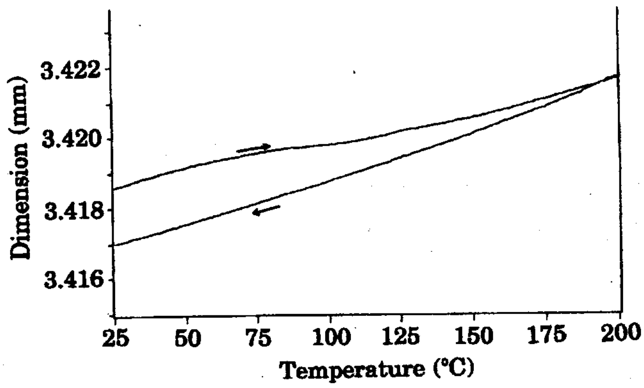

Fig. 8—Effect of heating and cooling, both at 2 C/min, on dimension of cement paste with silica fume.

cement paste, the reduction in creep rate by methylcellulose or latex is consistent with the increase in storage modulus (Fig. 1).

CONCLUSIONS

1. Silica fume (15 percent by weight of cement), latex (20 to 30 percent by weight of cement), and methylcellulose (0.4 to 0.8 percent by weight of cement) were effective for decreasing the thermal conductivity of cement paste by up to 46 percent, mainly due to the relatively low conductivity of these admixtures and the low density provided to the paste by these admixtures.

2. The specific heat was increased by adding silica fume, latex, methylcellulose, or carbon fibers such that silica fume was most effective for increasing the specific heat, which was increased by 9 percent.

3. The thermal conductivity of cement paste decreased and the specific heat increased with increasing latex or methylcellulose content. Methylcellulose (0.6 to 0.8 percent by weight of cement) was as effective as latex (20 to 25 percent by weight of cement) for decreasing the thermal conductivity. Methylcellulose (0.6 to 0.8 percent by weight of cement) was more effective than latex (20 to 30 percent by weight of cement) for increasing the specific heat.

4. The addition of short carbon fibers failed to increase the thermal conductivity of cement paste, due to the increase in air-void content. The thermal conductivity was either not changed or decreased by adding carbon fibers. The greater the fiber content, the lower the conductivity.

5. The flexural storage modulus decreased gradually with increasing temperature from 30 to 150 C for cement pastes such that the effect was reversible, in contrast to the irreversibility of the weight loss upon heating.

6. Among the admixtures used (latex, methylcellulose, and silica fume), silica fume gave the highest flexural storage modulus at all temperatures (30 to 150 C), but also the greatest

Table 4—Creep rate at 200 C

Cement paste	Creep rate, min^{-1}
Plain	1.3×10^{-5}, ± 4 percent
With methylcellulose	5.5×10^{-6}, ± 7 percent
With latex	6.8×10^{-6}, ± 5 percent
With silica fume	2.4×10^{-6}, ± 14 percent

fractional decrease in modulus upon heating. Methylcellulose (0.4 percent by weight of cement) gave a higher modulus than latex (20 to 30 percent by weight of cement). The modulus increased with increasing latex/cement ratio. Plain cement paste (without any admixture) gave the lowest modulus.

7. Cement pastes with methylcellulose or latex contracted in the compression direction upon heating above room temperature, mainly due to softening upon heating, though creep also contributed to the contraction. Plain cement paste expanded upon heating due to thermal expansion up to 113 C, beyond which contraction occurred due to softening and creep. Cement paste with silica fume expanded upon heating due to thermal expansion, with no contraction at least up to 200 C. The apparent coefficient of thermal expansion for the expansion regime was lower for cement paste with silica fume than plain cement paste.

8. The creep rate at 200 C was reduced by the presence of methylcellulose, latex, or silica fume, such that silica fume gave the most reduction.

ACKNOWLEDGMENTS

This work was supported in part by the National Science Foundation.

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