Pergamon

Cement and Concrete Research 31 (2001) 1633–1637

CEMENT AND CONCRETE RESEARCH

Communication

Carbon fiber reinforced cement mortar improved by using acrylic dispersion as an admixture

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Received 14 June 2001; accepted 27 June 2001

Abstract

Cement mortar reinforced by short carbon fibers was improved by using acrylic dispersion as an admixture in the amount of 15% by mass of cement. The improvement of the tensile properties (particularly strength and ductility) was more than those attained by using methylcellulose, styrene acrylic, or latex as admixtures. Acrylic was effective whether silica fume was present or not. However, for lowering the electrical resistivity, methylcellulose in combination with silica fume was most effective.

Keywords: Tensile properties; Electrical properties; Fiber reinforcement; Mortar; Silica fume

1. Introduction

Acrylic dispersions have long been used as admixtures to modify cement-based materials [1–29]. Effects of the acrylic admixture include decreasing the required water/cement ratio [3], enhancing the resistance to deterioration in water [7,10], and improving the mechanical properties [4,20,21], the dispersant properties [8], and the corrosion resistance [16,24,27,28]. Acrylic has also been used as a coating on concrete to improve concrete durability [30–34]. Moreover, acrylic dispersions have been used as admixtures in cement-based materials that contain short fiber reinforcement [35–38], as they improve the mechanical properties [35–37] through strengthening the matrix and increasing the fiber–matrix bond strength [36]. The use of an acrylic dispersion as an admixture along with fibers is to be distinguished from the use of an acrylic dispersion to treat the surface of the fibers [39]. It is also to be distinguished from the use of acrylic fibers [40–42].

This paper is focused on the use of an acrylic dispersion as an admixture in carbon fiber-reinforced cement. Previous related work has involved glass fibers [35,37] and steel fibers [36], but not carbon fibers.

Although acrylic dispersions have not been used along with carbon fibers in cement-based materials, latex (mainly styrene–butadiene copolymers) dispersions have been used and found to help improve the mechanical properties, the corrosion resistance, and the bonding ability [43–54]. Methylcellulose has also been used, particularly along with silica fume, to help the dispersion of carbon fibers in cement [43–45,47–49,54–56].

This paper compares the effects of acrylic, styrene acrylic, and latex dispersions in addition to those of methylcellulose solution. All these additives were used along with carbon fibers, whether or not silica fume was used. Silica fume is highly effective for enhancing the fiber dispersion [47], so its effect is also addressed. The acrylic dispersion was thus found in this work to be the most effective admixture for giving high tensile ductility and strength.

Carbon fiber-reinforced cement is attractive for its high tensile strength and ductility, low drying shrinkage, and self-sensing ability [43,44,49,52,56,57]. The electrical resistivity is relevant to the self-sensing ability. As the carbon fibers are much more conducting than the cement matrix, the resistivity is quite sensitive to the degree of fiber dispersion and is thus of fundamental interest as well. Therefore, this paper addresses not only the tensile properties, but also the electrical resistivity.

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0008-8846/01/$ – see front matter
PII: S0008-8846(01)00599-3

2. Experimental methods

The cement used was portland cement (Type I) from Lafarge (Southfield, MI). The sand used was natural sand (100% passing 2.36-mm sieve, 99.9% SiO_2). The sand/cement ratio was 1.0. Silica fume (EMS 965, Elkem Materials, Pittsburgh, PA), if applicable, was used in the amount of 15% by mass of cement. A water reducing agent (WR) was used in the amount of 2.0% by weight of cement. The WR was TAMOL SN (Rohm and Haas, Philadelphia, PA) which contained 93–96% sodium salt of a condensed naphthalene sulfonic acid. The water/cement ratio was 0.35. No coarse aggregate was used.

The carbon fibers were isotropic pitch-based, unsized, and of length ~5 mm, diameter 15 μm, and density 1.6 g/cm^3, as obtained from Ashland Petroleum (Ashland, KY). The fiber resistivity was 3.0×10^{-3} Ω cm. The fibers used were in the amount of 0.5% by mass of cement. This corresponded to a fiber volume fraction of 0.35% for the mortars.

The organic admixtures used separately were (i) acrylic dispersion with the polymer making up 47% of the dispersion mass (#413, Warren Paint an Color, Nashville, TN), (ii) styrene acrylic dispersion with the polymer making up 45% of the dispersion mass (#7104, Warren Paint and Color), (iii) latex dispersion (a styrene butadiene copolymer with the polymer making up 48% of the dispersion mass and with the styrene and butadiene having a mass ratio of 66:34, #460NA, Dow Chemical, Midland, MI), and (iv) methylcellulose (Methocel A15-LV, Dow Chemical, Midland, MI). Each dispersion [i.e., (i), (ii), or (iii)] was used in the amounts of 10%, 15%, and 20% by mass of cement. The methylcellulose [i.e., (iv)] was used in the amount of 0.4% by mass of cement. An antifoaming agent (#2410, Dow Corning, Midland, MI) was used along with each of the three dispersions in the amount of 0.5% by mass of cement. A defoamer (#1010, Colloids, Marietta, GA) was used along with methylcellulose in the amount of 0.13 vol.%. The methylcellulose powder was dissolved in water prior to use. The water in each dispersion and in the methylcellulose solution was taken into account in obtaining the water/cement ratio, which was 0.35 in all cases.

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. A polymer dispersion (if applicable) was mixed with the antifoaming agent by hand for about 1 min. Then the methylcellulose mixture (if applicable), the dispersion mixture (if applicable), cement, water, water-reducing agent, silica fume (if applicable), sand and fibers were mixed in the mixer for 5 min. After pouring into oiled molds, an external electrical vibrator was used to facilitate compaction and decrease the amount of air bubbles. The samples were demolded after 1 day and cured in air at room temperature (relative humidity = 100%) for 28 days.

DC volume electrical resistivity was measured on rectangular samples of size 70 × 10 × 10 mm, using the Keithley 2001 multimeter and the four-probe method. In this method, four electrical contacts were applied by silver paint around the whole perimeter at four planes perpendicular to the length of the specimen. The four planes were symmetrical around the midpoint along the length of the specimen, such that the outer contacts (for passing current) were 60 mm apart and the inner contacts (for measuring the voltage in relation to resistivity determination) were 50 mm apart. At least six specimens of each composition were tested.

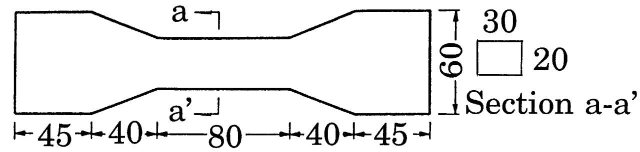

Fig. 1. Specimen configuration. Dimensions are in millimeters.

Dog bone-shaped specimens of the dimensions shown in Fig. 1 were used for tensile testing. The specimen cross section was 30 × 20 mm in the narrow part of the dog bone shape. They were prepared by using molds of the same shape and size. Tensile testing was performed using a Sintech 2/D screw-action mechanical testing system under static loading up to failure. A resistive strain gage was attached to the center of one of the two larger surfaces at the narrow part of a dog bone-shaped specimen for measuring the strain during tensile testing. The displacement rate was 1.20 mm/min. Six specimens of each composition were tested.

3. Results and discussion

Tables 1 and 2 show the tensile properties and electrical resistivity of mortars with and without silica fume, respectively. All mortars contained carbon fibers and the water/cement ratio was 0.35. The amount of water added to the mix containing a dispersion was less than 0.35 by mass of cement, due to the amount of water in the dispersion. The amount of water added thus varied from mortar to mortar and is given in Tables 1 and 2 as "the apparent water/cement ratio."

The electrical resistivity was decreased by the addition of methylcellulose, or any of the three dispersions (acrylic, styrene acrylic, and latex), whether silica fume was present or not. In the presence of silica fume (Table 1), the resistivity decrease was most significant for the case of methylcellulose, and next most significant for the case of the acrylic dispersion, particularly when the acrylic dispersion was in the amount of 15% or 20% by mass of cement. In the absence of silica fume (Table 2), the resistivity decrease was most significant for the case of the acrylic dispersion, particularly when the acrylic dispersion was in the amount of 15% or 20% by mass of cement, and was next most significant for the case of latex in the amount of 10% by mass of cement and for the case of methylcellulose. The use of the acrylic dispersion in an amount of 10% by

Table 1
Tensile properties and electrical resistivity of various mortars that contained carbon fibers and silica fume

Organic admixture type	Organic admixture amount (percentage[a] by mass of cement)	Apparent water/ cement ratio	Tensile strength (MPa)	Tensile modulus (GPa)	Tensile ductility (%)	Resistivity (10^6 Ω cm)
/	0	0.350	1.45 ± 0.11	9.8 ± 0.7	0.0121 ± 0.0006	1.13 (± 3.9%)
Methylcellulose	0.4	0.350	2.36 ± 0.06	13.5 ± 0.9	0.0168 ± 0.0009	0.31 (± 3.1%)
Acrylic	10	0.297	2.26 ± 0.07	11.5 ± 0.7	0.0258 ± 0.0010	0.55 (± 5.3%)
	15	0.270	2.54 ± 0.11	12.3 ± 0.4	0.0307 ± 0.0012	0.49 (± 5.1%)
	20	0.244	2.46 ± 0.09	10.5 ± 0.6	0.0273 ± 0.0008	0.51 (± 3.1%)
Styrene acrylic	10	0.295	2.04 ± 0.10	10.7 ± 0.5	0.0198 ± 0.0015	0.93 (± 3.4%)
	15	0.267	2.28 ± 0.15	11.5 ± 0.7	0.0255 ± 0.0012	0.85 (± 5.2%)
	20	0.240	2.41 ± 0.09	11.7 ± 0.3	0.0277 ± 0.0008	0.77 (± 4.6%)
Latex	10	0.298	2.19 ± 0.13	11.3 ± 0.5	0.0214 ± 0.0017	0.56 (± 4.7%)
	15	0.272	2.49 ± 0.11	12.1 ± 0.8	0.0291 ± 0.0008	0.63 (± 3.7%)
	20	0.246	2.40 ± 0.08	11.7 ± 0.6	0.0235 ± 0.0013	0.70 (± 6.1%)

[a] Including the mass of water in the dispersion, in case that a dispersion was used. Same as the true water/cement ratio when a dispersion was not used.

mass of cement gave higher resistivity than the use of the acrylic dispersion at 15% or 20% by mass of cement, whether silica fume was present or not. The use of latex in the same amount instead of acrylic gave slightly higher resistivity and the use of styrene acrylic gave even higher resistivity; the trend was the same whether silica fume was present or not. For the case of latex, the resistivity increased with increasing latex content, whether silica fume was present or not. For the case of styrene acrylic, the resistivity decreased with increasing styrene acrylic content, whether silica fume was present or not. For methylcellulose and any dispersion type and amount, the presence of silica fume decreased the resistivity.

The tensile strength was increased by the addition of methylcellulose, or any of the three dispersions, whether silica fume was present or not. The strength increase was most significant for the case of the acrylic dispersion in the amount of 15% or 20% by mass of cement, whether silica fume was present or not. The use of methylcellulose, or the acrylic dispersion, at 10% by mass of cement gave lower strength than the use of the acrylic dispersion at 15% or 20% by mass of cement, whether silica fume was present or not. The use of latex in the same amount instead of acrylic gave slightly lower strength and the use of styrene acrylic gave even lower strength; the trend was the same whether silica fume was present or not. The strength increased with increasing dispersion amount, except for the case of latex without silica fume. For any dispersion type and amount, the presence of silica fume increased the strength.

The tensile modulus was increased by the addition of methylcellulose, or any of the three dispersions, whether silica fume was present or not. The highest tensile modulus was attained by the use of methylcellulose in the presence of silica fume. In the absence of silica fume, the effect was similar for methylcellulose and the nine combinations of dispersion type and amount. In the presence of silica fume, the nine combinations of dispersion type and amount gave similar effect on the modulus. For methylcellulose, the presence of silica fume increased the modulus slightly; for any of the nine combinations of dispersion type and amount, the presence of silica fume decreased the modulus slightly.

The tensile ductility was increased by the addition of methylcellulose, or any of the three dispersions, whether silica fume was present or not. The ductility increase was most significant for the case of the acrylic dispersion, particularly when the acrylic dispersion was in the amount of 15% by mass of cement, whether silica fume was present or not. The use of the acrylic dispersion at 10% or 20% by mass of cement gave lower ductility than the use of the acrylic dispersion at 15% by mass of cement, whether silica

Table 2
Tensile properties and electrical resistivity of various mortars that contained carbon fibers, but without silica fume

Organic admixture type	Organic admixture amount (percentage[a] by mass of cement)	Apparent water/ cement ratio	Tensile strength (MPa)	Tensile modulus (GPa)	Tensile ductility (%)	Resistivity (10^6 Ω cm)
/	0	0.350	1.04 ± 0.11	10.2 ± 0.8	0.0098 ± 0.0005	1.59 (± 4.5%)
Methylcellulose	0.4	0.350	2.26 ± 0.08	12.5 ± 0.3	0.0150 ± 0.0009	0.68 (± 2.8%)
Acrylic	10	0.297	2.15 ± 0.08	12.0 ± 0.6	0.0240 ± 0.0012	0.67 (± 6.9%)
	15	0.270	2.49 ± 0.13	12.9 ± 0.7	0.0296 ± 0.0009	0.56 (± 4.3%)
	20	0.244	2.56 ± 0.20	11.7 ± 0.8	0.0251 ± 0.0006	0.58 (± 6.0%)
Styrene acrylic	10	0.295	1.98 ± 0.14	11.6 ± 0.6	0.0190 ± 0.0012	1.01 (± 4.9%)
	15	0.267	2.07 ± 0.20	12.5 ± 0.8	0.0246 ± 0.0020	0.96 (± 4.0%)
	20	0.240	2.23 ± 0.12	12.9 ± 0.7	0.0263 ± 0.0011	0.83 (± 5.1%)
Latex	10	0.298	2.02 ± 0.15	12.3 ± 0.9	0.0200 ± 0.0010	0.66 (± 5.8%)
	15	0.272	2.25 ± 0.17	13.0 ± 0.6	0.0283 ± 0.0011	0.70 (± 9.3%)
	20	0.246	2.08 ± 0.20	12.8 ± 0.9	0.0229 ± 0.0017	0.89 (± 7.7%)

[a] Including the mass of water in the dispersion, in case that a dispersion was used. Same as the true water/cement ratio when a dispersion was not used.

fume was present or not. The use of latex in the same amount instead of acrylic gave lower ductility and the use of styrene acrylic gave even lower ductility; the trend was the same whether silica fume was present or not. For any of the three dispersion types, the ductility was lower for a dispersion amount of 10% by mass of cement than for dispersion amounts of 15% or 20% by mass of cement, whether silica fume was present or not. For any dispersion type and amount, the presence of silica fume enhanced the ductility. Methylcellulose was less effective than any of the nine combinations of dispersion type and amount in increasing the ductility, whether silica fume was present or not.

The results on resistivity and tensile properties show that the use of acrylic dispersion at 15% by mass of cement is most attractive, whether silica fume is present or not. The low resistivity, high strength, and high ductility attained by this use is partly a consequence of a high degree of fiber dispersion. A higher fiber–matrix bond strength may contribute to causing the higher strength and ductility, but it is expected to contribute in a minor way to causing the lower resistivity. The presence of silica fume lowers the resistivity and increases the strength and ductility, also because of the enhanced degree of fiber dispersion.

In the presence of silica fume, methylcellulose gives the highest modulus, but the lowest ductility. In the absence of silica fume, methylcellulose does not perform well compared to the dispersions. On the other hand, the small amount of methylcellulose (only 0.4% by mass of cement) makes methylcellulose economically attractive compared to the dispersions, which are used in much larger amounts (10–20% by mass of cement). The relatively poor ductility effect of methylcellulose occurs in spite of the high degree of fiber dispersion suggested by the low resistivity. This means that ductility is enhanced not only by fiber dispersion, but by the volume of the organic admixture, which enhances the fiber–matrix bonding [55,58,59].

The resistivity increased with increasing latex amount and the strength and ductility did not vary monotonically with the latex amount, whether silica fume was present or not. This is attributed to the decrease in fiber dispersion and/or the increases in the contact resistivity and bond strength of the fiber–matrix interface caused by the increase in latex amount. On the other hand, the resistivity decreased and the strength and ductility increased with increasing styrene acrylic amount, whether silica fume was present or not. This is attributed to the increase in fiber dispersion caused by the increase in styrene acrylic amount. The resistivity trend is less clear for the acrylic case, but the correlation of the lowest resistivity with the highest strength and ductility suggests that the degree of fiber dispersion is the main factor, as in the case of styrene acrylic.

The performance of an organic admixture depends on the affinity (wettability) of the fiber with the admixture, the ability of the admixture to disperse itself in the cement mix, and the effect of the admixture on the fiber–matrix bond strength. Further study is needed to find out the cause for the superior performance of acrylic compared to latex, styrene acrylic, or methylcellulose.

4. Conclusions

The use of acrylic dispersion as an admixture in the amount of 15% by mass of cement is more effective than the use of methylcellulose solution, styrene acrylic dispersion, or latex dispersion in enhancing the tensile properties (particularly strength and ductility) of carbon fiber-reinforced mortar, whether silica fume is present or not. However, for attaining a low electrical resistivity in carbon fiber-reinforced mortar, methylcellulose solution in combination with silica fume is most effective.

Acknowledgments

This work was supported by the National Science Foundation, U.S.A. The authors thank Mr. Guocai Wu and Mr. Yunsheng Xu of the University at Buffalo for technical assistance.

References

[1] J.A. Lavelle, Acrylic latex-modified portland cement, ACI Mater. J. 85 (1) (1988) 41–48.

[2] P. Maslow, Latex emulsions with concrete, ACS Symposium Series, no. 113, Plastic Mortars, Sealants, and Caulking Compound, from a Symposium at the 177th National Meeting of the ACS, ACS, Washington, DC, 1979, pp. 79–100.

[3] P.S. Mangat, D.A. Evans, Influence of polymer admixtures on the strength, deformation and fracture of high strength concretes, ASTM Spec. Tech. Publ., (1980) 67–87.

[4] A. Bentur, Properties of polymer latex–cement composites, Int. J. Cem. Compos. Lightweight Concr. 4 (1) (1982) 57–65.

[5] J.D. Shaw, Use of polymers in concrete repair, Civ. Eng. (London) (1983), 33–34, 37, 39.

[6] J.A. Lavelle, Acrylic modified high solids cementitious coatings, Proceedings of the Ninth Water-Borne and Higher-Solids Coatings Symposium. University of Southern Mississippi, Hattiesburg, MS, 1982, pp. 74–95.

[7] M. Sakuta, Y. Yoshioka, T. Kaya, Use of acryl-type polymer as admixture for underwater concrete, Publ. SP-Am. Concr. Inst. '89, Polym. Concr.: Uses, Mater., Prop., American Concrete Institute, Detroit, MI, 1985, pp. 261–278.

[8] G. Bradley, I.M. Howarth, Water soluble polymer: The relationship between structure, dispersing action, and rate to cement hydration, Cem., Concr., Aggregates 8 (2) (1986) 68–75.

[9] E. Karuks, T. Hayes, Properties of polymer and fly ash modified cementitious materials, Proceedings of the Seventh International Ash Utilization Symposium and Exposition 2, U.S. DOE, Morgantown, WV, 1985, pp. 822–833.

[10] X. Aimin, S. Chandra, Influence of polymer addition on the rate of carbonation of portland cement paste, Int. J. Cem. Compos. Lightweight Concr. 10 (1) (1988) 49–52.

[11] J.A. Larbi, J.M.J.M. Bijen, Interaction of polymers with portland ce-

ment during hydration. A study of the chemistry of the pore solution of polymer-modified cement systems, Cem. Concr. Res. 20 (1) (1990) 139–147.

[12] D.R. Plum, Behaviour of polymer materials in concrete repair, and factors influencing selection, Struct. Eng. 68 (17) (1990) 337–345.

[13] Y. Ohama, K. Demura, M. Hamatsu, M. Kakegawa, Properties of polymer-modified mortars using styrene–butyl acrylate latexes with various monomer ratios, ACI Mater. J. 88 (1) (1991) 56–61.

[14] Z. Su, J.M.J.M. Bijen, J.A. Larbi, Influence of polymer modification on the hydration of portland cement, Cem. Concr. Res. 21 (2–3) (1991) 242–250.

[15] Z. Su, J.M.J.M. Bijen, J.A. Larbi, Influence of polymer modification on the hydration of portland cement, Cem. Concr. Res. 21 (4) (1991) 535–544.

[16] J.L. Heiman, P. Koerstz, Performance of polymer-modified cementitious repair mortars in chloride contaminated concrete, Trans. Inst. Eng., Aust.: Civ. Eng. (3) (1991) 169–175.

[17] C. Atzeni, L. Massida, U. Sanna, Dimensional variations, capillary absorption and freeze–thaw resistance of repair mortars admixed with polymers, Cem. Concr. Res. 23 (2) (1993) 301–308.

[18] M.-C. Tsai, M.J. Burch, J.A. Lavelle, Solid grade acrylic cement modifiers, ASTM Spec. Tech. Publ. 1176 (1993) 63–75.

[19] J.J. Bartholomew, Evaluation of latex modified concrete overlays for cathodic protection, ASTM Spec. Tech. Publ. 1176 (1993) 120–124.

[20] M.J. Burch, X. Ci, J.G. Brodnyan, New acrylic flexible cement modifier, ASTM Spec. Tech. Publ. 1187 (1995) 15–28.

[21] X. Ci, R.R. Falconio, Acrylic powder modified portland cement, Cem., Concr., Aggregates 17 (2) (1995) 218–226.

[22] R.P. Bright, Comparison of liquid dispersions with spray-dried acrylic polymers as modifiers of a cement-based patching material, Cem., Concr., Aggregates 17 (2) (1995) 227–230.

[23] M.L. Allan, Rheology of latex-modified grouts, Cem. Concr. Res. 27 (12) (1997) 1875–1884.

[24] N. DeBelie, R. Verschoore, D. Van Nieuwenburg, Trans. ASAE 41 (1) (1998) 227–233.

[25] F. Sandrolini, A. Saccani, Effect of polymer addition on the electrical behavior of ordinary and pulverized fly ash modified cement mortars, Mater. Struct. 30 (201) (1997) 412–417.

[26] M. Collepardi, Admixtures used to enhance placing characteristics of concrete, Cem. Concr. Compos. 20 (2/3) (1998) 103–112.

[27] S.X. Wang, W.W. Lin, S.A. Ceng, J.G. Zhang, Corrosion inhibition of reinforcing steel by using acrylic latex, Cem. Concr. Res. 28 (5) (1998) 649–653.

[28] N. De Belie, J. Monteny, Resistance of concrete containing styrol acrylic acid ester latex to acids occurring on floors for livestock housing, Cem. Concr. Res. 28 (11) (1998) 1621–1628.

[29] L.M. Saija, M. Uminski, Water-redispersible low-T_g acrylic powders for the modification of hydraulic binder compositions, J. Appl. Polym. Sci. 71 (11) (1999) 1781–1787.

[30] M. Ibrahim, A.S. Al-Gahtani, M. Maslehuddin, F.H. Dakhil, Use of surface treatment materials to improve concrete durability, J. Mater. Civ. Eng. 11 (1) (1999) 36–40.

[31] V. Saraswathy, N.S. Rengaswamy, Adhesion of an acrylic paint coating to a concrete substrate — some observations, J. Adhes. Sci. Technol. 12 (7) (1998) 681–694.

[32] R.N. Swamy, A.K. Suryavanshi, S. Tanikawa, Protective ability of an acrylic-based surface coating system against chloride and carbonation penetration into concrete, ACI Mater. J. 95 (2) (1998) 101–112.

[33] M. Ibrahim, A.S. Al-Gahtani, M. Maslehuddin, A.A. Almusallam, Effectiveness of concrete surface treatment materials in reducing chloride-induced reinforcement corrosion, Constr. Build. Mater. 11 (7–8) (1997) 443–451.

[34] J. Batchelor, Waterproofing concrete with sprayed acrylics, Concrete (London) 31 (3) (1997) 18–20.

[35] P. Soroushian, A. Tlili, M. Yohena, B.L. Tilsen, Durability characteristics of polymer-modified glass fiber reinforced concrete, ACI Mater. J. 90 (1) (1993) 40–49.

[36] W. Sun, J.A. Mandel, S. Said, Study of the interface strength in steel fiber-reinforced cement-based composites, J. Am. Concr. Inst. 83 (4) (1986) 597–605.

[37] J.M. West, R.C. De Vekey, A.J. Majumdar, Acrylic-polymer modified GRC, Composites 16 (1) (1985) 33–40.

[38] P.S. Mangat, M.C. Limbachiya, Repair material properties for effective structural application, Cem. Concr. Res. 27 (4) (1997) 601–617.

[39] P.R. Blankenhorn, M.R. Silsbee, B.D. Blankenhorn, M. DiCola, K. Kessler, Temperature and moisture effects on selected properties of wood fiber–cement composites, Cem. Concr. Res. 29 (5) (1999) 737–741.

[40] I. Padron, R.F. Zollo, Effect of synthetic fibers on volume stability and cracking of portland cement concrete and mortar, ACI Mater. J. 87 (4) (1990) 327–332.

[41] F. Accion, J. Gobantes, M.T. Blanco, Cements reinforced by acrylic fibers. Infrared studies: I. Hydration and hydrolysis processes in the fibers, Cem. Concr. Res. 20 (5) (1990) 702–710.

[42] T. Amat, M.T. Blanco, A. Palomo, Acrylic fibres as reinforcement for cement pastes, Cem. Concr. Compos. 16 (1) (1994) 31–37.

[43] S. Wen, D.D.L. Chung, Seebeck effect in carbon fiber-reinforced cement, Cem. Concr. Res. 29 (12) (1999) 1989–1993.

[44] S. Wen, D.D.L. Chung, Carbon fiber-reinforced cement as a thermistor, Cem. Concr. Res. 29 (6) (1999) 961–965.

[45] X. Fu, D.D.L. Chung, Effects of silica fume, latex, methylcellulose, and carbon fibers on the thermal conductivity and specific heat of cement paste, Cem. Concr. Res. 27 (12) (1997) 1799–1804.

[46] Z.-Q. Shi, D.D.L. Chung, Improving the abrasion resistance of mortar by adding latex and carbon fibers, Cem. Concr. Res. 27 (8) (1997) 1149–1153.

[47] P.-W. Chen, X. Fu, D.D.L. Chung, Microstructural and mechanical effects of latex, methylcellulose, and silica fume on carbon fiber reinforced cement, ACI Mater. J. 94 (2) (1997) 147–155.

[48] X. Fu, W. Lu, D.D.L. Chung, Improving the bond strength between carbon fiber and cement by fiber surface treatment and polymer addition to cement mix, Cem. Concr. Res. 26 (7) (1996) 1007–1012.

[49] P.-W. Chen, D.D.L. Chung, Comparative study of concretes reinforced with carbon, polyethylene, and steel fibers and their improvement by latex addition, ACI Mater. J. 93 (2) (1996) 129–133.

[50] K. Zayat, Z. Bayasi, Effect of latex on the mechanical properties of carbon fiber reinforced cement, ACI Mater. J. 93 (2) (1996) 178–181.

[51] P.-W. Chen, X. Fu, D.D.L. Chung, Improving the bonding between old and new concrete by adding carbon fibers to the new concrete, Cem. Concr. Res. 25 (3) (1995) 491–496.

[52] P. Soroushian, F. Aouadi, M. Nagi, Latex-modified carbon fiber reinforced mortar, ACI Mater. J. 88 (1) (1991) 11–18.

[53] B.K. Larson, L.T. Drzal, P. Sorousian, Carbon fibre–cement adhesion in carbon fibre reinforced cement composites, Composites 21 (3) (1990) 205–215.

[54] J. Hou, D.D.L. Chung, Effect of admixtures in concrete on the corrosion resistance of steel reinforced concrete, Corros. Sci. 42 (9) (2000) 1489–1507.

[55] X. Fu, D.D.L. Chung, Improving the bond strength of concrete to reinforcement by adding methylcellulose to concrete, ACI Mater. J. 95 (5) (1998) 601–608.

[56] Y. Xu, D.D.L. Chung, Effect of carbon fibers on the vibration-reduction ability of cement, Cem. Concr. Res. 29 (7) (1999) 1107–1109.

[57] D.D.L. Chung, Cement reinforced with short carbon fibers: a multifunctional material, Composites, Part B 31 (6–7) (2000) 511–526.

[58] X. Fu, D.D.L. Chung, Effects of water–cement ratio, curing age, silica fume, polymer admixtures, steel surface treatments, and corrosion on bond between concrete and steel reinforcing bars, ACI Mater. J. 95 (6) (1998) 725–734.

[59] X. Fu, W. Lu, D.D.L. Chung, Improving the bond strength between carbon fiber and cement by fiber surface treatment and polymer addition to cement mix, Cem. Concr. Res. 26 (7) (1996) 1007–1012.