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Corrosion Control of Steel-Reinforced Concrete

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The methods and materials for corrosion control of steel-reinforced concrete are reviewed. The methods are steel surface treatment, the use of admixtures in concrete, surface coating on concrete, and cathodic protection.

Keywords admixture, cathodic, cement, concrete, corrosion, steel

1. Introduction

Steel-reinforced concrete is widely used in construction. The corrosion of the steel reinforcing bars (rebars) in the concrete limits the life of concrete structures. It is one of the main causes for the deterioration of the civil infrastructure. Corrosion occurs in the steel regardless of the inherent capacity of concrete to protect the steel from corrosion; accelerated corrosion results from the loss of alkalinity in the concrete or the penetration of aggressive ions (such as chloride ions).

Methods of corrosion control of steel-reinforced concrete include cathodic protection,[1–12] surface treatments of the rebars (epoxy coating,[13–44] galvanizing,[21,32,45–51] copper cladding,[52] protective rust growth,[53] surface oxidation,[54] and sand blasting[54]), the use of admixtures (organic and inorganic corrosion inhibitors,[51,55–68] silica fume,[69–87] fly ash,[88,89,90] slag,[91] and latex [92–95]) in the concrete, and the use of a surface coating on the concrete.[96,97,98] This paper is a review of the methods and materials for corrosion control of steel-reinforced concrete.

2. Steel Surface Treatment

Steel rebars are mostly made of mild steel because of the importance of low cost. (Stainless steel is excellent in corrosion resistance,[99] but its high cost makes it impractical for use in concrete.) The coating of a steel rebar with epoxy (which acts as a barrier) is commonly used to improve the corrosion resistance of the rebar, but it degrades the bond between rebar and concrete, and the tendency of the epoxy coating to debond is a problem.[13–44] Furthermore, areas of the rebar where the epoxy coating is damaged and the cut ends of the rebar are not protected from corrosion. Galvanized steel attains corrosion protection by its zinc coating, which acts as a sacrificial anode. Galvanized steel tends to bond to concrete better than epoxy coated steel,[48] and the tendency of the coating to debond is also less for galvanized steel. Areas of the rebar where the zinc coating is damaged are still protected; the exposed areas, such as the cut ends, are protected, provided that they are less than 8 mm from the zinc coating.[49] Steel surface treatments that improve both corrosion resistance and bond strength are attractive. They include sand blasting and surface oxidation.[54]

Sand blasting involves the blasting of ceramic particles (typically alumina particles of a size around 250 μm) under pressure (typically around 80 psi or 0.6 MPa). It results in roughening and cleaning of the surface of the steel rebar. The cleaning relates to the removal of rust and other contaminants on the rebar surface, as rust and other contaminants typically cover a steel rebar here and there. The cleaning causes the surface of the rebar to be more uniform in composition, thus improving the corrosion resistance. The roughening enhances mechanical interlocking between rebar and concrete, thus increasing the bond strength.[54]

Water immersion means total immersion of the rebar in water at room temperature for 2 days. It causes the formation of a black oxide layer on the surface of the rebar, thus enhancing the composition uniformity of the surface and improving the corrosion resistance. In addition, the oxide layer enhances the adhesion between rebar and concrete, thereby increasing the bond strength. Water immersion times that are less than or greater than 2 days give less desirable effects on both bond strength and corrosion resistance.[54]

Steel rebars can also be coated with a corrosion-inhibiting cement slurry[51,55,100] or a cement-polymer composite[100] for the purpose of corrosion protection, as described in Section 3.

Of all the methods described above for treating the surface of the steel rebar, the most widely used methods are epoxy coating and galvanizing because of their relatively long history of usage.

3. Admixtures in Concrete

Admixtures are solids or liquids that are added to a concrete mix to improve the properties of the resulting concrete. Admixtures that enhance the corrosion resistance of steel-reinforced concrete include those that are primarily for corrosion inhibition and those that are primarily for improving the structural properties of concrete. The latter are attractive due to their multifunctionality. The former are mostly inorganic chemicals (such as calcium nitrite,[56,66–68,92] copper oxide,[59] zinc oxide,[59] sodium thiocyanate,[60] and alkaline earth silicate[63]) that increase the alkalinity of the concrete, although they can be organic chemicals, such as banana juice.[61] Admixtures that are used primarily for structural property improvement can be solid particles, such

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Table 1 Effect of carbon fibers (f), methylcellulose (M), silica fume (SF), and latex (L) on the corrosion resistance of steel rebar in concrete

	In saturated $Ca(OH)_2$ solution		In 0.5 N NaCl solution	
	E_{corr}(a) (−mV, ±5)	I_{corr}(a) (μA/cm^2, ±0.03)	E_{corr}(a) (−mV, ±5)	I_{corr}(a) (μA/cm^2, ±0.03)
P	210	0.74	510	1.50
+M	220	0.73	···	···
+M + f	220	0.68	560	2.50
+M + SF	137	0.17	···	···
+M + f + SF	170	0.22	350	1.15
+SF	140	0.19	270	0.88
+L	180	0.36	360	1.05
+L + f	190	0.44	405	1.28

Note: P = plain; (a) Value at 25 weeks of corrosion testing

as silica fume,[69–87] fly ash,[88,89,90] and slag,[91] and solid particle dispersions, such as latex.[92–95]

Silica fume (a fine particulate) as an admixture is particularly effective for improving the corrosion resistance of steel-reinforced concrete due to the decrease in the water absorptivity (or permeability), and, to a lesser extent, the increase in electrical resistivity.[69–87] Latex improves the corrosion resistance because it decreases the water absorptivity (or permeability) and increases the electrical resistivity.[92–95] Methylcellulose improves the corrosion resistance only slightly.[70] Carbon fibers (short, at a volume fraction below the percolation threshold) decrease the corrosion resistance due to a decrease in the electrical resistivity.[70] However, the negative effect of the carbon fibers can be compensated for by adding either silica fume or latex, reducing the water absorptivity.[70] In other words, the corrosion resistance of carbon-fiber-reinforced concrete, which typically contains silica fume for improving the fiber dispersion, is superior to that of plain concrete.[70]

Table 1[70] shows the effect of silica fume, latex, methylcellulose, and short carbon fibers as admixtures on the corrosion potential (E_{corr}, measured according to ASTM C876 using a high-impedance voltmeter and a saturated calomel electrode placed on the concrete surface; E_{corr} that is more negative than −270 mV suggests 90% probability of active corrosion) and the corrosion current density (I_{corr}, determined by measuring the polarization resistance at a low scan rate of 0.167 mV/s) of steel-reinforced concrete in both saturated $Ca(OH)_2$ and 0.5 N NaCl solutions. The saturated $Ca(OH)_2$ solution simulates the ordinary concrete environment; the NaCl solution represents a high chloride environment. Silica fume improves the corrosion resistance of rebars in concrete in both saturated $Ca(OH)_2$ and NaCl solutions more effectively than any of the other admixtures, although latex is effective. Methylcellulose improves slightly the corrosion resistance of rebar in concrete in $Ca(OH)_2$ solution. Carbon fibers decrease the corrosion resistance of rebars in concrete, mainly because they decrease the electrical resistivity of concrete. The negative effect of fibers can be compensated for by either silica fume or latex.

Instead of using a corrosion-inhibiting admixture in the entire volume of concrete, one may use the admixture to modify the cement slurry that is used as a coating on the steel rebar.[51,55] Compared to the use of rebars that have been either epoxy coated or galvanized, this method suffers from the labor-intensive site-oriented process involved.[100] The use of a shop coating based on a cement-polymer composite is an emerging alternative.[100]

Of all the admixtures described above for improving the corrosion resistance of steel-reinforced concrete, the ones most widely used are calcium nitrite, silica fume, and latex.

4. Surface Coatings on Concrete

Coatings (such as acrylic rubber) can be applied to the concrete surface for the purpose of corrosion control through improving the impermeability.[96,97,98] However, this method of corrosion control suffers from the poor durability of the coating and the loss of corrosion protection in the areas where the coating is damaged.

5. Cathodic Protection

Cathodic protection is an effective method for corrosion control of steel-reinforced concrete.[1–11] This method involves the application of an electrical current to force electrons to go to the steel rebar, thereby making the steel a cathode. Because the current needs to be applied constantly, the electrical energy consumption is substantial. This problem can be alleviated by the use of carbon fiber (short) reinforced concrete, as described below.

Because the steel rebar is embedded in concrete, the electrons need to go through the concrete in order to reach the rebar. However, concrete is not very electrically conductive. The use of carbon-fiber-reinforced concrete for embedding the rebar to be cathodically protected facilitates cathodic protection, as the short carbon fibers enhance the conductivity of the concrete.[5]

For directing electrons to the steel-reinforced concrete to be cathodically protected, an electrical contact is needed on the concrete. The electrical contact is electrically connected to the current supply. One of the choices for an electrical contact material is zinc, which is a coating deposited on the concrete by thermal spraying. It has a very low volume resistivity (thus requiring no metal mesh embedding), but it suffers from poor durability and corrosion resistance, the tendency to oxidize, a high thermal expansion coefficient, and high material and processing costs. Another choice is a conductor-filled polymer,[12] which can be applied as a coating without heating, but it suffers from poor wear resistance, a higher thermal expansion coefficient, and high material cost. Yet another choice is a metal (*e.g.*, titanium) strip or wire embedded at one end in cement mortar, which is in the form of a coating on the steel-reinforced concrete. The use of carbon-fiber-reinforced mortar for this coating facilitates cathodic protection, as it is advantageous to enhance the conductivity of this coating.[5]

Due to the decrease in volume electrical resistivity associated with carbon fiber addition (0.35 vol.%) to concrete (embedding steel rebar), concrete containing carbon fibers and silica fume reduces by 18% the driving voltage required for cathodic protection compared to plain concrete, and by 28% when compared to concrete with silica fume. Because of the decrease in resistivity associated with carbon fiber addition (1.1 vol.%) to mortar, overlay (embedding titanium wires for electrical contacts to steel reinforced concrete) in the form of mortar containing carbon fibers and latex reduces by 10% the driving voltage required for cathodic protection, compared to plain mortar overlay. In spite of the low resistivity of mortar overlay with carbon fibers, cathodic protection requires multiple metal electrical contacts embedded in the mortar at a spacing of 11 cm or less.[5]

6. Steel replacement

The replacement of steel rebars by fiber (continuous) reinforced polymer rebars is an emerging technology that is attractive because of the corrosion resistance of fiber-reinforced polymer.[101–106] However, this technology suffers from high cost and poor bonding between the concrete and the fiber-reinforced polymer rebar, in addition to the low ductility of the fiber-reinforced polymer.

7. Conclusion

Methods of corrosion control of steel-reinforced concrete include steel surface treatment, the use of admixtures in concrete, surface coating on concrete, and cathodic protection.

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References

1. B.S. Wyatt: *Corr. Sci.*, 1993, vol. 35 (5–8), part 2, pp. 1601-15.
2. S.C. Das: *Struct. Eng.*, 1993, vol. 71 (22), pp. 400-03.
3. J.S. Tinnea and R.P. Brown: *Materials for the New Millennium, Proc. 1996 4th Materials Engineering Conf.*, ASCE, New York, NY, 1996, vol. 2, pp. 1531-39.
4. I. Solomon, M.F. Bird, and B. Phang: *Corr. Sci.*, 1993, vol. 35 (5–8), part 2, pp. 1649-60.
5. J. Hou and D.D.L. Chung: *Cem. Concr. Res.*, 1997, vol. 27 (5), pp. 649-56.
6. R.J. Kessler, R.G. Powers, and I.R. Lasa: *Mater. Perform.*, 1998, vol. 37 (1), pp. 12-15.
7. R.J. Brousseau and G.B. Pye: *ACI Mater. J.*, 1997, vol. 94 (4), pp. 306-10.
8. F. Papworth and R. Ratcliffe: *Concr. Int.*, 1994, vol. 16 (10), pp. 39-44.
9. K.E.W. Coulson, T.J. Barlo, and D.P. Werner: *Oil Gas J.*, 1991, vol. 89 (41), pp. 80-84.
10. V. Dunlap: *Proc. Conf. Cathodic Protection of Reinforced Concrete Bridge Decks*, NACE, Houston, TX, 1986, pp. 131-36.
11. B. Heuze: *Mater. Perform.*, 1980, vol. 19 (5), pp. 24-33.
12. R. Pangrazzi, W.H. Hartt, and R. Kessler: *Corrosion*, 1994, vol. 50 (3), pp. 186-96.
13. R.E. Weyers, W. Pyc, and M.M. Sprinkel: *ACI Mater. J.*, 1998, vol. 95 (5), pp. 546-57.
14. S.W. Poon and I.F. Tasker: *Asia Eng.*, 1998, vol. 26 (8), p 17.
15. R.D. Lampton Jr. and D. Schemberger: *Materials for the New Millenium, Proc. 1996 4th Materials Engineering Conf.*, ASCE, New York, NY, vol. 2, pp. 1209-18.
16. J.L. Smith and Y.P. Virmani: *Public Roads*, 1996, vol. 60 (2), pp. 6-12.
17. B. Neffgen: *Eur. Coat. J.*, 1996, No. 10, pp. 700-03.
18. J. Shubrook: *Plant Eng.*, 1996, vol. 50 (10), pp. 99-100.
19. J.S. McHattie, I.L. Perez, and J.A. Kehr: *Cem. Concr. Composites*, 1996, vol. 18 (2), pp. 93-103.
20. J. Hartley: *Steel Times*, 1996, vol. 224 (1), pp. 23-24.
21. K. Thangavel, N.S. Rengaswamy, and K. Balakrishnan: *Ind. Concr. J.*, 1995, vol. 69 (5), pp. 289-93.
22. L.K. Aggarwal, K.K. Asthana, and R. Lakhani: *Ind. Concr. J.*, 1995, vol. 69 (5), pp. 269-73.
23. H.O. Hasan, J.A. Ramirez, and D.B. Cleary: *Better Roads*, 1995, vol. 65 (5), 2 pp.
24. K. Kahhaleh, J. Jirsa, R. Carrasquillo, and H. Wheat: *Infrastructure: New Materials and Methods of Repair, Proc. 3rd Materials Engineering Conf.*, K.D. Basham, ed., ASCE, New York, NY, 1994, No. 804, pp. 8-15.
25. R.G. Mathey and J.R. Clifton: *Proc. Structures Congr. 94*, ASCE, New York, NY, 1994, pp. 109-15.
26. P. Schiessl and C. Reuter: *Beton Stahlbetonbau*, 1992, vol. 87 (7), pp. 171-76.
27. R. Korman: *ENR (Engineering News-Record)*, 1992, vol. 228 (19), p 9.
28. K.C. Clear: *Concr. Int.: Des. Constr.*, 1992, vol. 14 (5), pp. 58 and 60-62.
29. T.E. Cousins, D.W. Johnston, and P. Zia: *ACI Mater. J.*, 1990, vol. 87 (4), pp. 309-18.
30. K.W.J. Treadaway and H. Davies: *Struct. Eng.*, 1989, vol. 67 (6), pp. 99-108.
31. R.A. Treece and J.O. Jirsa: *ACI Mater. J.*, 1989, vol. 86 (2), pp. 167-74.
32. S. Muthukrishnan and S. Guruviah: *Trans. SAEST*, 1988, vol. 23 (2–3), pp. 183-88.
33. T.D. Lin, R.I. Zwiers, S.T. Shirley, and R.G. Burg: *ACI Mater. J.*, 1988, vol. 85 (6), pp. 544-50.
34. H.A. El-Sayed, F.H. Mosalamy, A.F. Galal, and B.A. Sabrah: *Corr. Prev. Control*, 1988, vol. 35 (4), pp. 87-92.
35. D.P. Gustafson: *Civil Eng. (New York)*, 1988, vol. 58 (10), pp. 38-41.
36. L. Salparanta: *Valt Tek Tutkimuskeskus Tutkimuksia*, 1988, vol. 521, 48 pp.
37. R.J. Higgins: *Concr. Plant Prod.*, 1987, vol. 5 (6), pp. 197-98.
38. R.J. Higgins: *Concr. Plant Prod.*, 1987, vol. 5 (4), pp. 131-32.
39. H.A. El-Sayed, M.M. Kamal, S.N. El-Ebiary, and H. Shahin: *Corr. Prev. Control*, 1987, vol. 34 (1), pp. 18-23.
40. B.W. McLean and A.J.R. Bridges: *U.K. Corrosion '85*, Corrosion and Preparation, Corrosion Monitoring, Materials Selection, Institute of Corrosion Science and Technology, Birmingham, England, vol. 2, 1985, pp. 11-17.
41. S.L. Lopata: *ASTM Special Technical Publication 841*, ASTM, Philadelphia, PA, pp. 5-9.
42. T. Arai, K. Shirakawa, N. Mikami, S. Koyama, and A. Yamazaki: *Sumitomo Met.*, 1984, vol. 36 (3), pp. 53-71.
43. J. Clifton: *CIB 83, 9th CIB Congr., News Review*, National Swedish Institute for Building Research, Gavle, Sweden, 1983, pp. 68-69.

44. K. Kobayashi and K. Takewaka: *Int. J. Cem. Composites Lightweight Concr.*, 1984, vol. 6 (2), pp. 99-116.
45. V.R. Subramanian: *Ind. Concr. J.*, 1996, vol. 70 (7), pp. 383-85.
46. S.R. Yeomans: *Hong Kong Inst. Eng. Trans.*, 1995, vol. 2 (2), pp. 17-28.
47. N. Gowripalan and H.M. Mohamed: *Cem. Concr. Res.*, 1998, vol. 28 (8), pp. 1119-31.
48. O.A. Kayyali and S.R. Yeomans: *Constr. Building Mater.*, 1995, vol. 9 (4), pp. 219-26.
49. S.R. Yeomans: *Corrosion*, 1994, vol. 50 (1), pp. 72-81.
50. F.H. Rasheeduzzafar, F.H. Dakhil, M.A. Bader, and M.M. Khan: *ACI Mater. J.*, 1992, vol. 89 (5), pp. 439-48.
51. N.S. Rengaswamy, S. Srinivasan, and T.M. Balasubramanian: *Trans. SAEST*, 1988, vol. 23 (2–3), pp. 163-73.
52. D.B. McDonald, Y.P. Virmani, and D.F. Pfeifer: *Concr. Int.*, 1996, vol. 18 (11), pp. 39-43.
53. H. Kishikawa, H. Miyuki, S. Hara, M. Kamiya, and M. Yamashita: *Sumitomo Search*, 1998, No. 60, pp. 20-26.
54. J. Hou, X. Fu, and D.D.L. Chung: *Cem. Concr. Res.*, 1997, vol. 27 (5), pp. 679-84.
55. N.S. Rengaswamy, R. Vedalakshmi, and K. Balakrishnan: *Corr. Prev. Control*, 1995, vol. 42 (6), pp. 145-50.
56. J.M. Gaidis and A.M. Rosenberg: *Cem., Concr. Aggr.*, 1987, vol. 9 (1), pp. 30-33.
57. N.S. Berke: *Concr. Int.: Des. Constr.*, 1991, vol. 13 (7), pp. 24-27.
58. C.K. Nmai, S.A. Farrington, and G.S. Bobrowski: *Concr. Int.: Des. Constr.*, 1992, vol. 14 (4), pp. 45-51.
59. N.S. Rengaswamy, V. Saraswathy, and K. Balakrishnan: *J. Ferrocement*, 1992, vol. 22 (4), pp. 359-71.
60. C.K. Nmai, M.A. Bury, and H. Farzam: *Concr. Int.: Des. Constr.*, 1994, vol. 16 (4), pp. 22-25.
61. S.H. Tantawi: *J. Mater. Sci. Technol.*, 1996, vol. 12 (2), pp. 95-99.
62. R.J. Scancella: *Materials for the New Millennium, Proc. 1996 4th Materials Engineering Conf.*, ASCE, New York, NY, 1996, vol. 2, pp. 1276-80.
63. J.R. Miller and D.J. Fielding: *Concr. Int.*, 1997, vol. 19 (4), pp. 29-34.
64. I.Z. Selim: *J. Mater. Sci. Technol.*, 1998, vol. 14 (4), pp. 339-43.
65. D. Bjegovic and B. Miksic: *Mater. Perform.*, 1999, vol. 38 (11), pp. 52-56.
66. M. Tullmin, L. Mammoliti, R. Sohdi, C.M. Hansson, and B.B. Hope: *Cem., Concr. Aggr.*, 1995, vol. 17 (2), pp. 134-44.
67. C.M. Hansson, L. Mammoliti, and B.B. Hope: *Cem. Concr. Res.*, 1998, vol. 28 (12), pp. 1775-81.
68. N.S. Berke, M.P. Dallaire, R.E. Weyers, M. Henry, J.E. Peterson, and B. Prowell: *Symp. Corrosion Forms and Control for Infrastructure*, ASTM Special Technical Publication 1137, ASTM, Philadelphia, PA, 1991, pp. 300-27.
69. N.S. Berke: *Transp. Res. Rec.*, No. 1204, 1988, pp. 21-26.
70. J. Hou and D.D.L. Chung: *Corr. Sci.*, in press.
71. J.G. Cabrera and P.A. Claisse: *Constr. Building Mater.*, 1999, vol. 13 (7), pp. 405-14.
72. O.E. Gjorv: *ACI Mater. J.*, 1995, vol. 92 (6), pp. 591-98.
73. J.G. Cabrera, P.A. Claisse, and D.N. Hunt: *Constr. Building Mater.*, 1995, vol. 9 (2), pp. 105-13.
74. N.R. Jarrah, O.S.B. Al-Amoudi, M. Maslehuddin, O.A. Ashiru, and A.I. Al-Mana: *Constr. Building Mater.*, 1995, vol. 9 (2), pp. 97-103.
75. T. Lorentz and C. French: *ACI Mater. J.*, 1995, vol. 92 (2), pp. 181-90.
76. S.A. Khedr and A.F. Idriss: *J. Mater. Civil Eng.*, 1995, vol. 7 (2), pp. 102-07.
77. C. Ozyildirim: *ACI Mater. J.*, 1994, vol. 91 (2), pp. 197-202.
78. J.T. Wolsiefer Sr.: *Utilization of Industrial By-Products for Construction Materials, Proc. ASCE Nat. Conv. Expos.*, ASCE, New York, NY, 1993, pp. 15-29.
79. K. Torii, M. Kawamura, T. Asano, and M. Mihara: *Zairyo/J. Soc. Mater. Sci., Japan*, 1991, vol. 40 (456), pp. 1164-70.
80. H.T. Cao and V. Sirivivantnanon: *Cem. Concr. Res.*, 1991, vol. 21 (2–3), pp. 316-24.
81. Anon.: *Concr. Constr.*, 1988, vol. 33 (2).
82. K.P. Fischer, O. Bryhn, and P. Aagaard: *Publikasjon–Norges Geotekniske Institutt*, 1986, No. 161.
83. O. Gautefall and O. Vennesland: *Nordic Concr. Res.*, 1983, No. 2, pp. 17-28.
84. P.J.M. Monteiro, O.E. Gjorv, and P.K. Mehta: *Cem. Concr. Res.*, 1985, vol. 15 (5), pp. 781-84.
85. O. Vennesland and O.E. Gjorv: *Fly Ash, Silica Fume, Slag & Other Mineral By-Products in Concrete*, Publication SP-American Concrete Institute 79, American Concrete Institute, Detroit, MI, vol. 2, pp. 719-29.
86. A.H. Ali: *Corr. Prev. Control*, 1999, vol. 46 (3), pp. 76-81.
87. A.H. Ali, B. El-Sabbagh, and H.M. Hassan: *Corr. Prev. Control*, 1998, vol. 45 (6), 173-80.
88. M. Maslehuddin, H. Saricimen, and A.I. Al-Mana: *ACI Mater. J.*, 1987, vol. 84 (1), pp. 42-50.
89. M. Maslehuddin, A.I. Al-Mana, M. Shamim, and H. Saricimen: *ACI Mater. J.*, 1989, vol. 86 (1), pp. 58-62.
90. O.S.B. Al-Amoudi, M. Maslehuddin, and I.M. Asi: *Cem., Concr. Aggr.*, 1996, vol. 18 (2), pp. 71-77.
91. M. Maslehuddin, A.I. Al-Mana, H. Saricimen, and M. Shamim: *Cem., Concr. Aggr.*, 1990, vol. 12 (1), pp. 24-31.
92. K. Babaei and N.M. Hawkins: *Symp. Corrosion Forms and Control for Infrastructure*, ASTM Special Technical Publication No. 1137, ASTM, Philadelphia, PA, 1991, pp. 140-54.
93. N.S. Berke and A. Rosenberg: *Transp. Res. Rec.*, 1989, No. 1211, pp. 18-27.
94. S.H. Okba, A.S. El-Dieb, and M.M. Reda: *Cem. Concr. Res.*, 1997, vol. 27 (6), pp. 861-68.
95. S.X. Wang, W.W. Lin, S.A. Ceng, and J.Q. Zhang: *Cem. Concr. Res.*, 1998, vol. 28 (5), pp. 649-53.
96. F. Andrews-Phaedonos: *Transport Proc. 1998 19th ARRB Conf. of the Australian Road Research Board*, ARRB Transport Research Ltd., Vermont, Australia, 1998, pp. 245-62.
97. J.-Z. Zhang, I.M. McLoughlin, and N.R. Buenfeld: *Cem. Concr. Composites*, 1998, vol. 20 (4), pp. 253-61.
98. R.N. Swamy and S. Tanikawa: *Mater. Struct.*, 1993, vol. 26 (162), pp. 465-78.
99. B.G. Callaghan: *Corros. Sci.*, 1993, vol. 35 (5–8), part 2, pp. 1535-41.
100. K. Kumar, R. Vedalakshmi, S. Pitchumani, A. Madhavamayandi, and N.S. Rengaswamy: *Ind. Concr. J.*, 1996, vol. 70 (7), pp. 359-64.
101. K. Murphy, S. Zhang, and V.M. Karbhari: *Int. SAMPE Symp. Exhib.*, 1999, vol. 44 (II), pp. 2222-30.
102. H. Saadatmanesh and F. Tannous: *Proc. 1997 Int. Sem. Repair and Rehabilitation of Reinforced Concrete Structures: The State of the Art*, ASCE, Reston, VA, 1998, pp. 120-33.
103. S.S. Faza: *Materials for the New Millennium, Proc. 1996 4th Materials Engineering Conf.*, ASCE, New York, NY, vol. 2, 1996, pp. 905-13.
104. S. Loud: *SAMPE J.*, 1996, vol. 32 (1).
105. T.R. Gentry and M. Husain: *J. Composites Constr.*, 1999, vol. 3 (2), pp. 82-86.
106. H.C. Boyle and V.M. Karbhari: *Polymer-Plastics Technol. Eng.*, 1995, vol. 34 (5), pp. 697-720.