論文　The Role of Galvanized Steel Fibers in Corrosion-Protection of Reinforced Concrete

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ABSTRACT: Under an accelerated artificial aggressive conditions, the corrosion-protection behavior of zinc coating steel fibers in reinforced concrete specimens was studied. In general, the results showed that in the zinc coating steel fiber reinforced concrete matrix, although amount of diffused chloride ions were 10 times more than threshold limit to initiate corrosion, the embedded steel bars were not corroded. However, at the same conditions the steel bars which were not incorporated by zinc coating steel fibers in concrete matrix were seriously corroded. On the other hand, galvanized steel fibers had a sacrificial anode role to protect corrosion of reinforced concrete and also could tolerate a higher chloride concentration than no-fiber concrete matrix.
KEYWORDS: Acceleration test, chloride ions thresholds, deicers, galvanized steel fiber, half cell potential, saline solution, steel bar corrosion.

1. INTRODUCTION

Prior to the five decades, there was little use of chloride salts as deicers. As traffic on highways increased and the public became less tolerant of delays due to ice or snowstorms, chloride deicers became the rule rather the exception. Damage caused by chlorides on bridge decks, parking decks, and other structural components was not widely recognized until the early 1960. Deterioration of infrastructures as a corrosion of reinforcements in the highways and bridge decks in the north of Japan due to using chloride salt as deicer is a common problem as like as other parts of world.

Numerous efforts have been made to develop measures for preventing corrosion in new structures, and rehabilitating already deteriorated structures to prevent further corrosion problems. Among the recommended measures are the use of epoxy coated reinforcing bars, the application of cathodic protection systems, the use of lower-permeability concrete, increased concrete cover thickness over the steel, and galvanized coating on the reinforcing steel. Of these measures, cathodic protection is one the most popular technique to prevent corrosion of steel in concrete structures, but a recently published report demonstrates that hydrogen embrittlement is a serious disadvantage of the cathodic protection [1]. However, of these measures the use of galvanized reinforcing steel has one of the more extensive performance records in concrete structures. Much of this service history has been developed in Bermuda, where galvanized steel has been used the early 1950's and has been prescribed for many years as a matter of policy [2]. Comparisons of chloride concentrations in concrete adjacent to steel with average thickness of zinc corrosion layer indicated that little or no corrosion had occurred, even in concrete more than 23 years old. The good performance of galvanized reinforcing steel in concrete structures in rural, urban, and industrial locations [3], in marine exposure conditions [4], and subject to deicing salts [5] has been already published, and thus durability of zinc on protecting steel in the aggressive environments were made authors to apply this performance as a galvanized steel fibers not only to improve and increase durability of ordinary steel fibers but also to protect the corrosion of reinforcing bars as numerous sacrificial anode zones in aggressive environment due to in contact with the steel bars. The principal disadvantages of concrete are low tensile strength and brittleness. The steel fiber reinforced concrete is able to improve these tensile and brittle properties. General advantages of fibrous concrete such as; much greater resistance to cracking, improved fatigue characteristics, far superior resistance to thermal shock, isotropic properties, and others properties which can be obtained in concrete mix design incorporates with suitable steel fibers amount. All of these improvement

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Table 1: Mixture proportions of two groups of deck specimens

Type of specimen	Mixture proportions							
	Sand kg/m^3	Gravel kg/m^3	Cement kg/m^3	Water kg/m^3	W/C	Air entering agent L/m^3	Steel fiber kg/m^3	Initial Salt kg/m^3
No-fiber; **PC14**	850	1,070	280	154	0.55	0.22	0	3
Galvanized steel fibers; **SF14**	832	1,047	280	154	0.55	0.22	120	3

properties are effective to inhibit initiation and propagation of corrosion phenomenon. This study was initiated to test the capability of zinc coating; galvanized steel fiber in corrosive conditions and its efficiency on corrosion protection of reinforced concrete.

2. LABORATORY INVESTIGATIONS

To investigate corrosion protection possibility of galvanized steel fibers for decks of reinforced concrete bridges due to deicers, two test series using deck specimens were carried out in laboratory. Each group had two galvanized steel fiber-reinforced beams and two reinforced beams without any fibers. All the beams were 40 cm in length, 10 cm in width, and 10 cm in depth. Two No. 10 mm deformed bars with yield strength of 365 MPa and 35 cm length were separately placed in each beam which were connected to lead wires to measure electric potential of bars at necessary times. The bars were spaced at centers and provided with 25 mm of clear cover from both sides and 16-18 mm cover over the bars. Mechanical properties of specimens in each group at 28 days, 2, and 5 months after exposing were measured by three ϕ10x20 cm specimens. The galvanized steel fibers were sheared sheet fibers of 0.5x0.5x30 mm in sizes, yield strength of 165 MPa and with 0.01-0.02 mm zinc coating which applied 1.5 percent by volume of fibers or 120 kg/m^3 of concrete. The role of the no-fiber specimens either reinforced beams or cylinders were as control specimens in order to evaluate galvanized steel fibers effects for reinforcing bars and concrete matrix in the aggressive environments.

Ordinary portland cement was used for all concrete. The aggregate consisted of river aggregate with a specific gravity of 2.75, and natural sand with a specific gravity of 2.67. All concrete had W/C ratio of 0.55 and cement content of 280 kg/m^3. To accelerate electrolytic corrosion, 3 kg/m^3 NaCl were added to concrete mixture during mixing, as shown in Table 1. All specimens were left inside the mold for 24 hours after casting and then stripped off the mold and were cured by water at 21±2 °C for 27 days before setting in an automatic wet-dry artificial aggressive environment apparatus. The exposure conditions was selected in accordance with ASTM B-117 [6] with necessary modifications to apply for reinforced concrete specimens. The wet-dry cycles consisted of 12 hours wet and 12 hours dry every operational day. The wet portion used a flowing aerated recirculation of 5% of sodium chloride aqueous solution which was showered over the top surface of each specimens. The solution had an average temperature of 35°C temperature and initial pH of 6.8. Flowing over concrete specimens was made to increase pH of solution up to 9.5-10.3 in the first week but daily changing of saline solution was caused to decrease of pH 7.9-8.7 in later weeks. Dry cycle consisted of 35°C temperature of air circulation which was blowing over specimens. Compressive specimens after 30 days of exposing in order to make an uniform conditions of saline intrusion to surfaces of specimens, were set on other sides. In the dry conditions the average of relative humidity was about 30-35 percent.

Half-cell potentials of embedded steel bars in the all groups were monitored periodically with respect to the Silver-Silver Chloride electrode and then converted to Copper-Copper Sulfate Electrode (CSE) according to ASTM C 876 [7]. A small piece of moist sponge was placed between the electrode and the surface of concrete to minimize chloride contamination of the electrode.

3. RESULTS AND DISCUSSION

Results of this research included the behavior of embedded steel bars in the no-fiber concrete and in the galvanized steel fiber concrete matrix which were comparatively discussed. Table 2 gives concrete strength and specific density at 28 days and at the time of tests initiation.

Table 2: Characteristics of fresh and hard concrete

Type of specimens	Mechanical and physical properties							
	Ultimate compressive strength MPa			Specific density kg/m^3			Slump cm	Air content %
	28 days	2 months exposure	5 months exposure	28 days	2 months exposure	5 months exposure		
No-fiber; **PC14**	27.3	36	37.7	2,355	2,348	2,335	6.5	6.6
Galvanized steel fibers; **SF14**	32.9	36.8	44.7	2,493	2,475	2,486	0.5	4

3.1 AMOUNT OF DIFFUSED CHLORIDE IONS

Crushed pieces of 28 days compressive specimens which had been cured in fresh water were selected for determination of the initial chloride amount. For this purpose, pieces from 0.0-20 mm and 20.1-50 mm of concrete cylinders were separated. These pieces were then pulverized and screened through a No. 100 sieve to obtain 20-gm. This process was separately done for each cylinder. However, in beams specimens after 60 days of exposure to the artificial aggressive conditions and the measuring of the electric potential of the steel bars, a 10 mm diameter carbide-tip drill was used to drill out at least 10-15 gm. of powder specimens at preselected 5 mm intervals from the exposed surfaces. A 5-gm. specimens was then weighed, digested in 9 cc of 50 ± 2 °C distilled water and blended for 30 min. The temperature of the mixture was kept constant up to the end of the blending. The mix was then filtered, and by applying an automatic apparatus, 0.2 cc of filtered solution was used for determination of chloride percent. The recent process for each filtered solution was done five times in order to avoid any error of measuring by apparatus. Then, the highest and the lowest outputs were deleted and the average of three data were used for calculation of the chloride percent. Results of amounts of the initial salt and diffused chloride ions per cubic meter of concrete in the cylinder and the beam specimens were shown in Figures 1, 2, 3 and 4. In the both groups of no-fiber and galvanized steel fiber-reinforced beams, the steel bars were in concrete with chloride concentrations well above the threshold level of 0.15 percent by weight of cement, recommended by ACI as maximum chloride ions content for corrosion protection [8]. The analysis of chloride in no-fiber and fibrous concrete confirmed that the fibers in general, and galvanized steel fibers in particular, absorb more chloride ions from concrete matrix in the corrosion process due to the formation of quasi-stable ferrous and/or ferric oxychlorides. Also it was shown that galvanized steel fibers could tolerate a higher chloride concentration than plain concrete.

In bridges under marine environments on both the underside of the deck and on piers and pilings, and on the top side of the bridge deck subject to de-icing salt application, the situation is very similar to problems associated with the splash zone of offshore marine structures. The "cycle" time of salt application to decks is much longer; corrosion can occur apparently quickly during the summer months when de-icing salt is not being applied, when rain and elevated temperature, with wetting and drying, provide the optimum environment for corrosion. The data on bridge decks-for example, regarding the amount of chloride necessary to initiate corrosion-are in good agreement with those for marine structures. Summarizing results from 473 bridge decks, found that chloride levels of about 0.4% by weight of cement would initiate corrosion [9].

3.2 HALF-CELL POTENTIALS

The electrode potentials of embedded steels in no-fiber and galvanized steel fiber concrete specimens were monitored at the first at 28 days after casting and then after 1, 2, 3 and 5 months of exposing according to ASTM [7] at 2 cm intervals. For all results as shown in Figures 5, 6, 7 and 8 the initial potential at 28 days after casting and curing in the fresh water became more negative with values in the range -900 to -1100 mV. During 27-day curing in water, half cell potentials indicate more negative values according to lack of oxygen in the specimens. At the end of one month of exposing, potentials moved in the positive direction which confirmed passivation of the bars. However, passing of time and penetration of additional chlorides up to surfaces of steel bars had been made easy current between steel bars and measured surfaces. And also, between of the first and the second month of exposing, variations of potential for galvanized steel fiber specimens were lower than no-fibers
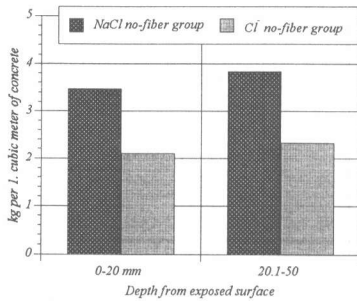
Fig. 1: Chloride salt and ions in no-fiber cylinder specimens after 28 days curing

Fig. 2: Chloride salt and ions in galvanized steel fibers cylinder specimens after 28 days curing

specimens. Revocation of potentials in the no-fiber specimens after 5 months exposing seems, the penetrated chlorides between the steel bars and applied surface for measuring potential had played an isolated layer. But the bars in the galvanized steel fibers matrix showed an uniform variation after each month of exposing. This uniform variation in the potentials of embedded steel bars in contact with the galvanized fiber is a main reason for showing anodic activity of connected fibers. And also it can be supposed, the connected fibers were as a body of steel bars and corrosion of them were made increasing in the measured potentials.

Finally, on the whole after 3 and 6 months of exposing, the reinforced concrete specimens were broken open, the embedded steel bars were examined visually for extent of coverage by corrosion products. In the no-fiber reinforced specimens, corrosion products had occurred in black & brown-colored, and pitting corrosion on the all bars. However, in the galvanized steel fiber specimens corrosion in any cases or any rust were not observed on any of the bars. Although, the chloride ions amount were more than no-fiber specimens. Galvanized steel fibers which in contact with the steel bars were corroded partially or were entirely sound. Corrosion phenomenon in groups of fibers were more than scatter fibers. On the exposed surfaces of the beams, in spite of severe corrosion of most galvanized steel fibers, corrosion products had been diffused of some distance from fibers to concrete matrix and consequently after scratching corrosion products and precision inspections there was not any crack around the fibers.

Fig. 3: Diffusion of chloride ions after 2 months exposure in reinforced specimens
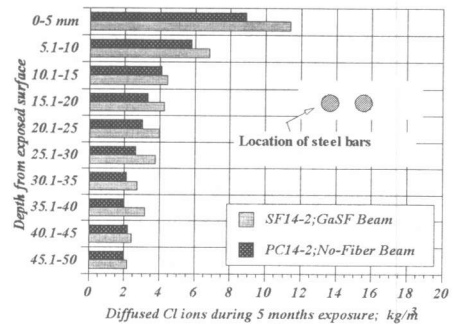
Fig. 4: Diffusion of chloride ions after 5 months exposure in reinforced specimens

Thickness of corrosion products of fibers on the exposed surfaces was about 0.1-0.15 mm, however, this products were superficial for the fibers inside of the beams even after 6 months. Corroded fibers with brown-colored or white-colored corrosion products were clearly observed by naked eyes over and beneath of the bars.

Reinforcement corrosion is mainly induced by ingress of chlorides of de-icing salts and the penetration of atmospheric carbon dioxide which promote local and general breakdown of the protective passive film on the steel surface. The mechanism of steel corrosion in concrete is essentially electrochemical in nature, i.e., the corrosion process ordinarily proceeds by forming electrochemical
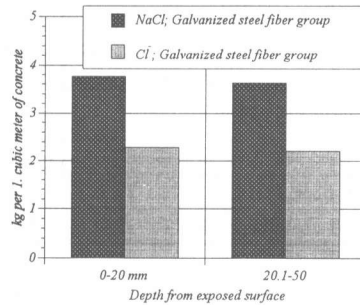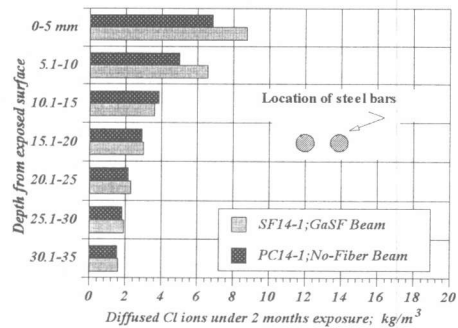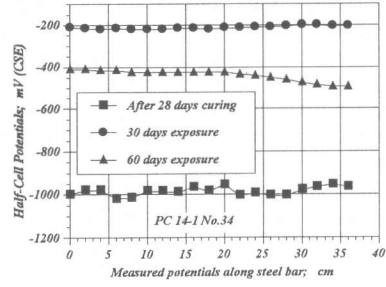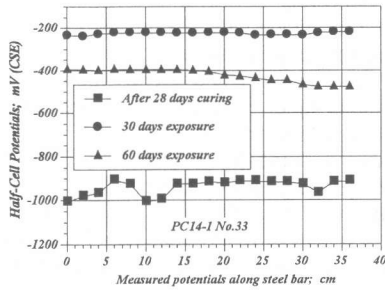
Fig. 5: Half-cell potentials of embedded steel bars in no-fiber concrete after 2 months exposure
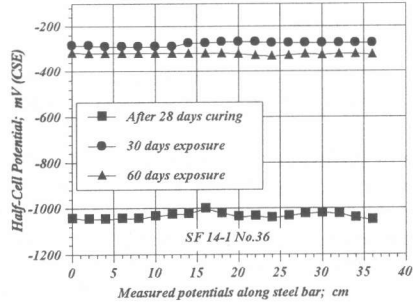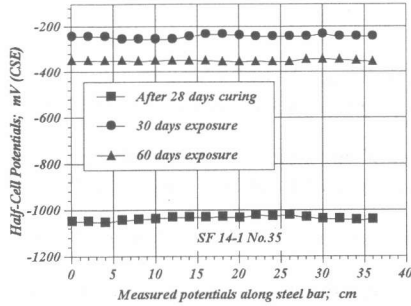

Fig. 6: Half-cell potentials of embedded steel bars in galvanized steel fiber concrete after 2 months exposure
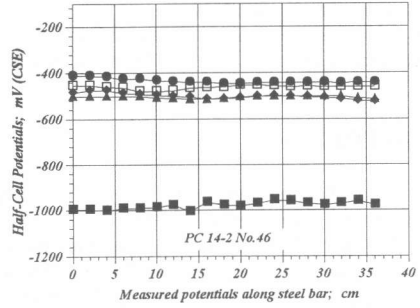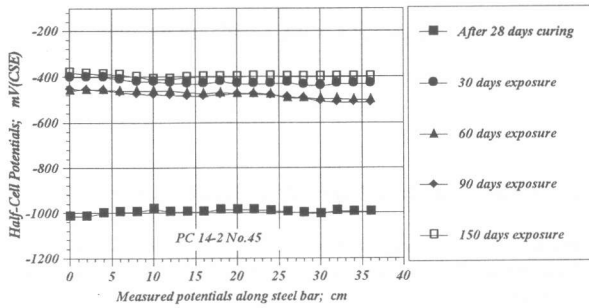

Fig. 7: Half-cell potentials of embedded steel bars in no-fiber concrete after 5 months exposure
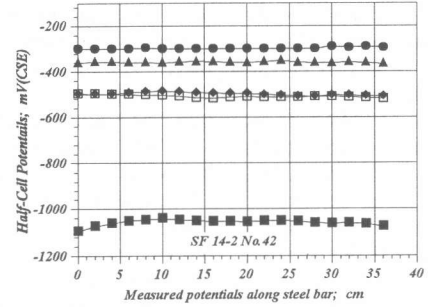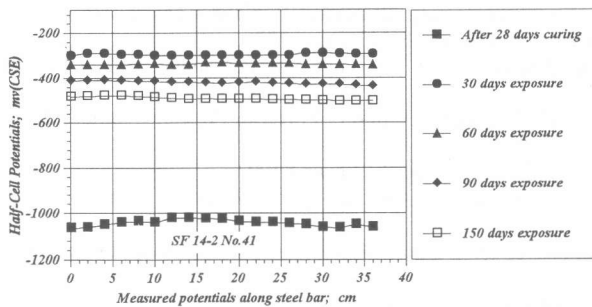

Fig. 8: Half-cell potentials of embedded steel bars in galvanized steel fiber concrete after 5 months exposure

cells with anodic and cathodic areas on the metal. In this respect a corroding steel surface may be regarded as a composite of anodes and cathodes electrically coupled through the body of the steel itself,

whereas the concrete pore solution serves as the electrolytic connection. However, present of galvanized steel fibers in connected to the steel bars provide many external anode sites. In this way, a galvanic "couple" will occur and corrosion of galvanized fibers will be accelerated and the corrosion of the steel bars will be reduced or stopped. Zinc corrosion products are less expansive and slightly more soluble in the concrete environment than rust, and therefore diffuse some distance from fibers/concrete interface. In this way the net volume increases and splitting pressure due to corrosion is reduced. One of the major advantages of steel fiber reinforced concrete in corrosion problem is that, the fibers, being non-continuous and discrete, provide no mechanism for the propagation of corrosion activity. This phenomenon has been clarified from the examination of numerous steel fiber reinforced concrete and steel fiber reinforced shotcrete structures subjected to aggressive exposure environments [10]. Besides, some studies have shown that galvanized steel could tolerate a higher chloride concentration than ungalvanized steel [11, 12].

4. CONCLUSIONS

Laboratory investigations to evaluate capability of galvanized steel fibers to inhibit corrosion phenomena in decks of bridges due to use of chloride salts as deicers, concluded following points:

1: In spite of diffusion of chloride ions more than 10 times of threshold limit to initiate corrosion, and during 6 months of acceleration test and aggressive exposing environments, embedded steel bars in galvanized steel fiber concrete matrix were not corroded.
2: Local corrosion with a pitting depth of 0.6 mm on the all steel bars of no-fiber concrete matrix were considerable after 3 and 6 months of exposing.
3: Most of corrosion phenomena in the galvanized fibers either inside or in connect with the steel bars were superficial. On the exposed surfaces and around the corroded galvanized fibers any crack were not observed, because of solubility of corrosion products and diffuse some distance from fibers/concrete interface.
4: Chloride salts absorption in the galvanized steel fiber specimens were 5-30% more than no-fiber specimens at the same conditions of exposing.

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