concrete, increased concrete cover over the steel, and galvanized coating on the reinforcing steel. 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 in Longbird Bridge since the early 1950's and has been prescribed for many years as a matter of policy (5). Comparisons of chloride concentrations in concrete adjacent to steel with average thickness of zinc corrosion layer indicate that little or no corrosion has occurred, even in concrete more than 23 years old. According to the results, 0.19 percent chloride by weight of concrete, and assuming available chloride levels are 75 percent of the total chloride content, chloride concentrations in the Longbird Bridge abutment were about 6 times as great as the threshold necessary to induce corrosion of untreated steel, but the average zinc corrosion layer thickness had reached only 0.005 mm, thus leaving at least 98 percent of the original coating unaffected and intact. Based on results of other surveys which were carried out by Stark (5) on Bermuda's structures, he concluded that, at locations where normal-quality concrete was sampled, averages of 92 to 100 percent of the original coating thickness were present after 7 to 23 years' exposure of concrete to sea-water. The good performance of galvanized reinforcing steel in concrete structures in rural, urban, and industrial locations (6), in marine exposure conditions (7), and subject to deicing salts (8) have been already published.

In spite of numerous good performance reports of galvanized steel bars durability, there are some opposite reports in the literature in which fourteen years of exposure tests conducted on galvanized bars showed severe corrosion similar to black steel bars (9). Also, in some cases the economics of galvanized bars are another problem because the cost of galvanized bars may be up to 50 percent or more of the cost of black steel bars (10).

Discussion of corrosion or no corrosion behavior of galvanized bars are not main purpose of this study, but both types of behavior could be occur in galvanized steel fibers when used to protect the steel bars in reinforced concrete. However, galvanized steel fibers have enough potential not only, to protect corrosion of reinforcing bars but also to absorb more chloride ions from the concrete matrix in the corrosion process due to the formation of quasi-stable ferrous and/or ferric oxychlorides. Some studies have shown that galvanized steel could tolerate a higher chloride concentration than steel (11, 12). Steel fibers in the fibrous reinforced concrete prevent microcracks from becoming working cracks, and thus protect the porous concrete from further aggressive environmental attack. Steel fibers rust only on the concrete surface. The amount of surface oxidation is very minimal, since the composite is about 99 percent concrete and insulates the individual discrete fibers with a passive skin of cement paste. The surface oxidation has no structural effect and the only cosmetic discoloration is an occasional surface freckle (13). One of the major advantages of steel fiber reinforced concrete in the corrosion problem is that the fibers, bein

non-continuous and discrete, provide no mechanism for the propagation of corrosion activity. This phenomenon has been clarified from the examination of numerous SFRC and steel fiber reinforced shotcrete structures subjected to aggressive exposure environments (14). In summary galvanized steel fibers are intended *to sacrifice* to protect corrosion of reinforced concrete.

# EXPERIMENTAL PROGRAM

# **Transparent Modified Ferroxyl Gel Specimens**

As stated above, in order to observe the corrosion phenomenon in the steel fibers and steel bars (15), and also the interaction between them, a transparent modified ferroxyl gel reagent was used. The ferroxyl reagent was a mixture of 1.5% agar, phenolphthalein alcoholic-aqueous solution, potassium ferrocyanide solution ( $K_3Fe(CN)_6$ ), 3% NaCl and 3% CaCl<sub>2</sub> dissolved in boiled distilled water. The main advantage of using this method was color discrimination of the anode and cathode zones from each other in any electrochemical reaction.

The ferroxyl reagent is a soft gel under 35°C temperature and this state is a stable state for many days. The compressive strength of ferroxyl gel is increases by addition of agar. However, the strain of gel by addition of the agar decreases. Modulus of elasticity of the gel up to 50% of ultimate compressive stress and corresponding strain was calculated and defined as  $E_{50}$ . The modulus of elasticity of gel,  $E_{50}$ , for 1.5% addition of agar was 0.648 kg/cm<sup>2</sup>. The modulus of elasticity is a function of agar content in solution and by addition of agar, the modulus of elasticity is increased. Conductivity coefficient, pH of ferroxyl reagent and stress-strain diagram of gel are shown in Figs. 2, 3, and 4.

Three series of tests were conducted to investigate the protective effects of steel fibers on steel bar corrosion. Specifications of steel fiber and steel bar are given in Tables 1 and 2. For ferroxyl gel specimens, straight low carbon steel fibers without any coating were used. The first series of tests had only 3 steel bars. The second series of tests had 3 steel bars with 5 gm. of steel fibers under each steel bar. The third series of tests had 3 steel bars with 5 gm. of steel fibers scattered around each steel bar. The steel bars and steel fibers were degreased by acetone before placing in the ferroxyl gel. At the beginning of each test, 3-5 mm ferroxyl solution was poured into a petri dish and solidified, and then the first layer of the steel fibers or the steel bars were set on the solidified gel. The steel bars were set over the steel fibers and then more steel fibers were set over the steel bars. Most of the steel fibers were contacting the steel bars. Finally 65°C ferroxyl reagent was poured over the specimens to a level of 10-15 mm above the surface of the specimens, and left to become a gel. After the ferroxyl solution had cooled and gelled, observations were made

of at 48, 72 and 120 hours.

# **Reinforced Concrete Specimens**

To find the capability of galvanic protection behavior of fibers on reinforced concrete, galvanized steel fibers were used and two series of experiments were carried out. The first series was  $\phi 10x20$  cm compressive specimens and 10x10x40 cm reinforced concrete beam specimens without any fiber addition. The second series was as same as the first series, but with galvanized steel fibers (GaSF). The first series was used as control specimens in order to compare effects of galvanized steel fibers on corrosion protection of reinforced concrete in aggressive environments. The amount of GaSF was 1.5 percent by volume of fibers or 120 kg/m<sup>3</sup>.

The experimental data were obtained using a moderate mixture with 20 mm gravel, sand to aggregate ratio of 45%, normal portland cement. To accelerate electrolytic corrosion, 3 kg/m<sup>3</sup> NaCl by weight of concrete was added to concrete mixture during mixing, (Table 3). The slump of the no-fiber mixture was 6.5 cm, however for the GaSF mixture it was 0.5 cm. Consequently, the air content of the GaSF mixture compared to no-fiber mixture decreased by 40 percent (Table 4). In the beam specimens, two profiled-prestain steel bars, \$10 mm and 35 cm in length, were embedded at 16-17 mm cover thickness. These were connected to lead wires to measure electric potential of bars at desired times. For the GaSF specimens, all fibers were space-oriented (randomly) around steel bars and within the matrix. Preparation of mixtures, casting, consolidation of specimens, measuring of air content, slump, and curing were done in accordance with JSCE-F503-1990, JSCE-F 551-1983, JSCE-F 552-1982, JIS A 1118-1995, and JIS A1132-1993 (16). All specimens were left inside the mold for 24 hours after casting and covered by a saturated burlap (approx. 80% relative humidity). After mold removal, they were water cured at  $21\pm2$  °C for 27 days before being put in an automatic wet-dry artificial aggressive environment apparatus. The exposure condition was selected in accordance with ASTM B-117 (17) with necessary modifications to apply to the 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 surface of each specimens. The solution had an average temperature of 35°C temperature and initial pH of 6.8. Flowing over the concrete specimens was done to increase the pH of the solution up to 9.5-10.3 in the first week but daily changing of the saline solution caused a decrease to pH 7.9-8.7 in later weeks. The dry cycle consisted of a 35°C air temperature which circulated over the specimens. In the dry conditions, the average relative humidity was about 30-35 percent.

Mechanical properties of the no-fiber and GaSF concrete were determined from  $\phi 10x20$  cm cylinders after 28 days and 60 days exposur

based on JSCE-G 551-1983, JIS<sup>\*</sup> A 1108-1993 (16). Before testing, the upper rough-surface of the specimens was capped by a hot-paste of sulfur-fly ash. Ultimate 28-day compressive strength,  $f_{c}$ , of the no-fiber specimens was 26.4 MPa. However, for the GaSF specimens, an average,  $f_{sp}$  of 31.6 MPa was obtained. After 1440 hours of exposure, both the no-fiber and GaSF specimens showed an increase in the ultimate compressive strength, (Table 3). Potentials of embedded steel bars in the both series were monitored periodically with respect to the Silver/Silver Chloride Electrode and then converted to the Copper/Copper Sulfate Electrode (CSE) according to ASTM C876-77 (18).

# **RESULTS AND DISCUSSION**

# **Ferroxyl Gel Environment**

The corrosion process of steel fibers in the ferroxyl gel matrix was observed by the naked eye. Corrosion in the anode zone of the steel fibers showed a blue-color, while the cathodic zone of the steel bars showed a pink-color. Thus, the ferroxyl gel allowed easy color discrimination between corrosion zones and cathodic zones on the steel fibers and steel bars. Results of the observations for each series of experiments were as follows:

(1) Steel bars without steel fibers -- The corrosion zones or anodic zones in the steel bars were at the ends of the steel bars (cut zones) or the ribs and lugs of the steel bars. Corrosion zones in the ferroxyl gel which showed a blue-color covered an area of about 1200 mm<sup>2</sup> at the ends of each bar and, on more than 95-100% of the ribs and lugs of the steel bars, anodic zones with an area of 4-25 mm<sup>2</sup> were observed (Fig. 5).

(2) Steel bars with one layer of steel fibers -- The corrosion zones at the ends of all three steel bars were decreased by 4 to 30 times and the biggest area was about 375 mm<sup>2</sup>. The steel fibers under the steel bars, which were almost in contact, formed a large anodic zone. There were considerable formations of anodic zones in the blocks of the steel fiber with an area 1200-1800 mm<sup>2</sup>. This phenomena also occurred in steel fibers which were not in contact with the steel bars with an area of 10 to 1600 mm<sup>2</sup> (Fig. 6).

(3) Steel bars surrounded by steel fibers -- In the third series of specimens, there was less corrosion zones at the ends of the steel bars than in the two previous series of specimens (about  $20 \text{ mm}^2$ ). More corrosion zones formed in the block of steel fibers under the steel bars than in the steel fibers on top of the steel bars. This was thought to be later cooling of the under layer of steel fibers compared to the over layer, which meant that the electrochemical activity of the under layer was higher than over

<sup>\*</sup> Japan Industrial Standard, Tokyo, Japan

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layers. Dispersion corrosion in single and scattered steel fibers also formed. Local corrosion zones on the ribs and lugs of steel bars was much less than that in the first series of samples (Fig. 7).

The results of the initial study showed that the steel fibers have more active sites for corrosion, such as sharp edges, pointed ends and more surface area, and usually have less noble potential compared to the steel bars. Thus, the steel fibers acted as sacrificial anode when they were in contact with the steel bars. Along with the potential of the steel fibers to inhibit corrosion of the steel bars and subsequent spalling of the concrete, but the fibers, by their nature, also retard crack growth. This is important for reducing further penetration of chloride ions into the concrete.

# **Reinforced Concrete Beams**

Results of this section of research included the behavior of embedded steel bars in no-fiber concrete and in the GaSF concrete matrix.

(1) Chloride Analysis -- 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 the chloride and NaCl weight in 1. m<sup>3</sup> of concrete are shown in Figs. 8, 9, and 10. In both the series of no-fiber and GaSF reinforced specimens, the steel bars were in concrete with chloride concentrations well above a threshold level of 0.025 percent by concrete weight. The analysis of chloride in the no-fiber and fibrous concretes confirmed that the fibers in the 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. It was also shown that the galvanized steel fibers could tolerate a higher chloride concentration than plain concrete.

(2) Potential analysis of embedded steel bars -- The electrode potential of embedded steel in no-fiber and GaSF concrete specimens was monitored first at 28 days after casting and then after 720 and 1440 hours of exposure according to ASTM C876-77(18) at 2 cm intervals. For all results, as shown in Figs. 11 and 12, the initial potential at 28 days after casting and curing in fresh water became more negative. While the basis of ASTM standard method is that the corrosion potential of the steel bar will shift in the negative direction if the surface changes from the passive to the active state. On the other hand, very negative rebar potential readings is when the corrosion is cathodically controlled. That means when the specimens had remained saturated in water for a long period of time, the oxygen availability became limited. Thus the non availability of oxygen can also produce corrosion potential values more negative than under aerated condition. Low oxygen concentrations lead to small corrosion rates although corrosion potentials are very negative. Consequently, the potentials of 28 days were with values in the range -870 to -1070 mV (CSE). Wet-dry cycles of specimens in the corrosion accelerated apparatus, the potential tended to move in the positive direction in spite of an ingress chloride in both series at the end of one month of exposure. In fact this condition was a passivation state for the rebars in both series. However, with the passing of time and penetration of additional chlorides up to surfaces of steel bars, the current flow between steel bars and the measured surfaces occurred more easily. At the end of 2 months of exposure, again the potential moved in the negative direction which for the no-fiber specimens was more negative than for the GaSF specimens. Also, between the first and the second month of exposure, variations of potential for GaSF specimens were lower than for the no-fibers specimens. The potentials of the rebars in the no-fiber specimens at the end of 2 months of exposure were with the values of -394 mV to -496 mV (CSE), which according to the ASTM C876-77 there was a greater than 90% probability that rebars corrosion occurred in that area at the time of measurement. For the GaSF specimens the potential of rebar No. 35 was -344 mV to -356 mV (CSE) with probability as same as the no-fiber specimens. However, the potential of rebar No. 36 was -319 mV to -324 mV (CSE), and corrosion activity of rebar in that area was uncertain. It is important to remark that half-cell potential data taken in this way can only be used to asses the probability for corrosion and not the rate of corrosion.

When two dissimilar metals (zinc-coated fibers and steel bar) in electrical contact with each other are exposed to an electrolyte, a current, which is called a galvanic current, flows from one to the other. Galvanic corrosion is that part of the corrosion which occurs to anodic member of such a couple, i.e., galvanized fibers, and is directly related to the galvanic current by Faraday's law (19). Under a galvanic corrosion condition, the simultaneous additional corrosion taking place on the steel fibers, the anode of the couple is called the local corrosion. The local corrosion may or may not equal the corrosion, called the normal corrosion, taking place when the fibers and steel bars are not electrically connected. The difference between the local corrosion and the normal corrosion is called

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the difference effect which may be positive if the local corrosion decreases when galvanic current flows, or negative. A galvanic current generally causes a reduction in the total rate of corrosion of cathodic member of the couple (steel bar). In this case the steel bar is cathodically protected. Consequently, simplified interpretation of such data for GaSF specimens in accordance with ASTM C876-77 may be not valid. Because due to presence of galvanized fibers in contact with the bars and galvanic corrosion activity of them, potentials of steel bars which shielded by the surrounding galvanized fibers is different from the potentials of no-fiber specimens.

#### VISUAL OBSERVATIONS OF REINFORCED CONCRETE BEAMS

After the concrete specimens were broken open, the embedded steel bars samples were examined visually to determine the extent of coverage of corrosion products, nature of products, and relationship of measured potentials and corrosion or no corrosion occurring phenomenon. After 2160 hours of exposure under initial addition of chloride salt and the effects of severe artificial aggressive environment, the following observations were made for the no-fiber reinforced concrete specimen and galvanized steel fiber-steel reinforced specimens:

# Steel Bars Behavior in No-Fiber Reinforced Concrete Beam --

a: Total corrosion length along the bar No. 33 was about 31 mm.

b: Main corrosion length in an area of  $24x10 \text{ mm}^2$  was at the interval of 32.6-35 mm of bar No. 33. At this area, the corrosion products that occurred were black-colored and brown-colored. The area of the black-colored corrosion product was more than 70% of total area as shown in Fig. 13.

c: At a distance of 14-19 cm on bar No. 33, there were two points with an area of 7x3 mm<sup>2</sup> brown-colored corrosion products.

d: For bar No. 34, the total corrosion length was 37 mm of which the biggest one had an area of  $15x6 \text{ mm}^2$  at the interval of 33.5-35 cm. Corrosion products were black-colored and brown-colored with more than 85% of corroded area having a black-colored corrosion product.

e: There were a superficial corrosion in an area of 22x4 mm<sup>2</sup> and one point corrosion zone in other parts of bar No. 34.

f: The depth of cover for bar Nos. 33 and 34 was 16 mm.

### Steel Bars Behavior in GaSF Reinforced Concrete Beam ---

a: The depth of cover for bar Nos. 35 and 36 were 17 and 16 mm, respectively.

b: Corrosion or rust was not observed for bar Nos. 35 and 36.

c: GaSF which was in contact with the steel bars corroded partially or entirely. Brown-colored and white-colored corrosion products were clearly observable.

d: Corrosion phenomenon in groups of the GaSF was more than in

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scattered fibers.

e: In spite of severe corrosion of the GaSF and expanding of the corrosion products on the exposed surfaces of beam, there was not any observed cracking around the fibers.

f: The thickness of the corrosion products of GaSF on the exposed surfaces was about 0.1-0.15 mm, however, this amount was superficial for the fibers inside of beam.

g: Corrosion of the GaSF were clearly seen over and beneath of steel bars by the naked eves.

h: At depths of 28 even 30 mm from the exposed surface and below the steel bars, corrosion of the GaFS occurred. The corroded fibers all had superficial corrosion products as rust, which indicated an electrochemical reaction of GaSF within the chloride concentrated matrix.

#### HYDROGEN EVOLUTION PROBLEM

According to Pourbaix (20), zinc " ... is thermodynamically unstable in the presence of water ..., and tends to dissolve with the evolution of hydrogen in ... very alkaline solutions". Further, according to Pourbaix, the corrosion rate of zinc is a minimum at a pH valve of 10.0; it amounts to about 0.18 gm./cm<sup>2</sup> per day. Above a pH of 10.0, corrosion rates of zinc increase drastically. For example, at a pH of 12, the corrosion rate for free and uninhibited continuous corrosion is about  $0.45 \text{gm}/\text{cm}^2$  per day. Investigations were carried out by Woods (21) suggests that " The products of reaction are not voluminous and, consequently, damaging stresses are not created". A recent report of RILEM (22) stated " .... depending on chromate content of cement, hydrogen evolution may occur in fresh concrete, but this process stops after hardening of concrete". To survey amount of chromate and other elements such as Na, Ca, O, Si, C, Cl, Fe, Al, Mg, and Zn in different samples, X-ray microscanning analysis were carried out. The results of analysis according to situations of the samples are as follows:

a: Sample of Corroded GaSF from fibrous specimens, Table 5.

b: Sample of concrete in contact with the steel fiber from fibrous specimens, Table 6.

c: Sample of concrete between steel bar and exposed surface from fibrous specimens, Table 7.

d: Sample of concrete between steel bar and exposed surface from no-fiber specimens, Table 8.

e: Sample of concrete in contact with the steel bar from no-fiber specimens, Table 9.

f: Sample of concrete from inside of no-fiber specimens, Table 10. Due to unevenness of samples surfaces and to decrease the standard deviation, the analysis of each sample was carried out at least four times.

According to the results of X-ray analysis of present elements, specific density, ultimate compressive strength and no-crack phenomenon

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of GaSF specimens which were better than no-fibers specimens, evolution of hydrogen and its possible abnormal effects were not found.

# CONCLUSIONS

Galvanized steel fibrous concrete, either in contact with or placed near steel bars considerably decreases the formation and propagation of corrosion zones in the steel bars. Steel fibers in contact with steel bars act in a sacrificial anode role for protecting the steel bars. However, corrosion phenomenon in the steel fibers which were not in contact to the steel bars tended to reduce the free chloride ions in the matrix. Corrosion phenomenon in the steel fibers, which are non-continuous and discrete in the concrete matrix, provide no mechanism for the propagation of any corrosion activity and spalling of concrete or de-bonding of concrete from steel bars. One measure for preventing corrosion is to minimize the penetration of chloride ions to steel bars in the concrete and this was accomplished by using galvanized steel fibers.

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