



## Corrosion risk of steel fibre in concrete



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### HIGHLIGHTS

- The corrosion risk of steel fibre in mortar is lowered by millscale on the surface.
- Chloride transport was increased by porosity at the interface of steel fibre.
- Pores were formed in the vicinity of steel fibre by trapping air bubbles in casting.

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### ABSTRACT

In the present study, the corrosion risk of steel fibre in concrete was assessed by measuring the corrosion rate of steel fibre in chloride-contaminated mortar. Simultaneously, the rate of chloride transport in steel fibre mortar was determined by chloride profiles. Then, the interface of the steel fibre was examined by the scanning electron microscopy to ensure the porosity in the vicinity. As a result, it was found that the corrosion resistance of steel fibre against chloride was slightly higher than for reinforcing steel rebar in concrete, presumably due to the presence of mill scale on the surface; the chloride threshold level ranged 0.8–1.0% by weight of cement. However, transport of chloride ions in concrete containing steel fibre was accelerated by increased porosities in the vicinity of steel fibre, implying that external aggressive ions may easily penetrate the concrete then to chemically degrade concrete properties. In fact, the diffusion coefficient of chloride in mortar containing steel fibre ranged  $4.79\text{--}9.61 \times 10^{-12} \text{ m}^2/\text{s}$ , as being 2–3 times higher for steel fibre-free mortar.

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### 1. Introduction

Due to increased capacity to both the compressive and tensile loading, steel fibre has been widely used to enhance concrete properties with no reinforcing steel reinforcement. However, the steel fibres placed in the vicinity of the cover concrete are always risky of corrosion, as corrosive environmental components (i.e. water and oxygen) are in directly contact with the steel fibre to corrode, leading to a reduction of concrete properties, depending on degree of fibre corrosion. Additionally, rust stain spread widely on the cover concrete arising from corrosion of steel fibre may be aesthetically irritated. Notwithstanding, the corrosion risk of steel fibre has been limitedly dealt with in qualitative ways, for example, by a destructive measurement of half-cell potential of the steel fibre [1] or/and by determining the occupation of rust stain on the surface of the cover concrete [2]. Despite corrosion of steel fibre, its impact on concrete properties has been thought marginal

[3,4], because the strength of concrete could be much already gained by steel fibre, of which increased tensile and compressive capacity may, therefore, compensate for a potential of concrete strength. However, the corrosion risk of steel fibre is not still clearly identified by quantitative assessment.

Concrete containing steel fibre may be subjected to chemical degradation, as the steel fibre in concrete may impose a dramatic increase in the content of air void or/and porosity. Air bubbles generated in the process of casting fresh concrete may be unexpectedly arrested underneath the steel fibre even after the vibration and compaction; in fact, only 0.5–1.0% point of air void and bubbles in volume can be removed by vibration [5]. The open pore structure of steel fibre concrete could be, therefore, more feasible for aggressive external ions to penetrate concrete then to deteriorate the cover concrete. Moreover, increased porosity in the vicinity of steel fibre may lower bond strength between steel fibre and concrete, and thus the steel fibre may separately behave from concrete body against external loadings. The bond strength between steel fibre and concrete was currently measured by a modified method, accounting for 0.7–1.0 MPa [6], even lower than between steel reinforcing bar and concrete.

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In the present study, the risk of adverse effect of steel fibre in concrete was evaluated in terms of corrosion of steel fibre and ionic penetration. A microscopic examination at the interface of steel fibre was simultaneously made by the scanning electron microscopy to determine the mechanism of corrosion and ionic transport in steel fibre concrete. For the corrosion risk, the corrosion rate and potential of steel fibre cast in a chloride-contaminated mortar were measured, while chloride transport in steel fibre mortar was determined, in terms of the apparent diffusion coefficient of chloride ions, by an exposure of the specimen to a salt solution for a given duration then to obtain chloride profile.

## 2. Experiments

### 2.1. Chloride transport in steel fibre concrete

Mortar was cast in a cylindrical mould ( $\varnothing 100 \times 200$  mm) with steel fibres at 2.0% in volume of mortar. For steel fibre, the specific gravity was 7.85 and its chemical composition is given in Table 1. Simultaneously the dimension of the steel fibre is  $\varnothing 0.39 \times 15.0$  mm. The mix proportion of mortar for ordinary Portland cement, water and sand (Grade M) was 1.00:0.40:2.65. The oxide composition of ordinary Portland cement used in this study is given in Table 2. The mortar specimen was demoulded 24 h after casting and then wrapped in a polythene film at  $20 \pm 2$  °C for 28 days to keep a curing condition.

To determine the rate of chloride transport in mortar containing steel fibre, two methods were used: (1) a direct exposure to salt solution to obtain chloride profile and (2) rapid chloride penetration under electric charge. For chloride profile, the steel fibre mortar was sliced off from the middle of the specimen to produce 50.0 mm of the thickness. A barrier coating of epoxy resin was applied to seal the cast surfaces except for one end, so that chloride transport could take place from the one direction only. The specimen was initially saturated in a tank containing water for 7 days and was then immersed in a 4.0 M sodium chloride solution at  $25 \pm 2$  °C for 100 days. The chloride profiles were obtained from samples collected by grinding the mortar surface with 2.0 mm depth increments. The chloride content of each sample was determined by acid soluble extraction in a nitric acid solution followed by potentiometric titration against silver nitrate. In calculating the chloride concentration, steel fibre was also ground and included in the sample. The apparent chloride diffusion coefficient was determined for each specimen by fitting the error function solution to the Fick's second law, for non-steady state diffusion in a semi-infinite medium, given by Eq. (1).

$$C(x, t) = C_s \left( 1 - \operatorname{erf} \frac{x}{2\sqrt{Dt}} \right) \quad (1)$$

where,  $C(x, t)$  is for chloride concentration at the depth  $x$  at time  $t$ ,  $C_s$  for surface chloride concentration and  $D$  for diffusion coefficient, respectively.

In rapid chloride penetration test, a 50.0 mm-thick mortar disc was again used. After being saturated with still water, the two ends of the specimen were connected to two chambers: one was filled with 3% sodium chloride and the other with 0.3 M sodium hydroxide to form electrodes. An electric charge of 60 V was applied to the electrodes. The current flowing through the mortar specimen was measured every 30 min for 6 h. Then, the total charge passed through the mortar cell was calculated to determine the penetrability. The test procedure and guided values for the penetrability are given elsewhere [7].

### 2.2. Corrosion resistance of steel fibre

Mortar was cast in a cylindrical mould ( $\varnothing 50 \times 150$  mm) with a centrally located steel fibre. One end of the steel fibre was electrically connected to an external source for measuring the polarisation resistance to corrosion. To accelerate the corrosion process, chlorides were admixed in mixing water, ranging from 0.0% to 5.0% by weight of cement. After casting and curing the mortar specimen by an equated method for measuring chloride transport, the specimen was immersed in 0.5 M NaCl solution with the top of specimen open to atmosphere for a supply of oxygen for 24 h before measuring the corrosion rate to enhance the electric conductivity in polarising the steel fibre to determine its corrosion rate, as seen in Fig. 1. The potential was swept +25 mV from the corrosion potential at a low scan rate of 0.1 mV/sec. The corrosion rate was calculated by the Ohm's law as given in Eq. (2). The polarisation resistance was determined by the curve of potential vs current density,

**Table 1**  
Composition of steel fibre (%).

Fe	C	Si	Mn	P	S
98.601	0.112	0.225	1.021	0.021	0.020

**Table 2**  
Oxide composition of ordinary Portland cement (%).

CaO	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	Na <sub>2</sub> O	K <sub>2</sub> O	SO <sub>3</sub>	LOI*
64.7	20.7	4.6	3.0	1.0	0.13	0.65	3.0	0.54

\* LOI: ignition loss for cement.

whilst the potential for corrosion was set as 26 mV for active corrosion. The electrical resistance of mortar (i.e. IR drop) was automatically compensated by using the interruption technique.

$$I_{corr} = \frac{B}{R_p} \quad (2)$$

where,  $I_{corr}$  is for the corrosion rate,  $B$  for corrosion potential and  $R_p$  for the polarisation resistance, respectively. Simultaneously, half-cell potential of the steel fibre in mortar was measured using a copper–copper sulfate electrode to ensure the corrosiveness of steel fibre.

### 2.3. Microscopic observation

To observe the interfacial condition in the vicinity of steel fibre in mortar, mortar was cast with one steel fibre, as mostly identical to the specimen for corrosion measurement, except for an electric connection. After 28 days of curing, a segment containing the steel fibre was obtained by cutting perpendicular to the direction of the steel fibre, using a diamond saw. The specimen was dried in an oven at  $50 \pm 1$  °C for 48 h before resin impregnation. The impregnated specimen was then ground with silicon carbide papers of successively finer grits and was further polished on cloths with diamond particles. After polishing, the specimen was cleaned ultrasonically in acetone and then further dried for 24 h in a vacuum pump at an order  $10^{-4}$  Pa, followed by carbon coating under about  $7 \times 10^{-5}$  Pa.

The image containing the steel fibre was obtained at scanning electron microscopy (SEM) and the instrumental parameters used for the SEM were: accelerating voltage = 20 kV; working distance = 15 mm; beam spot size (SS) = 12; lens current = 66  $\mu$ A. The magnification was basically  $\times 50$ . The SEM image obtained was transferred to the backscattered electron one to clearly identify pores at the interface of the steel fibre.

## 3. Results

### 3.1. Rate of ionic transport

The chloride profile of mortar is given in Fig. 2, after 100 days of exposure to 4.0 M NaCl solution. It is evident that chloride ingresses for mortars containing steel fibre at each depth were more or less higher than for steel fibre-free specimens. In fact, the apparent diffusion coefficient of chloride ions for steel fibre mortar ranged from  $4.79 \times 10^{-12}$  to  $9.61 \times 10^{-12}$  m<sup>2</sup>/s, while steel fibre-free mortar produced  $3.56 \times 10^{-12}$  m<sup>2</sup>/s of the diffusion coefficient. The higher ingresses of chloride in mortar containing steel fibre may arise from increased porosity. As non-hydraulic materials are present in the concrete matrix, the interface between cement paste and those materials, for example, aggregate–paste interface [8] and paste–steel interface [9] may be often occupied by pores, which are usually generated in the process of mixing fresh concrete and subsequently formed underneath them. Thus, these pores may provide further paths for ions to be mobile, thus to accelerate ionic transport. However, there was only a marginal difference arising from the presence of steel fibre in the concentration of surface chloride, of which the range was 2.31–2.42% by weight of cement. This may be attributed to the fact that the surface chloride is influenced by rather concrete mix and exposure duration [10].

As a rapid examination of ionic transport, chloride penetrability under electric charge was measured, as given in Fig. 3. It is clearly seen that the charge passed through the mortar cell was strongly dependent on curing age and whether or not steel fibre was admixed. As expected, an increase in the curing age resulted in a decrease in the passed charge in terms of chloride penetrability, due to densified concrete pore structure with hydration degrees. For steel fibre-free specimens, for example, the passed charge

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