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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 mille 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  $4.79-9.61 \times 10^{-12}$  m<sup>2</sup>/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

\* Corresponding author. E-mail addresses: kann@hanyang.ac.kr, kyann@daum.net (K.Y. Ann). [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 chloridecontaminated 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 ( $\emptyset$ 100 × 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  $\emptyset$ 0.39 × 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 ± 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 ± 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).

$$C(x,t) = C_s \left( 1 - erf \frac{x}{2\sqrt{Dt}} \right)$$
(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 with0.3 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 ( $050 \times 150$  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,

| Ta | bl | e | 1 |
|----|----|---|---|
|----|----|---|---|

Composition of steel fibre (%).

| Fe     | С     | Si    | Mn    | Р     | 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> | $Al_2O_3$ | $Fe_2O_3$ | MgO | Na <sub>2</sub> O | K <sub>2</sub> O | $SO_3$ | LOI* |
|------|------------------|-----------|-----------|-----|-------------------|------------------|--------|------|
| 64.7 | 20.7             | 4.6       | 3.0       | 1.0 | 0.13              | 0.65             | 3.0    | 0.54 |
| *    |                  | c         |           |     |                   |                  |        |      |

<sup>\*</sup> 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.

$$I_{corr} = \frac{B}{B_{P}}$$

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 ± 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  $9.61\times 10^{-12}\,m^2/s,$  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

(2)



Fig. 1. Schematic for measuring the corrosion rate and potential of steel fibre in mortar.



Fig. 2. Chloride ingresses of mortar containing steel fibre exposed to a 4 M NaCl solution for 100 days together with diffusion coefficient and surface chloride concentration.

was reduced from 1553 coulombs at 7 days to 854 coulombs at 91 days. It seems that the presence of steel fibre in concrete was, in fact, very crucial in determining the chloride penetrability. The charge passed for mortar containing steel fibre was in the range of 3125–5523 coulombs at all curing ages, being about 4 times higher than for steel fibre-free specimens. The increased chloride penetrability in steel fibre mortar may be again attributed to pores formed in the vicinity of the steel fibres. Moreover, the electrically

high conductive steel fibre in mortar could further contributed to increased charge even after a long curing age.

## 3.2. Corrosion behaviour of steel fibre

The corrosiveness of steel fibre in mortar was evaluated by measuring the corrosion rate and half-cell potential at different levels of chlorides in cast ranging from 0.0% to 5.0% by weight of

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Fig. 3. Charge passed for mortars containing steel fibre with curing age.

cement, as seen in Fig. 4. It is evident that an increase in the concentration of chloride in mortar resulted in an increase in the corrosion rate. In chloride-free mortar, the corrosion rate was lower than 0.01 mA/m<sup>2</sup>, indicating the very passive state, while the corrosion rate at 5.0% of chlorides was equated to 410.83 mA/m<sup>2</sup>. In particular, at 1.0% of chlorides in cast, the onset of corrosion was observed, of which the corrosion rate accounted for 1.63 mA/m<sup>2</sup>, in that the corrosion rate often exceeds  $1-2 \text{ mA/m}^2$  at initiation of steel corrosion [11]. In turn, the critical chloride concentration for the onset of corrosion was determined to range 0.8–1.0% by interpolating the curve for chloride vs corrosion rate.

The half-cell potential was simultaneously measured at corresponding concentrations of chloride in cast. As a result, it was seen that an increase in the concentration of chloride in mortar resulted in a decrease in the half-cell potential, being indicative of the corrosive state. For example, at 0.0% of chloride, the half-cell potential was equated to -251.3 mV vs CSE, while -485.0 mV of half-cell potential was measured at 5.0% of chlorides. The critical chloride concentration for corrosion of steel fibre was also determined by interpolating the curve for chloride vs half-cell potential, assuming that the corrosion potential is equated to -350 mV vs CSE at corrosion. In fact, the half-cell potential was -351.6 mV vs CSE at 1.0% of chlorides, as being mostly identical to the value determined by the corrosion rate measurement. Thus, it can be said that the corrosion resistance of steel fibre is higher than for steel reinforcement (i.e. rebar) in concrete, of which the chloride threshold level is often regarded as 0.4–0.6% by weight of cement [12]. The higher resistance of steel fibre to chloride-induced corrosion may be attributed to the presence of protective millscale on the surface, being resistive against oxidation and thus pit nucleation. In the present study, the millscale was not removed to mimic in-situ conditions.

## 3.3. Physical condition at interface of steel fibre

Microscopic observation at the interface of steel fibre in mortar was performed by SEM imaging at  $\times$ 50 to evaluate the distribution of hydration products and porosity, as shown in Fig. 5. To observe the distribution of pores in-depth, the image containing the steel fibre was further magnified at  $\times$ 150 if necessary. It is evident that a number of pixels indicating pores and air voids were present in the vicinity of steel fibre, of which the size was ranged at 10– 400 µm in different shapes. Air bubbles generated in casting concrete are usually cling to or underneath the steel fibres, which are subsequently formed in hardening. After compaction and vibration, the residual air bubbles may be still deposited along the steel fibre, presumably due to membrane potential between on the surfaces of steel fibre and air bubble. As the pores (i.e. air



Fig. 4. Corrosion potential and rate of steel fibre in mortar with concentration of chloride in cast.



Fig. 5. BSE images for the interfacial zone of steel fibre in mortar at ×50 magnification and explanation of pixels at ×150 magnification.

bubbles) are mainly formed in the vicinity of the steel fibre, adverse effects to concrete properties may occur, for example, a reduction of bond to cement paste.

# 4. Discussion

## 4.1. Corrosion risk of steel fibre

Corrosion of steel fibre in concrete was often measured in the majority of previous studies, due to a potential degradation of structural capacity and aesthetic irritation. However, information on the risk of corrosion seems less conclusive. For example, a ratio of rust stain on the surface of concrete was measured after removing the right cover of concrete by grinding [2]. Thus, the assessment of corrosion behaviour is only restricted for the steel fibres placed in near the surface of concrete, and degree of corrosion is not, moreover, possible to quantitatively evaluate, but to visually examine. Alternatively, half-cell potential of steel fibre placed was measured to assess the corrosion risk after demolishing cover concrete for steel fibre to partially protrude out of concrete for electric connection [1]. However, the corrosion potential of a single steel fibre is less measurable, because steel fibres in concrete could be often inter-connected with each other. In the present study, a steel fibre placed in inner concrete was preliminarily connected to external apparatuses for monitoring the corrosion behaviour in terms of corrosion potential and rate. The corrosion resistance of steel fibre against chloride was quantified by the critical chloride concentration for corrosion initiation, of which values ranged from 0.8% to 1.0% by weight of cement.

Corrosion of steel fibre in concrete may be more probable, as steel fibres are present from the surface of concrete. Steel fibres are usually well distributed from the surface of cover concrete to inner body, whilst the concentration of corrosive ions is highly ranked on the right surface of concrete in a short duration of inservice. Considering the resistance of steel fibre against chloride-induced corrosion, steel fibre in a concrete, for example, exposed to seawater, may be subjected to corrosion immediately after inservice, since the concentration of chloride at the depth of <1-2 mm would exceed 2.0–3.0% within a few weeks. Subsequently, corrosion of steel fibres can spread over the inner concrete with

time (i.e. with chloride permeation), implying that no effective barrier of cover concrete can be achieved to protect the steel fibre against chlorides; steel reinforcement in concrete would be protected by cover concrete, which is resistive for chlorides to reach the depth of the steel in a quite long duration.

Despite the risk of corrosion of steel fibre, it is very difficult to apply an inhibitive measure. To prevent or at least mitigate corrosion of reinforcing steel bar, electrochemical treatment, for example, can be widely used by flowing a direct current to the corrosion cell (i.e. cathodic protection). Simultaneously, corrosive ions such as chlorides are electrically removed from the surface of steel reinforcement. In the cell, an anodic body placed on the surface of concrete is usually connected to one or several cathodic steel reinforcements to form electric circuit for electrochemical treatment, as the steel reinforcements are inter-connected with each other. When it comes to the electrochemical treatment to steel fibre in concrete, an electric connection to steel fibre is, however, mostly impossible due to their poor inter-connection: in fact, several millions of steel fibre are separately present in concrete, and in turn an equivalent number of electric circuits must be accompanied to be effective in inhibiting corrosion of steel fibre. Alternatively, a chemical corrosion inhibitor, for example, Ca(NO<sub>2</sub>)<sub>2</sub> solution may enhance the corrosion resistance. However, corrosion of steel fibre placed in the region of concrete surface would be inevitable, due to easy access of corrosive ions to the steel fibre. Substantially, it seems that only surface treatment to concrete in terms of polymer coating is applicable to avoid corrosion of steel fibre, as it provides a barrier between steel fibre in concrete and corrosive sources.

The presence of steel fibre may impose the increased corrosion risk of steel reinforcement in concrete, as long as the reinforcing steel bar is simultaneously used in a concrete mix. As the steel fibres merely increase the tensile capacity of concrete as well, a combination of steel fibre and reinforcement in concrete has been limitedly used. If so, steel fibres may, however, form a galvanic cell with the steel reinforcement, as being usually nobler at electrochemistry. Thus, a loss of electrons may occur from the surface of steel reinforcement with no corrosive sources. Increased porosity at the interface of steel fibre, moreover, may accelerate the corrosion of steel reinforcement. As corrosion usually starts in the voids at the steel-concrete interface, due to the absence of hydraدائلر دکنده مقالات عل FRE دائلر دکنده مقالات عل tion products to resist the corrosiveness [13], the corrosion resistance of steel reinforcement would be reduced by an open pore structure formed in the steel fibre concrete. Additionally, a refinement of the pore structure to opener one in steel fibre concrete would provide an easier path for chloride ions to transport. As already shown in Figs. 2 and 3, concrete containing steel fibres, in fact, had a higher level of chloride ingress at a given exposure to salt solution. Substantially, more corrosive ions will reach the depth of the steel reinforcement to rapidly accelerate the corrosion process.

# 4.2. Modification of pore structure

Pores generated underneath the steel fibre, seemingly in the process of casting fresh mortar, may impose adverse effects in developing properties of concrete containing steel fibres. The pores in the vicinity of steel fibre are in the range of entrained air void. accounting for up to several hundred  $\mu$ m, as seen in Fig. 5, thereby leading to a reduction of strength of concrete; in fact, an increase in the air voids in concrete result in a decrease in the strength about 5–20%. Steel fibres in concrete is presumed to enhance the capacity to an external loading in terms of compressive and tensile strengths simultaneously, as the steel fibres are well dispersed in the longitudinal and transverse directions. Air voids formed in the vicinity of steel fibre, however, may partially offset increased buffering to external loadings. The air void generated by the steel fibre in concrete has not been clearly quantified, except for a current study showing that air voids at the interface of steel fibre were calculated by a 2-dimensional counting of pores [14]. The increased air void was about 0.5-1.0% depending on the shape of pores, and thus the compressive and tensile strength would be more or less reduced, although its strength might be still higher than for steel fibre-free concrete. Therefore, to maximise the benefit of steel fibre in concrete, a removal of air voids must be accompanied.

Increased porosity in concrete containing steel fibres may simultaneously impose a rapid transport of aggressive ions or molecules from external environments. In the present study, mortar containing steel fibres indicated a higher level of chloride ingresses in an exposure to salt solution and under electric charge. In particular, electric charge passed in the mortar containing steel fibres under 60 V was much higher than for control, presumably due to high porosity and high conductivity of steel fibres in mortar. In an exposure to salt solution, the mortar containing steel fibres indicated the higher chloride profile for a given condition (i.e. 4.0 M NaCl solution for 100 days). The diffusion coefficient for steel fibre mortar was always higher than for the control specimen, together with mostly no change in the surface chloride. Substantially, the porous cement matrix could be formed by steel fibres. It implies that the concrete containing steel fibres may be subjected to rapid chemical degradation, for example, carbonation, sulfate attack and acid erosion. Chemically aggressive ions or molecules are usually mobile through the inter-connected pores in the cement matrix. Thus, an increase in the porosity may result in an increase in percolation of external ions and molecules, leading to an accelerated reduction of concrete properties, when a concrete structure is exposed to chemically, environmentally severe conditions. With no modification of the pore structure to denser, steel fibre concrete may always impose chemical degradation. due to open pore structure.

A refinement of the pore structure must be made to secure properties of steel fibre concrete. Filling-up of pores in concrete can be conventionally achieved by mixing with finely grained binder, such as silica fume, which could dramatically reduce pores in the cement matrix and even in the interfacial zone. Alternatively, pozzolanic materials can further refine the pore structure. For example, pulverized fuel ash and ground granulated blast furnace slag could reduce pores in the range of the capillary pores. However, a binder modification cannot fully fill up the voids at the interface of steel fibre, as the voids and pores formed are mainly arrested by the membrane potential of the surface of steel fibre, which otherwise could be quite removed by compaction and vibration of fresh concrete. Thus, the membrane potential must be mitigated by a preliminary surface treatment to steel fibres before casting of concrete to minimise the pores in the vicinity of steel fibre. To date, a clear-cut solution to reduce pores and voids at the interface of steel fibre has not been known.

## 5. Conclusion

In the present study, the corrosion risk of steel fibre in concrete was evaluated by a monitoring of corrosion behaviour, chloride transport and microscopic examination at the interface of the steel fibre. The conclusion derived from the experimental work is given as follows:

- (1) The rate of chloride transport for mortar containing steel fibres at 2.0% in volume of a bulk mortar was even higher than for control specimen, when exposed to 4 M NaCl solution for 100 days, presumably due to increased porosity at the interface of steel fibre. Moreover, in the chloride penetrability under electric charge of 60 V, mortar containing steel fibre was dramatically increased by the high electric conductivity of steel fibre.
- (2) The corrosion rate and potential of steel fibre in mortar was measured at 1.0%, 2.0%, 3.0% and 5.0% of chlorides in cast by weight of cement. The corrosion risk in terms of the critical chloride concentration for the onset of corrosion was 0.8– 1.0% by weight of cement, as being higher than for reinforcing steel bar in concrete. However, the corrosion of steel fibre was more probable, as the steel fibre is paced from the surface of cover concrete, where is always directly exposed to a corrosive environment.
- (3) The pores at the interface of steel fibre were significantly increased presumably by the membrane potential on the surface of steel fibre, which would arrest air bubbles, seemingly generated in the process of casting of fresh mortar. Their size covered from the capillary to entrained air voids, which therefore might lower properties of concrete. Increased porosity by steel fibres would provide an open pore structure to aggressive ions from external environments then to further rapidly deteriorate concrete properties.

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