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Porosity generation arising from steel fibre in concrete

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HIGHLIGHTS

- The porosity generated at the interface of steel fibre was examined by BSE imaging.
- The occupation of the pores at the steel fibre interface accounted for 5.40–11.45%.
- The pores by steel fibre may increase air void in concrete about 0.5–1.0% in volume.

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ABSTRACT

The present study concerns a measurement of porosity at the steel fibre interface in mortar. Mortar cast with a centrally located steel fibre (Ø0.39 × 15.0 mm) was segmented for microscopic observation at a backscattered electron (BSE) image. In the BSE image, the interfacial zone was defined as long as 270 μm from the surface of steel fibre, where the porosity was measured by counting pixels after binarising the image for porosity. As a result, it was found that the pores generated in the vicinity of the steel fibre ranged from 5.40% to 11.45%, equivalent to 0.51–1.08% of air void in a bulk concrete. The high porosity at the interface may impose a reduction of concrete strength (i.e. up to a debondment with cement paste) and a potential risk of further supply of aggressive ions through the pores, leading to a lower durability against chemically severe environments.

1. Introduction

Steel fibre is often used in concrete to reinforce concrete properties, substituting for steel rebar reinforcement. As steel fibres are dispersed in bulk concrete both in the longitudinal and transverse directions, sustaining the higher level of tensile and compressive capacity to an external loading, the concrete member can gain supplementary strengths. Thus, steel fibre concrete is, in particular, used in pavement and sprayed concrete structures even to other uses. However, the steel fibre concrete is currently issued by its problematic limitation: corrosion of steel fibre. Unlike corrosion of steel rebar in concrete, fibre corrosion occurs from the right surface of concrete member, which may substantially lower the structural strength. As corrosion of steel fibre is, however, restricted in a small margin [1–4], no adverse effect on the structural behaviour of concrete was taken into account, except for irritated aesthetic view of the surface due to rust stain.

However, steel fibre corrosion is still under debate, because previous measurements of corrosion were only performed by a half cell potential for a single steel fibre in concrete. Moreover, a possibility of galvanic corrosion to steel rebar reinforcement has not considered in a case of concrete containing both steel fibres and rebar. To date, there was no informative measurement on rust generation from the steel fibre. Despite the importance of bond behaviour with cement paste, the interface of steel fibre in concrete has not been identified due to difficulties in segmenting a sample containing steel fibres with a conventional technique, for example, mercury intrusion porosimetry. The distribution of porosity and hydration products at the steel fibre interface would be informative on determining the corrosion risk, as steel corrosion in concrete always occurs in the void at the interface [5] and simultaneously hydration products have inhibitive nature to corrosive ions and environments [6].

In the present study, the interfacial zone between the steel fibre and cement paste was examined by microscopic observation using a backscattered electron imaging method to identify porosity in the vicinity. A segmented sample containing a steel fibre was obtained, and then the pore distribution in the size of capillary and entrained air voids was determined within 270 μm from the surface of steel fibre. Subsequently, volume of air voids formed at the interface was calculated to assess the influence on concrete properties.

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Table 1
Chemical composition of ordinary Portland cement (%).

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	SO_3	LOI*
64.7	20.7	4.6	3.0	1.0	0.13	0.65	3.0	0.54

* LOI: ignition loss for cement.

Table 2
Composition of steel fibre (%).

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

2. Experiments

To examine porosity in the vicinity of steel fibre, mortar was cast in a cylindrical mould with one centrally located steel fibre (Ø0.39 × 15.0 mm). The specific gravity of the steel fibre was 7.85 and its chemical composition is given in Table 1. Simultaneously, the mix proportion of mortar for ordinary Portland cement, water and sand was 1.00:0.40:2.65 by mass. The mortar specimen was cured in a polythene film at 20 ± 2 °C for 28 days before an image capture using the scanning electron microscope as seen in Table 2.

Then, 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 grit sizes of 68, 30, 18, 14 μm respectively 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 7×10^{-5} Pa.

The image containing the steel fibre was obtained by a JEOL 5410LV 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 μA. The digitised image provides a field of view of 1296 × 970 μm, and a pixel resolution was 0.633 μm. The distribution of porosity in the vicinity of steel fibre were determined by (1) defining the steel fibre interfacial zone, (2) binarising image for the porosity and (3) calculating the porosity in the interfacial zone, as seen in Fig. 1. The grey scale range (i.e. darkest level in histogram) for porosity was determined by selecting minimum values between peaks for porosity and CSH gel. Then, the backscattered electron (BSE) image was binarised to identify porosity in the interfacial zone within 270 μm from the surface of steel fibre to include the all pores generated in the vicinity of steel fibre. Then, the area of the interfacial zone was determined by counting the number of pixels covering the interface, and the porosity at the interface in the binarised image was simultaneously determined by an equated way then to calculate the ratio of porosity. Substantially, the pore volume, seemingly generated by the steel fibre was calculated assuming that equated pores were formed at the interface through the steel fibre in the longitudinal direction in a bulk concrete.

3. Results

The BSE image containing the steel fibre in mortar was obtained as given in Fig. 2, together with calculated porosity in the vicinity of the steel fibre. It is clearly seen that a large amount of porosity was generated at the interface of the steel fibre in the variation in types: for example, longish and round air voids in the vicinity of the steel fibre, and rim-shaped voids along the steel fibre. Unlike the pores generated in the cement matrix, the air voids in the steel fibre interfacial zone were even larger, ranging up to several hundreds of micrometers, indicating the range of entrained air void. This may be because the air bubbles generated in casting of fresh concrete were stick to the steel fibre, which were subsequently formed in the process of hardening. Thus, it is more probable that the air bubbles at the steel fibre interface would be void, rather than saturated with the pore solution. It suggests that the dry air voids in the vicinity of the steel fibres may partially offset the benefit of steel fibre concrete in raising the strength, which would notwithstanding remain still in the higher level of the strength, compared to concrete with no steel fibres.

The porosity generated in the vicinity of steel fibre, in particular, rim-shaped large air voids along the interface may impose a debondment between the steel fibre and cement paste. The very high level of porosity formed at the interface, often ranging beyond 50–60%, may be attributed to a combination of air bubble clinging to the surface of the steel fibre in mortar casting and evaporation of mixing water in the vicinity. Segregated mixing water from fresh concrete could, in fact, transport along the smooth surface of the steel fibre, which subsequently might form a longish air void after the completion of concrete hardening. Due to a very high level of the porosity, it can be said that the interfacial zone between the fibre and cement paste is mainly occupied by air voids: in turn a debondment may occur. It implies that the cement paste and steel fibre may behave separately against an external loading, unless the paste (i.e. cement matrix) could further be bonded or/and cling to the rest of the steel fibre surface in the longitudinal direction. Apart from a debondment, the high porosity at the interface of the steel fibre is still indicative of a lower bond strength with the cement paste. Moreover, increased porosity in the cement matrix, one way or another, may impose a further risk of aggressive ionic percolation: for example, chloride, sulphate and other aggressive ions may more rapidly penetrate concrete through the pores in the vicinity of the steel fibre interface.

Additionally it is evident that the occupation of the porosity at the interface was dependent on types of air voids: in fact, longish and round air voids significantly increased the porosity, ranging from 5.40% to 11.45%. To define the volume of air void generated at the steel fibre interface, the interfacial region was preliminarily confined to the doughnut-shaped realm after removing the area of centrally located steel fibre. The thickness of the realm was equated to 270 μm (i.e. about 1.5 times long as the radius of the steel

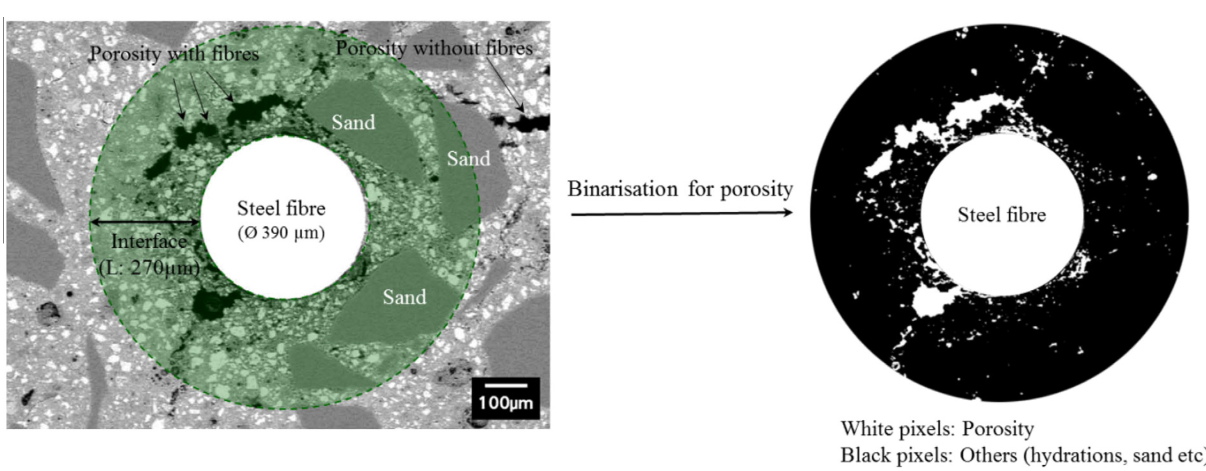

Fig. 1. Binarisation of the porosity generated within 270 μm from the surface of the steel fibre at backscattered electron imaging.