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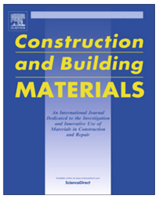

Bond stress between conventional reinforcement and steel fibre reinforced reactive powder concrete

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HIGHLIGHTS

- Ultimate bond stress between SF-RPC and conventional rebar was investigate.
- Direct pull out test on of SF-RPC was conducted.
- Bond stress did not increase linearly with cover and strength of concrete.
- No greater enhancement of bond strength is expected with 2% volume of steel fibre.
- The bond strength of SF-RPC can be evaluated by using Tepfers bond stress model.

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ABSTRACT

In this study, we investigated bond stress between steel-fibre-reinforced reactive powder concrete (SF-RPC) and conventional reinforcement to determine specific values for design bond stress. Test results were compared with previously suggested analysis methods. Tests were carried out using the direct pull-out test. The main variables are compressive strength of the concrete, concrete cover, and inclusion ratio of steel fibre.

The increase rate of ultimate bond stress between SF-RPC and conventional reinforcement was decreased although the ultimate bond stress was increased with increasing compressive strength of the SF-RPC matrix. The effect of the concrete cover on ultimate bond stress and its increase rate was similar to that of the compressive strength of concrete. However, an even more significant change was observed with change in concrete cover. We also observed an effect of steel fibre inclusion. Inclusion of a 1% volume fraction of steel fibre increases the ultimate bond stress by two times the bond stress between the plain RPC matrix and conventional reinforcement. However, a 2% steel fibre volume fraction does not increase the ultimate bond stress significantly.

In order to obtain safety for bond design of SF-RPC precast members, previously suggested analysis methods for ultimate bond stress and empirical equations for ultimate bond stress were evaluated. Most empirical ultimate bond stress equations cannot estimate the ultimate bond stress accurately. Analysis methods suggested by Tepfers can predict the ultimate bond stress more accurately than these empirical equations because the RPC matrix behaves as a linear elastic material until experiencing splitting failure.

1. Introduction

There has been much research on methods to prevent the brittle failure of the matrix of high performance concrete under tensile and compressive stress. Guidelines for ultra high strength concrete [1,2] have been suggested; however, these design guidelines still depend on the design method for normal strength concrete.

Since the 1990s, Richard and Cheyrezy [3] in France have been developing reactive powder concrete (RPC), a material that can attain a uniaxial compressive strength of 150 MPa or higher and a modulus of rupture of up to 25 MPa. RPC is a material with maximum density for high compressive strength. RPC achieves much higher density than normal and high strength concrete, but it does not use coarse aggregate like normal concrete. However, the lack of

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coarse aggregates cause brittle failure under compression or tension. As this material is extremely brittle and prone to rupturing when cracks occur, steel fibres are generally mixed into the RPC matrix. This material is designated as steel-fibre-reinforced reactive powder concrete (SF-RPC). SF-RPC generally has a low water-binder ratio. It requires high-temperature (90 °C) steam curing because the hydration process of the matrix needs to be accelerated actively. Therefore, SF-RPC members are generally used as a precast member.

The connection of SF-RPC precast members is an important design requirement in a precast structural system. This can be achieved by understanding the bonding mechanism between SF-RPC and steel reinforcements. Therefore, a clear understanding of the bonding behaviour of relevant materials is required to ensure the safe and economical use of SF-RPC precast members.

The bonding between concrete and conventional reinforcement is affected by the compression and tensile strength of the concrete and concrete cover. Although development length design equations [4] were derived from principles of bond stress between concrete and conventional reinforcement, the specific coefficients were determined based on the experimental results for normal strength concrete [5]. Because SF-RPC has different material characteristics than normal strength concrete, the development design equations may cause problems with safety. Hence, the present study aims to observe the bonding behaviour between SF-RPC and conventional reinforcement by conducting direct pull-out tests. Also, various prediction equations of ultimate bond stress were compared with the test results of this study and those carried out previously carried for verification of safety.

2. Bond stress between concrete and conventional reinforcement

Current design standards [4–9] define equations and coefficients based on the test results of normal strength concrete. These can be used to determine the development length of conventional reinforcements. Since the existing code provisions are entirely empirical, numerous limitations emerge when applying them to a newly developed material. As shown in Fig. 1, when current code provisions with their limitations are applied to SF-RPC members, which have a characteristic compressive strength of 200 MPa, the required development length for conventional reinforcement is seven times longer than the development length calculated by development length equations of code provision without consideration of limitations. This is because the value of $\sqrt{f'_c}$ cannot be larger than 8.4 MPa, according to the limitations of the current code provisions. In other words, if the current code provisions are applied, it is possible that the development length design for SF-RPC members could be conducted uneconomically, which would contradict the purpose of high performance material development.

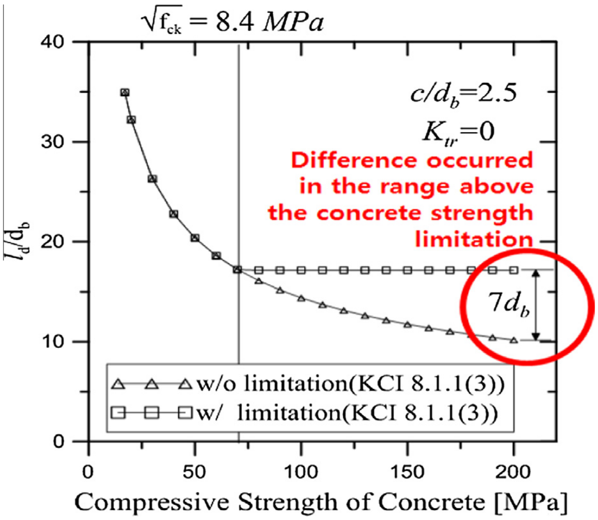

Fig. 1. Limitation of current code.

In this study, we investigated the bonding behaviour of SF-RPC without compressive strength limitations, and the bonding behaviour between concrete and conventional reinforcement and related models was investigated.

When using concrete compressive strength range over limitation of code provisions, ultimate bond stress between concrete and conventional reinforcement should be calculated for the design of anchorage and development length of concrete structures. Many researchers have investigated and suggested models for bonding behaviour and ultimate bond stress prediction.

Park [10] reported that the bonding behaviour was affected by the geometric properties of rebar. If the distance between the ribs is small while the height is high, a relatively large shear stress is generated between the concrete key and the surrounding concrete, thereby generating pull-out failure; in the opposite case, a splitting failure can occur because of the expansion force generated on the concrete by the wedging action caused by the crushing of the concrete in front of the rib.

Tepfers [11] noted that the bond splitting stress can be calculated by modeling the stress condition of the surrounding concrete around the loaded bar. Bearing force is generated at the rib surface at a slope angle α. This is expressed as bond stress using the force along the radial direction, which pushes against the concrete surrounding the conventional reinforcement. The radial stress is generated equally in all directions and induces cylindrical tensile stress, as shown in Fig. 2. The depth of the concrete cover and tensile strength of the concrete are regarded as major factors for enhancing the constraint effect and wedge generation. The Tepfers [11] splitting bond stress model is valid for three cases: when the concrete around the steel reinforcement is in an elastic state, a plastic state, and an elastic state where partial cracks have occurred. The splitting bond stress for the three types of stress states is summarized by the following equations:

$$\tau_{el} = f_{ct}\frac{(c_y + d/2)^2 - (d/2)^2}{(c_y + d/2)^2 + (d/2)^2} \tag{1}$$

$$\tau_{pl} = f_{ct}\frac{2c_y}{d} \tag{2}$$

$$\tau_{pt,el} = f_{ct}\frac{c_y + d/2}{1.664d} \tag{3}$$

where τ_{el} is the bond strength under elastic state, τ_{pl} is the bond strength under a perfectly plastic state, $\tau_{pt,el}$ is the bond strength under an elastic state with partial cracks, f_{ct} is the tensile strength of the concrete, c_y is the minimum depth of concrete cover, and d is the diameter of the steel reinforcement.

The ultimate splitting bond stress between conventional reinforcement and concrete can also be calculated in various ways. Many researchers suggested empirical equations. Most code provisions provided empirical equations for calculating lap splice length or bond stress. They are listed in Table 1. However, most of equations did not classify the failure pattern. MC2010 [17], one of the most recently developed ultimate bond stress equation only consider the failure pattern. According to Table 1, effective parameters for bond stress equations are compressive strength of concrete, concrete cover-rebar diameter ratio. Some equations consider the effect of embedded length because average bond stress can be varied with stress distribution. Typically, code provisions for struc-