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Bond behaviour of normal/recycled concrete and corroded steel bars

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HIGHLIGHTS

- Bond degradations of normal and recycled concrete non-stirrup specimens are similar.
- Stirrups effectively increase bond capacity of reinforced concrete.
- Stirrups reduce difference of bond behaviour between normal and recycled concrete.
- The parameters of steel stress transfer and bond stress distribution are defined.
- Stress–slip relationships are different at each location along steel bar.

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ABSTRACT

Pullout and beam tests were performed to study the bond behaviour between normal aggregate concrete (NAC) or recycled aggregate concrete (RAC) and corroded steel bars. The results show that the corrosion-induced bond degradation characteristics of NAC and RAC pullout specimens are similar. For specimens with stirrups, the ultimate bond strengths of both NAC and RAC specimens do not change significantly with steel corrosion growth; the stirrups reduce the difference in bond behaviour between NAC and RAC specimens. Stress transfer in steel and bond stress distribution parameters were defined to characterise the bond behaviour. The bond stress–slip relationships were observed to vary between different locations.

1. Introduction

Adequate bonding between reinforcing bars and concrete is essential for the satisfactory performance of reinforced concrete structures. In the absence of sufficient bond strength, effective beam action, as required by codes of practice, cannot be achieved, and hence, the specified design equations are no longer valid. Loss of strain compatibility at the depth of a reinforcement results in a redistribution of stresses in the reinforced concrete element, which may lead to excessive service deflections and altered load capacities.

It is well known that the use of deformed bars can greatly enhance the steel–concrete bond capacity. Three main components determine the bond strength between the adjacent ribs of a reinforcement bar [1]. These components are shear stresses due to adhesion along the bar surface, the bearing stresses against the faces of ribs (mechanical interlock), and the friction between bars with concrete in the rib dales and the surrounding concrete. The highest contribution to bond strength comes from mechanical interlock. Because of their widespread application, only deformed steel bars were considered in this study.

The available bond strength at the interface between a steel bar and concrete is affected by the corrosion of the steel bar. Corrosion products can alter the surface conditions at the boundary between the reinforcement and concrete and hence influence the development of bond stresses. Additionally, corrosion-induced cracking or spalling of the cover will reduce the confinement provided by the concrete to the reinforcement, which is accompanied by a corresponding reduction in the bond strength. The consequences of each of these effects have a great influence on the serviceability and loading capacity of concrete structures. Research on the topic of bond degradation due to reinforcement corrosion has produced a wide range of results [2–19]. The results of a previous study in which the effect of reinforcement corrosion on bond strength were investigated are summarised in Fig. 1, where the “relative bond strength” is the ratio of the ultimate bond strengths between the corroded and non-corroded specimens. Although the results show a high scatter, they indicate that the bond strength decreases with an increase in steel corrosion. Fig. 1a shows that when the extent of steel corrosion is less than 2%, the bond strength in specimens without stirrups is higher than the strength of non-corroded

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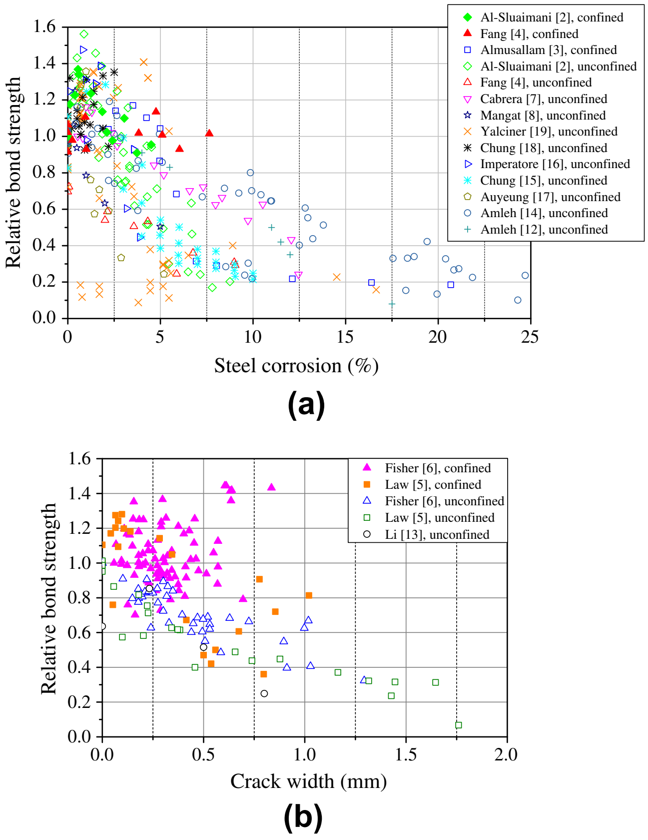

Fig. 1. Bond degradation due to steel corrosion: (a) relative bond strength versus steel corrosion; (b) Relative bond strength versus mean crack width induced by steel corrosion.

specimens. In addition, it can be seen that when the steel bar area lost to corrosion nears approximately 14%, the extent of bond strength degradation reaches as high as 80–90%. Generally, the relative decreases in the bond strength were significantly larger than the associated relative weight loss; this phenomenon has been noted in previous studies [7,11,12]. A considerable decrease in the bond strength at the steel–concrete interface can be more dangerous to the safety of a structural element than the loss of the rebar cross-sectional area at the bond interface. Furthermore, Fig. 1a and b show that the bond strength in specimens with stirrups is larger than the bond strength in specimens without stirrups. It is accepted that stirrups can control the development of cracking induced by steel corrosion (Fig. 1b) and increase the bond capacity effectively. However, it should be noted that, compared with that of specimens without stirrups, the tested bond strength of the specimens with stirrups is not sufficient. Therefore, because most concrete structural components are stirrups embedded together with longitudinal steel bars, the manner in which stirrups affect the bond behaviour between corroded steel bars and concrete must be further studied.

In previous studies, researchers [20–22] noted that the bond stress–slip relationships observed for steel–concrete structures varied from section to section; thus, the location of the steel–concrete interface was an important variable for describing the bond stress–slip relationship accurately. By milling steel bars at their centres to provide a channel on which to attach strain gauges, Nilson first measured the steel stress along steel bars of concentrically loaded tensile specimens and plotted the bond stress distribution [23]. Later, he used an analytical method to construct the corresponding bond stress–slip curves at different locations. The curves were observed to vary with the distance from the end face of the specimens [20]. Somayaji and Shah [21] developed an analytical model to describe the bond stress distribution along a steel bar in a tension concrete member. Based on their analysis, the obtained theoretical local bond stress–slip relationship was different at every section of the tension member. Kankam [22] conducted an experiment on double pullout specimens in which the steel bars were instrumented with electrical resistance strain gauges. Kankam observed that the relationship between bond stress and slip at different positions along the steel bar increased from the anchored midpoint to the pulling ends. According to these studies, it is clear that the bond stress–slip relationships vary with location along steel bars in concrete. However, the relevant body of work does not sufficiently indicate the influence of position on the bond stress–slip relationship when compared to other studies on the bond behaviour between steel bars and concrete. Moreover, the distribution of steel stress and bond stress along steel bars, or the bond stress–slip relationships at different locations, should be affected by the extent of steel corrosion. However, very few studies in this area of research have been published.

To achieve sustainable development, recycled aggregate concrete (RAC) is currently being considered for application in concrete projects. To popularise RAC in civil engineering, it should be reinforced with steel bars. As mentioned above, one of the most important requirements of reinforced concrete structures is the bond between concrete and steel bars. A few studies have been conducted in the field of bond behaviour between RAC and reinforcing steel bars [24–26]. Xiao [26] noted that the general shape of the load versus slip curve between RAC and steel bars is similar to that for normal aggregate concrete (NAC) and steel bars; additionally, Xiao observed that the bond strength between RAC and deformed rebar is not related to the RAC replacement percentage. Choi [25] observed that up to a replacement ratio of 50%, the bond stress–slip behaviour of RAC showed similar tendencies to that of NAC. The peak bond strength was influenced by the grade and replacement ratio of recycled aggregate (RA); however, at high w/c, the peak bond strength was not influenced by the quality or replacement ratio of the recycled aggregate. Using a modified pullout testing method, Kim's study [27] revealed that RAC showed a bond strength approximately 18% lower than that of NAC. However, Zuhud [28] observed the opposite experimental result: the bond strength between concrete and deformed steel bars increased as the percentage of recycled aggregate increased. Based on these studies, the effects of steel corrosion on the bond behaviour between corroded steel bars and RAC are contradictory and not yet clearly understood.

Therefore, the goal of this study was to investigate bond degradation and the distributions of bond stress in NAC and RAC specimens with and without stirrups. Pullout and beam tests were conducted to study the effects of steel corrosion, concrete type, and stirrups.

2. Experimental program

2.1. Material

Recycled coarse aggregate was obtained by crushing waste concrete, using a jaw crusher, the compressive strength of the original waste concrete is 30 MPa. Due to its high water absorption rate, the RA was pre-soaked in water for 24 h before casting. The typical physical characteristics of the recycled aggregates (RA) and natural aggregates (NA) used in this study are listed in Table 1. Ordinary Portland cement type 42.5 conforming to the Chinese standard GB 175-2007 was used for the test specimens.

The designed mixture ratios of RAC and NAC are shown in Table 2. The percentage of RAC used in this study was 50%. Cubic specimens measuring $150 \times 150 \times 150\ \text{mm}^3$ were cast to determine the 28-day compressive strength of the mixed concrete. It should be noted that the pullout specimens and beam specimens were not cast simultaneously; therefore, the 28-day compressive