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Bond characteristics between early aged fly ash concrete and reinforcing steel bar after fire

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HIGHLIGHTS

- Conduct 177 pull-out tests on the bond strength of fly ash concrete after fire.
- Study the influence of temperatures on the degradation of the bond strength.
- Investigate the bond behaviours of fly ash concrete with different curing ages.
- Understand the impact of different cooling methods on the residual bond strength.
- Provide valuable test data for the fellow researchers and structural engineers.

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ABSTRACT

In this paper a comprehensive experimental investigation on the residual bond strength between the early aged fly ash concrete and steel ribbed bar after exposed to high temperature has been presented. The research focused on the influences of different temperatures, curing ages, cooling methods and standing times of the specimens after high temperature. A total of 177 pull-out tests were conducted under different conditions. The research indicates that the curing ages of fly ash concrete, exposed temperatures, cooling methods and the standing time of the specimens after cooling have considerable influences on the residual bond strength of fly ash concrete. The research generated a set of reliable and valuable test data for the researchers and practical structural engineers in the field of structural fire engineering.

1. Introduction

Current research indicates that fly ash concrete is more environmental friendly compared to normal Portland cement concrete. Hence, the material has been widely used in the construction industry. Fire is one of the most common disasters to threat public safety and social development. It is possible a fire happened during the construction stage of reinforced concrete buildings due to the problem of construction procedure and management on the construction site. If a fire occurs during construction period it is important to assess the impact of the fire on the residual material strengths of the younger concrete. Therefore, it is needed to assess the safety and reparability of the building structure after a fire. At present there are considerable researches which have been done on the residual strengths of fly ash concrete after high temperatures. The research conducted by Jia et al. [1] indicates that the residual compressive strength, splitting tensile strength of the concrete with large dosage of fly ash are degraded significantly after exposed to elevated temperatures. The content of fly ash within cement has complex influences on the strength degradation of the material at elevated temperatures. The research conducted by Ma [2] points out that the concrete compressive strength and splitting tensile strength of concrete with different dosage of fly ash increase with increasing age of the concrete.

Amrutha et al. [3] conducted an experimental study to investigate the influences of different temperatures on the residual strength of the concrete with high volume of fly ash. Lee [4] also carried out a research on the mechanical properties of fly ash concrete exposed to different high temperatures. Nadeem et al. [5] and Shaikh and Vimonsatit [6] studied the influences of different dosage of fly ash, temperatures and cooling modes on the residual compressive strength, mass loss and other mechanical properties of fly ash concrete. The results show that the reduction of the

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compressive strength of the concrete under water spray cooling is more significant compared to the concrete using natural air cooling. Khan and Abb [7] studied the impact of high temperatures on the apparent characteristics, mechanical properties and the mass loss of concrete with high volume of fly ash.

Previous researches [8–10] indicated that the bond strength between concrete and reinforcing steel bar degraded under fire conditions. Hence, for structural fire engineering design of reinforced concrete buildings it is important to assess the bond strength between concrete and steel bar at elevated temperatures. It is also important to evaluate the residual bond strength of reinforced concrete structural members after fire for structures repairing and strengthening. A number of studies have been done on the bond properties of ordinary reinforced concrete members in fire or after fire. Diederichs and Schneider [11] studied the influences of different types of reinforcing steel bars on the bond characteristics between concrete and steel bar at elevated temperatures. Their results indicated that the bond strength of rib bar decreases as temperature increasing. The degradation ratio of the bond strength has the same order as the reduction of concrete compressive strength at elevated temperatures. At the same temperature the reduction of the bond strength of smooth bar is considerably bigger compared to rib bar. The research conducted by Ferhat and Ruestem [12] shows that the residual bond strength between concrete and steel bar after exposed to high temperature increases with increasing strength of concrete and the anchorage length of steel bar.

Zhu et al. [13] conducted a number of pull-out tests on bond behaviour of reinforced concrete specimens and their results indicated that the bond strength increased when temperature was lower than 150 °C. However, the bond strength reduced significantly at high temperature level. The bond slip at maximum bond stress increased with increasing temperature. Yuan et al. [14] investigated the bond characteristics between concrete and steel bar under different temperatures and cooling methods. Their results indicated that the maximum bond stress decreased and the ultimate bond slip (the slip corresponding to the maximum bond stress) increased as increasing temperature for both natural air cooling and water spray cooling. Compared to natural air cooling, the reduction of bond strength is more significant and the ultimate bond slip is also larger for water spray cooling.

As mentioned above fire incidents may happen during the construction stage of reinforced concrete buildings. Hence, it is important to assess the impact of the fire on the residual material strengths of younger concrete and the bond strength between early aged concrete and reinforcing steel bars. Also for assessing the safety and reparability of the building structure after a fire the recovery of bond strength is another important issue needed to be investigated. Previous researches [1–7] indicated that flay ash has lower activity in the early hardening period which affects the speed hydration of products within cement paste. Hence, compared to ordinary concrete, fly ash concrete has lower tensile and compressive strengths at early curing age. As the growth of the concrete age the activity of fly ash increases considerably and the strengths of the concrete increases quickly at the later stage of curing period. At later curing period the compressive strength, tensile strength and toughness of fly ash concrete are considerably higher than ordinary concrete. Also the shrinkage and creep of fly ash concrete are better than ordinary concrete. Therefore, the bond characteristics between early aged fly ash concrete and reinforcing steel bars are different compared to normal concrete.

Due to fly ash concrete has different mechanical properties (compared to normal concrete) it is necessary to study the bond characteristics between fly ash concrete and steel bar at both ambient and elevated temperatures. At present, the majority of the research mainly focuses on the bond behaviours at ambient temperature. Previous researchers conducted a series of pull-out tests to study the bond characteristics between fly ash concrete and steel bar at ambient temperature [15–17]. The results indicated that the bond strength of fly ash concrete increases with increasing concrete curing period. However, according to the authors' knowledge there is very limited research on the residual bond behaviour of fly ash concrete after fire.

Previous researches [12,14] indicated that the residual bond strength between concrete and reinforcing steel bar after fire is affected by a number of factors, such as concrete compressive and tensile strengths at ambient temperature, concrete curing age, degradation of concrete strengths at elevated temperatures, heating and cooling methods and so on. Therefore, the bond behaviour of fly ash concrete is different compared with normal concrete, even both concretes have the same tensile and compressive strengths at ambient temperature.

The main objectives of this research are:

- Conduct a series of pull-out tests to investigate the residual bond strength between fly ash concrete and steel rib bar under different temperatures, and cooling methods.
- Study the influence of temperatures (150 °C, 350 °C, 550 °C) on the degradation of the bond strength.
- Investigate the bond behaviours of fly ash concrete with different curing ages (7 days, 14 days, 28 days, 56 days and 90 days).
- Understand the impact of different cooling methods (natural air cooling, water spray cooling) and influence of different the standing time of the specimens after cooling on the bond characteristics of fly ash concrete.
- Generate a set of valuable test data for fellow researchers who develop numerical models and practical structural engineers who conduct performance-based structural fire engineering design for reinforced concrete buildings.

2. Test specimens

According to Chinese design code for fly ash concrete, the maximum content of fly ash within the concrete should be limited below 30%. Previous research [5] indicated that the fly ash concrete with 20% fly ash under fire conditions has good mechanic properties. Therefore, in this research the concrete with 20% fly ash was adopted to make test specimens. The P.O42.5R ordinary Portland cement manufactured by Huaihai Cement Production was used. The Chemical compositions of the cement are given in Table 1. The fly ash used was the byproducts generated by Xuzhou New Willow Peng Cheng power plant. The chemical compositions of the cement with fly ash are listed in Table 2. And Table 3 presents the physical properties of fly ash. For fly ash concrete, the sand used was medium sand and gravel used was local stone from Xuzhou local area. The water used was ordinary tap water. The procedure of adding fly ash into the concrete followed the recommendation proposed by Chinese code [18]. Table 4 gives the details of the mix proportion of the fly ash concrete and tested compression strength of the fly ash concrete at 28 days was 28 MPa.

The pull-out specimen is shown in Fig. 1, in which the concrete block is 150 mm × 150 mm × 150 mm with one steel rib bar with the diameter of 16 mm and length of 500 mm. The detailed bar characteristics and material properties are given in Table 5. However, previous research [19] indicated that the geometric of steel ribbed bar (such as bar diameter and rib shape) has a considerable influence on the bond strength between concrete and steel bar. In this study the ribbed bar with the diameter of 16 mm was adopted due to its popularity.

Based on the Chinese code [20], it is recommended that for a pull-out test the embed length of steel bar should not be less than