学 位 論 文 内 容 の 要 旨

DISSERTATION ABSTRACT

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Investigation on long-term durability of FRP-concrete bond interfaces under moisture conditions
(湿潤環境下における FRP とコンクリートの付着界面の長期耐久性に関する研究)

Strengthening by Fiber Reinforced Polymers (FRPs) is one of the most common solutions to the ageing infrastructures. However, long-term durability of such systems under different environment conditions needs to be understood properly before widely adopting these methods in the field. Among several different environmental issues, moisture and temperature are considered as key issues which can deteriorate the bond interface properties between FRP and concrete. Till date the long-term durability issues and its mechanism of deterioration is not clear. The environmental deterioration factor currently being proposed by some of the guidelines does not extensively cover deteriorations in various environmental conditions under long-term due to insufficient research in the field. Therefore, it is necessary to investigate the bond properties and propose interface laws to predict the member behavior incorporating such environmental actions. This research includes results of extensive experimentation performed to understand the behavior of moisture and temperature on material and bond properties between FRP and concrete.

The material properties and its durability characteristics under moisture conditions are determined in 8 epoxy resins and concrete for the maximum period of 18 months. The results of immersion in water revealed that the mechanical properties of most of the epoxy resins degraded after exposure indicating some harmful effects of water. The average reduction in the tensile strength of the resins was in the range of 11% to 38%, whereas the effect in the Young's modulus was not significant. These degradations are usually associated with the quantity of the absorbed water by epoxy resins but no such relationship was found between them in the study. The absorption by the resin specimens varied from 0.71% to 2.65% after 18 months of immersion, among which the degradation was the greatest when the water absorbed was the least. In few cases, no reduction in the mechanical properties was found despite over 2% water absorption, which concludes that the quantity of water absorption cannot solely explain the degradation mechanism of the epoxy resins. Further, analysis of thermal behavior through measurements of glass transition temperature (T_g) at different exposure durations confirmed that no plasticization effect in the epoxy resins due to water absorption. The concrete compressive strength was also unaffected throughout the exposure durations.

After confirming the material behavior, the effect of water was evaluated by the assessment of the shear bond interfaces under moisture conditions using 6 popular commercial FRP systems in the world for the maximum immersion period of 18 months. Two of systems showed 25% and 16% reductions in average shear bond strengths, while the remaining systems showed either improvement or insignificant effect. The results are indicating close relationship between loss in shear bond strength and the failure mode. The failure in two of those cases always occurred at the resin-concrete interface, while in other cases, it was mostly concrete cohesion or mixed failure of concrete cohesion and resin-concrete interface failure. Observation of the failure modes suggested that, the durability against water related deteriorations are worst when the adhesion bonds between concrete and resin interface are weaker than the cohesive bonds of the adjacent layers. This indicates the importance of proper surface roughness to ensure good mechanical interlocking action between the two layers.

The effect of water on the tensile bond properties between FRP and concrete were investigated by direct pull-off test using 6 FRP systems for the period of 18 months. Although there is a large scatter in the data, average tensile bond strength after exposure was significantly reduced which varied from 19% to 41% depending on the FRP systems. Despite such reductions in the tensile bond strength, the failures were governed by the concrete cohesion strength in almost all the cases. As the properties of the concrete did not change throughout the exposure duration, it can be concluded that loss in tensile bond strength after the immersion is due to adverse effects of water on the bond properties.

The role of surface roughness in determining the durability of the bond was examined for FRP bonded to normal and high-strength concrete substrates by single lap shear test. Proper surface preparation by disk-grinding method was sufficient in case of normal-strength concrete, whereas, sand-blasting method was more effective in high-strength substrate concrete. The higher degree of roughness generated due to the latter method ensures good mechanical interlocking action between the concrete and FRP composite. There was an increase in 110% bond strength when the average arithmetic roughness value increased from 0.11 mm to 0.54 mm by changing the method of surface preparation for the high-strength concrete case. The degree of roughness was found to greatly affect the durability of high-strength concrete and FRP. The average bond strength reduction was around 30% for disk-grinded high-strength substrate concrete case after the exposure along with the transition of failure mode from mixed to complete adhesion at the interface. Whereas, the average bond strength reduction was only about 7% in case of sand-blasted specimens and in those cases, no distinction could be made in between the two mixed failure modes. Similarly, the reductions in the bond strength for the disk-grinded normal-strength concrete substrate using the same FRP composites was also close to 7% along with the mixed mode of failure. Nevertheless, greater bond strength reduction occurred when the failures occurred at the interface between primer and concrete layer after immersion as a result of poor mechanical interlocking action after deterioration of chemical bonds at the interface due to water.

In order to evaluate the interfacial bond mechanism between Fiber Reinforced Polymer (FRP) and concrete, there is a necessity to develop related bond stress-slip models under moisture conditions. The simple method of determining the bond-slip models proposed by Dai et al. was used to develop the bond-slip models at different immersion durations. The proposed method was compared with the experimental local bond-slip curves for all six FRP systems which show fairly good agreement. The reduction in the bond strength and the analytically calculated fracture energies showed similar trends with the exposure duration. The calculated fracture energies were used to obtain the environmental reduction factor in moisture conditions.

At last, the effect of elevated temperature was investigated on the bonds between FRP and concrete in 6 FRP systems. Apart from the $20°C$ temperature case which is taken as the reference, the specimens were examined at $40°C$ and $50°C$. The latter temperature is closer to the (T_g) temperature for most of the resins. The results of shear bond test can be divided in the two parts. The first part includes all the 4 FRP sheet bonding cases in which bond strength remained unaffected till the temperature of $40°C$ with failures at either concrete cohesion or mixed modes. While at $50°C$, premature failures occurred due to rupture of the FRPs indicating that the temperature closer to (T_g) would severely affect the properties of the FRP composites. In contrary, the elevated temperature was beneficial in strand sheet and plate cases with substantial increase in the bond strength at both the temperatures. No premature failures occurred by rupture of FRPs which could possibly be due to greater tensile capacities and better quality of the composites as a result of factory impregnation process. In response to the temperature, the tensile bond was either unaffected or have positive effect for most of the cases. Nevertheless, the failures in all cases were governed by the concrete cohesion.