学　位　論　文　内　容　の　要　旨

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学　位　論　文　題　名

EXPERIMENTAL STUDY ON POLYMER CEMENT MORTAR (PCM) WITH SILICA FUME TO ENHANCE CONCRETE-PCM INTERFACE BOND
(シリカフュームを混入したポリマーセメントモルタル (PCM) によるコンクリート-PCM 界面接着性状改善効果に関する実験的研究)

In twentieth century, strengthening of reinforced concrete (RC) structures is one of the fast-growing, challenging but crucial questions, thus it becomes a significant central issue all over the world to be solved for the practical application. The polymer cement mortar (PCM) overlay method is known as one of viable, economical, environment friendly and promising solution for strengthening the deteriorated concrete structures due to its superior properties in terms of mechanical strength, durability, and good adhesive strength with concrete than ordinary mortar. In this method, the substrate concrete-PCM bond is considered a threshold and the occurrence of premature debonding at the concrete-PCM interface prevents the strengthened structures from achieving full serviceability and designed load-carrying capacity. The exposure of composite specimens/structures to severe environmental conditions caused further degradation of the interface leading to significant reduction of intended service life of repaired structures. Therefore, it becomes a very urgent subjects to find out an efficient method to improve the concrete-PCM interfacial bond and simultaneously ensure the highest level of safety operation. With such aim, this study focused on how this interface can be strengthened more effectively to prevent brittle fractures. Number of experimentation at microscopic, material and member level were conducted considering the impact of different influencing factors to simulate the actual bonding situation in real retrofitting fields and investigated the effectiveness of adding 5% silica fume to PCM, in order to achieve the great potential in practical design implications.

The research comprises of lot of experimental investigations of PCM-concrete bond properties with and without silica fume subjected to static loading. Experiments were conducted under tensile and shear stress condition along with the microstructure analysis using microscopic test to precisely understand the influence of silica fume in forming the chemical connection at the concrete-PCM interface. Performance evaluation of silica fume inclusion were also conducted considering experimental parameters, such as interface roughness, compressive strength of substrate concrete or moistness of the interface to clarify the effects of the considered parameters on the bonding mechanism. The issue of bonding durability of the concrete-PCM interface with the inclusion of silica fume under exposure to severe environmental condition were also evaluated. Meanwhile, PCM overlay strengthened beams with and without silica fume cementitious mortar having different cross-section area of the strengthening bar were tested under monotonic flexure loading. The major achievements through this research are summarized as follows:

The effectiveness of modified silica PCM as a repair material in forming a chemical connection at interface were evaluated qualitatively based on loading test (tensile and shear stress condition) using smooth and rough concrete surface roughness, and quantitatively based on microstructure analysis using scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), X-ray diffraction (XRD) and thermogravimeter-differential thermal analysis (TG-DTA). As a repair layer mortar, PCM modified with silica fume caused an improvement in the interfacial strength, even with smooth concrete substrate surface where mechanical bonding had less influence. The inclusion of silica fume increases the splitting tensile strength by approximately 16% and 22%, and interfacial shear strength by approximately 114% and 30% compared to the normal PCM for smooth and rough concrete surfaces, respectively. This fact indicates a higher possibility of the formation of chemical connection at the concrete-PCM interface by transformation of harmful $Ca(OH)_2$ into more C-S-H. Furthermore, lower Ca/Si ratio was observed through microscopic SEM-EDS test and a decrease in the $Ca(OH)_2$ content was observed qualitatively through XRD analysis and quantitatively through TG-DTA at the modified silica PCM-concrete interface compared to normal PCM-concrete interface. This suggests an increase in the extend of bond formation between silica compound and free $Ca(OH)_2$ (modified silica PCM cases) compared to the bond formation in normal PCM cases, thus the inclusion of silica fume contributing to the improvement of the interfacial performance in former cases.

Because of the absence of information about the bonding performance of PCM modified by silica fume as an overlay mortar under various influencing factors, more detailed experiments were designed to explore its effect on the interfacial bond performance. New research work was designed to study the effectiveness of modified silica PCM as a repair material based on a bi-surface shear test using three level of surface roughness (high, medium and low), concrete compressive strengths (two types), moistness of the interface (wet, dry and saturated surface dry condition) and early age behaviour (curing time) as an experimental parameter. It was observed that the inclusion of silica fume in the PCM significantly improves the interfacial bonding strength compared to normal PCM in each condition of surface roughness level and substrate concrete compressive strength. The moistness of the substrate concrete surface predominantly influenced the interfacial strength. The saturated surface dry interface state of substrate concrete facilitate bond strength development, especially in modified silica PCM cases. Significant improvement of the bond strength with the inclusion of silica fume were observed from the very first day of pouring of overlay mortar due the predominant reaction of silica compound with $Ca(OH)_2$ during the early hydration stage.

From the perspective of practical application of modified PCM overlaying method, long-term performance of the interface (durability) under the harsh environmental exposure were investigated, considering an individual action of freezing and thawing cycle (FTC), elevated temperature (constant and cyclic), and moisture content (continuous immersion, and wetting/drying (W/D) cycle) in the laboratory which resembles with the real environmental conditions. It was observed that the interfacial strength of normal PCM specimen under FTC decreased more quickly than that of modified silica PCM specimens. Mixing silica fume with PCM significantly increase interfacial bonding strength, provides better adhesion with substrate concrete, and improves the durability of the interfacial performance of concrete-PCM interface under harsh freeze-thaw environments. Normal PCM specimens resulted more decrease of interface strength than that of modified PCM specimens compared to their corresponding reference specimens under both constant and cyclic temperature exposure. Earlier occurrence of interface fracture and a greater number of pure interface fracture mode in normal PCM specimens compared to modified PCM specimens indicates higher adhesion of modified PCM overlay with substrate concrete with better durability. The interfacial strength of normal PCM specimens significantly reduced under both W/D condition and continuous immersion compared to the reference specimens, whereas it reduced insignificantly under continuous immersion exposure and moderately under W/D cycle compared to reference specimens in case of modified silica PCM specimens. The inclusion of silica fume significantly improves the interfacial bonding strength compared to without silica fume cases under the influence of moisture by wetting/drying and continuous immersion. The use of silica fume achieves adequate bond strength with concrete substrate, improves adhesion and durability under harsh environmental conditions.

For real application of the current work, performance of interface was also investigated at member level by conducting loading test of RC beams strengthened by both normal PCM and modified silica PCM overlaying with different types (steel rebar, CFRP grid and CFRP strand sheet) and amounts of reinforcement. Failure load of all strengthened beams were observed more than the unstrengthened beams. The occurrence of debonding failure delayed with the incorporation of silica fume compared to normal PCM strengthened beam or failure mode shifted to classical failure. In all cases, the crack numbers in strengthened beam with modified PCM were more than those observed in strengthened beam with normal PCM. Significant increase of ductility, peak load, debonding load were observed in modified PCM strengthened beam compared to normal PCM strengthened beam. The strain distribution of the strengthening bar in normal PCM specimens were unstable (many sudden jumps/variations with the load increase) compared to the modified PCM specimens, confirming uniform shear stress transfer at the interface between the strengthening layer and the substrate RC beam.

Conclusively, considering easy applicability of silica fume with PCM in practical application, environmentally friendly nature, and ability to achieve adequate bond strength with concretes substrate, this study can provide an indication to practitioner for engineering application of silica fume in polymer cement-based repair materials.