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SUMMARY OF DOCTORAL THESIS

Name: Muhammad Ashraf

Title: Sustainable Use of Industrial By-Products in Concrete and Its Characterization under Severe Conditions

(産業副産物を混入したコンクリートの特性と耐久性)

The recent industrial explosion is not only a major global environmental challenge but also rapidly exhausting the fragile resources of energy. This situation has potentially generated numerous economic, social and ecological issues especially in the developing countries. Since the production of ordinary portland cement is expensive and energy exhausting, therefore a sustainable safe environment emphasizes the need to use replacement material for cement. Recently a remarkable progress has been made in concrete research targeting energy conservation. Varied environmental conditions like acidic water, industrial effluents, or reactive aggregate, high sulfate soil, freeze-thaw condition, exposure to sewerage water, saline water, waterlogged- and hot conditions adversely affect concrete durability. The use of mineral admixture like fly ash and blast furnace slag or other natural pozzolanas could have perpetual effects on the durability of concrete in severe conditions. The experiments were carried out to evaluate the response of concrete to industrial waste [fly ash (FA) and ground granulated blast furnace slag (GGBS)] under diversified environments.

Investigations were made in the 1st experiment on the influence of mineral additives on mechanical, mineralogical and morphological properties of mortars under arid environmental conditions. Generally the arid environment characterized by high temperature and low humidity impairs the strength development and the durability of concrete. The early strength development of concrete enhances at higher temperature due to the accelerated rate of reaction during hydration. The low humidity expedites the moisture loss in the concrete paste and reduces its over all workability. During this experiment fly ash and blast furnace slag were used as mineral substitutive in the percentile ratio of 10, 20, 30 and 40, 50, 60. The specimens prepared from these ratios were subjected to the following four different curing conditions: i) normal curing i. e., by immersing in water at 20°C, ii) arid curing condition [40°C temperature plus 40% relative humidity], iii) 3-days normal curing and then arid curing, and iv) 7-days normal curing followed by arid curing. The experimental results showed that both fly ash and blast furnace slag additives exhibited higher compressive strength than control mortars under normal conditions whereas under arid conditions the compressive strength did not increase at all. The strength of mortars increased substantially by water curing in the arid environment. The X-Ray Diffraction analyses showed lower peaks

of calcium hydroxide in pozzolanic substituted mortars than control specimens under normal conditions. In arid environment dicalcium silicate and tricalcium silicate peaks were emerged along with calcium silicate hydrate and calcium aluminum silicate hydrate. Dispersed micro-structures were seen in arid specimens whereas in normal cured specimens regular and arranged pattern of microstructures were noticed.

In the 2nd experiment the adiabatic temperature fluctuations were determined in the massive concrete as controlled by the combination of fly ash plus blast furnace slag admixtures. Heat generated by the hydration of cement raises the temperature of concrete. In normal concrete construction, heat dissipates into the soil or air resulting insignificant temperature differences. Whereas in massive concrete structures such as dams, mat foundation and piers etc; the heat may not release readily. The temperature changes in the massive concrete develop tensile strain as well as stress causing thermal cracks and thus loss of structural integrity of concrete. The fly ash and furnace slag amendment appeared to reduce hydration rate in massive concrete structures. The combined effects of these mineral admixtures on adiabatic temperature rise in the massive concrete are not well understood. Two massive concrete specimens (size: $50 \times 50 \times 50$ cm^3) were designed incorporating combined mineral additives. Mechanical properties of massive concrete were measured at the stage of 8, 14, 28, 56, and 91 days. Samples were cored from the surface and central parts of the massive concrete specimens at the age of 91 days to determine compressive strength and dynamic modulus of elasticity. The findings showed that massive concrete specimen with no mineral additives exhibited a peak temperature as 64.5 °C after 7th hour of casting. The mineral substituted concrete gave its highest adiabatic temperature (49.6°C) after 19th hour of casting. We confirmed that the combined mixture of fly ash and blast furnace slag apparently lowered the temperature by 23% and delayed the evolution period of peak heat by approximately 3 folds. The lower rate of temperature rise in mineral incorporated concrete resulted in higher value of ultrasonic pulse velocity and compressive strength as compared to unsubstituted massive concrete specimen.

Third experiment was aimed to evaluate some mechanical features of concrete blended with fly ash and blast furnace slag admixtures under freezing and thawing conditions. Freeze-thaw cycling usually causes deterioration of concrete and became a major durability problem particularly in the cold regions. Studies have been carried out on the utilization of fly ash and ground granulated blast furnace slag as supplementary cementitious material. But the big challenge is to identify waste materials and their combinations so as to improve the cementitious nature of concrete. The reports on the optimal mix designs of cementitious materials for freeze-thaw conditions are scanty and poorly documented. The freeze-thaw tests were carried out on air-entrained concrete specimens as per Japan Industrial Standard (JIS A 1148-2001). Concrete samples were prepared with the four admixture ratios: control, 25% fly ash, 25% fly ash plus 25% blast furnace slag (FSC) and 50% blast furnace slag. The durability of concrete specimens exposed to 300 cycles of freezing and thawing was monitored by measuring density, ultrasonic pulse velocity (UPV) and dynamic modulus frequency after every 30 cycles. Our experiment demonstrated that the concrete parameters were substantially influenced by the addition of mineral additives. The mineral substitution improved durability factor (DF) substantially. The 100% DF recorded was remarkably encouraging under the combined effects of fly ash and blast furnace slag. The DF observed was more than 97% among all mineral substituted samples. Weight loss of concrete was not affected by the mineral additives. The blast furnace slag plus fly ash exhibited a weight loss of less than 0.5% at 300 cycles. No difference in ultrasonic pulse velocity was observed in FSC and furnace slag concrete samples; however, Portland cement and fly ash gave a reduced UPV. This preliminary study signified that FSC and blast furnace slag proved potentially beneficial for concrete durability.

The 4th research study was carried out to assess the influence of natural pozzolanas as partial substitutes for cement on the pozzolanic properties of lime mortar, cement paste, mortar and concrete. Since the role of natural pozzolanas is considered highly important when the concrete is subjected to acidic, alkaline, saline or waterlogged conditions, therefore, the studies on the influence of pozzolanic material on physico-chemical properties of mortar and concrete have received a greater attention in the recent years. Four natural pozzolanas-shale, slate, phyllite and volcanic ash were used as constituent mineral additives in the mortar at 10, 15 and 20% by cement replacement. In concrete specimens, the pozzolanas were utilized as 10, 20 and 30% by mass of cement. Compressive strength of the concrete specimens was measured at 7, 14 and 28 days, and flexural strength was recorded at the end of 28 days. Lime pozzolana reactivity test was carried out at 91 days. The use of pozzolanas produced substantial reactivity of the limed mortars. The compressive strength of cement paste, mortar and concrete was inversely related to the magnitude of pozzolan. As expected the compressive strength of all specimens increased with time irrespective of the additives. Phyllite and shale improved the strength of pastes and mortars more than slate and volcanic ash across all types of specimens. Water absorption capacity of cement paste specimens decreased whereas setting time and density increased by the pozzolan substitutions.

Based on these findings blast furnace slag and fly ash could prove to be technically sound and potentially serve as partial cement replacement materials at certain level. These materials exhibited proportional concrete strength in hot as well as freeze-thaw environment. The substantially higher durability factor of concrete emphasizes the need to use fly ash and blast furnace slag rationally in the mixed forms. The combined effects of additives lowered the hydration rate and were conducive to massive concrete durability. Moist curing was essentially important for pozzolanic activities in hard conditions. The disturbed micro-structural features signified the severe effects of hot environment on concrete. There is further need to validate these results for massive concrete under diversified conditions. This study would cover the fundamental information on safe and meaningful utilization of industrial wastes and would certainly help to develop a healthy environmental system.