学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

Compressive Mechanical Models of High Strength Mortar and Concrete under Severe Environmental Action

(過酷環境下における高強度コンクリートおよびモルタルの圧縮応力場における力学モデルの構築)

In recent years, it has been reported that the durability-related properties of mortar and concrete can be greatly improved with the incorporation of blast furnace slag (BFS) sand as the full amount of fine aggregates. Nevertheless, the mechanical properties of such mortar and concrete were not clarified yet. In the previous study, the author found improved monotonic behavior of high strength mortar with BFS sand compared to the ordinary mortar of high strength with crushed river sand (CS) in air and water. However, the mechanical behavior of high strength concrete with BFS sand subjected to the combined action of freezing and thawing and mechanical loading is not evaluated yet. Moreover, the constitutive laws for the analysis of RC structures built and repaired with such high strength mortar and concrete are not available. Therefore, this study aims to clarify the fatigue behavior and propose a simplified fatigue model of high strength mortar with BFS sand as fine aggregates in compression in air and water. The monotonic behavior of air-entrained (AE) and non-AE high strength concrete with BFS fine aggregates subjected to freezing and thawing cycles (FTC) is investigated and the stress-strain models of such concrete are formulated. Thereafter, the fatigue behavior of intact and frost-damaged AE high strength concrete with BFS sand is investigated and the S-N relationships for such concrete are proposed.

The fatigue compression tests were carried out on cylindrical BFS mortar specimens in air and water and the results are compared with those of ordinary (CS) mortar. The load was applied in the form of sine signal with constant amplitude and the frequency of cyclic loading was kept as 5 Hz. The stress level was varied from 60%, 70% and 80% of uniaxial compressive strength (f'_c). The damage progress is discussed based on the strain developments measured by using high-speed measuring system. Fatigue life (N_f) of both BFS mortar and CS mortar was also examined in air and in water. The experimental results reveal that BFS mortar exhibits longer N_f compared to CS mortar in air. Nevertheless, both types of mortar exhibit similar N_f in water and the N_f each mortar is shorter in water compared to air. This is because the adsorbed layers of moisture in the mortar during saturated state reduce the surface energy of the particles and consequently fracture energy of hydrated product due to the surface tension of water is reduced, resulting in a reduction in compressive strength of mortar in water. The other possible reason for the reduction of N_f of both mortars in water is because of pumping action and wedge effect of pore water pressure during the cyclic loading and due to leaching of $Ca(OH)_2$ while testing in water. Thereafter, the static stress-strain relationships for each mortar proposed by author in the previous study are extended to formulate the simplified fatigue model for the assessment of change in mechanical properties and for prediction of failure under cyclic loading. It is observed that the change in fracture parameter of each mortar under fatigue in air is almost similar as that of static loading. However, the fracture parameter for mortar subjected to cyclic loading in water reduces sharply compared to that in air and that of static loading. Therefore, the fatigue life of mortar in water is shorter compared to air. Moreover, at each stress level, the plastic strain development in CS mortar is higher in air and water compared to BFS mortar, resulting is rapid degradation and shorter fatigue life of CS mortar. The experimental results are compared those of obtained using proposed model, which shows satisfactory agreement.

In order to study the monotonic behavior of AE and non-AE high strength concrete with BFS fine aggregates concrete for different frost damage levels, the cylindrical and cuboidal specimens were used for carrying out freeze-thaw test according to ASTM C-666 type-A in 3% NaCl solution and the results are compared with AE normal concrete of normal strength and high strength concrete. The plastic strain measured during FTC test was used to explain the damage process. After certain number of FTC, the specimens were taken out from FTC chamber and were stored in controlled temperature room until the start of static compression tests. The experimental results show that overall rate of FTC equivalent plastic strain development in non-AE high strength concrete with BFS sand is slightly higher than that of AE high strength concrete with BFS and CS sand. However, it is slightly less than that of AE normal concrete. Higher the compressive strength of concrete, lower is the rate of plastic strain development for both AE and non-AE concrete. Moreover, the compressive strength and Young's modulus of AE concrete of both normal and high strength degrade at slower rate with the increase in FTC compared to non-AE concrete with BFS fine aggregates, because of less plastic strain development due to FTC in AE concrete. However, the mechanical properties of non-AE BFS concrete deteriorate at slower rate compared to non-AE normal concrete from the past study owing to high strength of non-AE BFS concrete. Nevertheless, the mechanical properties of each concrete change at almost same rate with the increase in FTC equivalent plastic strain. It is observed that Young's modulus of frost-damaged concrete reduces sharply compared to the compressive strength. In addition, the stress-strain model for frost-damaged high strength concrete are proposed based on the concept of elasto-plastic and fracture theory. It is observed that the rate of mechanical plastic strain in high strength concrete is less compared to that of normal concrete and consequently the fracture parameter of high strength concrete reduces slowly. The rate of mechanical plastic strain development increases with the increase in frost-damage, nevertheless, the change is fracture parameter is almost same for all frost damage levels. The relationships for fracture parameter and plastic strain for high strength concrete are formulated. The comparison between experimental and calculated results using proposed model show good agreement validating the model.

Lastly, the compressive fatigue tests were performed on intact and frost-damaged AE high strength concrete using BFS and CS fine aggregates. The sinusoidal wave of constant amplitude with frequency of 3.5 Hz was used for fatigue loading. The maximum stress levels (S_{max}) of 70%, 75% and 80% of f'_c were adopted. The S_{max}-N_f relationships for AE high strength concrete with BFS and fine aggregates are formulated. The N_f of AE BFS concrete is longer than that of AE high strength normal concrete at all stress levels and for all frost damage level. No significant effect of FTC is found on the N_f of AE high strength concrete because of very less frost damage caused by FTC. Moreover, overall the N_f of AE high strength concrete is more than that of non-AE high strength plain concrete from the literature. This difference is pronounced as the S_{max} decreases. It is found that the endurance limit of AE high strength concrete is at around 70% f'_c rather than 60% f'_c for non-AE normal concrete of normal strength and high strength.