学 位 論 文 内 容 の 要 旨

DISSERTATION ABSTRACT

博士の専攻分野の名称　博士（工学）　氏名　Idrees Zafar

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Corrosion Resistance of Steel Reinforcement in Fly Ash Concrete under Chloride Penetration

(塩分浸透を受けるフライアッシュコンクリートの鉄筋腐食抵抗)

Japan is now among the world's leading coal importers to fulfil its power generation demand and is generating more than 10 million tons of coal ash as a by-product from coal fired thermal power plants every year. The quantity of coal ash produced is estimated to increase due to the construction of new coal fired power plants to meet the power generation demands. To cope with the expected increase in the generation of coal ash in the future, the increase in its effective utilization in concrete, apart from dams and cement industry, is one of the important issues under focus. The increase in the utilization of fly ash in reinforced concrete structures like bridges and high rise buildings requires the durability aspect of the concrete to be tested. Specifically, in the region like Japan which is surrounded by sea and has harsh winter conditions (Hokkaido), the corrosion resistance of embedded steel subjected to salt attack becomes a primary concern. In this regard, the current study is focused on various stages of corrosion i.e. corrosion initiation, corrosion propagation, corrosion under flexural cracking in fly ash concrete with a main aim to understand the mechanism of corrosion in fly ash concrete and to recommend the increase in the usage of fly ash as a partial replacement of ordinary Portland cement in concrete to the construction industry.

In the first stage we evaluated the performance of fly ash concrete against the corrosion initiation subjected to chloride ion ingress. According to JIS A 6201, fly ash Type II which is recommended for use in concrete was used in this research. Two different replacement ratios of fly ash as a partial replacement to cement i.e. 15 and 30 percent at a constant water to binder ratio of 0.5 under different curing period of 28 days and 91 days with deformed and plain rebars were tested against 10 percent NaCl solution exposure. A lead-lead oxide electrode was embedded in all the specimen series to reliably detect the corrosion initiation of rebars in fly ash concrete along with combination of alternating impedance spectroscope. The experimental results have shown that the corrosion resistance was exceptionally improved for fly ash concrete with 30 percent cement replacement and combination of long curing and plain rebars. The fly ash concrete specimens having a cover depth of 20 mm with plain bar and curing of 91days have not shown corrosion initiation even after 7 years exposure to salt solution and are still under monitoring. The long curing period for fly ash concrete resulted in a dual beneficial effect of delaying the onset of corrosion due to lowered diffusion coefficient and pushing the chloride threshold values of fly ash concrete close to that of normal concrete. On the other hand the 28 day curing period for fly ash concrete led to the reduction in the corrosion initiation time along with the chloride threshold values. After 28 days of curing, the chloride threshold value for 30 percent replacement of fly ash was 0.41 percent by mass of binder, compared to 0.71 percent for normal Portland cement concrete. The chloride threshold value for fly ash concrete after 91days of curing, however, was increased to 0.66 percent by mass of binder. In addition it was also observed that the longer curing for fly ash concrete has resulted in better performance against corrosion than just increasing cover depth.

In the second stage the fly ash concrete was tested during the propagation period of corrosion from moderate to high corrosion rate. The corrosion state of the reinforcement in concrete containing 15 percent and 30 percent of fly ash as a partial replacement of cement was analyzed within specified limits of corrosion current density. Four

different series of reinforced concrete specimen based on the fly ash replacement ratio and curing period were tested against the salts solution exposure. All the reinforced concrete specimens were subjected to 10 percent NaCl solution to de-passivate the reinforcement bars. The specimens were of the same configuration as used for the initiation stage and an alternating current impedance spectroscope was used to obtain the impedance data at regular intervals of two weeks. It was observed that activation polarization was found to be the governing mechanism of rebar corrosion irrespective of the fly ash addition. In addition it was shown that during the propagation period, the corrosion resistance behavior of fly ash concrete is sensitive to curing period. Furthermore the fly ash concrete with a long curing had depicted the extended time period to reach the specific degree of corrosion but had also shown the highest surface corroded area and increased the probability of pitting corrosion.

In the third stage an effort was made to clarify the performance of fly ash concrete in the presence of flexural cracks against corrosion, under static loading conditions and different exposure conditions. The exposure conditions tested were wet-dry cycle, diffusion under gravity and diffusion against gravity or capillary suction. During all the exposure conditions the specimens were subjected to 10 percent NaCl solution for 106 days. All the specimens were of the same configuration as used for the initiation stage. The crack width for all the specimens was kept constant as 100 micro meters. A specially designed apparatus was used to generate the cracks and to keep the specimens under constant bending moment along with the application of salt solution only in the limited region. The measurement of half-cell potential was done by using Lead-Lead oxide electrode along with an alternating current impedance spectroscope, which was used to obtain the impedance data at the end of each cycle. The crack width was observed at the end of each cycle by using a digital microscope. After the completion of exposure duration, the specimens were cut to measure the chloride ion concentrations at the rebar level and also to visually observe the rebar condition, measure the corroded surface area and attack penetration of the rebar. The results of half-cell potential indicated that the corrosion initiation period for cracked fly ash concrete occurred to be the same as that of cracked normal Portland cement concrete in all the cases. The presence of cracks, irrespective of the fly ash replacement as a part of cement, can adversely affect the corrosion resistance of rebars embedded in concrete when exposed to salt solution under static loading. It was observed that fly ash concrete as compared to the normal concrete in cracked condition, subjected to 10 percent NaCl solution under all exposure conditions had shown suppressed values of corrosion current density. The better performance of fly ash concrete under cracked conditions is implied with considerations of high resistivity for fly ash concrete as compared to the normal concrete. Furthermore fly ash concrete had shown localized corrosion damage as compared to normal concrete under continuous application of salt solution through diffusion under gravity as well as capillary suction while suppression of localized corrosion was observed in cracked fly ash concrete, when exposed to wet and dry cycle under static loading. The different corrosion behavior for cracked fly ash concrete under different exposure conditions is mainly because of the difference in chloride ion movement along the crack as well as perpendicular to the crack.

Furthermore the electrochemical techniques applied on the laboratory scale during this study were used with the aid of X ray CT to evaluate the corrosion status of rebars in the real structures. The corrosion diagnosis of the steel reinforcement was done on a deteriorated bridge slab which had been in service for 38 years and a RC waste water outlet structure in electric power generation plant incorporating fly ash cement which is still in service for last 40 years. The electrochemical data has shown that the reinforcement in real structure incorporating fly ash are still in the passive state clearly indicating the high durability of fly ash against corrosion. The corrosion evaluation of real structures in service is of utmost importance from practical point of view.