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Micromechanical analysis of concrete and reinforcing steel exposed to high temperature

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HIGHLIGHTS

- Concrete, reinforcing steel have been exposed to high temperature.
- Microindentation of concrete, reinforcing steel samples pre exposed to temperature.
- Hot indentation of concrete samples only in heated state.
- Homogenization of microindetation results of concrete and reinforcing steel.
- Macroscale elastic modulus of concrete, steel obtained from micro scale properties.

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ABSTRACT

This study discusses determination of macroscale properties of concrete and reinforcing steel from micromechanical properties (elastic modulus) of individual phases in concrete (coarse aggregate, mortar), and reinforcing steel that have been exposed to high temperature through micro-indentation of their respective samples. Micro-indentation results are obtained by performing grid indentation. These results are then statistically analyzed through a deconvolution technique and a self-consistent homogenization scheme, to obtain the mechanical properties at macroscale. These obtained properties from samples are useful in assessing the nature and extent of damage that has taken place in concrete or steel due to high temperature expressed in terms of stiffness reduction. As a consequence this can provide a basis for designing a suitable structural repair with an understanding of the force flow in the element. Micro-indentation of concrete samples in hot state has also been undertaken, and these results suggest that combined thermos-mechanical loads result in more degradation of concrete due to thermo-mechanical coupling. Results of elastic modulus obtained from homogenization of micro-indentation data and the elastic modulus obtained from macroscale tests are in good agreement.

1. Introduction

Micro-indentation has become a useful method for the assessment of micro-mechanical properties of cementitious composites [9,10,15,22,26,29,31,35,36] and reinforcing steel [8,13] used in reinforced concrete structures. Properties such as elastic modulus, micro-hardness or creep [3,6,7,17,23] can be routinely investigated at microscale. Many examples of such application to cementitious composites, with special focus on the comparison of micro-mechanical properties of interfacial transition zone (ITZ) and those of bulk matrix have been published [14,18,20,37,38]. Cement based materials and natural rocks are among the most utilized materials essential to the construction industry. Studies on microscopic techniques, such as scanning electron microscope (SEM), transmission electron microscope (TEM) and image analysis, etc., have revealed that cementitious materials are complex, heterogeneous and composite, having a random microstructure [19,30] at different length scales, ranging from nano to macro scale. Therefore, when concrete and steel are exposed to high temperatures [16,25,28,33], reduction in stiffness and strength at micro level takes place which in turn reduces the overall stiffness and strength of the reinforced concrete element.

This work presents micro-indentation analysis of concrete and reinforcing steel exposed to high temperature. Micro indentation was performed on concrete and reinforcing steel samples that were *apriori* exposed to different temperature levels. Micro indentation was carried out to assess the changes that may have taken place

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in the micro mechanical properties such as the elastic modulus and micro hardness.

The main objective and contribution from this study is to determine the elastic modulus of concrete and steel at macro scale, that is obtained from the micro scale properties (elastic modulus) of individual phases in concrete (coarse aggregate and mortar) and reinforcing steel, that have been *a priori* exposed to high temperature over different periods of exposure. Samples in hot state (hot indentation - concrete samples only), using micro-indentation method have also been studied to assess effects of combined thermo-mechanical loads. This study is useful in assessing the nature, extent of damage and reduction in stiffness that has taken place in concrete exposed to high temperature. The results from the present study are useful for designing a suitable structural repair for concrete that has undergone damage due to thermos-mechanical loads, with an understanding of the force flow within the element. It is expected that micro samples of a damaged material that is tested in this manner can become a useful tool in damage assessment investigations.

Micro-mechanical properties of individual phases present in concrete, namely, coarse aggregate and cement mortar (only two phases) are measured in samples that have been exposed to different temperatures and time durations. The properties of interfacial transition zone (ITZ), between the cement mortar and coarse aggregate are not considered in this analysis. Micro indentation has been carried out on samples that have been extracted from three layers (top, middle and bottom) of a standard cylinder specimen (150 mm diameter and 300 mm in height).

This paper is organized in the following order. Macro level testing and sample preparation for micro indentation are discussed under Section 2. In Section 2, the details of the procedure to determine the macroscale properties(elastic modulus) of concrete and reinforcing steel has been discussed in Section 2.1 and, the details of sample preparation for micro indentation has been explained in Section 2.2 respectively. Section 3 presents the testing of samples for micro indentation. In Section 3, the details of micro indentation testing of test samples, apparatus and analysis procedures are discussed in Sections 3.1,3.2 and 3.3 respectively. Section 3.3.1, discusses the deconvolution method of analysis and Section 3.3.2 discusses the Self consistency method of analysis. The results and discussion of the present study has been presented in Section 4. The results and discussions of Deconvolution method (for individual phases in concrete and reinforcing steel) and homogenization technique (using self-consistent scheme), which are used to obtain the mechanical properties of concrete and reinforcing steel at macro scale utilizing the micro-indentation data, are discussed in Sections 4.1 and 4.2 respectively.

2. Macro level testing and sample preparation for micro indentation

2.1. Macro level testing: Concrete cylinders and steel rebars exposed to different temperature levels

Details of materials used and the macro scale testing procedure of concrete cylinders (uniaxial compression test) and reinforcing steel rebars (uniaxial tension test) that have been exposed to different temperatures over varying durations are described in detail in Sections 2.1.1 and 2.1.2 respectively.

2.1.1. Macro level testing of concrete cylinders: Casting, heat treatment and testing of concrete cylinders

The materials used to cast the concrete cylinders are Ordinary Portland Cement (OPC) having 53 grade (IS 12269,1987 [11]), fine aggregate used was river sand of grade II (IS 383,1970 [12]), coarse aggregate used was crushed granite stones passing 20 mm IS sieve (IS 383,1970 [12]) and potable water. Two concrete mixes having cylinder compressive strengths of 25 MPa and 35 MPa were adopted, to cast specimen concrete cylinders, having 150 mm diameter and 300 mm height in iron moulds. The concrete was compacted in iron moulds with the help of a needle vibrator. The concrete cylinders were demoulded after 24 h after casting and were immersed in water for curing for a period of 28 days. One set of concrete cylinders (having 25 MPa and 35 MPa cylinder compressive strengths) were heated in an electric furnace. The concrete cylinders were placed inside the furnace and were heated for a range of temperatures and exposure time as follows: 425 °C – 4 h, 550 °C – 4 h, 715 °C – 2 h & 4 h and 850 °C – 2 h & 4 h. The concrete cylinders heated to the above said temperature and exposure time were removed out of the furnace, and were allowed to cool in air until they attained ambient temperature. A second set of concrete cylinders were also heated in a similar manner to the above said temperatures and exposure time and, were allowed to cool in air until they attained ambient temperature. The first set of concrete cylinders which were exposed to heat was subjected to uniaxial monotonic compression tests, to assess their compressive strength and to obtain their stress strain response. The macro level elastic modulus, of concrete exposed to different temperature and exposure time was determined from the initial portion of the stress strain response. (The data corresponding to initial portion of the stress strain response of concrete, exposed to different temperature and exposure time has been tabulated in Tables TS1–TS14 in the Supplementary Section for reference). Electrical resistance strain gauges were adhered at the mid height of the cylinders in the axial direction, to record the axial strains of the cylinders when subjected to uniaxial monotonic compression, in a servo hydraulic material test system. Concrete chunks were cut using a diamond cutter from the second set of concrete cylinders, that were already exposed to the above said temperatures and exposure time.

2.1.2. Macro level testing of reinforcing steel rebars: Heat treatment and tension test

Reinforcing ribbed steel rebars having 415 MPa yield strength (Fe415) and 6 mm diameter were considered for the micro indentation study. Two sets (3 in one set) of reinforcing steel rebars, 300 mm in length were exposed to a range of temperature and exposure time as follows: 425 °C – 4 h, 550 °C – 4 h, 715 °C – 2 and 4 h and 850 °C – 2 h, in an electric furnace. The steel rebars were removed out of the furnace after exposure to the above said time interval, and allowed to cool until they attained ambient temperature. One set of steel rebars exposed to the above said temperature and exposure time were subjected to uniaxial tension test, to assess their tensile strength and their stress strain response. The macro level elastic modulus, of steel rebars exposed to different temperature and exposure time was determined from the initial portion of the stress strain response. (The data corresponding to the initial portion of the stress strain response of reinforcing steel, exposed to different temperature and exposure time has been tabulated in Table TS15 in the Supplementary Section for reference). An extensometer was fitted at the mid length of the steel rebars having a gauge length of 100 mm, to record the tensile strains. Steel samples were cut from the second set of reinforcing steel rebars exposed to different temperatures and exposure time as explained above.

2.2. Sample preparation for micro indentation: Concrete and reinforcing steel samples

In this section details of preparation of concrete and steel samples for micro-indentation has been described in sub Sections 2.2.1 and 2.2.2 respectively.