Assessment of microcrack development in concrete materials of different strengths

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ABSTRACT

Comprehensive microstructural investigations were performed on normal-strength (33 MPa) and relatively high-strength concrete (43 MPa) as well as concrete specimens with and without restraint against drying shrinkage movement. The effects of different load and environmental damaging phenomena (cold and hot environment) on concrete microcrack system were detected. Fluorescent and environmental scanning electron microscopy (ESEM) techniques with image analysis methodologies were employed to quantify microcrack attributes on planar sections. Stereological aspects were used to derive information on spatial (3-D) microcrack systems in terms of planar (2-D) quantitative data generated on perpendicular sections. Statistical analysis of data was used to determine the differences in microcrack characteristics between normal-strength versus relatively high-strength and unrestrained versus restrained specimens.

1. INTRODUCTION

Investigations of concrete microstructure are generally performed qualitatively using techniques such as visual inspection, microscopy, [1, 2] acoustic, [3, 4] neutron radiography, [5] and x-ray analysis. [6] Such analyses rely largely on investigator's experience to define different phases of cement and concrete, [7, 8] assess differences between concrete specimens, [9] identify chemical reaction/attack in concrete components, [10] or evaluate the conditions of concrete systems. [11, 12] Qualitative analysis approaches, however, lack the rigor and statistical viability of quantitative analysis approaches; besides, critical microstructure-property relationships cannot be developed unless the concrete microstructure is quantified.

Quantitative analyses of the concrete microstructure require powerful computational tools. [13-15] Previous studies visually investigated concrete microcrack and manually obtained planar measurements to relate microcrack attributes to concrete strength. [16] Recent developments in computer-based image processing and analysis and microscopy techniques provide powerful tools for quantitative microstructural investigation of concrete; and allowed to quantify microcrack density in mortar and cement paste. [17] Prior efforts towards quantification of damage characteristics in plain and fibrous concrete using microscopy tools were focused on the specific surface area of microcrack systems. [18, 19] More comprehensive quantification of microcrack development in concrete under different load and environmental effects can lead to development of structure (microcrack)-property relationships which provide substantial
insight into the performance and failure mechanisms of concrete. A quantitative comprehensive approach including specimen preparation, microscopy, image processing and stereological and statistical analysis techniques were integrated and dedicated to numerical investigation of the concrete microcrack system. Application of these methodologies towards comparative investigation of microcrack characteristics in normal-strength versus relatively high-strength and normal-restrained versus normal-unrestrained concrete specimens under different damaging load and weathering phenomena are reported herein.

2. EXPERIMENTAL PROGRAM

Two concrete mixtures were considered in the experimental program: (1) normal-strength “Mix I” (unrestrained and restrained specimens) and (2) relatively high-strength “Mix II”. Type I Portland cement and natural sand were used in both mixtures. Crushed limestone with maximum particle size of 19 mm was used as coarse aggregate in the normal-strength mix, with cement : fine aggregate : coarse aggregate : water mass ratios of 1 : 1.59 : 1.98 : 0.514, targeting 28-day compressive strength of 33 MPa. This mix was air-entrained, and provided an air content of 3.5 percent with a slump of 190 mm. The relatively high-strength mix incorporated natural granite with maximum particle size of 10 mm as coarse aggregate; it also incorporated silica fume and superplasticizer, with cement: fine aggregate : coarse aggregate : water mass ratios of 1 : 1.7 : 0.9 : 0.42 : 0.2, targeting 28-day compressive strength 43 MPa. This mix provided 1.9 percent air content and a slump of 64 mm. Mixtures I and II were designed to reach compressive strength of 30-35 MPa and 40-45 MPa, respectively. The following specimens were molded and consolidated throughout the research study: 76 × 76 × 305 mm prismatic specimens for compression tests; 152 mm diameter and 63.5 mm height cylindrical specimens for drop-weight impact testing. Restrained normal-strength concrete specimens were kept moist for 24 hours, after which they were stored (without demolding) for 28 days at 55°C for hot weather exposure or at −3.5°C for cold exposure, and then demolded and conditioned at 50% relative humidity and 22°C for 180 days. The restraint against shrinkage was effective as far as the specimens were not demolded. The relatively long period of conditioning of molded specimens allows for development of shrinkage microcracks.

3. MICROSTRUCTURAL ANALYSIS PROCEDURES

The proposed approach to microstructural investigation of concrete starts with preparation of concrete specimens. This step generates a sharp contrast between features of interest (microcracks and voids) and the body of concrete; automated image processing/analysis schemes can thus be used to detect and quantify the features of interest. For the purpose of specimen preparation, two pairs of two perpendicular sections were cut out of each specimen. One pair was cut in the direction of loading and the other parallel to the direction of loading or in the longer and shorter directions of concrete specimens when no mechanical loads were applied. One pair of sections was used for fluorescent microscopy and the other for the environmental scanning electron microscopy “ESEM” (backscattered technique). In order to provide a sharp contrast between the microcrack system and body of concrete in ESEM, the concrete sections were impregnated with Wood’s metal. [20] For the purpose of fluorescent microscopy, a two-stage ink/fluorescent epoxy impregnation was used to enhance the contrast. Wood’s metal impregnation starts with vacuum-drying of the specimen at 6.65 kPa for 30-40 minutes, after which the specimen is heated (under vacuum) to 93°C for 1-2 hours in order to allow for melting of Wood’s metal. Subsequently, the specimen is subjected (with vacuum turned off) to nitrogen gas at a pressure of 1.94-2 MPa for 3-4 hours in order to allow Wood’s metal to penetrate concrete (while the vacuum is off). The following configuration was used for environmental scanning electron microscopy of concrete as accelerating beam voltage of 20 kV, and a vacuum of approximately 1 × 10⁻⁵ kg/m². Ink-epoxy impregnation starts with vacuum-drying of the specimen at 2.66 kPa for at least one hour, then allowing ink to immerse the specimen. Subsequently, the specimen is subjected to nitrogen gas at pressure of 1.94 MPa for 18-24 hours, after which the specimen is dried in oven at 60°C for 24 hours to dry the ink. A similar procedure is then repeated to impregnate the specimen with fluorescent epoxy resin (except that the specimen is subjected to the nitrogen gas pressure for only 3-4 hours). Specimens were lapped using a lapping machine with abrasive liquid under 0.021 MPa (3.0 psi) pressure to remove the thin film of epoxy dye. All specimens were subjected to similar sequences of specimen preparation; they are thus affected similarly by the specimen preparation steps.

Each section was investigated 3 times at different magnifications (125X, 250X, 500X) using either of the two microscopy techniques. A total of 144 images were captured from each section at 125X magnification, and 256 images were captured from each section at 250X and 500X magnifications; these selections were made based on statistical criteria to yield representative data. Images were