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Strain energy and process zone based fracture characterization of a novel iron carbonate binding material

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ABSTRACT

The fracture behavior of a novel structural binder developed using carbonation of metallic iron powder is investigated using notched beams under three-point bending. The iron-based binder demonstrates significantly higher fracture energies compared to conventional ordinary Portland cement binders in both unreinforced and glass fiber-reinforced states. The influence of metallic iron particle inclusions and the carbonate binder on the strain energy release rates (R) and width of the fracture process zone (FPZ; which is the zone of strain localization at the tip of the crack) are evaluated and compared to that of Portland cement-based binders. Tensile constitutive response of these binders is extracted using a crack-face bridging model. The control and fiber-reinforced iron-based binders demonstrate higher tensile strength and ultimate strain capacity as compared to conventional cementitious binders.

1. Introduction

The past decade has seen the emergence of several alternatives to ordinary Portland cement (OPC) for building and infrastructural construction. Most of the alternative material systems rely on partial replacement of OPC, at levels varying from 20% to 50% (mass-based), by industrial waste or by-product materials including fly ash and blast furnace slag [1–4]. Attempts to develop OPC-free binding systems also had varying degrees of success, as exemplified by the development of geopolymers that use fly ash or metakaolin as the primary source materials [5–7], or alkali-activated slags [8,9]. This paper reports on the properties of an OPC-free binding system, synthesized in an unconventional, yet highly sustainable manner. Here, metallic iron powder discarded as waste from industrial shot-blasting operations or foundries is carbonated at ambient temperature and pressure to yield a binder with beneficial properties. The added benefit of this approach is that CO_2 emitted by an industrial operation such as a thermal power plant, or OPC production is sequestered permanently as carbonate in the binder material, thus ensuring that the material is carbon-negative.

A series of recent studies by the authors have described the material development, characterization, and properties of this novel binder [10–12]. Iron carbonate binders have been proportioned to attain compressive strengths in the range of 35–40 MPa, which is the upper limit of strength for more than 90% of OPC-based concretes used in practice. However, these matrices have been shown to demonstrate flexural strengths that are much higher than that of OPC-based systems. The

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Nomenclature

CMOD	crack mouth opening displacement
CTOD	crack tip opening displacement
e_{xx}, e_{yy}, e_{xy}	Lagrangian strains
FPZ	fracture process zone
DIC	digital image correlation
G_F	fracture energy
G_R, R	strain energy release rate
G_{elastic}, $G_{\text{inelastic}}$	elastic and inelastic components of strain energy release rate
σ	standard deviation of the normal distribution
σ_b	crack face bridging stress
w_b	crack-opening displacement
${\sigma_b}^0$	critical bridging stress
${w_b}^0$	maximum crack opening displacement
${l_b}^0$	bridging zone length
E	elastic modulus
ε_t	tensile strain

iron-based binder system has also been shown to provide significantly higher fracture resistance than conventional OPC-based systems [12]. Detailed characterization of the material microstructure and pore structure to establish the factors that aid in these performance features, most notable of them being the presence of elastic, partially reacted or unreacted metallic particles show the effect of these particles on crack bridging and deflection [11]. The study presented here investigates the fundamental reasons for the beneficial fracture performance of these binder systems through the evaluation of the fracture process zone (FPZ), defined as a complex localized zone of energy dissipation around the propagating crack, containing the main crack as well as various branches of secondary and micro-cracks. The development of FPZ in the iron-based binder systems will be significantly different from those of OPC-based systems due to the differences in the material microstructure, especially the presence of iron particles. The influence of fiber reinforcement in these systems is also explored with respect to its synergistic action with the matrix response, which also is very different from those of OPC-based systems.

By extending the evaluation of the fracture responses, the tensile constitutive behavior of the novel iron-based composite binder is extracted from resistance curves. The fracture energy is compared with the cohesive toughness of a unit tensile stress–crack width model [13,14] to predict the tensile response. The differences in tensile response between OPC and iron-based binder systems are elucidated. Results are further investigated for the strain localization and crack propagation behavior of the novel binder using Digital Image Correlation (DIC). Adoption of suitable analytical models for tensile response, and comparison with OPC systems are expected to provide useful insights that aid in the development of guidelines for widespread use of this material.

2. Experimental program

2.1. Materials, mixtures and specimen preparation

Metallic iron powder with a median particle size of 19 μm was used as the major starting material in this study. The iron powder was obtained from an industrial shot-blasting facility in Phoenix, AZ. The elongated and angular iron particles provide beneficial increased reactivity due to higher surface-to-volume ratio of the particles [10,11]. While the particle size distribution and shape of the iron powder is likely to influence the strength and fracture behavior, only one type of iron powder has been investigated in this study. The other additives used in the binder preparation included Class F fly ash and metakaolin conforming to ASTM C 618, and limestone powder (median particle size of 0.7 μm) conforming to ASTM C 568. Here fly ash was added as a silica source to potentially facilitate iron silicate formation [15–17] and limestone, to provide nucleation sites for reaction. Further details on mixture proportioning of this novel binder material can be found in [10]. In order to reduce the water demand and to maintain the cohesiveness of fresh mixture, a clay phase (metakaolin) was added. An organic reducing agent/chelating agent (oxalic acid in this case) was also added to facilitate better dissolution of the metallic iron and enhance its reactivity. Commercially available Type I/II OPC conforming to ASTM C150 was used to prepare conventional cement pastes to facilitate property comparisons with the novel binder. The chemical compositions of all the materials used here can be found in our previous publications [10–12]. The particle size distributions of the components of the blended mixtures are shown in Fig. 1. Iron powder is coarser than all the other materials used. While the results may vary depending on fineness and content of iron powder, the basic trends of the results are expected to remain same.

The binder component used in this study includes 60% iron powder, 20% fly ash, 8% limestone, 10% metakaolin and 2% oxalic acid by mass. These proportions were arrived at based on strength and porosity of several trial mixtures [10]. The