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Preface

This Geotechnical Special Publication has a collection of papers presented at GeoHubei International Conference – Sustainable Civil Infrastructures: Innovative Technologies and Materials, held during July 20 to 22, 2014 in Hubei, China. These papers were presented at the following technical sessions at the conference including 1) Soils and Rock Instrumentation, Behavior and Modeling; 2) Foundation Failure and Repair; 3) Bridge Approach Embankment; and 4) Engineering Issues in Ground Subsidence.

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Pathologic Interpretation of Loading and Cracking Process of SCARC Specimens Using Fiber Bragg Gratings

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ABSTRACT: An experimental procedure for load monitoring and fracture detection with FBG strain sensor arrays on a cylinder with back-filled material is described in this paper. This study was conducted as part of a coal-fire-energy byproduct mitigation technique, where incinerator ash was subjected to enhanced carbonation techniques to craft a material called ash carbon concrete (ACC). ACC is a dual porosity material constituted of variable amounts of incinerator ash, aluminum, carbon dioxide (CO_2), and water for the purpose of encouraging long term CO_2 mineral sequestration. The simulated carbon-ash retention cylinder (SCARC) was created as a host cell for ACC and fiber Bragg grating (FBG) monitoring. The optical strain sensors enable the archival of material forming and backfill interaction history. The test results indicate that SCARC can successfully capture the curing expansion and strain development rates of different ACC blends.

INTRODUCTION

Properly directed civil and energy infrastructure systems are complex interdependent assets, often crossing geographic, political, and cultural boundaries. The design, construction, operation, and maintenance of these critical infrastructure systems must hold paramount the safety, health, and welfare of the public they serve and affect (ASCE 2009). Continuous aging of critical infrastructural systems and the recognition of system improvement potential have prompted the proposal of many novel technologies and management strategies to address infrastructural operation including associated environmental protection.

One very important environmental issue is how to enhance the use of energy byproducts. In 2011, approximately 130 million tons of solid coal combustion byproducts were produced in the

US, of which 43.5 percent was reclaimed for productive implementation (American Coal Ash Association 2012). Regulatory uncertainties regarding the enhanced cost of material, labor, and operations of carbon control and sequestration are affecting the confidence levels of coal energy capacity planning (U. S. Energy Information Administration 2013).

One proposed technology is the carbon reduction and entombment of ash treatment (CREAT). CREAT technology exploits chemical and physical processes to concurrently stabilize solid wastes and greenhouse gas, in a material called ash carbon concrete (ACC). ACC is composed of fly ash, Portland cement, percolation agents, and water, and provides a highly porous host matrix for maximizing the chemical carbonation and physical storage of carbon dioxide (CO_2).

The expansion of ACC, and saturation of CO_2, will inflict significant internal pressure on any type of subterranean setting. Though some CO_2 is chemically stabilized by ACC carbonation, ambient CO_2 from pore oversaturation is eligible for transmission from a system breach. This makes physical storage partially reliant on the adjacent infrastructure. Special considerations should be given to implement an ACC monitoring strategy capable of promoting safety and material economy.

The ability to assess the timely occurrence of damage is dependent on two variables: 1) the sensing array and 2) the data-to-damage interpretation. The most common solution for ensuring the endurance of a sensor system is sensor redundancy coupled with intelligent processing. In a damage event, the sensors nearest the region of interest are not only the most likely to fail, they are also the most informative of the system's structural integrity. In this paper, a basic ACC monitoring regime using FBG strain sensors is being investigated. Preliminary experimental results are reported, which demonstrates the strain history of the encapsulated ACC material within a cementitious cylinder.

Optical Fiber Bragg Grating (FBG) Sensors

Fiber Bragg gratings are a subset of fiber optic sensing (FOS), possessing significant advantages like high accuracy, small size, corrosion resistance, and strong networking capabilities (Cappa 2006). Bragg gratings are intrinsic stop-band filter sensing elements, inscribed on single mode silica fibers, capable of forming multifunctional, multiplexed, systems. signals indicative of external parameters (Hao 2007). The reflected bandwidth, or Bragg wavelength (λ_B), is a function of the grating orientation (Λ) and the fiber core's effective refractive index (n_{eff}), as given by

$$\lambda_B = 2\ \Lambda\ (n_{eff}) \tag{1}$$

Light at other wavelengths is transmitted with minimal attenuation. The refractive index and the grating orientation vary with mechanical strain and thermal excitation. The Bragg wavelength shift can be summarized as

$$\frac{\Delta\lambda_B}{\lambda_{B_0}} = (1 - \rho_e)\ \varepsilon + (\alpha + \xi)\ \Delta T \tag{2}$$

where ρ_e is the effective photo-elastic constant of the fiber core, ε is the longitudinal strain, λ_{B_0} is the original Bragg wavelength value α is the thermal unit effect on grating orientation, ξ is the thermo-optic coefficient, and ΔT is the unit change in temperature. ρ_e is a function of the photo-elastic tensor of the fiber core material. (Zhou 2003, Yan 2007). It is possible to decouple the mechanical and thermal effects on the Bragg wavelength shift by manipulating the FBG boundary conditions.

Damage Interpretation

One of the defining attributes of health monitoring is that most sensors cannot directly measure damage. Feature extraction through signal processing is necessary to convert sensor data into damage information (Farrar 2010). The relationship between a measured quantity (i.e. strain) and a desired field (i.e. stress) often share some formulated proportionality or direct equation. In the case of complex damage conditions, the function/relationship linking a measured quantity to particular damage states must be extrapolated from the data itself (Worden 2007). This data-driven approach requires solutions with correct damage classification that can be archived and correlated to future data collections (Moore 2012).

EXPERIMENTAL SCARC MONITORING

The Simulated Carbon Ash Retention Cylinder (SCARC) was developed to provide a small scale containment unit, upon which ACC induced damage states (material expansion due to CO_2 injection) could be assessed. In the case of internal expansion pressure, the fracture process is somewhat randomized, as there is an even planar stress distribution under idealized conditions. Observing the failure time and location is difficult because subsurface flaws are often undetermined and visually undetectable.

The SCARC specimens can be conceptualized as thirty centimeter long un-axially restricted pressure vessels because of the relative wall thickness, as shown in Table 1. The strain in the circumferential direction was considered paramount because similar vessels, loaded only with internal pressure, develop minimal axial stress. The likely failure mode for SCARC specimens was predicted as a first-mode fracture, initiating on the interior surface, due to the circumferential stress concentration from internal/external surface flaws.

Table 1. SCARC dimensions prior to ACC application. All dimensions in cm.

Specimen #	1	2	3	4	5	6	7	Avg
Out Radius (Max)	15.7	15.9	15.9	15.9	15.8	15.9	15.9	15.86
Out Radius (Min)	15.2	15.4	15.2	15.4	15.4	15.7	15.4	15.39
Wall Width (Max)	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Wall Width (Min)	2.8	3	3	3	3.2	3	3	3

Compression tests were conducted on separate specimens for preliminary evaluation of the strength of the material used to cast the walls of the SCARC specimens. The average failure strength for the cement was 34.2 MPa, well beyond the standardized minimum strength of 28 MPa (C150 2013). The majority of cylindrical specimens showcased a brittle columnar vertical cracking failure mode.

FBG Strain Sensor Instrumentation

The proposed template for FBG application to SCARC specimens is shown in Figure 1. The eight FBGs applied to each optical fiber were angularly arrayed at forty-five degrees. The distribution of FBGs is shown in Table 2. Overall, 154 functional FBG strain sensors were directly applied to seven SCARC specimens. It should be noted that all fibers with less than eight functioning sensors experienced failure during the application phase because of the delicate nature of bare silica fiber.

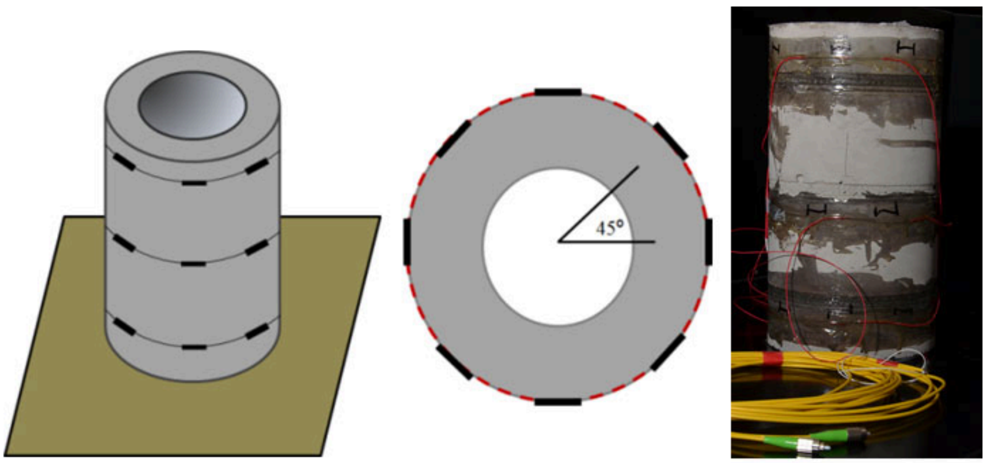

FIG 1. The proposed template for FBG application to SCARC specimens.

Table 2. Distribution of the functional Bragg gratings on the seven SCARC specimens.

Specimen #	1	2	3	4	5	6	7
Top Fiber Sensors	8	8	7	8	8	8	8
Middle Fiber Sensors	8	4	8	8	8	8	7
Bottom Fiber Sensors	8	0	8	8	8	8	8

ACC Introduction to SCARC Specimens

The constituents of the ACC material were cement, fly-ash, water, powdered aluminum, and carbonated water. The highly porous cellular structure is due to the reaction of aluminum with calcium hydroxide, which releases hydrogen gas and forms voided cavities (Kurama 2009). Table 3 displays the ACC blends introduced to each SCARC specimen. The ACC constituents were introduced to the voided central regions of the SCARC specimens and circumferential strain data was recorded.

Table 3. ACC constituents for each SCARC specimen.

Specimen #	1	2	3	4	5	6	7
% Fly Ash	50	0	0	50	50	50	50
CO_2	Yes	No	Yes	No	No	Yes	Yes
20 g Al	Yes	Yes	No	Yes	Yes	Yes	Yes

EXPERIMENTAL RESULTS

The extent of the temperature effect on the Bragg wavelength was investigated by modifying the boundary conditions of a single FBG on the first SCARC specimen. The second FBG on the top fiber was not fixed to the surface of the SCARC. This allowed the FBG to possess freedom from mechanically induced wavelength shifts, effectively isolating temperature as the dominant variable.

Damage Location and Severity

The most outstanding damage qualifiers were abrupt fluctuations in the circumferential strain resulting from subsurface crack development, or surface crack opening. The first strain fluctuations within each specimen were documented, as shown in Table 4. The time of initial strain fluctuations varied significantly depending on ACC expansion rates and severity of prior specimen flaws.

Table 4. Observations of early strain output fluctuations.

Specimen #	1	2	3	4	5	6	7
Strain Instability (s)	1169	5450	7230	531	10503	7325	1339

Advancing under the assumption of mode-I cracking as the dominant damage state, damage location and simple designations of damage severity can be assessed by isolating concurrent strain fluctuation in adjacent SCARC regions. The simplest assessment of damage location can be conducted when visually detectable cracks propagate within the boundaries of the actual sensor. Many data sets correlating temporal strain trends to the occurrence of damage states were recorded. A sample data set for correlative analysis is provided in Figure 2. In this example, a fully penetrating crack along the entire axial length of SCARC 3 was noted.

General observation showed that the crack developed adjacent to two FBGs (Ch3-7 and Ch3-8) and passed directly beneath two FBGs (Ch1-6 and Ch2-8). The strain output from the designated FBGs were isolated, and scrutinized for significant outlying data trends. Recognizing that the crack bisected two FBGs, it was likely that the damage event would be compatible to extreme tensile strain output at those locations. The FBGs on the lowest fiber (Ch3-7 and Ch3-8), adjacent to the crack, experienced a different phenomenon; the crack damage created a mechanism which removed significant tensile strain from the area of influence. Based on the strain reactions in Figure 2, it can be declared that the crack achieved full penetration near the fixed base of the SCARC specimen and immediately propagated to the central region (Ch2-8) at 13,100 seconds. After a period of system stabilization for 1,400 seconds, the crack achieved complete axial growth at 14,500 seconds.