ICM11

Characterization and performance optimization of a cementitious composite for quasi-static and dynamic loads

W.F. Heard[a,b], P.K. Basu[b], T. Slawson[a], B. Williams[a], N.A. Nordendale[b], a*

[a]U.S. Army Engineer Research and Development Center, 3909 Halls Ferry Road, Vickburg, Ms 39180, USA
bDepartment of Civil and Environmental Engineering, Vanderbilt University, VU Station B 351831, 2301 Vanderbilt Place, Nashville, TN 37235, USA

Abstract

The U.S. Army Engineer Research and Development Center conducted multi-scale material research directed towards enhancing the response of a rapid-set, high-strength geopolymer cement under quasi-static and dynamic loads. Four unique tensile experiments were conducted to characterize and optimize material response of the fiber, matrix, and interface. Single-fiber direct tension and single-fiber pull-out experiments were conducted with quasi-static and dynamic loads. Flexure from third-point loading and direct uniaxial tension of the fiber reinforced composite experiments was conducted with quasi-static loads. Initial results are presented for the ongoing research.

1. Introduction

A mission of the Geotechnical and Structures Laboratory of the U.S. Army Engineer Research and Development Center (ERDC) is to provide innovative engineering and scientific solutions to protect the U.S. warfighter and critical facilities. As observed in recent U.S. military operations, nontraditional threats and tactics from terrorists have presented new challenges to providing force protection for troops in foreign theaters of operation. In response, the ERDC has focused research efforts on advanced cementitious composites with randomly distributed fiber reinforcement. As with most cementitious

* W.F. Heard. Tel.: 601-634-2616; fax: 601-634-2341.
E-mail address: William.f.heard@usace.army.mil

Report Documentation Page			Form Approved OMB No. 0704-0188

1. REPORT DATE **2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Characterization And Performance Optimization Of A Cementitious Composite For Quasi-Static And Dynamic Loads	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Engineer Research and Development Cente,3909 Halls Ferry Road,Vickburg,MS,39180**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Procedia Engineering, Volume 10, 2011, Pages 3028-3033, 11th International Conference on the Mechanical Behavior of Materials (ICM11)

14. ABSTRACT

The U.S. Army Engineer Research and Development Center conducted multi-scale material research directed towards enhancing the response of a rapid-set, high-strength geopolymer cement under quasi-static and dynamic loads. Four unique tensile experiments were conducted to characterize and optimize material response of the fiber, matrix, and interface. Single-fiber direct tension and single-fiber pull-out experiments were conducted with quasi-static and dynamic loads. Flexure from third-point loading and direct uniaxial tension of the fiber reinforced composite experiments was conducted with quasi-static loads. Initial results are presented for the ongoing research.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

materials, these materials tend to exhibit a brittle tensile failure response. However when optimized, they can provide protection from blast and weapon fragmentation.

A particular cementitious composite of interest is an inorganic polymer cement or "geopolymer" cement. The term "geopolymer" stemmed from research by Davidovits [1] on inorganic polymers and refers to a broad class of alkali aluminosilicate materials. For the material investigated in this research program, a Class C [2] fly ash was combined with an alkali metal salt of citric acid. No hydraulic or Portland cement was used in the mix. To enhance tensile response, randomly distributed short discontinuous fibers were added to the geopolymer cement. A polypropylene fiber was selected and is shown in Figure 1. The fiber is approximately 41-mm long and consists of several monofilament polypropylene fibers bundled by two larger diameter helical monofilament fibers. After water is added to the dry cementitious mix followed by the polypropylene fibers, the material hardens and achieves 44 MPa in unconfined compression in 24 hours of curing and 62 MPa in 28 days at ambient temperatures with no additional curing requirements.

2. Description of Experiments

Four sets of experiments were conducted to quantify tensile properties of the fiber, matrix, and interfacial bond. First, individual fiber tests were conducted to establish the tensile strength of an individual fiber under a displacement-controlled load. To determine a dynamic increase factor for the fiber, these tests were conducted with four displacement rates. Secondly, for fiber pull-out tests, single fibers were embedded in the matrix at different embedment lengths and were also tested at different displacement rates. The single fiber pull-out experiments were conducted to establish the load versus displacement relationship and to determine the pull-out response to applied static and dynamic loads. The third experimental set was designed to capture the response of a fiber reinforced coupon subjected to a quasi-static direct uniaxial tensile load. The fourth experimental series was conducted to determine flexural performance of a beam with third-point loading. Each experimental setup is described below.

2.1 Individual fiber

The individual fiber experiments were conducted on an Instron Electropuls universal testing machine (UTM) with a 2-KN load cell. A closed-loop setup with a displacement-rate control ranging from 2.54 mm per minute to 25,400 mm per minute was provided by a built-in linear variable displacement transducer (LVDT). The sample rate for the LVDTs ranged from 13 Hz to 5000 Hz as required to collect enough data points to capture peak load for the various displacement rates used for the experiments. The fiber ends were set in epoxy and cured for 24 hours. This prevented slippage between the fiber and the grips and ensured that all of the bundled fibers were engaged, thus identifying the load capacity of the fiber independent of the bond. Further, transfer of load through the bond proved necessary, as preliminary tests with the fiber clamped directly in the UTM grips resulted in premature failure at the grips due to induced localized stresses. For the individual fiber tension experiments, a minimum of six fibers were tested at each displacement rate.

Fig. 1. Bundled polypropylene fiber

2.2 Single fiber pull-out

Single fiber pull-out experiments were conducted to determine the bond capacity between the matrix and the fiber. These tests were also conducted on the Instron Electropuls UTM with a 2-KN load cell and a displacement-rate control ranging from 0.254 mm per minute up to 25,400 mm per minute. Sample rates ranged from 13 Hz to 5,000 Hz as needed to capture peak response just prior to slippage between the fiber and matrix. Samples were cast with fibers embedded at 6.7 mm (L/6), 10.3 mm (L/4), and 20.5 mm (L/2). Figure 2 shows the specially designed mold (to position the fiber at the desired embedment depth) and a sample being tested in a single fiber pull-out experiment.

2.3 Direct uniaxial tension

In the literature, there appears to be no consensus on the recommend procedure for testing concrete in direct uniaxial tension. Some researchers attempted a uniform sample geometry with various epoxy bonded end designs to transfer the load to the sample through the grips of the UTM. However, this approach requires tedious sample preparation and allows the potential for slippage due to inadequate strength of epoxy. More importantly, this method tends to induce significant clamping forces on the sample area held within the grips of the testing equipment. An alternative approach is to use a variation in sample geometry near the ends to enable load transfer through friction. With this approach, stress concentrations are developed at any abrupt change in sample geometry. However, the sample geometry can be designed to minimize this effect. The Japan Society of Civil Engineers [3] adopted a recommended procedure for testing HPC under direct uniaxial tension employing this method. This procedure formed the impetus for conducting the direct tension experiments on the geopolymer concrete specimens. The sample geometry used in the study is shown in Figure 3 (a). Tests were conducted on an MTS 810 testing machine with a 98-KN load cell. The loading machine head was monitored with a built-in LVDT to maintain a displacement rate of 0.5 mm per minute throughout testing. Head displacement was recorded in addition to measurements obtained using two external LVDTs. The external LVDTs were Honeywell Model S5 with a ±5-mm stroke and were mounted on the sides of the sample slightly above the tapered region. The LVDTs were also positioned beyond the front of the sample plane on the right side and beyond the back of the sample plane on the left as shown in Figure 3 (b). Position of the LVDTs ensured that any possible eccentricity along two axes would be captured in the data. The sample rate for the exterior LVDTs was 20 Hz, or one sample every 0.05 second.
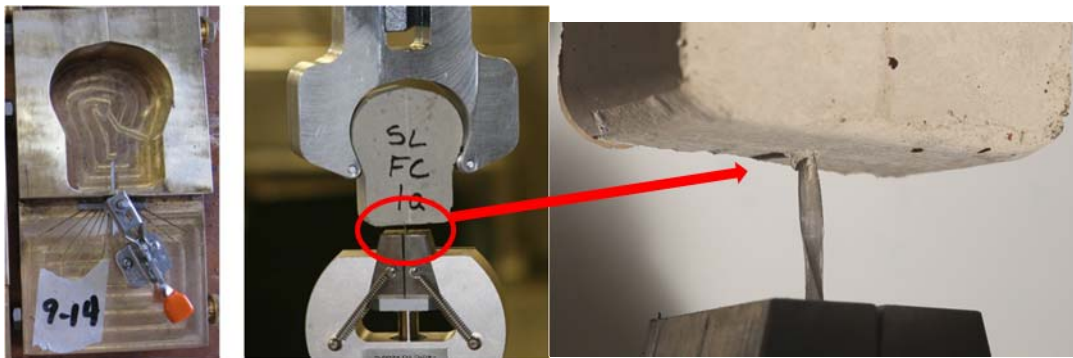

Fig. 2. (a) Fiber in mold ready for casting; (b) fiber pull-out experiment; (c) close-up of fiber during testing

2.4 Beam flexure with third-point loading

To observe flexural performance and quantify flexural toughness of the geopolymer concrete, a third-point loading experimental series was conducted on 8 beams with and without fiber reinforcement. These experiments followed the recommended procedure of ASTM 1609 [4]. Beam dimensions were 73-mm wide by 73-mm tall with a 228-mm clear span. The beam dimensions and span were the only modifications to the ASTM 1609 standard, which suggests 100-mm width, 100-mm height and a 300-mm span. However, ASTM 1609 also states "a specimen size different from the two preferred specimen sizes is permissible". Since the ratio of beam-depth to span was maintained, and ASTM 1609 allowed for alternate dimensions, this variation seemed acceptable. The beams were tested in the MTS 810 testing machine with a 98-KN load cell. The closed loop experiment was controlled by an internal LVDT providing a displacement control rate of 0.1 mm per minute. Additional displacement data were recorded from two external LVDTs mounted at mid-span on the front and back sides of the beam. The external LVDTs were mounted on a rectangular jig as shown in Figures 3 (c) and (d). The gage mount and rectangular jig are attached to the beam directly above the beam supports, thus ensuring accurate measurement of mid-span net deflection, exclusive of any support settlement or twisting in the beam, as the load was applied. Data were acquired at 20 HZ.

3.0 Results

Table 1 summarizes the average peak load and standard deviation of the peak load for the individual fiber tension experiments. These values were generated from six tests at each displacement rate. For all tests, the fiber failed without slippage in the epoxy bond. This satisfies the requirement of identifying the fiber strength independent of the bond while engaging all of the bundled fibers. Figure 4 (a) illustrates an example of the data collected from the single fiber pull-out experiment and the relative comparison between interfacial bond strength and fiber strength. To maximize energy dissipation, a balanced design between the fiber, matrix, and interface is required. Figure 4 (a) illustrates how the fiber fails independent of the bond and how the bond fails with slippage for this particular fiber and displacement control rate. Although the curve shown in Figure 4 (a) represents the response from loading with a displacement control rate of 0.254 mm per minute, these curves were generated for 1525 mm per minute, 6100 mm per
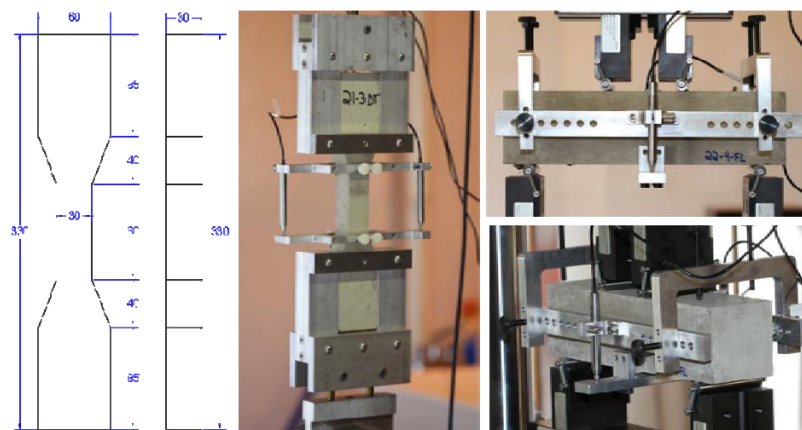

Fig. 3. (a) Dimensions (in cm) for direct tension sample; (b) direct tension experiment; (c) & (d) flexural experiment

minute, and 25,400 mm per minute displacement rates as well. The relationship between the fiber load-displacement curve and pull-out load-displacement curves indicate that the fiber has the potential for slippage and crack bridging prior to fiber failure. This condition is desirable for enhancing global ductility of the geopolymer concrete. This is also confirmed by Figure 4 (b) which shows the load-displacement curve of the direct uniaxial tension experiment. This curve indicates an initial crack in the matrix, followed by successful bridging of the crack until a second matrix crack is formed. Ultimately, the sample fails at the second crack as softening occurs. This same trend is observed in Figure 5 (a). The load-displacement curve in Figure 5 (a) represents the composite beam response to flexure during the third-point loading experiment. Similar to the direct uniaxial tension experiment, the beam forms an initial crack, and the fiber successfully arrests further propagation. A second crack occurs within the middle third of the beam, and ultimate failure occurs at either the initial or second crack. Figure 5 (b) is a posttest photo of the beam. Two cracks occur within the middle section of the beam. This pattern was repeated in all flexure experiments.

Table 1. Average of the peak load and standard deviation at failure for fiber in tension

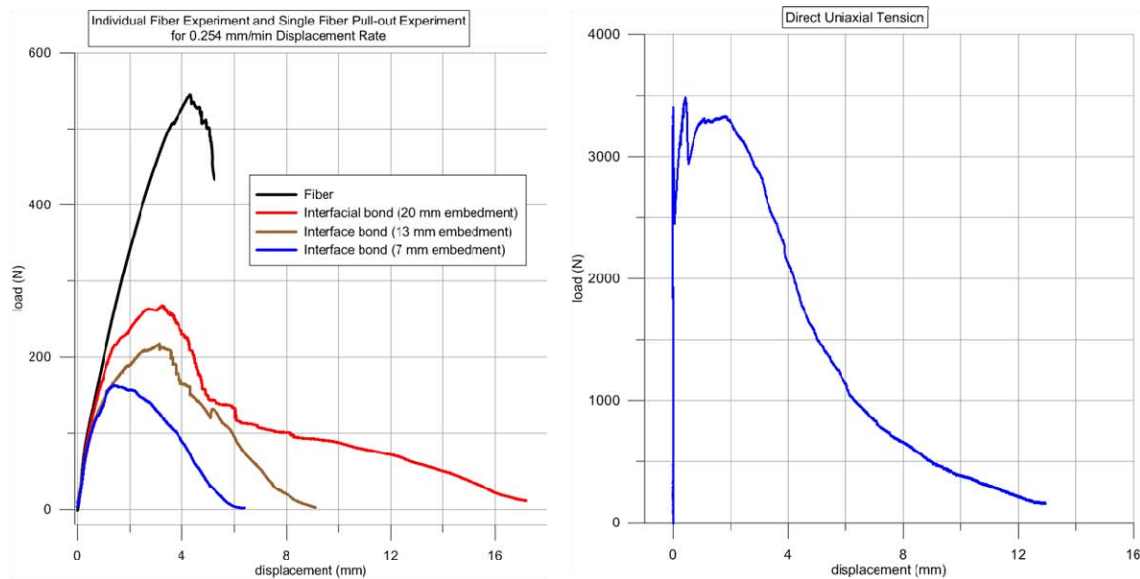| Displacement Rate	Avg. Peak Load (N)	Std. Deviation (N)
0.254 mm/ min	525	15.8
1525 mm/min	565	15.5
6100 mm/min	592	34.7
25,400 mm/min	694	140

Fig. 4. (a) Load versus deflection relationship for the fiber and for the interfacial bond with a loading rate of 0.254 mm / min; (b) Direct uniaxial tension response
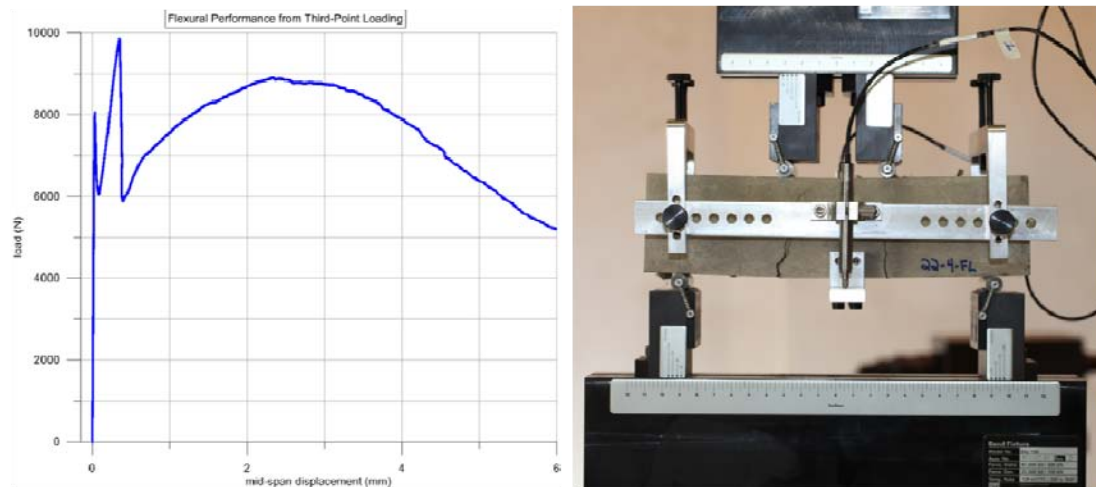
Fig. 5. (a) Load versus displacement for third-point loading flexure; (b) Beam cracking under third-point loading

4.0 Conclusions

Data from the individual fiber tension experiments indicate a propensity for rate effects. There was significant scatter in the data at 25,400 mm per minute displacement rate. Additional tests should be conducted to confirm the average peak load at this rate. Additionally, higher rate experiments are currently planned for both the single-fiber pull-out experiment and the individual fiber tension tests. For these experiments, adjustments will be made to increase data acquisition beyond 5,000 Hz. This sample rate appeared to be the lower limit to adequately define the peak load and could have contributed to some of the scatter observed in the data at 25,400 mm per minute. The experimental setup for both the direct uniaxial tension experiment and the flexure from third-point loading proved to be very reliable. Data from the external LVDTs indicate that there were no issues with the experimental procedure.

The four experimental series indicate that the bundled monofilament polypropylene fiber performs well as fiber reinforcement in the geopolymer concrete. The direct uniaxial tension experiment and the flexure with third-point loading exhibit tendencies for crack bridging. Additional testing is currently underway for the ongoing research.

Acknowledgements

References

[1] Davidovits, J., (1991). "Geopolymers Inorganic polymeric new materials." *Journal of Thermal Analysis and Calorimetry*, Vol. 37, 1633-1656.
[2] American Society for Testing and Materials, (2008). Designation C618-08. "Standard Specification for Coal fly Ash and raw or Calcined Natural Pozzolan for Use in Concrete."
[3] Yokota, H., Rokugo, K., and Sakata, N. (2007). JSCE Recommendations for design and construction of high performance reinforced composite with multiple fine cracks." Japan Society of Civil Engineers, Tokyo, Japan.
[4] American Society for Testing and Materials, (2005). Designation C1609-07. "Standard Test Method for Flexural Performance of fiber-Reinforced Concrete (Using Beam with Third-Point Loading)."