Direct Tensile Behavior of Smart Cement

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Abstract

Piezoresisitive behavior of the highly sensing smart cement was compared with the stress-strain behavior of cement under uniaxial direct tension after 28 days of curing under room conditions. The cement and smart cement samples were prepared with a water-to-cement ratio of 0.4. Smart cement samples were prepared using 0.1% carbon fibers to make the piezoresistive. Also specially designed molds were used to prepare the test specimens. The tensile stress-strain behavior of the cement was strain softening and was modelled using the Vipulanandan p-q stress-strain model. The tensile failure strain of the cement was 0.023%, about 11% of the compressive failure strain and the failure stress was 1.6 MPa (230 psi). The tensile stress-piezoresistive strain behavior of the smart cement was piezoresistive strain hardening and was modelled using the Vipulanandan p-q piezoresistive strain hardening model. The failure piezoresistive strain of the smart cement was 9.5% at a failure stress of 1.6 MPa. Compared to the tensile failure strain, the piezoresistive tensile strain was over 414 times (41,400%) higher and making the cement to be highly sensing.

1. Introduction:

There is very limited information in the literature about the mechanical properties and also the constitutive stress-strain modeling of cements with various additives. Cement is the largest manufactured material in the world and is being used in multiple applications, both onshore and offshore. Cement is used as the binder in many composites including concrete. Construction materials are subjected to many types of loading characterized as natural-mechanical-temperature-chemical and biological (NMTCB) based on the applications above the surface, buried in the ground and also under water. Unfortuantly we have seen failures of cement-based building, highway and oil wells. With all the cement-based construction materials there is need to ensure safety during the service life to minimize the losses.

It is important to develop innovative methods to make the cement highly sensing without any buried sensors in it. Also, highly sensing monitoring parameters have to be identified that could be easily adopted in the field. Past studies have investigated the changes in electrical resistivity with applied stress referred to as piezoresistive behavior of modified cement-based and polymer composites (Vipulanandan et al. 2008). These studies showed that the changes in resistivity with the applied stress were 30 to 50 times higher than the strain in the materials. Hence the change in resistivity has the potential to be used to determine the integrity of the materials. Recent studies have suggested that replacing the DC measurement with the AC measurement can eliminate the polarization effect (Zhang et al. 2010, Vipulanandan et al. 2013). In recent years, highly sensing smart cement has been developed with a real-time monitoring system (U.S. Patent 2019; Vipulanandan et al. 2015-2018). One of the weakest strengths of cement is in tension and there is a need for better characterization of the behavior.

The compressive stress- strain behavior of strain softening materials such as concrete, glass-fiber -reinforced polymer concrete, fine sands grouted with sodium silicate grout and cement mortar have been predicted using the Vipulanandan stress-strain p-q model. Also, the stress-strain behavior of Portland cement stabilized sand has been modeled using the p-q model. Also, the p-q model was used to predict the compressive stress-strain behavior of the sulfate contaminated CL soil treated with polymer and lime.

2. Objectives:

The overall objective was to characterize the direct tensile behavior of smart cement under different loading conditions and model the behavior and also compare the responses to the classical cements. The specific objectives are as follows:

1. Test the direct stress-strain and piezoresistive behavior cement and smart cement.
2. Model the direct tensile stress-strain behavior of cement and stress-piezoresistive strain behavior of the smart cement.

3. Models

Vipulanandan p-q Stress-Strain Model

Cement compressive, tension and bending stress (σ)-strain (ε) behaviors are nonlinear and also strain softening after the peak stress (σ_f) and hence the stress-strain model has to satisfy the following conditions:

(i) For $\sigma \leq \sigma_f$

$$\frac{d\sigma}{d\varepsilon} > 0 \ldots\ldots \quad (1)$$

$$\frac{d^2\sigma}{d\varepsilon^2} < 0 \ldots\ldots \quad (2)$$

(ii) At peak stress, when $\sigma = \sigma_f$

$$\frac{d\sigma}{d\varepsilon} = 0 \ldots\ldots \quad (3)$$

For $\sigma > \sigma_f$

$$\frac{d\sigma}{d\varepsilon} < 0 \ldots\ldots \quad (4)$$

Based on how the strength is lost with the increase in strain (low or high) it can be as follows:

$$\frac{d^2\sigma}{d\varepsilon^2} \geq 0 \ldots\ldots \quad (5a)$$

for lower strength drop with increase in strain and for higher strength drop with increase in strain it will be as follows:

$$\frac{d^2\sigma}{d\varepsilon^2} \leq 0 \ldots\ldots \quad (5b)$$

In order to satisfy the above five conditions, following stress-strain relationship was developed (Vipulanandan and Paul 1990) and the updated relationship is as follows:

$$\sigma = \left[\frac{\frac{\varepsilon}{\varepsilon_f}}{q_o + (1 - p_o - q_o)\frac{\varepsilon}{\varepsilon_f} + p\left(\frac{\varepsilon}{\varepsilon_f}\right)^{\frac{(p_o + q_o)}{p_o}}} \right] * \sigma_f \quad (6)$$

where σ is compressive/tension/bending stress; σ_f, ε_f are the peak stress and corresponding strain. The model material parameters p_o and, qo are related to material properties such as composition, density, resistivity and porosity and also mixing process, curing time, and environmental conditions (temperature, pressure and relative humidity).

Vipulanandan p-q Piezoresistivity Models

Resistive Strain Hardening: If the material is resistivity strain hardening the conditions is modified as follows:

For $\sigma \leq \sigma_f$

$$\frac{d\sigma}{dx} > 0 \quad (7)$$

$$\frac{d^2\sigma}{dx^2} > 0 \quad (8)$$

The new piezoresistive model is represented as follows:

$$\sigma = \left[\frac{\frac{x}{x_f}}{q_2+(1-p_2-q_2)\frac{x}{x_f}+p_2\left(\frac{x}{x_f}\right)^{\left(\frac{p_2-q_2}{p_2}\right)}}\right]\sigma_f \quad (9)$$

where $\sigma_{f:}$ is the failure strength (MPa); $x = \left(\frac{\Delta\rho}{\rho_o}\right) * 100$ = percentage of change in resistivity strain due to the stress; $x_f = \left(\frac{\Delta\rho}{\rho_o}\right)_f * 100$ = percentage of change in ρ at failure and Δρ is the change in the ρ. The initial electrical resistivity (ρ_o) (at σ=0 MPa) and the model parameters p_2, q_2 and q_2/p_2 are related to the material properties and testing environments.

4. Materials and Method:

Smart Cement: Cement was mixed with 0.1% carbon fibers to make it piezoresistive (U.S. Patent 2019). The cement and smart cement specimens were cast in specially designed molds to perform the direct tension test (Figure 1).

Direct Tension Test: Both cement and smart cement were tested in direct tension and the experimental setup is shown in Figure 1. During the test, strain was measured using 12 mm length strain gage and also an extensometer. Also during the testing, the change in resistivity was measured using the two probes connected to an LCR (L-Inductance; C-Capacitance; R- Resistance) meter which is an AC machine. Also the specimens were insulated from the testing machine (top connection and base connection) as shown in the Figure 1.

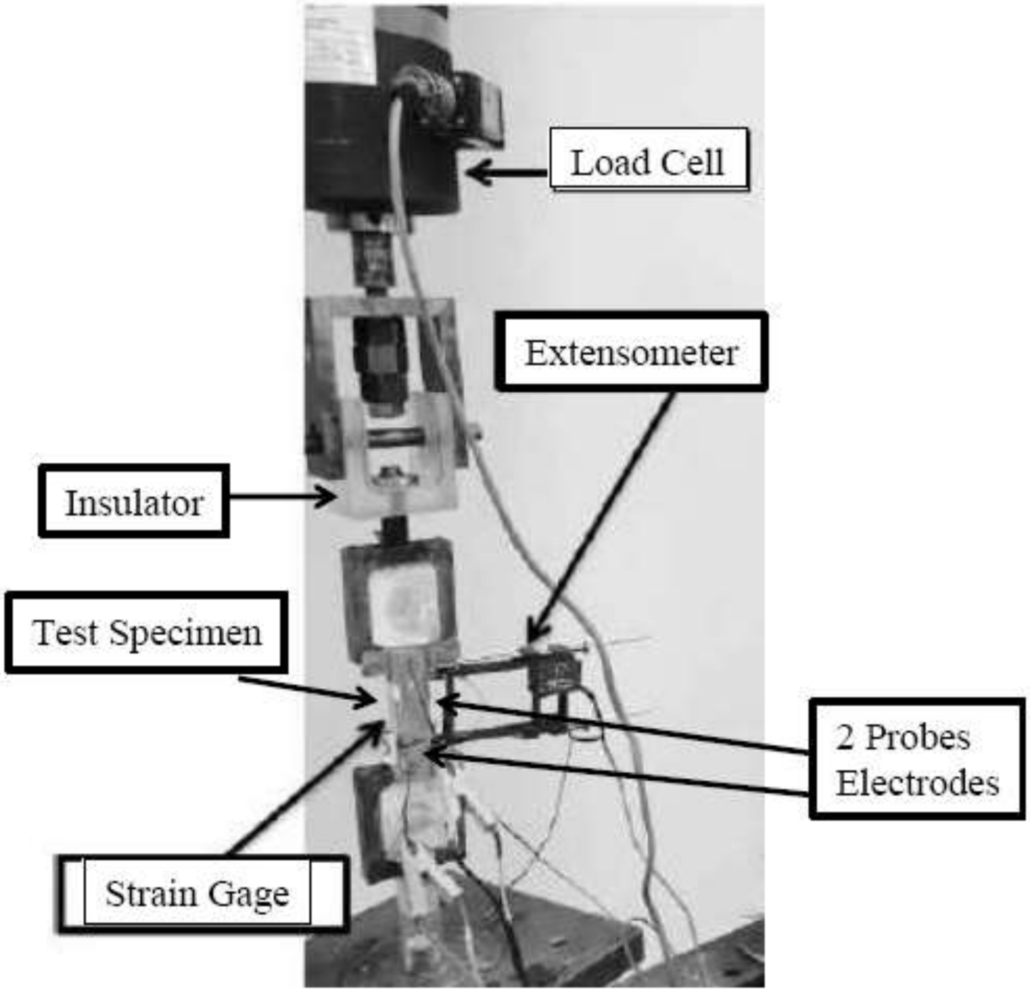

Figure 1. Direct Tensile Test Configuration.

5. Results and Discussion

Cement: Uniaxial direct tension tests were performed on cement samples cured at room condition. Typical tensile stress-strain relationship for the 28 days cured cement sample is shown in Figure 2 The tensile failure stress (σ_{tf}) was 1.6 MPa, 9.3% of the compressive strength. The tensile failure strain (ε_{tf}) was 0.023%, 12.1% of the compressive failure strain. The initial tangent modulus was 8300 MPa, about 83% of the compressive initial modulus. The secant modulus at failure was 6880 MPa, about 75% of the compressive secant modulus. Vipulanandan p-q stress-strain model was used to predict the behavior and the q_0 parameter was 0.80, indicates the non-linearity of the tensile response and the RMSE of prediction was 0.068 MPa.

Smart Cement: The direct tensile piezoresisitive behavior of the smart cement cured for 28 days is shown in Figure 3. The resistivity increased with the tensile stress. The tensile stress-piezoresisitive tensile strain response is resistivity strain hardening. The tensile strength was about 1.50 MPa and the resistivity strain change was 9.52%. The tensile strain failure for the cement was 0.023% (Figure 2), hence the change in resistivity was over 414 times (41,400%) higher, making the smart cement highly sensing.

Initial piezoresisitive modulus was 5 MPa and the secant modulus at failure was 15 MPa. The Vipulanandan piezoresisitive strain hardening model parameter q_2 was 3 and the RMSE 9root-measn-square-error) for the prediction was 0.068 MPa.

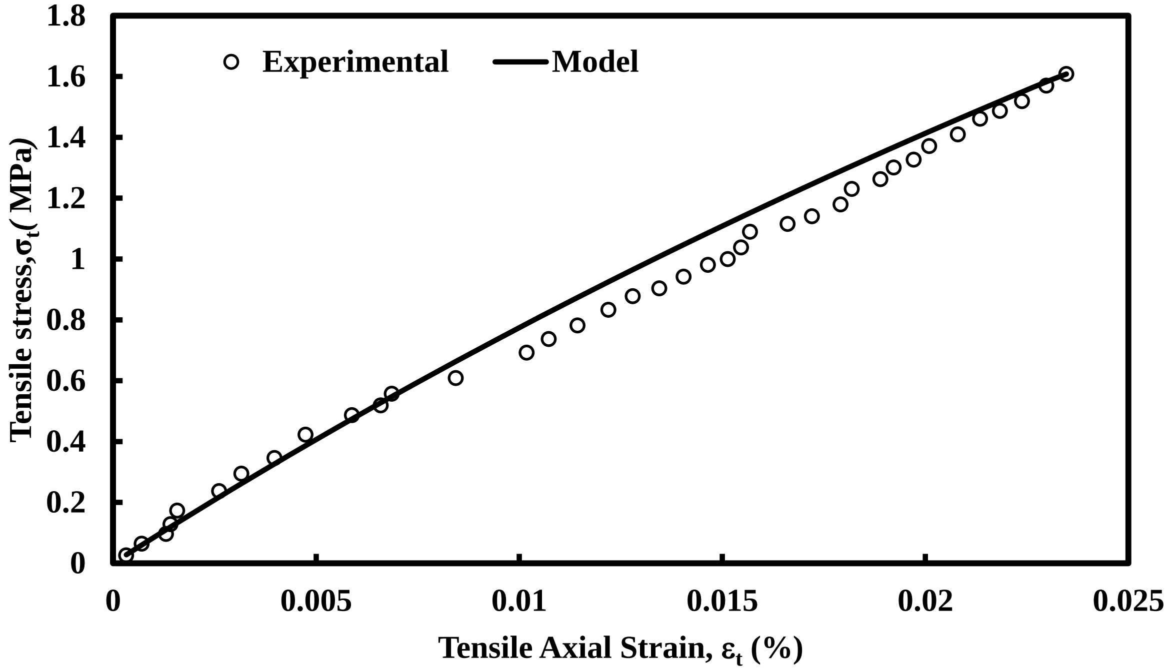

Figure 2. Direct tensile stress-strain response of cement after 28 days of curing

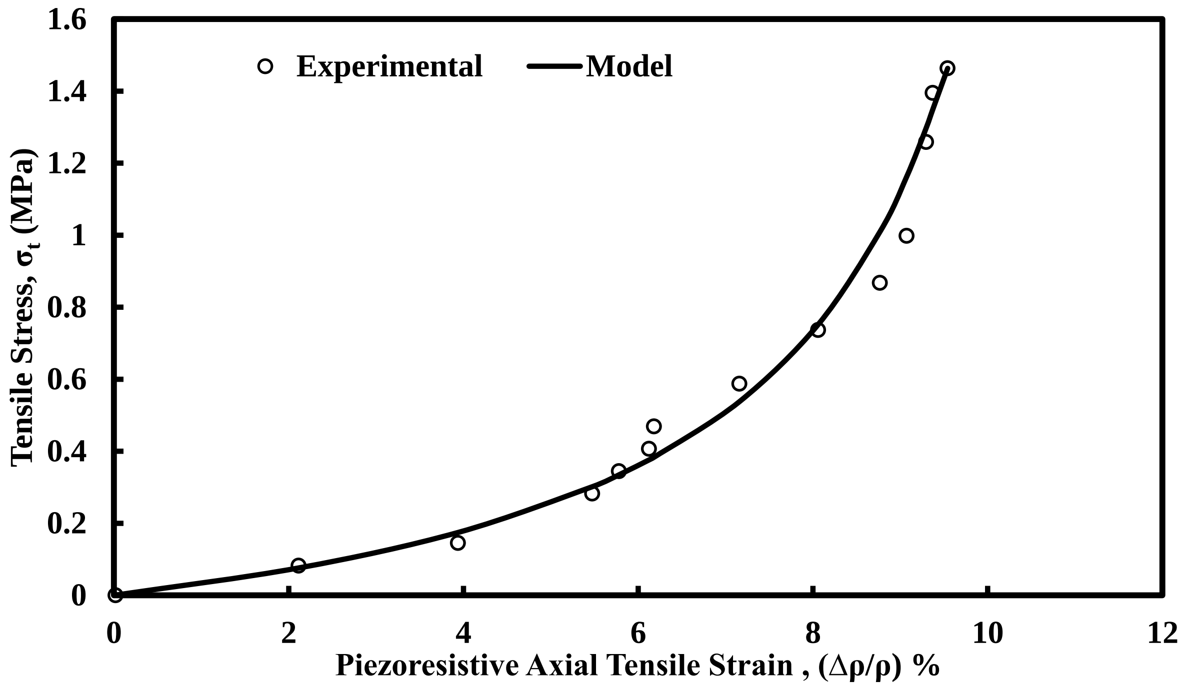

Figure 3. Direct tensile stress-piezoresistive axial strain response of cement after 28 days of curing

6. Conclusions

Cement and smart cement were tested in direct tension after 28 days of curing under room condition. The following conclusions are advanced:

1. Under direct tension the cement behavior was strain softening and the failure strain was about 0.023%.

2. Under direct tension the piezoresistive behavior of the smart cement was resistivity strain hardening. The failure piezoresistive strain was 9.5%, 414-time (41,400%) time higher than the tensile failure strain.

3. Vipulanandan p-q models were used to predict the direct tensile stress-strain and piezoresistive behaviors.

7. Acknowledgement

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8. References

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