Compressive Piezoresistive Behavior of Smart Cement with Class-C Fly ash Additive

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Abstract: In this study, the compressive strength and piezoresistive strain at failure of Ultrafine cement with up to 10% fly ash (FA) Type-C (binder replacement) were investigated after 28 and 56 days of curing. The study found that the compressive strength of smart cement with 0% and 10% fly ash (FA) with a water-to-binder ratio of 0.65 decreased from 28.5 to 18.5 MPa, respectively, at 28 days, a 35% decrease. However, the piezoresistive strain at failure after 28 days of curing increased by 36% with 10% FA. The compressive strength of smart cement with 10% fly ash (FA) increased by 54% after 56 days of curing. The piezoresistive strain decreased by 28% with the inclusion of 10% FA as the curing time increased to 56 days.

1. Introduction:

Although there have been notable technological developments in the area of cement materials and placement, real-time monitoring of the changes cannot be done (Vipulanandan et al., 2015). The two studies conducted between the years 1971-1991 and 1992-2006 both determined that cement failures were the leading cause of blowouts (Izon et al., 2007). In the later study period, there was a noticeable surge in cementing failures, which accounted for 18 of the 39 blowouts (Izon et al., 2007). Therefore, proper monitoring and tracking of the entire process of well cementing are important to ensure cement integrity during the service life of the well (Vipulanandan et al., 2014). Ultrafine cement is one type of cement composed of a finely ground mixture of Portland cement, pumice pozzolan, and dispersant (Sarkar et al., 2001). Ultrafine cement has an average particle size of 3 to 4 microns, which reduces its permeability. It can be used for seepage control in mines, dams, and tunnels (Sarkar et al., 2001). Fly ash is a common mineral additive that is often used to enhance the fluidity of the slurry and is known to boost cement strength and increase durability in traditional cement systems (Hou, et al., 2013; Sabet, et al., 2013).

2. Objective:

The overall objective was to compare the piezoresistivity of smart Ultrafine cement containing fly ash. The specific objectives of this study are the following:

a) Quantify the piezoresistive behavior and compressive strength of the smart cement containing 10% fly ash type C as a cement replacement.

b) Model the piezoresistivity behavior using the Vipulanandan p-q model.

3. Methodology:

Commercially Ultrafine cement was used in this study. Smart cement pastes were prepared by mixing the cement with water for 5 min after disturbing the carbon fiber in the water. A cylindrical mold of height 4 inches and 2 inches in diameter was used. Four insertions were made on the curved surface of the mold, two on each side and the other two on the diametrically opposite side, for wire probes to be inserted. 0% and 10% fly ash Type C was added as a cement replacement. Each mix was prepared with the addition of fixed carbon fiber content (0.05%) by weight of cement mass was prepared. The water-to-binder ratio for Ultrafine cement and fly ash was 0.65. A conductivity meter was also used to measure the conductivity of the specimen during casting. After casting and vibrating for 10 s, all specimens were cured in the molds for 24 h. After that, all specimens were capped and tested at a predetermined controlled displacement rate. Compression tests were performed on cement samples after 28 and 56 days of curing using a hydraulic compression testing machine. For each specimen, measurements of the resistance and reactance values using a commercial LCR device at 300 kHz were conducted.

The Vipulanandan piezoresistivity p–q model was used to predict the compressive stress–piezoresistive strain relationship for the smart cement with fly ash after 28 and 56 days of curing. The proposed models for strain softening and strain hardening are shown in Eq. 1 and Eq. 2, respectively:

$$\frac{\sigma}{\sigma_c} = \left[\frac{\frac{\varepsilon}{\varepsilon_c}}{q+(1-p-q)\frac{\varepsilon}{\varepsilon_c}+p\left(\frac{\varepsilon}{\varepsilon_c}\right)^{\frac{p+q}{(p)}}}\right] \quad (1)$$

$$\frac{\sigma}{\sigma_c} = \left[\frac{\frac{\varepsilon}{\varepsilon_c}}{q+(1-p-q)\frac{\varepsilon}{\varepsilon_c}+p\left(\frac{\varepsilon}{\varepsilon_c}\right)^{\frac{p-q}{(p)}}}\right] \quad (2)$$

where σ is compressive stress; σ_f, ε_c are the peak compressive strength and corresponding strain and p, q are model parameters (Table 1). Model parameters p and q increased with curing time based on the FA content.

4. Results and Discussion

(a) <u>28 days curing</u>

i. <u>UF cement with 0%FA-C:</u>

The average compressive strength (σ_f) of the smart cement with 0% FA after 28 days of curing was 28.5 MPa as shown in Figure 1. The piezoresistive strain at failure was 262% as summarized in Table 1. The p-q model prediction was good with the coefficient of determination (R^2) was 1, and the root-mean-square error (RMSE) was 0.61 MPa after 28 days of curing.

ii. <u>UF cement with 10%FA-C:</u>

The average compressive strength (σ_f) of the smart cement with 10% FA after 28 days of curing was 18.5 MPa, respectively a 35% decrease compared to the 0% FA mix, as shown in Figure 1. The addition of 10% FA increased the piezoresistive strain from 262% to 357%, a 36% increase as summarized in Table 1. The coefficient of determination (R^2) was 0.97, and the root-mean-square error (RMSE) was 1.30 MPa after 28 days of curing.

(b) <u>56 days curing</u>

i. <u>UF cement with 0%FA-C:</u>

The average compressive strength (σ_f) of the smart cement with 0% FA after 56 days of curing was 33.5 MPa as shown in Figure 2. The piezoresistive strain was 220% as summarized in Table 1. The coefficient of determination (R^2) was 0.99, and the root-mean-square error (RMSE) was 1.33 MPa after 28 days of curing.

ii. <u>UF cement with 10%FA-C:</u>

The average compressive strength (σ_f) of the smart cement with 10% FA after 56 days of curing was 28.5 MPa, respectively a 15% decrease compared to the 0% FA mix as shown in Figure 2. The addition of 10% FA increased the piezoresistive strain from 220% to 256%, a 16% increase as summarized in Table 1. The coefficient of determination (R^2) was 1.00, and the root-mean-square error (RMSE) was 0.66 MPa after 56 days of curing.

Table 1: Piezoresistive model parameters of smart cement with fly ash

Mix	Curing Time (days)	σ_f (MPa)	$\Delta\rho/\rho_0$ %	(q)	(p)	RMSE MPa	R^2
0% FA	28	28.50	262.00	1.000	0.219	0.61	1.00
	56	33.50	219.90	0.303	0.017	1.33	0.99
10% FA	28	18.49	356.80	0.053	0.002	1.30	0.97
	56	28.50	255.70	1.000	0.133	0.66	1.00

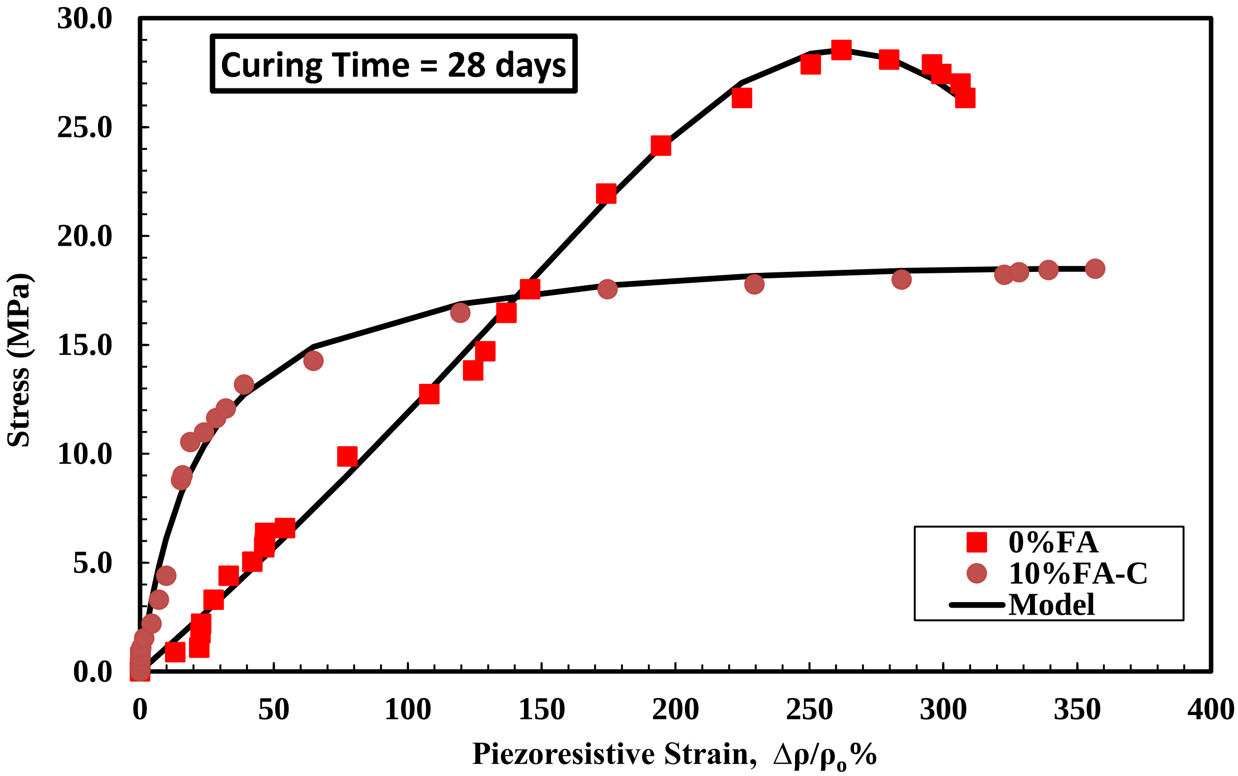

Figure 1: Stress versus change in resistivity of smart cement with 10%FA at 28 days curing

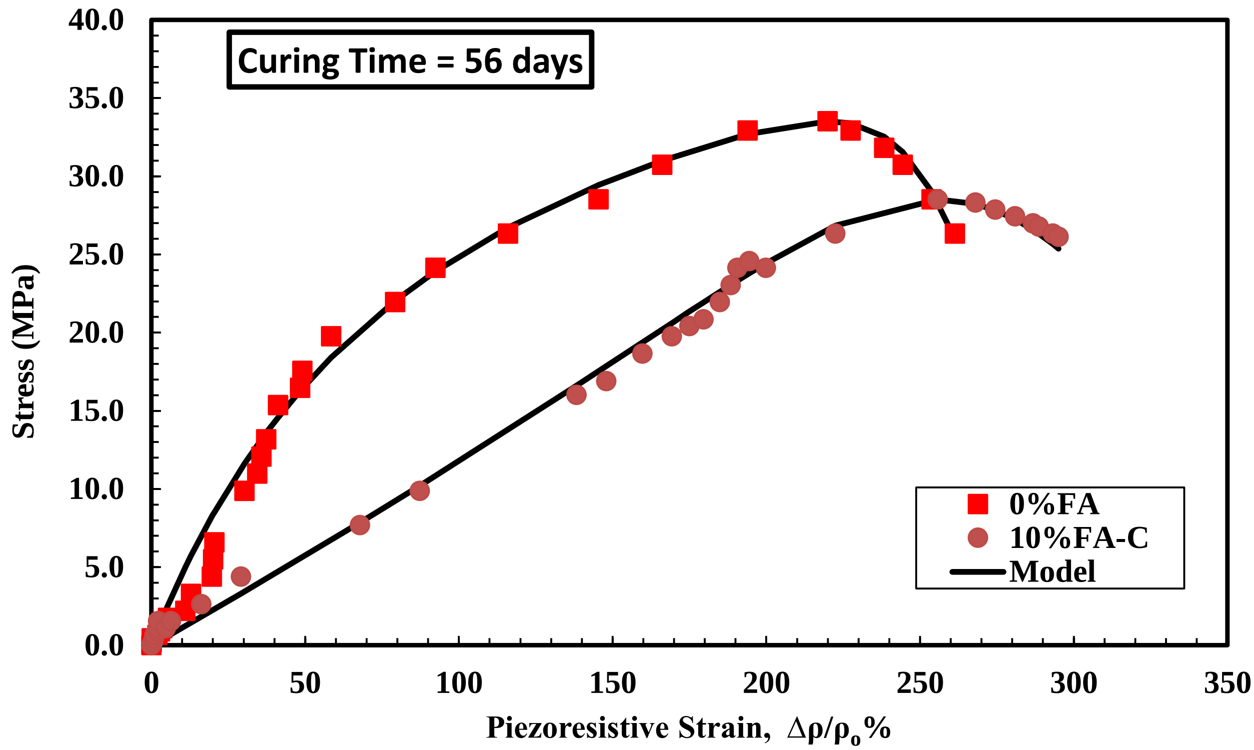

Figure 2: Stress versus change in resistivity of smart cement with 10%FA at 56 days curing

5. Conclusion:

Based on the testing and modeling, the following conclusions are advanced:

a. The compressive strength of smart cement with 10% fly ash decreased by 35% compared to the control mix after 28 days of curing. The piezoresistive strain at failure increased by 36% with the addition of 10% FA.

b. The addition of 10% fly ash to the smart cement resulted in a 15% reduction in its compressive strength after 56 days of curing when compared to the control mix. However, the piezoresistive strain at failure showed a 16% increase from 219% to 255.7% in the mix with 10% fly ash compared to the control mix after the same duration of curing.

c. As the curing time increased from 28 to 56 days, the smart cement with 10% fly ash exhibited a substantial increase in compressive strength, rising from 18.5 MPa to 28.5 MPa, representing a 54% increase. On the other hand, the addition of 10% fly ash caused a reduction of 28% in the piezoresistive strain at failure as the curing time increased from 28 days to 56 days.

6. Acknowledgments

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7. References

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