Constitutive Modeling of Smart Piezoresistive Self Sensing Well Cement

A. Aldughather and C. Vipulanandan, Ph.D., P.E.
Center for Innovative Grouting Material and Technology (CIGMAT)
Department of Civil and Environmental Engineering
University of Houston, Houston, Texas 77204-4003
E-mail: analdughather@uh.edu, cvipulanandan@uh.edu Phone: (713) 743-4278

Abstract: In this study, Vipulanandan p-q piezoresistivity model was validated using data from published papers. Results suggest that Vipulanandan's model accurately predict the piezoresistive behavior of the Smart Cement.

1. Introduction: Proper cementing is critical to ensure the integrity of the wellbore during placement operations and the entire service life of the oil and gas wells (Vipulanandan et. Al. 2015). At present there is no reliable technology available to monitor cementing operations in real time from the time of placement and throughout borehole service life (Vipulanandan et al. 2014). This challenge could be addressed by producing cements that exhibit sensing capabilities. Altering and improving the current well cement slurry design enables the visualization of cement operations by means of measuring the change in electrical resistivity due to induced mechanical stress known as piezoresistive effect. The technology is based on the nonlinear p-q model which was developed by (Vipulanandan et al., 1990). This model was modified in order to quantify the change in resistivity induced by applied stress. This study is dedicated to investigate the constitutive modeling of piezoresistive behavior of modified smart cement and to validate the p-q model presented in this report using experimental data.

2. Objective: The overall objectives of this project are the following:

a) Describe and discuss smart cement and its functions.
b) Study piezoresistive behavior and present a literature review on piezoresistivity studies.
c) Discuss the constitutive modeling of piezoresistivity.
d) Study Vipulanandan p-q model and validate the model using experimental data.

3. Data Collection:

The data was collected from Di Gao et. al. (2009). The method that was used in this study was the four probe method with a DC current. As for the material chosen for this experiment as shown in (Table 1) below is CNFSCC10-S which stands for Carbon nanofibers self-consolidating concrete that contains (1%) CNF PR-19-XT-PS (fibers stripped from polyaromatic hydrocarbons pyrolytically). CNFSCC 10-S has an average compressive strength value after 28 days of (5.97 ksi) and the following electrical properties: An average resistance R (8032 Ω), Resistivity (841 Ω.m) and Δ_R (0.223).

Table 1: Mixing Proportion for material used in study

Mix	Carbon nanofiber (vol% binder)	Water (kg m^{-3} concrete)	Cement (kg m^{-3} concrete)	Coarse aggregate (kg m^{-3} concrete)	Fine aggregate (kg m^{-3} concrete)	High-range water reducer (fl.oz./cw)	Sodium dodecyl sulfate (SDS) (kg m^{-3})	Antifoam (fl.oz./cw
C	0	188	572	1015	572	0	0	0
CNFC016	0.16	188	571	1015	572	5	0	0
CNFC031	0.31	188	570	1015	572	7	0	0
CNFC078	0.78	188	569	1015	572	16	0	0
CNFC155	1.55	188	566	1015	572	31	0	0
SCC	0	191	480	901	1005	11	0	0
CNFSCC025-S	0.25	191	480	901	942	11	0.18	11
CNFSCC05-S	0.5	191	448	838	877	14	0.36	24
CNFSCC10-S	1	191	448	838	877	14	0.77	43

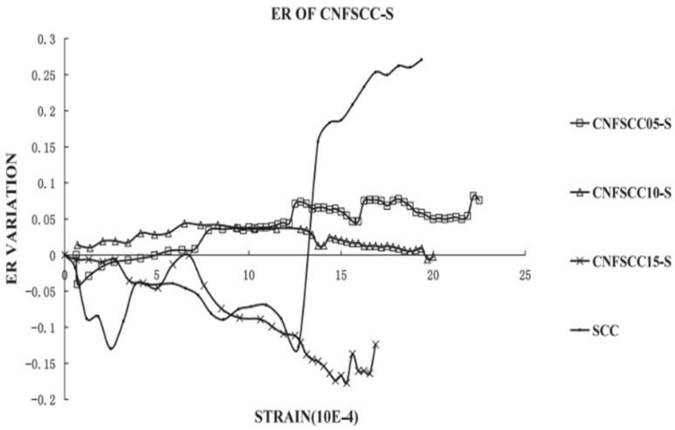

Figure 1: ER Variation of CNFSCC-S

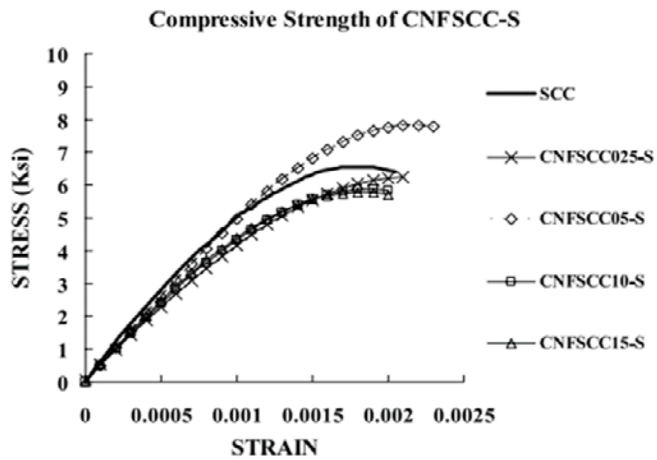

Figure 2: Compressive Strength of CNFSCC-S

From the graphs (Fig 1, Fig 2) above, the piezoresistivity was not plotted in one graph versus the stress. This is a practice in mostly all other studies and papers referenced in this report. Hence, being able to plot piezoresistivity and stress on the same graph is one of the advantages of Vipulanandan's p-q model.

Therefore, the method used to obtain the data from the two plot is to first collect the data points from the resistivity versus strain graph (Figure 1) and then use the strain values to find the corresponding stress values on the stress versus strain graph (Figure 2, Table 2).

Table 2: Piezoresistive Behavior

Electrical Resistivity Variation (%)	Stress (ksi)	Stress (Mpa)
0	0	0
0.005	0.25	1.72
0.01	0.5	3.44
0.015	0.75	5.17
0.02	0.95	6.55
0.025	1.95	13.44
0.03	2.25	15.5
0.35	3	20.7
0.04	3.2	22.1
0.045	3.35	23.1
0.05	3.8	26.2

4. Results and Discussion: Using the EXCEL sheet (Provided in the APPENDIX) we could predict the stress and the generated model parameters where the following (Table 3, Fig 3) :

Table 3: Model Parameters

q	**2.18**
p	**1.51**
R^2	**0.985**
RMSE	**1.123**

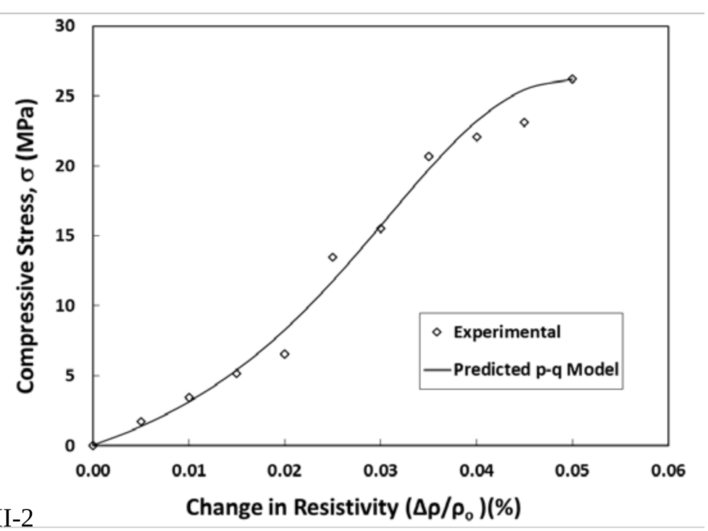

Figure 3: Model Prediction versus Experimental Data

We know that from the conditions in (Vipulanandan and Paul 1990) for strain softening material $0 < p + q < 1$. Therefore even though the value for R^2 looks good, we need to change the parameters to meet the condition. Therefore the new generated parameters are the following (Table 4, Fig 4) :

Table 4: Model Parameters

q	**0.99**
p	**0.009**
R^2	**0.962**
RMSE	**1.767**

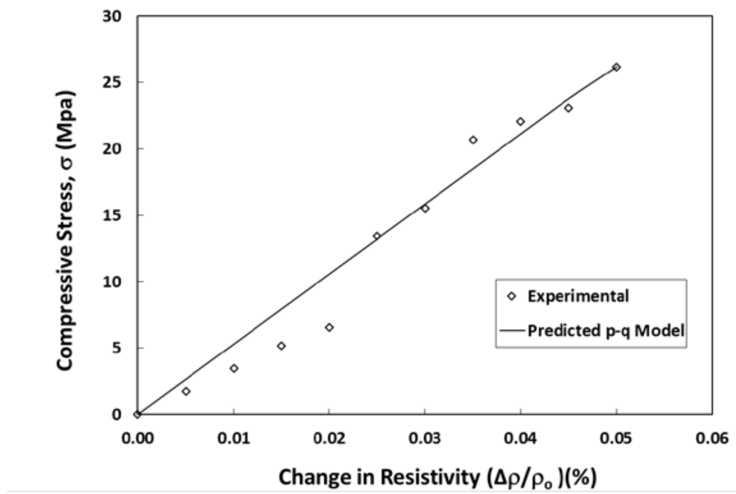

Figure 4: Model Prediction versus Experimental Data

From looking at the graph and the value of R^2 we can tell that the vipulanandan model predicts the experimental value with minimum error.

It should be noted that the values taken from the experimental data were only increasing value and not the whole plot of piezoresistivity versus strain as the p-q model will not be able to predict the plot for such data. The restriction and conditions for p-q models from (Vipulanandan and Paul 1990) are that derivative of the plot before the maximum stress value should be positive and the derivative at the peak should zero whereas the derivative or slope of the plot after the peak stress value be negative for the model to accurately predict the data.

5. Conclusion:

1. Vipulanandan Piezoresistive model predicts both behavior of cement during installation and after hardening (set cement).
2. Vipulanandan p-q model helps predicts plastic material behavior under various stresses (Compression/tension).
3. The model can only accurately predict strain softening piezoresistivity behavior if the experimental data were increasing or decreasing (following a trend).
4. The model could only plot increasing-decreasing values if the slope before the maximum stress was positive and the values of the slope at any point after the peak stress are negative.

6. Acknowledgements: This study was supported by the CIGMAT (Center for innovative grouting materials and Technology) and Texas Hurricane Center for Innovative Technology (THC -IT), University of Houston, Houston, Texas.

7. References:

1. Gao, D. et. al. (2009). “Electrical Resistance of Carbon-nanofiber Concrete.” Department of Civil and Environmental Engineering, University of Houston, Houston,TX 77204-4791, USA. 10 August.

2. Vipulanandan, C. (1989). "Curing and constitutive relationships for polyester mortar." Polym. Engrg. Set, 29(22), 1628-1635.

3. Vipulanandan C., Paul E. (1990), “Performance of epoxy and polyester polymer concrete,” ACI Mater. J. 87 (3) (1990) 241–251.

4. Vipulanandan C., S. Mebarkia, “Compressive behavior of glass-fiber-reinforced polymer concrete,” J. Mater. Civ. Eng. 4 (1992) 91–105

5. Vipulanandan C. et. al. (2014). "Development and Characterization of Smart Cement for Real Time Monitoring of Ultra-Deepwater Oil Well Cementing Applications." Offshore Technology Conference held in Houston, Texas, USA, 5–8 May 2014. OTC-25099-MS

6. Vipulanandan C. et. al. (2015). Behavior of Nano Calcium Carbonate Modified Smart Cement. Offshore Technology Conference held in Houston, Texas, USA, 4–7 May 2015. OTC-25845-MS.