Characterizing Class G Cement with Varying Carbon Fiber Contents using the Impedance-Frequency Response

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ABSTRACT: It is important to characterize the cement and verify the critical monitoring property that can be adopted in the field. In this study, class G oil well cement was modified with varying amount of carbon fibers to determine the electric properties of cement. The carbon fiber content was varied up to 0.5% (based on the cement weight) The two-probe method with varying alternative current frequencies (up to 10 MHz) was used to characterize the material. The cement with carbon fibers responses were different in magnitude but represented the CASE-2 of the Vipulanandan Impedance Model identifying the resistivity (related to resistance) to be the critical material parameter. With the increase in the fiber content the bulk resistivity (measured resistance) decreased. When the carbon fiber content was increased from 0.05% to 0.50% the resistivity decreased by 3.5%.

1. Introduction:

Structural health monitoring of Cementitious materials especially in the oil industry is a crucial part in the design and construction of new operating wells. Oil and gas wells are cemented in place in order to provide isolation between different zones and provide well integrity. Over the years, well cement evaluation tools have seen tremendous advancement (Imrie, 2021) providing valuable insights to the engineers after the cement job. Recently, however, there has been an increased interest in monitoring the performance of cements downhole and especially for the long term after the cement sets. Such technology was proposed by Vipulanandan (Vipulanandan et al. 2016a, 2019; Vipulanandan 2021). Using the two-probe method materials can be characterized and also the critical electrical property to be monitored can be determined (Vipulanandan et al. 2016b, 2019; Vipulanandan 2021).

2. OBJECTIVES:

In this study the focus was on verifying the characterization theory and providing new insight on the performance of cement with varying carbon fiber percentages.

The specific objectives of this study are the following:

a) Compare Class G impedance-frequency responses with different percentages of carbon fiber.
b) Identify the critical electrical property for the cement to be monitored.
c) Perform the tests up to 10 MHz to verify the Vipulanandan Impedance Model.

2. MATERIALS AND METHODS:

Class G cement 0.44 water to cement ration (w/c) using (400 g) cement and (176 mL) of water. Carbon fiber (0.05%, 0.1%, 0.5% BWOC). The carbon fibers used are 12 mm in length, which is condsidered "short carbon fibers" (Safiuddin et al. 2021). Cubic molds were used to cast the cement samples and were cured in a water bath under 180 °F (80 °C) and atmospheric conditions. Mixing of cement was performed in accordance with API RP10B-2 testing standards and procedures. Water was poured first into the blender, then the dispersant and fibers were placed in the blender. The cement with powder fluid loss additives were dry mixed. Then the dry mix was poured into the blender while spinning at 4000 RPMs within 15 s. Then the slurry was mixed for 35 s at 12000 RPMs.

Vipulanandan Impedance Model

CASE-2: Special Bulk Material - Resistance Only

In the CASE-2, the capacitance of the bulk material (C_b) was assumed to be negligible as shown in Figure 1.

The total impedance of the equivalent circuit for CASE-2 (Z_2) is as follows:

$$Z_2(\sigma) = R_b(\sigma) + \frac{2R_c(\sigma)}{1+\omega^2 R_c^2 C_c^2} - j\frac{2\omega R_c^2 C_c(\sigma)}{1+\omega^2 R_c^2 C_c^2}. \tag{1}$$

$$= R_2 + j\,X_2 \tag{2}$$

$$Z_{2real}(\sigma) = R_2 = R_b(\sigma) + \frac{1}{R_c C_c}\left(\frac{X_2}{\omega}\right) \tag{3}$$

The term R_2 in Eqn. (2) represents the real part of the impedance (Z_{real} of Z_2) and X_2 represents the imaginary part of the impedance (Z_2). When the frequency of the applied signal was very low, $\omega \rightarrow 0$, $Z_2 = R_2 = R_b + 2R_c$, and when it is very high, $\omega \rightarrow \infty$, $Z_2 = R_2 = R_b$ and X_2 will be equal to zero. In CASE-2, if the impedance is measured at very high frequency it will measure the resistance (R_b) in the material and eliminates the effects of the contacts and also it is frequency independent. This becomes another unique advancement in measurement and also monitoring since the resistance is independent of the very high frequency of measurement.

It is important to identify the electrical material properties of the testing material (bulk material) using the impedance-frequency relationship.

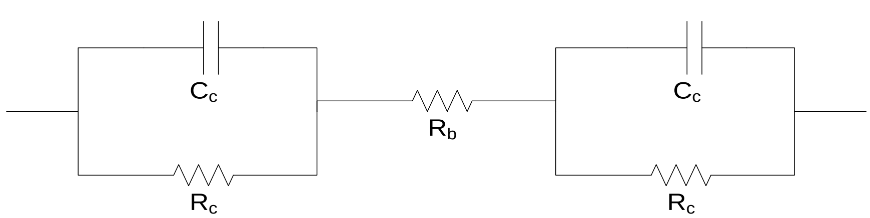

Figure 1 Equivalent Circuit for CASE 2.

3. Test Results and Analyses

Figure 2 shows the frequency dependency of the electrical impedance and both of its components, the Real R_2 (Resistance) and imaginary X_2 (Reactance). The responses were sensitive to the fiber content showing different responses. At low percentages, the resistance component follows the exact trend as the total impedance when the reactance effect diminishes. Also, with increase in frequency Z_{real} is reaching a liming value and $Z_{imaginay}$ (X_2) is reaching zero.

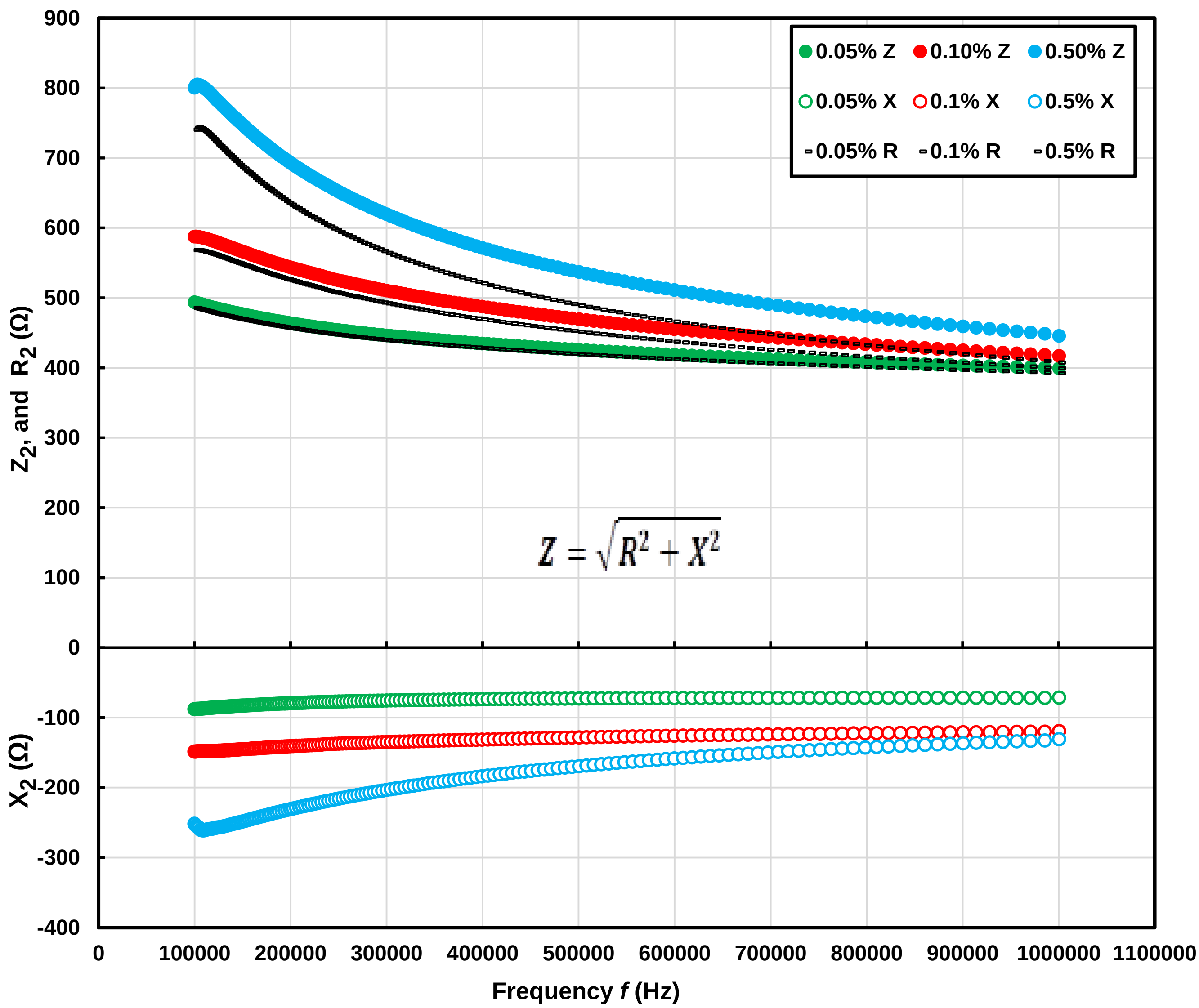

Figure 2 Impedance-Frequency Response of Tested Cement with Varying Carbon Fibers

From Figure 3, it is evident that all slopes are equal. The equations of the trendlines of the samples follow the following equation:

$$Z_{2real}(\sigma) = R_2 = R_b(\sigma) + \frac{1}{R_c C_c}\left(\frac{X_2}{\omega}\right)$$

where,

$\frac{1}{R_c C_c}$ = Slope (inverse of contact resistance * Contact capacitance), $(\Omega.F)^{-1}$

$\frac{X_2}{\omega}$ = Imaginary component of impedance / angular frequency, Ω.s/rad

R_b= Bulk Resistance, Ω

Zreal=Real component of Impedance , Ω

The test results, as shown in Figure 3, verified the linear relationship (Eqn (3)) of the Vipulanandan Impedance Model for CASE-2. The linear relation coeifficient of determination (R^2) was 0.99 as summrized in the Figure 3 index box..

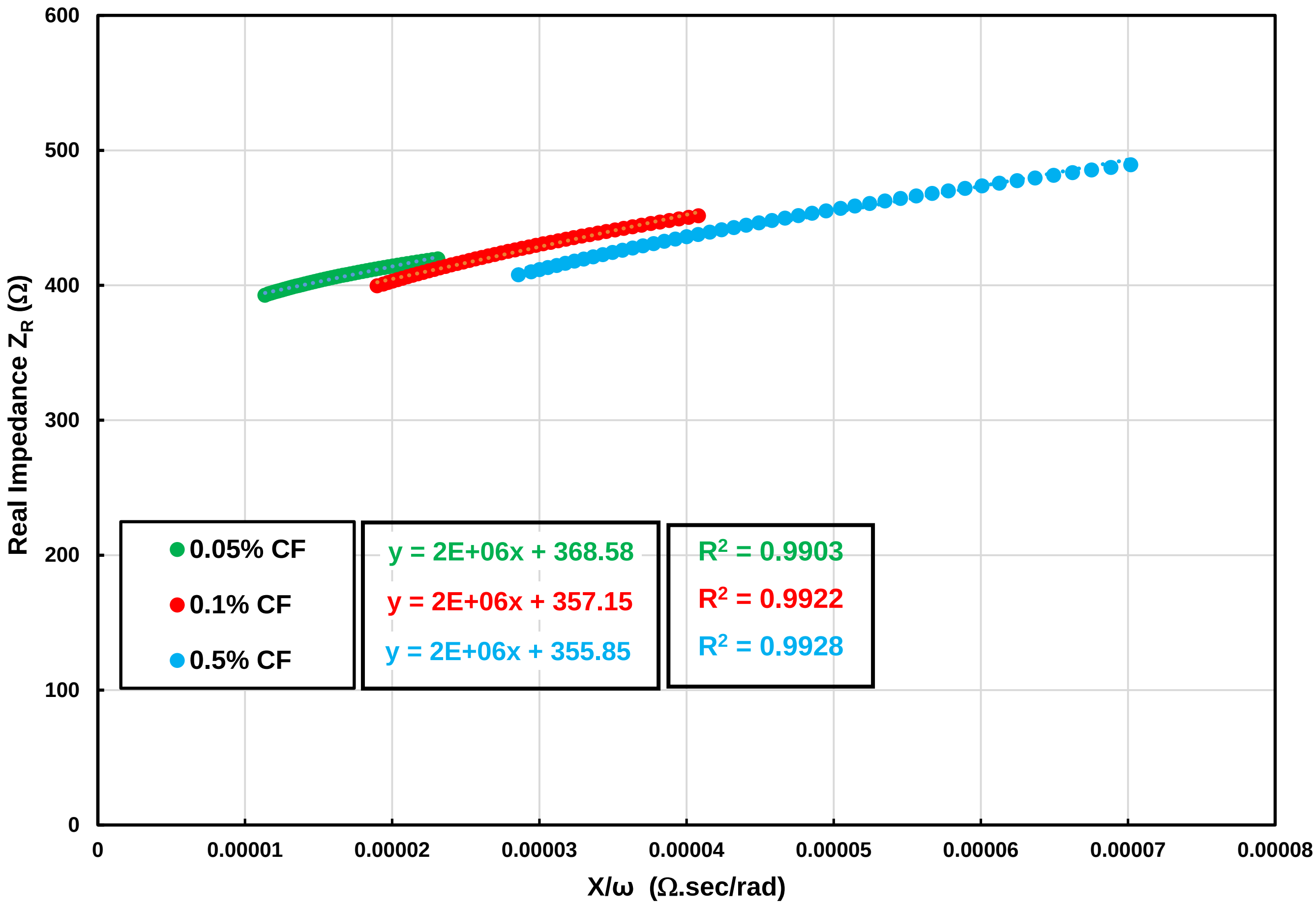

Figure 3. Real Impedance($Z_{2\ real}$) versus Imaginary Impedance / Angular Frequency (X_2/ω) was Verified as Linear Relationship

The inverse of the slope, represented RC (Vipulanandan Contact Index) = $\frac{1}{2*10^6}$ = $5*10^{-7}$ ΩF^{-1} and was not affected by the fiber content for the range of fiber content investigated. Studies have shown that Rc and Cc will be different for different fiber contents and are clealy shown in the response of R_2 and X_2 with the frequencies..

4. CONCLUSIONS:

Based on the experimental study (frequency up to 1 MHz) and analyses of the test results following conclusions are advanced:

1. The impedance-frequency responses were sensitive to the fiber content.
2. The impedance-frequency responses clearly matched the CASE-2 model, identifying resistivity (resistance) to be the critical parameter for the cement.
3. Test results also verified the linear relationship between Zreal and X/ω, which is also verifying the CASE-2 model for the cement with varying carbon fiber contents.
4. The bulk resistance of the samples with 0.05%, 0.1%, 0.5% CF were 368.6 **Ω**, 357.2 **Ω**, 355.9 **Ω** respectively. The bulk resistance reduced by 3.5% when the fiber content was increased from 0.05% to 0.5%.

5. ACKNOWLEDGEMENTS:

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