Assessment of an Axially Loaded Self-Sensing Concrete Element with Recycled Steel Residuals

David B. Scott 1 and Shen-En Chen 2,*

1 Energy Power Research Institute, Charlotte, NC 28262, USA; dscott@epri.com
2 Department of Civil and Environmental Engineering, University of North Carolina at Charlotte, Charlotte, NC 28223, USA
* Correspondence: schen12@uncc.edu

Abstract: This paper describes the fundamental evaluation of a self-sensing concrete column using recycled steel residuals (RSR) as functional fill and the testing of the column under slow-rate cyclic loading. The RSR modified concrete has the advantage of sustainably using the otherwise waste material from steel fabrication process. Two columns (one without and one with 2% of RSR by volume) were fabricated in the lab and load-tested in cyclic axial compression. The columns are connected to an alternating current power source and have three electrode sets each for electric property measurements. The results indicate that the 2% specimen can accurately detect the loading and unloading processes using electric-based measurements to calculate resistivity. Based on the test results, empirical linear equations are derived to correlate the mechanical and electrical behaviors.

Keywords: axial compression; electro-elasticity; recycled steel residuals; resistivity and strain relations; self-sensing concrete; strain detection

1. Introduction

Self-sensing concrete or autonomous sensing concrete is a subject matter that has drawn significant attention in recent years [1–5]. The technology focuses on modifying concrete material with added sensing functionalities, which is a significant contrast to traditional nondestructive testing/evaluation (NDT/E) or structural health monitoring (SHM) technologies that depend on the application of extraneous sensors to concrete structures [6,7]. For some concrete structures, traditional NDE has application limitations that include requiring being at the concrete, with some areas not accessible by sensors and sensor transmittants. Furthermore, NDT sensors provide only localized data that may not be representative of the health state of the entire structure. Hence, to supplement conventional inspections and offset some of these limitations, there is a growing emphasis to develop self-sensing or smart concrete.

Specifically, self-sensing concrete is a concrete material technology that has the ability to indicate strain (and potential damages) based on changes in the electrical properties of the concrete [8,9]. Researchers have used materials with electrostrictive properties that are ubiquitously embedded throughout the concrete mixture and infused with the concrete during and after hydration and final setting of the concrete. In most cases, electrodes are either embedded or attached to the surface [3]. The embedded electrodes usually consist of a perforated plate, mesh, or loop. Loading and strains are then applied to the concrete to detect the changes in electrical properties to indicate the change in material strain [2,3]. Several embedded functional materials have been experimented with, including single-walled carbon nanotubes, piezoelectric ceramic, electrochemicals, etc., most of which are costly, and most of the previous work in this realm has been on small samples containing little to no coarse aggregate and, in some cases, no fine aggregate [2,4,10]. There
are only few incidences of applying the technique to reinforced concrete members [5]. As a result, to date this technique has only maintained a low technical readiness level (TRL).

As a sustainable practice, recycled steel residual (RSR) is suggested in this paper as an alternative functional material to make concrete self-sensing. The steel industry recycles a significant amount of the steel scraps. However, not all scraps are equal, and depending on the residual elements, different efforts to recycle the scraps incurs and there is still a need for new ways to use the scraps instead of sending them to landfills [11]. The RSR used in the current study is resulted from steel fabrication and usually mixed with greasy muck.

To demonstrate the self-sensing method, compression tests have been performed on a concrete column that contains 2% of the recycled steel residual by volume. The concrete column was axially loaded, and the results are presented herein and include a theoretical summary of the monitoring technique for self-sensing concrete.

2. Theoretical Basis of Self-Sensing Concrete

The recycled steel residuals are procured waste products from steel fabricator shops, which may consist of steel shavings of various sizes with a significant amount of metal dust particles. Depending on the number of jobs, a typical steel fabricator may generate several pounds of such wastes per day, which are either sent to steel mills to be re-melted for new metal parts or straight to landfills. The choice of recycling is heavily dependent on the conditions of the waste and the efforts to process them prior to re-melting [11]. By suggesting the recycling and use of these steel residuals as functional materials for self-sensing concrete, a more sustainable approach to these materials is presented here.

Figure 1 shows the RSR materials used in the current study. Figure 1A shows the recycled steel materials, which may be in different degrees of rust and may be coated with oil that is used for cooling during metal forming processes. Hence, some work may be needed to process the material. Figure 1B,C show the same material after being washed and sieved. To ensure the material is rust and grease free, vinegar was used to wash the RSR prior to use in the concrete. Figure 1D,E show a close up of two cylinders made with washed and unwashed RSR that were left exposed to natural elements for a year, respectively. The results indicate that the unwashed cylinder has experienced severe rusting and the cylinder washed with vinegar has not experienced rusting. Figure 1F shows a close up of a steel wire rusting at the surface of the unwashed cylinder.
To ensure consistency, homogeneity, and workability of the modified concrete, only certain sizes of the material should be blended into the concrete mix.

The theory to support the placement of the electrodes comes from the Wenner test method and other electric methods to indicate resistivity of a material across a given section geometry and length [9,10]. It should be noted that electric properties such as resistivity tests have been used extensively in the NDT of concrete and geophysical investigations—in most cases, these investigations adopt a four-probe approach [12–15]. The reduction in electrical potential can be measured at any two points along the material, and given a known distance between the points, the resistivity of the material can be measured as follows:

$$\rho = \frac{R \times A}{L} = \frac{V \times A}{I \times L}$$

where $\rho$ = resistivity (ohms-in., ohms-cm), $R$ = resistance (ohms), $A$ = cross-sectional area (in.$^2$, cm$^2$), $L$ = distance between the two inner electrodes of measurement (in., cm), $V$ = potential drop (volts), $I$ = applied current (amps).

Equation (1) is established and applied for the Wenner probe test method to determine the electrical resistance of soil [15]. To indicate the suitability of material, laboratory experiments can be performed by sending a current through soil of a known length and cross section. The electrical potential difference between two inner connections is measured. Using this and the geometry of the box, material resistivity can be calculated.

In the study described herein, embedded electrodes imparted the current (at the outer electrodes) and measured the potential differences within the concrete (across pairs of inner electrodes). The specimen is then loaded axially and in compression. A correlation between the mechanical result (strain) of loading the specimen and changes in electric
properties within the concrete–resistance were quantified. The relationship is described as the electro-elastic parameter of the specimen and can be presented as:

\[ \varepsilon (1 + 2\nu) = \left( \frac{dR}{R} - \frac{dp}{\rho} \right) \]  

where \( \varepsilon \) = strain and \( \nu \) = Poisson’s ratio.

3. Experimental Setup

3.1. Axial Test Sensing

The raw recycled steel residuals were processed by sieving the material to determine the approximate fineness and approximate distribution of particle sizes. Large portions of the material passed through a No. 8 sieve (Figure 1C). Given the approximate size distribution between the material retained on the No. 8 sieve and that passing through it, the recycled steel residuals were proportioned as 2:1 (passing-through: retained on No. 8 sieve). The material was cleaned using water under pressure. Additional “cleaning” may be required to produce recycled steel residuals that are suitable for concrete as a functional filler. For instance, degreasing may be necessary to process the material such that potential chemicals will not impede the electrical conductivity of the material. The chemicals may also affect other plastic and hardened properties of the concrete. Again, Figure 1D,E show the contrast between the effect of washed and unwashed concrete elements. As noted in the introduction, electrical conductivity of concrete is a function of the cement matrix and the embedment of RSR within the matrix; hence, an understanding of how the recycled steel residuals will affect these parameters and, consequently, electric conductivity is essential to the technique.

The concentration of recycled steel residuals used in the studied concrete mixtures is based on ACI 544 [16,17]. Concrete mixture designs are based on ACI 211 [18,19] and trial batches were developed both with and without recycled steel residuals. Plastic and hardened properties of the various mixtures are tested and reported here. For resistance testing, prisms (columns) are 150 × 150 × 500 mm, which is consistent with the dimensions specified in the ASTM C78 and C1609 [20,21]. The prisms have been axially loaded with the long dimension being up/down. Given these dimensions, the first order buckling load is one to two orders of magnitude greater than the compression load to be used for the compression tests. Therefore, the column is determined to be a “short column”, with unidirectional compression failure (i.e., with no buckling) if loaded to failure. Nonetheless, strain has been measured using surface mounted gages on two planes of the column to determine if eccentricity of the loading develops.

Besides attaching strain gages to the concrete surface, the testing has included measuring changes in electrical conductivity as a function of axial load and strain. Electrical conductivity measurements were taken by embedded electrodes. Electrode placement in the concrete columns is shown in Figure 2. Prior to loading the specimen, the data acquisition device was connected to the electrodes such that a current is supplied to create a circuit using the outer electrodes (Figure 2B). An electrical bond breaker was placed between the load contacts and the specimen. To prevent polarization of the concrete, alternating current (AC) was imparted into the concrete through the outer electrodes [22].
Insulated wires were placed through the forms and the wire insulation was stripped at the location where electrical resistance was measured (Figure 3A). Electrodes consist of 10 Ga., stranded copper with 24-mil insulation. The length of the electrodes protruding through the wires were equivalent and the exposed length of wire was one inch. The forms were 19 mm thick to prevent bulging of the forms during creation of the specimens. Initial curing included covering the specimens with plastic to retain moisture. Companion cylinders consisted of 101 × 202 mm for strength testing and 150 × 300 mm for testing modulus of elasticity.

To ensure the moisture within the concrete columns will not interfere with the electric flow within the specimen, the tests were performed three months after the 28 days curing stage. During the three months, the specimens were stored in an air-dry lab.

The placement of the electrodes is intended to indicate changes in electrical conductivity as the concrete compresses. Load eccentricity has been verified by the attached strain gages on two adjacent planes of the concrete columns and was oriented axially. Electric current was applied at the electrodes near the column ends and passed through the cross-section of the column. Changes in conductivity were measured across three pairs of the electrodes at the exposed wires. Figure 4 indicates the expected relationship between current flow, equipotential lines, and placement of electrodes for the proposed specimens for this study. As shown in Figure 4, there were three pairs of electric potential...
measurements, indicated in the following sections as left, middle, and right measurements, respectively.

![Anticipated Current Flow](image)

Figure 4. Anticipated Current Flow and Locations of Electric Potential Measurements.

3.2. Concrete Mixture Design

Mixture proportioning and concentrations of recycled steel residuals was developed according to ACI 211 and 544 [16–19]. Sieve analysis of the fine and coarse aggregates was first performed. The aggregate was characterized according to ASTM C33 [23]. A dry-rodded unit weight of the coarse aggregate was measured (ASTM C125) [24]. To help prevent a reduction in workability and maintain consistent parameters, all mixtures had a w/cm ratio of 0.45. Additionally, two types of admixtures were used to reduce the likelihood of slump loss—water reducer (WR, Type A) and high-range water reducer (HRWR, Type F) (ACI 212.3R [25], ASTM C 494 [26]). For this project, the coarse and fine aggregates were reduced according to the corresponding volume of added steel. The reduction in coarse and fine aggregates was approximately equivalent, by volume. The concrete was mixed according to ASTM C94 and ASTM C192 [27,28].

Two mixture designs were developed and corresponded with recycled-steel-residual ratios of 0 and 2% relative to bulk volume. Table 1 indicates the concrete mixtures used for the column testing of this project and the theoretical plastic properties and mixture designations. It should be noted that ACI 544 recommends a maximum concentration of steel fibers to be 1% [17]. Based on preliminary studies and values in static electrical conductivity tests of the preliminary test members, one of the mixtures included a higher concentration—2%—than recommended by ACI 544 [17]. The proportioning of mixtures to include a graded recycled steel residual was a result of the findings of the preliminary test mixtures which produced material with significantly reduced workability.

<table>
<thead>
<tr>
<th>Mixture Component/Parameter</th>
<th>0.0%</th>
<th>2.0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement, kg</td>
<td>44.5</td>
<td>44.5</td>
</tr>
<tr>
<td>Water, kg</td>
<td>18.8</td>
<td>18.8</td>
</tr>
<tr>
<td>Coarse aggregate, kg</td>
<td>107.2</td>
<td>104.1</td>
</tr>
<tr>
<td>Fine aggregate, kg</td>
<td>112.5</td>
<td>109.2</td>
</tr>
<tr>
<td>Recycled steel residuals, kg (Retained on No. 8 sieve)</td>
<td>0.0</td>
<td>6.2</td>
</tr>
<tr>
<td>Recycled steel residuals, kg</td>
<td>0.0</td>
<td>12.4</td>
</tr>
</tbody>
</table>
Table 2. Batch Weights of Trial Concrete Mixtures Based on RSR Concentration.

<table>
<thead>
<tr>
<th>Mixture Component and Plastic Property</th>
<th>No RSR</th>
<th>with RSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement, kg</td>
<td>21.2</td>
<td>21.2</td>
</tr>
<tr>
<td>Water, kg</td>
<td>8.7</td>
<td>8.7</td>
</tr>
<tr>
<td>Coarse Aggregate, kg</td>
<td>57.1</td>
<td>50.9</td>
</tr>
<tr>
<td>Fine Aggregate, kg</td>
<td>52.8</td>
<td>51.6</td>
</tr>
<tr>
<td>Recycled Steel Residuals, kg</td>
<td>0.0</td>
<td>7.1</td>
</tr>
<tr>
<td>MRWR Admixture, mL (oz./cwt)</td>
<td>96.6 (7)</td>
<td>96.6 (7)</td>
</tr>
<tr>
<td>Batch Size, m³</td>
<td>0.056</td>
<td>0.056</td>
</tr>
<tr>
<td>Assumed Entrapped Air, %</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Theoretical Plastic Density, kg/m³</td>
<td>2378.7</td>
<td>2462.1</td>
</tr>
<tr>
<td>w/cm ratio</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>Slump, mm</td>
<td>152.4</td>
<td>76.2</td>
</tr>
</tbody>
</table>

3.4. Self-Sensing Measurements

Each column test involved three cycles between minimum and maximum values and the number of voltage measurements was approximately 20 measurements per loading cycle. The loading range was set between 10% and 60% of the concrete strength based on the 150 × 300 mm companion cylinders. At 45 kg per second, the loading rate was slower than recommended by ASTM C39 (ASTM C39) [34]. Voltage measurements were recorded in a National Instrument (NI) data logger NI 9205 with three parallel differential channels at a sampling rate of 1000 S/s and with a maximum voltage reading of 10 V. One-hundred samples were taken over six cycles of the 60 Hz. voltage input equivalent to 25.5
V at 650 mA. The same data logger was used to record strain using two channels of a NI 9237, having a minimum sampling rate of approximately 1620 S/s.

4. Results

Figure 5 shows the loading histories as stress–strain curves for both the 0% and 2% columns. Testing was repeated on the 2% specimen, hence, Figure 5B shows two response curves. The second load test was done one week after the first test to determine the repeatability of the measurements. Figure 6 shows the time histories of the strain and the voltage measurements (three pairs for each specimen) for the 0% and 2% specimens (Test 1). These raw data show that the concrete with 2% filler material has correlation with the strain loading; on the other hand, the concrete column without RSR has no visible trend in electric responses. Therefore, the following data analysis was only performed on the 2% specimen.

Figure 5. Stress–Strain Curves Showing Multiple Loading Cycles: 0% (A) and 2% (B) for both Test 1 and Test 2.
To quantify the correlation between electric measurements and mechanical strain, the response histories of all three electrode sets and the strain measurements were first reviewed. Figure 7 shows the first load test response histories for the 2% specimen, and it shows the time histories have slight deviation between all three measurements—left, middle, and right electrode sets. Similarly, Figure 8 shows the second load test response
histories of the electric properties and the strain. Figures 7 and 8 are plotted as resistance ratio \( \frac{\Delta R}{R_0} \) versus strain history. Please note that resistance was used in this paper instead of resistivity simply because of the limited specimen geometries involved.
Figure 7. Strain and Resistance Measurements Time History for 2% Specimen Load Test 1: Left Electrode (A), Middle Electrode (B), and Right Electrode (C).
To establish the electro-elastic correlation, the resistance calculations were made from the voltage measurements and compared to the measured strain. Each electric resistance ratio plot is segregated into six linear curves and plotted against the corresponding strain and a straight line is determined from the average values. Figures 9 and 10 each show three plots for left, middle, and right electrode set and for load Test 1 and Test 2.
respectively. Additionally shown in each plot is the linear best-fit line for each case. The straight lines are presented so that they converge at the origin of each coordinate system and are shown to be offset from the curves because the test results have not been normalized. Furthermore, the strains (x-axis) have been defined as negative to indicate compression. To develop the linear relationship, slope adjustment was made on the right side of Equation (2), similar to a gage factor for a strain gage. The value of the slope adjustment is provided in the legend of the plots and is hereby called $F$ (elasto-electric factor), and is defined as:

$$\varepsilon (1 + 2\nu) = F \frac{\Delta R}{R}$$  \hspace{1cm} (3)

Equation (3) replaces Equation (2) and $F$ can be experimentally determined for different concrete mix designs.
Figure 9. Elasto-Electric Parameter X–Y Scatter Plot with Mechanical vs. Electrical Measurements for Load Test 1 for ((A) Left Electrode, (B) Middle Electrode, and (C) Right Electrode).
Figure 10. Elasto-Electric Parameter X–Y Scatter Plot with Mechanical vs. Electrical Measurements for Load Test 2 for ((A) Left Electrode, (B) Middle Electrode, and (C) Right Electrode).

A best fit value is determined for each load test and for each electrode set. Respectively, for Test 1 and Test 2, Figures 11 and 12 show a total of six different plots of measured strain and computed strain relations using Equation (3). The measured strains are linear relations between the X and Y axes of each plot, and the measured strain curves represent the best fit line with different $\mathcal{F}$ values shown in the legend for each plot. Figure 11 shows the $\mathcal{F}$ absolute value ranges from 0.065 to 0.068 and Figure 12 shows that the $\mathcal{F}$ absolute values are more consistent and are equal to 0.026 for Tests 1 and 2, respectively.
A

Y = 0.9951X

Y = X

B

Y = 1.0067X

Y = X

Measured Strain 2% - 2W
Calculated E = F* (ΔR/R0)/(1+2v) (F=0.066)

Calculated E = F* (ΔR/R0)/(1+2v) (F=0.065)
Figure 11. Elasto-Electric Relations for Load Test 1 of Left Electrode (A), Middle Electrode (B), and Right Electrode (C) Pairs.
Figure 12. Design Elasto-Electric Relations for Load Test 2 of Left Electrode (A), Middle Electrode (B), and Right Electrode (C) Pairs.
5. Discussion

Results from the tests provide interesting information regarding the change in concrete conductivity due to the addition of RSR in the concrete mix. The electric resistance and the strain measurements both show a corresponding trend between the loading/unloading cycles. Two critical observations can be summarized from the testing of the 0% and 2% specimens: (1) there are different mechanical behaviors for the 2% specimen (Figure 5), and (2) it is possible to generate a linear correlation to quantify the electro-elastic relationship. First, the following section address the issue of material behavior of the 2% specimen.

5.1. Loading History Analysis

Table 3 indicates that the plastic properties of the concrete columns were affected by the introduction of recycled steel residuals. The introduction of recycled steel residuals caused the air content to increase from 2.5 to 5 times that of the concrete with 0% recycled steel residuals. Air content partially dictates the level of unit weight in the concrete, which decreased nearly linearly according to the increase in air content. While making the specimen, off-gassing from the concrete with large bubbles of gas escaping from the top of the specimens was observed. The evidence of off-gassing and high air content likely indicates that chemical reactions occurred between the hydrating cement and possible grease (oil-based chemicals) on the recycled steel residuals.

Table 3. Plastic Concrete Properties for Each Concrete Mixture Design.

<table>
<thead>
<tr>
<th>Measured Plastic Properties</th>
<th>0.0%</th>
<th>2.0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Content, %</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>Unit Weight, kg/m³</td>
<td>2340.3</td>
<td>2003.9</td>
</tr>
<tr>
<td>Temperature, °C</td>
<td>18.3</td>
<td>17.8</td>
</tr>
<tr>
<td>Slump, mm</td>
<td>76.2</td>
<td>82.6</td>
</tr>
</tbody>
</table>

Given the high air content, it is no surprise that strength and modulus of elasticity also reduced. Both strength and modulus of elasticity reduced by more than half for the addition of 2% recycled steel residuals. This also resulted in the different behaviors between the first and second load tests on the 2% specimen: Test 1 was shown (Figure 5) to provide a similar stress–strain cycles as the 0% specimen, which can be described as relatively linear during the loading and unloading paths. For Test 2, Figure 5 indicates that the modulus of elasticity of the concrete specimen reduced, rebounding was not exhaustive, and that a stage existed during both maximum and minimum loads in which the strain did not change. This interesting observation may indicate a change in the concrete material not unlike a permanent internal consolidation of the material. The result of this material consolidation is a more consistent electro-elastic behavior, as indicated by the singular $F$ factor for Test 2. Table 4 summarizes the statistical parameters for both tests and shows that the coefficient of variation is smaller for Test 2 than Test 1. The standard deviations for each of the averaging effects shown in Figures 9 and 10 are also larger for Test 1 than Test 2, respectively.

Table 4. Statistical Comparisons between Test 1 and Test 2 for 2% Specimen.

<table>
<thead>
<tr>
<th>Calculated $\Delta R/R_0$</th>
<th>Elasto-Electric Standard Deviation</th>
<th>Coefficient of Variation</th>
<th>Linear Regression, $R^2$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2%–2; W, L</td>
<td>-0.066</td>
<td>0.000225</td>
<td>0.98</td>
</tr>
<tr>
<td>2%–2; W, M</td>
<td>-0.065</td>
<td>0.000243</td>
<td>1.02</td>
</tr>
<tr>
<td>2%–2; W, R</td>
<td>-0.068</td>
<td>0.000226</td>
<td>0.88</td>
</tr>
<tr>
<td>2%–2; NonW, L</td>
<td>-0.052</td>
<td>0.000177</td>
<td>0.98</td>
</tr>
<tr>
<td>Test 2</td>
<td>Condition</td>
<td>Strain</td>
<td>Stress</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>2%-2; W, L</td>
<td>-0.026</td>
<td>0.000118</td>
<td>0.45</td>
</tr>
<tr>
<td>2%-2; W, M</td>
<td>-0.026</td>
<td>0.000119</td>
<td>0.45</td>
</tr>
<tr>
<td>2%-2; W, R</td>
<td>-0.026</td>
<td>0.000118</td>
<td>0.47</td>
</tr>
<tr>
<td>2%-2; NonW, L</td>
<td>-0.035</td>
<td>0.000158</td>
<td>0.45</td>
</tr>
<tr>
<td>2%-2; NonW, M</td>
<td>-0.034</td>
<td>0.000156</td>
<td>0.47</td>
</tr>
<tr>
<td>2%-2; NonW, R</td>
<td>-0.035</td>
<td>0.000159</td>
<td>0.47</td>
</tr>
</tbody>
</table>

There were also strain variations between the wire and non-wire faces, which indicates eccentricity developed in the column (Figure 13). This may be caused by uneven surfaces at each column face or uneven micro-failures of the concrete. It is shown that there is a smaller deviation between Test 1 strain measurements (Figure 13A) than that of Test 2 (Figure 13B).
Another interesting observation associated with the load test is that there is a skew in the voltage measurements during the first test, which may support the assumption of material consolidation. As shown in Figure 14, the voltage measurement for Test 1 (Figure 14A) shows an increasing trend, which is not as obvious as in Test 2 (Figure 14B). To prove that the voltage measurement skew is not associated with possible increase in material capacitance, a non-loading (static) measurement was conducted on the 2% specimen. Figure 15 shows that without any loading on the specimen, the voltage difference of electric current flowing through the specimen remained nearly constant.

**Figure 13.** Strain Differences between Strain Gauge Measurements of the Wire and Non-Wire Faces for Test 1 (A) and Test 2 (B).
Figure 14. Skew in Voltage Measurements for Test 1 (A) and Test 2 (B).
5.2. Linear Electric-Elasto Relationship

The validation that RSR addition can serve as a functional material for self-sensing of mechanical stressing of concrete is demonstrated in the establishment of the linear correlation, as presented in Equation (3). For the 2% specimen, two equations have been established for both Test 1 and Test 2, Equation (4) and Equation (5), respectively. These equations are modified from that of Equation (3) in order to directly correlate strain and resistance measurements by removing the resistivity term from Equation (3).

\[ \varepsilon (1 + 2\nu) = -0.059 \frac{\Delta R}{R} \]  

(4)

\[ \varepsilon (1 + 2\nu) = -0.026 \frac{\Delta R}{R} \]  

(5)

The \( F \) factor for Test 1 is averaged to be \(-0.059\) from all the curves shown in Figure 9. Likewise, the \( F \) factor for Test 2 is averaged to be \(-0.026\) from all the curves shown in Figure 10. The \( F \) factor needs to be established by conducting tests on full-scale specimens using similar electro-elastic tests for a mix design. It is possible to establish other load test procedures for other mechanical behaviors of concrete structures, such as tension and flexural tests, and the effects of reinforcing steel as a function of distance from the electrode.

In addition, other parameters, including plastic and hardened properties of the concrete, should be measured and/or observed. Besides the potential benefit of measuring strain through changes in electrical conductivity, the introduction of the reused steel has the potential of causing beneficial and/or detrimental effects to the concrete. For example, the introduction of the added recycled steel residuals might increase the compressive strength and modulus of elasticity of concrete. Alternatively, the recycled steel residuals may cause a lack of workability of the concrete, as indicated in some of the preliminary work performed for this study. If that is the case, then more consolidation energy will be required for the concrete to be adequately placed in forms during construction.
6. Conclusions

In this study, recycled steel residuals (RSR) are shown to be useful as a functional fill in concrete to enhance its electrical properties. The outcome of the fundamental study is a self-sensing material that can detect the strain responses under loading by electric resistance measurements. Electric-based testing of concrete containing 2% of the recycled steel residuals under cyclic compression test indicates corresponding responses in strain, which is not detected in concrete specimen without any filler. The test results can also be used to define experimental electro-elastic relations consistent with theoretical equations and to determine a newly introduced term, electro-elastic factor, $F$.

It is noted that the introduction of recycled steel residuals causes deleterious increase to the air content and mechanical capacity of the 2% concrete specimen. Thus, it is important to ensure that the RSR is fully cleaned. Full scale specimens can be developed according to the process described herein to determine the electro-elastic properties associated with other mechanical behaviors and to derive the calibration factors for different concrete mixtures.

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