Optimization of Instrumentation for Accelerated Creep

Undergraduate Research Project

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iii. Introduction

The objective of the project was to test the feasibility of using vibrating wire strain gage (VWSG) sensors for use in accelerated creep tests of concrete specimens. Creep is a time-dependent material property that involves deformation of a specimen under constant stress. The current methodology that has been used to monitor creep utilizes a handheld Whittemore gage to measure the difference in proximity of embedded inserts in the test specimen. This methodology is very time consuming and prone to error due to potential differences in pressure applied by the operator and inaccessibility of some of the embedded inserts. The VWSG is beneficial in that the instrument remains attached to the specimen, which reduces the likelihood of error due to the seating of the device and the accessibility. In addition, numerous readings may be taken electronically and averaged to reduce the likelihood for measurement error. To investigate the feasibility of using the VWSG for accelerated creep tests, a series of concrete test specimens were used that incorporated different types of instrumentation for comparison. Additionally, an aluminum test specimen was included in the study as a control. To decouple the parameters, tests were conducted under load at constant temperature and under varying temperature without load applied. In this way, mechanical strains could be decoupled from thermal strains. Because the concrete stiffness (modulus of elasticity) and coefficient of thermal expansion are variable depending on the particular concrete mix, the aluminum cylinder with known modulus of elasticity and coefficient of thermal expansion provided a control specimen that enabled comparison of the measured data with predicted results.

iv. Background

There is interest in understanding the long term creep of structural systems (e.g., nuclear containment vessels) to predict the effects of creep on the long term performance of the systems. Because the time-dependent effects occur over decades, there is interest in conducting accelerated creep tests that simulate the effects of longer time periods by increasing the temperature to produce similar results in a reduced time scale. In past, there has been testing done by researchers on topics such as the I-35w bridge using vibrating wire strain gages.

v. Description of Tests and Methodology

The following gages and specimens were utilized during testing.

Vibrating Wire Strain Gage

Geokon model 4200 vibrating wire strain gages (VWSGs) were used to measure the strain changes in the concrete as well as aluminum specimens. Vibrating wire strain gages record strain by electromagnetically "plucking" a steel wire held in tension within the gage. The changes in resonate frequency are associated with changes in strain. As temperature increases, this causes a decrease in wire tension, and is accounted for in equation (1-4) (Geokon). A GK 401, or "Redbox", readout box was utilized to collect the data on setting "D". Please see Figure 1b on the next page.

Figure 1a. Image of an external Vibrating Wire Strain Gage with ruler for scale

DEMEC and Related Tools

The DEMEC gage consists of points that are embedded in the cylinder during casting of the specimen. An Invar bar is then used to calibrate the measurement tool, in this case a Mitutoyo Absolute Model ID-C112TB Whittemore gage, and then this measurement tool is used to measure the distance between the two DEMEC points that were inserted into the specimen when it was cast. The Mitutoyo measurement tool has a digital readout that has a 0.0001 inch/0.0001 mm variation. This produces a strain accuracy of 0.0001 strain (or 100 microstrain).

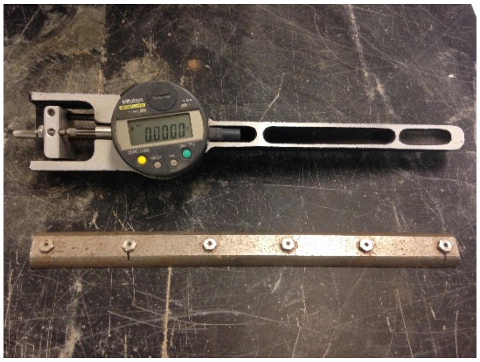


Figure 2. Image of a Mitutoyo Absolute Model ID-C112TB or "Whittemore Gage" (top) and invar

Figure 1b. Geokon 401, or “Redbox”

Specimens

The gages were used to measure changes in strain in cylinders of concrete and aluminum. Three 4x11 concrete cylinders were cast using concrete from the I-35W bridge, and so the coefficient of thermal expansion could be approximated to determine predicted values of strain, given a change in temperature by using the values that were calculated in a previous paper written by French, et al. These specimens were utilized in the Strain due to Temperature phase of testing. The aluminum (6061-T6) cylinder was 4x8 in dimension, and was available for use in the structures lab. This was utilized in the Strain due to Loading phase of testing. It must be noted that several other specimens were planned to be used in experiments, but the concrete pour failed. Details of this are in the Extension of Research section of this report.

Methods

1. Establishing the Accuracy of the Demec Whittemore gage.

Establishing the accuracy of the Demec Whittemore gage is important because the error induced by user error is an important aspect to consider when analyzing results. To establish this, 30 readings were taken, with 10 on each side of the pair of Demec points that were placed at third intervals around the concrete cylinder. It is important to note that the cylinder was rotated to the next point after each reading to eliminate potential bias. The cylinder was placed upon a manufactured wooden stand that allowed space for the vibrating wire strain gages, shown in Figure 1a and 2a in Appendix A. The cylinder was rotated after each reading to prevent user bias. The data was then taken and the task was performed again if more than three of the readings were more than 1

2. Total Strain

The general equation utilized as a benchmark for the testing within the study was the equation for total strain, given in the equation below.

$$\varepsilon_{total} = \varepsilon_{thermal} + \varepsilon_{mechanical} \tag{1-0}$$

Where $\varepsilon_{thermal}$ is the strain due to temperature change
$\varepsilon_{mechanical}$ is the strain due to mechanical loading
ε_{total} is the total strain of the specimen

This equation is of note, because this equation is the basis for this study. Creep is the permanent deformation of concrete over time as a result of sustained loading. A creep frame within a temperature varied environment was initially explored to examine this phenomenon, but it was determined that it would be more useful to examine temperature change and load change independently of one another to eliminate sources of error and additional variables when analyzing the results. Each of the components of the above equation was used in the study to assess the adequacy of the vibrating wire strain gage to assess creep.

3. Assembling the Specimens

Before testing could begin, the specimens had to be first assembled. Four cylinders had to be procured from the lab, three of which consisted of the same concrete as the I-35W bridge and were 4 inches in diameter and 11 inches tall, and the other of 6061-T6 Aluminum that was 4 inches in diameter and 8 inches tall. Both the aluminum and the concrete cylinders had 3 VWSGs applied to each cylinder on thirds of a circle. A protractor was used to mark thirds on the bottom of the cylinder with a black marker, and then lines were extended upward using a level that ensured the table was level, and a right angle was used to draw the line. They were initially applied with epoxy that was already in the shop. However, it was found that the epoxy was opened more than a month prior, when the suggested use indicated that it should not be opened for more than a month before use, and so the epoxy had to be stripped and a different epoxy applied to ensure the epoxy was not interfering with the readings. The epoxy used was GORILLA clear epoxy adhesive. The instructions followed are summarized

1. The surfaces must be clean, dry and free of grease and oil. The cylinders were rubbed with acetone before adhesion to ensure this.

2. The work area was covered to prevent spills
3. The syringe was pushed upward to eliminate air and ensure even dispensing
4. Even amounts of resin and hardener were placed into a clean disposable bowl
5. The mixture was mixed for at least 20 seconds to ensure uniformity
6. This mixture was applied to the surface within 5 minutes. It is stated on the package that the bond strength will deteriorate if one waits longer
7. The vibrating wire strain gages were firmly placed on the cylinder in position for at least one minute
8. Duct tape was used to secure the gages to the cylinder and left in this way overnight.

This particular epoxy was chosen because of the price point, the ease of attainability, and because its utilization parameters matched that of the experiment constraints. Some of the parameters include the ability to fill in gaps, the ability to bond to both concrete and aluminum, and its temperature tolerance of -10 °F to 180 °F. Before using the specimens, the duct tape was removed and light pressure was applied to ensure that the gages were firmly attached. Initially, it was a concern of what effect alignment would have on the readings of the gages, but it was found to have minimal effect up 10 degrees of alignment, which would be obvious to someone examining the specimen. The table below shows the minimum strain that could be read by a VWSG, the strain that would be read by the gage as a result, and the percent error. As one can see, it is not until about 10 degrees of error before 1 percent error is reached.

Table 1. Percent error resulting from misalignment of the VWSG from vertical

Strain	Degree of Inaccuracy	Radians of Inaccuracy	Resulting Strain	Percent Error
1.00E-06	1	0.017453293	1.00E-06	1.52E-02
1.00E-06	2	0.034906585	9.99E-07	6.09E-02
1.00E-06	3	0.052359878	9.99E-07	1.37E-01
1.00E-06	4	0.06981317	9.98E-07	2.44E-01
1.00E-06	5	0.087266463	9.96E-07	3.81E-01
1.00E-06	6	0.104719755	9.95E-07	5.48E-01
1.00E-06	7	0.122173048	9.93E-07	7.45E-01
1.00E-06	8	0.13962634	9.90E-07	9.73E-01
1.00E-06	9	0.157079633	9.88E-07	1.23E+00
1.00E-06	10	0.174532925	9.85E-07	1.52E+00
1.00E-06	11	0.191986218	9.82E-07	1.84E+00
1.00E-06	12	0.20943951	9.78E-07	2.19E+00
1.00E-06	13	0.226892803	9.74E-07	2.56E+00
1.00E-06	14	0.244346095	9.70E-07	2.97E+00
1.00E-06	15	0.261799388	9.66E-07	3.41E+00

4. Strain Due to Temperature Change

The purpose of this procedure was to test the accuracy of the readings of a VWSG during the deformation of concrete due to temperature variation. DEMEC and predicted strain, given an upper and lower bound to the coefficient of thermal expansion, were used as comparisons for accuracy of the procedure.

Background

The following is the general equation describing how a temperature change causes a change in the axial length of a specimen.

$$\Delta L = \alpha * \Delta T L_o \tag{1-1}$$

Where ΔL is the change in length that the member undergoes
α is the coefficient of thermal expansion of a material
(assumed constant) in ε/°C
ΔT is the change in temperature °C
L_o is the original gage length

The following equation is the generalized equation for strain.

$$\varepsilon = \frac{\Delta L}{L_o} \tag{1-2}$$

Where ε is the strain that the member experiences

Combining eqn (1-1) and (1-2), the thermal strain equation is derived as used in the experiment. Positive strains are defined as lengthening and negative strains are shortening in this document.

$$\varepsilon = \alpha * \Delta T \tag{1-3}$$

If one knows the coefficient of thermal expansion of the material that is undergoing study and the temperature change from time t_o to t_1, then the value of strain resulting from a given temperature change can be determined. Concrete's coefficient of thermal expansion is more difficult to determine due to factors such as variation between mixes and within the sample itself. A range was taken from the maximum and minimum values found to determine a range of acceptable values for the purposes of determining whether the results from where the experiment was within an acceptable level of error.

Procedure

The three concrete cylinders were placed in a temperature controlled room inside of the structures lab for an initial one full day. The temperature of the cylinders was checked via the Geokon box and the external gage on the temperature control room. The cylinders were left for another 24 hour period, and the temperature was checked once more. It was established that the temperature had not changed beyond 1/10 of a degree on average, and so it was concluded that one day was adequate to leave the cylinders in before the strain was read. It could have been tested whether the readings could be tested in less than a day, but this was not viable because the readings had to be all taken manually. The VWSG box was taken out of the chamber in between readings to reduce wear on the device, but the Whittemore gage was left in the room to eliminate some need for it to be calibrated between each reading due to changes in the length of the gage resulting from change in the actual gage itself not being in temperature equilibrium. The VWSGs were initially checked once for each gage, but later on in the experiment the gages were checked twice to ensure that both readings were the same. Similarly in the case of the Demec, the gages were initially checked once, using the stand that had been created earlier in the process. However, they were checked twice to ensure that the readings were not changing. To ensure user bias was not prevalent, the gages were all read once, then all again in a circle around the cylinder, rather than the same gage twice in a row. This was done at 0, 60, 130, 60, and 0 degrees Fahrenheit. This was initially chosen because it was determined through the coefficient of thermal expansion of the concrete cylinders and equation (1-3) that at least 22 degrees Fahrenheit of change was required for the VWG to register a change in reading due to the resolution of the gage. Please see Tables 2 and 3 for a summary of the resolution of the gages and the resulting requirements for the change in temperature. This cycle was done twice to because the concrete should not be exhibiting any permanent deformation, and so the results should be the same both times. In addition, the change in strain should be equivalent, whether the temperature is increasing or decreasing.

Corrections for Temperature

To determine the actual strain undergone by the concrete as measured by the VWSG devices, the formula that was previously derived by the manufacturer was used.

$$\varepsilon = (R_1 - R_o) * B * G + (T_1 - T_o) * (\alpha_{gage} - \alpha_{concrete}) \tag{1-4}$$

Where R_1 is the reading after temperature change
R_o is the reading before temperature change
B is the batch calibration factor, and is equal to 0.97 for model 4200
G is the gage factor, and is equal to 3.304 for model 4200
T_1 is the temperature at t=1
T_o is the temperature at t=0
α_{gage} is the known coefficient of expansion of steel, 12.2 $\mu\varepsilon/°C$
$\alpha_{concrete}$ is the coefficient of thermal expansion of Concrete

According to the Geokon manual[3], $\alpha_{cylinder}$ will be around 10.4 $\frac{\mu\varepsilon}{°C}$. The paper written on the topic of the I35-W bridge was utilized to have a better idea of what the coefficient of thermal expansion (α) is for this particular concrete, because the cylinders utilized were also used in this test. There isn't a good way to determine which part of the bridge this particular concrete was meant to simulate, but there were different alpha values for each. The largest and smallest values were taken from this paper to simulate bounds of predicted strain representing high and low values. Please reference Table 2 below for α values. Some values were converted using an online calculator mentioned in the Works Cited section. With the coefficient of thermal expansion known, the equation found within the manual was utilized to determine the strain of the cylinder.

Table 2. Materials and values for the coefficient of thermal expansion in both Celsius and Fahrenheit

Material	microstrain/degree F	microstrain/degree C
Low Alpha Concrete	4.73	8.51
High Alpha Concrete	6.45	11.61
Average Value Concrete	5.59	10.06
Steel	6.78	12.2

5. Strain due to Short Term Loading

The purpose of this test was to establish whether the VWSG provides an accurate tool to measure strain in a short term load environment.

Background

The following are the basic equations for stress and Hooke's law, which equates stress to strain using Young's Modulus.

$$\sigma = E\varepsilon \tag{1-8}$$

Where σ is the stress of the cylinder
E is Young's modulus
ε is the strain

$$\sigma = \frac{P}{A} \tag{1-9}$$

Where P is the force applied to the cylinder
A is the area of the cross section of the cylinder

$$A = \pi r^2$$

An aluminum cylinder with known Modulus of Elasticity was utilized to test the gages. From the resolution of the gages, it was established what the change in load needs to be to create a measurable amount of strain for the gage to register. The cross-sectional area of the cylinder was known, and the loads were applied at 1000, 50000, and 10000 pounds. This was cycled three times to ensure that the same values of strain were achieved at each loading.

Procedure

The aluminum cylinder with vibrating wire gages was utilized in this test. It was inserted into a loading machine as shown in the photo, below, under the supervision of a graduate student working in the Soils Lab in the Civil Engineering building.

Figure 3. The setup scheme for the loading test

The graduate student then operated the loading using a controller and pausing at specified loads so readings could be taken using the Geokon readout box. Based on the readings of strain and the known stress on the specimen, the Modulus of Elasticity was calculated and compared to the known modulus of Aluminum.

vi. Results

1.Strain Due to Temperature Change

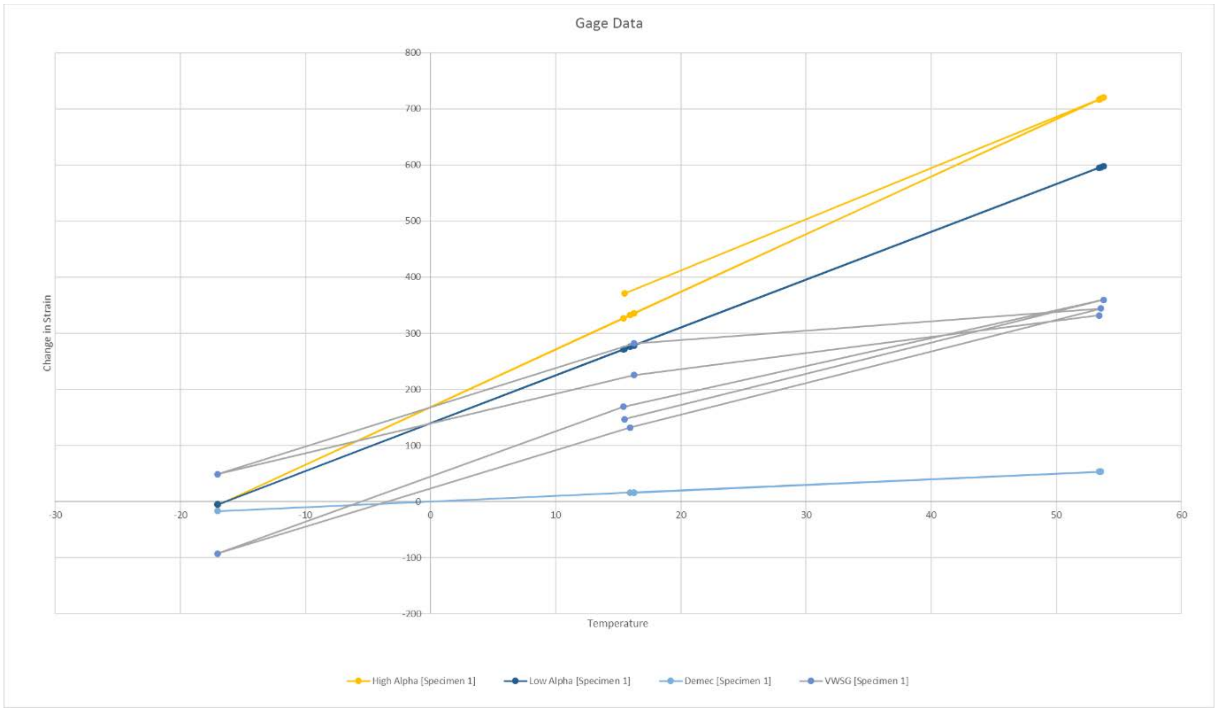


Figure 4. Specimen 1 Results for VWSG and Demec Gages

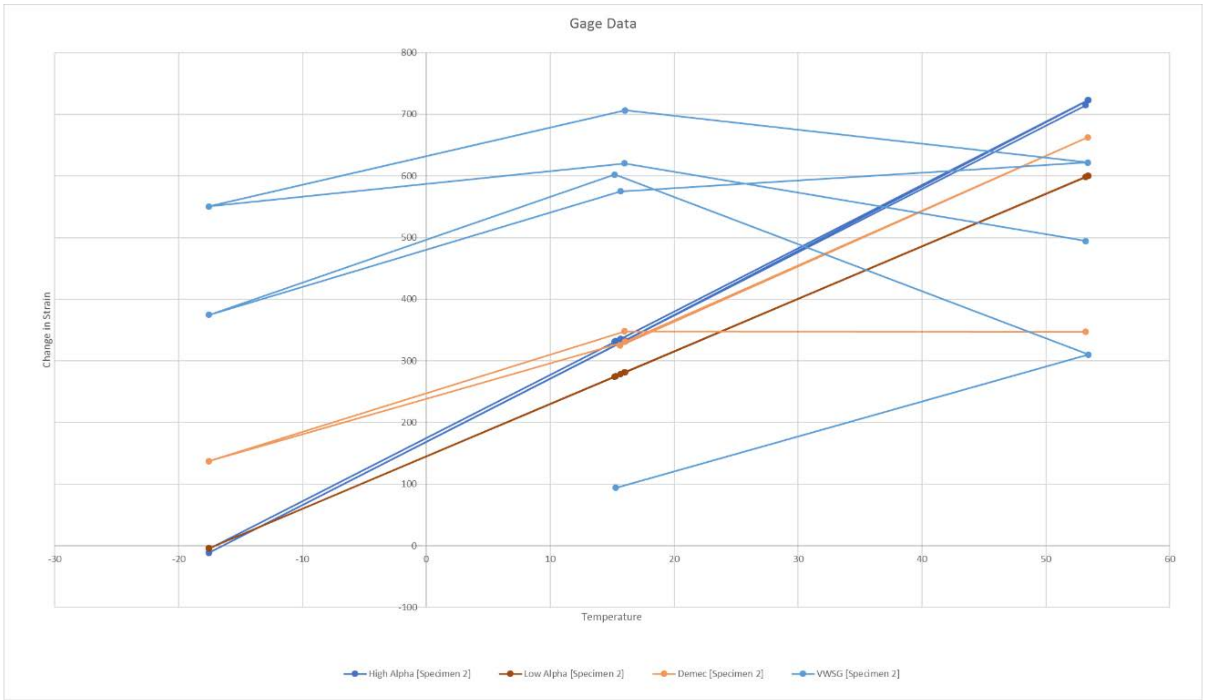


Figure 5. Specimen 2 Results for VWSG and Demec gages

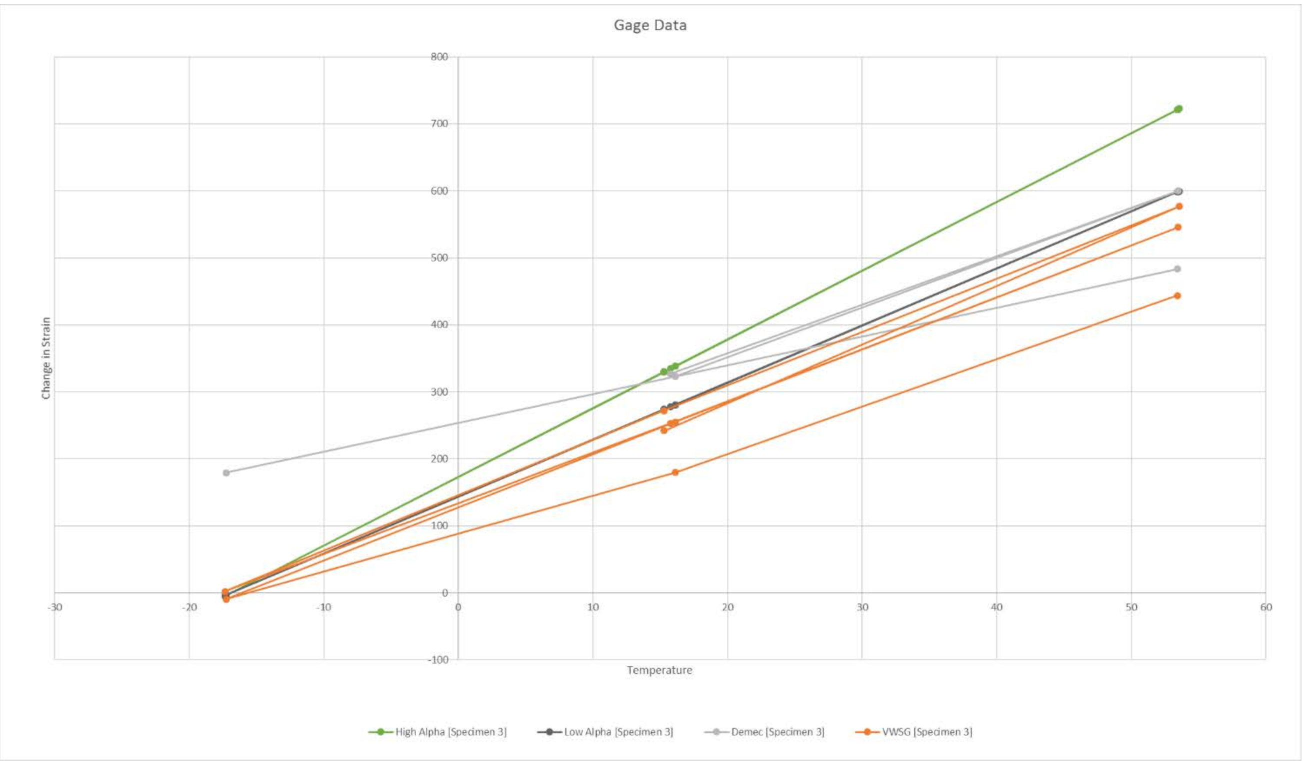


Figure 6. Specimen 3 Results for VWSG and Demec

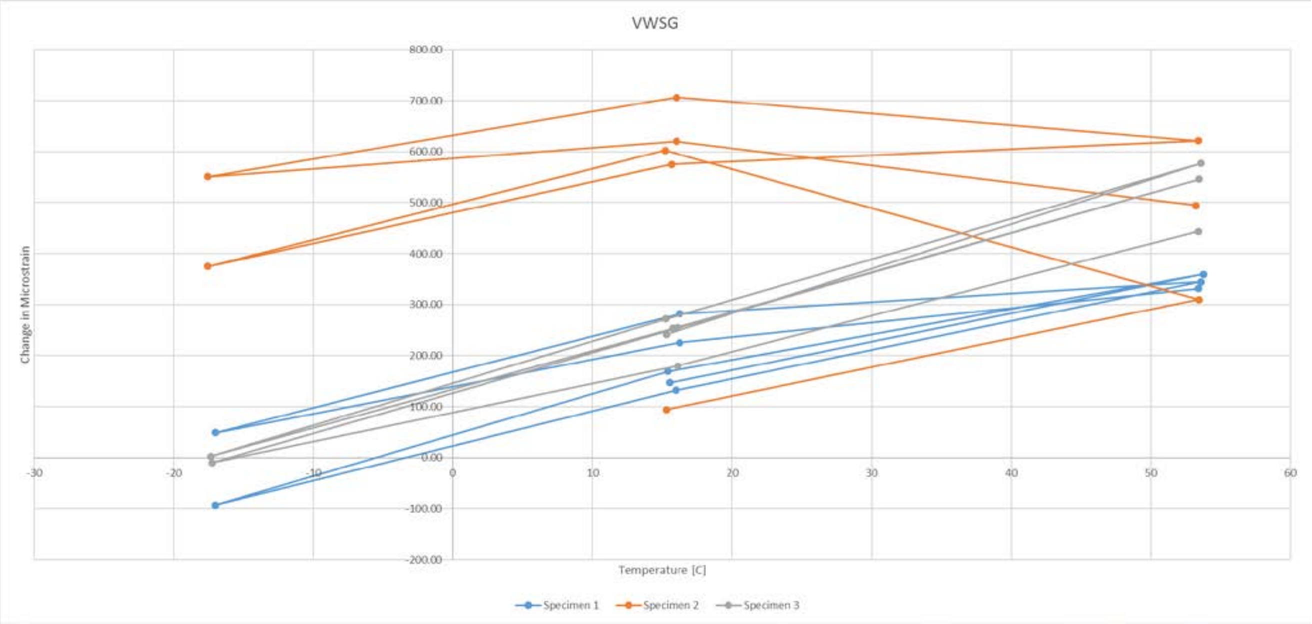


Figure 7. Specimen 1, 2, and 3 VWSG Comparison

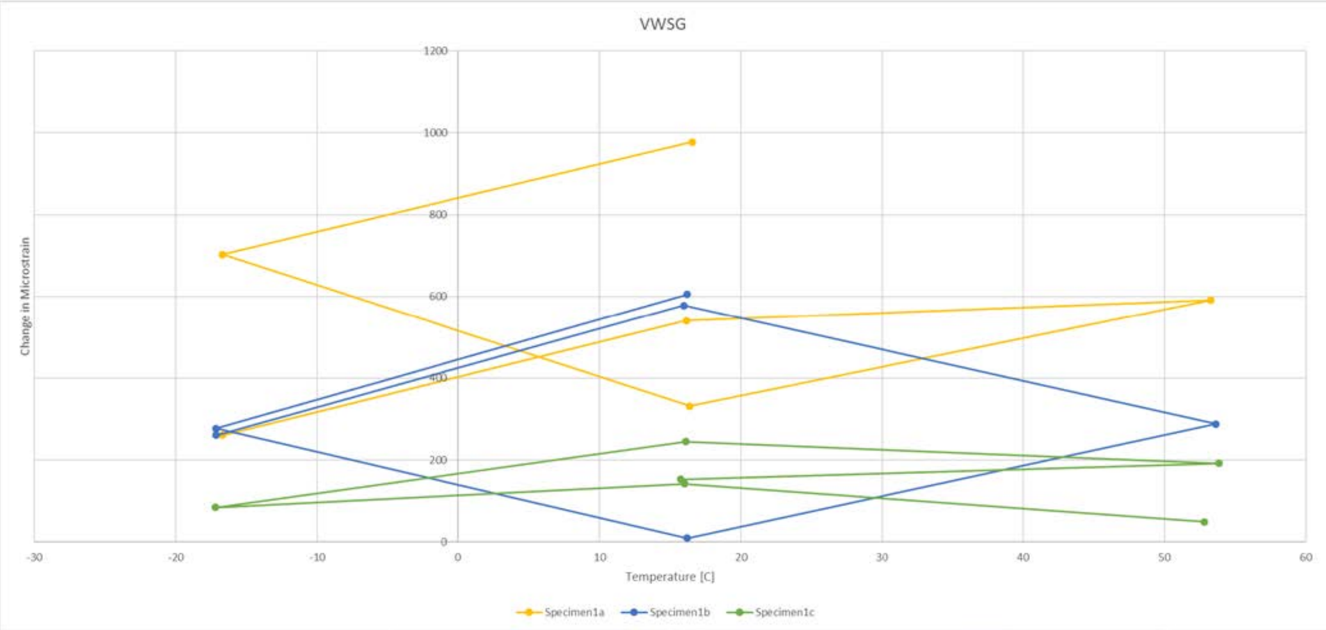


Figure 8. Specimen 1 VWSG gages A, B, and C

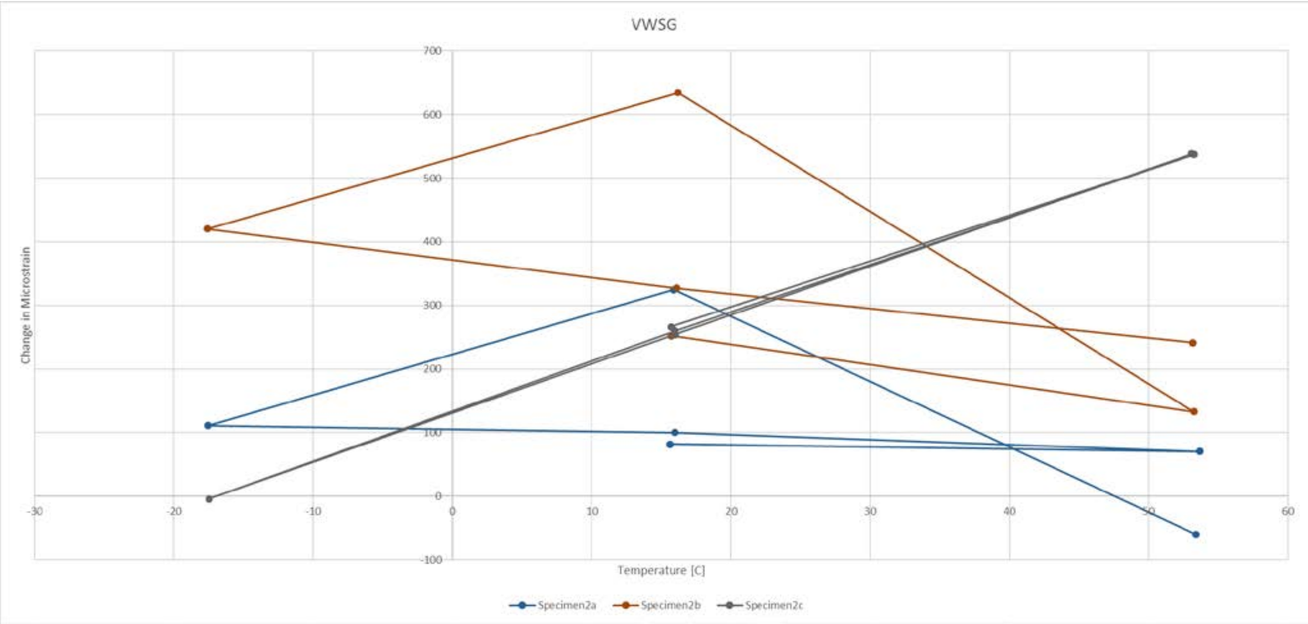


Figure 9. Specimen 2 VWSG gages A, B, and C

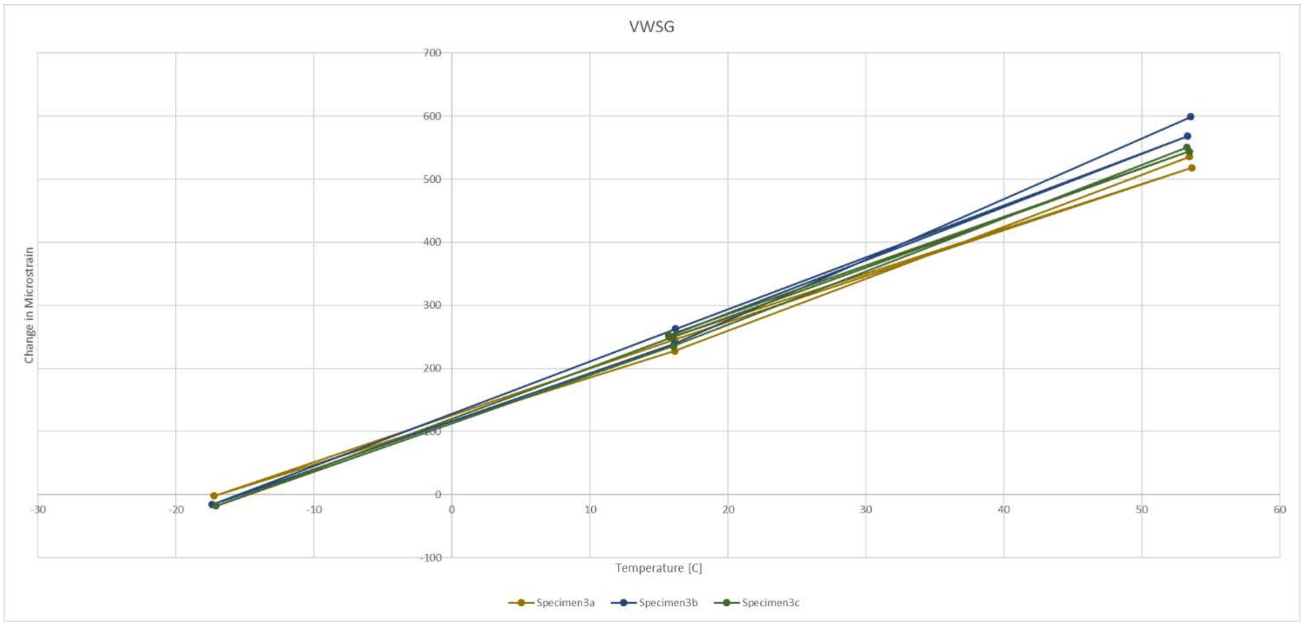


Figure 10. Specimen 3 VWSG gages A, B, and C

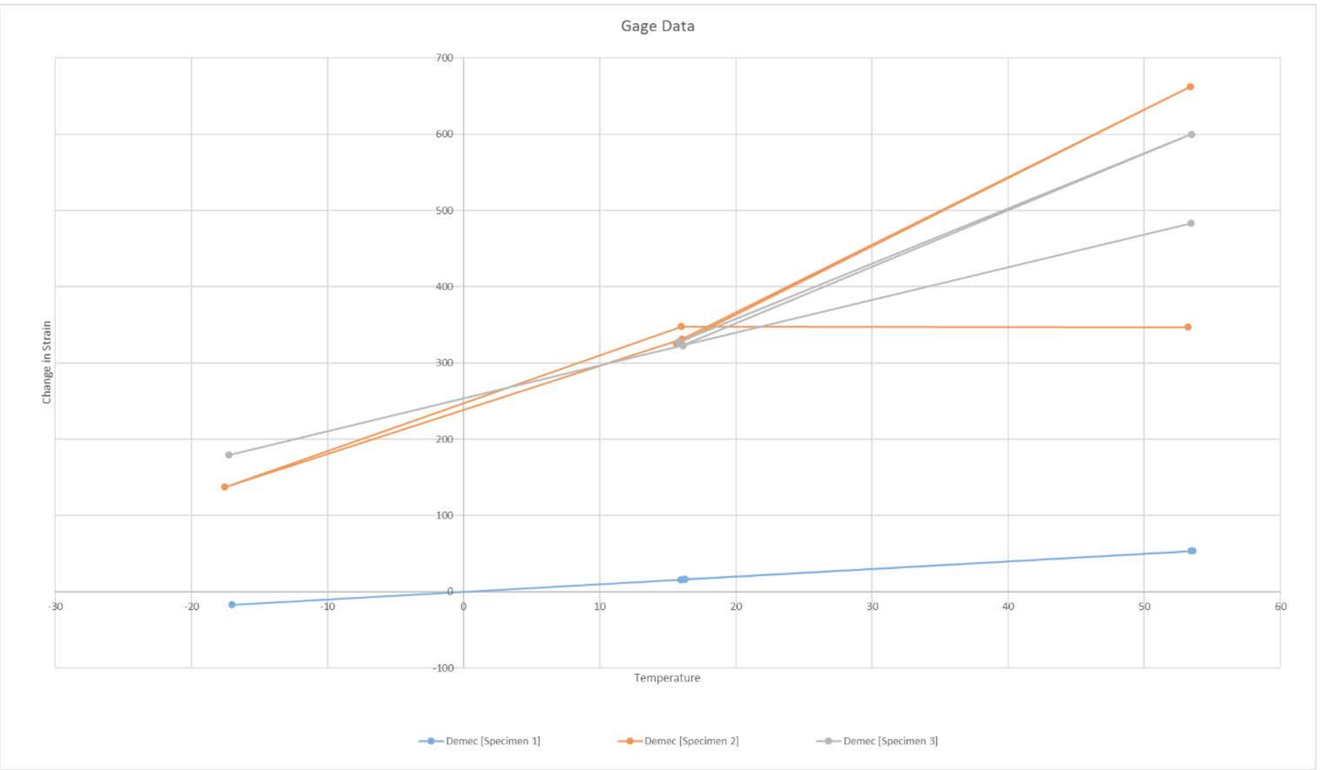


Figure 11. Demec Specimen 1, 2, and 3

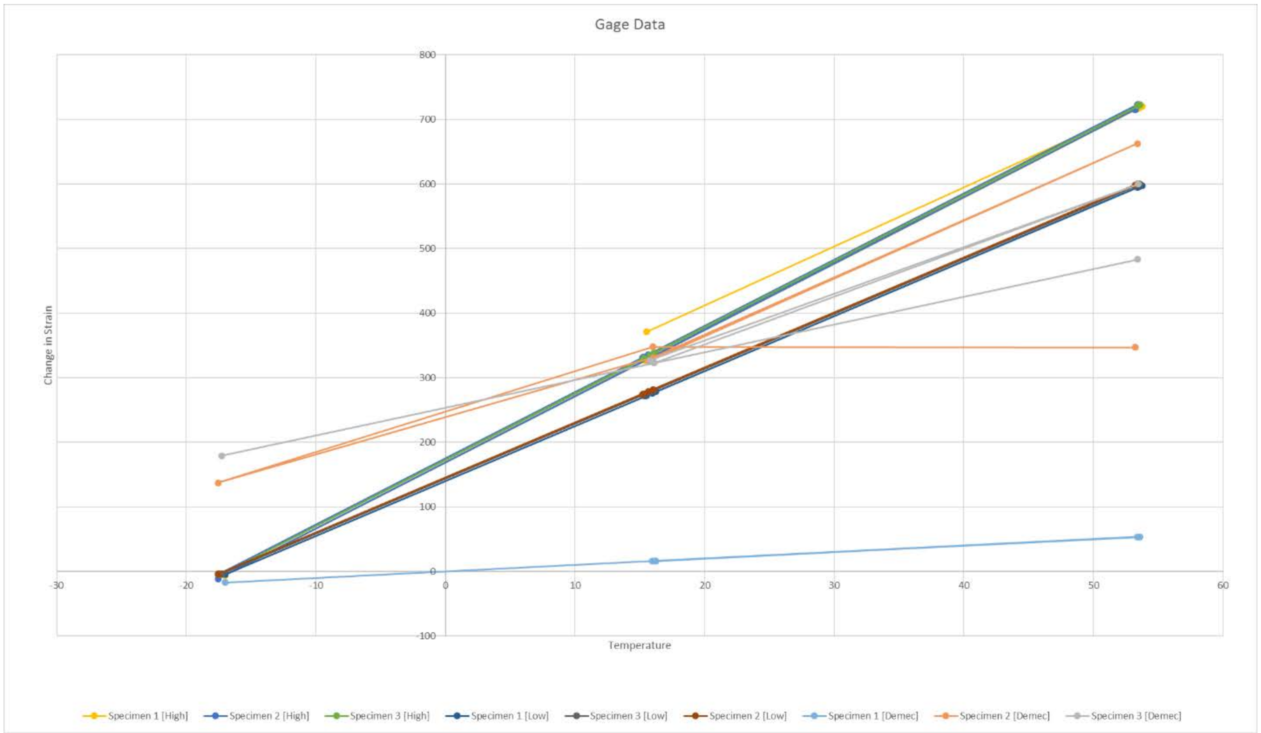


Figure 12. Demec Gages Compared to High and Low Predictions

2. Strain due to Short Term Loading

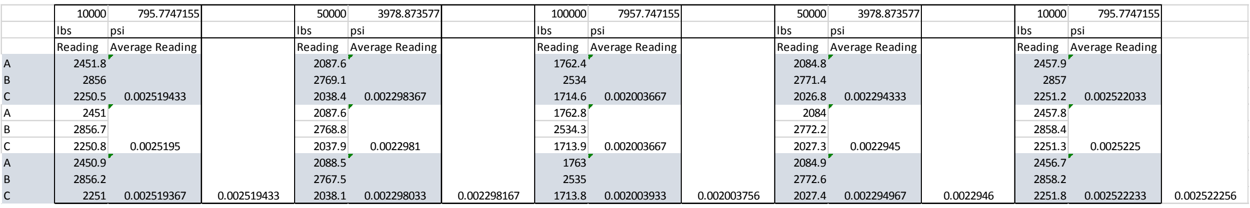
Table 3. Data from Short Term Load Test

	10000	795.7747155		50000	3978.873577		100000	7957.747155		50000	3978.873577	
	lbs	psi		lbs	psi		lbs	psi		lbs	psi	
	Reading	Average Reading		Reading	Average Reading		Reading	Average Reading		Reading	Average Reading	
A	2423.8			2091.9			1761.6			2074.3		
B	2823.4			2731			2497.1			2764.8		
C	2269.8	0.002505667		2033.8	0.002285567		1698.1	0.0019856		2038.2	0.002292433	
A	2427.8			2091.2			1761.6			2074.7		
B	2825.5			2730.1			2496.6			2764.5		
C	2270.6	0.002507967		2034.5	0.002285267		1697.7	0.0019853		2038.2	0.002292467	
A	2430.3			2090.4			1761.1			2075.6		
B	2826.2			2730.9			2496.4			2765.4		
C	2271.1	0.0025092	0.002507611	2034.2	0.002285167	0.002285333	1697.3	0.001984933	0.001985278	2038.1	0.002293033	0.002292644

Table 4. Data from Short Term Load Test (cont.)

	10000	795.7747155		50000	3978.873577		100000	7957.747155		50000	3978.873577	
	lbs	psi		lbs	psi		lbs	psi		lbs	psi	
	Reading	Average Reading		Reading	Average Reading		Reading	Average Reading		Reading	Average Reading	
A	2441.2			2078.7			1755			2076.7		
B	2850.7			2765.1			2532.4			2769.1		
C	2254.3	0.0025154		2038	0.002293933		1711.3	0.001999567		2027.4	0.002291067	
A	2440.7			2079.7			1755.1			2076.3		
B	2851.4			2766			2532.3			2769		
C	2254.4	0.0025155		2037.9	0.002294533		1711.4	0.0019996		2027.6	0.002290967	
A	2440.6			2081.4			1755.6			2077.3		
B	2851.7			2766.5			2532.3			2769.2		
C	2254.5	0.0025156	0.0025155	2037.9	0.002295267	0.002294578	1711.2	0.0019997	0.001999622	2027	0.002291167	0.002291067

Table 5. Data from Short Term Load Test (cont.)



	10000	795.7747155		50000	3978.873577		100000	7957.747155		50000	3978.873577		10000	795.7747155	
	lbs	psi		lbs	psi		lbs	psi		lbs	psi		lbs	psi	
	Reading	Average Reading		Reading	Average Reading		Reading	Average Reading		Reading	Average Reading		Reading	Average Reading	
A	2451.8			2087.6			1762.4			2084.8			2457.9		
B	2856			2769.1			2534			2771.4			2857		
C	2250.5	0.002519433		2038.4	0.002298367		1714.6	0.002003667		2026.8	0.002294333		2251.2	0.002522033	
A	2451			2087.6			1762.8			2084			2457.8		
B	2856.7			2768.8			2534.3			2772.2			2858.4		
C	2250.8	0.0025195		2037.9	0.0022981		1713.9	0.002003667		2027.3	0.0022945		2251.3	0.0025225	
A	2450.9			2088.5			1763			2084.9			2456.7		
B	2856.2			2767.5			2535			2772.6			2858.2		
C	2251	0.002519367	0.002519433	2038.1	0.002298033	0.002298167	1713.8	0.002003933	0.002003756	2027.4	0.002294967	0.0022946	2251.8	0.002522233	0.002522256

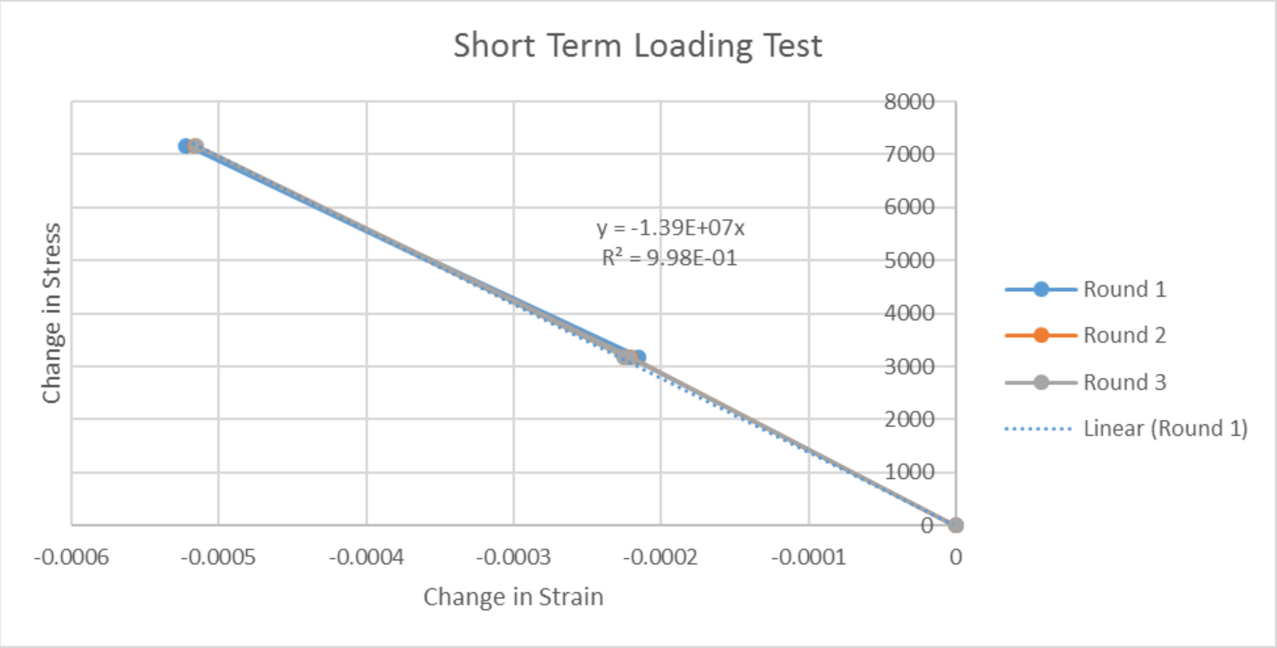
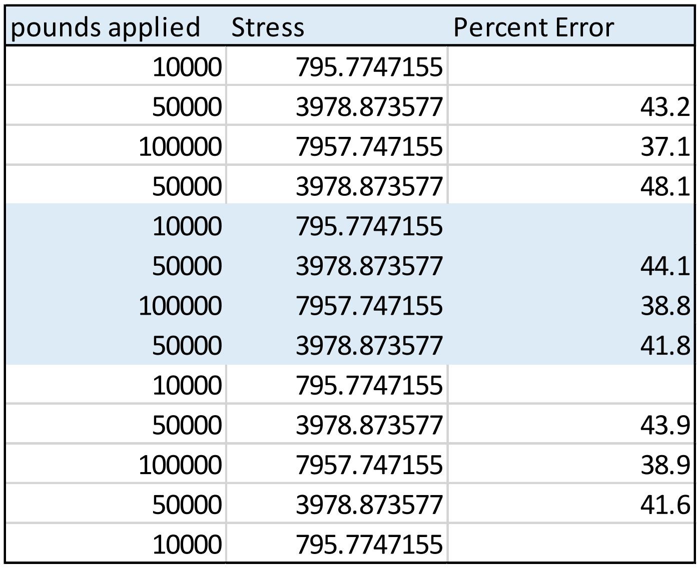


Figure 15. Short Term Loading Test Graph



pounds applied	Stress	Percent Error
10000	795.7747155	
50000	3978.873577	43.2
100000	7957.747155	37.1
50000	3978.873577	48.1
10000	795.7747155	
50000	3978.873577	44.1
100000	7957.747155	38.8
50000	3978.873577	41.8
10000	795.7747155	
50000	3978.873577	43.9
100000	7957.747155	38.9
50000	3978.873577	41.6
10000	795.7747155	

Table 6. Resulting Percent Error During Test

vii. Summary and Conclusion

The purpose of this study was to assess whether the vibrating wire strain gage is a good indication of the creep of concrete in situations of high temperature variability and loading. Originally, the proposal for the study included plans for creep frames (which apply a constant loading over a period of time) n the temperature control room, but this was judged to have too many variables, so the study was divided into two portions with temperature and loading being two independent portions of the study.

The temperature test yielded only one of the three specimens (Specimen 3) showing data that matched what was expected. Figure 10 shows this, with all three of the gages that were attached to the specimen following the expected linear path. This is further motivated by Figure 6, where the average of the gages follows a somewhat predictable pattern. It must be noted, however, that the Specimen 3 VWSG data falls outside of the high and low predicted values that were based on alpha values taken from a different report that used the same concrete. Therefore, it is possible that the coefficient of thermal expansion is lower for this particular specimen, but this cannot be discounted. The Demec gages were used in the test as a basis of comparison for the VSWG's, but they are shown in Figure 11 and Figure 12 as not being entirely consistent towards the high end of the temperatures, and deviated considerably from the original reading around 15 degrees Fahrenheit. Furthermore, Specimen 1's VWSG does not seem to follow the pattern that the other two take at all. Earlier in the testing, the Whittemore gage was taken out of the room between tests, but this does not fully explain the error because it was recalibrated between each measurement. Figure 6 depicting the high prediction, low prediction, Demec, and VWSG's of Specimen 3 is the closest approximation to what was expected from the test.

The load test very consistently yielded a Modulus of Elasticity for the Aluminum specimen of about 14,000,000 psi. This is incorrect because the Modulus for Aluminum is accepted to be 10,000,000 psi. This test was performed on one Aluminum cylinder that had three gages attached that were averaged. This data cannot be reliably compared from gage to gage for inaccuracy due to bending, unlike in the temperature test. Overall, this test yielded an error of around 43 percent.

Although the results of this study are somewhat inconclusive, there is very much documented on the steps that can be taken to continue this study. The workplan, located in Appendix II, maps out what would be necessary to continue this work. Part of this study was intended to include internal vibrating wire gages, resistive gages as another method to compare the VWSGs to, as well as thermocouples to give a second reading of temperature from within the cell. The plan included casting concrete cylinders to allow for the internal gages, but this portion of the plan had to be abandoned, as the cylinders were unusable due to the poor consolidation of the concrete despite the proper amount of water being weight prior to addition and an electric mixer being utilized to mix the concrete, which wasn't assessed due to the researcher's lack of experience in what the wet concrete should look like. It is recommended that perhaps a future researcher should use their own mixture of concrete, rather than premixed concrete as was used to eliminate any error on the manufacturer's part because of the nontechnical intention of the mix. It is also recommended that an experienced onlooker be present to assess and verify that the concrete appears to be adequate. Another test that could be performed during this study is utilizing the aluminum cylinder in the temperature control room to assess the viability of the VWSG's and comparing it against the accepted coefficient of thermal expansion of the aluminum material. Furthermore, a scientist may develop a scheme using the CE DAQ (Civil Engineering Data Acquisition System), located in the Stuctures Lab, to take readings at intervals throughout the day and obtain much more data in a short amount of time. This could be utilized to both assess when the temperature in the cylinders achieves a constant, and to allow the scientist to spend more time analyzing the data. This method was not explored in this study due to the time it would take to construct such a device.

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ix. Appendix A – Figures

Figure 1a. Demonstration of the stand built for stabilizing the cylinder, with a concrete cylinder installed

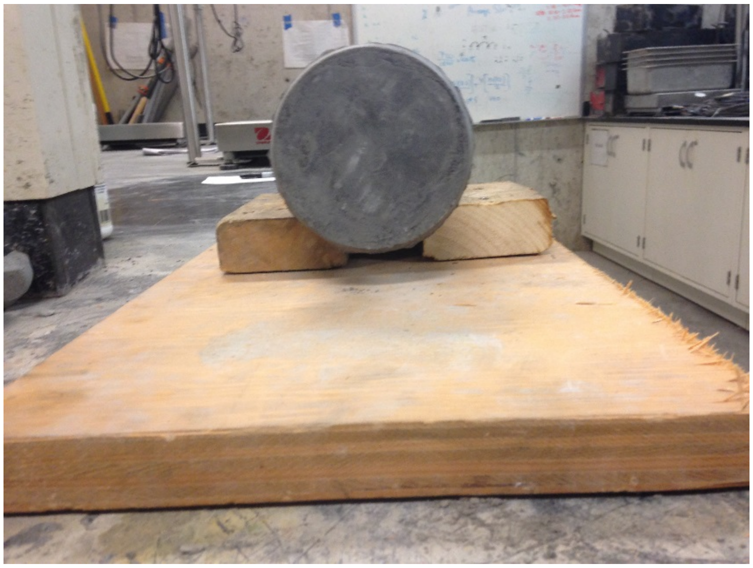


Figure 2a. Demonstration of the stand built for stabilizing the cylinder, with a concrete cylinder installed

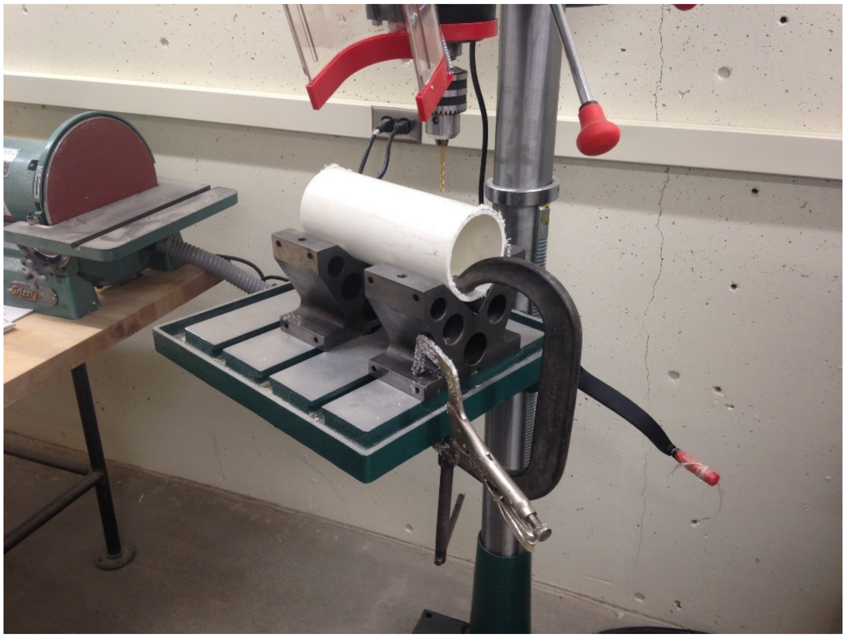


Figure 3a – Portion of scheme for cutting PVC pipe (Please see workplan in Appendix I for reference to this)

Figure 4a – Aluminum cylinder with vibrating wire strain gages attached

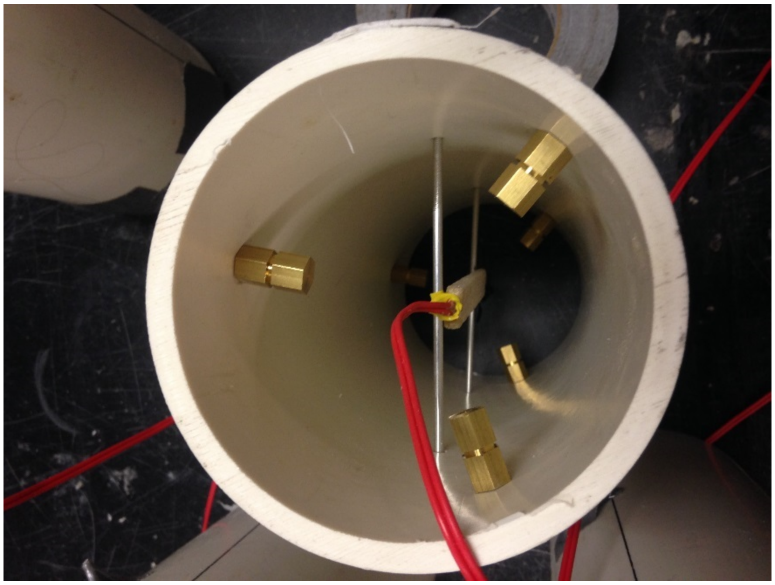


Figure 5a – PVC pipe mold for concrete cylinder with scheme for resistive gage shown (Please see workplan in Appendix I for reference to this)

Figure 6a – The three metal cylinders used for the molds meant for the cylinders meant to be destroyed in the effort to determine the concrete's modulus of elasticity (Please see workplan in Appendix I for reference to this)

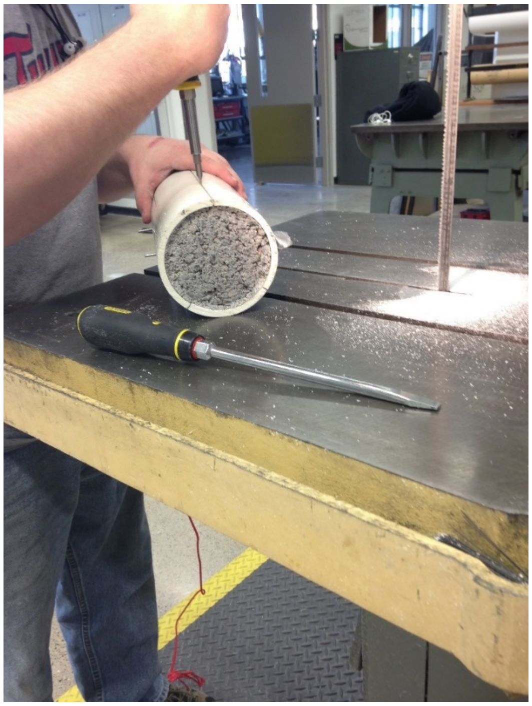


Figure 7a – Method for extracting concrete cylinders from PVC pipe (Please see workplan in Appendix I for reference to this)

Figure 8a – Example of cast cylinder shown – evidence of poor consolidation in the concrete apparent

Figure 9a – Concrete resistive gage (Please see workplan in Appendix I for reference to this)

x. Appendix B – Tables

Table 1b, Gage Parameters

	Resistive Gage I	Resistive Gage II	VWSG	DEMEC
Model	PML-60-2LT	PML-120-2LT	Geokon model 4200	ID-C112TB
Gage Length	60 mm	120 mm	6 inches	8 inches
Gage Width	1 mm	1 mm		
Resistance	120 ohms	120 ohms		
Batch Factor			0.97	

Material	Coefficient of Thermal Expansion [1/°F]
Steel (A992)	0.00000678
Aluminum	0.000013
Concrete	0.0000058
	0.00000473

Table 2b, Coefficients of thermal expansion for typical materials

Gage	Resolution of the Gage [strain]
VWSG	0.000001
DEMEC	0.0001
Resistor	0.000000001
Compressometer	N/A

Table 3b, Resolution of the Gages

	Degrees of Change Required [F]
Steel	0.07
Aluminum	7.692307692
Concrete	17.24137931
	0.000211416

Table 4b, Degrees of change required by the Vibrating Wire Strain Gage to produce 50 microstrain in a VWSG

Table 5b, Modulus of Elasticity of Relevant Materials

Gage	Modulus of Elasticity of Materials [ksi]
Steel (A992)	29000
Aluminum (6061)	10000
Concrete	29000
	33000

Table 6b, Required change in load to produce a change of 50 microstrain in a VWSG

Change in Compression Required (ksi)	
Steel	36.424
Aluminum	12.56
Concrete	36.424
	41.448

Table 7b. Specimens with Gages Listed

Specimen	Material	Quantity	Size	Applied Gages	Purpose
1	Concrete	3	4x11	• 3 DEMEC • 3 VWSG	To directly compare the two gages and to establish whether the internal gages create error
2	Concrete	3	4x11	• 3 DEMEC • 3 VWSG • 1 Internal Resistive Gage	To compare the DEMEC and VWSG and also compare the internal resistive gage against the DEMEC
3	Concrete	3	4x11	• 3 DEMEC • 3 VWSG • 1 Internal VWSG	To compare the DEMEC and VWSG and also compare the Internal VWSG against the DEMEC
4	Concrete	3	4x11	• 3 DEMEC • 1 Internal VWSG	To directly compare the DEMEC and Internal VWSG and also establish any inaccuracy that the VWSG causes
6	Aluminum	1		• VWSG • Compressometer (for Test 2 only)	To establish error between predicted strain and experimental strain under temperature and load change conditions

6	Concrete	3	6x12	None	To measure the concrete mix modulus of elasticity for the purposes of establishing predictive strains for the short term compression test
7	Concrete	VWSG	4x11	• 3 VWSG	To establish whether the internal gages or the Demec are affecting the strain results through loss of concrete

Note: Specimen 1 was cast previously for other experiments

Table 8b -. Strain Due to Temperature Change Data

Series	Temperature [F]	Specimen Number	Gage Designation	VWSG Redbox Reading [με]	Temperature Reading [C]	Temperature Reading [F]	Average Temperature [C]	Average Temperature [F]	Average Reading	Average Termperature by Gage [C]	Average Strain by Gage [C]	Average Corrected Strain by Gage [Δμε] [C]	Average Corrected Redbox Change in Strain Reading [Δμε] [C]	Predicted Change in Strain [alpha high] from original [Δμε] [F]	Predicted change in Strain [alpha low] from original [Δμε] [F]	Demec Gage Reading	Average Demec Gage Reading Per Specimen	Average Demec Gage Reading By Gage	Demec Strain Reading [Δε]	Averaged Change in Strain From Demec Reading	Demec Change in strain Reading from original			Average Change in Strain From Original per Specimen [Δμε]
Round 1	0	1	A	2679.3	-16.5	2.3	-16.45	2.39	2890.6							-0.0520	-0.0929		-0.0065					
			B	3101.9	-16.4	2.48										-0.0078			-0.000975					
			C	-	-											-0.2190			-0.027375					
		2	A	3138.3	-17.0	1.4	-17.05	1.31	3267.5							-0.0958	-0.0943		-0.011975					
			B	-	-											-0.0934			-0.011675					
			C	3396.7	-17.1	1.22										-0.0936			-0.0117					
		3	A	2910.8	-16.8	1.76	-16.86666667	1.64	3113.433							-0.0072	-0.0182		-0.0009					
			B	3328.9	-16.9	1.58										-0.0108			-0.00135					
			C	3100.6	-16.9	1.58										-0.0365			-0.0045625					
	60	1	A	3000.9	15.7	60.26	15.5	59.9	2823.433				146.89	370.9395	272.0223	-0.0065	-0.0264		-0.0008125					
			B	2577.4	15.4	59.72										-0.0470			-0.005875					
			C	2892	15.4	59.72										-0.0256			-0.0032					
		2	A	3138.4	15.2	59.36	15.3	59.54	3216.5				94.22	331.911	275.4279	-0.0915	-0.0679		-0.0114375					
			B	-	-											-0.0410			-0.005125					
			C	3294.6	15.4	59.72										-0.0711			-0.0088875					
		3	A	2814.2	15.3	59.54	15.3	59.54	3016.5				241.82	330.03	273.867	-0.0057	0.0054		-0.0007125					
			B	3231.9	15.3	59.54										-0.0086			-0.001075					
			C	3003.4	15.3	59.54										0.0304			0.0038					
	130	1	A	2883.7	53.7	128.66	53.76666667	128.78	2731.467				359.74	720.423	597.8247	0.0046	0.0259		0.000575					
			B	2463.7	53.6	128.48										0.0479			0.0059875					
			C	2847	54	129.2										0.0251			0.0031375					
		2	A	3094.3	53.2	127.76	53.45	128.21	3123.65				310.15	723.33	600.237	0.0918	0.0665		0.011475					
			B	-	-											0.0395			0.0049375					
			C	3153	53.7	128.66										0.0682			0.008525					
		3	A	2694.7	53.7	128.66	53.56666667	128.42	2886.4				576.89	722.646	599.6694	0.0048	0.0150		0.0006					
			B	3092.3	53.2	127.76										0.0076			0.00095					
			C	2872.2	53.8	128.84										0.0326			0.004075					
	60	1	A	2995.0	15.7	60.26	15.4	59.72	2816.567				169.11	326.781	271.1709	-0.0630	-0.0468		-0.007875					
			B	2582.9	15.5	59.9										-0.0500			-0.00625					
			C	2871.8	15	59										-0.0275			-0.00343125					
		2	A	3081.5	15.3	59.54	15.2	59.36	3058.067				602.19	330.885	274.5765	-0.0934	-0.0688		-0.011675					
			B	2822.3	15.3	59.54										-0.0415			-0.0051875					
			C	3270.4	15	59										-0.0714			-0.008925					
		3	A	2804.3	15.4	59.72	15.26666667	59.48	3007.167				271.81	329.688	273.5832	-0.0069	-0.0172		-0.0008625					
			B	3224.6	15.2	59.36										-0.0098			-0.001225					
			C	2992.6	15.2	59.36										-0.0350			-0.004375					
Round 2	0	1	A	3100.8	-16.6	2.12	-17.01666667	1.37	2919.917	-16.7	3101.9		-92.74	-5.814	-4.8246	0.0122	0.0335667	0.01235	0.001525	0.00154375				
				3103	-16.8	1.76										0.0125			0.0015625					
			B	2699.4	-17	1.4				-17.15	2700.3					0.0556		0.05555	0.00695	0.00694375				
				2701.2	-17.3	0.86										0.0555			0.0069375					
			C	2956.9	-17.2	1.04				-17.2	2957.55					0.0331		0.0328	0.0041375	0.0041				
				2958.2	-17.2	1.04										0.0325			0.0040625					
		2	A	3039.3	-17.5	0.32	-17.55	0.516666667	3150.867	-17.55	3039.1		374.87	-4.522	-3.75246667	0.0995	0.0747167	0.09925	0.0124375	0.01240625				
				3038.9	-17.6	0.32										0.099			0.012375					
			B	3039.9	-17.8	0.6				-17.6	3040.4					0.0469		0.04685	0.0058625	0.00585625				
				3040.9	-17.4	0.5										0.0468			0.00585					
			C	3374.1	-17.6	0.68				-17.5	3373.1					0.0769		0.07805	0.0096125	0.00975625				
				3372.1	-17.4	0.68										0.0792			0.0099					
		3	A	2909	-17.3	0.86	-17.35	0.77	3113.05	-17.2	2908.75		2.26	-4.959	-4.1151	0.0138	0.0232	0.01335	0.001725	0.00166875				
				2908.5	-17.1	0.86										0.0129			0.0016125					
			B	3330.5	-17.3	1.22				-17.45	3331.3					0.0155		0.0156	0.0019375	0.00195				
				3332.1	-17.6	0.32										0.0157			0.0019625					
			C	3098.3	-17.3	0.86				-17.4	3099.1					0.0404		0.04065	0.00505	0.00508125				
				3099.9	-17.5	0.5										0.0409			0.0051125					
	60	1	A	2998.7	16.2	61.16	15.95	60.71	2827.783	16.15	2998.6	260.765104	131.98	332.424	275.8536	0.0109	0.03215	0.0107	0.0013625	0.0013375	-0.00020625	-0.000177083	0.000177083	177.0833333
				2998.5	16.1	60.98										0.0105			0.0013125					
			B	2596.1	15.9	60.62				15.95	2596.95	260.390348				0.0545		0.05425	0.0068125	0.00678125	-0.0001625			
				2597.8	16	60.8										0.054			0.00675					
			C	2887.8	15.8	60.44				15.75	2887.8	153.02738				0.0317		0.0315	0.0039625	0.0039375	-0.0001625			
				2887.8	15.7	60.26										0.0313			0.0039125					
		2	A	2991.2	15.6	60.08	15.66666667	60.2	3066.2	15.6	2991.35	82.09202	575.13	335.673	278.5497	0.097	0.0721167	0.0972	0.012125	0.01215	-0.00025625	-0.000325	0.000325	325
				2991.5	15.6	60.08										0.0974			0.012175					
			B	2938.4	15.8	60.44				15.7	2939.45	252.270636				0.0455		0.04575	0.0056875	0.00571875	-0.0001375			
				2940.5	15.6	60.08										0.046			0.00575					
			C	3267.9	15.7	60.26				15.7	3267.8	266.425864				0.0733		0.0734	0.0091625	0.009175	-0.00058125			
				3267.7	15.7	60.26										0.0735			0.0091875					
		3	A	2808.3	15.9	60.62	15.76666667	60.38	3012.617	15.85	2808.8	249.600756	253.27	334.818	277.8402	0.0103	0.0205833	0.0104	0.0012875	0.0013	-0.00036875	-0.000327083	0.000327083	327.0833333
				2809.3	15.8	60.44										0.0105			0.0013125					
			B	3231.2	15.7	60.26				15.75	3230.75	251.202684				0.0129		0.013	0.0016125	0.001625	-0.000325			
				3230.3	15.8	60.44										0.0131			0.0016375					
			C	2998.8	15.7	60.26				15.7	2998.3	252.217904				0.0382		0.03835	0.004775	0.00479375	-0.0002875			
				2997.8	15.7	60.26										0.0385			0.0048125					
Round 2	130	1	A	2887	53.2	127.76	53.58333333	128.45	2736.383	53.25	2886.35	541.118884	344.37	718.542	596.2638	0.0103	0.02945	0.0094	0.0012875	0.001175	-0.00036875	-0.000514583	0.000514583	514.5833333
				2885.7	53.3	127.94										0.0085			0.0010625					
			B	2472.4	53.6	128.48				53.65	2472.55	578.39942				0.0536		0.0526	0.0067	0.006575	-0.00036875			
				2472.7	53.7	128.66										0.0516			0.00645					
			C	2847.1	53.7	128.66				53.85	2850.25	191.836624				0.0307		0.02635	0.0038375	0.00329375	-0.00080625			
				2853.4	54	129.2										0.022			0.00275					
		2	A	2970.6	53.8	128.84	53.4	128.12	3026.433	53.7	2969.55	70.424404	621.83	722.817	599.8113	0.0952	0.0694167	0.09505	0.0119	0.01188125	-0.000525	-0.0006625	0.0006625	662.5
				2968.5	53.6	128.48										0.0949			0.0118625					
			B	2950.8	53.3	127.94				53.25	2951.65	132.8141				0.0429		0.0429	0.0053625	0.0053625	-0.00049375			
				2952.5	53.2	127.76										0.0429			0.0053625					
			C	3158.9	53.2	127.76				53.25	3158.1	537.6442				0.0699		0.0703	0.0087375	0.0087875	-0.00096875			
				3157.3	53.3	127.94										0.0707			0.0088375					
		3	A	2699.4	53.7	128.66	53.46666667	128.24	2896.15	53.65	2699.7	518.361164	545.85	721.62	598.818	0.008	0.0184	0.0079	0.001	0.0009875	-0.00068125	-0.0006	0.0006	600
				2700	53.6	128.48										0.0078			0.000975					
			B	3106.4	53.2	127.76				53.3	3106.7	568.411048				0.0111		0.01105	0.0013875	0.00138125	-0.00056875			
				3107	53.4	128.12										0.011			0.001375					
			C	2883.4	53.4	128.12				53.45	2882.05	544.000204				0.0363		0.03625	0.0045375	0.00453125	-0.00055			
				2880.7	53.5	128.3										0.0362			0.004525					
	60	1	A	2894.9	16.4	61.52	16.23333333	61.22	2780.75	16.4	2895.35	591.133964	282.11	335.331	278.2659	0.0101	0.0314667	0.01025	0.0012625	0.00128125	-0.0002625	-0.0002625	0.0002625	262.5
				2895.8	16.4	61.52										0.0104			0.0013					
			B	2588.5	16.2	61.16				16.2	2588.15	288.058292				0.0526		0.05285	0.006575	0.00660625	-0.0003375			
				2587.8	16.2	61.16										0.0531			0.0066375					
			C	2859.9	16	60.8				16.1	2858.75	245.380144				0.0313		0.0313	0.0039125	0.0039125	-0.0001875			
				2857.6	16.2	61.16										0.0313			0.0039125					
		2	A	2985.5	16	60.8	16.03333333	60.86	3024.983	15.95	2985.45	100.251812	706.44	333.279	281.6715	0.097	0.0720667	0.097	0.012125	0.012125	-0.00028125	-0.00033125	0.00033125	331.25
				2985.4	15.9	60.62										0.097			0.012125					
			B	2817.8	16.2	61.16				16.2	2819.75	634.824772				0.045		0.0448	0.005625	0.0056	-0.00025625			
				2821.7	16.2	61.16										0.0446			0.005575					
			C	3269.8	15.9	60.62				15.95	3269.75	259.641348				0.0747		0.0744	0.0093375	0.0093	-0.00045625			
				3269.7	16	60.8										0.0741			0.0092625					
		3	A	2810.2	16.1	60.98	16.11666667	61.01	3011.883	16.15	2809.9	245.433388	254.87	338.409	280.8201	0.0103	0.0206167	0.0103	0.0012875	0.0012875	-0.00038125	-0.000322917	0.000322917	322.9166667
				2809.6	16.2	61.16										0.0103			0.0012875					
			B	3227.1	16.2	61.16				16.2	3226.85	262.738716				0.0131		0.0131	0.0016375	0.0016375	-0.0003125			
				3226.6	16.2	61.16										0.0131			0.0016375					
			C	2998.9	16	60.8				16	2998.9	249.652976				0.0385		0.03845	0.0048125	0.00480625	-0.000275			
				2998.9	16	60.8										0.0384			0.0048					

Table 9b. Strain Due to Temperature Change Data (cont.)

Series	Temperature [F]	Specimen Number	Gage Designation	VWSG Redbox Reading [με]	Temperature Reading [C]	Temperature Reading [F]	Average Temperature [C]	Average Temperature [F]	Average Reading	Average Termperature by Gage [C]	Average Strain by Gage [C]	Average Corrected Strain by Gage [Δμε] [C]	Average Corrected Redbox Change in Strain Reading [Δμε] [C]	Predicted Change in Strain [alpha high] from original [Δμε] [F]	Predicted change in Strain [alpha low] from original [Δμε] [F]	Demec Gage Reading	Average Demec Gage Reading Per Specimen	Average Demec Gage Reading By Gage	Demec Strain Reading [Δε]	Averaged Change in Strain From Demec Reading	Demec Change in strain Reading from original			Average Change in Strain From Original per Specimen [Δμε]
Round 3	0	1	A	2997.5	-16.6	2.12	-17.01666667	1.37	2875.717	-16.7	2998.5	331.384592	48.91	-5.814	-4.8246	0.0116	0.0330167	0.01145	0.00145	0.00143125	-0.0001125	-6.875E-05	6.875E-05	68.75
				2999.5	-16.8	1.76										0.0113			0.0014125					
			B	2697.7	-17	1.4				-17.15	2697.5	8.973664				0.0553		0.05535	0.0069125	0.00691875	-2.5E-05			
				2697.3	-17.3	0.86										0.0554			0.006925					
			C	2930.9	-17.2	1.04				-17.2	2931.15	84.608832				0.0321		0.03225	0.0040125	0.00403125	-6.875E-05			
				2931.4	-17.2	1.04										0.0324			0.00405					
		2	A	3004.4	-17.5	0.5	-17.55	0.41	3096	-17.55	3004.4	111.209336	550.71	-11.286	-4.257	0.0987	0.0736167	0.09875	0.0123375	0.01234375	-6.25E-05	-0.0001375	0.0001375	137.5
				3004.4	-17.6	0.32										0.0988			0.01235					
			B	2909.7	-17.8	-0.04				-17.6	2909.2	420.480256				0.0464		0.04635	0.0058	0.00579375	-6.25E-05			
				2908.7	-17.4	0.68										0.0463			0.0057875					
			C	3373.5	-17.6	0.32				-17.5	3374.4	-4.166344				0.0757		0.07575	0.0094625	0.00946875	-0.0002875			
				3375.3	-17.4	0.68										0.0758			0.009475					
		3	A	2909.7	-17.2	1.04	-17.25	0.95	3116.7	-17.25	2909.45	-2.136416	-9.65	-3.933	-3.2637	0.0112	0.0217667	0.0112	0.0014	0.0014	-0.00026875	-0.000179167	0.000179167	179.1666667
				2909.2	-17.3	0.86										0.0112			0.0014					
			B	3336.2	-17.4	0.68				-17.4	3336.25	-15.971156				0.0146		0.0144	0.001825	0.0018	-0.00015			
				3336.3	-17.4	0.68										0.0142			0.001775					
			C	3103.7	-17	1.4				-17.1	3104.4	-17.627864				0.0397		0.0397	0.0049625	0.0049625	-0.00011875			
				3105.1	-17.2	1.04										0.0397			0.0049625					
	60	1	A	2860.6	16.6	61.88	16.25	61.25	2780.983	16.55	2860.35	702.983764	225.35	335.502	278.4078	0.0105	0.0315	0.0105	0.0013125	0.0013125	-0.00023125	-0.000258333	0.000258333	258.3333333
				2860.1	16.5	61.7										0.0105			0.0013125					
			B	2591.3	16.2	61.16				16.2	2591.6	277.001456				0.0527		0.0529	0.0065875	0.0066125	-0.00033125			
				2591.9	16.2	61.16										0.0531			0.0066375					
			C	2890.6	16	60.8				16	2891	142.236764				0.031		0.0311	0.003875	0.0038875	-0.0002125			
				2891.4	16	60.8										0.0312			0.0039					
		2	A	2993.4	15.9	60.62	16	60.8	3034.183	15.9	2915.45	324.700412	620.44	332.937	281.3877	0.097	0.0719333	0.097	0.012125	0.012125	-0.00028125	-0.000347917	0.000347917	347.9166667
				2837.5	15.9	60.62										0.097			0.012125					
			B	2839.9	16.1	60.98				16.1	2915.8	327.210048				0.0455		0.04535	0.0056875	0.00566875	-0.0001875			
				2991.7	16.1	60.98										0.0452			0.00565					
			C	3271.4	16	60.8				16	3271.3	254.566784				0.0736		0.07345	0.0092	0.00918125	-0.000575			
				3271.2	16	60.8										0.0733			0.0091625					
		3	A	2815.3	16.2	61.16	16.1	60.98	3017.733	16.15	2815.4	227.806548	179.72	338.238	280.6782	0.0099	0.0206167	0.00995	0.0012375	0.00124375	-0.000425	-0.000322917	0.000322917	322.9166667
				2815.5	16.1	60.98										0.01			0.00125					
			B	3234.3	16.1	60.98				16.1	3234.5	238.435384				0.0132		0.01315	0.00165	0.00164375	-0.00030625			
				3234.7	16.1	60.98										0.0131			0.0016375					
			C	3003.3	16	60.8				16.05	3003.3	235.444504				0.0388		0.03875	0.00485	0.00484375	-0.0002375			
				3003.3	16.1	60.98										0.0387			0.0048375					
Round 3	130	1	A	2750.5	53.4	128.12	53.41666667	128.15	2703.1	53.6	2749.85	977.836004	331.79	716.832	594.8448	0.0094	0.03065	0.0094	0.001175	0.001175	-0.00036875	-0.000364583	0.000364583	364.5833333
				2749.2	53.8	128.84										0.0094			0.001175					
			B	2463.8	54	129.2				53.85	2464.05	605.2129				0.0524		0.05245	0.00655	0.00655625	-0.0003875			
				2464.3	53.7	128.66										0.0525			0.0065625					
			C	2896.7	52.8	127.04				52.8	2895.4	49.383292				0.0302		0.0301	0.003775	0.0037625	-0.0003375			
				2894.1	52.8	127.04										0.03			0.00375					
		2	A	3010.9	53.2	127.76	53.23333333	127.82	3028.75	53.4	3010.5	-60.173432	494.43	714.951	598.3923	0.0961	0.07365	0.09615	0.0120125	0.01201875	-0.0003875	-0.000346875	0.000346875	346.875
				3010.1	53.6	128.48										0.0962			0.012025					
			B	2918.5	53.1	127.58				53.2	2917.8	241.406288				0.0444		0.0444	0.00555	0.00555	-0.00030625			
				2917.1	53.3	127.94										0.0444			0.00555					
			C	3158.2	53	127.4				53.1	3157.95	538.445932				0.0905		0.0804	0.0113125	0.01005	0.00029375			
				3157.7	53.2	127.76										0.0703			0.0087875					
		3	A	2697.1	53.3	127.94	53.41666667	128.15	2890.583	53.45	2694.5	535.45454	443.48	721.107	598.3923	0.0093	0.0193333	0.00935	0.0011625	0.00116875	-0.0005	-0.000483333	0.000483333	483.3333333
				2691.9	53.6	128.48										0.0094			0.001175					
			B	3095.9	53.6	128.48				53.55	3097.05	598.80314				0.0118		0.01165	0.001475	0.00145625	-0.00049375			
				3098.2	53.5	128.3										0.0115			0.0014375					
			C	2880	53.4	128.12				53.25	2880.2	550.357232				0.037		0.037	0.004625	0.004625	-0.00045625			
				2880.4	53.1	127.58										0.037			0.004625					

xi. Appendix I – Workplan

Note: this was the original workplan for the investigation, and was the document guiding the process.

Work Plan

Casting of Concrete Cylinders (ASTM C31)

1. PVC Pipe will be cut into four (4) 11 inch sections. The pipe will be cut by using a bandsaw by being firmly clamped to the table, and then will be cut at a 90 degree angle to the side of the tube at 11 inch increments longitudinally 4 times to create 4 molds.
2. The following table is a summary of the cylinders that will be created

Specimen	**Material**	**Quantity**	**Size**	**Applied Gages**
1	Concrete	3	4x11	• 3 DEMEC • 3 VWSG Cast in a Previous Experiment
2	Concrete	3	4x11	• 3 DEMEC • 3 VWSG • 1 Internal Resistive Gage
3	Concrete	3	4x11	• 3 DEMEC • 3 VWSG • 1 Internal VWSG
4	Concrete	3	4x11	• 3 DEMEC
6	Aluminum	1	4x11	• 3 VWSG
7	Concrete	3	6x12	• Compressometer
8	Concrete	3	4x11	• 3 Demec Cast in a Previous Experiment

Table I. Specimens with Gages Listed

Note: Specimen 1 and 7 was cast previously for other experiments

Parameter	Specimens being Compared
To directly compare the gages and/or to establish whether the internal gages create error	1,2,3,4
To establish any inaccuracy that the VWSG causes	4
To establish whether the internal gages or the Demec are affecting the strain results through loss of concrete in a temperature varying test.	6
To establish error between predicted strain and experimental strain under temperature and load change conditions	6
To measure the concrete mix modulus of elasticity for the purposes of establishing predictive strains for the short term compression test	7
To establish whether the stiffness in the VWSG is affecting the strain reading in the concrete	8

Table II: Purpose of each specimen

Quantity	Type	Gage Type	Gage Application	Operational Temp	Bonding Adhe	Gage Length	Resistanc	Temp Comp.
50	PML-60-2L	Resistive Gage	Concrete, Mortar	-20 / +60 Celcius	Embedment	60 mm	120	-
25	PL-60-11-5LT	wire strain gage	Concrete, mortar, rock material	-20 / +80 Celcius		60 mm	120	+10 / +80
3	FRA-3-11-3LT	Rossette	metal, general	-20 / +80 Celcius		3 mm	120	+10 / +80
55	Demec Points	Demec				8 inches		

Table III: Gages available and characteristics of each

3. Holes for the Demecs will be drilled at third intervals around nine of the pipes. The thirds will be sectioned off by drawing a circle on a piece of paper using the pipe, and then a protractor will section the paper circle into thirds. A plumb bob and a straightedge is used to draw a straight line up the third intervals on the pipe. The 2 holes will be ___ in diameter and placed at 8 inches apart to allow for the Demec.

4. On two (2) of the pipes, a hole will be cut large enough to account for the threaded metal wire commonly used by the EERI team directly through to the other side of the pipe. This will be accomplished through use of a drill press. The holes will be placed at 30 degrees to the Demec holes and a total of four holes will be drilled on the pipes. Each of the pairs of holes will be drilled at 3 inches from the ends such that there is 5 inches of space between them. The bolts will be adjusted such that they are directly in the center and the top pair of bolt is directly over the bottom set of bolts. This will be ensured by tying a plumb bob to the top of the set of bolts and ensuring that the plumb bob hangs directly through the bottom set of bolts.
5. A fishing line will then be tied directly between the bolts. A light layer of superglue will be applied to the top and bottom of the gage, along with the wires attached to the gage. The gage is placed approximately in the middle of the fishing line, taking care to center the gage and ensure that it is firmly attached.
6. A plastic cap of diameter of 4 inches will be affixed with duct tape to the bottom of the pipe such that the bottom of the container is completely sealed
7. The following materials will be procured in the following quantities to form the cylinders described from Lab 4 of CEGE 3402w. This mix was chosen for its consistency across all groups in the class lab sections

Material	**Quantity for 1.8 cft [lb]**
Large Aggregate	115.43
Small Aggregate	78.51
Portland Cement	45.33
Water	20.39
Water to Cement Ratio	0.45

Table IV. Breakdown of quantities for the mixture

Although only approximately 1.31 cft of concrete should be needed (see below table), this provides ample concrete in the case that extra cylinders need to be made. Please note that the original recipe was multiplied by a factor of 1.5. The water to cement ratio was kept the same.

4x11		
cylinders	[]	9.00
length	[in]	11.00
radius	[in]	2.00
cross sectional area of 1	[in^2]	12.56
volume of 1	[in^3]	138.16
volume of 9	[in^3]	1243.44
volume in ft	[ft^3]	0.72
6x8		
cylinders	[]	3.00
length	[in]	12.00
radius	[in]	3.00
cross sectional area of 1	[in^2]	28.26
volume of 1	[in^3]	339.12
volume of 3	[in^3]	1017.36
volume in ft	[ft^3]	0.59
Total Volume	[ft^3]	1.31

Table V. Example of how the volume of concrete necessary for the experiment was calculated

8. Each of the materials will be weighed on a scale, currently located in the structures lab
9. The materials will then be mixed thoroughly using the mixer that is on site for 5 minutes. No admixture will be utilized
10. The slump of the concrete, air content, and temperature of this mix are tested using appropriate apparatus
11. The concrete is placed into the prepared molds using a scoop
12. The specimens being created are 4x11 inches, which is smaller than the ASTM standard of 6x12 inches, but larger than the smaller size. Therefore, three equal layers within the cylinder with 10 to 15 taps on the side of the cylinder after the layer is rodded 25 times is sufficient. The rod that will be used is the one utilized for the 4 inch rod, that is, 3/8” plus/minus 1/16”. This criterion meets ASCE standards as it sufficiently taps the side of the container, and the rod is small enough for the cylinder.
13. The top layer of concrete is sloughed off with the rod so that it is exactly at level with the top of the mold.
14. The molds are covered with a wet cloth to prevent evaporation
15. The molds are uncovered at around 24 hours (16-32 hours), and the specimens are left in a room with relative humidity of not less than 95 percent and 73 degrees Fahrenheit.
16. The specimens are left to cure for 28 days
17. Neoprene pads will comprise the caps of the cylinders for use in compressive testing
    a. See ASTM C617
18. The vibrating wire gages will be attached to the cylinder. Epoxy existing within the structures lab will be used and will account for space between the cylinder and the vibrating gage. A circle will be drawn on a piece of paper, using the aluminum or steel specimen, and a protractor will mark three (3) 120 degree increments around the paper. Using a plumb bob and a ruler, a longitudinal

line will be drawn on the specimen at the third points. Assuming that the cylinder is 11 inches, the VWSG will be placed at approximately 2.5 inches from either the top or the bottom of the cylinder. After mixing the epoxy, the vibrating wire strain gage will be held onto this line for 10 seconds. This will also be done for the other two thirds of the cylinder where the lines are drawn. There will be a total of 3 VWSG on the cylinder.

Materials Needed

- ☐ 44 inches of 4 inch (diameter) PVC pipe
- ☐ Plumb bob
- ☐ Small T square
- ☐ Compressometer
- ☐ Fishing line
- ☐ EERI threaded rod
- ☐ 16 small nuts to fit on threaded rod
- ☐ Drill press
- ☐ C-Clamp
- ☐ Bandsaw
- ☐ Scale
- ☐ Shovel
- ☐ Mixer
- ☐ Bucket
- ☐ 24 Demec
- ☐ 18 external VWSG
- ☐ 3 internal VWSG
- ☐ 3 internal resistive gage
- ☐ 30 Neoprene pads

Need from Shop Manager at Time of Procedure

- ☐ advisement on EERI stiff threaded wire
- ☐ supervision or help with the drill press, band saw, and mixer
- ☐ possible location of each of the items above

Temperature Controlled Test

Phase I – Aluminum and already present Concrete Specimens

1. The same will be done for three of the already-present concrete specimens with pre-inserted DEMEC points
2. The aluminum specimen and concrete specimens will be subjected to temperature changes based off of the required temperature change to produce 0.0001 strain in the Demec. The temperatures required are noted below.

	Degrees of Change Required [F]
Steel	14.75
Aluminum	7.692307692
Concrete	17.54385965
	21.14164905

Table VI. Degrees of change required for the Demec to read a change in reading according to the resolution

Because the Concrete requires the greatest change in temperature if the coefficient of thermal expansion is low, it will be utilized as the change in temperature. The change in temperature for the test will be rounded to 25 degrees.

Series		Aluminum	
	Temperature [F]	Predicted Strain [Δε]	Experimental Strain [Δε]
Round 1	0	0	
	65	0.000845	
	130	0.00169	
	65	0.000845	
	0	0	
Round 2	65	0.000845	
	130	0.00169	
	65	0.000845	
	0	0	
Round 3	65	0.000845	
	130	0.00169	
	65	0.000845	
	0	0	

VII. Example work table for resulting change in strain for the aluminum specimen

Series		Concrete			
	Temperature [F]	Predicted Strain [Δε] (low)	Predicted Strain [Δε] (high)	Experimental Strain [Δε] VWSG	Experimental Strain [Δε] Demec
Round 1	0	0	0		
	65	0.00030745	0.0003705		
	130	0.0006149	0.000741		
	65	0.00030745	0.0003705		
	0	0	0		
Round 2	65	0.00030745	0.0003705		
	130	0.0006149	0.000741		
	65	0.00030745	0.0003705		
	0	0	0		
Round 3	65	0.00030745	0.0003705		
	130	0.0006149	0.000741		
	65	0.00030745	0.0003705		
	0	0	0		

VIII. Example work table for resulting changing in strain for a concrete specimen

3. The strain at 0 degrees will be noted, and this strain will be taken as “0” for the experiment. Two rounds of temperature testing will be performed to ensure repeatable results as well as ensure that the strain at the same temperature is the same going up in temperature as going down. The cylinders will be left in a day to start, and the strain will be noted. The temperature will not change for the second day, and the strain will be noted again. If the change between the first and second day is significant enough to the order of 10 microstrain, then the gage will be left in a third day. This will continue until the strain change reads under 10 microstrain to ensure consistent temperature throughout the specimen. If the change is under 10 microstrain from the first to second day, then the requirement will only be one day for the rest of the readings (for example).
4. The Vibrating Wire Strain Gage will be read with a “redbox”, while the Demec will be read with Mitutoyo Absolute Model ID-C112TB.

5. The percent error will be recorded for each of the findings, and an average will be taken of each of the repeating instruments. Readings of more than one standard deviation from the other two readings, the strain will be noted but effectively thrown out as “error”.

Phase II – Testing of Concrete Specimens

1. The same temperature change will be noted on the cast concrete specimens, highlighted above.
2. It should be noted that the quantity of days necessary for the specimen to achieve equal strain can also be used in this experiment
3. The same methodology will be taken to read the gages. The resistive gage and internal vibrating wire strain gages will be read with the Civil Engineering Data Acquisition (CE DAQ) system and the data will be saved to RTDAQ 1.1.1.8 software. The external VWSG will also utilize the CE DAQ and associated software.

Series	Temperature [F]	Predicted Strain [Δε] (high)	Predicted Strain [Δε] (low)
Round 1	0	0	0
	65	0.00030745	0.0003705
	130	0.0006149	0.000741
	65	0.00030745	0.0003705
	0	0	0
Round 2	65	0.00030745	0.0003705
	130	0.0006149	0.000741
	65	0.00030745	0.0003705
	0	0	0
Round 3	65	0.00030745	0.0003705
	130	0.0006149	0.000741
	65	0.00030745	0.0003705
	0	0	0

Table IX. Predicted Strains when temperature is changed

Series	Temperature [F]	Specimen 2			Specimen 3			Specimen 4	
		Experimental Strain [Δε]							
		Demec	VWSG	Internal Resistive Gage	Demec	VWSG	Internal VWSG	DEMEC	Internal VWSG
Round 1	0								
	65								
	130								
	65								
	0								
Round 2	65								
	130								
	65								
	0								
Round 3	65								
	130								
	65								
	0								

Table X. Gages and strain reading results work table

Materials Needed

- ☐ Redbox
- ☐ Mitutoyo Absolute Model ID-C112TB
- ☐ RTDAQ 1.1.1.8 software
- ☐ CE DAQ
- ☐ Temperature control room
- ☐ External thermometer (to leave next to specimens)

Need from Shop Manager at Time of Procedure

- ☐ Advisement on temperature control room
- ☐ Advisement on software and CE DAQ

Short Term Compression Test

ASTM C39 was used as a basis for these tests
ASTM 469 was used in phase 2 of these tests

Phase I – Aluminum Specimen

1. The cylinder is first measured with a ruler to ensure cross sectional area size is accurate
2. The VWSG's will be removed from the aluminum cylinder from the temperature controlled test. It must be noted that that test must be done before this occurs.
3. The compressometer is applied to the aluminum cylinder. Knowing the modulus of elasticity of aluminum, the compressometer's strain is compared to 10 different readings to calibrate it. The readings should comply with the predicted readings by plus or minus 1 microstrain. This number was chosen because the VWSG is accurate up to 1 microstrain.

Phase II -- Establishing the modulus of elasticity of the concrete cylinders (ASTM 469)

1. The effective length of the gage line is established as less than three time the maximum size of the aggregate in the concrete
2. The aggregate also should not be more than two thirds the height of the specimen
3. The gage line is established as one half the height of the specimen
4. The compressometer consists of two yokes where one is rigidly attached to the specimen and the other is attached at two diametrically opposite points so that it is free to rotate. A pivot rot is utilized to maintain a constant distance between the yokes (Figure 1). The gage reading is equal to the sum of the displacement due to the specimen deformation and the displacement due to the rotation of the yoke about the pivot rod (Figure 2).

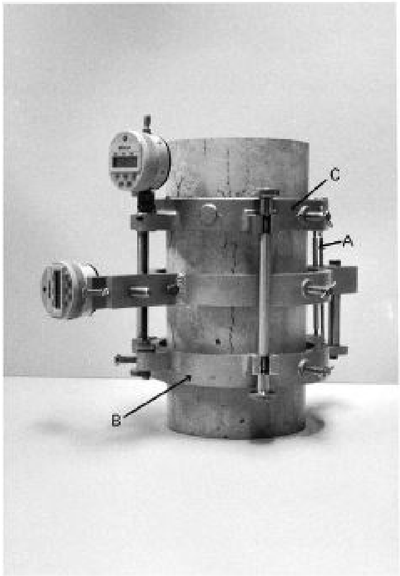
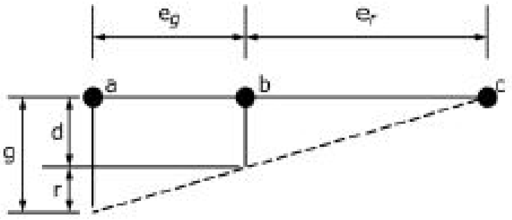


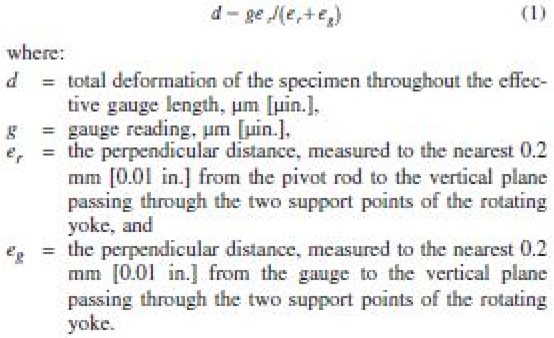
FIG. 1 Suitable Compressometer



d = displacement due to specimen deformation
r = displacement due to rotation of the yoke about the pivot rod
a = location of gauge
b = support point of the rotating yoke
c = location of pivot rod
g = gauge reading

FIG. 2 Diagram of Displacements

5. The deformation is measured by the dial gage. The deformation of the specimen I equal to one-half of the gage reading. The deformation is measured by the equation below.



$$d = ge_r/(e_r+e_g) \quad (1)$$

where:

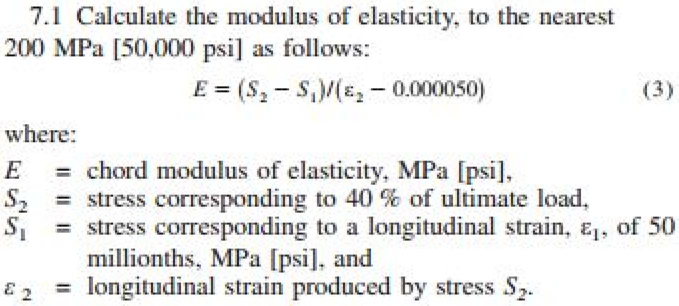
d = total deformation of the specimen throughout the effective gauge length, µm [µin.],
g = gauge reading, µm [µin.],
e_r = the perpendicular distance, measured to the nearest 0.2 mm [0.01 in.] from the pivot rod to the vertical plane passing through the two support points of the rotating yoke, and
e_g = the perpendicular distance, measured to the nearest 0.2 mm [0.01 in.] from the gauge to the vertical plane passing through the two support points of the rotating yoke.

6. The cylindrical specimens were created according to ASTM C31. The ends of the specimens shall be made such that it is perpendicular to the axis plus/minus 0.5 degrees and plane within 0.002 inches. This is achieved by casting with the PVC pipes, which will ensure perpendicularity. If the requirements are not met, the cylinders must be capped in accordance with ASTM C617.
7. The diameter of the test specimen is measured by caliper to the nearest 0.01 inch by two diameters at right angles to one another through the center of the specimen. The length of the specimen is recorded to the nearest 0.002 inches. A caliper is the preferred tool, but a ruler can be utilized to measure length if a large enough one is not present
8. The temperature of the room shall be recorded before and after each loading to ensure that the temperature does not vary by more than 4 degrees Fahrenheit
9. The compressive strength was measured from an average of two cylinders in a lab of CEGE 3402. The result was 4492 psi.
10. The specimen will be placed, with the compressometer attached, on the lower platen or bearing block of the testing machine. The axis of the specimen is aligned with the center of thrust of the spherically-seated upper bearing block. The reading on the compressometer is read. Before applying the load on the specimen, the movable portion of the spherically seated block is tilted so that the bearing face appears to be parallel to the top of the test specimen based on visual observation
11. The specimen will be loaded 6 times, with the first loading being thrown out.
    a. The loading will be applied continuously. It is a hydraulic testing machine, and so the load will be applied within a range of 250 plus/minus 50 kpa. The specimen is loaded

   until the applied load is 40 percent of the average ultimate load of the companion specimens. This is the maximum load for the modulus of elasticity test

   b. During the first loading, the performance of the gages are noted. Any attachment or alignment defects that may be causing erratic readings prior to the second loading are corrected. The applied load and longitudinal strain at the point when the longitudinal strain is 50 microstrain to where the applied load is 40 percent of the ultimate load of the companion specimens.

12. The load is reduced to zero at the same rate that it was applied
13. The following equation is used to determine the modulus of elasticity



7.1 Calculate the modulus of elasticity, to the nearest 200 MPa [50,000 psi] as follows:

$$E = (S_2 - S_1)/(\varepsilon_2 - 0.000050) \qquad (3)$$

where:

E = chord modulus of elasticity, MPa [psi],
S_2 = stress corresponding to 40 % of ultimate load,
S_1 = stress corresponding to a longitudinal strain, ε_1, of 50 millionths, MPa [psi], and
ε_2 = longitudinal strain produced by stress S_2.

14. This is performed on at least two out of the three cylinders (specimen 6) and the result is averaged
15. $40\%\ of\ Compressive\ Strength = 0.4 * Compressive\ Strength$
16. $1796.8\ psi = 0.4 * 4492\ psi$

Compression [psi]	Predicted Strain [ε] (low E)	Predicted Strain [ε] (high E)	Measured Strain [ε]	Modulus of Elasticity [ksi]
5.40	5.02E-05	4.98E-05		
450.55	4.19E-03	4.16E-03		
901.10	8.38E-03	8.31E-03		
1796.80	1.67E-02	1.66E-02		
901.10	8.38E-03	8.31E-03		
450.55	4.19E-03	4.16E-03		
5.40	5.02E-05	4.98E-05		

Table XI. Work table during testing with predicted strains for comparison

Phase III – Measuring strain

1. Knowing the modulus of elasticity, the strains under 4 loading conditions are predicted
2. Using the same methodology as in Phase II, the specimens are loaded under 4 loading conditions (to establish potential error), and this is cycled through twice. Percent error is reported and the results are analyzed.

Compression [lbs]	Modulus of Elasticity [psi]	Predicted Strain [ε]	Measured Strain [psi]		
			Specimen 1	Specimen 2	Specimen 3
5.40					
450.55					
901.10					
1796.80					
901.10					
450.55					
5.40					

Table XII. Work table during testing for the VWSG

Materials Needed

- ☐ Ruler
- ☐ Aluminum cylinder
- ☐ Compression machine (capable of imposing a load at the rate and the magnitude adequate as per ASTM 469)
- ☐ Compressometer
- ☐ Caliper
- ☐ Thermometer

Need from Shop Manager at Time of Procedure

- ☐ Compression machine assistance

xii. Appendix II

Finding the Coefficient of Thermal Expansion of Concrete

Note: This is included because it was meant to be part of the original investigation, but is not a part of the main report.

By combining equations 1-4 and 1-3, the coefficient of thermal expansion of the cylinder is found.

$$\frac{[(R_1 - R_o) * B + (T_1 - T_o) * \alpha_{gage}]}{(T_1 - T_o)} = \alpha_{cylinder}$$

$$[\frac{(R_1 - R_o)}{(T_1 - T_o)} * B + \alpha_{gage}] = \alpha_{cylinder} \qquad (1\text{-}5)$$

By taking 30 different readings at temperatures both increasing and decreasing, a coefficient of thermal expansion is determined. Temperatures from both extremes in the calculation for strain will be used. From these values, an average value is calculated using the arithmetic average method.

$$\alpha_{cylinder\ avg} = \frac{\Sigma\alpha_{cylinder}}{30} \qquad (1\text{-}6)$$

To perform the test, a compressometer was introduced to an aluminum cylinder, and using known modulus of elasticity, it was calibrated such that the measured strain of the compressometer matches the predicted strain on the specimen. Three VWSG’s and the compressometer was applied to a concrete cylinder using the same methodology for the application of the VWSG’s as described in Test 1. The cylinder will then go under loading, where the compressometer was regarded as the “true” measurement and a comparison of error was drawn. Thirty tests with different loads applied were performed, with two cycles of increasing and decreasing loading to ensure that increasing the loads did not change the error in comparison to decreasing the load. This was done on two cylinders to ensure repeatability.