Engineering the Thermal Resistivity of Concrete Duct Banks

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***Abstract* -- Cables are often installed in underground conduits surrounded by concrete. To calculate the cable ampacity in these duct banks the concrete thermal resistivity must be known. A set of experiments were performed to determine the effects that the concrete mixture has on resulting thermal resistivity. Concrete flow fill mixtures containing water-cement-sand and water-cement-fly ash-sand were studied. Experiments showed that water content of the mixture is not a factor in final concrete thermal resistivity unless fly ash was included in the mixture, however, the water to cement ratio is significant for all mixtures. Empirical equations were derived to find the resistivity of concrete as a function of the constituents of the concrete mixture. These equations may be used to design a concrete mixture to produce a desired thermal resistivity or calculate the thermal resistivity of a known concrete mixture.**

***Index Terms*-- Cable Ampacity, Duct Bank Design, Soil Moisture, Soil Properties, Thermal Conductivity, Thermal Stability, Thermoresistivity, Underground Cable Design.**

I. INTRODUCTION

Underground conduit is often surrounded by concrete in the form of a concrete duct bank. This is done to protect the electrical conduits and their enclosed cables from damage due to excavation or traffic on the soil above the ducts. The presence of the concrete has an additional benefit of improving the negative effects of any soil thermal instability that may be suspected at a particular location. Concrete improves soil thermal stability since the concrete surrounding the electrical conduit will be relatively thermally stable compared with most soils, and little water migration through hydrated concrete is expected. Furthermore, the duct bank will result in a larger area through which surrounding soil moisture can return to the drying interface between the duct bank concrete, which will be heated by the enclosed cables, and the soil in contact with the concrete. Since the drying effects on the soil will be reduced, the changes in soil thermal resistivity due to soil drying will also be reduced [1]. Using a concrete duct bank will thereby improve thermal stability of the underground cable system and the resulting stability will be determined to some degree by the diameter of the concrete surrounding the electrical ducts.

When concrete surrounds the electrical conduits, the concrete becomes part of the thermal circuit through which heat must be conducted to escape the vicinity of the cables [2]. To calculate the ampacity of the enclosed cables the thermal resistivity of the concrete must be known. It is often desirable to have the capability of designing a concrete mix that will produce a certain target thermal resistivity. It is also useful to have the means of predicting the thermal resistivity that will result when concrete of a known mixture is used.

This paper examines the hypothesis that the thermal resistivity is a function of the proportioning of a concrete mixture. Two experiments were designed to test this hypothesis. The first experiment tested concrete mixtures containing cement, water and sand; and the second experiment tested mixtures containing cement, fly ash, water and sand. The experiments encompassed the complete range of concrete flow-fill mixtures commonly used in duct bank construction. The results of the experiments, statistical analysis of the data, and the final design equations are reported herein.

II. PROPORTIONING CONCRETE

Concrete is a mixture of water, cementitious material (cement and fly ash), aggregate (sand and gravel), and air. The experiments that were performed tested the thermal resistivity of mixtures made of type II Portland Cement, sand and water; and type II Portland Cement, type F fly ash, sand and water. No air entrainment admixtures were used, and the air content was assumed to be approximately 3% in all cases. All materials were procured locally from sources near Denver, Colorado.

Concrete mixes have two design factors of concern. The first is water content, which affects workability and controls concrete slump. The second is water to cementitious material ratio (w/c ratio) which controls concrete compressive strength, usually given in pounds per square inch (psi). If fly ash is used to replace some of the cement then an additional design factor will be the ratio of fly ash to cementitious material [3].

The water content needed for a target slump value is calculated in lbs/yd^3 of final concrete volume. Slump is a measure of the workability (viscosity) of the concrete. Increasing the water content increases the slump and makes the concrete more fluid. Lower slump results in a stiffer mixture. The slump for the mixtures used in this study was between 2 inches and 7 inches, resulting from a water content of 350 lbs/yd^3 to 420 lbs/yd^3.

Concrete strength is determined by the ratio of the water to the cementitious material (w/c). This is the mass of the water divided by the mass of the cementitious material. In this study w/c ratios between 0.9 and 0.3 were studied. These w/c ratios will produce concrete strengths ranging between approximately 1500 psi and 7000 psi [3].

Cement is sometimes replaced with fly ash in concrete mixtures. This reduces the amount of cement needed in the cementitious material and also reduces the amount of water needed in the mix. The fly ash to cementitious material ratio also becomes a factor of interest. The fly ash to cementitious material ratio is normally between 0.05 and 0.4 (5% to 40%) and is measured by dividing the mass of fly ash by the mass of the total cementitious material needed for the desired strength. The experiments used studied the range of 5-40% fly ash to cementitious material ratios.

The experiments in this study cover the typical ranges of concrete mixtures found in duct bank designs. Once the water, water to cementitious material ratio, and if fly ash is used the fly ash to cementitious material ratio is chosen, the fine aggregate (sand) is then added to make up the volume needed. Therefore, the amount of sand used, while possibly affecting the thermal resistivity of the concrete, is not an independent variable in the concrete mix. The amount of sand (lbs/yd^3) is dependent upon the amount of water and cementitious materials (lbs/yd^3) used.

III. EXPERIMENT 1: WATER-SAND-CEMENT MIXTURE

To explore the effects concrete mixture may have on the thermal resistivity of the concrete a two-factor two-level (2^2) factorial experiment was designed [4] [5] [6]. The two factors used in the experiment were the water content in lbs/yd^3 and the water to cement ratio. The measured response variable was the thermal resistivity of the concrete. The thermal resistivity was measured using standard methods [8] [9] [10]. To discover any curvature of the final regression equation four center point samples were also examined.

A total of twelve four-inch diameter by eight-inch high concrete test cylinders were prepared. Two replicates of the four factorial combinations and four replicates of the center points were prepared. Four cylinders were tested each day and the day of testing was used as a blocking factor. The cylinders were prepared and tested in random order within their blocks. The mixture in each test cylinder is shown in Table I. After preparation the cylinders were allowed to cure in air for 28 days before testing.

TABLE I
CONCRETE MIXES USED FOR EXPERIMENT 1

Sample Number	*w/c*	*Water (lbs/yd^3)*	*Cement (lbs/yd^3)*	*Sand (lbs/yd^3)*
1	0.3	350	1,166.7	1,270.9
2	0.3	350	1,400.0	1,238.6
3	0.9	420	388.9	2,451.1
4	0.9	420	466.7	2,369.9
5	0.3	350	1,166.7	1,270.9
6	0.3	350	1,400.0	1,238.6
7	0.9	420	388.9	2,451.1
8	0.9	420	466.7	2,369.9
9	0.6	385	641.7	2,491.8
10	0.6	385	641.7	2,491.8
11	0.6	385	641.7	2,491.8
12	0.6	385	641.7	2,491.8

The results of the tests are shown in Table II. The Run Order is the order in which the samples were tested; the Coded Variables are the coding within the two level testing and analysis; the Actual Variables are the concrete mix values corresponding to the Coded Variables; and the Results are the measured thermal resistivity for each sample.

TABLE II
TEST RESULTS.

		Coded Variables		*Actual Variables*		*Result*
Sample Number	*Run Order*	*w/c*	*Water lbs/yd^3*	*w/c (A)*	*Water lbs/yd^3 (B)*	*Resistivity cm-°C/W*
1	1	-1	-1	0.3	350	64.85
2	2	1	-1	0.9	350	35.56
3	4	-1	1	0.3	420	63.87
4	3	1	1	0.9	420	32.04
5	5	-1	-1	0.3	350	71.30
6	7	1	-1	0.9	350	36.43
7	8	-1	1	0.3	420	54.06
8	6	1	1	0.9	420	35.50
9	11	0	0	0.6	385	36.01
10	10	0	0	0.6	385	35.25
11	9	0	0	0.6	385	36.41
12	12	0	0	0.6	385	39.08

An analysis of variance approach was used to determine the significance of the measured data [4] [5] [6]. This statistical approach can provide insight into the effect each of the process variables, w/c ratio and water content, has on the response variable, thermal resistivity. This analysis technique can also provide insight into any interactions that may occur between the process variables.

The analysis of variance for the recorded data is shown in Table III. Factor A corresponds to the w/c ratio and Factor B corresponds to the water content. Factor AB is the interaction between the two factors.

TABLE III
ANALYSIS OF VARIANCE FOR DATA IN Table II.

Factor	*Effect Estimate*	*SS*	*DF*	*MS*	*F_0*	*$F_{test,0.05}$*
Model		1,728.04	3	576.01	41.43	4.35
Blocking		0.119	1	0.119	0.0086	5.59
A	-14.32	1,640.14	1	1,640.14	117.98	5.59
B	-2.39	64.22	1	64.22	4.62	5.59
AB	1.72	23.67	1	23.67	1.70	5.59
b_o	49.20					
Quadratic		208.78	1	208.78	15.02	5.59
Pure Error y_f		75.1	3			
Pure Error y_c		8.31	3			
Total Pure Error		83.41	6	13.901		
Total		2,020.23	11			

The effect estimates are the regression coefficients for the coded values. SS is the sum of squares for each factor; DF is the number of degrees of freedom; MS is the mean square value of the factor and F_0 is the F statistic calculated from the mean square of the factor and the pure error. $F_{test,0.05}$ is the statistical F distribution value for a 95% significance level and the appropriate numbers of degrees of freedom.

Analysis is done on the information in Table III by comparing the F_0 statistic calculated from the measured data with the $F_{test,0.05}$ statistic. This comparison will determine if the null hypothesis can be statistically rejected based upon the measured data. The null hypothesis, H_0, states that the factor being examined has no effect on the response variable. If $F_0 < F_{test,0.05}$ for a particular factor, this means that to a significance level of 95%, the null hypothesis, H_0, that the particular factor has no effect on the response variable, cannot be rejected. If $F_0 > F_{test,0.05}$ then the null hypothesis H_0 must be rejected and the alternative hypothesis H_1, that the factor does have an effect on the resistivity, must be accepted.

Examining the values in Table III it may be seen that for Factor A, the w/c ratio, the F statistic is 117.98 and the $F_{test,0.05}$ value is 5.59. Since $117.98 > 5.59$ the null hypothesis must be rejected and it may be seen that statistically the w/c ratio does have an effect on the resistivity of the concrete.

It may also be seen that Factor B, the water content, has a test statistic of 4.62 which is compared with $F_{test,0.05}$ of 5.59. Since $4.62 < 5.59$ the null hypothesis cannot be rejected and the conclusion is that there is no evidence from the experimental data that the water content has an effect on the thermal resistivity of the concrete.

By the same type of comparison it may also be seen from Table III that there are no significant interaction effects between the w/c ratio and the water content (AB), the effect of variations between the blocks was insignificant, and the quadratic effects are statistically significant. The quadratic effects show that there is some curvature in the regression line between the process variables and the response variable that will have to be considered when determining the final regression equation for the effect.

Since it appears from the statistical analysis that the water content and the interaction effects have negligible effects on the concrete thermal resistivity, the model that will be fitted to the data needs to consider only the w/c ratio. After several attempts at fitting various equation types to the modeled data, the equation form of Equation (1) was found to produce the best fit. It accounts for the evident curvature by using the squared term. In this model the x's are the w/c ratio, and the β's are the regression coefficients. The y term is the thermal resistivity in cm-°C/W.

$$y = \beta_1 x^2 + \beta_2 x + \beta_0 \qquad (1)$$

The final empirical equation derived by linear regression from the experimental data, and that may be used to predict the thermal resistivity y in cm-°C/W if given the w/c ratio x, is Equation (2). This equation is valid over the test conditions of a water content between 350 and 420 lb/yd^3, and a w/c ratio of 0.3 to 0.9. Equation (2) has a coefficient of determination (R_{adj}^2) of 0.9846 [6].

$$y = 139.4x^2 - 214.6x + 115.37 \qquad (2)$$

The 95% prediction interval for any subsequent value of y, y_0, calculated from Equation (2) may be found using Equation (3).

$$y_0 - 2.262\sqrt{1.149\left(5.75 - 35x + 05.8x^2 - 111x^3 + 46.3x^4\right)} \le y_0 \le y_0 + 2.262\sqrt{1.149\left(5.75 - 35x + 05.8x^2 - 111x^3 + 46.3x^4\right)} \qquad (3)$$

Table IV contains the results using Equation (2) and Equation (3) to calculate the expected value (mean value) and the 95% prediction limits for thermal resistivity of concrete mixture between the w/c ratios that were tested in the experiment. Any concrete sample prepared at the w/c ratio given in the Table would be expected to fall between the minimum and maximum values shown, and a large number of such samples would be expected to have an average value equal to the mean value given.

TABLE IV
EXPECTED VALUE AND PREDICTION LIMITS FOR THERMAL RESISTIVITY IN CM-°C/W AS A FUNCTION OF W/C RATIO.

w/c ratio	*Mean Value*	*Minimum Limit*	*Maximum Limit*
0.3	63.5	53.1	74.0
0.4	51.8	41.7	61.9
0.5	42.9	32.5	53.3
0.6	36.8	26.2	47.4
0.7	33.4	22.9	44.0
0.8	32.9	22.5	43.3
0.9	35.1	24.2	46.1

Fig 1 is a graph showing the actual measure data (shown by the square markers) and the regression line which was calculated using Equation (2). The curvature of the original data indicated by the analysis of variance can be clearly seen in this Figure.

The graphs in Fig 2, Fig 3, and Fig 4 show the residual analysis resulting from the fitted model, and are shown as an aid to determining the quality of the data. The residuals appear generally normally distributed. The only points of concern are the two that depart from the normal distribution line shown in Fig 2. Although they appear to be possible outliers from this Figure, the testing methodology that resulted in these points was closely examined and no reason could be found to justify excluding these points from the analysis. These are the same two points that are the farthest from the zero line in Fig 3 and Fig 4. The test samples that produced these two points both contained low water/cement ratios. Rather than being outliers, it may be that the variance of the resistivity is greater for low water/cement ratios than for larger water/cement ratios.

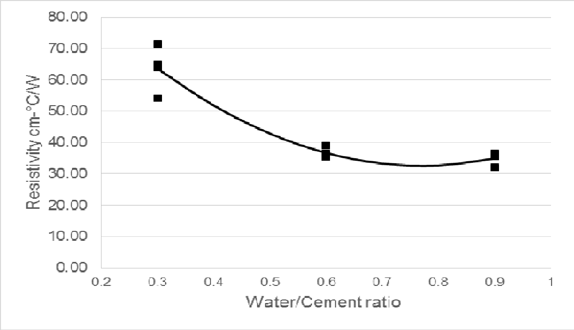

Fig. 1. Measured data points and regression line from Equation (2).

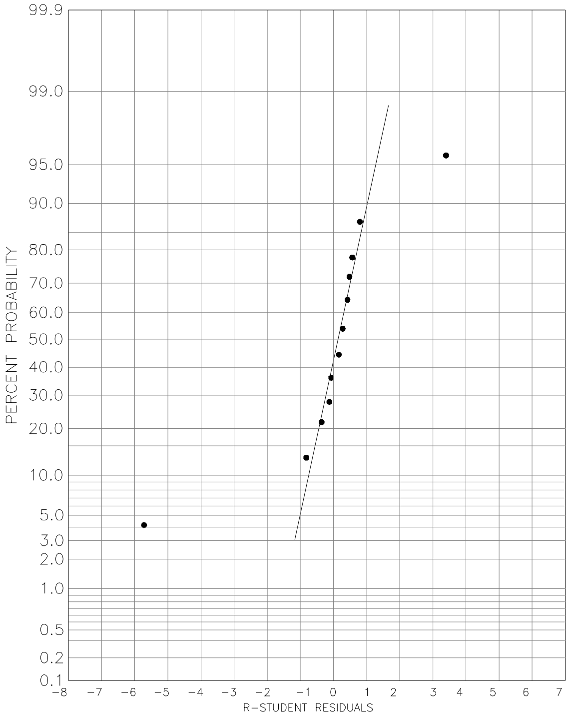

Fig. 2. Normal distribution plot of R-Student residuals.

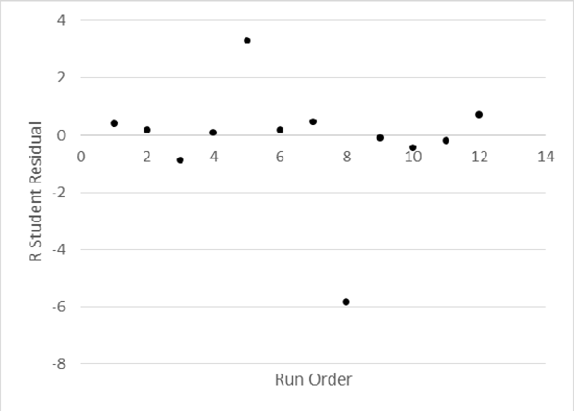

Fig. 3. Scatter plot of R-Student residuals plotted against the order of testing.

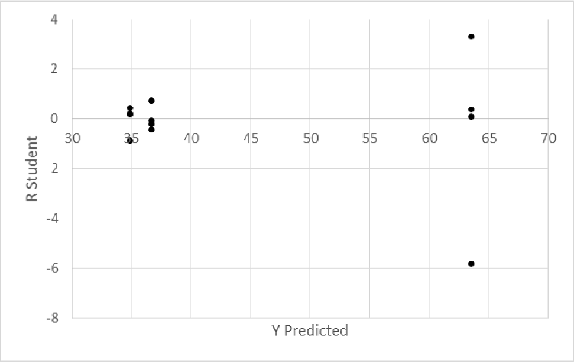

Fig. 4. Scatter plot of R-Student residuals vs predicted values of resistivity.

IV. Experiment 2: Water-Sand-Fly Ash Mixture

A three factor two level (2^3) experiment was designed to find an empirical equation for the thermal resistivity of concrete where type F fly ash was used to replace part of the cementitious material. The two levels of fly ash used in the experiment were 5% to 40% of the cementitious material.

A single replicate of factorial samples was used but four replicates of center point samples were prepared to determine both regression curvature and pure experimental error for statistical analysis of the results. The experiment was performed in a similar manner to the first experiment. Twelve test cylinders were prepared (8 factorial mixtures and 4 center point mixtures) in random order and were allowed to cure for 28 days before testing. Their thermal resistivity of each cylinder was then tested. Table V shows the actual mixtures of the concrete samples.

Table V

Concrete Mixes used for experiment 2

Sample Number	*Sand (lb/yd³)*	*Cement (lb/yd³)*	*Fly Ash (lb/yd³)*	*Water (lb/yd³)*
1	1,482	1,097	58	350
2	2,441	350	20	350
3	1,276	1,418	75	420
4	2,460	448	23	420
5	1,765	647	431	350
6	2,487	224	149	350
7	1,651	858	571	420
8	2,558	275	183	420
9	2,373	524	152	385
10	2,373	524	152	385
11	2,373	524	152	385
12	2,373	524	152	385

Table VI shows the order in which the samples were tested along with the actual tested variables used in the mixes and the results of the test. W/c ratio is the water to cementitious material ratio, the variable used for this in the final equation is x_1, and the variable used for this factor in the analysis of variance is A. Water is the water content in lbs/yd^3, x_2 is the variable used in the final equation and B is the factor identifier in the analysis of variance. Fly ash is the ratio of fly ash to total cementitious material, x_3 is used in the final regression equation and C is its identifier in the analysis of variance. The resistivity column gives the resultant thermal resistivity measured for each sample.

Table VII shows the analysis of variance for the data. The effect estimate is the estimate of the regression variable for coded factors. SS is the sum of squares for each variable, DF is the degrees of freedom, MS is the mean square, F_0 is the F statistic calculated from the measured data, and $F_{test,0.05}$ is the F distribution statistic for the appropriate number of degrees of freedom for each test. The F_0 value is compared to the $F_{test,0.05}$ value to determine if the null hypothesis for each variable should be rejected meaning the variable has an effect on the resistivity of concrete.

TABLE VI

SAMPLES, SAMPLE RUN ORDER, AND THE VARIABLES USED FOR EACH FACTOR.

Sample Number	*Test Order*	*w/c (x_1) (A)*	*Water Content (x_2) (B)*	*Fly Ash (x_3) (C)*	*Resistivity cm-°C/W*
1	8	0.3	350	0.05	69.00
2	1	0.9	350	0.05	46.27
3	7	0.3	420	0.05	62.11
4	2	0.9	420	0.05	42.63
5	5	0.3	350	0.4	55.35
6	6	0.9	350	0.4	46.64
7	3	0.3	420	0.4	45.93
8	4	0.9	420	0.4	42.97
9	12	0.6	385	0.225	42.27
10	10	0.6	385	0.225	39.91
11	11	0.6	385	0.225	44.29
12	9	0.6	385	0.225	37.82

TABLE VII

ANALYSIS OF VARIANCE TABLE FOR DATA IN TABLE V AND TABLE VI

Factor	*Estimated Effect*	*SS*	*DF*	*MS*	*F_0*	*$F_{test,\ 0.05}$*
Model		667.05	7	95.29	12.08	8.89
A	-13.47	363.07	1	363.07	46.02	10.13
B	-5.91	69.74	1	69.74	8.84	10.13
C	-7.28	105.96	1	105.96	13.43	10.13
AB	2.25	10.12	1	10.12	1.28	10.13
AC	7.63	116.57	1	116.57	14.78	10.13
BC	-0.64	0.81	1	0.81	0.10	10.13
ABC	0.63	0.78	1	0.78	0.10	10.13
b_0	102.73					
Pure error		23.67	3	7.89		
Quadratic		282.40	1	282.40	35.79	10.13
Total		973.11	11			

The null hypothesis, H_0, is that a particular variable has no effect on the final thermal resistivity. The alternative hypothesis, H_1, is that the variable has an effect on the final thermal resistivity. If $F_0<F_{test,0.05}$ then to a 95% significance level the null hypothesis cannot be rejected and it must be concluded that the particular factor under test was not shown to have an effect on the material's resistivity. If $F_0>F_{test,0.05}$ then the H_0 should be rejected and is should be concluded that that factor does have a significant effect on the material's resistivity of concrete.

A comparison of the F_0 and $F_{test,0.05}$ columns show that the water/cement ratio (factor A), has the largest effect on thermal resistivity. Furthermore, factor C, the fly ash ratio, and the interaction between the water/cement and fly ash ratio (factor AC) also have significant effects on the final thermal resistivity. The other interaction factors, w/c with water content (AB), water content with fly ash ratio (BC) and w/c with water content with fly ash ratio (ABC) have no significant effect on resistivity and the H_0 cannot be rejected for these interactions.

The water content (factor B) also has an F_0 statistic less than the test statistic and therefore the null hypothesis cannot be rejected for this factor at the 95% significance level. However, it may be found that at a slightly different significance level, 96%, $F_0>F_{test,0.05}$ and the null hypothesis would be rejected. It was also determined that the fit for the final regression equation was significantly improved by including the water content in the final analysis. So it was concluded that, unlike the former case with the water-cement-sand mix, for the water-cement-fly ash-sand mixes the water content did have an significant effect on the material's thermal resistivity although a relatively smaller one.

The quadratic F_0 statistic shows that there is once again significant curvature to the regression line. So the final regression equation must include a term or terms to account for this curvature. After testing the range of possible forms of equations it was determined that an equation of the form of Equation (4) produced the best fit.

$$y = \beta_1 x_1^2 + \beta_2 x_1 + \beta_3 x_2 + \beta_4 x_3 + \beta_5 x_1 x_3 + \beta_0 \tag{4}$$

Linear regression using the form of Equation (4) resulted in the final empirical equation in (5).

$$y = 114.34x_1^2 - 176.02x_1 - 0.08444x_2 - 64.421x_3 + 72.709x_1x_3 + 142.68 \tag{5}$$

Where:
x_1=water/cement ratio
x_2=water content in lb/yd^3
x_3=fly ash/cementitious ratio
y=thermal resistivity in cm-°C/W

The coefficient of determination (R_{adj}^2) for this equation is 97.1%.

For any set of variables, x_1, x_2, and x_3, the expected value of the resistivity, y, may be found using Equation (5). The 95% prediction interval may also be found. Given any set of variables, x_1, x_2, and x_3, within the range tested in this experiment ($0.3<x_1<0.9$; $350<x_2<420$; $0.05<x_3<0.4$) the matrix ***X₀*** may be formed using Equation (6).

$$X_0 = \begin{bmatrix} x_1^2 \\ x_1 \\ x_2 \\ x_3 \\ x_1x_3 \\ 1 \end{bmatrix} \tag{6}$$

The single element matrix ***Z*** is then found using Equation (7).

$$Z = X_0^{'} W X_0 \tag{7}$$

Where ***X₀'*** is the transpose of ***X₀***.

Matrix ***W*** was derived from the experimental measured data. For this experiment the ***W*** matrix was found to be:

$$W = \begin{bmatrix} 46.2963 & -55.5556 & 0 & 0 & 0 & 13.88889 \\ -55.5556 & 70.35174 & 0 & 6.122449 & -10.2041 & -18.8776 \\ 0 & 0 & 0.000102 & 0 & 0 & -0.03929 \\ 0 & 6.122449 & 0 & 20.40816 & -27.2019 & -4.59184 \\ 0 & -10.2041 & 0 & -27.2019 & 45.35147 & 6.122449 \\ 13.88889 & -18.8776 & -0.03929 & -4.59184 & 6.122449 & 20.90816 \end{bmatrix}$$

After the one element of matrix *Z* is found from Equation (6) and Equation (7), y_{add} is found using Equation (8).

$$y_{add} = 2.447\sqrt{7.6535\,(1-Z)} \tag{8}$$

The value y_{add} is then both added and subtracted from the y found using Equation (5) to find the 95% prediction interval of resistivity for any set of x values of interest. Any set of x values should produce a value of resistivity that falls between the minimum and maximum values calculated using this method. Table VIII lists the expected ranges of resistivity for a sample of mixtures calculated using this method.

TABLE VIII
THE MINIMUM AND MAXIMUM RANGE OF RESISTIVITY FOR A SAMPLE OF MIXES.

w/c (*x_1*)	*Water Content* (*x_2*)	*Fly Ash* (*x_3*)	*Expected resistivity (y)*		
			Mean (*y*)	*Minimum* (*y_{min}*)	*Maximum* (*y_{max}*)
0.3	350	0.05	68.5	64.3	72.6
0.6	350	0.05	47.6	42.9	52.4
0.9	350	0.05	47.4	43.2	51.5
0.3	385	0.05	65.5	60.7	70.3
0.6	385	0.05	44.7	39.3	50.0
0.9	385	0.05	44.4	39.6	49.2
0.3	420	0.05	62.6	58.4	66.7
0.6	420	0.05	41.7	36.9	46.5
0.9	420	0.05	41.5	37.3	45.6
0.3	350	0.225	61.0	55.7	66.4
0.6	350	0.225	44.0	38.6	49.4
0.9	350	0.225	47.6	42.2	52.9
0.3	385	0.225	58.1	52.2	63.9
0.6	385	0.225	41.0	35.2	46.9
0.9	385	0.225	44.6	38.7	50.5
0.3	420	0.225	55.1	49.8	60.5
0.6	420	0.225	38.1	32.7	43.4
0.9	420	0.225	41.6	36.3	47.0
0.3	350	0.4	53.6	49.4	57.7
0.6	350	0.4	40.4	35.6	45.1
0.9	350	0.4	47.7	43.6	51.9
0.3	385	0.4	50.6	45.8	55.4
0.6	385	0.4	37.4	32.1	42.8
0.9	385	0.4	44.8	40.0	49.6
0.3	420	0.4	47.7	43.5	51.8
0.6	420	0.4	34.4	29.7	39.2
0.9	420	0.4	41.8	37.7	46.0

The following Figures are provided for analysis of the residuals. No unusual concerns with the data are apparent.

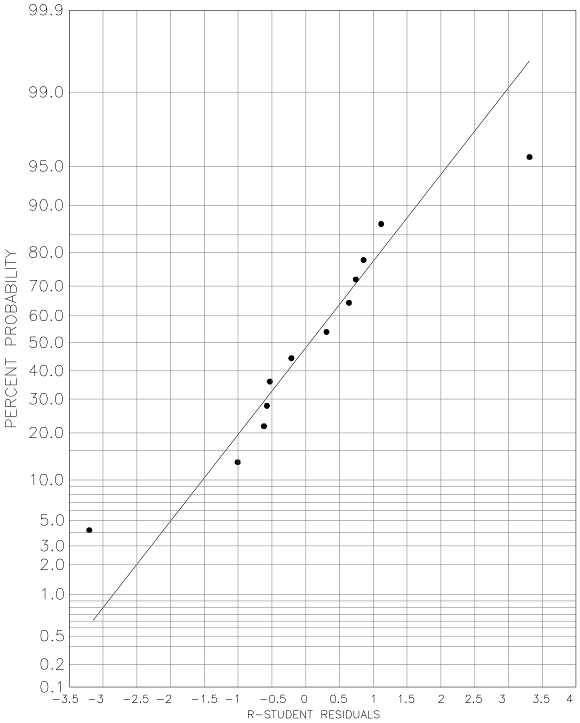

Fig. 5. Normal distribution plot of the R-Student residuals.

Fig. 6. R-Student residuals vs order of tests.

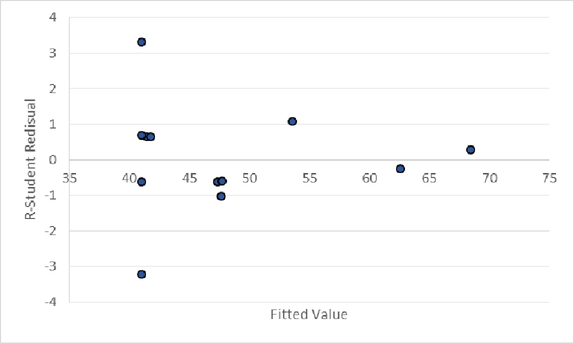

Fig. 7. R-Student residuals vs the fitted resistivity value using Equation (5).

V. CONCLUSIONS

The two experiments whose results are reported herein show that the thermal resistivity of concrete mixes may be designed or predicted if the proportions used in a concrete mixture are known. In the case of the water-cement-sand mixture, the resistivity was found to be a function of only the water to cement ratio. Equation (2) and Equation (3) are empirical equations derived from experimentation that may be used to calculate the expected values of thermal resistivity for any typical water-cement-sand concrete mix.

The experiment using a water-cement-fly ash-sand mixture resulted in a more complex equation since the resistivity was found to be a function of not only the water to cementitious material ratio, but also of water content and fly ash ratio. There was also found to be a significant interaction between the water to cement ratio and the percentage of fly ash in determining the thermal resistivity. Equations (5), (6), (7) and (8) may be used to calculate the range of thermal resistivity that will be expected with any typical water-cement-fly ash-sand concrete mixture.

These experiments used cement, fly ash, and sand from a single source at a single location. Additional experimentation is needed to determine if there will be any variation in resistivity due to the source of the raw materials.

REFERENCES

[1] Keith Malmedal, Carson Bates, and David Cain, "Measurement of Soil Thermal Stability, Thermal Resistivity, and Underground Cable Ampacity," *2014 IEEE Rural Electric Power Conference*, Fort Worth, TX, May 18-21, 2014.

[2] J.H. Neher and M.H. McGrath, The Calculation of the Temperature Rise and Load Capability of Cable Systems, *AIEE Transactions*, Part III, Volume 76, pp 752–772, October, 1957

[3] Stephen H. Kosmatka and Michelle L. Wilson, *Design and Control of Concrete Mixtures, Fifteenth Edition*, Portland Cement Association, ISBN 978-0-89312-272-0, 2013

[4] Douglas C. Montgomery, *Design and Analysis of Experiments, Eighth Edition*, ISBN 978-1-118-14692-7, John Wiley & Sons Inc., Hoboken, NJ, 2013

[5] Robert W. Mee, *A Comprehensive Guide to Factorial Two-Level Experimentation*, ISBN 978-0-387-89102-6, Springer Science, New York, NY, 2009.

[6] Douglas, C. Montgomery, Elizabeth A. Peck, G. Geoffrey Vining, *Introduction to Linear Regression Analysis*, ISBN 978-0-470-54281-1, Wiley & Sons, Inc. Hoboken, NJ, 2012.

[7] *IEEE Guide for Soil Thermal Resistivity Measurements,* IEEE Std. 442-1981,

[8] DeWitt, Bergman, and Lavine, *Fundamentals of Heat and Mass Transfer, 6th edition*, John Wiley & Sons, 2007, pp. 207-211

[9] Leonard R. Ingersoll, Otto,J. Zobel, and Alfred C. Ingersoll, *Heat Conduction with Engineering, Geological, and Other Applications*, University of Wisconsin Press, Madison Wisconsin, 1954.

[10] *Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure*, 2008, ASTM D5334

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Keith Malmedal (M'91–SM'13) received his BSEET degree from Metropolitan State College of Denver in 1995, MSEE degree (Power), a MSCE degree (Structures) from the University of Colorado Denver in 1998 and 2002, respectively. In 2008 he received his PhD at Colorado School of Mines, Golden, CO. He has over 25 years engineering experience and is presently the President of NEI Electric Power Engineering. Dr. Malmedal is a member of the American Society of Civil Engineers (ASCE) and a registered professional engineer in 20 states (US), Alberta, British Columbia, and Ontario, Canada.

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