SP 101-2

Analysis of Maturity/Pullout Testing Data

by R. Dilly, V. Beizai, and W. Vogt

Synopsis: Pullout testing provides a measurement of inplace strength of concrete and maturity can be used to estimate strength development. Test statistics are useful tools for interpreting the significance of the data. Maturity may correlate to pullout strength by regression analysis. The simplest correlation would be linear using the logarithm of maturity. Linear relationships may be compared using test statistics to determine if slopes and/or intercepts are significantly different. Statistical analysis techniques are used to evaluate pullout strength and maturity data. Some limitations associated with these techniques are discussed. A programmable calculator was utilized in developing the programs to illustrate the application of these analysis techniques.

Keywords: age-strength relation; coefficient of variation; computer programs; concretes; evaluation; nondestructive tests; pullout tests; regression analysis; standard deviation; statistical analysis

ACI Member Ronald L. Dilly is an assistant professor of Civil Technology, University of Houston-University Park, Houston, Texas. He is a member of ACI Committee 214, Evaluation of Results of Tests Used to Determine the Strength of Concrete, and a member of the American Society of Civil Engineers.

ACI Member Vahid (Vic) Beizai is the Manager of Engineering for MRA/Materials Engineers, Inc. in Houston, Texas. He holds a B.S. degree in Civil Engineering from Syracuse University. He is active in the American Society of Civil Engineers.

ACI Member Woodward L. Vogt, P.E., is the President of MRA/Materials Engineers, Inc. He is active in the American Society of Civil Engineers, National Society of Professional Engineers, and American Society for Testing and Materials.

INTRODUCTION

The pullout test provides a method of determining inplace strength of concrete. The maturity method can be used to estimate concrete strength development. These methods may be combined and used when construction activities require monitoring of strength development. Statistical analysis can be used to interpret test data acquired with these methods and to determine if significant differences occur between test ages, test locations, or curing regime.

BACKGROUND

The maturity concept is reported to have been presented by Saul(1) in 1951 as an empirical approach for predicting concrete strength development based upon time-temprature histories(2).

The time-temperature curing history of a concrete mixture can be used to calculate maturity by:

$$M = \Sigma(T-T_o)\Delta t.....(1)$$

where M is the maturity of the concrete, T is the average concrete temperature where the change occurs at an approximately constant rate for an increment of time, Δt; and T_o is the datum temperature at which or below concrete ceases to gain strength with time.

This concept postulates that strengths will be approximately equal at the same maturity. However, the results of an experimental investigation conducted by Carino, Lew, and Volz(3) confirmed that different early age temperatures can affect the strength-maturity relationship, as recognized earlier by McIntosh(4) and Klieger(5).

The maturity concept has been investigated by a number of other researchers. Strength prediction equations using the logarithm of maturity for accelerated curing methods were developed by Ramakrishnan and Dietz(6) using a linear form of an equation originally suggested by Plowman(7). Nonlinear regression analysis has been used by researchers to develop compressive strength relationships with maturity. An experimental investigation by Naik(8) has shown that a predetermined strength/maturity relationship for a concrete mixture can be used with about the same degree of accuracy as a core strength. ASTM C 918 is a standard method for estimating later-age strengths using early-age compression test values with maturity calculations(9). A datum temperature is not used in this method. ACI 306 has recognized the use of the maturity concept(10).

Malhotra(11) and Richards(12) undertook many of the initial experimental investigations of pullout testing conducted in North America. The pullout test is a method of determining the inplace strength of concrete. A standard method is provided by ASTM C 900(13). Bickley has reported on the use of pullout testing to evaluate inplace strength during construction(14). Vogt, Beizai, and Dilly(15) reported the results of pullout testing conducted on a project in which ACI 214(16) statistical methods were used to report the data, although these methods were developed exclusively for compressive strength evaluation.

The pullout strength of concrete is determined by measuring the force required to extract an embedded insert from hardened concrete and dividing by the surface area generated from fracturing the concrete. Relationships have been developed between pullout strength and concrete maturity to evaluate inplace concrete strength. Maturity-pullout relationships have been reported by Parsons and Naik(17), and Dilly and Ledbetter(18).

APPLICATION OF STATISTICS FOR INTERPRETATION OF TEST RESULTS

Single variable tests can be used to estimate if significant differences exist between different test locations or test ages. Multivariable methods, such as linear regression analysis, can be used to estimate if significant differences exist between different curing regimes.

Two HP, Hewlett-Packard 41C/41CV programs were developed for statistical analysis of test results. Each program utilizes the calculator's statistical functions. The first program designated "ST" provides an analysis of two test sample means, while the second program, "LT" performs a least square regression multiple variable analysis of slopes and intercepts of two linear relationships. "ST" includes a test statistics for significant differences between sample means, and "LT" includes test statistics for significant differences between the slopes and the intercepts of least square regression relationships. Reference 19 was used to develop program "ST", and references 20 and 21 were used to develop program "LT". Flowcharts, user's manuals, and program listings appear in the Appendix.

Two examples are discussed, illustrating the use of these programs. Table 1 is a summary of test statistics used in "ST", and Table 2 is a summary of test statistics used in "LT". The data in the examples was the result of an experimental investigation reported by references 18 and 22. Both of these refer to the same experimental investigation in which a hydraulic centerpull ram pullout testing apparatus was used to estimate the inplace strength of a 6.0 ft (1.8 m) tall concrete column. Sets of inserts were placed at the base and top of the column at a vertical spacing of 5.0 ft (1.5 m). When inserts were extracted, the resulting approximate conic frustums had heights of 1.8 in (30 mm) and base diameters of 2.76 in (70 mm) and 1.8 in (30 mm). The apex angle for the assumed conic frustum is 67.4 degrees resulting in a surface area of 8.79 in^2 (56.6 cm^2)

The pullout strengths which appear in the first example were obtained by dividing the force on the ram at failure by the assumed conic frustum area. The average pullout strengths which appear in the second example were obtained by averaging three pullout strengths determined in the same manner.

Example using program "ST"

At an age of 28 days, the following pullout strengths resulted from tests conducted on the column:

fp-Individual pullout strength, psi	
Top of column	Base of column
376	681
376	704
400	634

Note: 1 psi = 6897 Pa

Program "ST" performs an analysis of this limited data. The input and output shown in Figure 1 indicate that for set 1 (top of column), the average is 384 psi, the standard deviation is 13.9 psi, and the coefficient of variation is 3.6%. For set 2 (base of column), the average is 673 psi, the standard deviation is 36 psi, and the coefficient of variation is 5.3%. "F" calculated is 6.63, and "F" tabulated is 19.00 at the 5% significance level. "F" calculated is less than "F" tabulated, so the calculated "t" test statistics value of 13.08 applies. For this example, the two "t" test statistics values are the same due to the equal number of observations from each set. At a significance level of 5%, "t" tabulated is 2.13, thus a significant difference exists between top and bottom average pullout strength. Refer to reference 19 for details on these statistical testing concepts.

Example using program "LT"

At ages 3, 7, 14, and 28 days, the average pullout strengths shown below resulted from tests conducted on a column. The values of logarithm of maturity shown on each of the following test ages was calculated using Equation (1), where 14 ^{o}F (-10 ^{o}C) was used as the datum temperature, T_o.

Test age days	Log of maturity ^{o}F-hrs	fp-average of three pullout strength tests psi: Top of column	fp-average of three pullout strength tests psi: Base of column
3	3.8104	224	490
7	4.1671	290	548
14	4.4476	361	575
28	4.7249	384	673

Note: Log of maturity(^{o}F-hrs) = 0.2553 + Log of maturity(^{o}C-hrs)

Program "LT" provides an analysis for this limited data. The linear regression expression corresponding to the output would have the general form:

$$fp = a + b \times \text{Log of maturity} \ldots\ldots(2)$$

where "a" is the intercept and "b" is the slope.

The input and output shown in Figure 2 indicate that for set 1 (top of column), the intercept is -470 psi, the slope is 183, the standard error of the estimate squared is 212, and the coefficient of determination is 0.97. For set 2 (base of column), the intercept is -238 psi, the slope is 189, the standard error of the estimate squared is 573, and the coefficient of determination is 0.93. "F" calculated is 2.71 and "F" tabulated is 19.00 at the 5% significance level. "F" calculated is less than "F" tabulated, so the test statistics for slope and intercept ap-ply. The "t" calculated values are 0.14 for the slope, and 1.30 for the intercept. At a significance level of 5%, which is generally used, "t" tabulated is 2.13 suggesting that there is no significant difference between the slopes or the intercepts, and the data may be pooled. If this pooling was done, the accuracy of prediction would be expected to decrease. If the sample sizes had been larger, significant differences may have been more apparent for the intercepts.

DISCUSSION AND CONCLUSIONS

A requirement for the statistics incorporated in these programs is for the data to be acquired randomly. Pullout testing of inplace concrete using preplaced inserts may not represent a random sample due to factors such as installation constraints. Even though this requirement may not be satisfied for single variable analysis, two-sample tests of means may be used to distinguish whether significant differences are apparent between concrete strength at different locations. Correct interpretation of inplace strength differences can influence project safety and the construction schedule. These differences may be attributed to many factors, and to be properly evaluated, the influence of top-to-bottom effects may have to be considered.

Linear regression analysis test statistics for comparing slopes and intercepts requires assumptions in addition to random sampling. These additional assumptions are based upon conditional distributions of the dependent variable, Y, on the regression line. For pullout strength vs. logarithm of maturity relationship, these other assumptions as well as the assumption of randomly obtained observations, may not be satisfied. With an accurate temperature recorder for maturity data collection, an additional assumption that X values are known without error may be nearly satisfied. Even though all assumptions may not be met, the logarithm of maturity may still be used in reducing errors of predicting required pullout strength and in determining whether significant differences are apparent between slopes and/or intercepts due to variations in concrete mixture and curing conditions.

The results of the logarithm of maturity relationships established in the second example were not significantly different. However, the resulting general trends established with limited observations indicate that top and bottom differences are apparent and perhaps the vertical locations of embedded inserts should be considered in order to reduce variations of f_p about the best fit line established with logarithm of maturity.

Although not specifically stated in this paper, larger sample sizes improve estimates of the mean pullout strength and pullout strength vs. logarithm of maturity relationships. Significant differences may not be detected unless larger sample sizes are used.

REFERENCES

1. Saul. A.G.A., "Principles Underlying the Steam Curing of Concrete at Atmospheric Pressure," Magazine of Concrete Research (London), V. 2, No. 6, March 1951, pp. 127-140.

2. Carino, N. J., and Lew, H. S., "Temperature Effects on Strength-Maturity Relations of Mortar," ACI Journal, Proceedings, V. 80, No. 3, May-June 1983, pp. 177-182.

3. Carino, N. J., Lew, H. S., and Volz, C. K., "Early Age Temperature Effects on Concrete Strength Prediction by the Maturity Method," ACI Journal, Proceedings, V. 80, No. 2, March-April 1983, pp. 93-101.

4. McIntosh, J. D., "The Effect of Low-Temperature Curing on the Compressive Strength of Concrete," Proceedings, RILEM Symposium on Winter Concreting (Copenhagen, 1956), Danish National Institute for Building Research, Copenhagen, 1956, 17 pp.

5. Klieger, Paul, "Effect of Mixing and Curing Temperature on Concrete Strength," ACI Journal, Proceedings, V. 54, No. 12, June 1958, pp. 1063-1081.

6. Ramakrishnan, V., and Dietz, J., "Accelerated Methods of Estimating the Strength of Concrete." Transportation Research Record, No. 558, 1975, pp. 29-44.

7. Plowman, J. M., "Maturity and Strength of Concrete," Magazine of Concrete Research, Vol. 8, No. 22, March 1956, pp. 13-32.

8. Naik, T.R., "Concrete Strength Prediction by the Maturity Method," ASCE Journal of Engineering Mechanics Division, EM3, June 1980.

9. "Standard Method for Developing Early Age Compression Test Values and Projecting Later Age Strengths," (ASTM C918-80), 1985 Annual Book of ASTM Standards, Section 4, Volume 04.02, ASTM, Philadelphia, pp. 586-591.

10. ACI Committee 306, "Cold Weather Concreting," (ACI 306R-78), American Concrete Institute, Detroit, 1978, pp. 16-20.

11. Malhotra, V. M., Testing Hardened Concrete: Non-Destructive Methods, ACI Monograph No. 9, Iowa State University Press, 1976.

12. Richards, O., "Pullout Strength of Concrete," Reproducibility and Accuracy of Mechanical Tests, STP-626, ASTM, 1979, pp. 32-40.

13. "Standard Test Method for Pullout Strength of Hardened Concrete," 1984 Annual Book of ASTM Standards, Section 4, Volume 04.02, ASTM, Philadelphia, pp. 582-585.

14. Bickley, J. A., "The Variability of Pullout Tests and In-Place Concrete Strength," Concrete International, Vol. 4, No. 4, April 1982, pp. 44-51.

15. Vogt, W. L., Beizai, V., and Dilly, R. L., "In Situ Pullout Strength of Concrete with Inserts Embedded by "Finger Placing," In Situ/Nondestructive Testing of Concrete, ACI Publication SP-82, American Concrete Institute, Detroit, 1984, pp. 161-175.

16. ACI Committee 214, "Recommended Practice for Evaluation of Strength Test Results of Concrete," (ACI 214-77), ACI Manual of Concrete Practice 1983, Part 1, American Concrete Institute, Detroit.

17. Parsons, T. J., and Naik, T. R., "Early Age Concrete Strength Determination by Pullout Testing and Maturity," In Situ/Nondestructive Testing of Concrete, ACI Publication SP-82, American Concrete Institute, Detroit, 1984, pp. 177-199.

18. Dilly, R. L., and Ledbetter, W. B., "Concrete Strength Based on Maturity and Pullout," Journal of Structural Engineering, ASCE, Vol. 110, No. 2, February 1984, pp. 354-369.

19. Hawkins, Clark A. and Jean E. Weber, Statistical Analysis: Applications to Business and Economics. New York: Harper & Row, 1980, pp. 234-239, 250-252.

20. Summers, George W., Peters, William S., and Charles P. Armstrong, Basic Statistics in Business and Economics, California: Wadsworth Publishing, 1981, pp. 281-318.

21. Kleinbaum, David G. and Lawrence L. Kupper, Applied Regression Analysis and Other Multivariable Methods, Massachusetts: Duxbury Press, 1980, pp. 95-106.

22. Dilly, R. L., "The Use of the Maturity Concept in Evaluating Development of Concrete Pullout Strength," Thesis for a Master of Science in Civil Engineering, Texas A & M University.

TABLE 1--SINGLE VARIABLE ANALYSES (TESTS CONCERNING MEANS)

Function	Standard symbol	Display symbol	Expression
Average of X values	$\bar{X}$	XM*	$\frac{\Sigma X}{n}$
Standard deviation of X values	S_x	SDM*	$\sqrt{\frac{\Sigma X^2 - \frac{(\Sigma X)^2}{n}}{n-1}}$
Coefficient of variation	V	VM*,%	$\frac{S_x}{\bar{X}} \times 100$
Sample size	n	NM*	-
F test to determine the equality of variances	F	F	$\frac{S_x^2 \text{ largest}}{S_x^2 \text{ smallest}}$
Tabulated F values	$F_{m1,m2,r.t.}$**	FT	Obtain from F Distribution tables
If F < FT***			
Student t Distribution	t	T	$\frac{\lvert\bar{X1}-\bar{X2}\rvert}{\sqrt{\frac{(n1-1)S_{x1}^2+(n2-1)S_{x2}^2}{n1+n2-2} \times (\frac{1}{n1}+\frac{1}{n2})}}$
Degrees of freedom	d.f.	D.F.	n1+n2-2
If F > FT***			
Student t Distribution	t	T	$\frac{\lvert\bar{X1}-\bar{X2}\rvert}{\sqrt{\frac{S_{x1}^2}{n1}+\frac{S_{x2}^2}{n2}}}$
Degrees of freedom (approximate)	$d.f._{approx.}$	D.F.APRX	$\frac{\left[(\frac{S_{x1}^2}{n1})+(\frac{S_{x2}^2}{n2})\right]^2}{(\frac{S_{x1}^2}{n1})^2(\frac{1}{n1-1})+(\frac{S_{x2}^2}{n2})^2(\frac{1}{n2-1})} - 2$

* M reflects the set number

** m1 is the degrees of freedom for the numerator, (n_n-1)

m2 is the degrees of freedom for the denominator, (n_d-1)

r.t. is the right tail of the distribution

***See text for details