Coarse-Aggregate Effect on Mechanical Properties of Plain Concrete

M. REZA SALAMI, GARY SPRING, AND SHILONG ZHAO

The influence of three coarse-aggregate types on the relationships between compressive and tensile (split tensile and modulus of rupture) strengths of a plain concrete was investigated. It was found that, in some cases, aggregate type has significant effects on these strength relationships. The mineralogical differences in the aggregate types are considered to be responsible for this behavior. The commonly accepted 0.5 power relationship between compressive strength and tensile strength was found to be applicable neither for all aggregate types nor at different ages. From the available experimental data for modulus of rupture and splitting tensile strengths of concrete, alternative relationships between the tensile and compressive strengths were calibrated and are presented. Finally, a previous study of the effect of three coarse aggregates on the coefficient of linear thermal expansion and water-cement ratio was discussed and enhanced using graphic representations of the relationships. The correlation between the experimental results and analytical predictions provides a simple approach for developing tensile strength models for plain concrete using three types of aggregate. Tables of results and figures supporting these observations and conclusions are included.

It is generally assumed that concrete performance is governed mostly by its compression capabilities, but tensile strength (which directly influences cracking at prestress release) and shear capacity are important with respect to the appearance and durability of concrete structural members. It has been accepted by concrete researchers and the American Concrete Institute (ACI) that a 0.5 power relationship exists between the tensile strength and the compressive strength of concrete. Investigations have been conducted into the applicability of this 0.5 power relationship to medium-strength concrete (*1*). Several relations have been proposed for the tensile strength prediction from the compressive strength, but the effect of aggregate type on the prediction has not previously been clearly established. Chapter 18 of the ACI Building Code (ACI 318-83) represents the relationship between concrete tensile strength f_t and compressive strength by the relation

$$f_t = 6[f_c']^{0.5} \tag{1}$$

Ahmad and Shah reported that tensile strength of concrete with compressive strength between 6 and 12 ksi does not conform to the conventional ACI formulation (*1*). Therefore, they proposed an alternative relation for concrete compressive strength up to 12 ksi as

$$f_t = 4.34[f_c']^{0.55} \tag{2}$$

Department of Civil Engineering, North Carolina A&T State University, Greensboro, N.C. 27411.

ACI Committee 363 proposed another relation in the form of

$$f_t = 7.4[f_c']^{0.5} \tag{3}$$

as an upper bound (*2*).

Gardner and Poon suggested that splitting tensile strength is not necessarily proportional to the 0.5 power of compressive strength (*3*). They found that the tensile strength is proportional to the 0.8 power of the cylinder strength. A thorough review of literature related to this subject is presented by Oluokun (*4*).

As stated, none of the several relationships proposed for predicting tensile strength from compressive strength has clearly established the effect of aggregate type on their predictions. The conventional wisdom has been that for conventional concrete (less than 5.81 ksi), the properties of coarse aggregate seldom become strength-limiting because conventional concrete mixtures typically correspond to water-cement ratios (w/c's) of 0.4 to 0.7. Within this w/c range, the weakest components in concrete are the hardened cement paste and the transition zone between cement paste and coarse aggregate, rather than the coarse aggregate itself (*5*). Similarly, in designing conventional concrete mixtures, the mineralogy of coarse aggregate is rarely a matter of concern unless the aggregate contains some constituents that could have a deleterious effect on durability. For example, the presence of a reactive silica mineral such as opal in an aggregate can be harmful to concrete when the aggregate is used in combination with a portland cement containing more than 0.6 percent alkalies (Na_2O equivalent).

Given the lack of information in the published literature on the influence of coarse-aggregate characteristics, especially mineralogy, on the mechanical behavior of medium-strength concrete mixtures, the objectives of this paper are as follows:

- To investigate the effects of three coarse aggregates on the relationships between the compressive strength and the splitting tensile strength and moduli of rupture of a medium-strength concrete mixture;
- To calibrate a set of prediction models for the splitting tensile strength and moduli of rupture of concrete, as a function of its cylindrical compressive strength, f_c'; and
- To enhance discussions by Alungbe et al. (*6*) about the effects on linear thermal expansion of concrete due to aggregate type, curing time, saturation condition, and water-cement ratio.

PRESENTATION AND DISCUSSION OF TEST RESULTS

Test data reported by Alungbe et al. (*6*) were used to study the following tensile strength (a property that affects both resistance to cracking at prestress release and shear capacity) relationships as they pertain to aggregate type, and to derive associated prediction models. The test results and predicted models are shown in figures and tables as indicated:

1. Normalized tensile strength of concrete versus compressive strength: Equation 4 (Figures 1 and 2; Table 1), and
2. Normalized modulus of rupture versus compressive strength: Equation 5 (Figures 3 and 4; Table 2).

It should be noted that Equations 4 and 5 were normalized primarily to provide unitless constants. This normalization has no effect on the power values of the models (e.g., 0.5 in the ACI relationship).

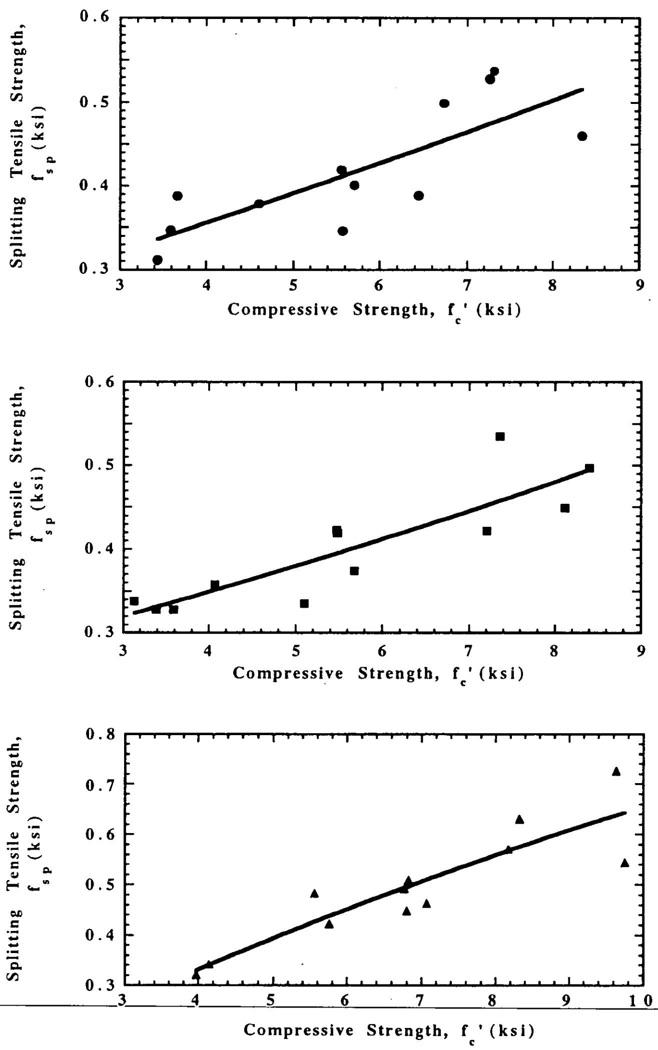

FIGURE 1 Plots of splitting tensile strength versus compressive strength for PL (*top*), RG (*middle*), and DL (*bottom*), Ruplicates 1 and 2 at 28 and 90 days.

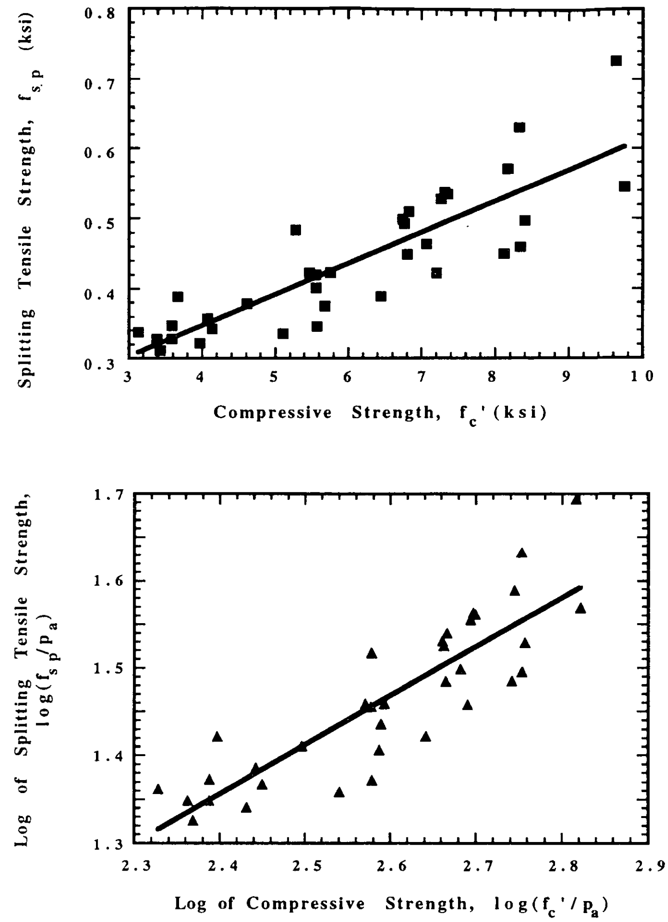

FIGURE 2 Plots of splitting tensile strength versus compressive strength (*top*) and log of splitting tensile strength versus log of compressive strength (*bottom*), for all data.

TABLE 1 Values of Parameters α_{sp} and β_{sp} from Proposed Expression of Splitting Tensile Strength for Three Types of Concrete Material

		28 days	90 days	28 & 90 days
Porous Limestone	R^2	0.56	0.63	0.59
	Mean α	0.535	0.401	0.462
	α 95% CI	0.23 to 0.85	0.20 to 0.60	0.30 to 0.63
	Mean β	1.1846	2.592	1.812
River Gravel	R^2	0.62	0.87	0.82
	Mean α	0.435	0.42	0.523
	α 95% CI	0.21 to 0.66	0.31 to 0.53	0.42 to 0.63
	Mean β	2.1	2.246	2.33
Dense Limestone	R^2	0.82	0.81	0.81
	Mean α	0.751	0.715	0.719
	α 95% CI	0.52 to 0.98	0.49 to 0.95	0.57 to 0.87
	Mean β	0.342	0.408	0.407
Combination of all three	R^2	0.7	0.75	0.72
	Mean α	0.586	0.547	0.56
	α 95% CI	0.46 to 0.72	0.44 to 0.65	0.48 to 0.64
	Mean β	0.157	0.162	0.161

For each of three aggregate types—namely, porous limestone (PL), river gravel (RG), and dense limestone (DL)—a set of tensile and compressive tests was conducted at three different w/c's at 28 and 90 days. In the original tests, as described by Alungbe et al. (*6*), two replicates of three speci-

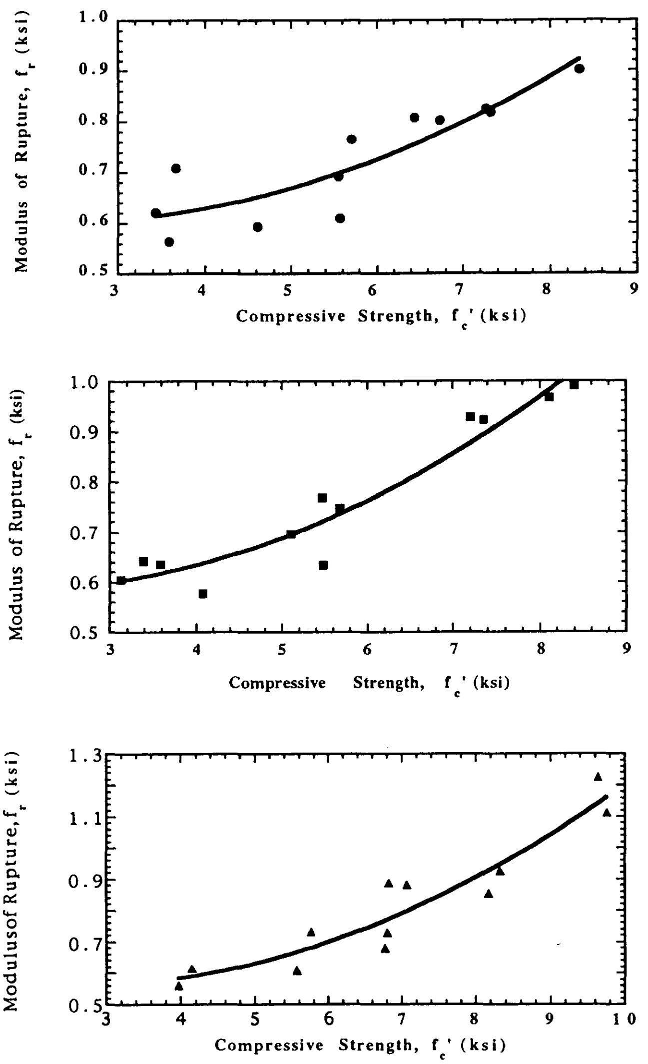

FIGURE 3 Plots of modulus of rupture versus compressive strength for PL (*top*), RG (*middle*), and DL (*bottom*), Ruplicates 1 and 2 at 28 and 90 days.

mens each for each material were conducted. Among the sets of three specimens, one consistently appeared to be an outlier. Thus, the best two specimens from each replicate were used in this study to derive the relationships presented in Tables 1 and 2. The raw data shown in Figures 1 and 3 for each aggregate, along with previous studies [e.g., Salami (*7–9*)], suggest the use of a logarithmic formulation as shown in Figures 2 and 4.

Splitting Tensile Strength

Equation 4 was used as the functional form for the model and was calibrated using simple linear regression for three types of concrete using different coarse aggregates and for different curing times. Regression results are presented in Table 1:

$$f_{sp} = -\beta_{sp} p_a \left\{ \frac{f_c'}{p_a} \right\}^{\alpha_{sp}} \tag{4}$$

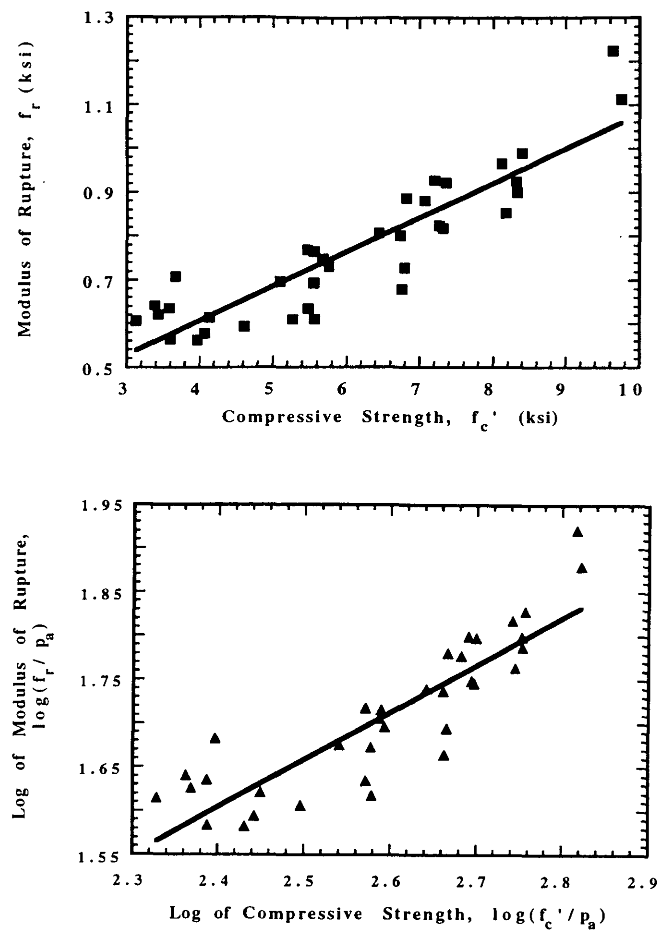

FIGURE 4 Plots of modulus of rupture versus compressive strength (*top*) and log of modulus of rupture versus log of compressive strength (*bottom*), for all data.

TABLE 2 Values of Parameters α_{sp} and β_{sp} from Proposed Expression of Moduli of Rupture for Three Types of Concrete Material

		28 days	90 days	28 & 90 days
Porous Limestone	R^2	0.37	0.95	0.66
	Mean α	0.271	0.602	0.422
	α 95% CI	0.05 to 0.49	0.51 to 0.70	0.29 to 0.55
	Mean β	10.03	1.351	4.01
River Gravel	R^2	0.71	0.92	0.73
	Mean α	0.455	0.603	0.423
	α 95% CI	0.26 to 0.65	0.49 to 0.72	0.30 to 0.63
	Mean β	3.488	1.452	2.24
Dense Limestone	R^2	0.85	0.96	0.82
	Mean α	0.644	0.778	0.76
	α 95% CI	0.46 to 0.81	0.67 to 0.88	0.61 to 0.91
	Mean β	0.975	0.503	0.521
Combination of all three	R^2	0.56	0.91	0.75
	Mean α	0.388	0.676	0.54
	α 95% CI	0.27 to 0.50	0.60 to 0.75	0.47 to 0.62
	Mean β	0.372	0.233	0.291

where β_{sp} and α_{sp} are the model parameters and p_a is atmospheric pressure in the same units as those of f_{sp} and f_c'.

The model, in all cases, demonstrates good statistics: α is statistically significant from zero at very high levels (i.e., *t*-values ranging from 5 to 100), and adjusted R^2- and *F*-values

are generally very high. For the PL, RG, and combined materials, α is not significantly different, at the 95 percent level of confidence, from the ACI suggested value of 0.5, although β-values are quite different: none turns out to be anywhere near previously reported values of greater than 4. The DL material, however, exhibits α-values in line with those proposed by Gardner and Poon (*3*). It is interesting to note that time does not appear to affect the relationship or its parameter estimates, except with respect to the confidence that one may reasonably place in the models. In general, the strength of the model's statistics increases with time. Adjusted R^2-, F-, and t-values all increase dramatically from 28- to 90-day data.

Beam Flexural Tensile Strength, f_r

Equation 5 was used as the functional form for the model and was also calibrated using simple linear regression for three types of concrete using different coarse aggregates and for different curing times. Regression results are presented in Table 2:

$$f_r = -\beta_r p_a \left\{ \frac{f_c'}{p_a} \right\}^{\alpha_r} \tag{5}$$

Again, the model, in all cases, exhibits good statistics: α is statistically significant from zero at very high levels (t-values from 5 to 100), and adjusted R^2- and F-values are generally very high. For models calibrated using 28-day data, aggregate type does not affect α-values: none is significantly different from the ACI 0.5 value. At 90 days, however, all values are significantly greater than 0.5. Additionally, as with the split tensile strength models, the 90-day model statistics are stronger. Adjusted R^2-values increase to greater than 0.9, and t- and F-statistics again increase dramatically. There is, however, no apparent effect on the parameter values due to aggregate type. All α-value ranges have substantial overlap, indicating little (if any) effects of aggregate type on modulus of rupture predictions.

Coefficient of Thermal Expansion

Alungbe et al. performed a factor analysis using analysis of variance techniques on the effects of w/c, aggregate type, curing time, and saturation condition on linear thermal expansion. Figure 5 supports their conclusions about influence of aggregate type and saturation condition on thermal expansion. However, the figures also indicate that data are insufficient to make meaningful quantitative conclusions regarding the influence of w/c on the expansion variable. For each aggregate type there are only three data points (corresponding to the three w/c values). Although variation may be measured among three data points, statistical inferences appear dubious. It appears that more experimental work should be done in this regard.

CONCLUSIONS

This paper, using sets of uniaxial compressive and tensile tests performed on plain concrete for three aggregate types, examines the effects of aggregate type on the strength behavior of plain concrete. The results of these tests were used to calibrate a tensile strength prediction model of plain concrete on the basis of uniaxial compressive loading. Model parameters are presented in Tables 1 and 2. The following conclusions can be made from those results:

1. The relationships between splitting tensile strength and compressive strength of medium-strength concrete were shown to be influenced by choice of aggregate.
2. The splitting tensile strength of the DL aggregate concrete material and the moduli of rupture for all three aggregate types at 90 days were found not to be proportional to the 0.5 power of the compressive strength.
3. Tensile strength prediction relations (Equations 4 and 5) different from—and, given the results of this study, more accurate than—the ACI relation were formulated.

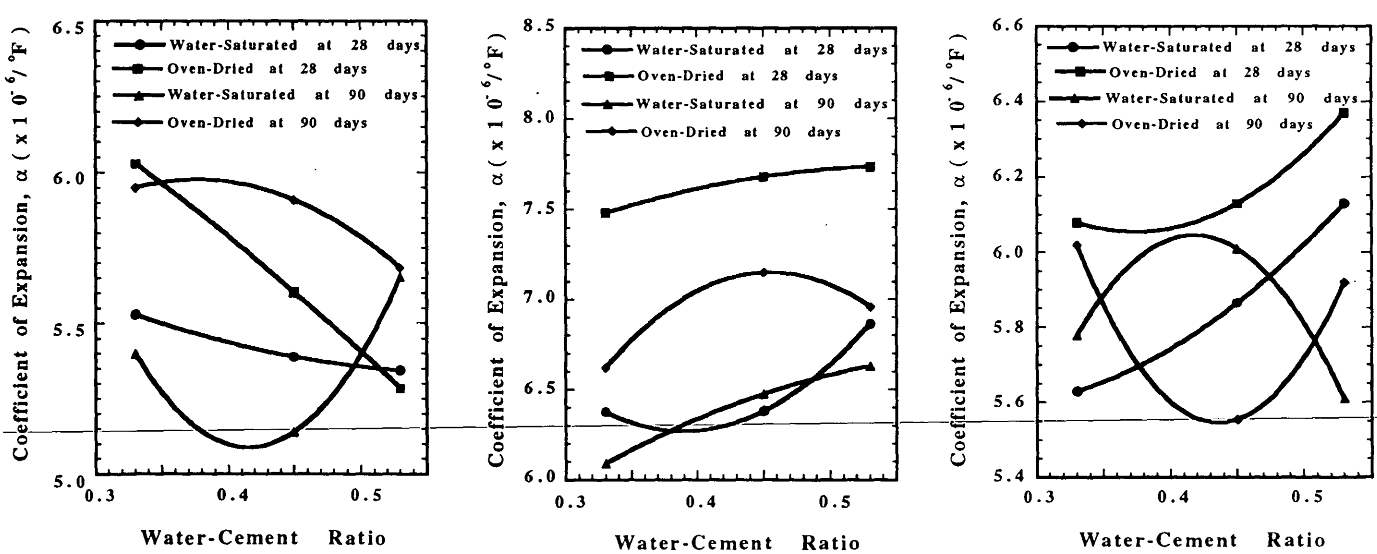

FIGURE 5 Plots of w/c versus coefficient of expansion for PL (*left*), RG (*middle*), and DL (*right*).

ACKNOWLEDGMENTS

The authors appreciate the support of the Department of Civil Engineering at the North Carolina A&T State University. This work was partially supported by a grant from the North Carolina Board of Science and Technology.

REFERENCES

1. S. H. Ahmad and S. P. Shah. Structural Properties of High Strength Concrete and Its Implications for Precast Prestressed Concrete. *PCI Journal*, Vol. 30, No. 6, Nov.–Dec. 1985, pp. 92–119.
2. ACI Committee 363. State-of-the-Art Report on High Strength Concrete. *ACI Journal*, Vol. 81, No. 4, July–Aug. 1984, pp. 364–411.
3. N. J. Gardner and S. M. Poon. Time and Temeprature Effects on Tensile, Bond, and Compressive Strengths. *ACI Journal*, Vol. 73, No. 7, July 1976, pp. 405–409.
4. F. A. Oluokun. *Investigation of Physical Properties of Concrete at Early Ages*. Ph.D. dissertation. University of Tennessee, Knoxville, May 1989, pp. 16–59.
5. P. K. Metha. *Concrete: Structure, Properties, and Materials*. Prentice-Hall, Inc., Englewood Cliffs, N.J., 1986, pp. 36–40.
6. G. D. Alungbe, T. Mang, and D. G. Bloomquist. The Effects of Aggregate, Water-Cement Ratio, and Curing on the Coefficient of Linear Thermal Expansion of Concrete. In *Transportation Research Record 1335*, TRB, National Research Council, Washington, D.C., Jan. 1992.
7. M. R. Salami. Analytical Expressions for Uniaxial Tensile Strength of Concrete in Terms of Uniaxial Compression Strength. In *Transportation Research Record 1335*, TRB, National Research Council, Washington, D.C., Jan. 1992.
8. M. R. Salami. *Constitutive Modelling of Concrete and Rocks Under Multiaxial Compressive Loading*. Ph.D. dissertation. Department of Civil Engineering and Engineering Mechanics, University of Arizona, Tucson, June 1986.
9. M. R. Salami and C. S. Desai. A Constitutive Model for Plain Concrete. *Proc., 2nd International Conference on Constitutive Laws for Engineering Materials: Theory and Application*. Tucson, Ariz., Vol. I, Jan. 1987, pp. 447–455.

APPENDIX A

Notation

The following symbols are used in this paper:

f_t = direct tensile strength
f_c' = uniaxial cylindrical compressive strength
f_{sp}', f_r = beam flexural and split cylinder tensile strengths
α_r, β_r = dimensionless constants for moduli of rupture
α_{sp}, β_{sp} = dimensionless constants splitting tensile strength
$\alpha_{o\text{-}d}$, $\alpha_{w\text{-}s}$ = coefficient of linear expansions (oven-dry) and (water-saturated)
p_a = atmospheric pressure
R^2 = proportion of variation explained by the model
Adj R^2 = R^2 reduced as penalty for adding a variable
t = number of standard deviations the coefficient lies from a value of zero
F = measure of overall explanatory power of the model

Publication of this paper sponsored by Committee on Mechanical Properties of Concrete