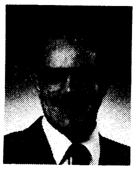
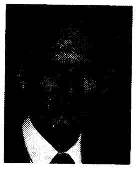
Title no. 91-M21

Effect of Moisture Condition on Concrete Core Strengths

by F. Michael Bartlett and James G. MacGregor

In accordance with the provisions of ASTM C 42-90 and ACI 318-89, it is current practice to either dry concrete core specimens in air for 7 days or soak them in lime-saturated water for at least 40 hr before they are tested. In this paper, the effect of moisture condition on the strengths of mature cores obtained from well-cured elements is investigated by reviewing available literature and performing regression analyses of data from tests of 727 core specimens.

It is shown that the compressive strength of a concrete specimen is influenced both by moisture content changes that are uniform throughout the specimen volume and moisture content gradients between the surface of the specimen and interior. The air-drying and soaking periods specified in ASTM C 42-90 and ACI 318-89 are too short to cause a uniform change of moisture content throughout the volume of the core. The effect of these treatments is to create a moisture gradient that artificially biases the test result.

The strength of air-dried cores is on average 14 percent larger than the strength of soaked cores. The strength of cores with a negligible moisture gradient is on average 9 percent larger than the strength of soaked cores. These general average values are constant for concretes with strengths ranging from 2200 to 13,400 psi. However, the strength ratios for any particular mix may differ appreciably from these general average values.

Keywords: compressive strength; concrete cores; curing; drying; evaluation; high-strength concrete; **moisture content**; tests; wetting.

The practice of soaking concrete cores in water for at least 40 hr before testing has evolved from the 1927 version of ASTM C 42, "Standard Methods of Securing Specimens of Hardened Concrete from the Structure.[1]"

"In order that the tests be made under uniform conditions as to moisture content, the test specimens shall be completely submerged in water for 48 hours and the compression test shall be made immediately thereafter."

Studies by Bloem[2] and Meininger, Wagner, and Hall[3] indicate that cores tested after air-drying are consistently 10 to 20 percent stronger than cores tested after soaking in water. Based on these studies, the provisions of ACI 318-89[4] require cores to be immersed in water for at least 40 hr before testing if the concrete in the structure will be more than superficially wet. Otherwise, the cores shall be dried in air at 60 to 80 F and relative humidity less than 60 percent for 7 days before testing. These provisions have also been adopted in ASTM C 42-90.[5]

Similarly, a report on concrete core testing by the Concrete Society[6] recommends that cores be capped and then soaked for at least 2 days before testing. If the concrete in the structure is wet, the equivalent actual cube strength is taken to be 1.5 times the crushing strength of a core with length-to-diameter ratio equal to 1. If the concrete in the structure is dry, the equivalent actual cube strength is taken to be 1.65 times the core crushing strength.

Both ACI 318-89 and the Concrete Society provisions therefore allow the evaluator of an existing structure to take account of the beneficial effect of dry in-service moisture conditions on the apparent concrete strength. This is a departure from conventional design practice, since any effect of the in situ moisture condition on the concrete strength is neglected when proportioning the structure. Moreover, it is tacitly assumed in both publications that the in situ moisture conditions can be accurately reproduced by conditioning the specimen in air or water for relatively short periods of time.

RESEARCH SIGNIFICANCE

The main objectives of the present study are to determine the magnitude of the differences between the strengths of soaked and air-dried concrete cores, and to identify reasons for these differences. It is shown that both of these moisture conditioning treatments, which are recommended in ACI 318 and ASTM C 42, cause moisture gradients across the cross section of the test specimen that appreciably affect its strength. To avoid these artificial factors affecting the test outcome, testing of cores in their as-drilled condition is investigated.

LITERATURE SURVEY

The strength loss caused by soaking concrete compression test specimens in water has been attributed to the absorption of water by the gel pores. Soaking the specimens in benzine or paraffin, which are not absorbed by the cement

ACI Materials Journal, V. 91, No. 3 May-June, 1993.
Received Jan. 27, 1993, and reviewed under Institute publication policies. Pertinent discussion will be published in the March-April 1994 *ACI Materials Journal* if received by Dec. 1, 1994.

*ACI member **F. Michael Bartlett** is a PhD candidate at the University of Alberta, Edmonton, Alberta, Canada. After receiving a BSc degree from Queen's University at Kingston, Ontario, and an MASc degree from the University of Waterloo, Ontario, he worked for 7 years with Buckland and Taylor Ltd., a structural engineering consultant firm in Vancouver, British Columbia.*

***James G. MacGregor,** FACI, is University Professor of Civil Engineering at the University of Alberta. He is a member of ACI Committee 318, Standard Building Code; and joint ACI-ASCE Committees 441, Reinforced Concrete Columns; and 445, Shear and Torsion. He was installed as the 69th President of ACI at the 1992 spring meeting.*

gel, has no effect on strength.[7] The same phenomenon is likely responsible for the strength gain that occurs after leaving specimens to dry in air. However, in either case, it is useful to distinguish between uniform and nonuniform moisture changes throughout the volume of the specimen, and their respective influences on the specimen strength.

Effect of uniform moisture change on strength

Water absorbed into the gel pores is believed to cause distension within the test specimen.[7-9] As the applied load increases, a hydrostatic excess pressure develops, since the absorbed water is prevented from being squeezed out of the specimen. This pressure must be resisted by the solid matrix along the sides of the specimen, thus causing a transverse bursting effect. Distension is eliminated by drying the specimen.

Bessey and Dilnot[10] state that, according to the distension hypothesis, the moisture effect for autoclaved specimens should be much less than that for specimens steam-cured at atmospheric pressure. Their experimental data indicate that the relative strength of soaked autoclaved specimens is only slightly less than that of their other specimens. They therefore conclude that the strength loss due to soaking should not be entirely attributed to distension.

It has been suggested by Feldman and Sereda[11] that the presence of adsorbed water on the gel particles provides an environment where the Si-O bonds break more readily to form Si-OH HO-Si bonds. When the concentration of water molecules is sufficient to maintain the delivery of moisture to a spreading crack, no further decrease in strength will occur. This is disputed by Glucklich and Korin,[12] who question whether enough water can be continually present at the crack tip to maintain the necessary aggressive environment.

A third explanation[9,12] is based on the Griffiths fracture theory. When water is absorbed into the gel, forcing the gel surfaces further apart, Van der Walls forces between gel particles are reduced. These adhesive forces are proportional to the specific surface energy; the critical stress for a given crack size is therefore reduced when the intermolecular distances are increased. Calculations following this approach have reproduced trends observed experimentally.[9,12]

Data pertaining to the relationship between compressive strength and moisture content have been reported to substantiate the various hypotheses. Observations by Bessey and Dilnot,[10] who tested 3-in. cubes of an aerated cement-sand mortar, are shown in Fig. 1. The strength is constant for high moisture contents and becomes increasingly larger for lower moisture contents, which agrees with Feldman and Sereda's[11] stress corrosion cracking explanation. A similar form of the relationship between compressive strength and moisture content for very small paste and mortar specimens has been reported by others.[9,11-13] In all cases, it may reasonably be assumed that the variation of the moisture content throughout the specimen volume is negligible, given the small sizes of specimens tested or the long period of moisture conditioning applied.

Effect of nonuniform moisture changes on strength

Recently, de Larrard and Bostvironnois[14] have investigated the effect of air-drying 6.3-in.-diameter molded cylinder specimens by measuring the variation of moisture content across the cross section using gammadensimetry. In Fig. 2, their data from specimens made of an ordinary portland cement concrete with a strength of roughly 6000 psi are reproduced. The figure shows the moisture change from the condition at demolding for a cross section through the axis of the cylinder. After a 27-day-long drying period, only the material within about 1 in. of the surface is affected, while, after 4 years, the moisture loss is relatively constant over the full cross section. The two 90-day-old specimens have similar moisture losses at their centers, but the specimen demolded at 1 day has lost considerably more moisture than the specimen molded at 28 days. If the specimens were left in air for only 7 days, according to the provisions of ASTM C 42-90,[5] the moisture gradients between the surface and center of the specimen would be even more severe than those shown in Fig. 2.

Similarly, rough calculations based on concrete permeability constants reported by Neville[7] indicate that, after 2 days of soaking, water is unlikely to penetrate more than perhaps $\frac{1}{8}$ in. from the surface of the core. For a 4-in.-diameter core, the smallest permitted by ASTM C 42-90, the annular region affected is only about 12 percent of the overall area of the cross section.

Therefore, the length of the moisture conditioning periods specified for cores in ASTM C 42-90 or ACI 318-89 are too short to allow a uniform change of moisture to occur throughout the entire volume of the specimen. It is interesting to note that, while the original rationale for soaking cores was to achieve "uniform conditions as to moisture content,"[1] the effect of the recommended short soaking period is to cause a moisture gradient between the surface and interior of the core that is hardly uniform.

The effect of a moisture gradient on the specimen has been considered by Popovics.[8] Soaking causes swelling at the surface of the core where the moisture content is increased. Air-drying causes the surface layer to shrink. These volume changes are restrained by the material at the center of the core, which does not gain or lose moisture. The restraint creates a set of residual strains and corresponding self-equilibriated residual stresses.

The unrestrained swelling of the top and bottom ends of a soaked core is shown in Fig. 3(a). Restraint of the swelling causes small compressive stresses in the soaked area and slight tensile stresses in the adjacent unsoaked region. These stresses are unlikely to significantly reduce the failure load, because this region is confined by the loading platen and so

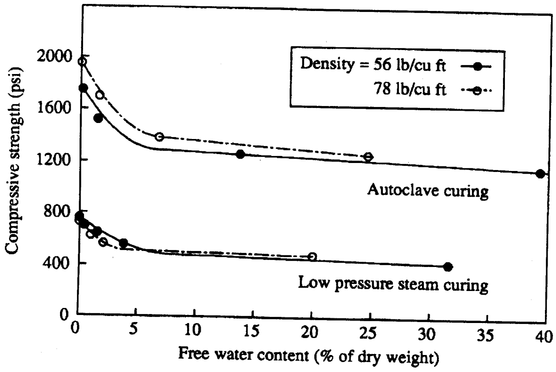


Fig. 1—Strength versus moisture content for aerated mortars[10]

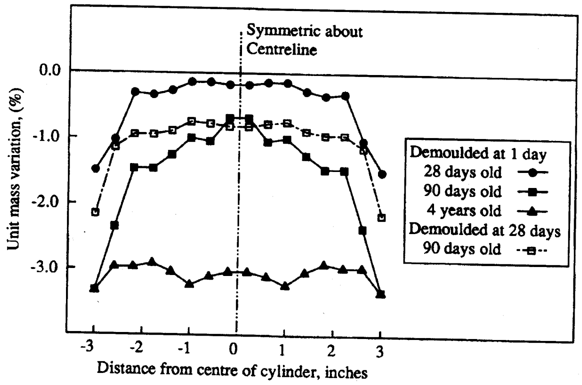


Fig. 2—Unit mass variation across width of air-dried cylinders[14]

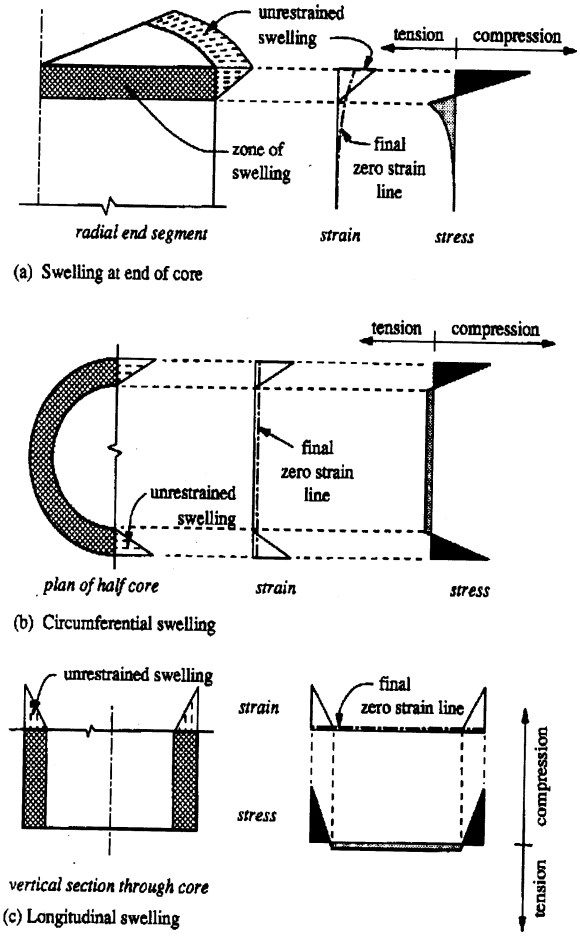


Fig. 3—Swelling due to soaking and associated residual stresses

the failure is initiated elsewhere (see Reference 15, for example).

The swelling of the surface layer in a circumferential direction is shown in Fig. 3(b). Restraint of this swelling causes compression stresses in the soaked outer region and slight tension stresses throughout the unsoaked inner region. The confinement of the inner region by the outer region is slightly reduced, which causes a very slight reduction of the capacity of the inner region.

The swelling of the surface layer in a direction parallel to the axis of the core is shown in Fig. 3(c). Restraint of this swelling causes compression stresses in the soaked surface layer and small tension stresses in the unsoaked central region. The stresses in the skin are largest at the core surface and decrease rapidly.

If the core is air-dried, the surface layer shrinks and the sense of the deformations and residual stresses are reversed from the soaked condition shown in Fig. 3. Circumferential surface shrinkage may cause cracks or microcracks parallel to the axis of the core, which would relieve the residual stresses. Surface shrinkage parallel to the axis of the core has been identified by Raphael[16] as the reason for direct tension tests of air-dried cores giving lower strengths than splitting tests.

Therefore, the effect of conventional core moisture conditioning treatments on the moisture content of the interior of the core is negligible. The capacity of the inner region may be slightly changed by residual circumferential strains in the surface layer. Residual longitudinal strains in the surface layer cause residual longitudinal stresses in the inner region. These two effects counteract each other, whether the core has been dried in air or soaked in water.

Conversely, the moisture content and residual stresses near the surface of the core are greatly affected by brief soaking or air- drying treatments. Soaking reduces the strength of the concrete and causes swelling, which in turn causes residual compressive stresses in this region. Given the relatively small area affected by soaking, it is likely that these two factors in combination are responsible for significant overall strength loss. These factors also combine to increase the surface layer strength, and overall strength, of cores dried in air.

De Larrard and Bostvironnois[14] observed a significant loss of strength for very high-strength silica fume concrete specimens left in air for extended time periods. In contrast to the behavior described previously, they attribute the strength loss to the moisture gradients caused by drying. In their silica fume concrete specimens, the moisture losses after 4 years of air-drying produced moisture gradients more severe than that shown in Fig. 2 for the 90-day-old specimens demolded at 1 day. However, the moisture losses extend much further

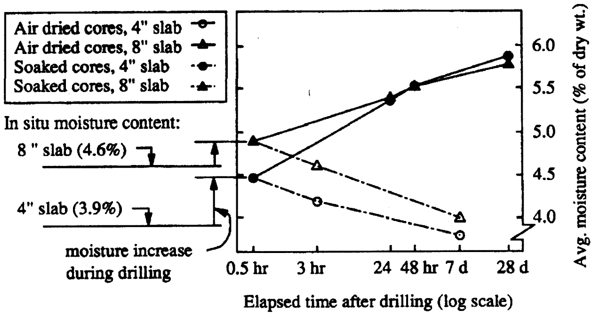


Fig. 4—Average moisture content change for core moisture treatments

into the specimen than might be expected for cores after a 7-day drying period. The corresponding residual tension stresses at the surface of the silica fume concrete specimens dried for 4 years would therefore be smaller than those for cores dried for 7 days, and the internal residual compressive stresses would be comparatively large. The capacity of the interior region to resist applied compression loads may therefore be reduced to a much greater extent. It is also possible that, since de Larrard and Bostvironnois apparently do not consider the consequences of circumferential shrinkage in their analysis, their conclusion may be flawed.

ANALYSIS OF BLOEM'S DATA[2]

As part of the research for this study,[2] changes to the average moisture content of cores were monitored from the initial in situ condition to the final test condition. The variation of core strength with core moisture content can be examined by analyzing these data. Mimeographed tabulations showing results for individual specimens were retrieved from the files of the National Aggregate Association/National Ready Mixed Concrete Association and made available for use in the present study by Meininger.

The original investigation considered the effects of excellent and average curing on the strength of normal and lightweight concrete slabs and columns. The present investigation considers only the data for two well-cured, normal weight concrete slabs. One 4-in.-thick slab, one 8-in. slab, and a number of 6 x 12-in. cylinders were poured from one batch of ready-mixed concrete. The concrete had a standard cylinder strength of 5130 psi, an air content less than 2 percent, and a maximum aggregate size of about 1 in. The slabs were left in the forms, and a curing membrane was sprayed on the top surface promptly after pouring. Next, they were covered with damp burlap and polyethylene for 7 days, and left in the laboratory for 7 weeks with only the top surface exposed. At the age of 91 days, 4-in.-diameter cores were drilled vertically through the slab thickness using a water-cooled diamond bit. Half of the cores from the 8-in. slab were sawn into two 4-in.-long test specimens. Four categories of cores resulted: 8-in. cores, 4-in. cores from the top of the 8-in. slab, 4-in. cores from the bottom of the 8-in. slab, and 4-in. cores from the 4-in. slab. Twelve core specimens were obtained for each category.

Each set of twelve cores received four different treatments before testing. Three cores were tested 2 to 3 hr after drilling, three were tested after being soaked for 48 hr, three were tested after drying in laboratory air for 7 days, and three were tested after 28 days of soaking. All cores were capped with a sulfur capping compound before testing.

The mimeographed tabulations reveal that the original investigators kept a running record of the moisture content of each core between the time of drilling and that of testing. Each core was weighed immediately after drilling, immediately before and after capping, and immediately before and after testing. Core damage during testing was limited by stopping the test after the load had dropped off 5 to 10 percent. The sulfur caps were carefully removed to permit oven-drying of each core at 225 to 230 F to constant weight. Average moisture contents at various stages of treatment were calculated, expressed as percentages of the weight of the core after oven-drying.

Effect of treatment on average moisture content

The average changes of the average moisture content due to different durations of soaking and air-drying treatments are shown in Fig. 4. Two curves are shown, since the initial moisture conditions were different for the 4- and 8-in. slabs. The thinner slab had a larger ratio of surface area to volume, and therefore dried out more during the 7-week-long period of storage. The initial in situ moisture content values shown are the averages of two pushout cylinders from each slab. These cylinders were cast in metal sleeves in the slab and received curing identical to the surrounding cored concrete.

The average core moisture content immediately after coring is larger than the in situ moisture content due to absorption of cooling water by the concrete during the drilling process. The change of moisture content due to soaking or air-drying treatments is initially very rapid. Almost two-thirds of the total moisture gain after 28 days of soaking occurred within the first 24 hr. Similarly, about a quarter of the total moisture loss after 7 days of air-drying took place in the first 3 hr.

Effect of moisture gain on strength

The 48 core strength observations consist of three replicate values in each of 16 categories. Each group of three replicate strength observations was checked for outliers, using the procedures of ASTM E 178.[17] No outliers were identified, although the ASTM E 178 procedures are not very powerful when applied to only three replicate observations.

The data were adjusted slightly to account for the age of the specimens at the time of testing, which ranged from 91 to 119 days. An equivalent 91-day strength was calculated for cores more than 91 days old. The adjustment factor for 119-day-old cores was assumed equal to the ratio of the average strength of three 6 x 12-in. cylinders tested at 91 days age to that of three companion cylinders tested at 119 days. These cylinders were cast separately from the slabs but were cured in a manner that simulated the curing of the test slabs. The adjustment factor for cores between 91 and 119 days old was assumed to vary linearly with time from 1.0 at 91 days to 0.959 at 119 days. The raw strength data, age adjustment factors, adjusted core strengths, and moisture content information for all cores are shown in the Appendix.*

Preliminary scatter plots suggested a second-order polynomial fit for the relationship between the core strength and average moisture content in the core at the time of testing. The relationship between the core strength and the change in core moisture content between drilling and testing is also well simulated by a second-order polynomial. Preliminary analyses of variance indicated a significant difference between the strengths of the cores from the top and bottom of the 8-in. slab. Also, the cores from the 4-in. slab were appreciably stronger those from the 8-in. slab.

In light of these findings, a model was selected with the form

$$f_c = \left(\beta_0 + \beta_1 X + \beta_2 X^2\right)(1 + \beta_3 Z_t)(1 + \beta_4 Z_b)(1 + \beta_5 Z_h) + \varepsilon \quad (1)$$

In this model, f_c is the strength of the core modified to accont for the different ages of the cores at testing, β_0 .. β_5 are the various parameters estimated by regression analysis, and ε represents the random error component of f_c assumed to be normally distributed with constant variance. Indicator variable Z_t equals 1 for the 4-in. cores from the top of the 8-in. slab or 0 otherwise, so the factor $(1 + \beta_3 Z_t)$ reflects any difference in strength between these cores and the rest. Similarly, Z_b equals 1 for cores from the bottom of the 8-in. slab or 0 otherwise, and Z_h equals 1 for cores from the 4-in. slab or 0 otherwise.

Analyses were first carried out setting the variable X in Eq. (1) to the average moisture content in the core at the time of testing M_t, expressed as a percentage of the oven-dried core weight. Nonlinear regression analysis using the SAS software package[18] gave the fitted model

$$\hat{f}_c = (16,200 - 4160 M_t + 366 M_t^2)(1 + 0.099 Z_t)(1 + 0.164 Z_b)(1 + 0.164 Z_h) \quad (2)$$

with all parameter estimates significantly different from zero at the 95 percent confidence level. The standard error of regression is 240 psi, and the coefficient of determination R^2 is 0.87.

The analyses were repeated with the variable X in Eq. (1) equal to the change in moisture content in the core between drilling and testing $M_t - M_{ad}$, again expressed as a percentage of the oven-dried core weight. The corresponding fitted model is

$$\hat{f}_c = [4660 - 607(M_t - M_{ad}) + 273(M_t - M_{ad})^2](1 + 0.088 Z_t)(1 + 0.150 Z_b)(1 + 0.230 Z_h) \quad (3)$$

with all parameter estimates significant. The standard error of regression in this case is 190 psi and R^2 is 0.92. Eq. (3) fits the data reasonably well, as indicated by the partial regression plot shown in Fig. 5.

Comparison of the standard errors of regression and coefficients of determination suggests that the model based on

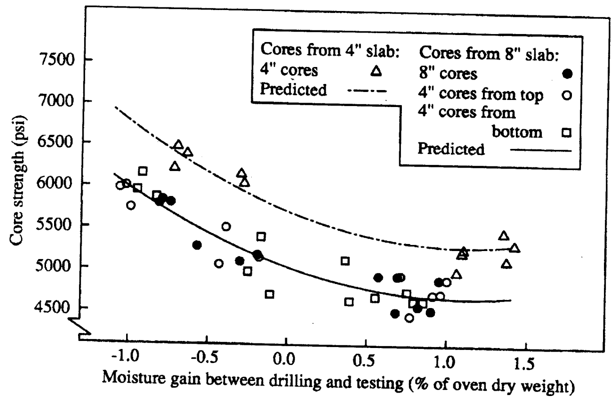


Fig. 5—Partial regression plot of core strength versus moisture gain

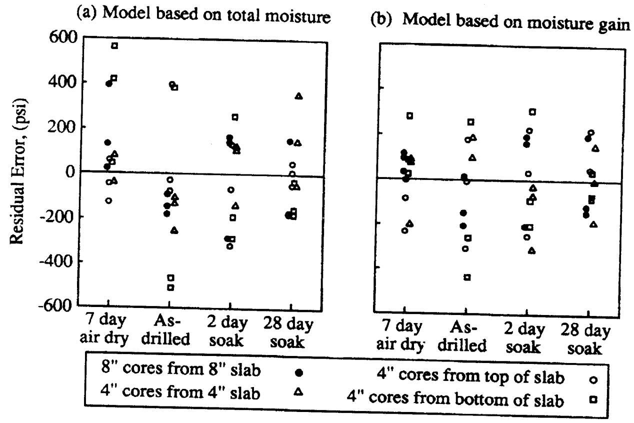


Fig. 6—Core strength residuals versus moisture-conditioning treatments

the average moisture content, Eq. (2), does not seem to reflect the strength change as well as the model based on the moisture gain (or loss), Eq. (3). This preliminary conclusion is corroborated by the graphs of the residual errors versus the various moisture conditioning treatments shown in Fig. 6. There is a clear pattern to the residuals from the model based on average moisture content, since the residuals for the air-dried cores are typically greater than zero and those for the as-drilled cores are typically less than zero. There is no corresponding pattern to the residuals from the model based on the moisture gain.

The effect of moisture treatment on core strength is therefore related to the moisture change of the specimen before testing instead of the average moisture content of the specimen at the time of testing. Since the region affected is a small proportion of the overall specimen volume, the moisture conditioning effect on the specimen strength represents essentially an artificial testing bias. The implicit assumption in ACI 318-89[4] and in the provisions recommended by the Concrete Society,[6] that the moisture conditioning effect observed on small core specimens can be extrapolated to concrete in large structures, seems unrealistic.

An attempt was made to quantify the dimensions of the inner region and surface layer, estimate the moisture differential, and determine the relationship between the strength and moisture content of the surface layer using regression

---

*The appendix is available in xerographic or similar form from ACI headquarters, where it will be kept permanently on file, at a charge equal to the cost of reproduction plus handling at time of request.

Table 1— Strength of cores from Alca's Beam MH2

Treatment	Bend end	n	psi	s, psi
Air-dried	South	7*	14,020	1190
	North	8	13,990	960
	Combined	15	14,000	1040
Coated and air-dried	North	14*	13,440	520
Coated and soaked	South	5*	12,610	610
Soaked	South	8	10,760	920
	North	7	10,970	700
	Combined	15	10,860	800

*One low-strength outlier removed from data.

analysis. The attempt failed because the available data were insufficient for the task. In particular, both the surface moisture content and surface layer strength were extremely sensitive to the unknown surface layer thickness.

ANALYSIS OF CORES FROM ALCA'S BEAM MH1

To further investigate the effect of moisture condition on core strengths, a number of 2-in.-diameter cores were obtained from Beam MH1 tested by Alca at the University of Alberta.[19] The beam was cast from a superplasticized ordinary portland cement concrete with negligible entrained air. The cores were drilled through the thickness of the beam, perpendicular to the direction of concrete placement, when the beam was 93 days old. The cores were left in laboratory air for 9 days while they were sawn to nominal 4-in. lengths and their ends were ground. At that time, the side surfaces of some of the cores were painted with a waterproof epoxy coating. The ends of these cores were not coated. Then half the cores were soaked for 9 days in water, while the other half were left in laboratory air. Complete details may be found elsewhere concerning the mix design and casting procedures[19] and the core drilling, conditioning, and testing procedures.* Four low-strength outlying observations were identified using the criteria given in ASTM E 178.[17] The strengths of the remaining 39 cores are summarized in Table 1.

The differences of the average strengths of cores from north and south ends of the beam are not statistically significant, whether the cores were air-dried ($p = 0.96$) or soaked ($p = 0.62$). Direct comparisons of the strengths of cores from both ends can therefore be made. The difference between the average strengths of the uncoated soaked and uncoated air-dried cores is 3150 psi. If the sides of the cores are coated, the strength difference between soaked and air-dried cores is only 830 psi, about one-quarter of the value for uncoated cores. Since this small difference is statistically significant ($p = 0.048$), some of the observed strength change must be due to either a moisture gradient or reduction in capacity in the regions at the ends of the cores. The remainder, almost three-quarters of the observed total strength change, is probably caused by moisture gradients effects along the sides of the core.

The average strengths of the uncoated air-dried cores are slightly greater than the average strengths of the coated air-dried cores, although the difference is not statistically significant ($p = 0.30$). Given that both sets of cores were left in air for 9 days before the coating was applied, one would perhaps expect only a slight difference anyway. The observed difference may indicate that the coating causes a slight loss of strength. It also may indicate that the uncoated cores continued to gain strength because their sides were exposed to laboratory air for the extra 9 days. The latter explanation is consistent with the continued loss of moisture of specimens exposed to laboratory air for prolonged periods, as shown in Fig. 2.

*Bartlett, F. M., and MacGregor, J. G., "Cores from High Performance Concrete Beams," *ACI Materials Journal*, forthcoming.

FACTORS REPRESENTING OVERALL CORE STRENGTH VARIATION DUE TO MOISTURE CONDITION

Regression analyses were carried out to determine the relationships between the strength of air-dried, soaked, and as-drilled cores.

Air-dried core strengths versus soaked core strengths

The relationship between air-dried and soaked core strengths was examined using data reported by Bloem,[2] Meininger et al.,[3] and Bartlett and MacGregor.* The moisture conditioning treatments used, in all cases, either storage in air at 50 to 70 F at 40 to 60 percent relative humidity for 7 days, or storage in lime-saturated water for at least 40 hr, are in accordance with ASTM C 42-90.[5] Altogether, these data represent tests of 617 4-in.-diameter cores obtained from 10 separate elements cast using ordinary portland cement concretes with standard cylinder strengths ranging from 2200 to 13,400 psi.

The numbers of specimens, average strengths, and corresponding standard deviations are shown in Table 2 for soaked and air-dried specimens with common length-to-diameter ratios. The strength of Bloem's cores have been modified to account for minor variations in their age at the time of testing, as described previously. All strengths for cores with nominal length-to-diameter ratios less than 2 have been transformed to equivalent strengths of standard cores with l/d ratios of 2 using the correction factors proposed by Bartlett and MacGregor.†

The model selected has the form

$$\bar{f}_{c,dry} = \beta_6 + \beta_7\left(\frac{l}{d}\right) + \beta_8\bar{f}_{c,wet} + \varepsilon \qquad (4)$$

where $\bar{f}_{c,dry}$ and $\bar{f}_{c,wet}$ are the average strengths of the air-dried and soaked cores respectively, β_6 .. β_8 are unknown parameters determined by regression analysis, and ε is the error. A weighted regression analysis was carried out, since, for these data, the variance of the dependent variable may not be constant for all observations and also the independent variable includes a significant measurement error. The weights for each observation were determined following the

*Bartlett, F. M., and MacGregor, J. G., "Cores from High Performance Concrete Beams," submitted to *ACI Materials Journal*, forthcoming.

†Bartlett, F. M., and MacGregor, J. G., "Effect of Core Length to Diameter Ratio on Concrete Core Strength," *ACI Materials Journal*, forthcoming.

Table 2—Strength data for air-dried and soaked cores

Reference	Element no.	Air-dried core data				Soaked core data			
		l/d	n	$\bar{f}_{c,dry}$, psi	s, psi	l/d	n	$\bar{f}_{c,wet}$, psi	s, psi
Meininger et al.[3]	1	1.00	13*	4699	170	1.01	14	4167	230
	1	1.26	12	4648	105	1.26	11*	4049	158
	1	1.51	12	4687	129	1.51	11*	4090	141
	1	1.75	9†	4594	114	1.75	12	4088	187
	1	2.00	10	4726	217	1.99	9*	4059	179
	2	1.00	14	2264	155	1.00	12	1934	138
	2	1.25	10	2331	130	1.25	10	2031	146
	2	1.50	14	2300	144	1.50	14	2082	116
	2	1.74	15	2360	138	1.75	14	2036	67
	2	1.99	9	2335	106	2.00	8	2042	144
	3	1.00	25	3102	163	1.01	19*	2653	124
	3	1.26	9	3116	151	1.26	9*	2585	112
	3	1.51	11	3137	160	1.52	7*	2671	37
	3	1.76	7‡	3135	31	1.75	8	2645	73
	3	2.00	10	3085	169	2.00	8*	2686	85
	4	1.04	6	3527	155	102	16	3025	170
	4	1.52	6	3277	120	1.52	16	3048	87
	4	1.99	6	3495	110	1.99	16	3128	147
	5	1.04	6	5630	234	1.03	16	5190	178
	5	1.52	6	5510	265	1.49	16	5016	265
	5	2.01	5*	5481	145	1.98	16	4945	234
	6	1.04	6	7540	269	1.03	16	7218	296
	6	1.50	6	7476	238	1.50	16	6979	222
	6	1.97	6	7417	212	1.95	14‡	6829	247
Bloem[2]	7	2.11	3	5381	21	2.13	6	4375	197
	7	1.07	3	5299	130	1.06	6	4370	166
	7	1.06	3	5674	140	1.09	6	4620	191
	8	1.09	3	5701	122	1.09	6	4790	151
Bartlett and MacGregor**	9	0.99	5	13,122	525	0.99	5	11,691	436
	9	2.03	5	13,670	457	2.03	5	11,906	434
	10	0.98	5	13,173	374	0.99	5	11,150	192
	10	2.00	5	13,033	509	1.99	5	11,454	182

Note: One*, three†, or two ‡, low-strength outliers removed from data.
**Bartlett, F. M., and MacGregor, J. G., "Cores from High-Performance Concrete Beams," *ACI Materials Journal*, forthcoming.

procedure given elsewhere.*

Analysis using the linear regression procedures of the SAS software package[18] indicated that only the parameter estimate of β_8 is significant at the 5 percent level. The fitted model is

$$\hat{f}_{c,dry} = 1.144\ \bar{f}_{c,wet} \qquad (5)$$

with R^2 equal to 0.998 and the standard error of regression equal to 2.31. The high R^2 value indicates that the wet and dry average core strengths are strongly correlated. However, the standard error of regression is also rather high, indicating that the fit of Eq. (5) to the data is actually not very good. This is also suggested by Fig. 7, which shows considerable scatter of the observed average values about the predicted value of 1.144.

As-drilled core strengths versus soaked core strengths

The relationship between as-drilled core strengths and soaked core strengths was examined using data from 115 core tests reported by Bloem[2,20] and Bartlett and MacGregor.* The as-drilled strengths are for cores subjected to slightly different test conditions. In Bloem's earlier investigation,[2] cores were obtained using a water-cooled drill and tested after about 3 hr of drying in laboratory air, whereas, in his later investigation,[20] cores were obtained using an air-cooled bit and tested the same day. Bartlett and MacGregor's cores were left in air for about 15 min until the drilling water had evaporated from the sides, and then were stored in plastic bags until the test. Therefore, it is reasonable to assume that the moisture gradient in the as-drilled cores from these three investigations is negligible. In all cases, the soaked cores were stored in lime-saturated water for at least 40 hr.

The numbers of specimens, average strengths, and corresponding standard deviations are shown in Table 3 for the as-drilled and soaked specimens. The values shown have again been adjusted slightly to account for differing ages of the cores at the time of testing, and have been converted to equivalent strengths of standard cores with l/d of 2. Three sets of cores were obtained by Bloem from each element in his 1968 investigation,[20] at 28, 91, and 364 days. Only the 28- and 91-day data are shown in Table 3, since the strengths

*Bartlett, F. M., and MacGregor, J. G., "Effect of Core Length to Diameter Ratio on Concrete Core Strength," *ACI Materials Journal*, forthcoming.

*Bartlett, F. M., and MacGregor, J. G., "Cores from High Performance Concrete Beams," *ACI Materials Journal*, forthcoming.

Table 3—Strength data for as-drilled and soaked cores

			As-drilled core data				Soaked core data		
Reference		Element no.	l/d	n	$f_{c,ad}$, psi	s, psi	l/d	n	$\bar{f}_{c,wet}$, psi
Bloem[2]	7	2.17	3	4803	85	2.13	6	4375	197
	7	1.08	3	4771	215	1.06	6	4370	166
	7	1.11	3	4864	339	1.09	6	4620	191
	8	1.11	3	5536	58	1.09	6	4790	151
Bartlett and	9	2.01	6	12,908	701	2.03	5	11,906	434
MacGregor**	9	1.00	6	13,155	504	0.99	5	11,691	436
	10	1.99	5*	11,862	739	1.99	5	11,454	182
	10	0.99	6	11,838	324	0.99	5	11,150	192
Bloem[20]	11	1.50	3	4193	239†	1.50	3	3543	252‡
	11	1.50	3	4339	247†	1.50	3	4022	286‡
	12	1.50	3	3049	176†	1.50	3	2958	210‡
	12	1.50	3	3667	209†	1.50	3	3280	233‡
	13	1.50	3	3317	189†	1.50	3	2978	211‡
	13	1.50	3	3444	196†	1.50	3	3095	220‡

*One low-strength outlier removed from data.
†Calculated using average coefficient of variation of 5.7 percent[22]
‡Calculated using average coefficient of variation of 7.1 percent[22]
** Bartlett, F.M., and MacGregor, J. G., "Cores from High Performance Concrete Beams," *ACI Materials Journal*, forthcoming.

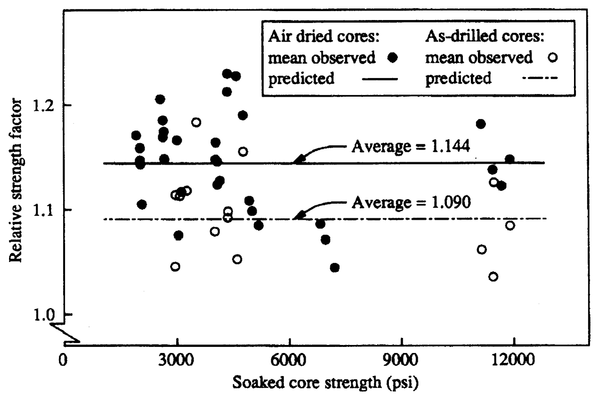


Fig. 7—Strength of air-dried and as-drilled cores relative to soaked cores

of the 364-day-old soaked cores are in all cases considerably less than the corresponding 91-day strengths.

Analysis was carried out on a model similar to Eq. (4) using the linear regression procedures of the SAS software package.[18] The best fit was obtained with a constant term in the regression

$$\hat{f}_{c,ad} = 275 + 1.044 \ \bar{f}_{c,wet} \qquad (6)$$

where is the predicted average strength of the as-drilled cores. Both parameters in Eq. (6) are significant; R^2 is equal to 0.994 and the standard error of regression is equal to 1.32. If the constant term is neglected, the fit is

$$\hat{f}_{c,ad} = 1.090 \ \bar{f}_{c,wet} \qquad (7)$$

with R^2 equal to 0.998 and the standard error of regression equal to 1.50. Comparing the R^2 values alone erroneously indicates that Eq. (7) is a better fit than Eq. (6), because R^2 is defined differently for models with and without a constant. In fact, although Eq. (6) is a slightly better fit than Eq. (7), both are reasonably good. The scatter of the observed averages around the value predicted from Eq. (7) is shown in Fig. 7.

Air-dried core strengths versus as-drilled core strengths

The available data are insufficient to precisely determine the relationship between the strength of cores tested as-drilled and those left to dry in air for 7 days. The ratio of the average air- dried core strength to the average as-drilled core strength for the cores from Elements 7 through 10 has an average of 1.09 and a standard deviation of 0.05. This ratio can also be estimated by dividing Eq. (5) by Eq. (7), which gives 1.05. Therefore, on average, air-dried cores are probably 5 to 9 percent stronger than as-drilled cores.

Accuracy of strength conversion factors

In Fig. 8, the residual errors obtained from Eq. (5) and (7) are plotted against the corresponding predicted value for the data shown in Tables 2 and 3. Lines where the residual error equals ±5 percent of the predicted value are also shown. Three of the 14 average as-drilled core strengths and 9 of the 32 average air-dried core strengths fall outside these limits.

Typically, residual errors for the strengths of cores drilled from a common source are clustered together. For example, the four large positive residuals for $\overline{f}_{c,\,dry} \cong 5000$ psi are all from Elements 7 and 8. Similarly, the three large negative residuals for $\overline{f}_{c,\,dry} \cong 6000$ psi are all from Element 5 and the three large negative residuals for $\overline{f}_{c,\,dry} \cong 8000$ psi are all from Element 6. This suggests that the general relationships given by Eq. (5) and (7) may not be accurate for cores from a specific element. If accurate conversion factors are required, it may be necessary to obtain cores from the element of interest and, after carrying out the moisture conditioning treatments, establish the specific factors directly.

DISCUSSION

In his landmark paper, Bloem[2] concludes that "for the conditions employed in this research, which simulated interior structural concrete, it appeared that cores dried for 7 days to eliminate water absorbed during drilling provided the most accurate measure of strength in place." This conclusion is based on the observation that the average strength of three replicate cores drilled and tested dry was consistently slightly greater than the average strength of three replicate cores drilled wet and tested after 7 days air-drying for four slabs cast of lightweight concrete.

To determine the true in situ strength, it is clearly desirable to eliminate any moisture gradient effect caused by absorption of the drilling water. However, it seems probable that a 7-day drying period is excessively long for this purpose. Fig. 4 shows that the cores from Bloem's 8-in. normal weight concrete slab achieved their in situ moisture content after about 3 hr of drying and those from the 4-in. slab achieved their in situ moisture content after about 24 hr of drying.[2] The observations of de Larrard and Bostvironnois[14] shown in Fig. 2 indicate that the extent of the moisture gradient, and therefore the strength of the specimen, is affected by the length of the drying periods. The analysis presented in the previous section, although based on a small quantity of data, indicates that the effect of 7 days of air-drying is to cause a moisture gradient that artificially increases the strength of the specimen by about 5 percent above the true in situ strength.

In the same paper, Bloem also observes that "the standard treatment—soaking for 48 hours—is probably more indicative of the in-place strength of wet concrete."[2] The literature clearly indicates that concrete strength is reduced if the moisture content is increased uniformly throughout the specimen volume. It is also true that soaking the specimen causes a moisture gradient that reduces the test strength obtained. However, the first factor reflects a true influence of the in situ concrete strength, whereas the second factor is a more artificial effect that biases the test outcome. If it is necessary to evaluate the strength of wet concrete, it may be more appropriate to obtain cores by drilling with a water-cooled bit, allow the cores to sit a few minutes in air to permit excess water to evaporate, and then test the cores in that condition.

SUMMARY AND CONCLUSIONS

In accordance with the provisions of ASTM C 42-90[5] and ACI 318-89,[4] it is current practice to either dry concrete core specimens in air for 7 days or soak them in lime-saturated water for at least 40 hr before they are tested. In this paper,

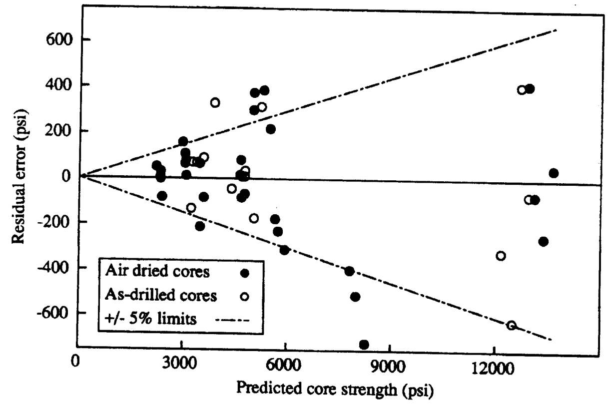


Fig. 8—Residual-versus-predicted core strengths

the effect of moisture condition on the strengths of mature cores obtained from well-cured elements is investigated by reviewing available literature and performing regression analyses of data from tests of 727 core specimens. The elements were all cast using ordinary portland cement concrete with standard strengths between 2200 and 13,400 psi.

From the literature review and data analyses, the following observations and conclusions appear warranted:

1. The compressive strength of a concrete specimen is decreased if its moisture content is uniformly increased throughout its volume. Conversely, the strength is increased if the moisture content is uniformly decreased.

2. The compressive strength is also considerably affected if a moisture gradient is created between the exterior and interior of the specimen. Soaking the specimen causes swelling at the surface. The interior of the specimen does not undergo any change in moisture content and so restrains the swelling at the surface. This restraint causes a set of self-equilibriated residual stresses, which, in turn, cause a reduction in the compressive strength of the specimen. Drying the specimen causes shrinkage at the surface and increases the compressive strength.

3. Analysis of Bloem's[2] data indicates that the strength of cores is affected by change in moisture content between drilling and testing instead of total moisture content at the time of testing. The observed change in strength should therefore be attributed mostly to the moisture gradient effect.

4. The lengths of both drying and soaking periods specified in ASTM C 42-90 and ACI 318-89 are too short to cause a uniform change of moisture content throughout the volume of the core. The effect of these treatments is to create a moisture gradient that artificially biases the test result.

5. The most accurate estimate of in situ concrete strength is obtained from a specimen with no gradient of moisture content through its volume. Such a specimen may be obtained using an air-cooled drill, or by letting excess water evaporate from cores obtained using a water-cooled drill. The 7 days of air-drying treatment permitted by ASTM C 42-90 and ACI 318-89 seems excessively long for letting excess cooling water evaporate.

6. The strength of cores left to dry in air for 7 days is on average 14 percent larger than that of cores soaked at least 40 hr before testing. The strength of cores with a negligible

moisture gradient is on average 9 percent larger than that of soaked cores. These general average values are constant for concretes with strengths ranging from 2200 to 13,400 psi. However, the strength ratios for any particular mix may differ appreciably from these general average values.

ACKNOWLEDGMENTS

Financial support from the Killam Trust, the Natural Sciences and Engineering Research Council, the University of Alberta Faculty of Graduate Studies and Research, the Canadian Society of Civil Engineering, ENCON Insurance Managers Inc., the Canadian Council of Professional Engineers, and the Alberta Heritage Scholarship Fund is gratefully acknowledged. The testing of cores at the University of Alberta was financed by the Canadian Network of Centres of Excellence on High-Performance Concrete.

NOTATION

d = diameter of concrete core specimen
f_c = strength of concrete core specimen
$\hat{f}_c$ = predicted strength of concrete core specimens
$\bar{f}_{c,ad}$ = average strength of as-drilled concrete core specimens
$\bar{f}_{c,dry}$ = average strength of air-dried concrete core specimens
$\bar{f}_{c,wet}$ = average strength of soaked concrete core specimens
$\hat{f}_{c,ad}$ = predicted average strength of as-drilled concrete core specimens
$\hat{f}_{c,dry}$ = predicted average strength of air-dried concrete core specimens
l = length of concrete core specimen
M_{ad} = average moisture content of core immediately after drilling
M_t = average moisture content of core at time of test
n = number of replicate observations of quantity
p = probability of null hypothesis being true
R^2 = coefficient of determination
d = sample standard deviation
X = independent variable representing moisture content
Z_b = indicator vriable for cores from bottom of Bloem's 8-in.-thick slab
Z_h = indicator variable for cores from Bloem's 4-in.-thick slab
Z_t = indicator variable for cores from top of Bloem's 8-in.-thick slab
$\beta_1 ... \beta_2$ = parameters to be estimated by regression analysis
$\hat{\beta}_1$, etc. = actual estimate of Parameter β_1
ε = normally distributed error in regression analysis model

CONVERSION FACTORS

1 in. = 25.4 mm
1 psi = 6.895 MPa

REFERENCES

1. ASTM Committee C 9, "Standard Method of Securing Specimens of Hardened Concrete from the Structure (ASTM C 42-27)," *Book of ASTM Standards,* Pt. II, ASTM, Philadelphia, 1928, pp. 149-150.

2. Bloem, D. L., "Concrete Strength Measurement—Cores versus Cylinders," *Proceedings,* ASTM, V. 65, 1965, pp. 668-696.

3. Meininger, R. C.; Wagner, F. T.; and Hall, K. W., "Concrete Core Strength—The Effect of Length to Diameter Ratio," *Journal of Testing and Evaluation,* V. 5 No. 3, May 1977, pp. 147-153.

4. ACI Committee 318, "Building Code Requirements for Reinforced Concrete and Commentary (ACI 318-89/ACI 318R-89)," American Concrete Institute, Detroit, 1989, 353 pp.

5. ASTM Committee C 9, "Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete (ASTM C 42-90)," *Annual Book of ASTM Standards,* V. 04.02, ASTM, Philadelphia, 1992, pp. 27-29.

6. "Concrete Core Testing for Strength," *Technical Report* No. 11, Concrete Society, London, 1976, 44 pp.

7. Neville, A. M., *Properties of Concrete,* 3rd edition, Pitman Publishing Ltd., London, 1981, 779 pp.

8. Popovics, S., "Effect of Curing Method and Final Moisture Condition on Compressive Strength of Concrete," ACI Journal, *Proceedings* V. 83, No. 4, July-Aug. 1986, pp. 650-657.

9. Wittmann, F. H., "Interaction of Hardened Cement Paste and Water," *Journal of the American Ceramic Society,* V. 56, No. 8, Aug. 1973, pp. 409-415.

10. Bessey, G. E., and Dilnot, S., "Relation between Strength and Free Water Content of Aerated Concretes," *Magazine of Concrete Research,* V. 1, No. 3, Dec. 1949, pp. 119-122.

11. Feldman, R. F., and Sereda, P. J., "New Model for Hydrated Portland Cement and Its Practical Implications," *Engineering Journal,* Aug.-Sept. 1970, pp. 53-59.

12. Glucklich, J., and Korin, U., "Effect of Moisture Content on Strength and Strain Energy Release Rate of Cement Mortar," *Journal of the American Ceramic Society,* V. 58, No. 11-12, Nov.-Dec. 1975, pp. 517-521.

13. Pihlajavaara, S. E., "Effect of Moisture Conditions on Strength, Shrinkage and Creep of Concrete," *Cement and Concrete Research,* V. 4, 1974, pp. 761-771.

14. de Larrard, F., and Bostvironnois, J.-L., "On the Long Term Strength Losses of Silica Fume High-Strength Concretes," *Magazine of Concrete Research,* V. 43, No. 155, June 1991, pp. 109-119.

15. Ottosen, N. S., "Evaluation of Concrete Cylinder Tests Using Finite Elements," *Journal of Engineering Mechanics,* V. 110, No. 3, Mar. 1984, pp. 465-481.

16. Raphael, J. M., "Tensile Strength of Concrete," ACI Journal, *Proceedings* V. 81, No. 2, Mar.-Apr. 1984, pp. 158-165.

17. ASTM Committee E 11, "Standard Practice for Dealing with Outlying Observations (ASTM E 178-80)," *Annual Book of ASTM Standards,* V. 14.02, ASTM, Philadelphia, 1989, pp. 101-117.

18. SAS Institute, Inc., *SAS/STAT User's Guide, Version 6, Fourth Edition, Volume 2,* SAS Institute Inc., Cary, North Carolina, 1990, 1739 pp.

19. Alca, N., "Bending Tests of High performance Concrete Beams," MASc thesis, Department of Civil Engineering, University of Alberta, 1993, 91 pp.

20. Bloem, D. L., "Concrete Strength in Structures," ACI Journal, *Proceedings* V. 65, No. 3, Mar. 1968, pp. 176-187.