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The Evaluation and Acceptance of Concrete Quality by In-Place Testing

By J.A. Bickley

Synopsis: The standard method of determining the quality of hardened concrete is the cylinder test. Unless test results fail to meet specified values, and other test procedures are called into play, the standard cylinder test is usually the only quantitative measure of the quality of concrete in a structure. Analysis of test results to ACI 214 enables assessments of this quality to be made.

On two large projects in Toronto, horizontal elements were extensively tested by in-place testing for form removal, termination of shoring, and confirmation of specified 28-day strength. Permission to waive standard cylinder testing for these elements was obtained from the City Building Department.

Out of interest the cylinders were made and tested. It is therefore possible to evaluate the quality of the concrete on these projects by both the standard procedure, and by in-place testing. This is addressed in this paper together with a discussion of statistical evaluation of in-place test data.

Keywords: acceptability; compressive strength; concretes; form removal; inserts; nondestructive tests; post-tensioning; pullout tests; quality control; statistical analysis.

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INTRODUCTION

The quality of concrete can be assessed by one or more of the following procedures.

Prior to the manufacture of concrete acceptance and quality control tests on cement, aggregates, admixtures, and water; and on the proposed mix proportions can confirm the potential quality of the concrete.

During concreting slump and air tests are made on fresh concrete, its temperature and sometimes its unit weight are checked, the age of the concrete from the time of batching to the time of discharge is checked, and finally standard concrete test cylinders are made for compressive strength tests.

In the event that any of these standard cylinder tests indicate a potential deficiency in the concrete additional tests are made. These range from non-destructive tests such as impact hammer, ultrasonic and penetration tests to core tests to load testing of the structural elements in question.

Assuming, however, that nothing indicates potential deficiencies in the concrete the third stage described above would not occur. Presuming also that the approval of materials and mix proportions takes place at the beginning of a project, which is normal, then the assessment of concrete quality during the course of a contract is based on the tests on fresh concrete and on the results of concrete compressive strength tests. Normally slump and air tests are considered to be part of the control and acceptance of the concrete. They are intended to be, and usually are, a means of ensuring that the measured properties of the fresh concrete fall within the specified parameters in the contract documents.

It can be said therefore that in the normal course of events the quality of concrete in a project is judged by the results of the standard compressive strength cylinder tests. Because it was realized a considerable time ago that a simple assessment based on a tabulation of results could give a misleading picture a statistical approach was adopted.

In his book "Statistics For Concrete" 1955, Himsworth showed how statistics could be applied for a logical interpretation of the meaning of strength test results. In 1965 the American Concrete Institute published "ACI 214, Recommended Practice For Evaluation Of Strength Tests Of Concrete" and this was superseded in 1977 by the current edition. During this period of time it has become common practice to use statistical analyses in order to determine the quality of concrete on a project and the extent to which it does or does not comply with project specifications. Furthermore, the degree of acceptance of the statistical approach is confirmed both by its international inclusion in national and international specifications, and also by its wide acceptance in litigation in disputes about the quality of concrete.

RELEVANCE OF CYLINDER TESTS

The concrete cylinder test has been used for more than seventy-five years and is still, overwhelmingly, the single most often used test procedure throughout the concrete construction industry. While it is commonplace to document its deficiencies there has been very little action to date to replace it with alternative test procedures.

The standard test procedure determines the strength of cylinders 28 days after casting, having subjected them to specified standard casting, curing, capping and testing procedures. Used in this way the cylinder test merely determines the potential quality of the concrete as delivered to site and may therefore bear no relation to the strength or other qualities of the concrete in place. After discharging the concrete on delivery it is subjected to various transportation, compaction and curing processes, none of which may result in concrete of the same maturity or density as a standard cylinder. In addition, the use of a 28-day criterion is seen by many as inappropriate for today's construction process. It is common to slip-form several hundred feet or to cast in excess of ten floors per calendar month.

In the last three decades many attempts have been made to produce satisfactory accelerated test procedures which produce an answer equivalent to the standard cylinder test but at much earlier ages. A number of these test procedures have been recognized as having acceptable qualities and have been enshrined in American, Canadian and other national standards. It is a fact of life, however, that while much of the industry deprecates the use of 28-day tests they are still almost universally used, and today accelerated testing is used in the industry to a limited degree only.

Despite the problems which are perceived with regard to standard cylinder testing procedures to determine the potential quality of concrete almost all the effort put into testing concrete determines the strength of these disparate tests specimens. The fact is that none of them may have any relevance to the structure.

It would therefore seem logical that what is required is a test procedure which produces an answer at an early age. Also that the properties of the concrete in the structure should be determined by tests on that concrete in the structure.

THE PROBLEM IN USING IN-PLACE TESTS

The standard cylinder test is universally accepted. Tests are made at variable but generally specified frequencies. The tests represented by such random sampling are taken to be representative of the whole. A statistical analysis to ACI 214 is agreed to be a measure of quality in terms of compliance with a specific strength value, the consistency with which this criterion is met, and a measure of to what extent (if at all) it fails to meet the specified criterion.

The situation with regard to in-place testing is totally different:

- There are many different test methods.
- No one method has general acceptance.
- All in-place test methods except one measure properties other than compressive strength (to which they have to be correlated).
- The tests are usually made at an early age in the concrete's life, at which time variations in strength may be greatest, and an error in test results could have serious consequences.

Because of the above, in-place test methods should be used in each concrete placement in numbers sufficient to produce adequate data for statistical evaluation. In addition, in-place test results should be evaluated by statistical methods.

IN-PLACE TESTING TODAY AND STANDARDS

In Canada, CAN3-A23.1 M-77 "Concrete Materials and Methods of Construction" is the usually referenced document. It provides no mandatory requirements for in-place testing for use in the control and evaluation of construction. The current (1977) edition recommends the use of in-place testing and gives a very brief summary of the most commonly used methods, and their advantages and disadvantages. ACI 318 recognizes only field cured cylinders, and then only as a means for "checking the adequacy of curing and protection".

Some in-place test procedures are recognized by ASTM as follows:

ASTM C873-80 "Compressive Strength of Concrete Cylinders - Cast In Place In Cylindrical Moulds"
ASTM C803-79 "Penetration Resistance Of Hardened Concrete"
ASTM C900-82 "Pullout Strength of Hardened Concrete
ASTM C597-71 "Pulse Velocity Through Concrete"
ASTM C805-79 "Rebound Number Of Hardened Concrete"

With the exception of the C873 procedure, the results of all of these procedures have to be correlated with the strength of standard cylinder tests.

PULLOUT TESTING PROCEDURE

For most projects the author prefers the use of pullout tests for determining optimum safe times for form removal, post-tensioning, and removal of shores. The system used places a 25 mm pullout disc 25 mm from the concrete surface. In cold weather additional information is obtained by the use of disposable maturity meters placed at the most exposed locations of the placement being tested. This provides a cross-check on the pullout test results and confirmation based on the approximate maturity values obtained that the compressive strengths indicated are of the correct order, and that the concrete is not frozen.

The specification quoted in the section on demonstration projects was developed to follow the principles of statistically valid numbers and evaluation.

In practice, it is felt that in a typical 100 m³ floor placement, probably supplied with 10 m³ loads of ready-mixed concrete, the random placing of 15 inserts and the random testing of 10 of these are as representative a measure on the in-place strength as it is practicable (economically possible) to get.

The procedure followed is to take the 10 test results (or some other appropriate number in larger placements) and process these as shown in the following example.

Specified Strength, f'_c: 30 MPa.

Minimum Strength for Form Removal $0.75\ f'_c$: 22.5 MPa.

Example 1.

Individual Pullout
Test Results (MPa)
(Converted from force measurements) #

See Fig 1.

27.5				
25.0				
24.5	Mean	($\bar{x}$)	=	25.8 MPa
25.0	Standard Deviation	(σ)	=	2.3 MPa
22.5				
24.0	Constant	(k)	=	1.67*
25.5				
28.5	Minimum strength		=	$\bar{x} - k\sigma$ MPa
25.0			=	22.0 MPa
30.0				

In calculating minimum strength the same degree of confidence or reliability must be maintained in the test results regardless of the number of tests made. For practical reasons it is seldom that the same number of inserts are tested for each and every placement. The size of the placement, and therefore the number of inserts that is appropriate, may vary. Sometimes inserts are damaged. If minimum strength for stripping is slow in developing fewer than 10 inserts may be available for testing after initial tests show inadequate strength. If the same confidence limits are to be maintained a variable constant must be used to calculate the minimum strength indicated by a set of test results. This is to maintain the same degree of reliability.

These values result in 95% confidence limits for the minimum strength result calculated.

As will be seen the larger the number of tests made the more reliable the result is deemed to be and the smaller the reduction in value from mean strength ($\bar{x}$) that results.

Equally if the standard deviation (σ) is high the minimum strength calculated even for a large number of inserts will be lower. This is shown in the following example.

Example 2.

Individual Pullout
Test Results (MPa)
(Converted from force measurements)#

* The constant (k) to be used in the calculation of the minimum strength are given in Table I.

\# See Fig 1.

31.5			
25.0			
24.0	Mean	$(\bar{x})$	= 26.8 MPa
23.0	Standard		
22.5	Deviation	(σ)	= 3.8 MPa
29.0	Constant	(k)	= 1.67*
32.0			
28.5	Minimum Strength		$= \bar{x} - k\ \sigma$ MPa
22.5			= 20.5 MPa
30.0			

SPECIFICATION CRITERIA

The question of how to specify in-place strength needs review. Historically, specifications have required forms to stay in place until a minimum of 75% (or some similar value) of f'_c has been reached. Generally specifications have been vague on how the in-place strength should be determined. Frequently, field-cured cylinders have been used as a determinant. These can be misleading, abused, and are typically only made at the same frequency as sets of standard cylinders. One or two field cylinders would therefore be used to determine the strength of a placement of significant quantities of concrete. Most of the time, however, form removal has been at ages of 7 days or greater and there have been few problems.

With the trend towards faster construction schedules, form removal and post-tensioning is commonly occurring during the first few days of the life of the concrete (1 to 3 days) and often, in northern areas, during periods of sub-zero temperature weather.

It is considered therefore that the earlier the age of the concrete and the more hostile the environment to strength development the greater the degree of confidence that is needed in the test data.

Let us re-examine the in-place test data given above. If any one or all of these test results were for field-cured cylinders historically they would have been considered acceptable for form removal. The statistical analysis shows however that there is a high degree of probability that some of the concrete in the placement is slightly below the specified minimum strength.

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* The constant (k) to be used in the calculation of the minimum strength are given in Table I.

The statistical approach is therefore considerably more conservative than previous custom, both because of larger number of tests and because of the adoption of a consistent degree of confidence.

Some engineers have adopted a different approach. Form removal strength is specified as 75% of f'_c and the minimum strength as calculated above must equal or exceed 75% of the specified form removal value (i.e. 56.25% of f'_c). When this approach has been used, the writer has applied these criteria to form removal at ages of 3 days or greater, and has arbitrarily increased the minimum value to 80% and 90% of the specified form removal value for ages of 2 days and 1 day respectively (i.e. 60% and 67.5% of f'_c). There is no quantitative justification for this, just the principle stated above that the greater the potential risks the greater the degree of confidence required that the concrete is strong enough.

DEMONSTRATION PROJECTS

In order to compare the quality of concrete as determined by standard cylinder tests with that determined by in-place tests, two demonstration projects in Toronto were chosen. These were the Trinity Square Head Office for Bell Canada, and the 30 storey College Park Phase II office building.

All floors in both buildings were tested in-place to determine form removal times and time to remove shores. In addition, in-place tests were specified at 28 days. The relevant specification clauses for both projects were as follows.

> "Issue reports of in-place testing to Structural Engineer, Resident Engineer and Construction Manager immediately after tests are made and checked. Keep file on site.
>
> (b) Concrete Tested with Pullouts
>
> Until correlation between 28-day pullout tests and concrete cylinder tests is satisfactory to the Engineer, make 2 cylinders per 100 cubic meters or less of each pour for testing at 28 days.
>
> 2. Where In-Place Testing is Required
>
> Install at least 15 pullout inserts per 100 M^3 pour of concrete. For pours in excess of 100 M^3 provide at least an additional 1 insert per 20 M^3. Install 2 additional pullout inserts per pour for testing at 28 days.

In the substructure install inserts on the top of slabs at ramdon locations agreed by the Engineer. In the superstructure, direct the installation of inserts in the soffit of slabs at random locations agreed by the Engineer.

Test inserts just prior to the time it is proposed to remove forms. Generally, at least 10 tests will be made. If the first five results indicate the concrete is below form removal strength, discontinue testing and reschedule. If a set of 10 tests indicates results marginally below the required values, recommend further tests then or additional curing time.

After checking, report the results on the approved form as provided in the Terms of Reference.

Where necessary to check exposed areas, make additional tests either using additional inserts or maturity meters.

Test two inserts at 28 days.

During cold weather concreting make temperature checks within the heated or insulated areas and record."

These are innovative clauses for a contract specification. They worked well in practice and are recommended as a model for guidance.

For all floors tested the City of Toronto waived standard cylinder test requirements. In order to obtain data by which the two approaches could be compared standard cylinders were made and tested, but not reported.

Tables II and III summarize the relevant data for both in-place tests and standard cylinders for both projects.

Table II gives the results for form removal and also all tests made at later ages. Table III compares 28-day results for both pullouts and standard cylinders.

Table IV gives essential 28-day standard cylinder test data for both sites.

Table V gives examples of test data from the College Park site.

DISCUSSION

In Example 1 all test results equalled or exceeded the specified minimum strength of 22.5 MPa, but the minimum strength calculated was 22.0 MPa. In Example 2 although the mean was higher, the calculated minimum strength was lower due to a greater variation in the test results. In both cases all individual test results met strength requirements for form removal but the statistical evaluation is shown to result in a more conservative answer. The statistically determined minimum strength is however valid to a high degree of confidence and can be relied upon. It is up to the Structural Engineer to set realistic values for form removal or post-tensioning. Perhaps a specified value for form removal with a minimum which is a percentage of this value is a more cost-effective but still safe approach.

In specifying 28 day in-place tests it was understood that the maturity of the concrete would be both variable and different to that of standard cylinders. However this practice did confirm both satisfactory strength with time and the achievement of adequate ultimate strength.

On both sites where pullouts and cylinders were compared it is seen that the concrete quality as judged by pullout tests at 28 days or other later ages was satisfactory. Where 28-day test results for both methods are compared it is seen that the pullouts were an average of 89% and 94% of the strength of standard cylinders respectively for the two sites. If, however, it is accepted that specified strength requirements, f'_c, is met if in-place tests are 85% of f'_c then the in-place test results show the concrete to be better than if judged by standard cylinders. In this latter case the chance of failure would be less than 1 in 1,000. For both sites the standard deviation of the sets of pullouts at later ages was equal to or lower than that of the equivalent standard cylinders.

CONCLUSIONS AND RECOMMENDATIONS

The quality of concrete can be determined by routine in-place test results made during construction instead of standard cylinders.

Depending on the criteria used, the quality of the concrete as determined by in-place tests is shown to be as good as if judged by standard cylinders or better.

In-place testing at early ages should be based on statistically valid numbers of tests to determine the strength of a concrete placement.

In-place test results should be evaluated by statistical procedures. ACI 214 should be amended to provide suitable procedures.

TABLE I

Constants k For Different Numbers Of Pullout Inserts Tested In A Placement

n	3	4	5	6	7	8	9	10	11	12	13	14
k	2.50	2.13	1.96	1.86	1.79	1.74	1.70	1.67	1.65	1.62	1.61	1.59
n	15	16	17	18	19	20	25	30	35	40	45	50
k	1.58	1.57	1.55	1.54	1.54	1.53	1.50	1.47	1.46	1.44	1.43	1.43

TABLE II

Superstructure Test Data
Pullout Test Results *

a) Tests for Form Removal

	Trinity Square		College Park Phase II
	Inserts Placed In:		
	Top of Slab	Bottom of Slab	Bottom of Slab
Age at time of test: days	3-7	2-7	3-21
No. of sets of test results (n)	24	177	102
No. of pullout inserts in a set of test results	6-14 Average 9	2-14 Average 9	3-23 Average 12
Mean strength* of all sets of test results ($\bar{x}$) (MPa)	26.2	27.8	25.9
Mean standard deviation of all sets of test results σ (MPa)	3.5	2.4	2.8

b) Tests at Later Ages

	Trinity Square	College Park Phase II
Age at time of test: days	9-87	26-63
	(but usually 28 or close to 28)	
No. of sets of test results (n)	127	68
No. of pullout inserts in a set of test results	2	1-5 (usually 2)
Mean strength* of all sets of test results ($\bar{x}$) (MPa)	35.6	37.6
Mean standard deviation of all sets of test results σ (MPa)	4.1	4.2
Lowest test results (MPa)	30.9	30.7

* Compression strength values obtained from correlation curve. See Fig. 1.

TABLE III

28-Day Test Results

f'$_c$ 30 MPa

		Trinity Square		College Park Phase II	
		Pullouts	Standard Cylinders	Pullouts	Standard Cylinders
No. of results (sets of 2 cylinders)	n	84	84	15	15
Mean strength* (MPa)	$\bar{x}$	34.4*	38.8	35.9*	38.2
Standard deviation (MPa)	σ	2.7	3.9	2.7	3.5
Range (MPa):		30.5-44.5	29.9-47.7	32.5-40.5	30.9-43.5
Difference between f'$_c$ and $\bar{x}$		1.63 σ	2.26 σ	2.18 σ	2.34 σ
Expected percentage of results below f'$_c$		4.9	1.2	1.4	1
Actual percentage of results below f'$_c$		Nil	1.2	Nil	Nil

* From correlation curve. See Fig. 1.

TABLE IV

28-Day Cylinder Test Results

f'$_c$ 30 MPa

	Trinity Square	College Park Phase II
n	132	79
$\bar{x}$	39.5	39.1
σ	4.2	4.2

TABLE V
Pullout And Standard Cylinder Test Data
(Data Related To 28-Day In-Place Tests)

Age Hours	Initial Pullout Tests: n	$\bar{X}$	σ	Min.	28-Day Pullout Tests: 1	2	$\bar{X}$	28-Day Cylinder Tests: 1	2	$\bar{X}$
72	4	20.0	1.7	16.4	32.8	----	32.8	31.0	30.8	30.9
96	12	23.0	2.1	19.6	33.4	31.5	32.5	41.7	41.4	41.5
120	18	25.5	2.6	21.5	39.5	41.4	40.5	42.4	41.7	42.1
96	8	20.4	1.7	17.4	34.0	----	34.0	40.5	41.0	40.8
76	2	15.8	---	----	31.5	32.8	32.2	33.2	33.4	33.3
144	18	23.5	2.9	19.0	34.0 31.5	38.9	34.8	36.6	35.9	36.3
120	20	30.1	4.1	23.8	40.1 34.0	41.4 41.4	39.2	40.7	40.2	40.4
120	15	24.6	3.1	19.7	36.5	32.8	34.7	40.2	39.5	39.8
120	5	20.4	3.5	13.4	35.2 34.6	37.7 39.0	36.7	41.9	41.2	40.5
120	8	23.5	---	21.0	37.7	32.8	35.3	35.4	35.6	35.5
96	3	16.3	2.6	9.9	37.7	35.2	36.5	40.2	40.7	40.5
96	2	17.1	---	----	41.5	39.0	40.3	37.6	38.3	37.9
120	16	20.7	2.8	16.3	36.1 37.2	36.1	36.7	43.6	43.4	43.5
72	3	18.4	2.3	12.6	33.4 34.5	34.5	34.1	38.3	36.8	37.5
96	16	28.7	3.3	23.6	39.9	36.6	38.2	36.1	34.9	35.5

Note: All strength values in MPa.

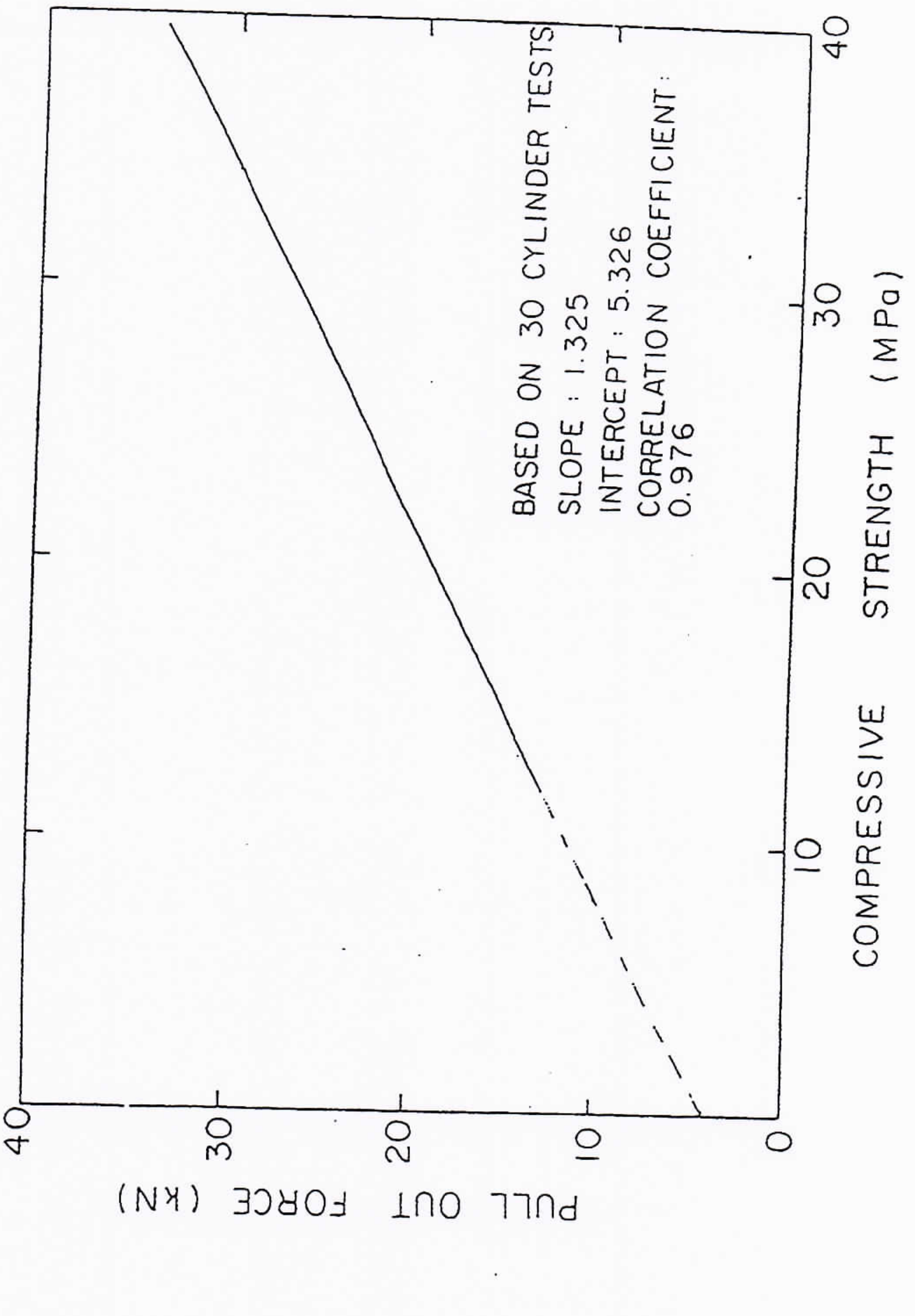

Fig. 1--Correlation curve: Trinity square
Pull out force versus cylinder compressive strength