

TRINITY SQUARE: COMMENTARY ON CONCRETE

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Trinity Square: Commentary on Concrete Test Data

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ABSTRACT: The paper describes the use of in-place testing instead of standard cylinder testing. Removal of forms and shores, and determination of concrete strength compliance with specifications were all controlled by pullout tests.

The criteria were written into the contract specification, and the relevant sections are quoted as a model for future use. Based on correlation with standard cylinder tests, the building officials allowed the elimination of the usual mandatory standard cylinder tests. Standard tests were made however to provide comparison with the in-place tests. The paper shows that the in-place test provided an adequate measure of the quality and strength of the concrete.

KEYWORDS: concretes, concrete structures, reinforced concrete, in-place testing, pullout testing, early form removal

The building, Trinity Square, is the new head office for Bell Canada in Toronto, Canada. The structural frame was completed late in 1981 and used 53,000 m³ of concrete. In building the reinforced concrete frame for this building, a number of innovative approaches to concrete technology were used to accelerate construction and optimize savings [1]. These were

- (1) the use of a 91-day criterion for specified strength in the vertical elements of the frame;
 - (2) extensive use of in-place testing of horizontal elements to (a) permit early removal of forms, (b) determine earliest acceptable initiation of reshoring, and (c) confirm in-place strength at 28 or later; and
- the elimination of the normal statutory requirement for standard concrete test cylinders for concrete that was tested by in-place test methods.

The main purpose of the paper is to show that in-place testing can be used alone to determine the strength of concrete in a structure.

Specification

Requirements for concrete were based on National Standard of Canada Concrete Materials and Methods of Concrete Construction (CAN 3-A23.1-M77). Quality requirements are similar to those specified in American Concrete Institute Standard (ACI) Building Code Requirement for Reinforced Concrete (ACI 318).

To enable early stripping of forms at whatever age produced optimum progress, alternative mixes for slabs were specified to meet a

strength requirement of 75% of the specified compressive strength of concrete f'_c at one, two, and three days, as well as meeting f'_c requirements at 28 days.

For in-place testing, the relevant specification clauses (ACI 318) 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 M³ pour of concrete. For pours in excess of 100 M³ provide at least an additional 1 insert per 28 M³. Install 2 additional pullout inserts per pour for testing at 28 days.

In the substructure install inserts on the top of slabs at random 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 test 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.

Correlation

In order to correlate pullout force with the compressive strength of standard cylinders, a total of thirty 150-mm-diameter 300-mm-long cylinders were cast from two loads of 30-MPa concrete. A pullout insert was fixed centrally and axially in the bottom of each cylinder mold before casting. At intervals, pairs of cylinders were tested to determine pullout force, and the cylinders were then capped and tested in compression [2]. The range of cylinder compressive strength was 5 to 35 MPa. Regression analysis of the data gave the following results:

¹ Vice-president, Trow Ltd., 43 Baywood Rd., Rexdale, Ontario, Canada M9V 3Y8.

slope = 1.325,
intercept = 5.326, and
correlation coefficient = 0.98.

Therefore, the relationship used to convert pullout force to equivalent standard cylinder compressive strength was

$$\text{in-place compressive strength (MPa)} = 1.325 \\ \times \text{pullout force (kN)} - 5.325$$

Statutory Requirement for Cylinder Tests

Building regulations require that concrete shall be sampled and tested in accordance with (CAN 3-A23.1-M77 quality requirements similar to those specified in ACI 318), and the specification for the project required this. However, on one previous project with the same structural engineer where in-place testing and an accelerated construction program had been used (Continental Bank), cylinder testing had, with the agreement of the Toronto City Building Department, been much reduced in the latter stages of the project. This was because all parties involved felt that the 28-day cylinders were meaningless for elements of the structure that had been given extensive in-place testing, and in which mixes having higher potential strength than that specified for structural reasons were being used in order to achieve acceleration.

On the Trinity Square project, in-place testing was used in the latter stages of the substructure in order to catch up with time lost through inclement weather. However, a full program of in-place testing was not applied until the superstructure was started. Discussions were held with the Toronto City Building Department well in advance of concreting. The Building Department had signified that they would be receptive to the elimination of concrete cylinders where elements were tested in-place, subject to receiving satisfactory correlation data.

At the start of the superstructure, therefore, a program of correlation tests was made to produce data showing the relationship between the compressive strength and the pullout strength of standard concrete cylinders. This was submitted to the Building Department, and approval was received early in the construction of the superstructure to eliminate concrete cylinders for slabs where in-place testing was being done.

Because of the size of the project, a resident technician from the testing company was available on site. Initial discussions with the ready mix supplier indicated that he was extremely negative towards the possibility of accepting tests other than standard cylinder tests on his concrete.

Because of the presence of a resident technician, it was therefore decided that standard cylinders would be cast at the minimum rates specified in the contract documents, so that these would be available in case the in-place tests indicated the possibility of low-strength concrete. If such an event occurred, standard cylinders would be available, and there would therefore be no potential legal problem should the contractor find it necessary to discuss with the supplier the possibility of concrete below the specified quality. As shown by the test data, none of the in-place test results indicated unsatisfactory strength, and the specified strength was met consistently by a wide margin.

However, in the interests of obtaining information for this paper and because having cast the cylinders, it was simple to cap and test them, the author carried out normal testing of these cylinders, but they were not reported to the client. As will be seen, the cylinder

tests confirmed that the concrete supplied was adequately represented by the in-place tests, and, in fact, no problem arose because of eliminating the testing of standard cylinders.

Test Procedures

Sampling, casting, curing, and testing of standard cylinders were performed in accordance with CAN 3-A23.1-M77 (equivalents ASTM Standard for Making and Curing Concrete Test Specimens in the Field [C 31] and Test for Compressive Strength of Cylindrical Concrete [C 39]). Pullout tests were made in accordance with ASTM Test for Pullout Strength of Hardened Concrete (C 900-78T). The pullout inserts used were 25 mm in diameter and were placed 25 mm from the concrete surface.

Test Data

The data were comprised of about 2500 standard cylinder tests and 2300 pullout tests.

Analysis of Data

In the absence of any recognized standard procedures, pullout test data have been analysed as follows.

1. Each set of test results consists of a number of pullout tests. For form removal the number is usually about ten, and for 28-day testing, two. The tables show these numbers.
2. Each pullout test result is converted to an equivalent standard cylinder's strength using the correlation data described above. The mean \bar{x} and standard deviation σ are calculated for each set of pullout tests.
3. Minimum in-place strength is calculated as follows:

$$\text{minimum strength} = \bar{x} - k\sigma$$

where k is a constant that varies depending on the number of pullout tests comprising a test result. Table 1 is used with the specific pullout system for the tests described in this paper [3].

Tests for form removal are made at the time at which it is estimated the maturity and strength of the concrete will meet form removal criteria. The age at which this occurs varies, and form removal test data given in the tables reflect this.

Substructure

A summary of standard cylinder test results analyzed in accordance with ACI 214 and pullout test results is given in Table 2. All cylinder tests met specification requirements.

TABLE 1—Variation of k depending on the number of pullout tests comprising a test result n .

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 2—Substructure test data.

Specified Strength	Standard Concrete Cylinder Tests Results		
	7 Day	28 Day	91 Day
25 MPa at 91 days, <i>n</i>	36	32	34
\bar{x} , MPa	22.8	28.2	32.0
σ , MPa	2.7	3.5	4.0
30 MPa at 28 days, <i>n</i>	not calculated	218	...
\bar{x} , MPa	...	37.8	...
σ , MPa	...	4.2	...
40 MPa at 91 days, <i>n</i>	85	80	81
\bar{x} , MPa	38.5	47.1	55.1
σ , MPa	3.6	5.2	5.1

PULLOUT TEST RESULTS*

30 MPa at 28 days	age at time of test between 3 and 9 days
	number of sets of test results = 61
	number of pullout tests in a set of test results = 4 to 12, average = 8
	mean strength (all results) = 25.3 MPa
	range of standard deviation for each set of pullout tests = 1.2 to 6.9 MPa
	mean standard deviation for all sets of pullout tests = 3.6 MPa

*Note: All pullout test results are for inserts placed in the top surface of the concrete slabs. Compressive strength values obtained from correlation curve.

TABLE 3—Superstructure test data.

Specified Strength	Standard Concrete Cylinder Tests Results		
	7 Day ^a	28 Day	91 Day
30 MPa at 28 days ^b , <i>n</i>	17	29	...
\bar{x} , MPa	30.4	37.3	...
σ , MPa	2.1	2.9	...
30 MPa at 28 days ^c , <i>n</i>	132	132	...
\bar{x} , MPa	32.6	39.5	...
σ , MPa	3.5	4.2	...
40 MPa at 28 days, <i>n</i>	67	70	...
\bar{x} , MPa	40.2	48.1	...
σ , MPa	4.0	4.5	...
30 MPa at 91 days, <i>n</i>	15
\bar{x} , MPa	31.1	37.0	42.4
σ , MPa	3.2	3.9	4.2
35 MPa at 91 days, <i>n</i>	63
\bar{x} , MPa	62	62	63
σ , MPa	31.4	37.9	43.6
40 MPa at 91 days, <i>n</i>	3.6
\bar{x} , MPa	2.6	3.0	45
σ , MPa	44	45	49.8
	35.2	42.6	4.5
	3.2	4.2	...

^aSeven-day test results are for one cylinder and 28- and 91-day test results are for sets of two cylinders.

^bTests on concrete in slabs before waiving of statutory requirements for cylinder testing.

^cTests after cylinder testing requirement waived.

Superstructure

A summary of standard cylinder test results are given in Table 3, and pullout test results are given in Table 4. Until typical floors were reached at Level 4, pullout inserts were placed in the top of slabs. From Level 4 onwards, the reusable forms were modified to allow the placing of pullout inserts in the bottom of slabs. The results of tests made at later ages to confirm strength at or about 28 days are also shown in Table 4. All cylinder test results met specification requirements.

There were 84 occasions on which in-place tests were made at 28 days and for which 28-day standard cylinder test results were also available. For both types of tests a result comprised two individual tests. This data are given in Table 5.

Discussion

While there is nothing new or special about the cylinder test data, these provide a reference point by which the in-place data can be judged. In assessing the data, a number of factors should be kept in mind.

Some of the 30-MPa at 28-days superstructure concrete was of higher strength to allow form stripping at early ages. Because most of the superstructure was placed in mild weather, only a small proportion of that concrete was of higher strength.

For all in-place tests the strength of the concrete is a function of the curing history of the concrete, and no data were kept on that. At 28 days, concrete does not necessarily have the same maturity in place as a 28-day standard cylinder, nor has the in-place concrete been kept saturated. Such tests only show the in-place strength at that location at the time and age of test.

A number of clear trends are evident, however. In-place strength increased with age and by a significant percentage even though no

special curing was provided, and the test method only tests the outer 25 mm of the slabs. In only 6 cases out of 127 were the pullout strength at later ages equal to, or slightly less, than the pullout strength at the time of stripping. The former were determined by two random tests and the latter by about ten random tests.

In all six cases 28-day standard cylinder strengths were satisfactorily greater than the early in-place tests and confirmed adequate concrete strength potential.

The variability of concrete in a pour judged by the in-place tests at early ages was very similar to that which we have found on many other sites, the mean standard deviation being about 3.2 MPa.

It will be seen that the standard cylinders confirm the ultimate acceptability of the concrete but eliminating them does not make the assessment of the quality of concrete difficult. Based on in-place tests at either early ages or later ages, the concrete is acceptable. The two together also confirm satisfactory strength gain with age.

Since the tests at later ages merely involved testing two inserts placed as part of the group from which the early tests are made, providing later age in-place tests was simple and cheap.

Provided, therefore, that there is some control of the age and water content of the concrete at the time it is delivered, the in-place testing program used eliminates the need for cylinder testing for the client and his construction team. With regard to the legal position between the supplier and the buyer, the failed cylinder test is seldom accepted by either party. When there is a low cylinder test result, the parties to a contract usually make tests on the concrete in-place.

With regard to the use of a 91-day criterion for specified strength for the columns and other vertical elements, relationships between strength at 7, 28, and 91 days for standard cylinders were very consistent for all mixes (Fig. 1). This reinforces the concept that strength at later ages can be predicted from tests at early ages. It is suggested, therefore, that having established these relationships, testing for 91-day specifications could be safely terminated with 28-

TABLE 4—Superstructure test data pullout test results.*

Tests	Inserts Placed In	
	Top of Slab	Bottom of Slab
Form Removal		
Age at time of test, days		
Number of sets of test results n_1	3 to 7	2 to 7
Number of pullout inserts in a set of test results, MPa	24	177
Mean strength of all sets of test results \bar{x}_1 , MPa	6 to 14 average 9	2 to 14 average 9
Standard deviation of standard deviations of all sets of test results σ_1 , MPa	26.2	27.8
	3.5	2.4
		(174 results)
LATER AGES		
Age at time of test, days	9 to 87 but usually 28 or close to 28	
Number of sets of test results	127	
Number of pullout inserts in a set of test results	2	
Mean strength of all sets of test results, MPa	35.6	
Standard deviation of all sets of test results, MPa	4.1	
Lowest test results, MPa	30.9	

*Compressive strength values obtained from correlation curve.

day cylinder testing or earlier. With the increasing use of 56- and 91-day strength requirements for vertical elements, particularly for high-strength concrete, reliable prediction of ultimate strength at early ages is important. Otherwise failure to meet strength requirements will not be discovered until significant numbers of floors have been built above the defective floor.

The data in Table 5 show the relationship between 28-day in-place pullout tests and standard cylinder tests at the same age. It will be seen from the data, that the variability of the strength of the in-place tests is of the same order as that of cylinder tests over the period of the contract. For the standard cylinders, both the actual and expected percentage of results below f_c^1 was the same (that is, 1%), and the only set of cylinders below f_c^1 had a strength of 29.9 MPa. With regard to the in-place tests, no pullout test results fell low the equivalent of f_c^1 , although statistically 5% would have been expected. The average in-place strength as determined by pullout tests was 89% of the average core strength of standard cylinders. When tests are made on concrete in a structure by coring, both American and Canadian codes accept the concrete as structurally acceptable if the average core strength is equal to, or exceeds 85% of f_c^1 and no result is below 75% of f_c^1 . If, therefore, we accept that 0.85 f_c^1 is acceptable for all in-place tests then an average strength of

25.5 MPa for the in-place tests would meet strength requirements. If this value is taken, then the difference between f_c^1 and the average strength is 3.3 standard deviations and the estimated number of results below f_c^1 becomes 1 in 1000.

Table 6 gives the results of tests on six pours in which inserts were placed in both the top and bottom of the slab. Variability was similar for both locations, but on average the in-place strength indicated by the pullout tests was about 6% less at the top of the slabs than at the bottom.

Conclusions

The elimination of standard cylinders did not make the assessment of concrete quality more difficult.

TABLE 5—28-day test results f_c^1 30 MPa.

Parameters	Pullouts	Standard Cylinders
Number of results n	84	84
Mean strength \bar{x} , MPa	34.4	38.8
Standard deviation σ , MPa	2.7	3.9
Range, MPa	30.5 to 44.5	29.9 to 47.7
Difference between f_c^1 and \bar{x}	1.63 σ	2.26 σ
Expected number of results below f_c^1	4 (4.9%)	1 (1.2%)
Actual number of results below f_c^1	nil	1 (1.2%)

*From correlation curve.

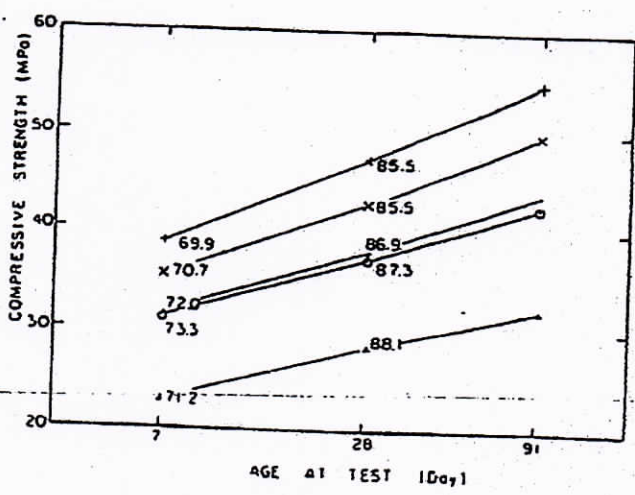


FIG. 1—Age-strength relationship.

TABLE 6—Comparison of top and bottom inserts in the same concrete placement.

Location ^a	Number of Inserts	Mean Strength, MPa ^b	Standard Deviation, MPa	Calculated Minimum Strength, MPa ^b
T	6	22.6	1.2	20.3
B	8	23.8	1.3	21.5
T	5	22.9	1.0	20.9
B	9	27.6	2.1	24.1
T	5	21.2	3.2	14.9
B	3	21.3	2.0	16.2
T	8	23.1	1.3	20.8
B	9	22.9	1.2	20.9
T	10	29.5	2.5	25.3
B	10	29.7	2.2	26.0
T	9	25.1	1.0	23.4
B	10	28.8	2.2	25.2

^aT is inserts in the top of slab and B is inserts in the bottom of slab.
^bCompressive strength values obtained from correlation curve.

The in-place tests also confirmed a satisfactory strength gain with age and demonstrated that in-place tests at later ages can be used for the assessment of the acceptability of a concrete structure as well as early in-place strength tests, and both can be used together or separately instead of standard cylinder tests.

Cylinder test data at ages up to 91 days confirm that strength at later ages can be accurately predicted by tests at early ages. The data also show that pullout inserts can be used either in the bottom or the top of a slab and that both procedures have about the same variability although the strength in the top of a slab is about 6% less than that of the bottom of a slab.

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