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A NONDESTRUCTIVE TESTING PROCEDURE
FOR IN-PLACE EVALUATION OF FLEXURAL
STRENGTH OF CONCRETE

A. S. Nishikawa

PURDUE UNIVERSITY

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Informational Report

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OF FLEXURAL STRENGTH OF CONCRETE

TO: R. L. Eskew, Chairman
Joint Highway Research Project

August 30, 1983

FROM: H. L. Michael, Director
Joint Highway Research Project

File: 7-1

Attached is a Report titled "A Nondestructive Testing Procedure for In-Place Evaluation of Flexural Strength of Concrete". It is submitted as an Informational Report because of its possible usefulness to DOH.

The research was performed in the Structural Engineering Area of the School of Civil Engineering. Mr. Alvin S. Nishikawa was the student researcher with faculty guidance from Professors W. F. Chen, M. Yener and C. F. Scholer.

The research reported herein had as its objective the development of empirical relationships correlating breakoff strength and flexural strength as measured by the conventional beam test. The objective was accomplished with the results detailed in the report.

Respectfully submitted,

Harold L. Michael
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Informational Report

A NONDESTRUCTIVE TESTING PROCEDURE FOR IN-PLACE EVALUATION
OF FLEXURAL STRENGTH OF CONCRETE

by

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This research was performed by the author under the direction of Professors W. F. Chen and M. Yener in partial fulfillment of the requirements for the MSCE Degree.

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TABLE OF CONTENTS

	Page
LIST OF TABLES	vi
LIST OF FIGURES	vii
ABSTRACT	x
CHAPTER I - INTRODUCTION	1
1.1 General	1
1.2 Objectives	2
1.3 Scope	3
CHAPTER II - TESTING PROGRAM	5
2.1 General	5
2.2 Cylinder Test	8
2.3 Beam Test	9
2.4 Breakoff Test	12
2.4.1 The Principle of the Test Method	12
2.4.2 Testing Apparatus	14
2.4.3 Testing Procedure	16
CHAPTER III - EVALUATION OF TESTING PROGRAM	24
3.1 General	24
3.2 Within Test Variation	25
3.3 Analysis of Variance	26
3.4 Evaluation of Figure 14	35
3.5 Regression Analysis	39

TABLE OF CONTENTS, cont'd

	Page
CHAPTER IV - CONCLUSION AND RECOMMENDATIONS . . .	49
4.1 Conclusions.	49
4.2 Recommendations for Further Research . . .	52
LIST OF REFERENCES.	55
APPENDICES	
Appendix A: Original Test Data	57
Appendix B: Detailed Description of the Norcem Load Apparatus.	62

LIST OF TABLES

Table	Page
1. Variations within parameters being investigated.	6
2. Constitutive makeup, curing condition, and age of each batch	7
3. Within test variation (COV, %) of all tests performed	26
4. F statistics and corresponding levels of significance for the breakoff and cylinder tests.	35
5. Data used in regression analysis to obtain equation 3	41
Appendix	
Table	
A1.Original Test Data.	58

LIST OF FIGURES

Figure	Page
1. Schematic diagram and critical dimensions of three point loading device for the beam test. .	10
2. Beam specimen being loaded by the Universal testing machine	11
3. Ruptured specimen	11
4. Schematic of concrete core projection established by the tubular form and location of applied load.	13
5. Norcem Breakoff Tester loading apparatus. . . .	15
6. Calibration of the Norcem apparatus manometer	15
7. Layout of breakoff specimens in the test slab	17
8. Insertion of tubular forms into fresh concrete.	18
9. Influence of tubular forms on adjacent aggregate.	18
10. Removal of tubular form with use of key	21

LIST OF FIGURES, cont'd

Figure	Page
11. Application of load on concrete core.	21
12. Calibration of manometer pressure to breakoff strength obtained from this manufacturer's graph.	22
13. Damaged region due to concrete core removal . .	23
14a. Profiles of breakoff test and beam test with respect to water-cement ratio.	29
14b. Profiles of breakoff test and beam test with respect to age of concrete	30
14c. Profiles of breakoff test and beam test with respect to curing environment.	31
14d. Profiles of breakoff test and beam test with respect to cement type	32
14e. Profiles of breakoff test and beam test with respect to aggregate shape	33
14f. Profiles of breakoff test and beam test with respect to aggregate size.	34

LIST OF FIGURES, cont'd

Figure	Page
15. Data used in obtaining regression Equation (3).	45
16. Data used in obtaining regression Equation (4).	46
17. Best fit curves representing breakoff and beam strength using only the mean values. .	47
18. Relationship between beam strength and breakoff strength	48
Appendix	
Figure	
B1. Schematic of Norcem Load Apparatus.	65

ABSTRACT

Nishikawa, Alvin S., M.S.C.E., Purdue University, August 1983.
Breakoff Method: A Nondestructive Testing Procedure for
In-Place Evaluation of Flexural Strength of Concrete.
Major Professors: Muzaffer Yener and Wai-Fah Chen.

The primary objective of this research was to develop empirical relationships correlating breakoff strength and flexural strength as measured by the conventional beam test. To accomplish this objective, the differential influence of several potentially significant parameters were investigated. The parameters considered were (a) aggregate size, (b) aggregate shape, (c) water-cement ratio, w/c, (d) age of concrete, (e) curing conditions, and (f) cement type. In order to determine a possible correlation between the breakoff strength and compression strength of concrete, conventional cylinder tests were also carried out. A total of 122 breakoff, 140 beam and 110 cylinder tests were carried out.

Evaluation of the results has indicated that w/c ratio, age of concrete, curing condition, and cement type have a significant differential effect on the breakoff and beam tests. On the other hand, all six parameters were

found to have a differential effect on the breakoff and cylinder tests. Concluding that the correlation between breakoff strength and compressive strength would be highly impractical, linear regression analyses were performed only to correlate beam strength with breakoff strength as a function of the w/c ratio. It should be noted that the resulting statistical relationships so obtained are valid only for the specified type of cement, age of concrete, and curing condition.

It was found that, by passing best fitting curves through the means of the breakoff and beam test data, the differential effect of w/c ratio may be neglected for a practical range of w/c ratios. Thus, by normalizing beam strength with breakoff strength, and plotting the f_{bm}/f_{bo} ratio against the w/c ratio, it became evident that the beam strength may be approximated as being 78% of the breakoff strength, independent of w/c ratio. This approximation is valid for 7 day strength, Type I cement concrete cured under moist conditions.

CHAPTER I

INTRODUCTION

1.1 General

Presently, there exist several methods which predict the in-place strength of concrete. Of these methods, only the Pullout Test [5,6,7] and the Breakoff Test [1,2,3,4,8,13,15] directly measure a strength parameter. The Pullout test appears to directly measure compressive strength and the breakoff test the flexural strength. Other methods, such as the Penetration Test [8,9,10,11], Concrete Hardness Test [8,9,10,11], Ultrasonic Pulse Velocity Method [8,11], and the Maturity Method [8,9,11] all measure a substitute parameter.

In current practice, the cylinder test is normally used to determine the compressive strength and the beam test is used for flexural strength of concrete. It has long been argued that the strength of the concrete in the actual structure itself may deviate significantly from that of the test specimen cast from the same concrete. The difference in strength may be due to different transport, casting, compacting and/or curing. In view of this, it may

be concluded that tests based on conditions other than those that exist at the actual site may be misleading. This in turn may cause unwarranted failure of structures either during or after completion. Hence, it is clear that while cylinder tests are of the utmost importance, the determination of concrete strength in the structure at critical stages of its life is imperative.

The traumatic cooling tower failure in West Virginia early in 1978 has focused the American Government's interest on the desirability and necessity of adopting an in-place method of determining concrete strength. At the Fall Convention of the American Concrete Institute, an entire symposium was devoted to this subject. A past president of ACI put it this way: "I'm not aware of an example where collapse followed the verification of concrete quality by in-situ testing" [2].

1.2 Objectives

The primary objective of the present investigation was to develop empirical relationships correlating break-off strength, as measured by the NORCEM Breakoff Tester, to the flexural strength, as measured by the conventional beam test, since it appears that concrete behavior is basically similar under both test methods. The principle of the Norcem tester is discussed in Chapter 2, and its description is given in Appendix B.

Unlike earlier investigations of the breakoff test method [2,3,4,8], in which only two to three variables were considered, this program examined six common variables which may differentially affect the strength as measured by conventional cylinder and beam tests, as well as the breakoff test. The following potentially significant variables were considered; (1) water-cement ratio, (2) aggregate size, (3) aggregate shape, (4) age of concrete, (5) curing conditions and (6) cement type.

In order to evaluate a test method for suitability in practice, its reproducibility should be thoroughly checked. Hence, the secondary objective of this study was to evaluate the within test variation of the Norcem Breakoff Test Method. The Norcem breakoff tester has been widely used in Norway during the last few years. Furthermore, cylinder tests were also conducted to explore the possibility of substantial correlation between the breakoff strength and the cylinder compressive strength of concrete. It should be noted, however, that considering the mode of concrete behavior under the two test procedures, a practical suitable correlation should not be expected.

1.3 Scope

The details of the testing program are discussed in Chapter II. Section 2.1 gives a general overview of the testing program, whereas the details of the cylinder test,

beam test, and the breakoff test procedures are discussed in sections 2.2, 2.3, and 2.4.3, respectfully. The principle behind the breakoff method , as well as a brief discription of the apparatus, are presented in sections 2.4.1 and 2.4.2.

Chapter III includes a critical look into the within test variation of the test methods, analysis of variance, and the regression analysis in their respective sections 3.2, 3.3 and 3.4. Conclusions and recommendations for further research are listed in the final Chapter (Chapter 4). This Chapter is then followed by a list of references and two Appendices. The original test data are given in Appendix A, while Appendix B gives a detailed description of the Norcem breakoff tester.

CHAPTER II

TESTING PROGRAM

2.1 General

In order to determine the effects of each parameter on the breakoff test, beam test, and cylinder test separately, a single parameter at a time was experimentally examined while keeping all others at their standard values. The variations within each parameter are indicated in Table 1. In columns 1 through 8 of Table 2, the contents of the original 11 batches of concrete are given. The curing conditions that the specimens made from these batches were subjected to, and the age at which they were tested, are listed in columns 9 and 10, respectively.

As indicated in Table 2, the standard combination of parameters, (batch No. 2) was chosen to be the following:

Parameter -----	Variations -----
Water-Cement Ratio	0.44
Cement Type	I
Maximum Aggregate Size	0.5" (1.3 cm)
Aggregate Shape	Rounded
Curing Condition	Moist
Age of Concrete	7 days

Table 1. Variations within parameters being investigated.

PARAMETER	VARIATIONS WITHIN THE PARAMETER
Water-Cement Ratio	0.41, 0.44, 0.53
Cement Type	Type I, Type III
Aggregate Size	3/8", 1/2", 3/4", 1"
Aggregate Shape	Rounded, Crushed
Curing Conditions	Moist, Dry
Age of Concrete	7-days, 28-days

The original batches No. 1, 2, and 3, were used to examine the effect of the water-cement ratio on concrete strength as measured by cylinder, beam, and breakoff tests. The effect of the cement type was examined using batches 2 and 11. Batches No. 2, 4, 5, and 6 were prepared

Table 2. Constitutive makeup, curing condition, and age of each batch.

(1) Batch No.	(2) W/C Ratio *	(3) Cement (lb/yd ³)	(4) Coarse Aggregate (lb/yd ³)	(5) Sand (lb/yd ³)	(6) Cement Type	(7) Max. Aggr. Size (in.)	(8) Aggr.** Shape	(9) *** Curing Conditions	(10) Age (days)
1	0.41	817.1	1509.8	1273.3	I	1/2	R	M	7
2	0.44	761.4	1509.8	1321.2	I	1/2	R	M	7
3	0.53	632.1	1509.8	1430.4	I	1/2	R	M	7
4	0.44	761.4	1509.8	1321.2	I	3/8	R	M	7
5	0.44	704.6	1697.9	1244.3	I	3/4	R	M	7
6	0.44	681.8	1829.5	1178.2	I	1	R	M	7
7	0.44	761.4	1471.6	1375.9	I	1/2	C	M	7
8	0.44	761.4	1509.8	1321.2	I	1/2	R	D	28
9	0.44	761.4	1509.8	1321.2	I	1/2	R	M	28
10	0.44	761.4	1509.8	1321.2	I	1/2	R	D	7
11	0.44	761.4	1509.8	1321.2	II	1/2	R	M	7
12	0.35	957.1	1509.8	1155.9	I	1/2	R	M	7
13	0.38	881.6	1509.8	1218.7	I	1/2	R	M	7
14	0.47	712.8	1509.8	1360.9	I	1/2	R	M	7

* W/C Ratio is by weight

** R=Rounded, C=Crushed

*** M=Moist, D=Dry

to examine the aggregate shape. Batches No. 2 and 10 were utilized to study the effects of the curing conditions at 7 day strength and batches No. 8 and 9 at 28 days. To study the the effect of the age of concrete, batches No. 2 and 9 were prepared.

A Lancaster model 30-DP mulling-mixer was used to prepare each of the eleven batches. From each batch ten cylinders, ten beams and a slab containing twelve tubular breakoff forms were cast. Details of each test preparation and test procedure are discussed in the following sections. The original data obtained for each batch made during the course of this investigation are listed in Appendix A, Table A1.

2.2 Cylinder Test

The standard 6x12 inch cylinders were selected due to their availability and common use in practice. Ten cylinders were cast and compacted according to ASTM C39-Method, Test for Compressive Strength of Molded Concrete Cylinders. The specimens were allowed to harden in the laboratory for twenty-four hours prior to being demolded, at which time they were allowed to cure under appropriate conditions in the laboratory.

The specimens were then capped and the compressive tests were performed on the concrete cylinders as specified by ASTM C39-72, Compressive Strength of Cylindrical

Concrete Specimens. The load was applied by a Forney model No. FT-0040-DR hydraulic compressive testing machine, at a rate of approximately 1000 lbs/sec. The load at which failure occurred was recorded. The test data are presented in Appendix A for each batch.

2.3 Beam Test

3x4x16 inch beams were used due to the availability of the reusable steel molds. The beams were cast in two separate lifts, each being rodded fifty-five times. The ten beam specimens were allowed to harden in the laboratory for twenty-four hours prior to being demolded and placed into the proper curing environment.

The three point flexural test was performed as specified by ASTM C78-75; Flexural Strength of Concrete. Each beam was simply supported with a twelve inch clear span and a two inch overhang at each end. Equal loads were then applied at the third points as illustrated in Figures 1 and 2.

The load was applied by a 100,000 lb. capacity Universal hydraulic operated testing machine (Southwark-Emery). Loading was done at a constant rate of approximately 600 lbs/min. until rupture occurred, as illustrated Figure 3. The total load at rupture is listed in Appendix A.

Figure 1. Schematic diagram and critical dimensions of three point loading device for the beam test.

Figure 2. Beam specimen being loaded by the Universal testing machine.

Figure 3. Ruptured specimen.

2.4 Breakoff Test

2.4.1 The Principle of the Test Method

The breakoff method is the only nondestructive testing procedure presently available for the in-place determination of flexural strength of concrete. The method is based on direct measurements of flexural strength of concrete in a plane parallel to and at a certain distance from the surface. The region which is to be investigated is established by inserting tubular forms into fresh concrete, immediately after casting and leveling. At the time of testing the forms are removed, thereby establishing a narrow tubular slit surrounding a concrete core projection. A splitting force in the upper zone is introduced until rupture occurs. This principle is illustrated in Figure 4. In essence, the procedure is similar to a cantilever beam subjected to a concentrated force at its free end.

In its present form, the breakoff procedure is simple and can be conducted very rapidly. Since the forms are placed into fresh concrete, this procedure is primarily applied for the flexural strength determination of fresh concrete. Special diamond drills have been used to adapt the procedure for the determination of in-place concrete strength in existing structures. The drills are capable of establishing tubular slits in hardened concrete without affecting the test results [2].

Figure 4. Schematic of concrete core projection established by the tubular form and location of applied load.

2.4.2 Testing Apparatus

The loading apparatus consists of two separate main components; a tubular shaped load cell connected through a flexible delivery hose to a hydraulic hand pump and a manometer, as illustrated in Figure 5. The pressure reading of the manometer is recorded in units of kp/square centimeter as shown in Figure 6 (1 kp = 9.807N or 1 kp = 2.205 lbs.). A detailed description of the loading device is given in Appendix B.

The tubular shaped disposable forms are made out of plastic and have a coating of temperature resistant slip agent. These forms are easily removed from the concrete by the aid of a special tool (a key) that is a standard accessory (see Figure 10).

Figure 5. Norcem Breakoff Tester loading apparatus.

Figure 6. Calibration of the Norcem apparatus manometer.

2.4.3 Testing Procedure

A minimum of five inch center-line to center-line spacing and a minimum depth of four inches for the tubular forms were used as a guide [3] in adapting the 23x23x4.75 inch slab. Originally the slab was to contain sixteen tubular forms, but later 12 breakoff specimens for each batch was thought to be statistically sufficient. This resulted in more than adequate center-line spacing and sufficient depth. The layout of the tubular forms is shown in Figure 7.

The form for the concrete slab was constructed out of 3/4 inch plywood. Grease was applied to the interior face of the plywood form to provide a water tight seal. The slab was cast in two lifts, each being rodded four hundred times. The tubular forms were then carefully inserted by hand with a twisting motion. In batches with the lower water-cement ratios, a depression always occurred within the confines of the tubular forms. Also, the concrete adjacent to the exterior face of the tubular forms, bulged upward in the insertion process. This raised portion of concrete was then utilized to fill the depression until the entire slab had a smooth and level surface. Figure 8 illustrates the insertion process, while Figure 9 illustrates the resulting depression and slight bulge as well as the final seating of the tubular forms.

Figure 7. Layout of breakoff test specimens in the test slab.

Figure 8. Insertion of tubular forms into fresh concrete.

Figure 9. Influence of tubular forms on adjacent aggregate.

It appears that one difficulty would consistently occur while placing the tubular forms; smooth insertions would be interrupted by large aggregates as the tubular forms are placed. The tubular forms would then have to be slightly juggled from side to side. This usually alleviates the problem and smooth insertion can be continued.

Similar to the cylinders and beams, the slab was allowed to harden in the laboratory for twenty-four hours. Following this period, the slab mold was removed and the specimen was allowed to cure under proper environmental conditions. Tubular forms remained in place during the curing stage and were removed just prior to the performance of the breakoff test. Figure 10 illustrates the removal of the tubular forms.

An opening in which the load cell would rest was left after the removal of the forms. The load cell is self-positioning, such that the location of the applied load is automatically established. The load cell was in turn connected to a hand pump that controlled the rate of load application, as shown in Figure 11. The cores were loaded at a rate of 2.5 kp/cm^2 (35.56 psi) per second. This load rate was applied until the core ruptured in flexure and the corresponding pressure reading of the manometer recorded. The pressure reading was then converted to the breakoff strength of the core using a typical calibration curve shown in Figure 12 [16]. After the completion of the

test, the resulting void left by the removal of the core (Figure 13) could easily be filled with fresh concrete. Thus, in practice, the original surface contour could be reestablished to appear as a nondestructured surface.

Originally, excluding three deficient breakoff tests, a total of 107 breakoff, 110 beam and 110 cylinder tests were performed. Several breakoff tests were considered deficient because failure did not take place at the base of the core, but instead occurred at a closer distance to the applied transverse load. This suggested that an imperfection or poor compaction existed in the region. The data was therefore disregarded. All other breakoff data were recorded and are presented in Appendix A along with data points for the cylinder and the beam tests made from the original eleven batches.

Figure 10. Removal of tubular form with use of key.

Figure 11. Application of load on concrete core.

Figure 12. Calibration of manometer pressure to breakoff strength obtained from this manufacturer's graph.

Figure 13. Damaged region due to concrete core removal.

CHAPTER III

EVALUATION OF TESTING PROGRAM

3.1 General

In order to accomplish the objectives of the investigation, the data collected on the original sets of specimens were analyzed using appropriate statistical procedures. In order to determine the degree of reliability of the present breakoff test method, the within test variation of the method was statistically compared with that of accepted procedures. Later, two-way analyses of variance were carried out to determine whether any of the parameters studied had a differential effect on the relationship between breakoff and beam tests, and between breakoff and cylinder tests. If a differential effect was detected, the parameter involved was studied further.

3.2 Within Test Variation

The distribution of the experimental data indicates that the breakoff test method has the highest within test variation (Coefficient of Variation, COV) of the three test methods examined. Table 3 lists the COV for each batch. The average within test variation (percentage) was found to be 3.3 for the cylinder test, 7.5 for the beam test, and 9.1 for the breakoff test.

Using the average COV and utilizing alpha-P curves [11], it can be shown that 5 breakoff tests are sufficient to obtain 90% probability that the average strength obtained is within 10% of the actual average breakoff strength of the concrete.

Table 3. Within test variation (COV, %) of all tests performed.

Batch No.*	Cylinder Test	Beam Test	Breakoff Test
1	1.9	6.2	5.1
2	2.6	5.0	11.2
3	3.5	8.2	6.2
4	3.1	7.5	4.7
5	4.2	6.0	9.0
6	4.0	10.3	13.3
7	3.6	5.9	8.0
8	2.9	8.7	13.4
9	4.5	4.2	7.0
10	4.3	9.4	9.4
11	2.3	7.9	10.2
12		7.8	3.2
13		4.2	13.2
14		13.0	13.7
Average	3.3	7.5	9.1

*Refer to table 2.

3.3 Analysis of Variance

In an effort to identify the parameters which do have a differential effect on the beam and breakoff tests, as well as on the breakoff and cylinder tests, two-way analyses of variance (type of test by level of parameter) were performed on the original eleven batches. These analyses were done by implementing the use of the Statistical Package for the Social Sciences, SPSS Version 8.3, and a significance level, p , of 0.05 or less was established as the criterion of significance. In the analyses on the breakoff and beam test results, significant interactions between type of test and level of parameter were evident

for the following parameters: (a) water-cement ratio ($F = 7.128$, $p < 0.002$), (b) age of concrete ($F = 21.196$, $p < 0.001$), (c) curing conditions ($F = 4.239$, $p < 0.047$), and (d) cement type ($F = 5.616$, $p < 0.023$). Subsequent Newman-Keuls analyses confirmed that these significant results were due to the differential effects of the various levels of each parameter on the breakoff and beam tests. Analysis of variance results for aggregate shape ($F = 0.521$, $p < 0.475$) and aggregate size ($F = 2.259$, $p < 0.089$) indicated no significant interaction; therefore, no differential effects.

Profiles of the breakoff test and beam test with respect to water-cement ratio, age of concrete, curing conditions, cement type, aggregate shape, and aggregate size are shown in Figures 14a through 14f, respectively. All data points are plotted, and the mean values of the data from each test at each level of a parameter are connected to form a profile. These profiles graphically illustrate the relationships between the two tests for each parameter. In general, parallel or nearly parallel profiles would indicate no significant differential effect of the parameter on the results of the breakoff and beam tests. The significant deviations from parallel, for the first four parameters listed, are readily evident by inspection of the profiles in Figures 14a through 14d. For example, Figure 14a shows that the differences between the

breakoff and beam test results are greater at some levels of water-cement ratio than at others. The relatively smaller deviations from parallel in Figures 14e and 14f are statistically nonsignificant.

The analysis of variance on the breakoff and cylinder test data resulted in significant interactions between type of test and all of the variables considered (Table 4), indicating that the relationship between the breakoff and cylinder strengths would be highly nonlinear. On the basis of this evidence, a linear regression analysis was performed only to determine the correlation between break-off strength, f_{bo} and beam strength f_{bm} . Thus, in general the beam stress is expected to be a function of the variables indicated in Equation 1 below.

$$f_{bm} = F(f_{bo}, w/c, \text{age}, \text{curing}, \text{cement type}) \quad (1)$$

Figure 14a. Profiles of breakoff test and beam test with respect to water-cement ratio.

Figure 14b. Profiles of breakoff test and beam test with respect to age of concrete.

Figure 14c. Profiles of breakoff test and beam test with respect to curing environment.

Figure 14d. Profiles of breakoff test and beam test with respect to cement type.

Figure 14e. Profiles of breakoff test and beam test with respect to aggregate shape.

Figure 14f. Profiles of breakoff test and beam test with respect to aggregate size.

Table 4. F statistics and corresponding levels of significance for the breakoff and cylinder tests.

Parameter	Value of F	Significance of F, p
Water-Cement Ratio	243.411	0.001
Age of Concrete	87.301	0.001
Curing Condition	47.805	0.001
Cement Type	150.018	0.001
Aggregate Shape	10.773	0.001
Aggregate Size	16.793	0.001

3.4 Evaluation of Figure 14

The trend of test results shown in Figure 14a is as expected. Both the beam and the breakoff strengths increase as the w/c ratio decreases. Furthermore, the beam tests yield lower strength than breakoff tests. This behavior is attributed to the fact that failure may initiate at the weakest section within the uniform moment region in beam tests (weak-link theory). On the other hand, the critical section at which rupture occurs is at one location, namely at the bottom of the breakoff specimen.

Figure 14b illustrates that the breakoff test is not sensitive to the age difference while the beam strength increases considerably as the age of concrete is increased from 7 days to 28 days. This may be attributed to the fact that the w/c ratio at the critical section in the breakoff test is not noticeably altered within these age limits. On the other hand, the rate of hydration is much higher at

the critical outer surface of the beam specimens.

It is speculated here that the reason why the age of testing has indicated a significant differential effect on the breakoff and beam tests is due to the procedures followed in the test methods involved. If the critical point of maximum tensile stress, where rupture is assumed to initiate in breakoff tests, experiences the same curing condition with age as in the beam tests, it is possible that breakoff strength may show similar sensitivity to the age of concrete. This speculation can be easily verified experimentally by removing the tubular forms from the slab at the same time the beam molds are stripped. This would expose the critical section in breakoff tests to free air during the curing period. With the increased rate of hydration, if adequate curing time is allowed, concrete properties at the outer surface of beams and at the outer periphery of the critical section in breakoff specimens may be similar.

The fact that the level of the critical section influences the breakoff strength may be alternatively verified by casting a 3"x4"x16" beam, as well as a 3"x8"x16" beam from the same batch of concrete. At 28 days the 3"x8"x16" beam may be cut at its middepth, such that the resulting beam is identical in size to the 3"x4"x16" beam. Both beams can then be loaded at the third points as in the standard flexural test, with the freshly cut face of

the beam as the extreme fiber in tension. If the level of the critical section does have an influence, both beams will differ in strength by an amount approximately equal to that observed between breakoff and beam tests using present testing procedures. This would be true provided the mode of concrete behavior both in breakoff and beam tests is the same.

The above speculation raises another interesting argument. Assuming the critical state of stress in the concrete under both breakoff and beam tests is similar, and if the concrete properties at the time of testing are identical, the only reason why the breakoff strength is higher than the beam strength would be due to the weak-link theory. Hence, if the beam test is carried out in such a manner that the uniform moment region is eliminated, it is reasonable to assume that both a beam loaded at its midspan and a breakoff specimen which is allowed to hydrate at a similar rate should yield the same results. To experimentally verify this observation, beam tests with one point loading can be conducted at 28 days and results compared with corresponding breakoff tests with the tubular forms removed during the curing period.

Figure 14c illustrates that, for tests conducted at 7 days, the breakoff strength is only slightly sensitive to the curing conditions. It is speculated that 7 days is insufficient time to affect the critical section in the

breakoff test, 70mm (2.75 inches) below the surface. Apparently, efforts to moist-cure the slab have very little effect on the critical surface within 7 days. On the other hand, beam specimens where the critical surface is directly exposed to the environment register a significant difference in strength.

As indicated in Figure 14d, it appears that the breakoff strength is only slightly sensitive to the types of cement considered. Although types I and III have identical chemical make-up, they do differ in the percentages of each component chemical. It appears reasonable to believe that the local conditions at critical sections within the specimen affect the rate of chemical interaction. Apparently, 7 day curing time is not sufficient to activate the necessary chemical interactions to the desired degree in breakoff tests.

Unless very high strength concrete or weak aggregate are used, the rupture due to flexural loading is controlled by the aggregate-cement bond. It is therefore expected that the aggregate shape and size would not have considerable effect on either the breakoff or the beam test method. As indicated by the statistical analysis and as can be seen from Figures 14e and 14f, neither beam tests nor breakoff tests are sensitive to aggregate shape or size.

From the arguments presented in this section it appears that the differential effects reflected by the statistical analyses for most of the variables may not be due to differences in test methods but due to actual differences in concrete properties at different critical section levels. Hence, if these observations can be verified experimentally as outlined in this section, the breakoff test method as is may prove to be a very reliable nondestructive testing procedure for determining flexural strength of in-place concrete. In the absence of further experimental evidence, these observations remain only as speculations.

3.5 Regression Analysis

Considering that the age of concrete, the curing conditions and the cement type are discrete parameters, a linear regression analysis was performed on the effects of water-cement ratio only. Thus, to obtain statistically reliable equations, additional breakoff and beam tests were carried out varying only the water-cement ratios. The general form of such an equation is given in Equation 2, which would be valid for specific values of concrete age, curing conditions, and cement type; specifically 7 day strength, moist curing, and type I cement.

$$f_{bm} = f(f_{bo}, w/c) \quad (2)$$

Three additional batches with $W/C = 0.35$, 0.38 , and 0.47 were made. Specimens were prepared and tested in the same manner as the original eleven batches. Several of these additional breakoff tests were rejected on the basis that, on the first load application, specimens did not rupture within the loading capabilities of the testing apparatus. This resulted in an additional 30 beams and 15 breakoff tests.

Since the aggregate size and shape had no differential effect on the beam and breakoff tests, it follows that all the batches listed in Table A1 except for batches No. 9, 10, and 11, could be used in the regression analysis. This would leave 60 test points for $w/c = 0.44$, far outweighing the available data in the other water-cement ranges. Thus, in order to avoid weighing the analysis toward a $w/c = 0.44$, only batches 1, 2, 3, 12, 13, and 14 were considered. This left 60 beam and 42 breakoff tests available for analysis.

Having only 42 breakoff tests, a corresponding number of beam tests was selected from the 60 available values. The correspondence was randomly made within the respective water-cement ratios, and the associated values of beam to breakoff tests are shown in Table 5.

Table 5. Data used in regression analysis to obtain equation 3.

=====		
Batch No.	Breakoff Stress (MPa)	Beam Stress (MPa)

1	7.07	8.97
	6.43	8.28
	6.34	8.13
	6.34	8.13
	6.22	8.05
	6.22	7.95
	6.09	7.60
2	5.74	7.49
	5.45	6.99
	5.33	6.57
	5.33	6.19
	5.26	6.08
	5.21	6.00
	5.12	5.89
	5.03	5.78
	4.98	5.62
	4.81	5.09
3	5.21	6.27
	5.21	6.23
	5.17	6.16
	5.17	6.12
	5.10	6.00
	4.93	5.78
	4.76	5.78
	4.52	5.43
	4.40	5.43
	4.10	5.32
12	7.86	9.46
	7.46	9.04
13	7.52	9.31
	7.22	8.59
	6.97	8.32
	6.71	6.95
	6.60	6.91
=====		

Table 5, Continued.

Batch No.	Breakoff Stress (MPa)	Beam Stress (MPa)
14	6.69	9.49
	5.69	9.49
	5.43	9.04
	5.43	8.81
	4.91	7.98
	4.79	7.14
	4.76	6.99
	4.67	6.84

A linear regression performed using the SPSS program on all 42 cases, as given in Table 5 and shown graphically in Figure 15, resulted in the following correlation equation with r-squared = 0.80:

$$f_{bm}(MPa) = 0.32f_{bo}(MPa) - 9.39(w/c) - 7.61 \quad (3)$$

where w/c is determined by weight and 1MPa = 0.145ksi.

Using the means of the beam test and breakoff test data as presented in Table A1 and shown graphically in Figure 16, (i.e., with regression carried out using only six cases), the following relationship was obtained with r-squared = 0.88:

$$f_{bm}(MPa) = 0.10f_{bo}(MPa) - 13.73(w/c) + 11.13 \quad (4)$$

Although Equations (3) and (4) represent the best statistical relationships between the variables involved for the data obtained, a simpler, more direct means of

correlating breakoff strength and beam strength would be desirable from the viewpoint of the practitioner. It is desirable to see in which regions the w/c ratio has a more pronounced differential effect and whether there is a region in which the effect of w/c can be neglected.

It appears from Figure 16 that best fitting second degree parabolic curves passed through the means of the breakoff and beam test points indicate that the differential effect of w/c ratio is negligible. To substantiate this observation without resorting to statistical analysis a normalized curve is plotted in Figure 18, where f_{bm}/f_{bo} ratio was plotted against the w/c ratio.

It can be seen from Figure 18 that the variation introduced by the w/c ratio for normalized concrete strength is indeed negligible. Hence, it can be concluded that for a practical range of w/c ratios, especially for w/c ratios larger than 0.41, the relationship between breakoff and beam strengths can be expressed independently of the w/c ratio for the specific values of concrete age, type of cement and curing condition. Within the specified range of w/c ratio, it appears from Figure 18 that the beam strength, on the average, is about 22% smaller than the corresponding breakoff strength. The beam strength as a function of breakoff strength may therefore be expressed as:

$$f_{bm} = 0.78 f_{bo}(\text{MPa}) \quad (5)$$

It should be noted that, at the present, Equation (5) has the same restrictions as those of Equations (3) and (4) regarding other variables examined.

Figure 15. Data used in obtaining regression Equation (3).

Figure 16. Data used in obtaining regression Equation (4).

Figure 17. Best fit curves representing breakoff and beam strength using only the mean values.

Figure 18. Relationship between beam strength and breakoff strength.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The following conclusions can be drawn from the present investigation:

(1) The breakoff test results yield a relatively high within test variation as compared to the cylinder and beam tests (Table 3). Due to this high variation, care should be taken in interpreting the concrete strength as obtained through the use of the Norcem breakoff tester. Although it is not within the scope of this investigation to determine the source of such a high variation, it is speculated that it may be due to one or more of the following: (1) the loading apparatus, (2) the rate of loading, (3) the dimensions of the tubular form, and/or (4) the operator of the testing device.

(2) Since it was obvious that a simple relationship between the breakoff and cylinder tests could not be found, no attempt was made to correlate these two test methods. This highly nonlinear nature of correlation is reflected in the fact that all six parameters investigated

were found to have a significant differential effect on the two test methods. The resulting expression would have been complex and practically useless.

(3) Water-cement ratio, age of concrete, curing conditions, and cement type were found to have significant differential effects on the breakoff and beam tests, while aggregate size and aggregate shape did not.

(4) Recognizing that age, curing conditions and cement type are discrete parameters, a regression analysis was performed only with respect to the water-cement ratio. The resulting linear regression analysis performed on all 42 cases, as listed in Table 5 and presented in Figure 15, had a coefficient of correlation of 0.30 (Equation 3). When the same analysis was done using the means of the beam and breakoff tests, as listed in Table A1 and presented in Figure 16, the coefficient of correlation was increased to 0.88 (Equation 4). It should be noted that both Equations (3) and (4) are valid only for 7 day, Type I cement concrete cured under moist conditions.

(5) In an effort to obtain a direct correlation between breakoff strength and beam strength, smooth curves were passed through the respective means of the breakoff and beam test data as shown in Figure 17. By normalizing beam strength with breakoff strength, as shown in Figure 18, it was observed that the beam strength on the

average is about 22% lower than the corresponding breakoff strength. Thus, the beam strength, for practical purposes, may be approximated as being 78% of the breakoff strength (Equation 5). This direct correlation is valid only for 7 day, Type I cement concrete cured under moist conditions.

(6) A total of at least 5 tests should be conducted in order to determine the average breakoff strength of a concrete batch, such that 9 out of 10 specimens would be within 10 percent of the average of a very large group of specimens from the same concrete.

(7) Beam strengths obtained through Equations (3), (4), and (5) may be interpreted as results obtained from tests conducted on hypothetical beam specimens which have been exposed to the same conditions as the breakoff specimens.

(8) The breakoff method may be performed very rapidly. With the loading rate of 2.5 kp/cm²/sec (1 kp = 9.807 or 1 kp = 2.205 lbs.), the entire testing procedure for a single test may take less than two minutes.

(9) The Norcem Breakoff Tester has insufficient load capacity. A total of twenty-one breakoff tests, when loaded to the capacity of the test apparatus, did not fail on the first load application. The cores were unloaded and then reloaded, and in some cases it took up to six load

applications for failure to occur. Of course, these test results were not included in the analysis of the data.

4.2 Recommendations for Further Research

In an effort to better understand the feasibility of the breakoff test method, the following suggestions are made:

(1) For the purpose of minimizing the within test variation of the breakoff test, it is highly recommended that a reliable rate of load be established through further investigation.

(2) There are two significant apparatus variables that may affect the breakoff force; (1) the diameter and (2) the length of the tubular forms. The effect of these variables on the breakoff force should be investigated in a further study so as to obtain the optimal form size. The diameter and length of the forms should be limited so as not to result in a large damaged area in the concrete. On the other hand, the diameter of the forms should be sufficiently large to accommodate relatively large aggregate particles.

(3) The influence of existing stresses on a concrete structure should be examined. For example, how is the breakoff force affected by the presence of precompression in existing structures? This knowledge would provide

valuable guidance in the interpretation of breakoff strengths obtained in the field.

(4) The influence of environmental conditions existing at the construction site should also be investigated in cooperation with a local contractor. These environmental conditions could include freezing, ponding of water, freeze-thaw, and exposure to winds, among other things.

(5) Although Philleo [2] has found that the drilling of tubular slits in hardened concrete to obtain the necessary breakoff specimen does not affect the test results, it is recommended that further investigation be conducted to validate this conclusion. The possibility of less costly procedures applicable to already hardened concrete should also be investigated.

(6) The relationship of Equations (3), (4), and (5) obtained in this investigation are valid only for 7 day strength, Type I cement concrete, cured under moist conditions. These restrictions limit the range of applicability of these Equations. Thus, further research should be conducted to explore the individual effects of each of these 3 parameters upon the relationship between beam and break-off strength.

(7) Further research should be conducted, as suggested in Section 3.4, to determine whether the test methods or the actual differences in concrete properties

at the exposed critical face of the beam specimen as opposed to the critical section of the breakoff test, 70mm below the concrete surface, are the cause of differential effects indicated by the statistical analyses.

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Table A1. Original Test Data.

Batch No.	Cylinder Test		Beam Test		Breakoff Test	
	f'<c> MPa, Mean		f <r> MPa, Mean		f <bo> MPa, Mean	
1	41.23	40.12	7.07	6.22	8.97	8.16
	41.08		6.43		8.28	
	40.71		6.34		8.13	
	40.53		6.34		8.13	
	40.53		6.22		8.05	
	39.82		6.22		7.95	
	39.45		6.09		7.60	
	39.45		5.95			
	39.22		5.83			
	39.15		5.69			
2	36.70	35.67	5.74	5.23	7.49	6.17
	36.70		5.45		6.99	
	36.70		5.33		6.57	
	36.46		5.33		6.19	
	35.72		5.26		6.08	
	35.36		5.21		6.00	
	34.99		5.12		5.89	
	34.87		5.03		5.78	
	34.63		4.98		5.62	
	34.38		4.81		5.09	
3	28.77	27.58	5.21	4.86	6.27	5.85
	28.41		5.21		6.23	
	28.29		5.17		6.16	
	28.29		5.17		6.12	
	28.16		5.10		6.00	
	27.56		4.93		5.78	
	26.95		4.76		5.78	
	26.95		4.52		5.43	
	26.58		4.40		5.43	
	25.85		4.10		5.32	
4	37.55	35.39	6.36	5.50	6.23	5.91
	36.21		5.77		6.16	
	36.09		5.69		6.16	
	35.85		5.62		6.04	
	35.24		5.55		6.00	
	34.63		5.45		5.93	
	34.38		5.33		5.89	
	34.26		5.21		5.70	
	34.14		5.08		5.70	
	33.53		4.90		5.32	

Table A1, Continued.

Batch No.	Cylinder Test		Beam Test		Breakoff Test	
	f'<c> MPa, Mean		f <r> MPa, Mean		f <bo> MPa, Mean	
5	34.63	31.96	5.71	5.30	6.31	5.46
	32.80		5.71		5.93	
	32.55		5.65		5.81	
	32.55		5.43		5.66	
	32.19		5.31		5.43	
	31.82		5.17		5.36	
	31.33		5.12		5.32	
	31.33		5.12		5.17	
	30.60		4.93		4.98	
	29.75		4.81		4.60	
6	34.38	31.63	6.03	5.22	6.99	5.93
	32.92		5.76		6.65	
	32.68		5.45		6.57	
	31.21		5.41		6.27	
	31.09		5.29		6.23	
	31.09		5.21		5.70	
	31.09		5.17		5.59	
	30.97		5.14		5.55	
	30.60		4.55		5.51	
	30.24		4.15		4.22	
7	35.36	33.79	5.98	5.40	6.65	6.13
	34.87		5.67		6.61	
	34.87		5.55		6.52	
	34.26		5.53		6.38	
	34.14		5.45		6.31	
	34.14		5.45		6.23	
	33.16		5.27		6.08	
	33.04		5.15		5.89	
	32.68		5.10		5.32	
	31.33		4.84		5.28	
8	42.06	40.52	6.00	5.27	7.68	6.29
	41.70		5.79		7.60	
	41.45		5.52		6.61	
	41.21		5.46		6.61	
	40.60		5.38		6.23	
	40.24		5.31		6.00	
	40.24		5.08		5.70	
	39.87		4.93		5.62	
	39.63		4.67		5.51	
	38.16		4.57		5.32	

Table A1, Continued.

Batch No.	Cylinder Test		Beam Test		Breakoff Test	
	f'<c> MPa, Mean		f <r> MPa, Mean		f <bo> MPa, Mean	
9	45.11	42.35	7.07	6.51	6.54	6.14
	44.01		6.79		6.54	
	43.77		6.67		6.46	
	43.28		6.60		6.38	
	42.67		6.45		6.38	
	42.06		6.33		6.31	
	41.82		6.31		6.16	
	41.70		6.29		5.70	
	40.84		6.27		5.55	
	38.28		6.27		5.40	
10	34.14	31.26	4.77	4.25	6.54	5.85
	32.19		4.64		6.38	
	32.19		4.62		6.27	
	31.21		4.59		6.23	
	31.21		4.36		6.16	
	31.21		4.17		5.66	
	30.85		3.95		5.55	
	30.36		3.91		5.51	
	29.75		3.81		5.40	
	29.51		3.69		4.79	
11	44.38	42.53	7.45	6.48	7.45	6.59
	43.41		6.96		7.22	
	43.28		6.79		7.22	
	42.80		6.50		7.22	
	42.67		6.50		6.84	
	42.31		6.43		6.38	
	42.06		6.33		6.00	
	41.82		6.29		5.97	
	41.45		5.95		5.81	
	41.09		5.64		5.78	
12	-	-	7.86	7.36	9.46	9.25
			7.46		9.04	
			8.62			
			7.58			
			7.34			
			7.24			
			7.14			
			6.96			
			6.89			
			6.55			

Table A1, Continued.

Batch	Cylinder Test		Beam Test		Breakoff Test	
No.	f'<c> MPa, Mean		f <r> MPa, Mean		f <bo> MPa, Mean	
13	-	-	7.52	7.04	9.31	8.02
			7.22		8.59	
			6.97		8.32	
			6.71		6.95	
			6.60		6.91	
			7.43			
			7.16			
			6.97			
			6.91			
			6.88			
14	-	-	6.69	5.15	9.49	8.22
			5.69		9.49	
			5.43		9.04	
			5.43		8.81	
			4.91		7.98	
			4.79		7.14	
			4.76		6.99	
			4.67		6.84	
			4.65			
			4.50			

APPENDIX B

Detailed Description of the Norcem Load Apparatus.

B1 DESIGN

The in-situ concrete strength testing apparatus consists of two separate main parts (see Figure B1). In the following, the numbers in parentheses refer to the parts indicated in Figure B1.

B1.1 PUMP AND MANOMETER (class 06, range 0-250 kp/square cm).

The pump includes an oil reservoir (2) with a lid (3), piston (4), air escape valve (5) with a pull-out chain, pump casing (1) including a delivery valve (28), unloading valve (18), pump piston (12), pump lever (22), return spring (15), and manometer (23) with a scale (47).

B1.2 LOAD CELL

The load cell consists of a main pipe (8), a lid (10), load lever (9), hinge (11), load cylinder (32) including a piston (33), return spring (43) and a flexible tube (38) (1/4" hydraulic tube, type 4J04 with coupling MP0404 MU at both ends).

B1.3 SPARE PARTS

<6> 0" ring RMO 255-30, <17> 0" ring SOR 1, <19> 0" ring SOR 1, <20> valve ball (ballbearing ball 0 49, <21> valve seating (copper), <34> 0" ring R 2043 silicon.

B2 MODE OF OPERATION

The pump works in two stages:

Stage #1; The hydraulic oil is supplied by the pump piston (12) through the delivery valve (28).

Stage #2; The return spring (15) forces the pump piston (12) to the rear position when the pump lever (22) is released. The delivery valve (28) will close and a vacuum is created above the pump piston. The supply hole from the oil reservoir (2) is uncovered. The atmospheric pressure above the piston (4) in the oil reservoir will then fill up the pump cylinder.

The oil reservoir is full when the rear of the piston (4) is positioned approximately 10-15mm (3/8-5/8") from the top of the oil cylinder (2). The oil reservoir is emptied when this distance is 80 mm (3 and 1/8 in.). The apparatus contains in all about 65 cubic cm of oil type S40 (for example TEXACO Way Lubricant D, ESSO Product EF - 177, SHELL Tonna Oil 33).

Figure B1. Schematic of Norcem Load Apparatus.

COVER DESIGN BY ALDO GIORGINI