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Comparative Evaluation of Nondestructive Test Methods for In-Place Strength Determination

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Abstract: This paper presents an investigation to determine the within-test variability of various nondestructive test (NDT) methods and the correlation between NDT test results and the corresponding compressive strength of cores. The size effects of coarse aggregate on the variability and correlation were also evaluated. The NDT test methods evaluated in the test series include: rebound hammer; pulse velocity; probe penetration; pullout; and CAPO (Cut and Pullout). Companion tests of field-cured standard cylinders and cores were also made at the ages when the NDT tests were made. The tests were performed on plain concrete slabs, 1000 mm x 1000 mm x 300 mm, at the ages of 1,3,7,14,28 and 90 days. The test variables included the size of coarse aggregate (sand only, 25 mm and 40 mm) and the compressive strength of concrete (210,280 and 350 kg/sq cm).

The test results show that the within-test variability of the in-situ tests herein reported except the pulse velocity test is 2-5 times higher than that of the corresponding standard compression test, and is affected significantly by the amount of coarse aggregate and its size. There is a good relationship between the results of in-situ tests and the compressive strength. In general, the highest degree of correlation is for pullout test followed by that for CAPO(cut and pullout) test and rebound test, probe penetration test and pulse velocity test.

Keywords: aggregates; compressive strength; concretes; curing; evaluation; impact hammer tests; nondestructive tests; probes; pullout tests; ultrasonic tests; variability

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1. INTRODUCTION

It is important to determine the in-place strength of concrete to establish the safety of the concrete structures. Until recently, the in-place strength of concrete was determined by the standard cylinder test. Because the condition under which the test cylinders are made and cured differ from that of the concrete in the structure, the strength of the test cylinder may be different from that of the concrete in the structure. Therefore, there is a need for reliable test methods to determine the in-place strength of concrete. At the present time, various nondestructive test (NDT) methods are used for this purpose. But the application of these methods are limited because the accuracy and reliability of these NDT methods are not well established. This paper reports an investigation to determine the within-test variability of various NDT methods and correlation between the NDT values and the corresponding core strength. The effects of coarse aggregate on the variability and the correlation were also evaluated.

2. SCOPE OF INVESTIGATION

The NDT methods evaluated in this paper include : rebound hammer; pulse velocity; probe penetration; pullout; CAPO (cut and pullout). Tests were performed on the four sides of plain concrete slabs, 1000 x 1000 x 300 mm in size, at ages of 1,3,7,14,28 and 90 days. The test specimens were made of two different mortar mixes and five different concrete mixes. For each mix, six slabs were cast together with forty 150 x 300 mm cylinders (16 standard-cured cylinders and 24 field-cured cylinders). The test variables included the size of coarse aggregate (sand only, 25 mm and 40 mm maximum size coarse aggregate) and the design compressive strength of concrete (210,280 and 350 kg/sq cm). Cores drilled from the slab were tested at the time when cylinders were tested. The core test at the age of 1 day was not performed because of difficulty in obtaining samples.

3. TEST SPECIMENS

3.1 Materials and Mix Proportions

Because of the large amount of required concrete, ready-mix concrete was used with a special attention paid to maintain uniform quality of concrete. ASTM type I cement, river gravel and natural sand were used for concrete. The cement factor, water-cement ratio, slump, air content and the other properties for each mix are given in Table 1.

3.2 Preparation and curing

A total of 42 test slabs were cast in wooden forms. Compaction was carried out in equal two layers using internal vibrators to ensure uniform casting. The 150 x 300 mm cylinders were cast using ASTM single-use plastic molds and were compacted in three equal layers using the standard rodding procedure. Immediately after casting, the slabs and the field cylinders were covered with wet burlap to maintain the uniform moisture condition until the day of testing. Standard cylinders was placed in the water bath one day after casting. The investigation was performed from August to November of 1986.

4. NON-DESTRUCTIVE TEST

The locations where each NDT was performed on the slab specimens are shown in Fig.1. To maintain the surface moisture condition uniform, the side form was removed just prior to testing. The number of tests for each NDT procedure was selected based on available research information (1,2,3,and 4).

- Rebound Hammer Test: Fifteen readings were taken at each test location for each test age according to ASTM C805.

- Pulse Velocity Test: Eight measurements were made using a portable digital ultrasonic pulse velocity apparatus through the slab width of 1000 mm. This number of readings was somewhat greater than the minimum of five which is a common practice because of non-uniform surface conditions for contact of the transducer. To reduce the effects of the surface irregularities, the rubber couplant was used. The transducer was calibrated using the standard reference bar before and after each test. Between tests the slabs were kept moist using a wet burlap.

- Probe Penetration Test: Four penetration tests were performed at each test location according to ASTM C803.

Explosive charges required to fire the steel probe were selected as follows:

* Low power charge for concrete strength of 210 kg/sq cm.

* Standard power charge for concrete strength of 350 kg/sq cm.

* Low and standard power charges for concrete strength of 280 kg/sq cm.

- Pullout Test: Eight pull out tests were performed on each specimen. Both the depth and diameter of the insert were 25mm, which met the requirements of ASTM C900.

- CAPO Test: The purpose of the CAPO (cut and pullout) test was to compare its results with those of the Pullout Test. In general, the CAPO test is to overcome the requirement of the Pullout test that inserts need to be placed in concrete before setting of the concrete. The

diameter and depth of the insert used in the CAPO test were 25 mm, respectively. Eight CAPO tests were performed at each test age.

5. COMPRESSIVE STRENGTH TEST OF CYLINDERS AND CORE

The compressive strength tests were performed on three kinds of specimens. They were standard-cured cylinders, field-cured cylinders and cores taken from the slab specimen. Table 2 shows the number of compressive strength tests carried out at each curing age. All cylinders were capped with a sulphur flint mixture according to ASTM C617 and tests were carried out following the procedure specified in the ASTM C39.

6. DISCUSSION OF TEST RESULTS

This investigation was carried out to obtain information on the accuracy of each NDT method in the following aspects.

- Comparison of the within-test variability of various in-situ tests.

- Comparison of the degree of correlations between compressive strength and in-situ test results.

- Evaluation of the effects of the coarse aggregate on the variability and the correlation referred above.

The within-test variability is expressed in terms of the coefficient of variation (COV). The correlation between the compressive strength and the results of in-situ tests was obtained by means of linear regression analysis.

The compressive strength tests in this investigation were performed on standard cured cylinders, field cured cylinders (150 x 300 mm) and drilled core from the slab specimen. Fig.2 and Fig.3 show the compressive strength relationships among the three types of specimens for all ages (1,3,7,14,28, and 90 days).

6.1 Within-test Variability

In this paper, the within-test variability relates to the single-operator-material precision of the test methods. The number of tests for each of th in-situ tests was based on the variability which was reported in literature. The within-test variability can be described in terms of either the standard deviation or the coefficient of variation. Herein, the variability is represented using the coefficient of variation. For the probe penetration test, the coefficient of variation was calculated for the embedded probe length instead of the exposed length because the strength of concrete is related to the embedded length. Table 3 gives the average coefficient of variation for each test method at various test ages. The compressive strength, the NDT values and the coefficient of variation for each mix case are shown in Appendix.

In general, the within-test variability of the in-situ tests is 2-5 times higher than that of the compressive strength test except for the pulse velocity test. The variability is also affected appreciably by the size of coarse aggregate.

For the specimens made of mortar, the COV was the lowest for the pulse velocity test, less than 1 percent. The COV increased, in increasing order, for the pullout test, the probe penetration test and the CAPO test. The highest within-test coefficient of variation was for the rebound test with 7.7 percent. However, for concrete mixes with maximum aggregate sizes of 25 mm and 40 mm, the rebound test results are the lowest with about 10 percent except the pulse velocity test, and for the pullout, the probe penetration and the CAPO tests, COV increases to 11 to 19 percent. These test results are substantially different from those of the CANMET tests (1) which analyzed various within-test variabilities at early ages (1,2 and 3 days) for mixes with 19 mm coarse aggregate. This difference may be due to the fact that for this investigation, relatively large aggregate sizes, over 25 mm, were used and they significantly affected the pullout, the CAPO, and the probe penetration test values, but not so much the rebound hammer test. From these results, it appears that the tests which are related to local failure are affected by the size of aggregate.

The highest COV for the within-test variation was for the CAPO test whose COV was about 19 percent for 40 mm aggregate size. This high value probably resulted from the complex test procedure. Furthermore, the CAPO test could be more significantly affected by coarse aggregate than the pullout test because it was performed after hardening of concrete.

The pulse velocity test was not affected by the coarse aggregate and exhibited a low COV, less than 1 percent. Also, the within-test variability of all in-situ tests was not affected by age of concrete.

6.2 Correlation between compressive strength and in-situ test results

The correlations between the in-situ test results and the corresponding core strengths were obtained. The effects of the size of coarse aggregate were also obtained for several mix combinations.

- Combination 1 : Concrete with max. aggregate size of 25 mm and 40 mm.
- Combination 2 : Concrete with max. aggregate size of 25mm.
- Combination 3 : Concrete with max. aggregate size of 40mm.

The correlations for individual mixes (7 mix cases) were also obtained.

All in-situ test results showed good correlation to the corresponding core strength. In general, the best correlation was shown by the pullout test followed by the CAPO and the rebound hammer, the probe penetration, and the pulse velocity tests (Table 4).

For mortar specimens, the coefficient of correlation (COC) for the pullout was 0.98 and standard error (SE) was 14.0 kg/sq cm. The COC for the rebound hammer, the CAPO and the probe penetration tests were also relatively high, over 0.94. But for the pulse velocity test, the COC was poor, 0.77, as compared to other in-situ tests and the SE was 41.1 kg/sq cm (Fig.4-9).

For Combination 1, the correlation between the core strengths and the corresponding in-situ test results was calculated. The correlation coefficient was 0.97 and the SE was 15.3 kg/sq cm for the pullout test. The COC was 0.81 and the SE was 35.2 kg/sq cm for the probe penetration test using the regular charge (Fig.4-9).

For the pullout and the rebound tests, there was some difference between each correlation for Combinations 2 and 3 and the correlation for Combination 1. It indicates that maximum size of coarse aggregate may have some effects on the correlation in these tests. The test results also showed that the coarse aggregate content had greater effect than aggregate size.

For the pulse velocity test, two individual mixes of mortar specimens gave a COC over 0.92, but the combined data gave a COC of 0.77. From this results, it is seen that the difference in the content of fine aggregate affects the pulse velocity significantly. Similar results were also shown by Sturrup (5).

For concrete specimens, the correlation coefficients were 0.94 for both Combination 3 and 4. But for Combination 2, the correlation coefficient decreased to 0.84. This large decrease may be caused by the difference in the amount of coarse aggregate rather than its size. In this investigation, however, the difference was only 7 percent,so it is not clear whether the coarse aggregate content was truly the main factor for this difference.

For the probe penetration test using the regular charge,the correlation coefficient was affected significantly by the coarse aggregate size. For Combination 3 and 4 with the maximum aggregate size of 25 mm and 40 mm, respectively, the correlation coefficient was over 0.93 and the SE was below 18.5 kg/sq cm. But for Combination 2 with the maximum aggregate size of 25 mm and 40 mm together, the correlation coefficient was 0.81 and the SE was 35.2 kg/sq cm.

7. CONCLUSION AND APPLICATIONS

This investigation evaluated the within-test variation of a number of commonly used nondestructive test methods to determine the in-place strength of concrete. These NDT methods included rebound, pulse velocity, probe penetration, pullout and CAPO tests. The correlation between the compressive strength predicted by these NDT tests and the corresponding core strength was also evaluated. Based on this investigation the following conclusions are drawn:

7.1 Within-Test Variability

- The within-test variability of the in-situ tests herein investigated is 2 to 5 times greater than that of standard compression test, the only exception being pulse velocity test.

- The coefficient of variation of the in-situ tests except for pulse velocity test is affected by the content of coarse aggregate and its size, but not by the curing age.

- For pullout, CAPO, and probe penetration tests, it may be necessary to increase the test number in concrete containing coarse aggregate over 25 mm.

7.2 Relationships Between The Results of In-situ Tests and Compressive Strength.

- There is a good relationship between the results of in-situ tests and the compressive strength of cores.

- The degree of correlation is good for the pullout test followed by that for the CAPO and the rebound tests,the probe penetration, and the pulse velocity tests.

- The size of coarse aggregate has considerable effect on the probe penetration test, but has little effect on the pullout and rebound tests.

7.3 Field Applications

1) Prediction of concrete strength at early ages.

- The pullout test is the most promising method.

- Improvement of the CAPO test equipment is needed for economy and simplicity in testing.

- When the probe penetration test is performed on concrete with maximum aggregate size over 25 mm, the cost increases considerably.

2) Prediction of concrete strength at later ages.

- The CAPO, the probe penetration and the rebound hammer tests can be used to predict the in-place strength after the relationship between in-situ test and core strength is obtained.

- The pullout test may be used to predict the in-place strength of critical parts in a target structure with installation of the pullout assembly before placing concrete.

- The pulse velocity test is very useful in evaluating uniformity of concrete and damaged zone in the concrete structure.

8. REFERENCES

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TABLE 1--MIX PROPORTIONING DATA

Mix No.	Water Cement Ratio	Maximum Aggregate Size(mm)	Nominal Cement Content(Kg/m^3)	Fine Aggregate Content(Kg/m^3)	Coarse Aggregate Content(Kg/m^3)	Properties of Fresh Concrete: Unit Weight(Kg/m^3)	Slump(mm)	Air Content(%)	Specified 28-day Strength (Kg/cm^2)
1	0.44	NK	560	1500	-	2119	100 ± 10	4 ± 1	1:3 *
2	0.39	"	700	1310	-	2131	"	"	1:2 *
3	0.53	25	326	760	1115	2262	"	"	210
4	0.44	"	405	693	1109	2282	"	"	280
5	0.37	"	479	652	1083	2291	"	"	350
6	0.56	40	299	739	1178	2305	"	"	210
7	0.46	"	367	678	1176	2313	"	"	280

* Cement - Sand Ratio

TABLE 2--NUMBER OF COMPRESSION TEST WITH CURING AGE

Age(day) \ Type of Cylinder	Number of Test		
	Standard-Cured Cylinder	Field-Cured Cylinder	Core
1		4	
3	4	4	4
7	4	4	4
14	-	4	4
28	4	4	4
90	4	4	4
Sum	16	24	20
Total	60		

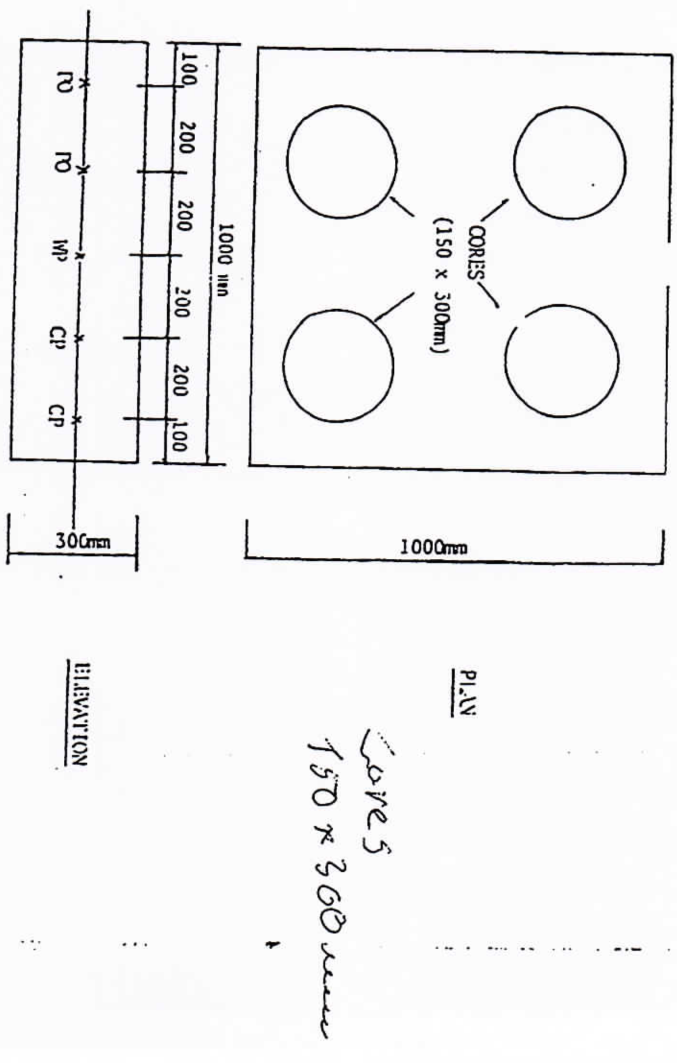
TABLE 3--AVERAGE WITHIN TEST COEFFICIENT OF VARIATION FOR COMPRESSIVE STRENGTH AND IN SITU TEST RESULTS

Test \ Max Aggregate size / Age	Mortar (Mix No.1-2)							25MM (Mix No.3-5)							40MM (Mix No. 6-7)						
	1d	3d	7d	14d	28d	90d	Ave.	1d	3d	7d	14d	28d	90d	Ave.	1d	3d	7d	14d	28d	90d	Ave.
Compressive Strength of Cylinder																					
Standard Curing(150x300mm)		2.9	1.7		3.1	5.0	2.7		3.5	5.2		2.7	3.3	5.2		2.9	2.9		6.7	4.7	4.
Field Curing(150x300mm)	5.6	5.4	4.7	2.6	3.1	3.8	3.9	4.9	2.4	5.7	1.4	2.2	1.8	2.7	2.7	3.2	2.3	4.0	3.9	4.6	3.5
Core (150x300mm)		2.6	5.1	3.2	3.2	1.8	3.2		2.5	3.9	3.2	3.3	3.4	5.3		3.5	5.3	4.0	5.6	4.2	4.5
Pullout	4.8	4.1	4.9	6.6	3.4	2.9	4.5	15.8	9.1	14.2	8.0	11.5	11.3	11.7	16.1	21.7	15.5	12.9	12.1	7.7	14.3
CAPO	10.8	7.7	7.0	4.0	5.9		7.1								17.6	27.0	19.0	15.9	15.6		19.0
Rulse Velocity	1.2	0.6	0.6	0.7	0.4	0.8	0.7	0.5	0.4	0.5	0.5	0.5	1.1	0.6	0.8	0.6	0.8	0.5	0.5	0.6	0.6
Rebound Hammer	7.7	6.8	9.4	8.6	8.4	5.5	7.7	13.2	11.9	8.8	10.1	8.0	10.2	10.4	11.0	11.4	11.6	10.1	11.0	7.9	10.5
Probe Regular Charge									15.5	13.2	7.4	13.9	16.1	13.2	11.1	20.4	12.1	21.3	9.2	18.3	15.4
Probe Low Charge	4.7	1.9	3.4	6.0	7.2	9.4	6.3	11.7	12.1	14.5	10.4	7.0		11.1	15.2	12.1	11.7	15.5	13.4		13.6

TABLE 4--CORRELATIONS BETWEEN COMPRESSIVE STRENGTH TESTS AND IN SITU TESTS

Test \ Mix No.	Correlation Coefficient														
	Core											Field Cured Cylinder			
	Combined Data				Individual Mix Data							Combined Data			
	1-2 [1]	3-7 [2]	3-5 [3]	6-7 [4]	1	2	3	4	5	6	7	1-2 [1]	3-7 [2]	3-5 [3]	6-7 [4]
Pullout	0.98	0.97	0.98	0.98	0.96	0.99	0.99	0.95	1.00	0.98	0.98	0.96	0.97	0.98	0.97
CAPO	0.94			0.95	0.95	0.95				0.96	0.99	0.98			0.95
Pulse Velocity	0.77	0.84	0.94	0.94	0.92	0.99	1.00	0.98	0.98	0.95	0.96	0.84	0.87	0.93	0.95
Rebound Hammer	0.95	0.94	0.94	0.95	0.94	0.99	0.98	0.94	0.98	0.94	0.99	0.92	0.95	0.94	0.97
Probe															
· Regular Charge		0.81 [5]	0.93 [6]	0.94 [7]				0.96	0.89		0.94		0.86 [5]	0.98 [6]	0.93 [7]
· Low Charge	0.94	0.86 [8]	0.91 [9]	0.87	0.92	0.99	0.96	0.95		0.87	0.96	0.97	0.88 [8]	0.92 [9]	0.92

1) Mortar
2) Concrete(G_{max}: 25MM, 40MM)
3) Concrete(G_{max}: 25MM)
4) Concrete(G_{max}: 40MM)
5) Mix No.4,5,7
6) Mix No.4,5
7) Mix No. 7
8) Mix No.3,4,6,7
9) Mix No.3,4



PO: Pullout Test
WP: Probe Penetration Test
CP: CAPO Test
* Rebound and pulse velocity test were performed before other tests

Fig. 1--Slab specimen showing positions of drilled cores and in situ test

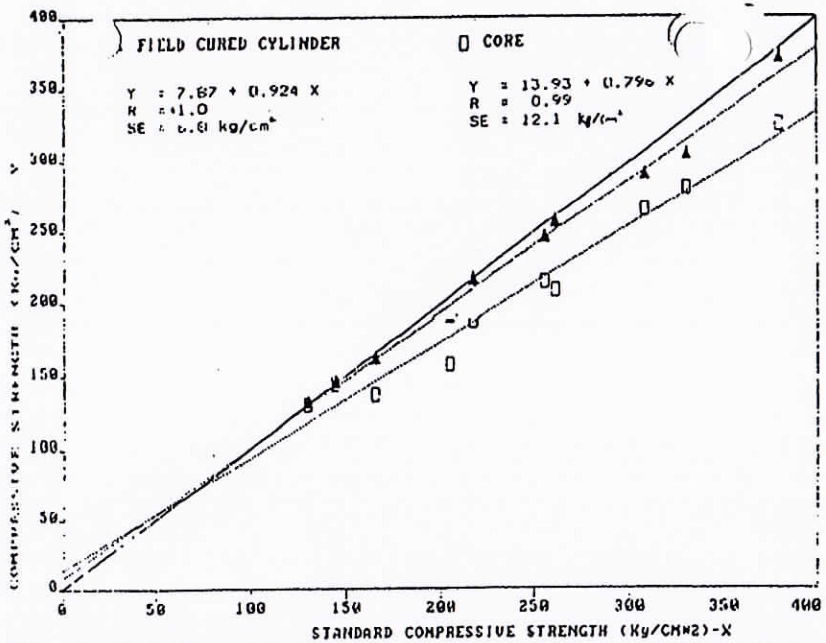


Fig. 2--Relationship between compressive strength of field cured cylinders and cores and compressive strength of standard cured cylinders for mortar

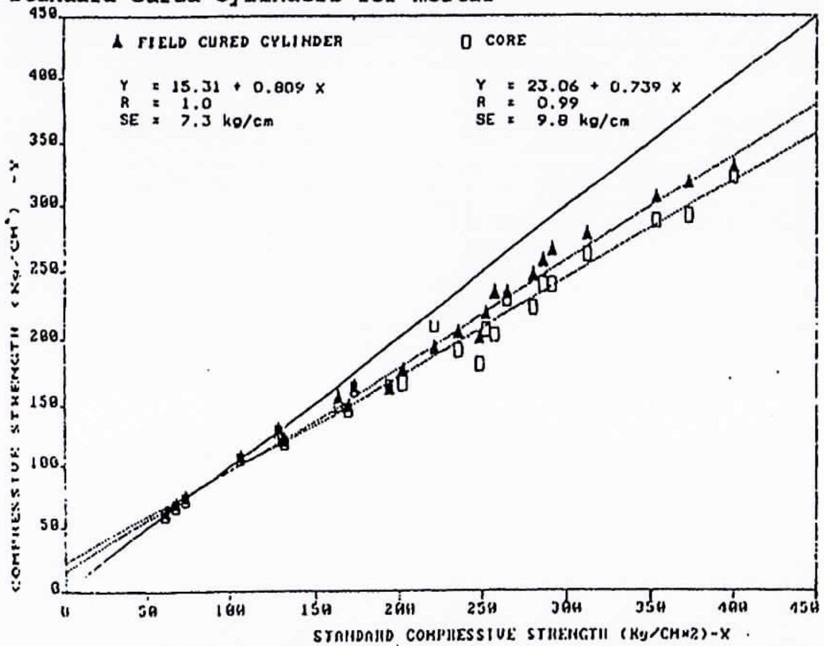


Fig. 3--Relationship between compressive strength of field cured cylinders and cores and compressive strength of standard cured cylinders for concrete

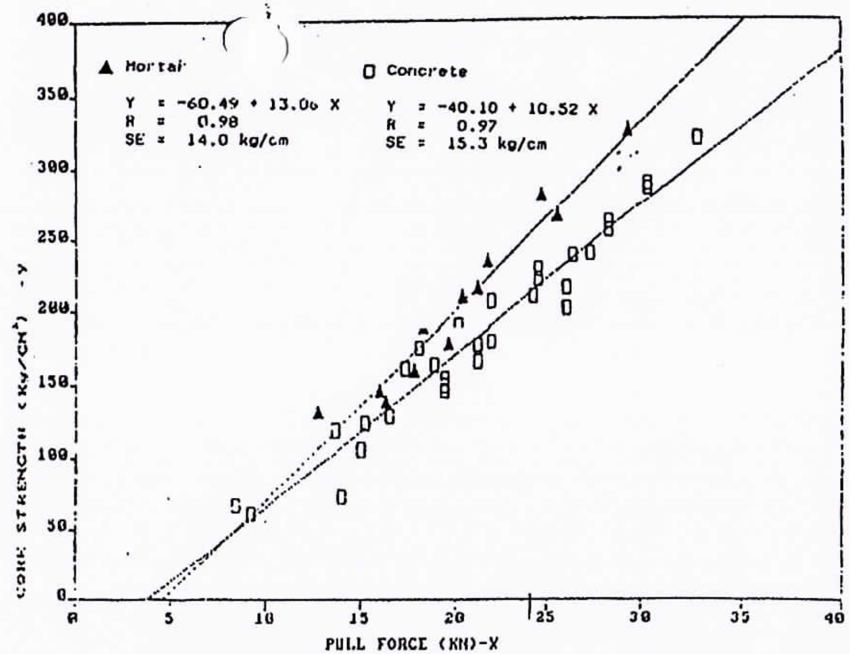


Fig. 4--Relationship between core strength and pullout force

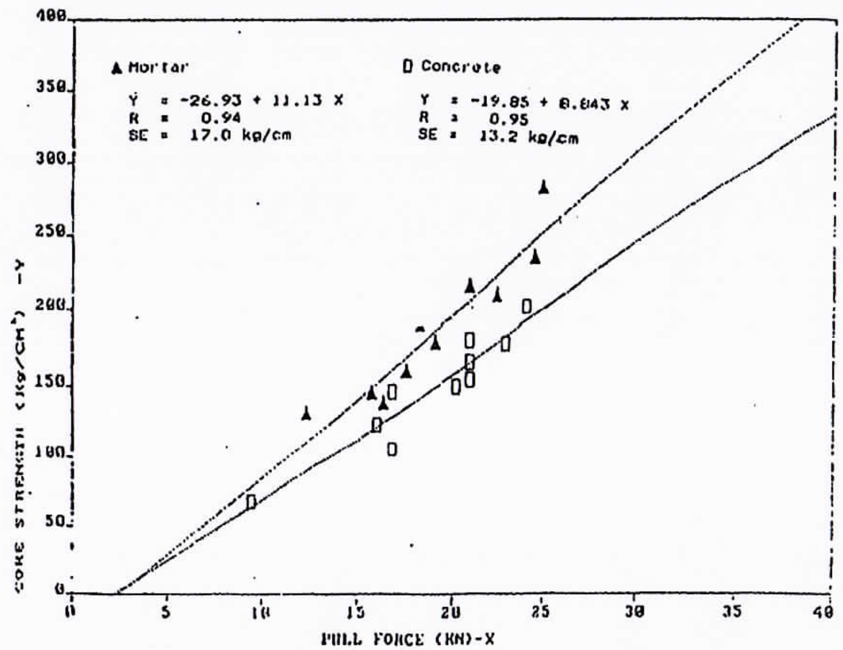


Fig. 5--Relationship between core strength and CAPO pullout force

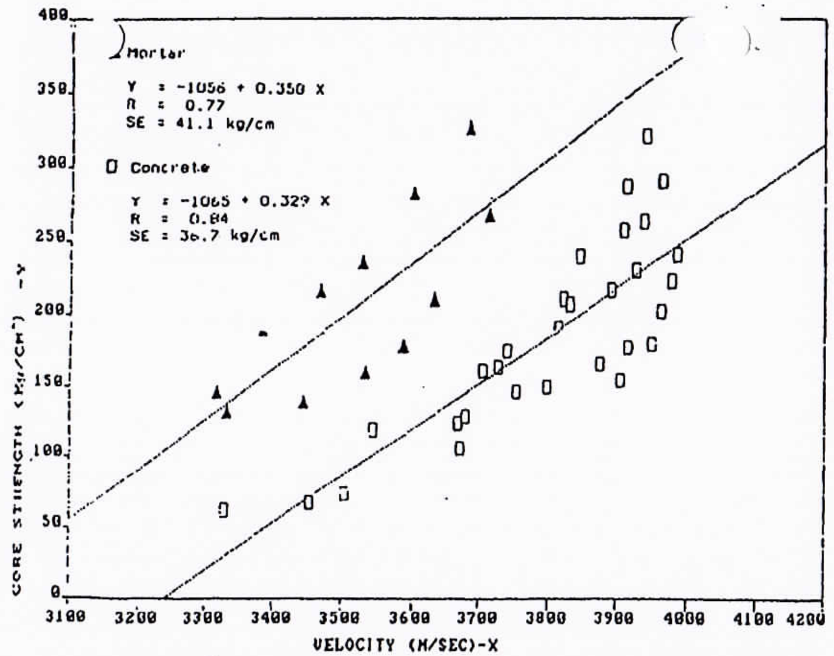


Fig. 6--Relationship between core strength and pulse velocity

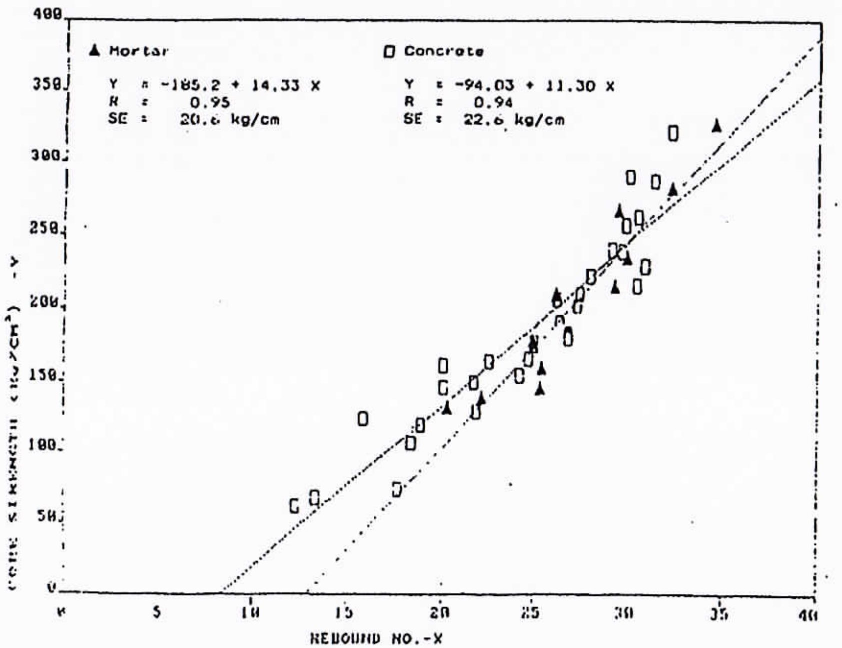


Fig. 7--Relationship between core strength and rebound number

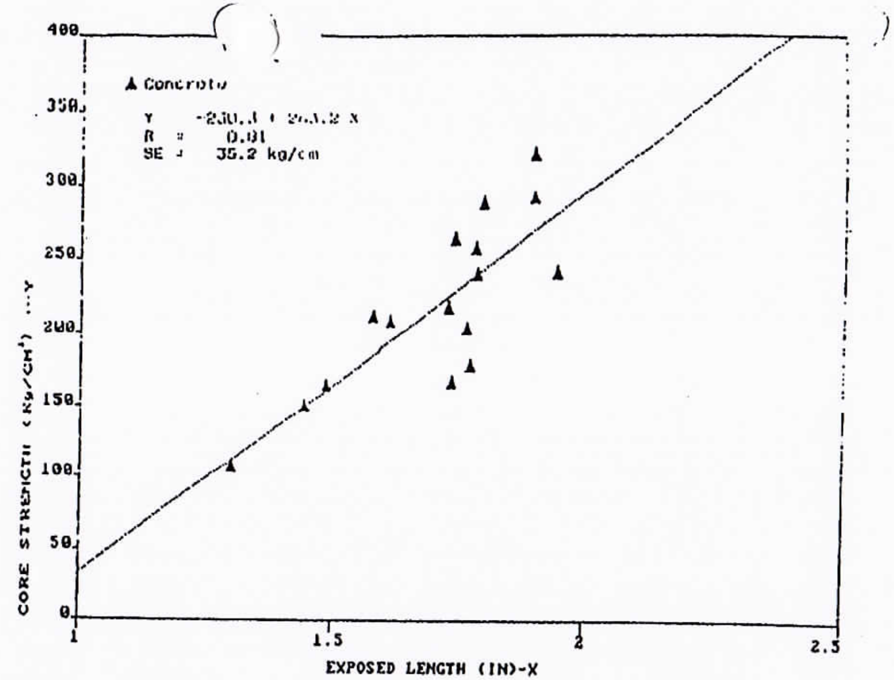


Fig. 8--Relationship between core strength and exposed length (regular charge)

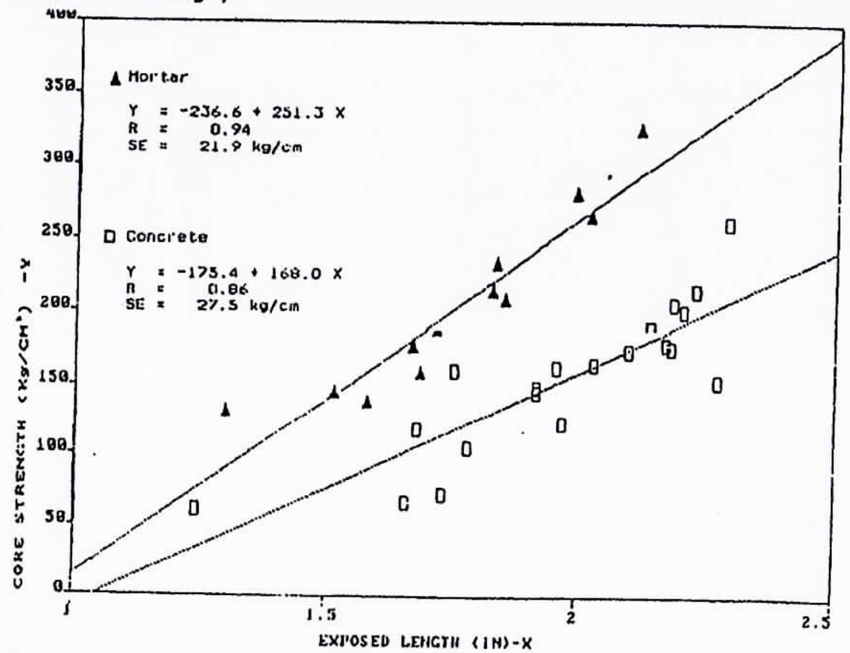


Fig. 9--Relationship between core strength and exposed length (low charge)

APPENDIX

TABLE A1--SUMMARY OF COMPRESSIVE STRENGTH AND IN SITU TEST RESULTS (MIX 1)

Test	n*	Average 1d	3d	7d	14d	28d	90d	Coefficient of Variation,% 1d	3d	7d	14d	28d	90d
Compressive Strength of Cylinder													
Standard Curing(150x300mm,Kg/Cm²)	4		166	205		261	308		3.9	2.3		3.5	2.8
Field Curing(150x300mm,Kg/Cm²)	4	130	160	189	218	254	288	6.6	3.5	4.8	0.6	2.3	4.6
Core (150x300mm,Kg/Cm²)	4		137	158	176	208	265		3.2	4.8	2.9	4.2	1.8
Pullout (Pullout force:KN)	8	12.8	16.3	17.8	19.6	20.4	25.5	4.5	3.3	3.8	5.8	3.8	4.3
CAPO (Pullout force:KN)	8	12.3	16.3	17.5	19.1	22.4		10.6	5.9	4.1	4.2	2.9	
Pulse Velocity (Velocity: M/sec)	8	3331	3444	3534	3587	3632	3715	1.4	0.8	0.5	0.3	0.4	0.7
Rebound Hammer (Rebound No.)	15	20.3	22.2	25.4	24.9	26.1	29.5	7.3	6.8	12.4	11.1	6.5	6.1
Probe Penetration Low Charge Exposed length:IN	4	1.300	1.575	1.683	1.668	1.850	2.019	7.2	1.6	11.8	8.9	3.9	12.2

- COV of the probe test is based upon the embedded length.

* Number of test

TABLE A2--SUMMARY OF COMPRESSIVE STRENGTH AND IN SITU TEST RESULTS (MIX 2)

Test	n*	Average 1d	3d	7d	14d	28d	90d	Coefficient of Variation,% 1d	3d	7d	14d	28d	90d
Compressive Strength of Cylinder													
Standard Curing(150x300mm,Kg/Cm²)	4		218	256		330	380		1.9	1.0		2.6	3.1
Field Curing(150x300mm,Kg/Cm²)	4	144	214	244	270	302	369	4.6	3.3	4.5	4.6	3.9	3.0
Core (150x300mm,Kg/Cm²)	4		188	214	233	280	325		1.9	5.3	3.5	2.2	1.8
Pullout (Pullout force:KN)	8	16.0	18.3	21.2	21.7	24.7	29.4	5.0	4.9	5.9	7.3	2.9	1.4
CAPO (Pullout force:KN)	8	15.7	18.3	20.9	24.5	25.0		10.9	9.4	9.9	3.8	8.8	
Pulse Velocity (Velocity: M/sec)	8	3315	3384	3471	3530	3602	3686	1.0	0.4	0.7	1.0	0.4	0.9
Rebound Hammer (Rebound No.)	15	25.3	26.8	29.3	30.0	32.3	34.5	8.1	6.7	6.4	6.1	10.2	4.9
Probe Penetration Low Charge Exposed length:IN	4	1.510	1.717	1.825	1.833	1.989	2.113	2.1	2.1	5.0	3.0	10.5	6.5

- COV of the probe test is based upon the embedded length.

* Number of test

TABLE A3--SUMMARY OF COMPRESSIVE STRENGTH AND IN SITU TEST RESULTS (MIX 3)

Test	* n	Average 1d	3d	7d	14d	28d	90d	Coefficient of Variation,% 1d	3d	7d	14d	28d	90d
Compressive Strength of Cylinder													
Standard Curing(150x300mm,Kg/Cm²)	4		132	175		235	265		1.3	2.9		2.8	2.4
Field Curing(150x300mm,Kg/Cm²)	4	61	122	161	187	203	231	6.6	2.7	3.6	1.6	2.9	0.0
Core (150x300mm,Kg/Cm²)	4		119	161	175	191	229		2.4	3.0	4.1	4.6	4.4
Pullout (Pullout force:KN)	8	9.2	13.7	17.5	18.1	20.2	24.5	21.0	11.2	23.0	6.9	8.4	15.6
CAPO (Pullout force:KN)													
Pulse Velocity (Velocity: M/sec)	8	3327	3545	3704	3740	3815	3929	0.6	0.4	0.8	0.6	0.4	1.0
Rebound Hammer (Rebound No.)	15	12.3	18.9	20.1	25.0	26.3	30.9	17.2	12.3	11.8	12.6	6.7	9.0
Probe Penetration Low Charge Exposed length: IN	4	1.224	1.678	1.750	2.094	2.138		17.2	11.9	15.3	12.5	7.6	

- COV of the probe test is based upon the embedded length.

* Number of test

TABLE A4--SUMMARY OF COMPRESSIVE STRENGTH AND IN SITU TEST RESULTS (MIX 4)

Test	* n	Average 1d	3d	7d	14d	28d	90d	Coefficient of Variation,% 1d	3d	7d	14d	28d	90d
Compressive Strength of Cylinder													
Standard Curing(150x300mm,Kg/Cm²)	4		194	252		312	373		3.2	1.3		1.9	1.2
Field Curing(150x300mm,Kg/Cm²)	4	73	160	216	256	275	315	4.0	3.7	4.4	0.8	2.3	4.5
Core (150x300mm,Kg/Cm²)	4		163	207	217	262	291		3.0	5.0	2.5	2.2	2.0
Pullout (Pullout force:KN)	8	14.0	18.9	21.9	26.0	28.3	30.3	15.2	5.1	12.8	9.4	13.9	11.7
CAPO (Pullout force:KN)													
Pulse Velocity (Velocity: M/sec)	8	3504	3727	3831	3893	3940	3965	0.6	0.3	0.5	0.4	0.5	1.7
Rebound Hammer (Rebound No.)	15	17.7	22.6	26.2	30.5	30.6	30.1	13.0	14.4	6.5	6.5	8.9	9.4
Probe Penetration Exposed length: IN — Regular Charge			1.484	1.613	1.731	1.744	1.900		18.8	17.9	4.5	7.7	21.0
Probe Penetration Exposed length: IN — Low Charge	4	1.728	1.955	2.181	2.225	2.288		6.1	12.2	13.6	8.3	6.3	

- COV of the probe test is based upon the embedded length.

* Number of test

TABLE A5--SUMMARY OF COMPRESSIVE STRENGTH AND IN SITU TEST RESULTS (MIX 5)

Test	* n	Average						Coefficient of Variation,%					
		1d	3d	7d	14d	28d	90d	1d	3d	7d	14d	28d	90d
Compressive Strength of Cylinder													
Standard Curing(150x300mm,Kg/Cm²)	4		221	256		353	400		5.9	2.2		3.3	4.1
Field Curing(150x300mm,Kg/Cm²)	4	128	191	255	281	303	328	4.0	0.8	3.0	1.7	1.4	2.9
Core (150x300mm,Kg/Cm²)	4		211	239	257	287	321		2.1	3.6	3.0	3.1	3.7
Pullout (Pullout force:KN)	8	16.5	24.2	26.3	28.3	30.3	32.9	11.1	10.9	6.8	7.6	12.2	6.6
CAPO (Pullout force:KN)													
Pulse Velocity (Velocity: M/sec)	8	3678	3823	3846	3912	3915	3943	0.4	0.4	0.3	0.4	0.5	0.7
Rebound Hammer (Rebound No.)	15	21.9	27.4	29.7	29.9	31.4	32.3	9.3	8.9	8.2	11.3	8.4	12.3
Probe Penetration Exposed length:IN Regular Charge	4		1.578	1.788	1.785	1.800	1.900		12.1	8.4	10.2	20.1	11.2

\- COV of the probe test is based upon the embedded length.

* Number of test

TABLE A6--SUMMARY OF COMPRESSIVE STRENGTH AND IN SITU TEST RESULTS (MIX 6)

Test	* n	Average						Coefficient of Variation,%					
		1d	3d	7d	14d	28d	90d	1d	3d	7d	14d	28d	90d
Compressive Strength of Cylinder													
Standard Curing(150x300mm,Kg/Cm²)	4		130	169		248	280		3.6	3.2		5.1	7.5
Field Curing(150x300mm,Kg/Cm²)	4	67	119	147	186	198	245	2.3	3.0	0.0	6.4	6.1	2.2
Core (150x300mm,Kg/Cm²)	4		123	146	154	180	222		3.0	5.8	4.8	7.0	4.5
Pullout (Pullout force:KN)	8	8.4	15.2	19.4	19.4	21.9	24.5	13.4	21.0	18.3	13.3	10.5	8.5
CAPO (Pullout force:KN)	8	9.4	16.0	16.8	20.9	20.9		17.5	28.8	17.7	11.3	12.7	
Pulse Velocity (Velocity: M/sec)	8	3454	3668	3754	3906	3951	3979	0.9	0.6	1.1	0.5	0.3	0.5
Rebound Hammer (Rebound No.)	15	13.4	15.9	20.1	24.2	26.8	28.0	11.3	12.7	11.3	7.1	8.9	6.3
Probe Penetration Exposed length:IN Low Charge Charge	4	1.656	1.967	1.913	2.269	2.165		22.7	4.9	15.5	17.2	18.5	

\- COV of the probe test is based upon the embedded length.

* Number of test

TABLE A7—SUMMARY OF COMPRESSIVE STRENGTH AND IN SITU TEST RESULTS (MIX 7)

Test	n*	Average 1d	3d	7d	14d	28d	90d	Coefficient of Variation,% 1d	3d	7d	14d	28d	90d
Compressive Strength of Cylinder													
Standard Curing(150x300mm, Kg/Cm^2)	4		163	202		257	292		2.1	2.5		8.2	1.9
Field Curing(150x300mm, Kg/Cm^2)	4	106	154	173	194	232	263	3.0	3.4	4.5	1.6	1.7	7.0
Core (150x300mm, Kg/Cm^2)	4		149	166	178	202	240		4.0	4.7	3.2	4.2	3.8
Pullout (Pullout force:KN)	8	15.0	19.4	21.2	21.2	26.0	27.3	18.8	22.3	12.6	12.4	13.7	6.9
CAPD (Pullout force:KN)	8	16.8	20.2	20.9	22.9	24.0		17.6	25.2	20.2	20.4	18.4	
Pulse Velocity (Velocity: M/sec)	8	3672	3798	3876	3918	3964	3986	0.7	0.5	0.4	0.4	0.7	0.6
Rebound Hammer (Rebound No.)	15	18.4	21.8	24.7	25.0	27.3	29.2	10.7	10.0	11.9	13.0	13.0	9.4
Probe Penetration Regular Charge	4	1.299	1.444	1.738	1.775	1.767	1.944	11.1	20.4	12.1	21.3	9.2	18.3
Exposed length:IN Low Charge		1.780	1.913	2.025	2.175	2.200		7.7	19.2	7.9	13.7	8.3	

— COV of the probe test is based upon the embedded length.

* Number of test