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COMPARISON OF PULL-OUT STRENGTH OF CONCRETE WITH COMPRESSIVE STRENGTH OF CYLINDERS AND CORES, PULSE VELOCITY AND REBOUND NUMBER

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COMPARISON OF PULL-OUT STRENGTH OF CONCRETE WITH COMPRESSIVE STRENGTH OF CYLINDERS AND CORES, PULSE VELOCITY AND REBOUND NUMBER

by

V. M. Malhotra* and G. Carette*

- - -

SYNOPSIS

This paper presents comparisons of pull-out strength of concrete with compressive strength of cylinders and cores, pulse velocity and rebound number. Briefly, a pull-out test, which is relatively a new technique, measures with a special tension ram the force required to pull out a specially shaped steel rod whose enlarged end has been cast into the concrete. In this study pull-out tests were performed on 2 x 2 x 1-ft (610 x 610 x 305-mm) concrete blocks. Compressive strengths were obtained on 4 x 8-in. (102 x 203-mm) and 6 x 12-in. (152 x 305-mm) cylinders; also 4 x 8-in. (102 x 203-mm) cores were drilled from the blocks and tested in compression. In addition, pulse velocity measurements and Schmidt rebound hammer readings were also taken on the blocks.

The analysis of the test data shows that a significant correlation exists between the compressive strength of cylinders cured under standard conditions and the pull-out strength of concrete. This is equally true for the compressive strength of the cores drilled from the concrete blocks.

For the same concrete mix, the pull-out strength increased with increasing age, indicating the possible usefulness of these tests for comparative studies.

The ratio of the pull-out strength to the cylinder compressive strength decreases with increase in the compressive strength of concrete. At 28 days, this ratio varies from 24 per cent for 2860 psi (19.7 MPa) concrete to 18 per cent for 7510 psi (51.8 MPa). In general, for any strength level, the ratio does not change significantly with age.

The pull-out strength is of the same order of magnitude as the direct-shear strength of concrete indicating that the pull-out test result may be a measure of the direct-shear strength of concrete.

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LABORATOIRES DES SCIENCES MINERALES

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COMPARAISON ENTRE LA RESISTANCE AU RETRAIT DU BETON, LA RESISTANCE A LA COMPRESSION DE CYLINDRES ET DE CAROTTES, LA VITESSE D'IMPULSION ET LA VALEUR DU REBONDISSEMENT

par

V.H. Malhotra* et G. Carette**

SYNOPSIS

Ce rapport présente des comparaisons entre la résistance au retrait du béton, la résistance à la compression de cylindres et de carottes, la vitesse d'impulsion et la valeur du rebondissement. Bref, l'essai de la résistance au retrait, une technique assez récente, mesure, avec un cric de traction spécial, la force requise pour retirer une tige d'acier spécialement modelée dont le bout élargi a été coulé dans du béton. Dans cette étude, des essais de résistance au retrait ont été effectués sur des blocs de béton de 2x2x1 pi. (610x610x305 mm). Des résistances à la compression ont été obtenues sur des cylindres de 4x8 po. (102x203 mm) et de 6x12 po. (152x305 mm); des carottes de 4x8 po. (102x 203 mm) ont été percées dans les blocs et mises à l'épreuve en compression. De plus, les mesures de vitesse d'impulsion et les données de la technique Schmidt du marteau de rebondissement ont été relevées.

L'analyse de ces données démontre qu'il y a une corrélation significative entre la résistance à la compression des cylindres mis à l'épreuve dans des conditions normales et la résistance au retrait du béton. C'est également vrai pour la résistance à la compression des carottes percées dans les blocs de béton.

Pour le même mélange de béton, la résistance au retrait augmentait à mesure que le béton vieillissait; c'est une bonne indication de l'utilité possible de ces essais pour des études comparatives.

Le rapport entre la résistance au retrait et la résistance à la compression des cylindres diminue à mesure que la résistance à la compression du béton augmente. Après 28 jours,

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ce rapport varie de 24% pour 2,860 lpc (19.7 MPa) de béton à 18% pour 7,510 lpc (51.8 MPa). En général, pour n'importe quel niveau de résistance, le rapport ne change pas de façon significative avec l'âge.

La résistance au retrait est du même ordre de magnitude que la résistance au cisaillement direct du béton, indiquant que les résultats de l'essai de retrait peuvent constituer la mesure de la résistance au cisaillement direct du béton.

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INTRODUCTION

It is increasingly being recognized that strength of concrete in structures should be measured by in-situ testing. Among the many non-destructive techniques being investigated, the pull-out test appears to offer considerable promise. Briefly, a pull-out test measures, with a special ram, the force required to pull out a specially designed steel rod whose enlarged end has been cast into the concrete. Because of its shape, the steel rod pulls out a cone of the concrete. The concrete is believed to be in shear and the slope of the cone is approximately 45 degrees. The pull-out force is related to the compressive strength of companion test cylinders. In a preliminary study Malhotra (1) had investigated the relationship of the pull-out strength to the strength of the companion cylinders only and had concluded:

> "The pull-out test is satisfactory for estimating the strength of in-situ concrete at both early and late ages, and its results can be reproduced with an acceptable degree of accuracy.
>
> The pull-out test is superior to the rebound hammer and the Windsor probe tests because a greater depth and volume is tested. However, unlike the latter two tests, the pull-out test has to be planned in advance and the pull-out assemblies have to be set in the formwork before concrete is placed. This somewhat limits the usefulness of the technique."

This investigation was undertaken to obtain additional data on pull-out tests for concrete made with gravelstone aggregates and to establish correlations between the pull-out strength of concrete and strength parameters derived from other nondestructive test methods.

SCOPE OF INVESTIGATION

In this study nine 5-ft^3 (0.14-m^3) concrete mixes were made. The water-cement ratio varied from 0.36 to 0.70 and corresponding cement contents varied from 845 to 390 lb/yd^3 (500 to 230 kg/m^3). From each mix, one 24 x 24 x 12-in. (610 x 610 x 305-mm) concrete block, nine 4 x 8-in. (102 x 203-mm) cylinders and three 6 x 12-in. (152 x 305-mm) cylinders were cast. The pull-out tests on the concrete blocks were made at 7, 28 and 91 days. Also, the blocks were subjected to tests by the Schmidt rebound hammer and pulse velocity measurements were taken. In addition, 4 x 8-in. (102 x 203-mm) cores were drilled from the blocks at the above ages. The cores along with the companion moist-cured test specimens were tested in compression.

THE PULL-OUT ASSEMBLIES AND THEIR INSTALLATION

The pull-out assembly consisted of a threaded steel shaft 3/4 in. (19 mm) in diameter and 4.25 in. (107 mm) long together with a 2.25-in. (57-mm) by 1/8-in. (2.8-mm) thick washer which was to serve as the embedded head. The assembly was held in position in the formwork by nuts and washers, as shown in Figure 1. The critical dimensions were the diameter of the washer and the distance between the top of the washer and the inside of the formwork. This distance was kept constant at 2.08 in.(52.8 mm). The steel shaft and the embedded head are pulled out of the hardened concrete by means of a hollow tension ram which exerts pressure through a bearing ring with an inside diameter

5.00 in. (127.0 mm) and thickness 1/2 in. (12.5 mm). The inside diameter of the bearing ring, the outside diameter of the embedded head, and the distance between them control the size and the apex angle of the concrete frustrum that will be pulled out (Figure 2).

The pull-out assemblies were installed in the 24 x 24 x 12-in. (610 x 610 x 305-mm) wooden moulds at the CANMET laboratory. Great care was taken to ensure that the height "h" was kept constant in each assembly. All threaded shafts, washers, and nuts were cleaned to ensure a satisfactory bond between steel and concrete. There were three to six pull-out assemblies in each mould, one or two on each of the three faces. No form oil of any kind was used on the inside of the moulds.

CONCRETE MIXES

A total of nine 5-ft^3 (0.14-m^3) concrete mixes were made in the CANMET laboratory between January-March 1975. A 5-ft^3 laboratory counter-current mixer was used for preparing the concrete batches with mixing time kept constant at 6 minutes.

Materials

Normal portland cement CSA Type 10 (ASTM Type I) was used for the concrete mixes. The physical properties and chemical analysis of the cement are given in Table 1.

Minus 1-in. (25-mm) river gravel was used as the coarse aggregate and local sand was the fine aggregate. To keep the grading uniform for each mix, the sand was separated into different size fractions which were combined to a specified grading.

The grading and physical properties of both the coarse and fine aggregates are given in Tables 2 and 3.

Mix Proportioning

Mix proportioning data for the concrete mixes are given in Table 4. The aggregates were room dry, and the mixing water was adjusted according to the water absorbed by the aggregates.

An air-entraining agent was used in all the mixes.

Properties of Fresh Concrete

The properties of the fresh concrete, i.e., temperature, slump, unit weight and air content, are also given in Table 4.

PREPARATION AND TESTING OF SPECIMENS

One concrete block 24 x 24 x 12-in. (610 x 610 x 305-mm), nine 4 x 8-in. (102 x 203-mm) cylinders and three 6 x 12-in. (152 x 305-mm) cylinders were cast from each mix. The blocks were cast by filling the forms progressively from one end and compacting with an internal vibrator. The 6 x 12-in. (152 x 305-mm) cylinders were cast by filling the steel moulds in approximately two equal layers and compacting by an internal vibrator. The 4 x 8-in. (102 x 203-mm) cylinders were compacted in approximately two equal layers using a vibrating table. After casting, all the moulded specimens were covered with water-saturated burlap, left in the casting room for 24 hours, and then they were demoulded. The cylindrical specimens were removed to a moist curing room* while the concrete blocks were transferred to the basement adjacent to the moist curing room. The blocks were again covered with a wet burlap and kept wet by a continuous water spray.

*73 ± 3.0°F (23 ± 1.7°C) and 100 per cent relative humidity.

At 7, 28 and 91 days, three 4 x 8-in. (102 x 203-mm) cylinders were capped with a sulphur and flint mixture and tested in compression on a 600,000 lb (270,000 kg) testing machine; at 28 days, three 6 x 12-in. (152 x 305-mm) cylinders were also tested in compression. Before capping, the pulse velocity was measured through the cylinders with pulse path being 12 in. (305 mm).

The tests to which the concrete blocks were subjected are described below. Figure 3 shows a sketch giving the location of the various tests in relation to the block.

Pull-out Tests

A hand-operated hydraulic pump and a 30-ton tension ram were used for the pull-out tests; the tension ram having been calibrated before use against the compression testing machine (1). The pull-out tests were carried out in accordance with the procedure outlined elsewhere (1). Briefly, with the threaded shaft of one of the pull-out assemblies as the centre, a 5-in. (127-mm) diameter circle was drawn on the concrete surface with a marking pencil. Next, a 3-in. (76-mm) long sleeve was screwed on the exposed portion of the shaft, and a 3/4-in. (19-mm) diameter high-strength steel rod approximately 16-in (410-mm) long was threaded into the steel sleeve. The tension ram was then mounted on the shaft so that the bearing plate, which had been bolted to the bottom of the ram, was flush with the concrete surface and centered on the marked circle. Another washer with a short head was then screwed into the exposed steel rod and tightened against the top of the piston opening of the ram. Pressure was applied with the hydraulic pump and continued until the gauge needle started to fall back. The maximum gauge reading was noted and the pumping was continued until the pull-out assembly was free of the conrete block. The pull-out strength of the concrete was calculated from the total load applied, as determined from a chart obtained in the calibration mentioned above, and the area of the frustrum removed in the test. Figures 4 to 9 show views of the concrete blocks, the tension ram and the pull-out assemblies after the test.

Pulse Velocity Measurements

Pulse velocity measurements were performed on each of the concrete blocks, at 7, 28 and 91 days. The measurements were performed at right angles to the direction of casting, the path length being 24 in. (610 mm). As far as possible the testing was done in accordance with the ASTM Standard C 597 using one of the portable testing machines. At 7 days, the pulse velocity measurements were taken in a square grid pattern. At 28 and 91 days, in order to avoid drill holes, the velocity measurements were taken in a rectangular grid pattern and along a vertical line respectively (Figure 3). The surfaces of the blocks were in a saturated-surface dry condition at the time of testing.

Schmidt Rebound Hammer Readings

Surface hardness of the concrete blocks at 7, 28 and 91 days was determined by the rebound hammer (2). At each age, 5 hammer readings were taken on each of the four side faces of the concrete block and these 20 readings were averaged to give a rebound number. The surfaces of the blocks were in a saturated-surface dry condition at the time of testing.

Drilled Cores

Three 4-in. (102-mm) diameter drill cores were taken at 7, 28 and 91 days from each concrete block, the drilling being done in the direction of casting of the blocks. The cores were drilled for the full depth of the blocks and were then cut at the ends to give a length of 8 in. (203 mm) so that L/D was equal to 2. Where necessary, the ends of the cores were lapped to smooth, even surfaces, then were capped and immediately compression tested dry to simulate field-curing conditions. It was ensured that the drill holes were at least 1.5 in. (38 mm) apart and at least 3 in. (76 mm) away from the nearest edge of the concrete slab. Pulse velocity measurements were also taken on the concrete cores immediately after drilling.

TEST RESULTS AND THEIR ANALYSES

Eighty one 4 x 8-in. (102 x 203-mm) cylinders, eighty-one 4 x 8-in. (102 x 203-mm) drilled cores, twenty-seven 6 x 12-in. (152 x 305-mm) cylinders and nine 24 x 24 x 12-in. (610 x 610 x305-mm) blocks were tested in this investigation. The density and strength results for the specimens are summarized in Tables 5 to 9. The standard deviations and coefficients of variation for the test data, when calculated, are shown in Table 10.

The relationships between the pull-out strengths, rebound numbers, pulse velocity and compressive strengths of cylinders and drilled cores together with other comparisons are shown in Figures 10 to 21. Where possible, regression lines have been fitted to the test data.

DISCUSSION OF TEST RESULTS

Nature of the Pull-Out Strength

The state of stresses in the pull-out test is rather complex and difficult to analyze. However, the magnitude of strengths obtained in this test indicates that perhaps the test measures the direct-shear strength of concrete (Table 11). The 28-day pull-out strengths vary from 535 psi (3.70 MPa) for 2860 psi (19.7 MPa) strength level of concrete to 1280 psi (8.85 MPa) for 7510 psi (51.8 MPa) strength level of concrete. In the published literature (3), the direct-tensile strength of concrete for the corresponding strength levels varies from 270 psi (1.85 MPa) to 530 psi (3.70 MPa) respectively. Thus the pull-out strength values appear to be twice the corresponding values for direct-tensile strength. The direct-shear strength of concrete (4) is also about twice the value of the direct-tensile strength thereby indicating that the pull-out strength may be a measure of the direct-shear strength of concrete.

At compressive strength levels beyond 8000 to 9000 psi (55.2 to 62.1 MPa), the pull-out strength should reach a maximum value beyond which there may be no increase in the pull-out strength regardless of the compressive strength of concrete. Thus the pull-out test may not be useful in predicting the compressive strength of concrete beyond 8000 psi (55.2 MPa).

Ratio of Pull-Out Strength to Compressive Strength

As is the case with tensile, flexural and shear strengths, the ratio of the pull-out strength to compressive strength appears to decrease with increase in the strength of concrete. For example, at 28 days the ratio varies from 24 per cent for 2860 psi (19.7 MPa) to 18 per cent for 7510 psi (51.8 MPa) concrete (Table 7). However, for any strength level the ratio does not significantly change with age.

Detection of Increase in Strength with Age

The pull-out strengths increased with the increasing age of concrete. This was true for concrete at all strength levels. For example, the average pull-out strength for mix No. 1 increased from 495 psi (3.40 MPa) at 7 days to 640 psi (4.40 MPa) at 91 days, an increase of about 30 per cent. The pull-out strengths can thus be useful for studying the relative strengths of concrete in a structure and for other comparative studies.

Size of Concrete Blocks Under Test

The size of blocks under test was 24 x 24 x 12 in. (610 x 610 x 305 mm). The blocks made from high-strength concrete mixes were damaged during the pull-out tests. No such damage had occurred during the preliminary investigation (1) in which the size of the blocks was 24 x 24 x 24 in. (610 x 610 x 610 mm). Thus the minimum size of a concrete block necessary for high-strength concrete for laboratory studies appears to be a cube with a 2-ft (610-mm) minimum dimension. This implies that the quantity of concrete needed for one such test block and associated companion cylinders is of the order of 10 ft^3 (0.3 m^3), a rather large volume of concrete for one test mix.

Within-Test Variation

No comparison can be made of the within-test reproducibilities of the various tests because a different number of specimens were used for different tests. For example, twenty readings constituted one test for the Schmidt rebound hammer but only two (and sometimes only one) values were available for the pull-out test; for the compression test, only three cylinders of each size and three drilled cores were tested at each age. Notwithstanding this, the within-test coefficient of variation (C.V.) for the pull-out test at 7 days varies from 0.9 to 14.3 per cent with an average value of 5.3 per cent; the corresponding values for the compressive strength of 4 x 8-in. (102 x 203-mm) cylinders are from 2.6 to 8.3 per cent, with an average value of 4.6 per cent. These values are comparable.

The average within-batch C.V. for the 7-day compressive strength of 4 x 8-in. (102 x 203-mm) cores is 3.3 per cent. This is significantly lower than the values for the pull-out and cylinder compressive strengths.

THE PULL-OUT AND OTHER TESTS

Pull-Out Test Versus Compressive Strength of Drilled Cores

The pull-out test has been suggested as an alternative to drilling cores from structural concrete and testing them in compression. The suggestion has some validity but the disadvantage is that whereas pull-out tests have to be planned in advance of concreting, the cores can be drilled at any time after the concrete has sufficiently hardened. However, the multitude of variables that affect drill core test results should encourage engineers to look favourably at the pull-out test in spite of the disadvantages mentioned above.

The pull-out test costs considerably less than the drill cores. A set of three pull-out assemblies, a desirable minimum for a test*, costs approximately three dollars and requires about 15 minutes of the operator's time. Furthermore, the pull-out assemblies can be reused. A set of two 4 x 8-in. (102 x 203-mm) drill cores, a desirable minimum for a valid test, can cost up to ten dollars per core if allowances are made for operator time, transportation of the cores to the laboratory, smoothening of the ends, curing, capping and testing.

The pull-out strength results are available within minutes of the testing whereas the drilling and testing of cores can take several hours to several days depending upon whether the cores are tested dry or wet.

*This was not possible in this study because of the need to obtain data at various ages.

Pull-Out Test Versus Schmidt Rebound Hammer Test

Although there is a degree of correlation between these two tests (Figure 18), no direct comparison can be made between the two because they are basically measuring two different parameters. The pull-out test appears to be a quantitative measure of the direct-shear strength of concrete in-situ whereas the rebound hammer is basically a surface hardness tester from which an estimate of strength of concrete may be made. The pull-out test results are much more meaningful. The pull-out strengths are not likely to be influenced by surface moisture, texture, and carbonation effects because of the in-depth position of the pull-out assemblies. Against this, there are the expenses of the pull-out assemblies and only a limited number of pull-out tests can be done in a given area. The rebound hammer does not suffer from these disadvantages because an almost unlimited number of test "shots" can be taken and repeated, if necessary, without added expense.

Pull-Out Test Versus Windsor Probe Test

No Windsor probes (5, 6) were fired into the concrete blocks in this study and thus no correlation data are available between the pull-out strength and the Windsor probe test results. The Windsor probe, unlike the pull-out test, does not quantitatively measure the strength of concrete; on the contrary, it measures the resistance to penetration of a projectile fired into concrete from which an estimate of concrete strength may be obtained. Thus the probe test is more similar to the Schmidt rebound hammer than to the pull-out test.

Pull-Out Test Versus Pulse Velocity Measurements

As mentioned earlier, the pull-out strength is a measure of in-situ strength of concrete. Under very controlled laboratory conditions, there may be a correlation between the pull-out strength and pulse velocity through concrete (Figure 19). In general, pulse velocity measurements do not correlate well with strength of concrete and therefore these measurements should not be used to predict pull-out or compressive strength of concrete.

STANDARDIZATION OF THE PULL-OUT TEST

A number of organizations* and some individuals** are carrying out studies to evaluate this new technique of in-situ testing of concrete. The ASTM Committee C.09.02.05 on Nondestructive Methods of Testing Concrete is currently discussing a draft standard on the subject. The Canadian Standards Association Committee A23.1 on Concrete Materials and Methods of Concrete Construction is looking favourably on the adoption of this test, though no decision on the subject has been taken to date.

COMPARISON OF RESULTS OF THIS INVESTIGATION WITH THOSE OBTAINED BY OTHERS

The pull-out technique is still in its infancy and little published data are available on its use. The results obtained in this investigation have been compared with those reported (but unpublished) by the United States Bureau of Reclamation (7) and those reported by CANMET in 1972 (Figure 17). Though these data cannot be compared directly because of the use of different materials and pull-out assemblies, the correlations appear to be much alike. This is very encouraging indeed.

ADVANTAGES AND LIMITATIONS OF THE PULL-OUT TEST

The advantages and limitations of the pull-out test have been discussed elsewhere (1) and will not be repeated here. However, it is emphasized that the

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*National Ready-mixed Concrete Association, Washington, D.C.,
*U.S. Bureau of Reclamation, Denver, Colorado,
**Owen Richards, Consultant, Box 43 R.D.1, The Plains, Va. USA, 22171

simplicity of the test outweighs any disadvantages it may have. It is one of the few tests available which quantitatively measures the strength of concrete in-situ and this alone is sufficient reason for its adoption by the construction industry.

CONCLUDING REMARKS

In-situ strength of concrete can be quantitatively determined using the pull-out technique. The technique is simple, effective, and cheap, and test results can be reproduced with an acceptable degree of accuracy.

The pull-out strength is of the same order of magnitude as the direct-shear strength of concrete indicating that the strength value obtained in the pull-out test is probably a measure of the direct-shear strength. The correlations between the pull-out strength and the compressive strength of cores drilled from concrete and between the pull-out strength and the compressive strength of companion cylinders are statistically significant.

The pull-out test is superior to the rebound hammer, the Windsor probe, and pulse velocity tests. The pull-out test quantitatively measures the strength of concrete in-situ whereas the other three tests measure other parameters from which only an estimate of the strength may be obtained.

ACKNOWLEDGEMENT

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TABLE 1

Physical Properties and Chemical Analysis of Cement*

Description of Test	
Physical Tests - General	
Time of Set (Vicat): Initial	2 hr 20 min
Final	4 hr 10 min
Fineness, No. 200 (passing)	95.7 %
Soundness - Autoclave	0.54%
Physical Tests - Mortar Strength	
Compressive Strength (2-in. cubes)	
3-day	3020 psi (20.8 MPa)
7-day	3990 psi (27.5 MPa)
28-day	4960 psi (34.2 MPa)
Chemical Analysis	
Silica (SiO_2)	20 80%
Alumina (Al_2O_3)	5.36%
Iron Oxide (Fe_2O_3)	2.96%
Calcium Oxide (CaO), Total	63.29%
Calcium Oxide (CaO), Free	0.61%
Magnesium Oxide (MgO)	3.00%
Sulphur Trioxide (SO_3)	2.56%
Loss on Ignition	0.61%
Insoluble Residue	0.14%

*Test results and chemical analysis supplied by the cement manufacturing company.

TABLE 2

Grading of Aggregates

Coarse Aggregate			Fine Aggregate		
Sieve Size		Cumulative percentage retained	Sieve Size		Cumulative percentage retained
in.	mm		Mesh	mm	
3/4	19.0	33.3	No. 4	4.75	0.0
			No. 8	2.36	10.0
3/8	9.5	66.6	No. 16	1.18	32.5
			No. 30	0.60	57.5
No.4	4.75	100.0	No. 50	0.30	80.0
			No. 100	0.15	94.0
			Pan	–	100.0

TABLE 3

Physical Properties of Coarse and Fine Aggregates

	Gravelstone	Natural sand
Specific Gravity	2.70	2.70
Absorption, %	0.4	1.0

TABLE 4

Mix Proportioning Data

Mix No.	Water-Cement Ratio*	Aggregate-Cement Ratio*	Properties of Fresh Concrete						
			Temperature		Slump		Unit Weight		Air Content, %
			°F	°C	in.	mm	lb/cu ft	Kg/cu m	
1	0.70	8.0	72	22.2	3.5	90	138.4	2217	7.5
2	0.60	7.5	71	21.7	2.0	50	140.0	2243	6.4
3	0.60	7.3	73	22.8	1.5	40	147.2	2358	4.3
4	0.56	6.6	74	23.3	1.5	40	146.0	2339	4.4
5	0.53	6.1	70	21.1	2.0	50	148.0	2371	4.3
6	0.51	5.8	70	21.1	2.5	60	147.2	2358	4.3
7	0.42	4.4	69	20.6	2.5	60	146.4	2345	4.3
8	0.39	3.8	72	22.2	2.0	50	148.0	2371	4.4
9	0.36	3.4	72	22.2	1.5	40	149.2	2390	4.2

*All ratios are by weight.

TABLE 5

Densities of Cores and Cylinders at Various Ages

Mix No.	4 x 8-in. (102 x 203-mm) Cylinders and Cores												6 x 12-in. (152 x 305-mm) Cylinders	
	7 Days				28 Days				91 Days				28 Days	
	Cylinders		Cores		Cylinders		Cores		Cylinders		Cores			
	lb/cu ft	Kg/cu m	lb/cu ft	Kg/cu m	lb/cu ft	Kg/cu m	lb/cu ft	Kg/cu m	lb/cu ft	Kg/cu m	lb/cu ft	Kg/cu m	lb/cu ft	Kg/cu m
1	-	-	141.5	2267	143.1	2292	141.4	2265	141.9	2273	141.8	2272	143.0	2291
2	-	-	141.9	2273	143.0	2291	141.5	2267	143.0	2291	141.7	2270	144.0	2307
3	150.3	2408	148.9	2385	150.9	2417	148.9	2385	148.6	2381	148.8	2384	150.7	2414
4	149.1	2389	149.7	2398	150.5	2411	148.7	2382	-	-	-	-	151.0	2419
5	150.8	2416	-	-	151.8	2432	-	-	150.9	2417	-	-	151.2	2422
6	150.3	2408	149.3	2392	150.6	2413	149.0	2387	151.0	2419	153.2	2454	150.7	2414
7	149.3	2392	148.6	2381	149.7	2398	148.8	2384	150.4	2409	-	-	149.4	2393
8	150.0	2403	-	-	150.0	2403	-	-	150.1	2405	-	-	149.4	2393
9	149.9	2401	149.4	2393	150.4	2409	149.5	2395	150.6	2413	148.8	2384	148.3	2376

All values are averages of 3 results.

TABLE 6

Summary of Test Results for 7-Day Old Concrete

Mix No.	Compressive strength+ of 4x8-in. (102x203-mm) specimens				Pull-out strength++ of 2x2x1ft (610x610x305-mm) concrete blocks		Ratio of Pull-out to cylinder compressive strength, %	Pulse velocity* through 2x2x1-ft (610x610x305-mm) concrete blocks		Rebound number** on 2x2x1-ft (610x610x305-mm) concrete blocks
	Cylinders		Cores							
	psi	MPa	psi	MPa	psi	MPa		ft/sec	m/sec	
1	2040	14.1	1930	13.3	495	3.40	24	12610	3845	23
2	2710	18.7	2080	14.3	475	3.25	17	12820	3910	22
3	3740	25.8	2630	18.2	635+++	4.40	17	13920	4245	25
4	3640	25.1	3280	22.6	675	4.65	18	14050	4280	23
5	4490	31.0	-	-	710+++	4.90	16	13600	4145	24
6	4620	31.8	4410	30.4	665	4.60	14	14050	4280	29
7	5220	36.0	3600	24.9	785	5.40	15	13980	4260	31
8	6250	43.1	-	-	875+++	6.05	14	14060	4285	29
9	5900	40.7	4830	33.3	1165	8.05	20	14240	4340	36

+ Average of three test results.
++ Average of two test results except when otherwise specified; +++ one test result only.
* Average of 9 readings; path length 24.0 in.(610 mm).
** Average of 20 readings.

TABLE 7

Summary of Test Results for 28-Day Old Concrete

Mix No.	Compressive strength+ of 4x8-in. (102x203-mm) specimens				Compressive strength+ of 6x12-in. (152x305-mm) cylinders		Pull-out strength++ of 2x2x1-ft (610x610x305-mm) concrete blocks		Ratio of pull-out to compressive strength of 6x12-in. (152x305-mm) cylinders,	Pulse velocity* through 2x2x1-ft (610x610x305-mm) concrete blocks		Rebound number ** on 2x2x1-ft (610x610x305-mm) concrete blocks
	Cylinders		Cores									
	psi	MPa	psi	MPa	psi	MPa	psi	MPa	%	ft/sec	m/sec	
1	2860	19.7	2290	15.8	2270	15.7	535+++	3.70	24	13260	4040	24
2	3620	25.0	2740	18.9	2970	20.5	615+++	4.25	21	13600	4145	26
3	4880	33.6	3700	25.5	4100	28.3	860	5.95	21	14580	4445	29
4	4890	33.7	4730	32.6	4100	28.3	925+++	6.40	22	14750	4495	30
5	6220	42.9	-	-	5100	35.2	1040	7.15	20	14400	4390	29
6	5970	41.2	5200	35.8	5160	35.6	805	5.55	16	14700	4480	33
7	6400	44.1	4990	34.4	5710	39.4	925+++	6.40	16	14780	4505	38
8	6570	45.3	-	-	5970	41.2	975	6.70	16	14460	4405	34
9	7510	51.8	5310	36.6	7160	49.4	1280	8.85	18	14560	4440	39

+ Average of three test results.
++ Values for one test only unless otherwise specified; +++ Average of two test results.
* Average of six readings; path length 24.0 in. (610 mm)
** Average of 20 readings.

TABLE 8

Summary of Test Results for 91-Day Old Concrete

Mix No.	Compressive strength+ of 4x8-in. (102x203-mm) specimens				Pull-out strength of 2x2x1-ft(610x610x305-mm) concrete blocks		Ratio of Pull-out to cylinder compressive strength	Pulse velocity* through 2x2x1-ft (610x610x305-mm) concrete blocks		Rebound number** on 2x2x1-ft (610x610x305-mm) concrete blocks
	Cylinders		Cores							
	psi	MPa	psi	MPa	psi	MPa	%	ft/sec	m/sec	
1	3220	22.2	2600	17.9	640+++	4.40	20	13680	4170	27
2	4050	27.9	2960	20.4	640+++	4.40	16	14050	4280	27
3	5800	40.0	4730	32.6	1090++	7.50	19	15130	4610	30
4	5770	39.8	5310	36.6	-	-	-	15110	4605	32
5	6710	46.3	-	-	-	-	-	15100	4600	-
6	6250	43.1	5480	37.8	-	-	-	14970	4565	38
7	7000	48.3	6130	42.3	-	-	-	15130	4610	40
8	7850	54.2	-	-	1090++	7.50	14	14770	4500	37
9	7830	54.0	5670	39.1	-	-	-	14890	4540	41

\+ Average of three test results.
++ Values for one test only; +++ Average of two test results.
* Average of 3 readings; path length 24.0 in. (610 mm).
** Average of 20 readings.

TABLE 9

Summary of Compressive Strengths and Pulse Velocities on Drilled Cores

Mix No.	7-Day				28-Day				91-Day			
	Compressive* strength		Pulse velocity**		Compressive* strength		Pulse velocity**		Compressive* strength		Pulse velocity**	
	psi	MPa	ft/sec	m/sec	psi	MPa	ft/sec	m/sec	psi	MPa	ft/sec	m/sec
1	1930	13.3	13200	4025	2290	15.8	13470	4105	2600	17.9	14030	4275
2	2080	14.3	13470	4105	2740	18.9	13470	4105	2960	20.4	14030	4275
3	2630	18.2	14430	4395	3700	25.5	-	-	4730	32.6	14980	4570
4	3280	22.6	14650	4465	4730	32.6	-	-	5310	36.6	15330	4670
5	-	-	-	-	-	-	-	-	-	-	-	-
6	4410	30.4	14440	4400	5200	35.8	14920	4550	5480	37.8	14980	4570
7	3600	24.9	14240	4340	4990	34.4	14750	4495	6130	42.3	15400	4695
8	-	-	-	-	-	-	-	-	-	-	-	-
9	4830	33.3	14340	4370	5310	36.6	14880	4535	5670	39.1	14980	4570

* Average of three test results.
** Average of three test results; path length = 8.0 in. (203 mm)

TABLE 10

Within-Batch Standard Deviation and Coefficient of Variation for 7-Day Test Results

Mix No.	4x8-in.(102x203-mm) Cylinders					4x8-in.(102x203-mm) Cores					Pull-out Tests				
	Average strength*		S. D.		C.V., %	Average strength*		S. D.		C.V., %	Average strength**		S. D.		C.V., %
	psi	MPa	psi	MPa		psi	MPa	psi	MPa		psi	MPa	psi	MPa	
1	2040	14.1	83	0.57	4.1	1930	13.3	140	0.97	7.2	495	3.40	33	0.23	6.7
2	2710	18.7	144	1.00	5.3	2080	14.3	131	0.90	6.3	475	3.25	4	0.03	0.9
3	3740	25.8	311	2.14	8.3	2630	18.2	78	0.54	3.0	635+	4.40	-	-	-
4	3640	25.1	224	1.54	6.1	3280	22.6	46	0.32	1.4	675	4.65	17	0.12	2.5
5	4490	31.0	122	0.84	2.7	-	-	-	-	-	710+	4.90	-	-	-
6	4620	31.8	120	0.83	2.6	4410	30.4	109	0.75	2.5	665	4.60	95	0.66	14.3
7	5220	36.0	209	1.44	4.0	3600	24.9	35	0.24	1.0	785	5.40	21	0.15	2.7
8	6250	43.1	250	1.72	4.0	-	-	-	-	-	875+	6.05	-	-	-
9	5900	40.7	247	1.70	4.2	4830	33.3	103	0.71	2.1	1165	8.05	56	0.38	4.8

* Average of 3 test results.
** Average of 2 test results; + one test available only.

TABLE 11

Comparison of Pull-Out and Shear Strengths

This Investigation					From Published Data+				
Compressive strength at 28-days of 6x12-in. (152x305-mm) cylinders		Pull-out strength at 28-days		Ratio of pull-out to compressive strength, %	Compressive strength* of 6x12-in. (152x305-mm) cylinders		Shear strength*		Ratio of shear to compressive strength, %
psi	MPa	psi	MPa		psi	MPa	psi	MPa	
2270	15.7	535	3.7	24	1750	12.1	400	2.8	23
2970	20.5	615	4.3	21	2250	15.5	500	3.4	22
4100	28.3	860	5.9	21	3040	21.0	680	4.7	22
4100	28.3	925	6.4	22	3810	26.3	830	5.7	22
5100	35.2	1040	7.2	20	4530	31.2	1020	7.0	23
5160	35.6	805	5.6	16	5000	34.5	1040	7.2	21
5710	39.4	925	6.4	16	5450	37.6	1090	7.5	20
5970	41.2	975	6.7	16	5740	39.6	1140	7.9	20
7160	49.4	1280	8.8	18	6120	42.2	1230	8.5	20
					6590	45.4	1360	9.4	21
					8500	58.6	1880	13.0	22

+ Reference (4).

* Max size of agg was $1\frac{1}{2}$ in. (38 mm) - Testing ages varied from 28 days to 2 years, with data collected from different projects.

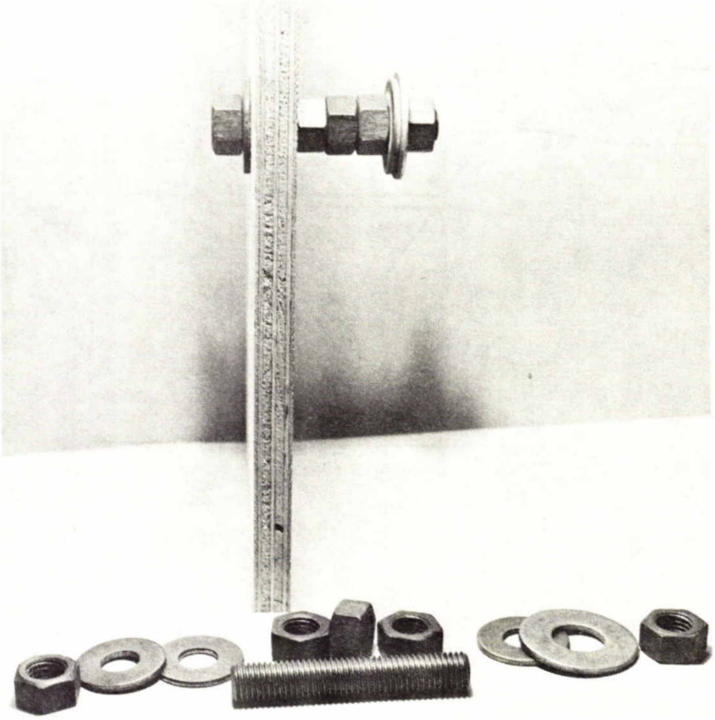
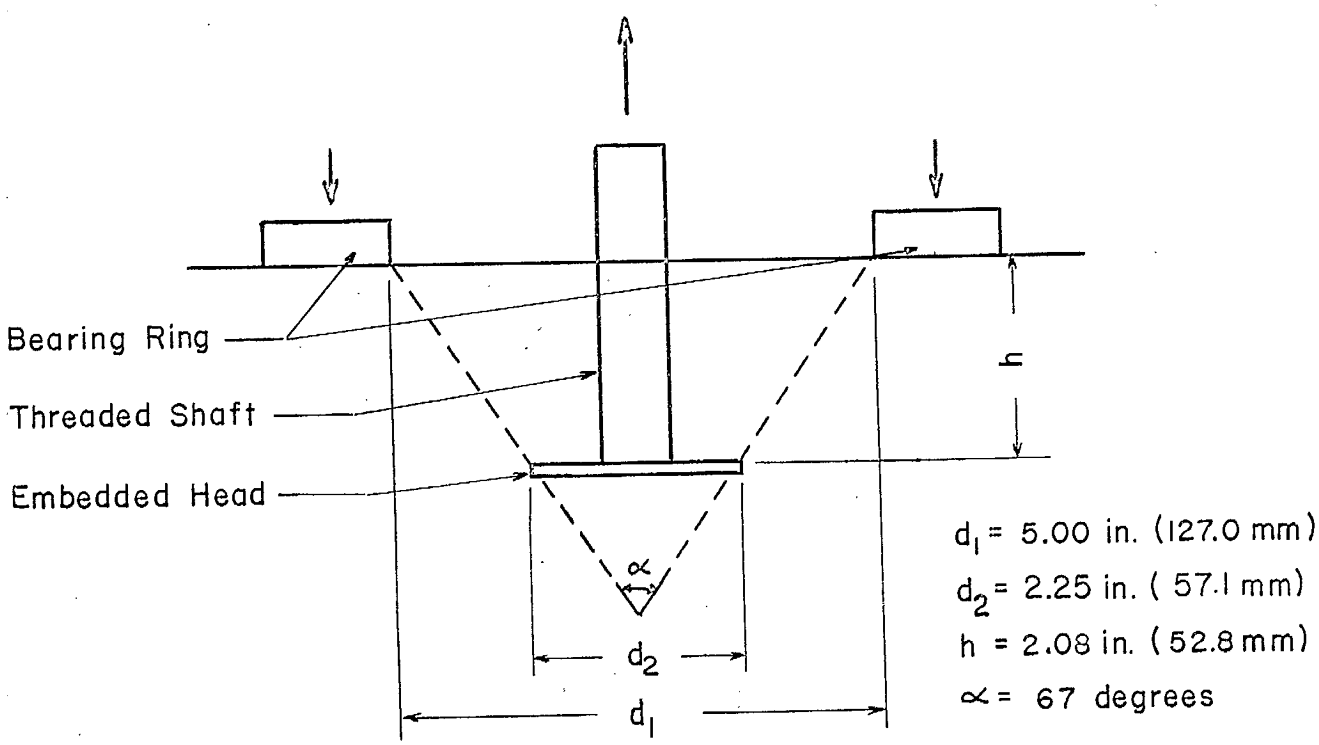


Figure 1. A pull-out assembly with plywood form (exploded view at bottom).
The diameter of the threaded shaft is 3/4 in. (19 mm).



Note 1: Experience indicates that the above dimensions are most suitable.

Note 2: Total area "A" of convex surface of a frustrum of a right circular cone is equal to i.e.

$$A = \pi\, s\left(d_1/_2 + d_2/_2\right)$$

where $s = \sqrt{h^2 + (d_1/_2 - d_2/_2)^2}$

substituting for s, d_1 and d_2, we get:

$$A = 28.40 \text{ in.}^2 \quad (181.8 \text{ cm}^2)$$

Figure 2. Sketch showing position and dimensions of the bearing plate, threaded shaft, and the embedded head.

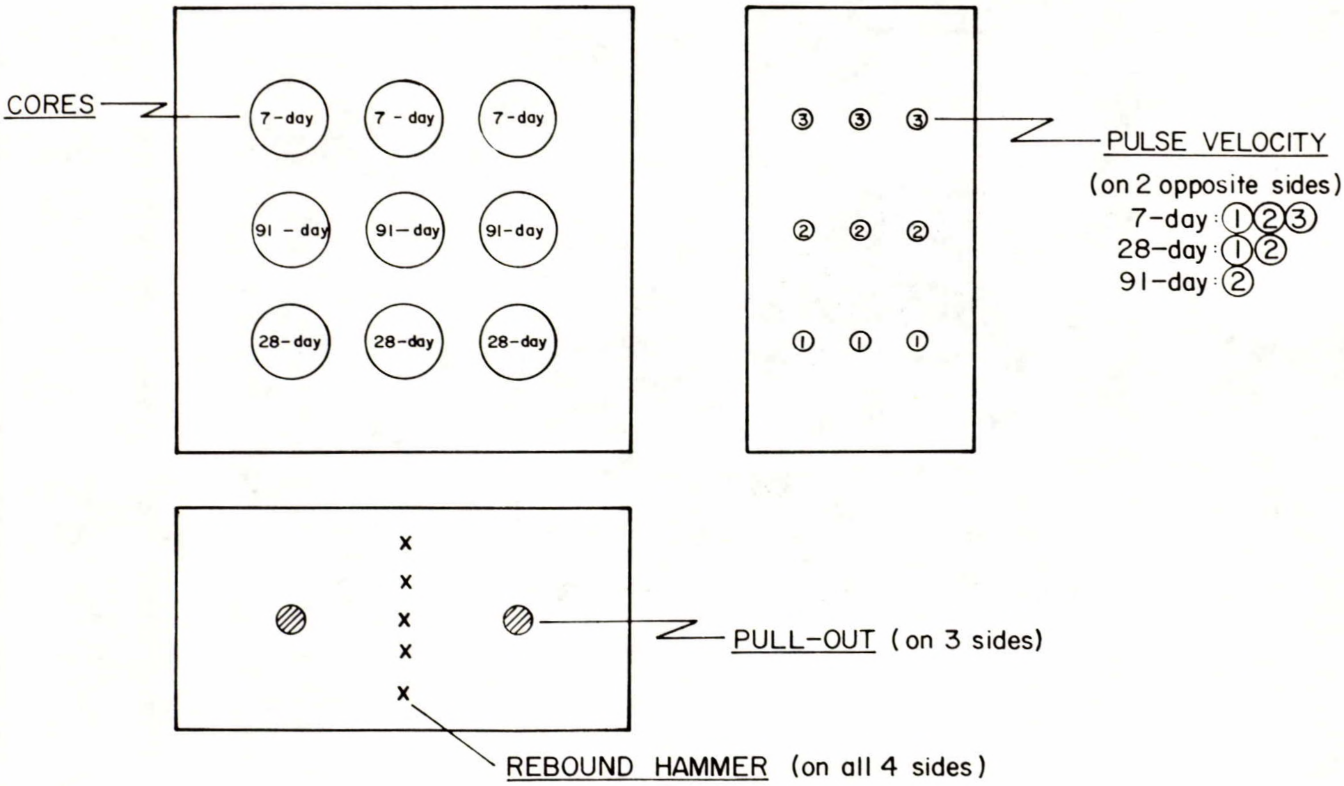


Figure 3. Sketch of a concrete block showing positions of the pull-out tests, drilled cores, rebound hammer readings and pulse velocity measurements.

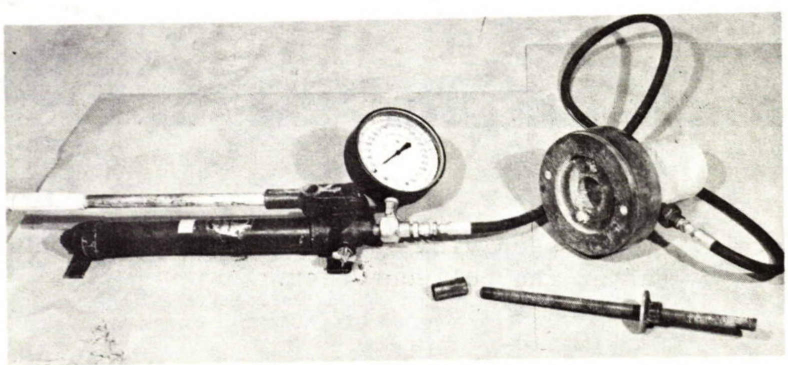


Figure 4. The tension-ram assembly.

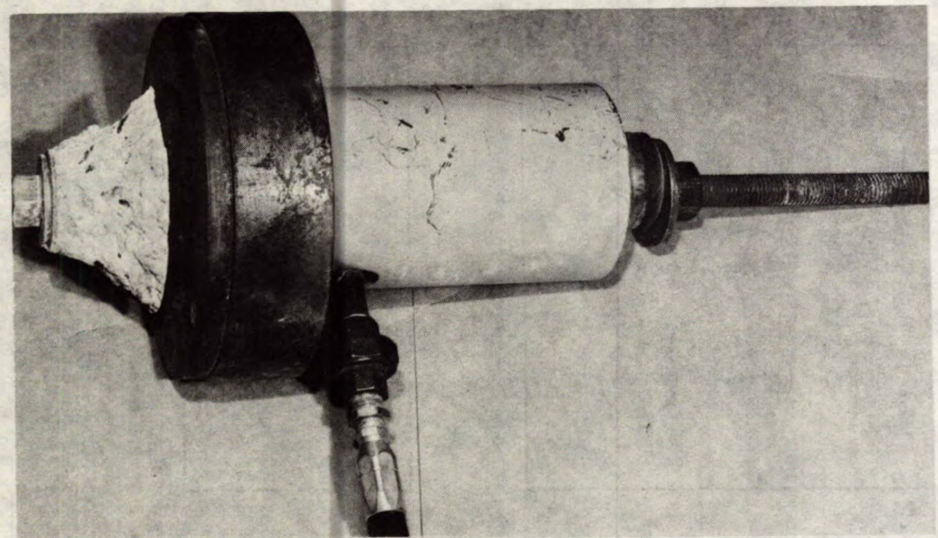


Figure 5. The tension ram immediately after the test.

Figure 6. A close-up view of the hole left in concrete after the pull-out test.

Figures 7. Pull-out assemblies with adhering cones of concrete immediately after the test.

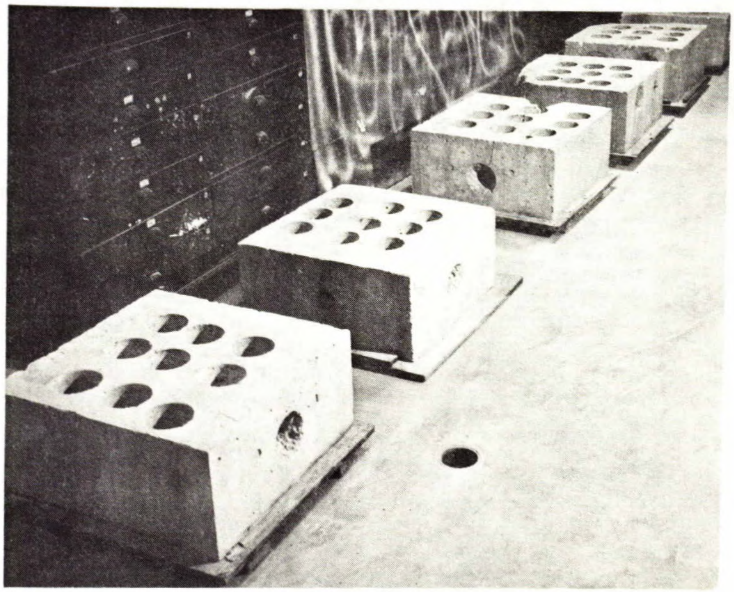


Figure 8. A view of 24x24x12-in.(610x610x305-mm) concrete blocks after tests.

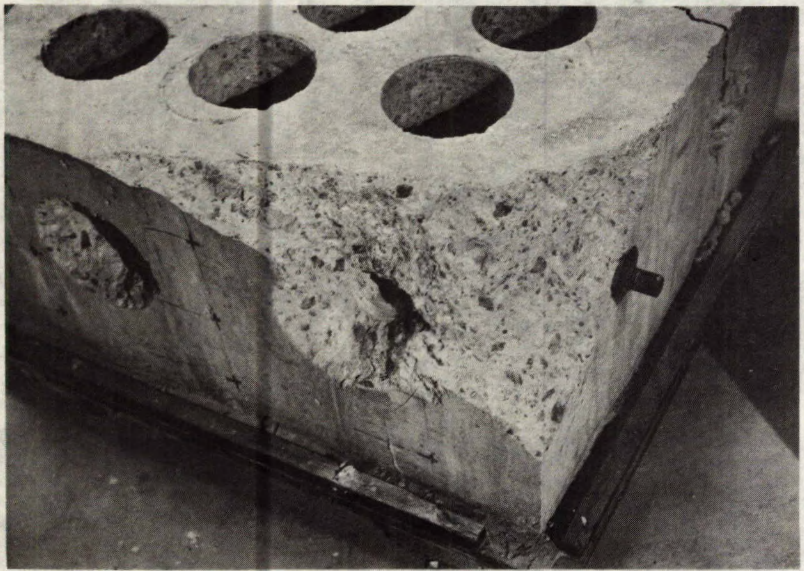


Figure 9. A close-up view of a damaged high-strength concrete block after the pull-out test.

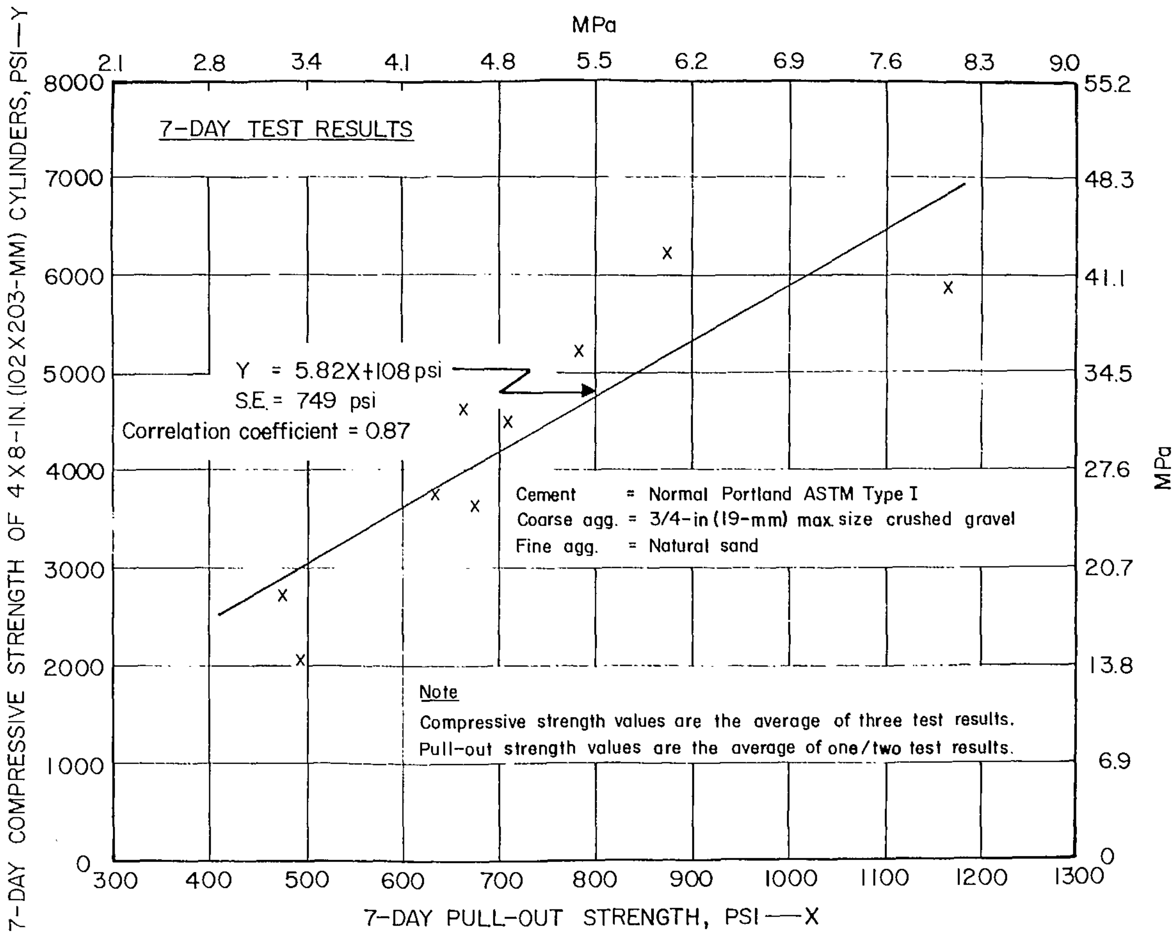


Figure 10. Relationship between pull-out and 7-day compressive strength of 4 x 8-in. (102 x 203-mm) cylinders.

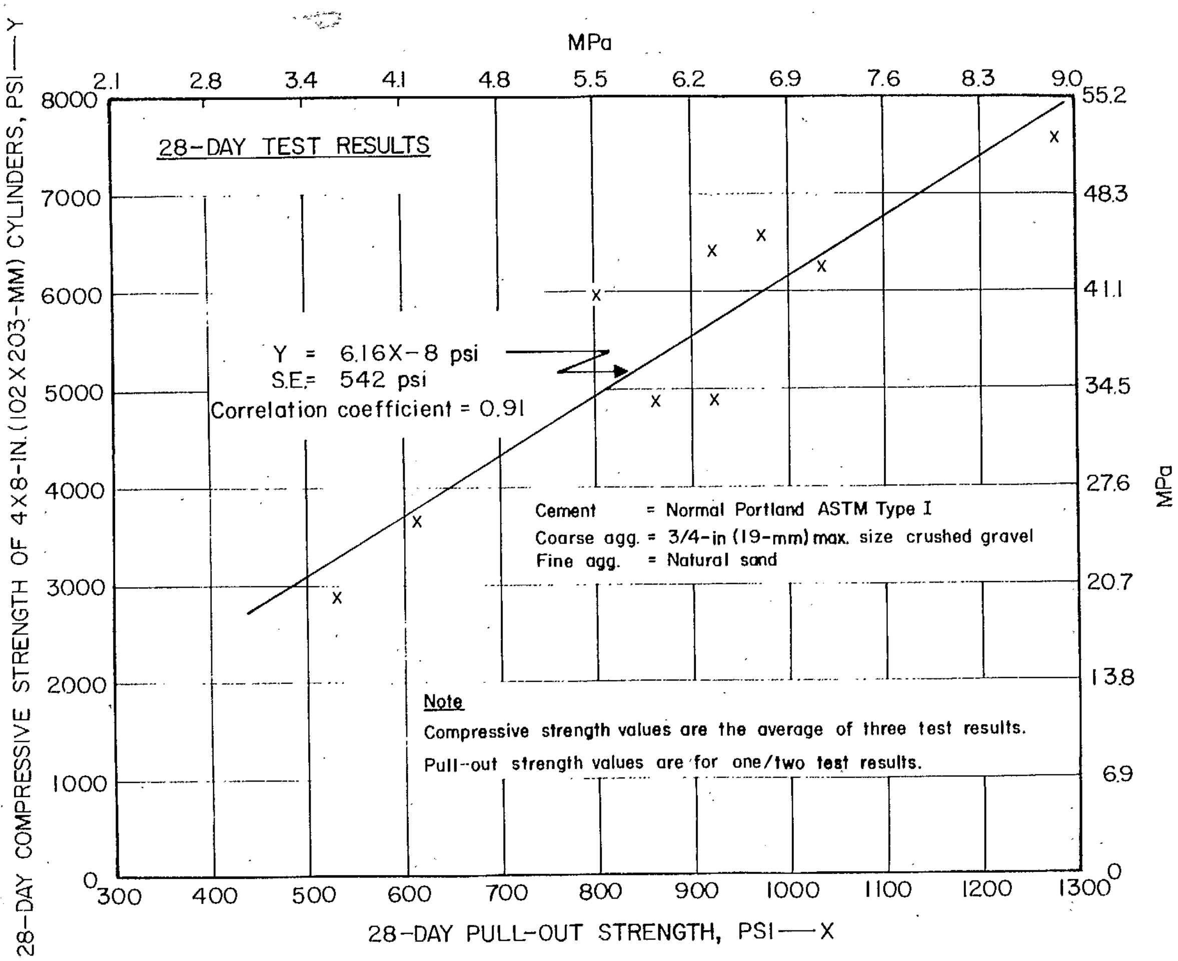


Figure 11. Relationship between pull-out and 28-day compressive strength of 4 x 8-in. (102 x 203-mm) cylinders.

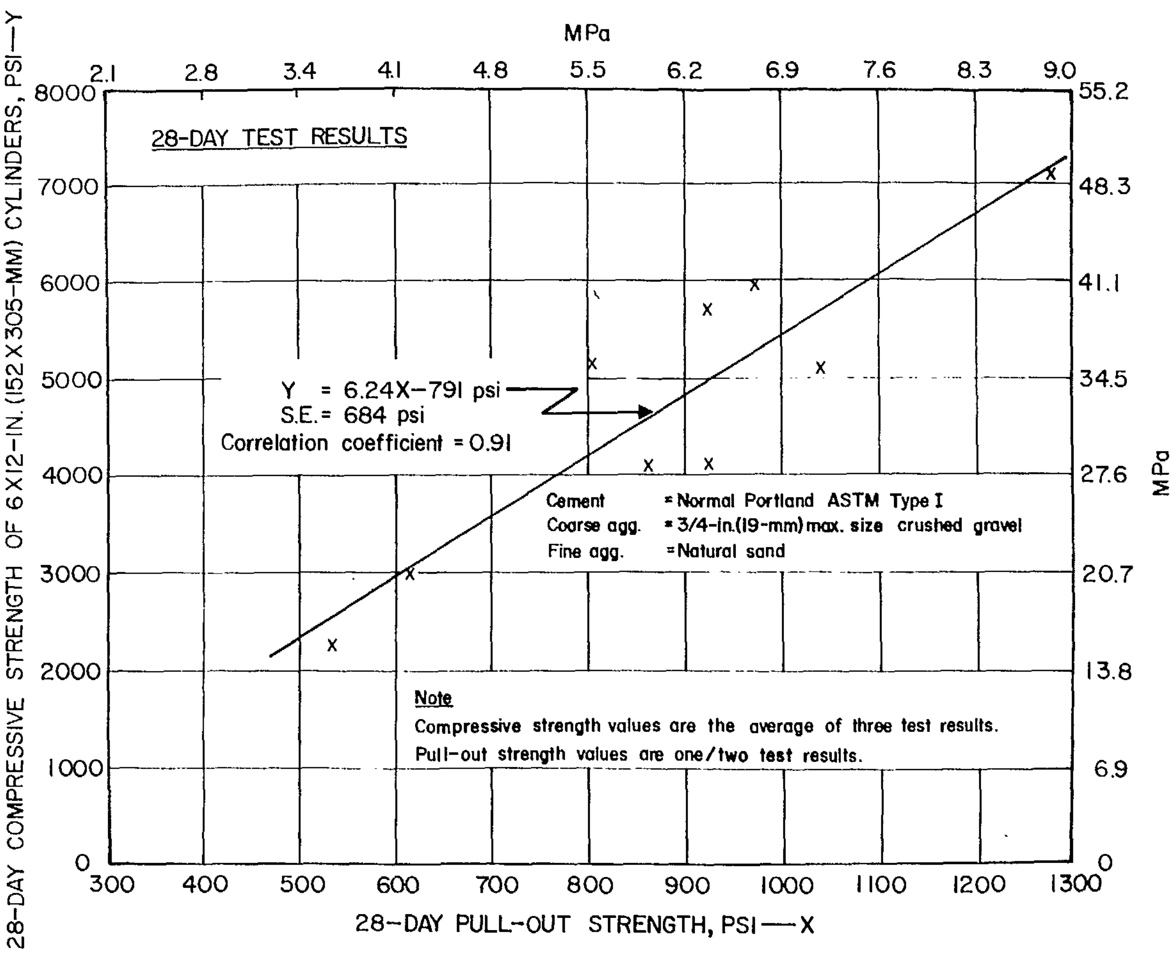


Figure 12. Relationship between pull-out and 28-day compressive strength of 6 x 12-in. (152 x 305-mm) cylinders.

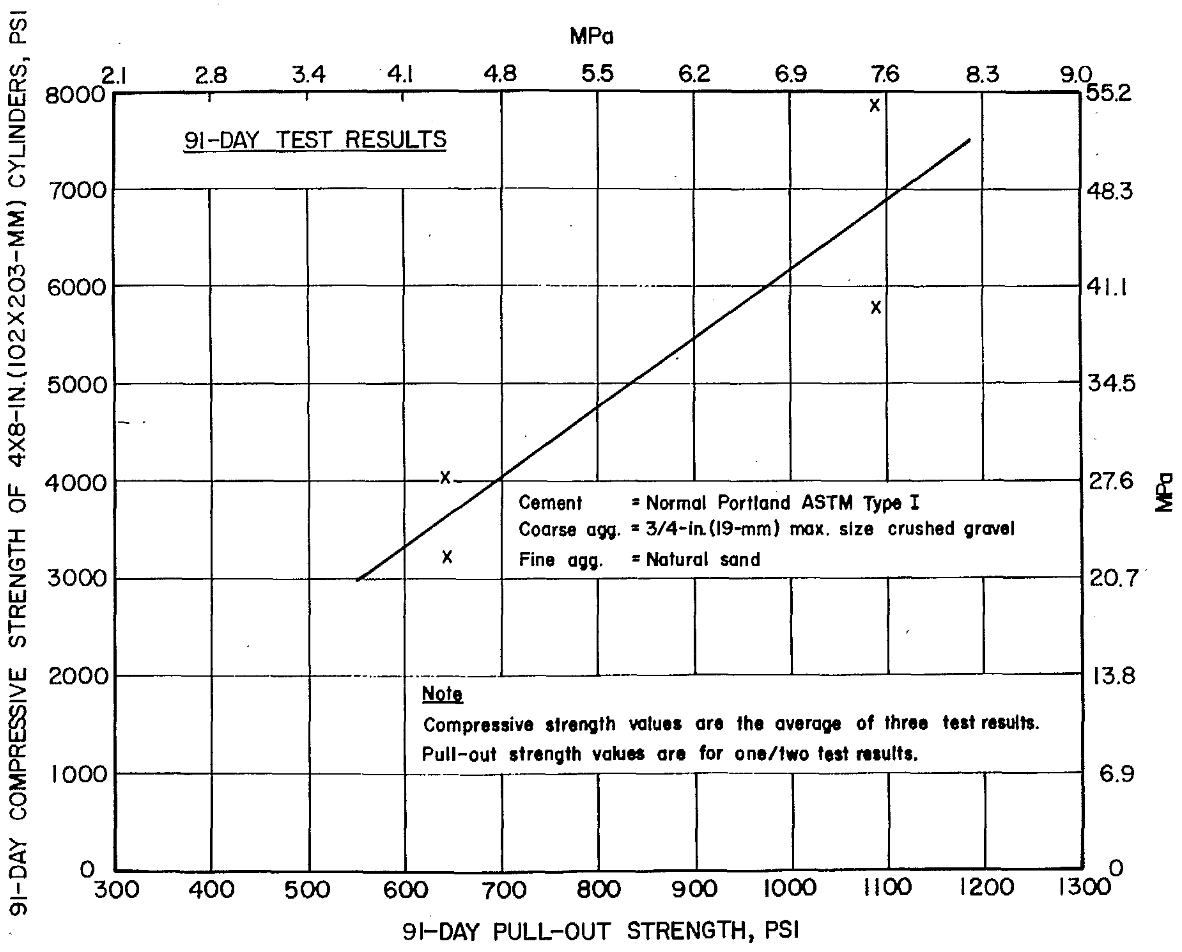


Figure 13. Relationship between pull-out and 91-day compressive strength of 4 x 8-in. (102 x 203-mm) cylinders.

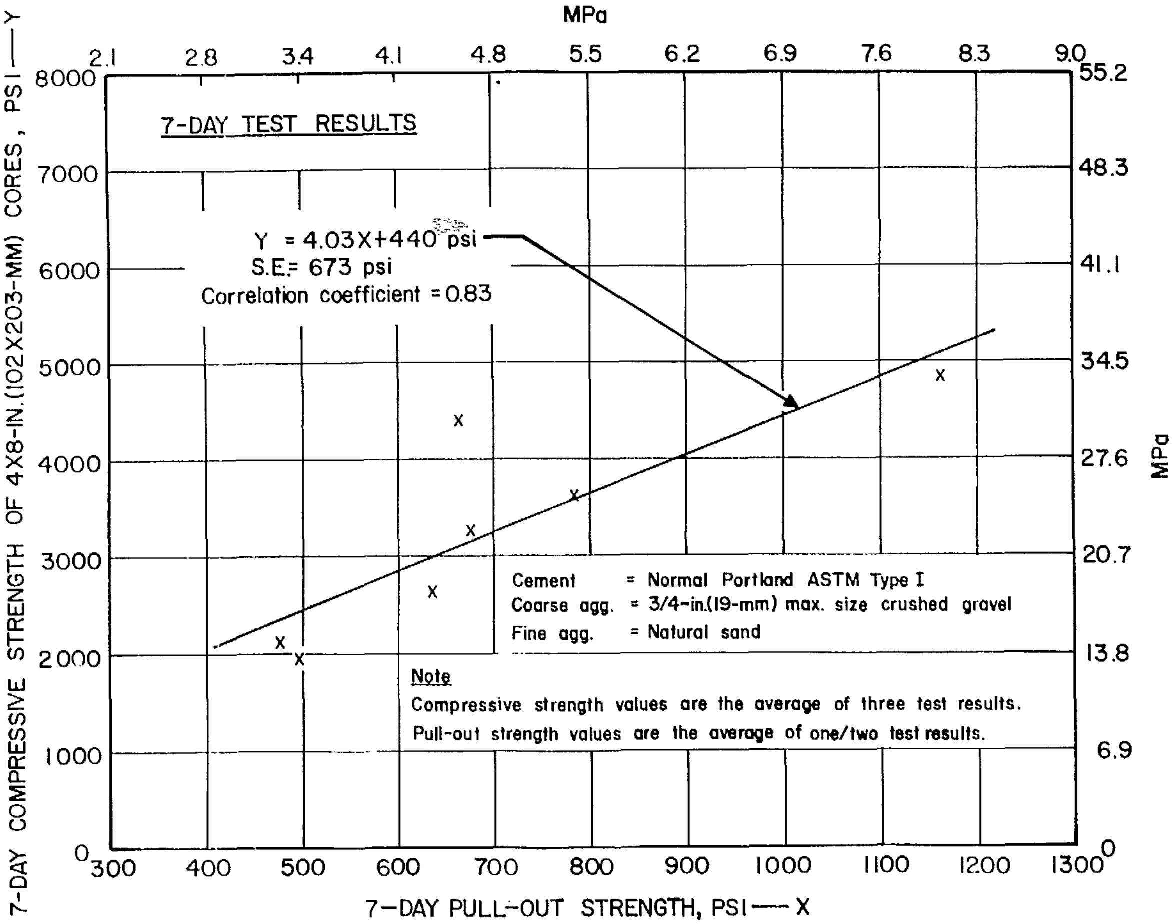


Figure 14. Relationship between pull-out and compressive strength of 4 x 8-in. (102 x 203-mm) cores drilled after 7 days.

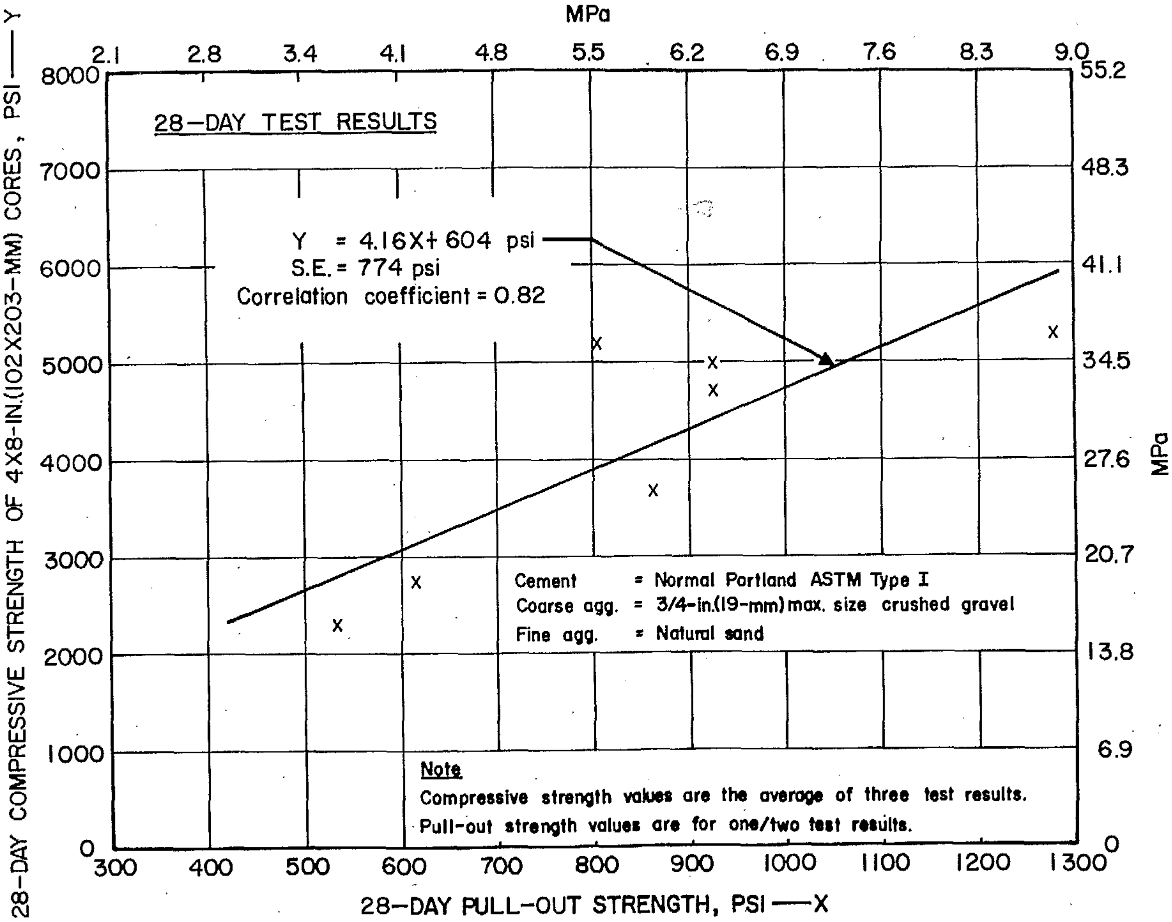


Figure 15. Relationship between pull-out and compressive strength of 4 x 8-in. (102 x 203-mm) cores drilled after 28 days.

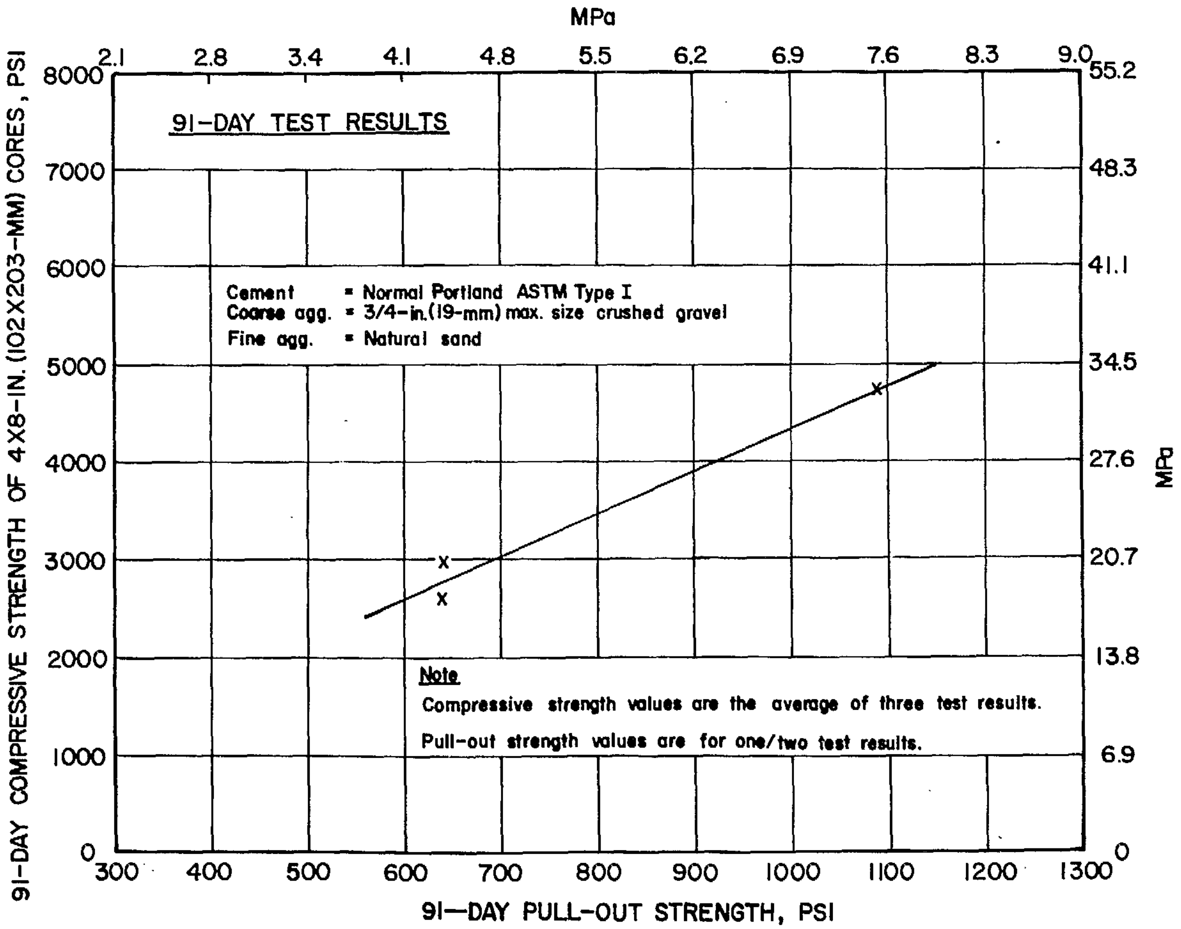


Figure 16. Relationship between pull-out and compressive strength of 4 x 8-in. (102 x 203-mm) cores drilled after 91 days.

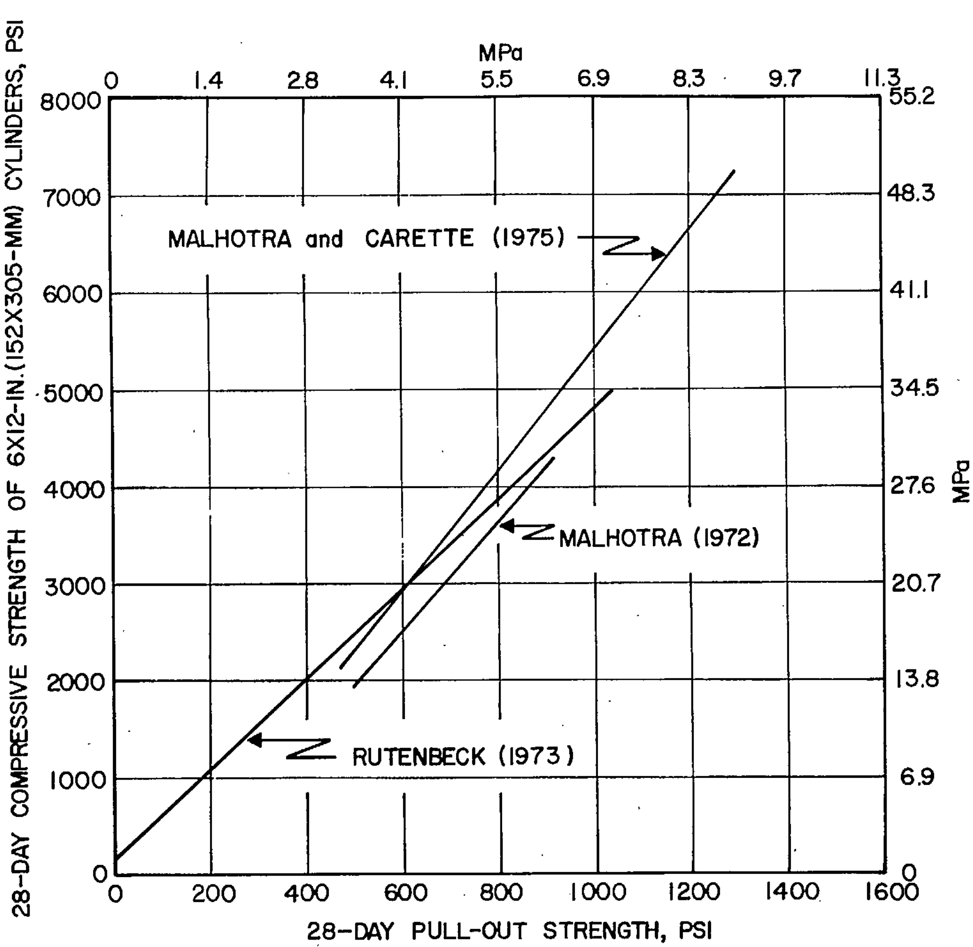


Figure 17. Comparison of relationships obtained in this investigation with those obtained by others.

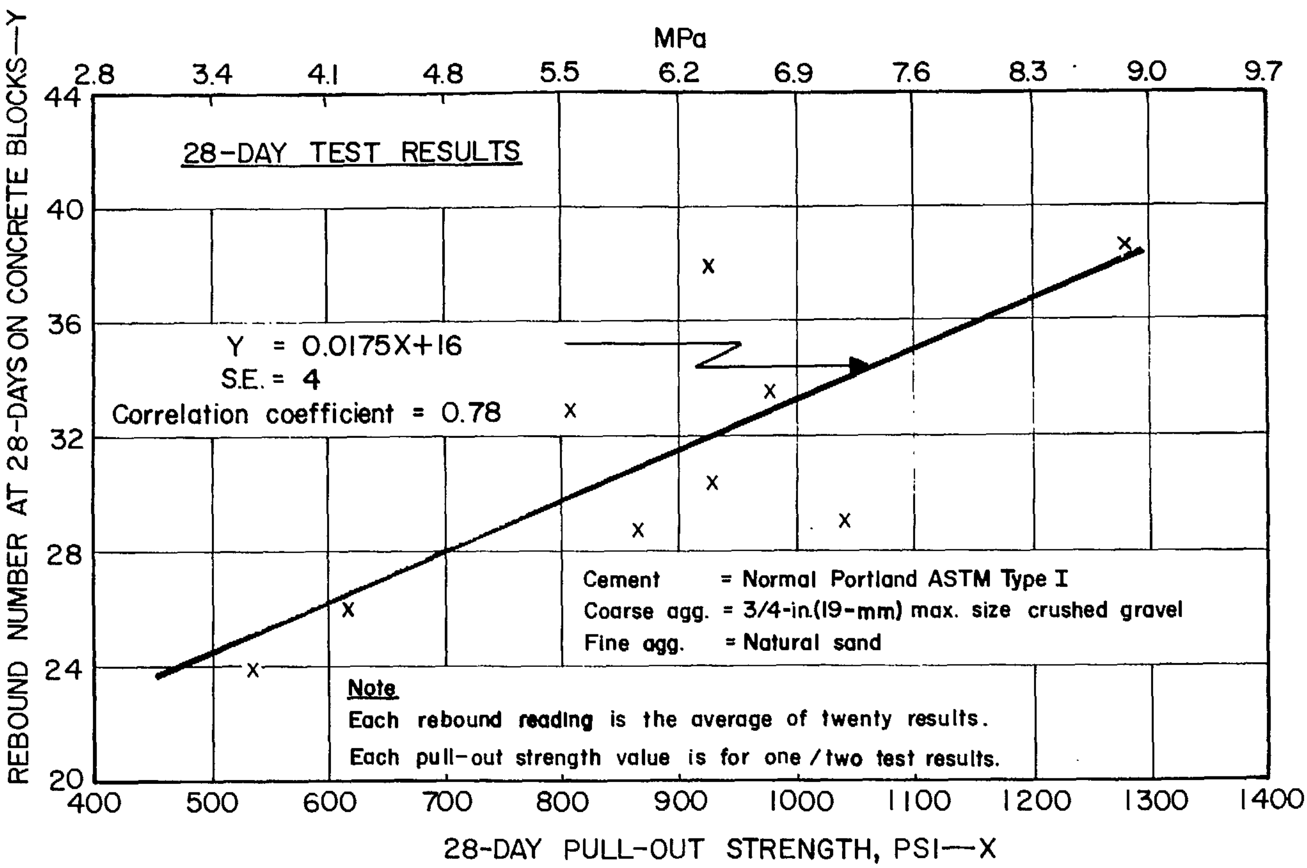


Figure 18. Relationship between pull-out strength and rebound number of 28 days.

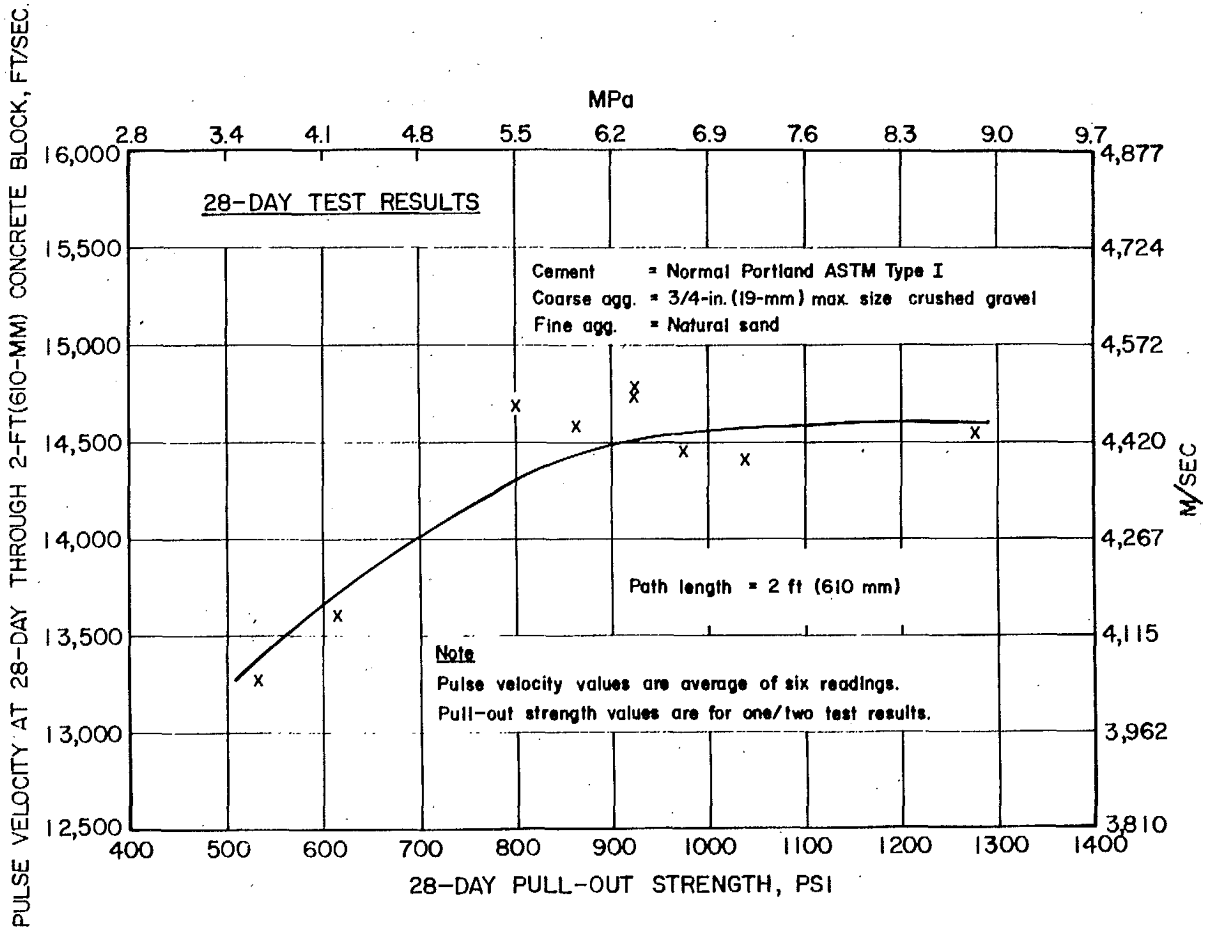


Figure 19. Relationship between pull-out strength and pulse velocity at 28 days.

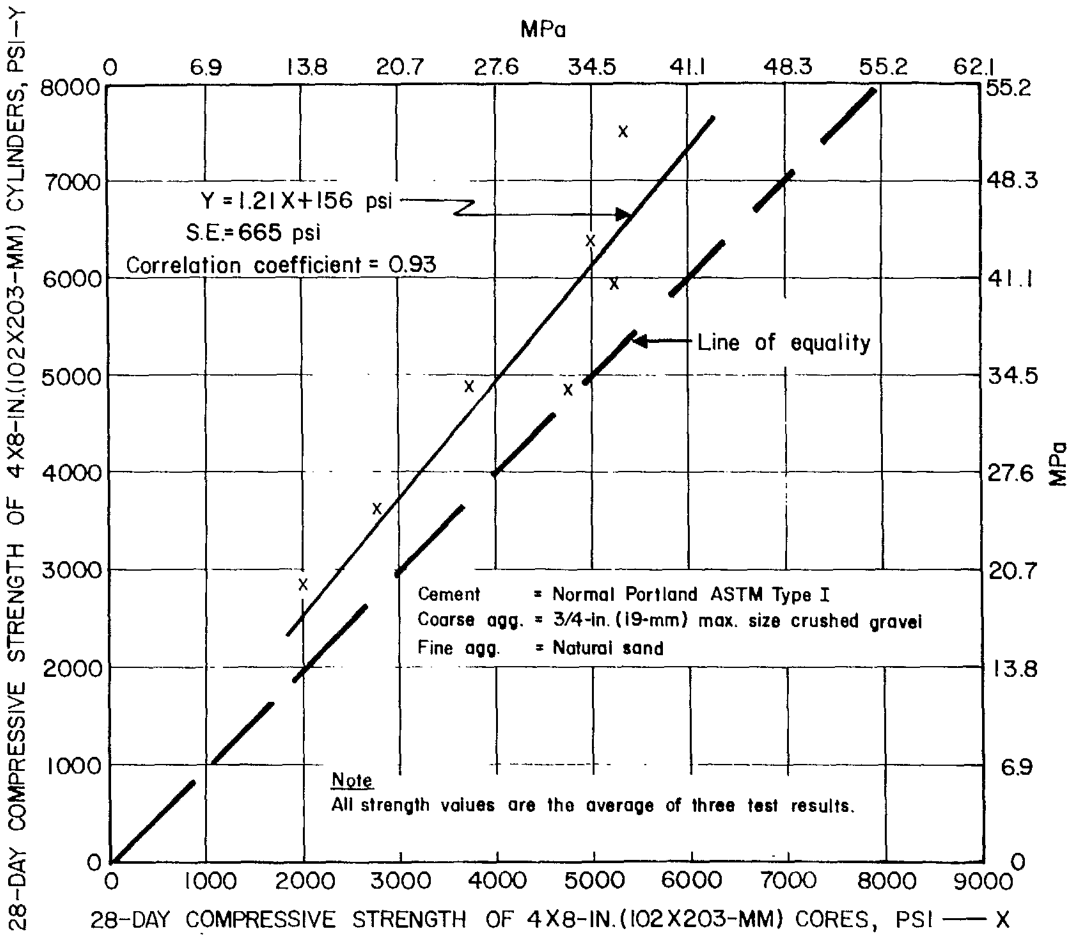


Figure 20. Relationship between compressive strength of 4 x 8 in. (102 x 203-mm) cores drilled after 28 days and compressive strength of 4 x 8-in. (102 x 203-mm) cylinders.

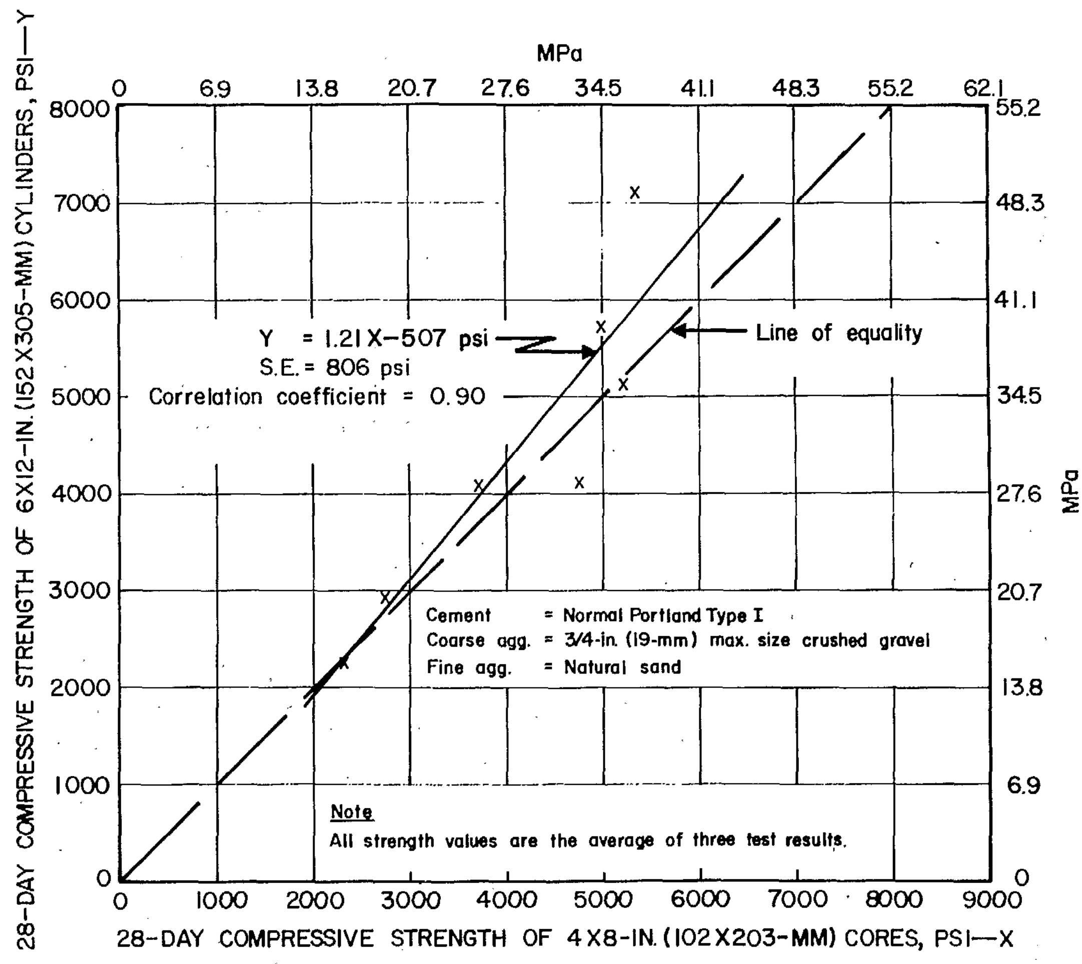


Figure 21. Relationship between compressive strength of 4 x 8-in. (102 x 203-mm) cores drilled after 28 days and compressive strength of 6 x 12-in. (152 x 305-mm) cylinders.

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