CONCRETE TENSILE STRENGTH STUDY

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16. ABSTRACT

Construction of double-curvature, thin-arch dams prompted an acute interest in the tensile strength, both static and dynamic, of concrete. The influence on tensile strength of such variables as specimen size and shape, aggregate size and shape, cement content, and water-reducing admixtures was questioned. This report considers only static tensile strength. Many indirect methods, whereby tensile strength is derived rather than measured, were studied and it was apparent that the "splitting test" was the best substitute for the direct method. Constituents used for this study included aggregates from three sources graded to 19-, 37.5-, 75-, and 100-mm (¾-, 1½-, 3-, and 4-in) maximum size, two cements, one fly ash, and one WRA. Two specimen sizes and configurations were used. The most notable conclusion was that the tensile strength ranged from 4.8 to 6.6 percent of the corresponding compressive strength and was not as much affected by the various constituents as was previously supposed. The "splitting test" was a fairly good substitute for, and simpler than, the direct method.

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by

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Prepared Under Contract No. 0-07-DV-00109 with E.L. Ore

April 1983

Concrete and Structural Branch
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INTRODUCTION

For many years, the Bureau of Reclamation was concerned with the qualities of concrete important to the construction of mass concrete-gravity or gravity-arch type dams, but was only mildly concerned with the tensile strength of concrete. Concrete has been extensively tested for behavior under compression with respect to the effects of cement, aggregate size and shape, admixtures, and other factors. However, the need to build more economically led to the design of thin-arch or double-curvature type dams, and the tensile behavior of concrete inherently became more important in these design analyses. Various testing programs were instigated to fill this void in the data on the tensile behavior of concrete.

The testing programs included a review of the literature, investigation of the best size and shape of specimens, and a series of tests on concrete specimens. The constituents of the concrete mixes studied included: natural and crushed 9.5-, 19-, 37.5-, 75-, and 100-mm (⅜-, ¾-, 1½-, 3-, and 4-in) MSA's (maximum size aggregates), different W/C's (water to cement ratios) with and without WRA (water reducing admixture), and fly ash. The concrete specimens were tested for compressive, direct-tensile, and splitting-tensile strengths after having been aged for 7, 28, 90, 180, and 365 days. Most of the test program was accomplished; however, there were some changes made during the program concerning the shape of test specimens, and not all of the differently aged samples were tested.

This report integrates these various tensile strength studies. Since the studies evolved somewhat independently, the report references parts I, II, and III. Part I of the overall program investigated specimen shape, direct-tensile testing methods, and indirect-tensile testing methods whereby tensile strength is derived rather than measured. Part II used the direct-tensile testing method and evaluated the effects of aggregate shape. Part III was undertaken to investigate the influence of using fly ash and WRA on direct-tensile strength. Both parts II and III used cylindrical specimens which created some stress concentrations at the interface between the end-plate and the specimen; however, this stress did not seem to adversely affect the results.

Many investigators have attempted to use indirect tests such as the "splitting test" or the "ring test" to avoid the difficulty of attaching apparatus to the ends of the specimens to apply a direct-tensile load. Direct methods included embedding devices to be used as attachments to the testing machine such as "spiders" in either end of each specimen, or embedding deformed bars through the specimen with slip joints at the midpoint. There were no consistent or convincing tensile strength test data obtained which would be helpful to designers. The "splitting test" appeared to be the best type of test, in that it was comparatively simple to perform and utilized the standard 150- by 300-mm (6- by 12-in) cylinders; however, the results obtained in this manner relative to true direct tension were largely unknown.

CONCLUSIONS

1. The ratio of tensile strength of concrete to the corresponding compressive strength varied only slightly from a low of 4.8 to a high of 6.6 percent due to cement content, MSA, age, or admixtures.

2. Within the small MSA concrete, cement content had very little effect on direct-tensile strength; however, in the 75- and 100-mm (3-and 4-in) MSA concrete the increased cement factor increased the strength.

3. The addition of WRA alone improved the concrete strength at all ages. Additions of fly ash and fly ash plus WRA reduced the 7- and 28-day tensile strengths and increased the later age values compared to the control concrete.

4. Crushing portions of the parent aggregate had little effect on tensile strength, except that concrete in the high-strength range with both crushed sand and crushed coarse aggregate had appreciably lower strengths from the 7th through the 28th day of aging.

5. Lower cement content concrete showed a slight increase in tensile strength during 7 to 28 days but showed little or no increase at later ages. This is also true of the 19- and 37.5-mm MSA from the 28th through the 365th day of aging.

6. The tensile-strength values obtained by splitting the specimens were slightly higher than by the direct-tension results, but not enough to preclude the use of this test as an expedient alternative.

7. The tensile strength of the concrete with 280-kg/m^3 (470-lb/yd^3) cement content was greatest in the 37.5-mm MSA, followed in descending order by the 19-, 75-, and the 100-mm MSA's. However, there were too many variables in this test to allow this to be a very strong conclusion.

MATERIALS

Materials used in the concrete mixes for these studies included the following:

Cement

The cement (laboratory No. M-4909) used in parts I and III of the tensile-strength investigation was type II low-alkali cement, obtained in sacks from a single source, which was then blended and stored in steel drums containing approximately 250 kg (550 lb). The chemical and physical properties of this cement are shown in table 1. Cement (No. M-6200) used in part II of the investigation was a blend of type II cements from 12 different plants, which was also blended and stored in 250-kg metal drums. All cement met Bureau requirements for type II low-alkali cement.

Fly Ash

Some of the cement was replaced by fly ash (No. M-6498) in part III of this research. Chemical and physical properties of this material are shown in table 2.

Water-reducing, Set-controlling Admixture

The WRA (No. M-6441) was an unaltered lignin-type material which met Bureau performance requirements for water reduction, set retardation, and compressive strength.

Aggregate

The aggregate used in each part of the investigation was from a different source. The materials were received in bulk, in an unwashed and ungraded condition. Each aggregate was processed by laboratory equipment which separated it into different sizes that were stored wet, but reached a dry condition before use. Aggregate gradings for each part of the program are shown (table 3). The aggregate (No. M-3942) used in part I was from Montana and was described as follows[1]:

> The gravel is generally subround, pitted and streamworn, but contains some subangular and flattened particles also. Six percent of the gravel is heavily coated by calcium carbonate, sand grains, and some clay which is bonded to the particle surface. The gravel is composed of quartzite, limestone, sandstone, altered andesite, basalt, granite siltstone, shale, chert, and glassy andesite. About 1.5 percent of the gravel is unsound in physical quality. Thirteen percent of the gravel is deleteriously reactive with high-alkali cement. The sand varies in shape from subangular to angular. The sand contains the same rock types contained in the gravel, with increasing amounts of individual monomineralic grains of quartz, feldspar, mica, garnet, pyroxene, amphibole, magnetite, calcite, and a few miscellaneous detrital minerals, occurring in the fines. About 13 percent of the sand is unsound in physical quality. Four percent of the coarse sand and a trace of the fine sand contains deleteriously reactive rock types.

Part II aggregate (No. M-6124) was from California, and it is described as follows[2]:

> The gravel, subrounded to subangular in shape with about 13 percent flat particles, is composed of metasedimentary rocks, vein quartz, altered volcanics, amphibolite, schist, granitic rocks, serpentine, and ultrabasic rocks, chert, and epidote rock. The sand, subrounded to angular in shape, contains the same rock types found in the gravel plus feldspar, amphibole, mica, magnetite, and a few miscellaneous detrital minerals. Some carbonaceous material, removable by washing, is present in the sand. About 2 percent of the gravel and 11 percent of the sand is physically unsound. About 3 percent of the gravel and 2 percent of the sand is alkali-reactive.

Part III aggregate (No. M-6396) was a crushed quarry rock from California, and it is described as follows[3]:

> "The gravel, subangular and crushed with about 20 to 60 percent flat particles increasing in percentage with smaller size, is

[1] Bechtold, C. A. (Summary extracted by Concrete and Structural Branch) Petrographic description: Memorandum No. 61-91, USBR, August 29, 1961.

[2] Bechtold, C. A. (Summary extracted by Concrete and Structural Branch) Petrographic description: Memorandum No. 70-49, USBR, June 30, 1970.

[3] Bechtold, C. A. Petrographic description: Memorandum No. 72-58, USBR, September 26, 1972.

composed of altered amphibolite breccia. No physically unsound or alkali reactive rock types were seen. The sand, subangular to angular in shape, is composed of the same rock type found in the gravel. About 5 percent of the sand is physically unsound. About 60 percent flat or elongate particles are present. No alkali-reactive rock types were seen."

TEST METHOD

The test program initially proposed that most of the variables such as strength levels, various MSA's, and aggregate particle shape were to be investigated. The type and shape of specimen for the direct tension test was first investigated by a photoelastic study resulting in the modified prism shape (figs. 1 and 2). The end plates were fastened to the specimen by an epoxy resin adhesive (fig. 3). The mix proportions and complete test results performed on the fresh and hardened concrete for each segment of study are shown (table 4).

Part I

Of all the proposed concrete mixes tested, only those with 19- and 37.5-mm MSA were made during this phase. Two sets of these tests were run. Three concrete mixes with 37.5-mm MSA were made at cement contents of approximately 280, 400, and 500 kg/m^3 (470, 670, and 850 lb/yd^3), slumps varying from 65 to 75 mm (2.5 to 3 in), with about 5 percent air content. Consequently, the water-cement ratio varied from 0.32 to 0.47. Two direct-tension specimens, one splitting-tension, and one compression specimen were cast from each mix for tests at 28, 90, and 365 days of curing time. All specimens were stripped at 24 hours and cured in a standard manner until test age. The direct-tension specimens were cast horizontally in 200- by 300-mm (8-by 12-in) prisms with reduced midsections (fig. 2), while the compression and splitting-tensile specimens were standard 150- by 300-mm (6- by 12-in) cylinders cast vertically.

Another series of tests was made and later duplicated with 19-mm MSA, at the same cement contents and slumps, with about 6 percent air, and slightly higher water-cement ratios due to the higher water requirement of 19-mm MSA. Similar test specimens were cast for tests at the same ages as the previous set.

The compressive strength test cylinders were capped in the usual manner with sulfur compound before the compression test. The splitting-tensile specimens were loaded in the horizontal position in the manner prescribed in [4]ASTM: C 496, except that a 3-mm (⅛-in) square balsam loading pad was used instead of the 25-mm (1-in) loading pad (figs. 4, 5, and 6). The ends of specimens for the direct-tensile test were dried and sandblasted before attaching the end plates with an epoxy-resin adhesive and were loaded in a vertical position.

Part II

Some of the objectives of part I were abandoned and some were changed for the tests in part II. A series of five mass concrete mixes was made using cement contents of 165 and 280 kg/m^3 (280 and 470 lb/yd^3) and incorporating both crushed and natural aggregate graded to 100-mm (4-in) MSA (table 3). The crushed material was obtained from the same source as the natural material described previously (No. M-6124). The cement was a type II low alkali (No. M-6200) (table 1).

Low strength (low cement content) concrete specimens were cast from each mix for testing at 7, 28, 90, 180, and 365 days of curing time. Three 300- by 900-mm (12- by 36-in) tensile cylinders and two 300- by 600-mm (12- by 24-in) compression cylinders were cast vertically and tested for each age and mix proportion tested (table 4). The cylinders were sealed and cured at 23 °C (73 °F) until tested.

The ends of the compression specimens were ground parallel before testing. Tensile specimens were prepared by epoxy bonding 50-mm (2-in) thick steel plates to each end, such that the load could be applied through bolts and a chain linkage at the center of the plates (fig. 7). The end plates were usually attached 24 hours prior to testing. The most satisfactory method of preparing the ends of each specimen was to saw about 25 mm (1 in) off and sandblast before attaching the end plates with epoxy.

Part III

The effect of different combinations of WRA or fly ash, or both, on the water requirement and

[4] American Society for Testing and Materials, ASTM: C 496-71 (reapproved 1979), "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens," Annual Book of ASTM Standards, Part 14, pp. 324-329.

compressive strength were tested in this part of the program. For example, the water requirement was reduced by 6.3 percent due to the addition of fly ash, and 11.1 percent by using WRA with the fly ash in the low-strength concrete. In the higher strength concrete, the water requirement was reduced 5.3, 6.8, and 12.1 percent by the addition of fly ash alone, WRA alone, and both fly ash and WRA, respectively. Cementitious contents of 165 and 280 kg/m^3 were used for seven test specimens. Properties of cement (No. M-4909) were described previously, as was the aggregate (No. M-6396) which was graded to 75 mm (3-in) maximum with the proportions shown (table 3).

Specimens were cast from the high strength concrete (mixes 1, 3, 5, and 7) for tests at 7, 28, 90, 180, and 365 days of curing time and with different mix proportions (table 4). The low strength concretes were tested at 7, 90, and 365 days' age. Two 300- by 900-mm tensile cylinders and two compressive cylinders were cast and tested as described in part II (table 4). Elastic property tests were performed on the compressive strength specimens, and the static modulus of elasticity and Poisson's ratio were recorded (table 5).

TEST RESULTS

General Mix to Strength Trends

Elastic properties. — The modulus of elasticity was greatest for the 75-mm MSA concretes of part III, followed in descending order by the 37.5-, 19-mm MSA's of part I, and lastly the 100-mm MSA concretes of part II (table 5). The values of the 19-mm MSA's were only slightly less than for the 37.5-mm MSA. At the common cement content of 280 kg/m^3, the 28-day modulus for the 75-mm MSA concretes of part III averaged 43.4 GPa (6.30 x 10^{-6} lb/in^2); 28.3 GPa (4.1 x 10^{-6} lb/in^2) for the 100-mm MSA's, part II; 35.2 GPa (5.1 x 10^{-6} lb/in^2) for the 37.5-mm MSA's; and 31.3 GPa (4.54 x 10^{-6} lb/in^2) for the 19-mm MSA concretes. Within each group, there was a slight trend for the modulus to increase with age. The varying conditions within the groups of parts II and III did not significantly affect the values for modulus of elasticity. Poisson's ratio was barely affected and ranged from a low 0.14 to a high of 0.26 for all tests.

Maximum-size aggregate and concrete strength. — The effect on the tensile strength of concrete by varying the MSA was tested by using three aggregates, four MSA's, two cements, and two specimen configurations. Additional variables introduced into the research included the use of five cement contents of 165, 280, 400, 500 kg/m^3; and included specimens cast horizontally in part I, and vertically in parts II and III. Thus, only the 280 kg/m^3 cement factor was common to all the mixes.

A comparison is shown of tensile strength from various MSA's for this cement content (fig. 8). It is only in part I that the 19- and 37.5-mm MSA may be compared directly, since both concretes were made with a single cement, aggregate, and specimen configuration. Also, the specimens were cast horizontally for both mixes. However, it was only for a cement content of 280 kg/m^3 that the tensile strength for 37.5-mm MSA was higher. Variations of other factors did not result in continuation of this trend.

Specimens for parts II and III were 300- by 900-mm cylinders cast in a vertical position. The same cement was used in part III as was used in part I. In comparing the tensile strengths of the 75- and 100-mm MSA concrete mixes, the smaller MSA concrete created the higher strength of the two, but both were appreciably lower than the strengths of the smaller MSA concretes in part I.

There is some speculation on the difference in tensile strength from specimens cast vertically and those cast horizontally. From another report[5], the average tensile strength of four vertical cores was 0.98 MPa (142 lb/in^2) while the average of the horizontal cores was 1.97 MPa (285 lb/in^2), or an increase of 200 percent. Although this may not be conclusive, it does substantiate the theory that the accumulation of bleeding water on the underside of large aggregate particles creates a weakened bond. The tensile strength may be affected more than the compressive strength, since the average compressive strength of the vertical cores shown on the same table was 36 MPa (5235 lb/in^2) and the average for the horizontal cores was 32 MPa (4670 lb/in^2). Applying a factor to the tensile strength values of the vertically cast specimens, and adjusting for the difference in specimen size, the data show that the MSA had very little effect on the static tensile strength.

[5] Riffle, H. C., and F. L. Smith, "Strength and Elastic Properties of Concrete in Flaming Gorge Dam 10-Year Core Report," GR-13-76, USBR, February 1976.

Part I

Compressive strength. — The three factors which affected the compressive strength are cement content, age, and MSA, as can be seen (fig. 9) by the plotted results. For these concretes, the strength development appears to be normal with respect to age. The effect of the two MSA's used in this part is very evident at the cement content of 280 kg/m^3. The 37.5-mm MSA was around 6.9 MPa (1000 lb/in^2) higher at all ages. At the cement contents of 400 to 500 kg/m^3, neither MSA gave higher strength values at all ages, although the values were a bit erratic (table 4). The effect of increasing the cement content was rather peculiar, since the 400-kg/m^3 concrete for both MSA's had higher strengths than did the 500-kg/m^3 mix. A check of the mix proportions shows that the water requirement increased more as the cement was increased from 400 to 500 kg/m^3 than from 280 to 400 kg/m^3.

Tensile strength, direct. — Only the 280 kg/m^3 cement content concrete mixes displayed (fig. 10) any appreciable indication that the MSA affected the tensile strength. The tensile strength of the 37.5-mm MSA concrete was about 0.69 MPa (100 lb/in^2) greater than the 19-mm MSA. Each concrete showed a mild trend toward developing tensile capability with increasing age, although there were some exceptions. Except for the 280-kg/m^3 cement content concrete mix, the remaining mixes had strength values which were well bunched and intermingled randomly within 0.21 and 0.35 MPa (30 to 50 lb/in^2).

In comparison of the average tensile strength with the average compressive strength (table 6), perhaps the most striking observation was that the values for direct tension of concrete with any MSA, at any age, and at any cement content (except the 280 kg/m^3 cement content, 19-mm mix) had amazing similarity, and might well have come from a single concrete mix. The values for the 400 kg/m^3 mix were slightly higher as were the compressive strengths. The average of all direct tension strengths was 3.0 MPa (440 lb/in^2) with a standard deviation of 0.19 MPa (27 lb/in^2) and a coefficient of variation of 6.2 percent. The strengths ranged in magnitude from a low of 2.6 MPa (375 lb/in^2) to a high of 3.3 MPa (480 lb/in^2). The ratio of direct tension to the companion compressive strength averages 6.0 percent at the 28-day, 5.6 percent at the 90-day, and 5.1 percent at the 365-day age.

Tensile strength, splitting. — The splitting test tensile strengths appear to follow the trend of the direct tension values, but are slightly higher and show no significant relation to MSA, cement content, or age. The average tensile strength was 3.5 MPa (510 lb/in^2), with a standard deviation of 0.39 MPa (58 lb/in^2) and a coefficient of variation of 11.4 percent. The ratio of splitting tension to the corresponding compressive strength averaged 7.2 percent at the 28-day, 6.3 percent at the 90-day, and 6.0 percent at the 365-day age. Even though the values obtained by the splitting test are slightly higher than those obtained by the direct method, it is a useful test since the splitting test can be performed in any field laboratory. Also, with an unconfined compression test, an approximate coefficient of internal friction and shear can be calculated. Although the results might not be completely accurate, there would be a correlation.

Part II

Compressive strength. — The strength development of both the high- and low-cement content concrete appeared to be about normal up to 180 days' age. After that, the compressive strength (fig. 11) declined, and the 1-year values were all less (except one mix) by an average of 1.5 MPa (215 lb/in^2) than the 180-day age. The reason for this is not evident.

The crushed sand and coarse aggregate concrete in the lower cement content range had a higher water requirement and, consequently, at the higher water-cement ratio, the strengths were lower. Any mechanical advantage from the use of more angular aggregate was more than offset by the higher water-cement ratio (compare mixes 1 and 4, fig. 11).

At the higher cement content range, the water requirement was only mildly affected by substituting crushed, coarse aggregate for natural aggregate, and the strengths were higher at all ages except 90 days (compare mixes 2 and 3, fig. 11). When crushed sand and coarse aggregate were exchanged for natural aggregate, the water requirement was 7 kg/m^3 (12 lb/yd^3) higher. The strength was less at 7 days but greater at the later ages (compare mixes 2 and 5, fig. 11).

Tensile strength, direct. — Following the compressive strength trend, the direct tensile strengths (table 2) at 365 days were less than the 90-day

values for both the high and low ranges (fig. 12). Crushing the coarse aggregate had no consistent or appreciable effect on tensile strength of either the low- or high-strength concrete. Crushing both the sand and coarse aggregate lowered the 7- and 28-day strengths by 0.28 MPa (40 lb/in^2) compared to concrete with both natural sand and coarse aggregate. There was a noticeable increase in tensile strength with the increase in cement content (with the exception of mix 5 with its low 7-and 28-day values). The average strength of 10 tests for the 165 kg/m^3 cement content concrete was 1.1 MPa (164 lb/in^2) with a standard deviation of 0.20 MPa (28.7 lb/in^2) and a coefficient of variation of 17.0 percent. The average of 15 tests for the 280 kg/m^3 cement content concrete was 1.6 MPa (239 lb/in^2) with a standard deviation of 0.13 MPa (18.7 lb/in^2) and a coefficient of variation of 7.8 percent.

Referring back to a similar tabulation of part I (table 7), there is a remarkable similarity between the two groups of tests. The tensile strength in this test was 4.6 to 6.6 percent of the compressive strength at any age or strength level (table 8).

Part III

Compressive strength. — With the water reduction and the retarding effect of either fly ash or WRA or both, the compressive strengths were about as expected. The strength increased normally with age (fig. 13). In the low-cement (low-strength) range, concrete with fly ash alone had the lowest strength at all ages. Concrete with fly ash and WRA was lower than the reference concrete at 7 days, slightly lower at 28 days, and higher at later ages.

In the higher cement (higher strength) range concretes, the fly ash without WRA had lower strength than the control at 7 and 28 days, equal strength at 90 days, and greater strength at later ages. Concrete with WRA and fly ash had greater strengths than the control at all ages, than the plain fly ash mix, but strengths were lower at 7 and 28 days and higher at later ages. The WRA mix had the greatest strength at all ages, except at 1 year, where it was slightly less than the mix with both WRA and fly ash.

Tensile strength, direct. — The tensile strength of the high-strength range concretes increased from 7 through 28 days, after which they continued to gain, but more slowly, through 365 days. The exception was the control concrete with no WRA or fly ash which had lower strengths at successive ages (fig. 13). Low-range strength concrete gained tensile strength through 90 days; however, after this the control mix strength decreased, while the other two concrete mixes continued to slowly gain strength (fig. 14).

Concretes in the high-strength range, both with fly ash alone and with fly ash plus WRA, had less strength at 7 and 28 days and higher values at 90, 180, and 365 days. Concrete with only WRA had slightly less strength at 7 days, equal strength at 28 days, and appreciably greater strength after that. In the low-strength range, concretes with fly ash and with fly ash plus WRA had higher strength at 7, lower at 90, and higher at 365 days than the control concrete. Here, as in part II, the average tensile strength of the 165 kg/m^3 concrete was 1.3 MPa (189 lb/in^2), the standard deviation was 0.31 MPa (46 lb/in^2), and the coefficient of variation was 25 percent. The addition of 113 kg/m^3 (190 lb/yd^3) of cement raised the average tensile strength to 1.7 MPa (254 lb/in^2) and the standard deviation to 0.41 MPa (60 lb/in^2), while the coefficient of variation was 23.4 percent. The crushed material showed increased strength over the natural and partly crushed fractions of part II. The companion compressive to tensile strength ratios were about the same here as for parts I and II (table 9).

Table 1. — *Test results on cement*

Type II, low alkali Laboratory No.	M-6200	M-4909
1. Chemical Composition	(Percent)	
Silicon Dioxide (SiO_2)	22.8	22.44
Aluminum Oxide (Al_2O_3)	4.0	3.89
Ferric Oxide (Fe_2O_3)	3.6	4.38
Calcium Oxide (CaO)	63.8	65.01
Magnesium Oxide (MgO)	2.1	0.87
Sulfur Trioxide (SO_3)	2.0	2.06
Alkalies as Sodium Oxide (Na_2O)	0.30	0.44
Loss on Ignition	1.23	0.63
Insoluble Residue	0.20	0.03
Tricalcium Silicate (C_3S)	48.6	55.73
Dicalcium Silicate (C_2S)	28.9	22.38
Tricalcium Aluminate (C_3A)	4.5	2.91
Tetracalcium Aluminoferrate (C_4AF)	11.0	13.32
Calcium Sulfate ($CaSO_4$)	3.4	3.50
2. Specific Surface:	Blaine cm^2/gram	
	3572	3850
3. Soundness: Autoclave Expansion	(Percent)	
	0.007	0.014
4. Specific Gravity	3.17	3.19
5. Time of Setting:	hrs:min	
Vicat, Initial	3:45	4:00
Vicat, Final	5:50	6:00
	MPa (lb/in^2)	
6. Compressive Strength:		
3 day	NT NT	19.9 (2877)
7 Day	23.1 (3342)	28.9 (4182)
28 Day	33.0 (4783)	41.1 (5958)
90 Day	41.0 (5938)	NT NT

[1]NT — Not tested

Table 2. — *Test results on fly ash*

Laboratory No.		M-6498
Chemical Composition		(Percent)
Silicon Dioxide (SiO_2) + Aluminum Oxide (Al_2O_3) + Ferric Oxide (Fe_2O_3) =		83.74
Magnesium Oxide (MgO)		1.33
Sulfur Trioxide (SO_3)		1.55
Loss on Ignition		2.04
Exchangeable Alkalies		0.72
Physical Properties		
Specific gravity		2.44
Specific surface, cm^2/gram		7,413
Compressive strength: 50-mm (2-in) cubes		MPa (lb/in^2)
Control	28-day	4.14 (6004)
	90-day	NT NT
Pozzolan replacement	28-day	33.9 (4197)
	90-day	NT NT
Water requirement (percent of control)		81.8
Reduction in reactive expansion at 14 days		Percent 45.43%

Table 3. — *Aggregate gradings for each MSA*

Aggregate Size	Percent Retained, Individual						
	Pan	#100	#50	#30	#16	#8	Remarks
Sand	5	15	22	25	15	15	Part I & II
Sand	6	20	24	18	17	15	Part III
MSA	4.7 mm (3/16 in)	9.5 mm (3/8 in)	19 mm (3/4 in)	37.5 mm (1 1/2 in)	75 mm (3 in)		
19 mm (3/4 in)	40	60	0	0	0		Part I
37.5 mm (1 1/2 in)	22	33	45	0	0		M-3942
100 mm (4-in)	10	15	30	30	15		Part II M-6124
75 mm (3-in)	10	15	30	25	0		Part III M-6396

Table 4a. — *Mix proportions and test results on fresh and hardened concrete* (SI units)

Mix No.	Ratio water to cement plus pozzolan	Ratio sand to aggregate (%)	Mix quantities per cubic meter: Air entraining admixture (cc)	Water reducing admixture (cc)	Water (kg)	Cement (kg))	Pozzolan (kg)	Sand (kg)	Aggregate (kg)	Properties of fresh concrete: Temperature (°C)	Slump (mm)	Density (kg/m³)	Air content Grav. (%)	Air content Press. (%)	Properties of hardened concrete: Compressive strength, MPa 7 days	28 days	90 days	180 days	365 days	Direct tension, MPa 7 days	28 days	90 days	180 days	365 days	Splitting tension, MPa 7 days	28 days	90 days	180 days	365 days	Remarks
												Part I																		
280 kg cement, M-4909, 37.5-mm MSA, M-3942																														
1A	0.47	38	325	-	131.7	280.6	-	745.2	1215.6	22.8	55.9	2373.9	3.9	4.5	-	48.7	52.5	-	-	-	3.03	2.90	-	NT	-	4.34	3.31	-	3.52	
1R	0.45	38	323	-	125.2	278.8	-	745.2	1212.1	22.2	53.3	2361.1	4.5	4.7	-	44.2	49.4	-	-	-	2.90	3.10	-	2.96	-	3.31	3.52	-	3.58	
Avg.	0.46	38	324	-	128.4	279.7	-	745.2	1213.8	22.5	54.6	2367.5	4.2	4.6	-	46.5	50.7	-	57.1	-	2.96	3.00	-	2.96	-	3.83	3.41	-	3.55	
400 kg cement, M-4909, 37.5-mm MSA, M-3942																														
2B	0.36	34	584	-	141.8	395.1	-	629.5	1218.0	22.2	63.5	2385.1	3.3	3.8	-	52.7	57.7	-	-	-	3.10	3.10	-	NT	-	3.38	4.00	-	4.00	
2R	0.35	34	610	-	140.6	396.9	-	634.8	1226.3	22.2	73.7	2398.0	2.9	3.8	-	58.7	59.4	-	-	-	3.17	3.38	-	NT	-	3.38	3.65	-	4.69	
Avg.	0.35	34	597	-	141.2	396.0	-	632.2	1222.2	22.2	68.6	2391.6	3.1	3.8	-	55.7	58.5	-	69.7	-	3.14	3.24	-	NT	-	3.38	3.83	-	4.34	
500 kg cement, M-4909, 37.5-mm MSA, M-3942																														
3A	0.32	28	1843	-	162.0	504.3	-	474.0	1213.8	22.2	66.0	2354.7	3.9	4.4	-	51.7	60.1	-	-	-	3.24	2.96	-	3.72	-	4.00	3.24	-	4.41	
3R	0.32	28	1848	-	160.2	500.7	-	469.9	1202.6	21.7	68.6	2332.3	4.8	5.1	-	45.2	55.6	-	-	-	3.03	3.03	-	3.03	-	3.58	3.03	-	2.90	
Avg.	0.32	28	1845	-	161.1	502.5	-	472.0	1208.2	22.0	67.3	2343.5	4.4	4.8		48.5	58.3	-	59.1	-	3.14	3.00	-	3.38	-	3.79	3.14	-	3.65	
280 kg cement, M-4909, 19-mm MSA, M-3942																														
4A	0.50	45	299	-	138.2	277.6	-	845.4	1029.9	20.6	66.0	2290.1	6.4	6.2	-	37.5	43.6	-	-	-	2.48	2.76	-	2.55	-	2.55	2.82	-	3.03	
4R	0.50	45	301	-	138.8	279.4	-	850.8	1035.9	20.0	66.0	2305.0	5.8	6.0	-	40.3	48.0	-	-	-	2.69	2.76	-	2.96	-	3.03	2.69	-	2.96	
Avg.	0.50	45	300	-	138.5	278.5	-	848.1	1032.9	20.3	66.0	2297.6	6.1	6.1	-	39.0	45.8	-	50.6	-	2.58	2.76	-	2.76	-	2.79	2.76	-	3.00	
400 kg cement, M-4909, 19-mm MSA, M-3942																														
5B	0.37	40	600	-	145.9	395.7	-	721.4	1078.0	21.7	61.0	2341.9	4.7	5.2	-	51.8	61.4	-	-	-	3.03	3.17	-	3.38	-	3.79	3.79	-	-	
5R	0.37	40	1004	-	144.8	391.6	-	714.9	1067.9	21.7	53.3	2319.5	5.6	6.0	-	51.4	59.4	-	-	-	3.10	3.10	-	3.24	-	3.52	3.65	-	3.93	
Avg.	0.37	40	800	-	145.4	393.6	-	718.2	1073.0	21.7	57.2	2330.7	5.1	5.6	-	51.6	60.4	-	69.6	-	3.07	3.14	-	3.30	-	3.65	3.72	-	3.93	
500 kg cement, M-4909, 19-mm MSA, M-3942																														
6A	0.33	36	1774	-	166.1	503.1	-	588.5	1042.4	21.7	71.1	2300.0	5.7	6.1	-	48.2	55.0	-	-	-	2.48	3.03	-	2.96	-	3.24	3.72	-	3.65	
6R	0.33	36	1762	-	164.9	500.1	-	584.4	1035.3	21.7	68.6	2284.2	6.4	6.5	-	48.7	56.2	-	-	-	NT	3.38	-	3.10	-	3.24	3.72	-	3.52	
Avg.	0.33	36	1768	-	165.5	501.6	-	586.4	1038.8	21.7	69.8	2292.1	6.0	6.3	-	48.4	55.6	-	62.9	-	2.48	3.21	-	3.03	-	3.24	3.72	-	3.58	
												Part II																		
165 kg cement, M-6200 100-mm MSA, M-6124 and M-6124C																														
1	0.63	25	253	-	106.8	169.1	-	536.3	1638.6	21.1	50.8	2450.8	2.6	-	13.6	21.4	24.8	23.6	24.8	0.89	1.10	1.38	1.31	1.10						Natural sand and aggregate
4	0.70	27	599	-	117.5	167.3	-	543.4	1603.6	21.1	48.3	2460.4	2.4	-	11.5	19.2	22.1	23.0	21.4	0.69	1.17	1.24	1.31	1.10						Natural sand and crushed aggregate
280 kg cement, M-6200, 100-mm MSA, M-6124 and M-6124C																														
2	0.41	21	696	-	113.3	277.1	-	424.8	1628.0	21.1	53.3	2441.2	3.2	-	22.8	27.8	32.8	32.5	30.8	1.45	1.65	1.79	1.72	1.65						Natural sand and aggregate
3	0.41	24	1196	-	115.1	276.5	-	482.9	1581.1	20.6	45.7	2455.6	3.4	-	25.0	30.1	32.7	33.8	32.5	1.38	1.65	1.72	1.79	1.65						Natural sand and crushed aggregate
5	0.44	25	606	-	120.4	276.5	-	517.9	1553.3	20.6	50.8	2466.8	3.2	-	22.6	28.2	35.6	38.5	37.3	1.17	1.38	1.86	1.79	1.72						Crushed sand and crushed aggregate
												Part III																		
165 kg cement, M-4909, plus fly ash, M-6498, 75-mm MSA, M-6396																														
2	0.67	30	151	-	112.7	169.1	-	681.7	1590.6	12.2	50.8	2553.6	2.6	-	13.6	-	25.3	-	25.6	0.83	-	1.62	-	1.38						No WRA and no fly ash
6	0.64	30	238	-	105.6	124.6	40.9	672.2	1569.2	12.8	63.5	2513.3	4.2	-	11.0	-	24.1	-	28.0	0.86	-	1.52	-	1.58						No WRA and with fly ash
8	0.60	30	159	654	100.3	125.2	41.5	678.1	1582.9	12.2	53.3	2527.7	4.0	-	11.4	-	26.3	-	31.2	0.90	-	1.45	-	1.58						With WRA and fly ash
280 kg cement, M-4909, plus fly ash, M-6498, 75-mm MSA, M-6396																														
1	0.44	27	499		122.8	278.3	-	575.5	1555.6	13.3	50.8	2532.5	3.2	-	29.6	36.0	38.2	38.3	41.7	1.72	1.93	1.79	1.90	1.72						No WRA and no fly ash
5	0.41	27	1288		116.3	211.2	70.0	575.5	1556.2	15.0	63.5	2529.3	3.1	-	21.9	31.0	38.1	42.4	45.2	1.38	1.86	1.93	2.00	2.14						No WRA and with fly ash
3	0.41	27	176	*1089	114.5	280.0	-	580.8	1570.4	13.9	58.4	2545.3	3.3	-	32.0	41.0	42.2	44.8	45.7	1.69	1.93	1.93	2.14	2.00						With WRA and no fly ash
7	0.39	27	646	*1089	108.0	208.2	68.8	574.9	1553.8	12.8	61.0	2514.9	4.1	-	22.5	35.0	41.8	43.4	46.0	1.52	1.79	2.00	2.00	2.07						With WRA and fly ash

* WRA dosage rate 0.2 percent solids by weight of cementitious material.

Table 4b. — *Mix proportions and test results on fresh and hardened concrete* (English units)

Mix No.	Ratio water to cement plus pozzolan	Ratio sand to aggregate (%)	Mix quantities per cubic yard: Air entraining admixture (cc)	Water reducing admixture (cc)	Water (lb)	Cement (lb)	Pozzolan (lb)	Sand (lb)	Aggregate (lb)	Properties of fresh concrete: Temperature (°F)	Slump (in)	Density (lb/ft³)	Air content Grav. (%)	Air content Press. (%)	Properties of hardened concrete: Compressive strength, lb/in2: 7 days	28 days	90 days	180 days	365 days	Direct tension, lb/in2: 7 days	28 days	90 days	180 days	365 days	Splitting tension, lb/in2: 7 days	28 days	90 days	180 days	365 days	Remarks
Part I																														
470 lb cement, M-4909, 1-1/2-in MSA, M-3942																														
1A	0.47	38	325	-	222	473	-	1,256	2,049	73	2.2	148.2	3.9	4.5	-	7,060	7,610	-	-	-	440	420	-	NT	-	630	480	-	510	
1R	0.45	38	323	-	211	470	-	1,256	2,043	72	2.1	147.4	4.5	4.7	-	6,420	7,160	-	-	-	420	450	-	430	-	480	510	-	520	
Avg.	0.46	38	324	-	216	472	-	1,256	2,046	72	2.1	147.8	4.2	4.6	-	6,740	7,355	-	8,285	-	430	435	-	430	-	555	495	-	515	
670 lb cement, M-4909, 1-1/2-in MSA, M-3942																														
2B	0.36	34	584	-	239	666	-	1,061	2,053	72	2.5	148.9	3.3	3.8	-	7,640	8,370	-	-	-	450	450	-	NT	-	490	580	-	580	
2R	0.35	34	610	-	237	669	-	1,070	2,067	72	2.9	149.7	2.9	3.8	-	8,520	8,610	-	-	-	460	490	-	NT	-	490	530	-	680	
Avg.	0.35	34	597	-	238	668	-	1,065	2,060	72	2.7	149.3	3.1	3.8	-	8,080	8,490	-	10,115	-	455	470	-	NT	-	490	555	-	630	
850 lb cement, M-4909, 1-1/2-in MSA, M-3942																														
3A	0.32	28	1,843	-	273	852	-	799	2,046	72	2.6	147.0	3.9	4.4	-	7,500	8,830	-	-	-	470	430	-	540	-	580	470	-	640	
3R	0.32	28	1,848	-	270	844	-	792	2,027	71	2.7	145.6	4.8	5.1	-	6,560	8,070	-	-	-	440	440	-	440	-	520	440	-	420	
Avg.	0.32	28	1,845	-	271	848	-	795	2,037	72	2.7	147.0	4.4	4.8	-	7,030	8,450	-	8,580	-	455	435	-	490	-	550	455	-	530	
470 lb cement, M-4909, 3/4-in MSA, M-3942																														
4A	0.50	45	299	-	233	468	-	1,425	1,736	69	2.6	143.0	6.4	6.2	-	5,450	6,330	-	-	-	360	400	-	370	-	370	410	-	440	
4R	0.50	45	301	-	234	471	-	1,434	1,746	68	2.6	143.9	5.8	6.0	-	5,840	6,970	-	-	-	390	400	-	430	-	440	390	-	430	
Avg.	0.50	45	300	-	234	470	-	1,430	1,742	69	2.5	143.5	6.1	6.1	-	5,650	6,650	-	7,345	-	375	400	-	400	-	405	400	-	435	
670 lb cement, M-4909, 3/4-in MSA, M-3942																														
5B	0.37	40	600	-	246	667	-	1,216	1,817	71	2.4	146.2	4.7	5.2	-	7,520	8,900	-	-	-	440	460	-	490	-	550	550	-		
5R	0.37	40	1,004	-	244	660	-	1,205	1,800	71	2.1	144.8	5.6	6.0	-	7,460	8,610	-	-	-	450	450	-	470	-	510	530	-	570	
Avg.	0.37	40	800	-	245	663	-	1,210	1,808	71	2.2	145.5	5.1	5.6	-	7,490	8,755	-	10,100	-	445	455	-	480	-	530	540	-	570	
850 lb cement, M-4909, 3/4-in MSA, M-3942																														
6A	0.33	36	1,744	-	280	848	-	992	1,757	71	2.8	143.6	5.7	6.1	-	6,990	7,980	-	-	-	360	440	-	430	-	470	540	-	530	
6R	0.33	36	1,762	-	278	843	-	985	1,745	71	2.7	142.6	6.4	6.5	-	7,060	8,150	-	-	-	NT	490	-	450	-	470	540	-	510	
Avg.	0.33	36	1,768	-	279	845	-	988	1,751	71	2.8	143.1	6.0	6.3	-	7,025	8,065	-	9,120	-	360	465	-	440	-	470	540	-	520	
Part II																														
280 lb cement, M-6200 4-in MSA, M-6124 and M-6124C																														
1	0.63	25	253	-	180	285	-	904	2,762	70	2.0	153.0	2.6	-	1,980	3,100	3,600	3,420	3,600	130	160	200	190	160						Natural sand and aggregate
4	0.70	27	599	-	198	282	-	916	2,703	70	1.9	153.6	2.4	-	1,670	2,780	3,200	3,340	3,110	100	170	180	190	160						Natural sand and crushed aggregate
470 lb cement, M-6200, 4-in MSA, M-6124 and M-6124C																														
2	0.41	21	696	-	191	467	-	716	2,744	70	2.1	152.4	3.2	-	3,300	4,030	4,760	4,720	4,470	210	240	260	250	240						Natural sand and aggregate
3	0.41	24	1,196	-	194	466	-	814	2,665	69	1.8	153.3	3.4	-	3,630	4,360	4,740	4,910	4,710	200	240	250	260	240						Natural sand and crushed aggregate
5	0.44	25	606	-	203	466	-	873	2,618	69	2.0	154.0	3.2	-	3,280	4,090	5,160	5,590	5,410	170	200	270	260	250						Crushed sand and crushed aggregate
Part III																														
280 lb cement, M-4909, plus fly ash, M-6498, 3-in MSA, M-6396																														
2	0.67	30	151	-	190	285	-	1,149	2,681	54	2.0	159.4	2.6	-	1,980	-	3,670	-	3,720	120	-	235	-	200						No WRA and no fly ash
6	0.64	30	238	-	178	210	69	1,133	2,645	55	2.5	156.9	4.2	-	1,600	-	3,500	-	4,120	125	-	220	-	230						No WRA and with fly ash
8	0.60	30	159	654	169	211	70	1,143	2,668	54	2.1	157.8	4.0	-	1,660	-	3,810	-	4,520	130	-	210	-	230						With WRA and fly ash
470 lb cement, M-4909, plus fly ash, M-6498, 3-in MSA, M-6396																														
1	0.44	27	499		207	469	-	970	2,622	56	2.0	158.1	3.2	-	4,300	5,230	5,540	5,560	6,050	250	280	260	275	250						No WRA and no fly ash
5	0.41	27	1,288		196	356	118	970	2,623	59	2.5	157.9	3.1	-	3,180	4,500	5,520	6,150	6,560	200	270	280	290	310						No WRA and with fly ash
3	0.41	27	176	*1,089	193	472	-	979	2,647	57	2.3	158.9	3.3	-	4,640	5,940	6,120	6,500	6,630	245	280	280	310	290						With WRA and no fly ash
7	0.39	27	646	*1,089	182	351	116	969	2,619	55	2.4	157.0	4.1	-	3,270	5,080	6,060	6,300	6,670	220	260	290	290	300						With WRA and fly ash

* WRA dosage rate 0.2 percent solids by weight of cementitious material.

Table 5a. —*Elastic properties — 150- by 300-mm cylinders for part I and 300- by 600-mm cylinders for parts II and III* (SI units)

Mix No.	7 days GPa	7 days r	28 days GPa	28 days r	90 days GPa	90 days r	180 days GPa	180 days r	365 days GPa	365 days r
Part I										
280 kg cement, M-4909, 37.5-mm MSA, M-3942										
1	-	-	34.68	0.18	37.02	0.22	-	-	42.33	0.25
1R	-	-	35.64	0.23	38.96	0.20	-	-	40.33	0.24
Avg.	-	-	35.16	0.20	37.99	0.21	-	-	41.37	0.25
400 kg cement, M-4909, 37.5-mm MSA, M-3942										
2	-	-	33.30	0.20	38.82	0.22	-	-	43.37	0.19
2R	-	-	34.40	0.20	40.61	0.20	-	-	42.82	0.24
Avg.	-	-	33.88	0.20	39.71	0.21	-	-	43.09	0.22
500 kg cement, M-4909, 37.5-mm MSA, M-3942										
3	-	-	35.92	0.22	38.33	0.24	-	-	43.37	0.27
3R	-	-	34.96	0.21	36.68	0.27	-	-	39.92	0.27
Avg.	-	-	35.44	0.22	37.51	0.26	-	-	41.64	0.27
280 kg cement, M-4909, 19-mm MSA, M-3942										
4	-	-	31.10	0.20	35.09	0.21	-	-	39.16	0.23
4R	-	-	31.44	0.19	35.99	0.21	-	-	41.58	0.27
Avg.	-	-	31.30	0.20	35.58	0.21	-	-	40.40	0.25
400 kg, cement, M-4909, 19-mm MSA, M-3942										
5	-	-	-	-	38.54	0.20	-	-	42.68	0.24
5R	-	-	33.44	0.23	35.58	0.21	-	-	41.71	0.25
Avg.	-	-	33.44	0.23	37.09	0.21	-	-	42.20	0.25
500 kg, cement, M-4909, 19-mm MSA, M-3942										
6	-	-	33.23	0.19	32.96	0.21	-	-	39.30	0.26
6R	-	-	33.65	0.21	36.33	0.22	-	-	39.02	0.25
Avg.	-	-	33.44	0.20	34.68	0.22	-	-	39.16	0.26
Part II										
165 kg cement, M-6200, 100-mm MSA, M-6124										
1	21.17	0.18	23.65	0.14	26.68	0.15	28.89	0.17	28.61	0.17
4	23.99	0.10	22.13	0.15	25.92	0.16	26.06	0.17	27.92	0.18
280 kg, cement, M-6200, 100-mm MSA, M-6124										
2	31.51	0.16	28.68	0.17	32.96	0.17	33.44	0.18	35.16	0.18
3	24.27	0.17	27.85	0.16	32.27	0.17	33.78	0.15	40.26	0.22
5	25.65	0.15	29.10	0.16	35.37	0.14	38.57	0.18	37.58	0.18
Part III										
165 kg cement, M-4909, plus fly ash M-6498, 75-mm MSA, M-6396										
2	22.41	0.21	-	-	37.02	0.20	-	-	33.78	0.19
6	20.48	0.25	-	-	40.95	0.15	-	-	41.16	0.19
8	25.51	0.20	-	-	37.23	0.18	-	-	43.57	0.23
280 kg cement, M-4909, plus fly ash M-6498, 75-mm MSA, M-6396										
1	38.47	0.21	42.40	0.19	43.85	0.22	46.26	0.23	46.12	0.21
5	33.92	0.22	40.82	0.18	47.02	0.22	48.61	0.23	53.98	0.24
3	43.30	0.22	46.19	0.23	48.54	0.22	50.19	0.25	45.50	0.20
7	38.20	0.22	44.26	0.22	49.09	0.26	53.30	0.26	53.23	0.26

Table 5b. — *Elastic properties — 6- by 12-in cylinders for part I and 12- by 24-in cylinders for parts II and III* (English units)

Mix No.	7 days lb/in^2 x 10^6	7 days r	28 days lb/in^2 x 10^6	28 days r	90 days lb/in^2 x 10^6	90 days r	180 days lb/in^2 x 10^6	180 days r	365 days lb/in^2 x 10^6	365 days r
					Part I					
470 lb cement, M-4909, 1-1/2-in MSA, M-3942										
1	-	-	5.03	0.18	5.37	0.22	-	-	6.14	0.25
1R	-	-	5.17	0.23	5.65	0.20	-	-	5.85	0.24
Avg.	-	-	5.10	0.20	5.51	0.21	-	-	6.00	0.25
670 lb cement, M-4909, 1-1/2-in MSA, M-3942										
2	-	-	4.83	0.20	5.63	0.22	-	-	6.29	0.19
2R	-	-	4.99	0.20	5.89	0.20	-	-	6.21	0.24
Avg.	-	-	4.91	0.20	5.76	0.21	-	-	6.25	0.22
850 lb cement, M-4909, 1-1/2-in MSA, M-3942										
3	-	-	5.21	0.22	5.56	0.24	-	-	6.29	0.27
3R	-	-	5.07	0.21	5.32	0.27	-	-	5.79	0.27
Avg.	-	-	5.14	0.22	5.44	0.26	-	-	6.04	0.27
470 lb cement, M-4909, 3/4-in MSA, M-3942										
4	-	-	4.51	0.20	5.09	0.21	-	-	5.68	0.23
4R	-	-	4.56	0.19	5.22	0.21	-	-	6.03	0.27
Avg.	-	-	4.54	0.20	5.16	0.21	-	-	5.86	0.25
670 lb cement, M-4909, 3/4-in MSA, M-3942										
5	-	-	-	-	5.59	0.20	-	-	6.19	0.24
5R	-	-	4.85	0.23	5.16	0.21	-	-	6.05	0.25
Avg.	-	-	4.85	0.23	5.38	0.21	-	-	6.12	0.25
850 lb cement, M-4909, 3/4-in MSA, M-3942										
6	-	-	4.82	0.19	4.78	0.21	-	-	5.70	0.26
6R	-	-	4.88	0.21	5.27	0.22	-	-	5.66	0.25
Avg.	-	-	4.85	0.20	5.03	0.22	-	-	5.68	0.26
					Part II					
280 lb cement, M-6200, 4-in MSA, M-6124										
1	3.07	0.18	3.43	0.14	3.87	0.15	4.19	0.17	4.15	0.17
4	3.48	0.10	3.21	0.15	3.76	0.16	3.78	0.17	4.05	0.18
470 lb cement, M-6200, 4-in MSA, M-6124										
2	4.57	0.16	4.16	0.17	4.78	0.17	4.85	0.18	5.10	0.18
3	3.52	0.17	4.04	0.16	4.68	0.17	4.90	0.15	5.84	0.22
5	3.72	0.15	4.22	0.16	5.13	0.14	5.59	0.18	5.45	0.18
					Part III					
280 lb cement, M-4909, plus fly ash M-6498, 3-in MSA, M-6396										
2	3.25	0.21	-	-	5.37	0.20	-	-	4.90	0.19
6	2.97	0.25	-	-	5.94	0.15	-	-	5.97	0.19
8	3.70	0.20	-	-	5.40	0.18	-	-	6.32	0.23
470 lb cement, M-4909, plus fly ash M-6498, 3-in MSA, M-6396										
1	5.58	0.21	6.15	0.19	6.36	0.22	6.71	0.23	6.69	0.21
5	4.92	0.22	5.92	0.18	6.82	0.22	7.05	0.23	7.83	0.24
3	6.28	0.22	6.70	0.23	7.04	0.22	7.28	0.25	6.60	0.20
7	5.54	0.22	6.42	0.22	7.12	0.26	7.73	0.26	7.72	0.26

Table 6[1]. — *Relationship of direct tensile strengths, splitting tensile strengths, and corresponding compressive strengths — part I*

Mix No.	W/C	MSA mm (in)	Cement kg/m³ (lb/yd³)	Average Tensile Strength MPa (lb/in²)			Average Tensile Splitting Strength MPa (lb/in²)			Average Compressive Strength MPa (lb/in²)		
				28 days	90 days	365 days	28 days	90 days	365 days	28 days	90 days	365 days
1	0.46	37.5 (1½)	280 (470)	3.0 (430)	3.0 (430)	3.0 (430)	3.8 (555)	3.4 (495)	3.5 (515)	46.5 (6740)	50.9 (7385)	57.1 (8285)
4	0.50	19 (¾)	280 (470)	2.6 (375)	2.7 (400)	2.7 (400)	2.8 (405)	2.7 (400)	3.0 (435)	38.9 (5645)	45.8 (6650)	50.6 (7345)
2	0.36	37.5 (1½)	400 (670)	3.1 (455)	3.2 (470)	NT	3.4 (490)	3.8 (555)	4.3 (630)	55.7 (8080)	58.5 (8490)	69.7 (10115)
5	0.37	19 (¾)	400 (670)	3.1 (445)	3.1 (455)	3.3 (480)	3.6 (530)	3.7 (540)	3.9 (570)	51.6 (7490)	60.4 (8755)	69.7 (10115)
3	0.32	37.5 (1½)	500 (850)	3.1 (455)	3.0 (435)	3.2 (470)	3.8 (550)	3.1 (455)	3.6 (530)	48.5 (7030)	58.3 (8450)	59.1 (8580)
6	0.33	19 (¾)	500 (850)	2.5 (360)	3.2 (465)	3.0 (440)	3.2 (470)	3.7 (540)	3.6 (520)	48.4 (7025)	55.6 (8065)	62.9 (9120)

[1] This table contains summary data from Table 4.

Table 7. — *Ratios of tensile and tensile splitting strengths to companion compressive strength — part I*

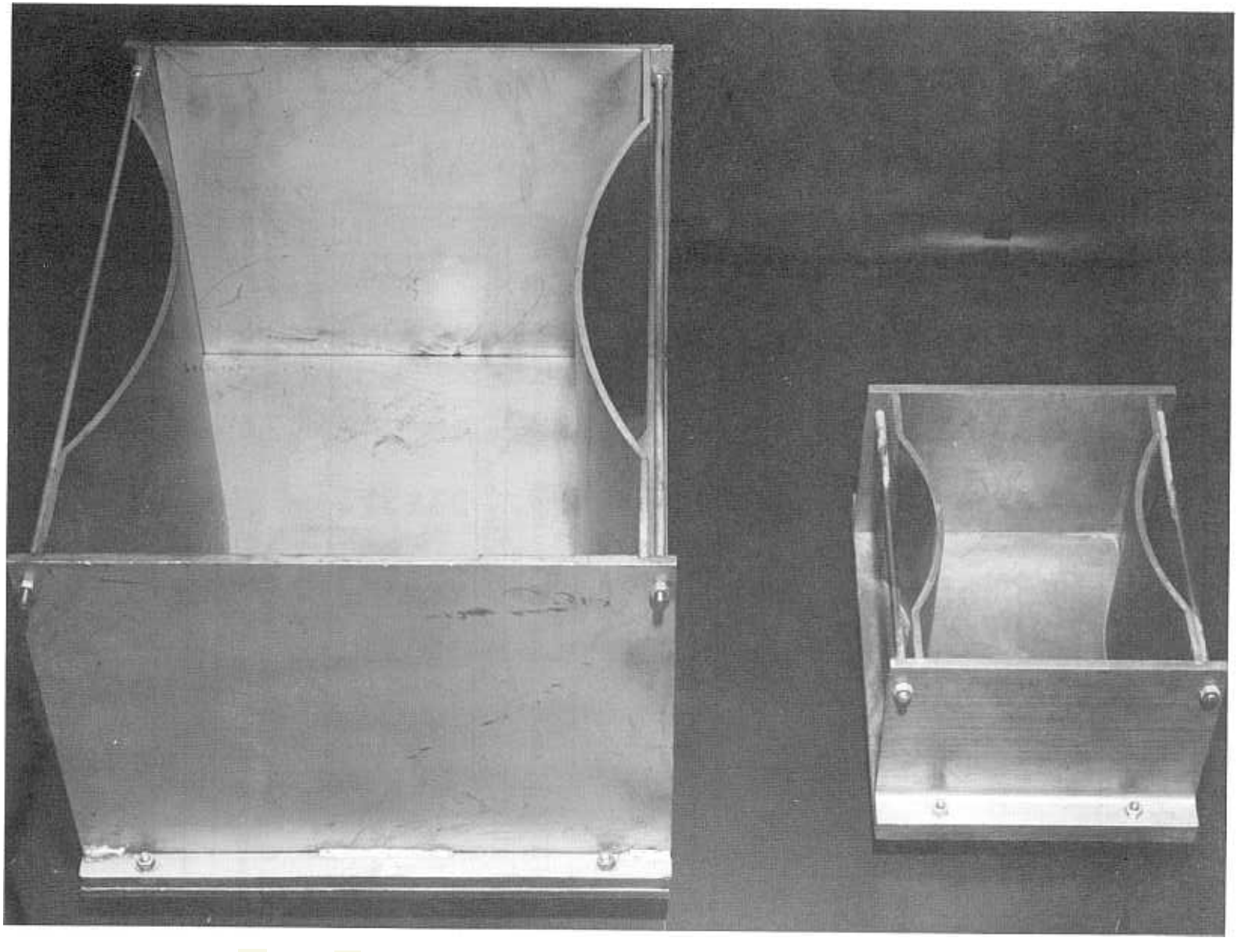
Mix No.	Ratio, Tensile to Compressive Strength percent			Ratio, Tensile Splitting to Compressive Strength percent		
	28 days	90 days	365 days	28 days	90 days	365 days
1	6.4	5.9	5.2	8.2	6.7	6.1
4	6.6	6.0	5.4	7.1	6.0	5.9
2	5.6	5.5	NT	6.1	6.5	6.2
5	5.9	5.2	4.8	7.1	6.2	5.6
3	6.5	5.1	5.5	7.8	5.4	6.2
6	5.1	5.8	4.8	6.7	6.7	5.7

Table 8. — *Ratios of tensile strength to companion compressive strength — part II*

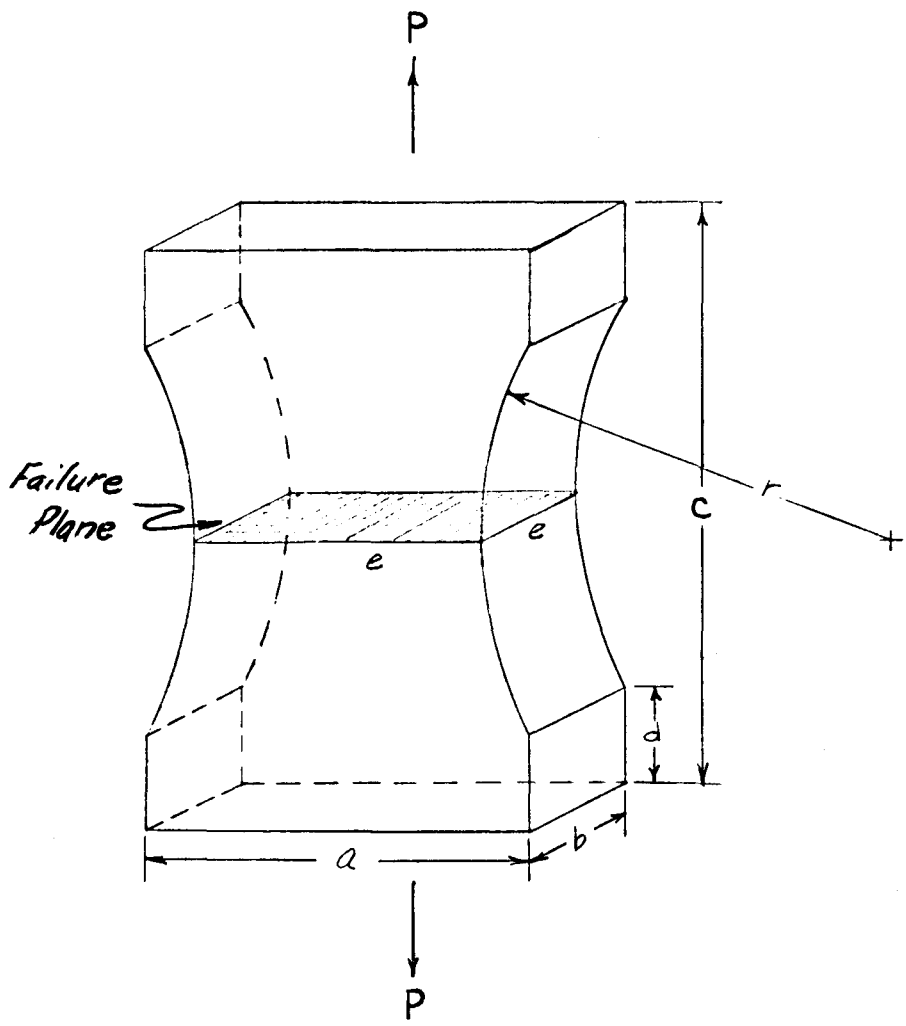
Mix No.	Age, Days				
	7	28	90	180	365
1	6.6	5.2	5.6	5.6	4.4
4	6.0	6.1	5.6	5.7	5.1
2	6.4	6.0	5.5	5.3	5.4
3	5.5	5.5	5.3	5.3	5.1
5	5.2	4.9	5.2	4.7	4.6

Table 9. — *Ratios of tensile strength to companion compressive strength — part III*

Mix No.	Age, Days				
	7	28	90	180	365
2	6.1	—	6.4	—	5.4
6	7.8	—	6.3	—	5.6
8	7.8	—	5.5	—	5.1
1	5.8	5.4	4.9	4.9	4.7
5	6.3	6.0	5.1	4.7	4.7
3	5.3	4.7	4.6	4.8	4.4
7	6.7	5.1	4.8	4.6	4.5



Figur Molds for by 300-mm -in) and 400- by by strength imer



Note: Dimensions vary with maximum-size aggregate.
See table below.

MSA, mm	MSA, in.	Dimensions mm (in) a	b	c	d	e	r
150	6	600 (24)	450 (18)	900 (36)	150 (6)	450 (18)	25.5
113,75	4½, 3	400 (16)	300 (12)	600 (24)	100 (4)	300 (12)	17
37.5	1½	200 (8)	150 (6)	300 (12)	50 (2)	150 (6)	3.5
19	¾	200 (8)	150 (6)	300 (12)	50 (2)	150 (6)	8.5
9.5	⅜	200 (8)	150 (6)	300 (12)	50 (2)	150 (6)	8.5

Figure 2. — Dimensions of tensile strength mold

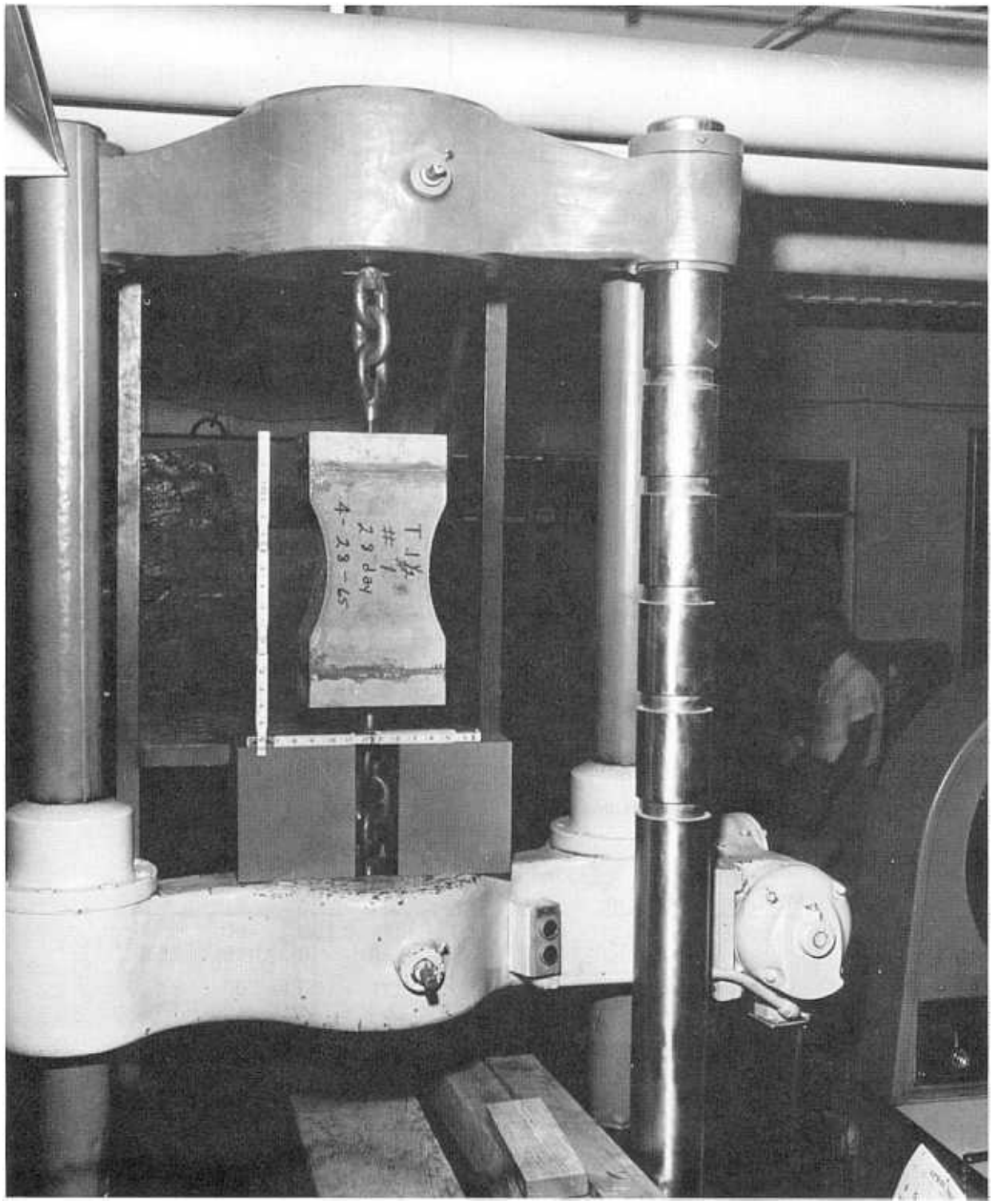


Figure 3. — A 200- by 300-mm (8- by 12-in) modified prism specimen with end plates attached ready to be tested in tension. P801-D-80202

Figure 4. — A 3-mm (⅛-in) square pad on top of a 150- by 300-mm (6- by 12-in) splitting tensile specimen mounted in testing machine. P801D-80203

Figure 5. — A 25- by 3-mm (1- by ⅛-in) pad on top of a 150- by 300-mm (6- by 12-in) splitting tensile specimen mounted in testing machine. P801-D-80204

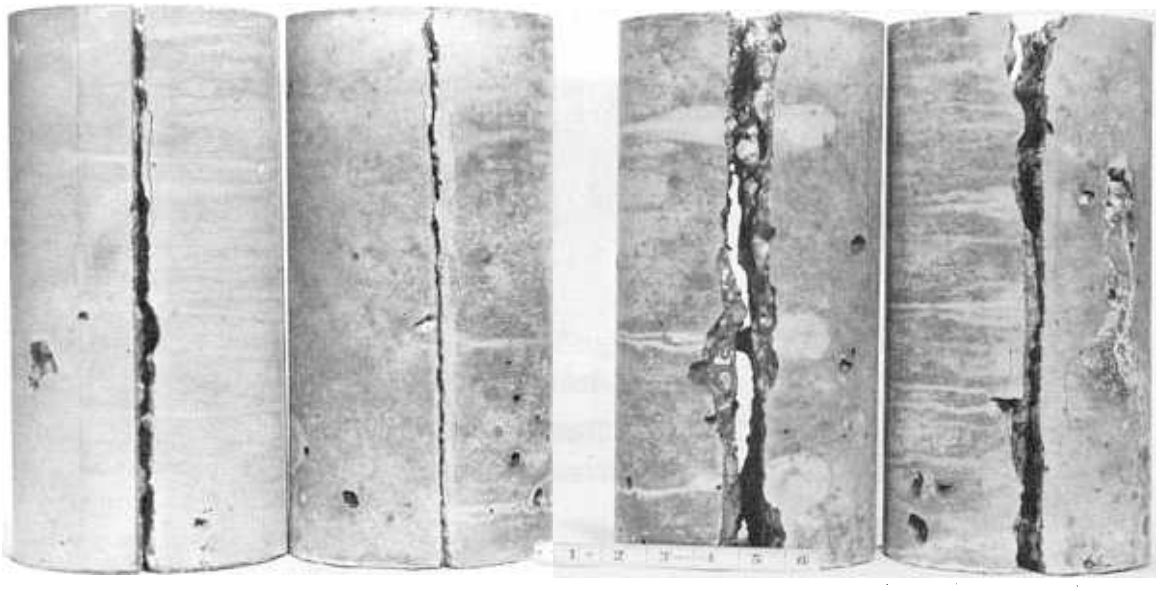


Figure 6. — Types of failure caused by different pads on top of 150- by 300-mm (6- by 12-in) splitting tensile specimens. P801-D-80205

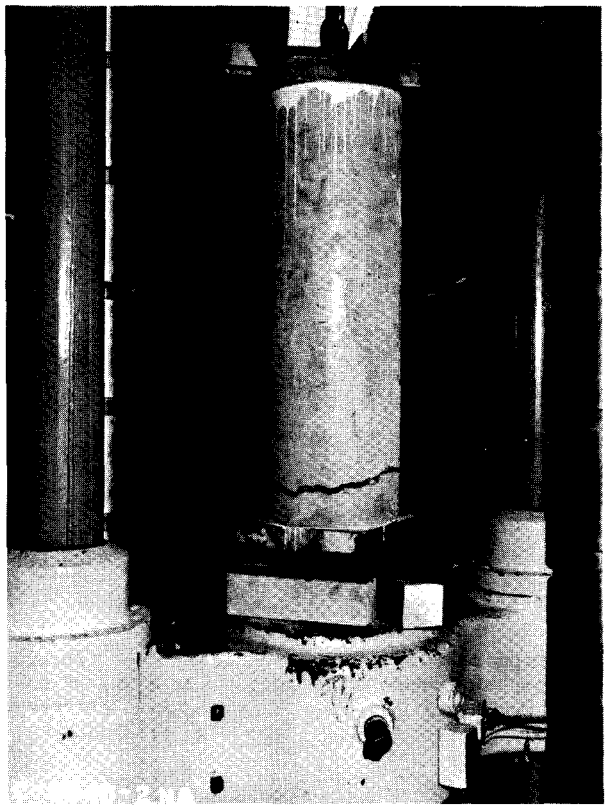


Figure 7a. — A 600- by 900-mm (12- by 36-in) cylinder after failure in testing machine. P801-D-80206

Figure 7b. — Failure of cylinder occurred along the lower portion of the large aggregate. P801-D-80207

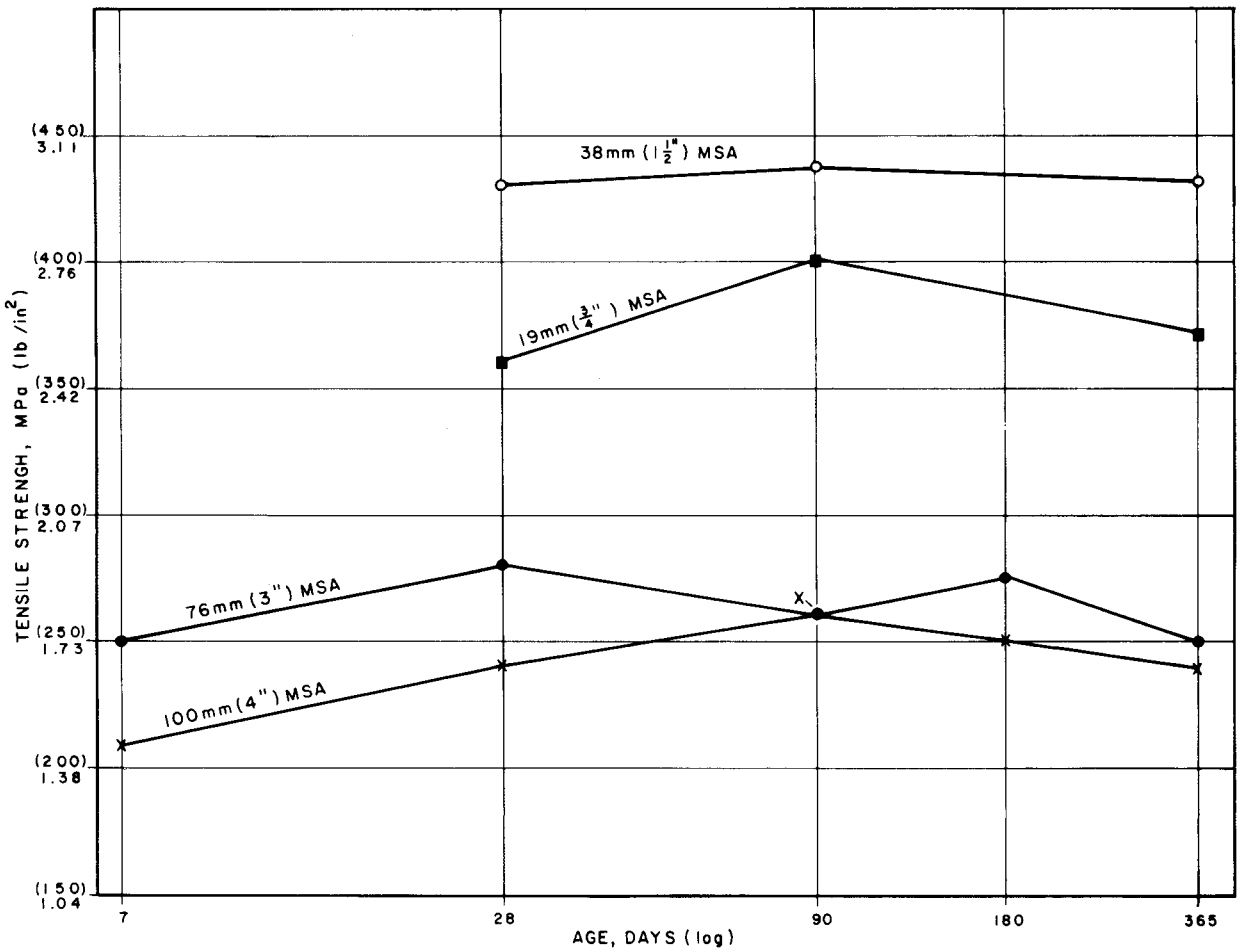


Figure 8. — Tensile strength as affected by different MSA at a constant cement content of 280 kg/m³ (470 lb/yd³)

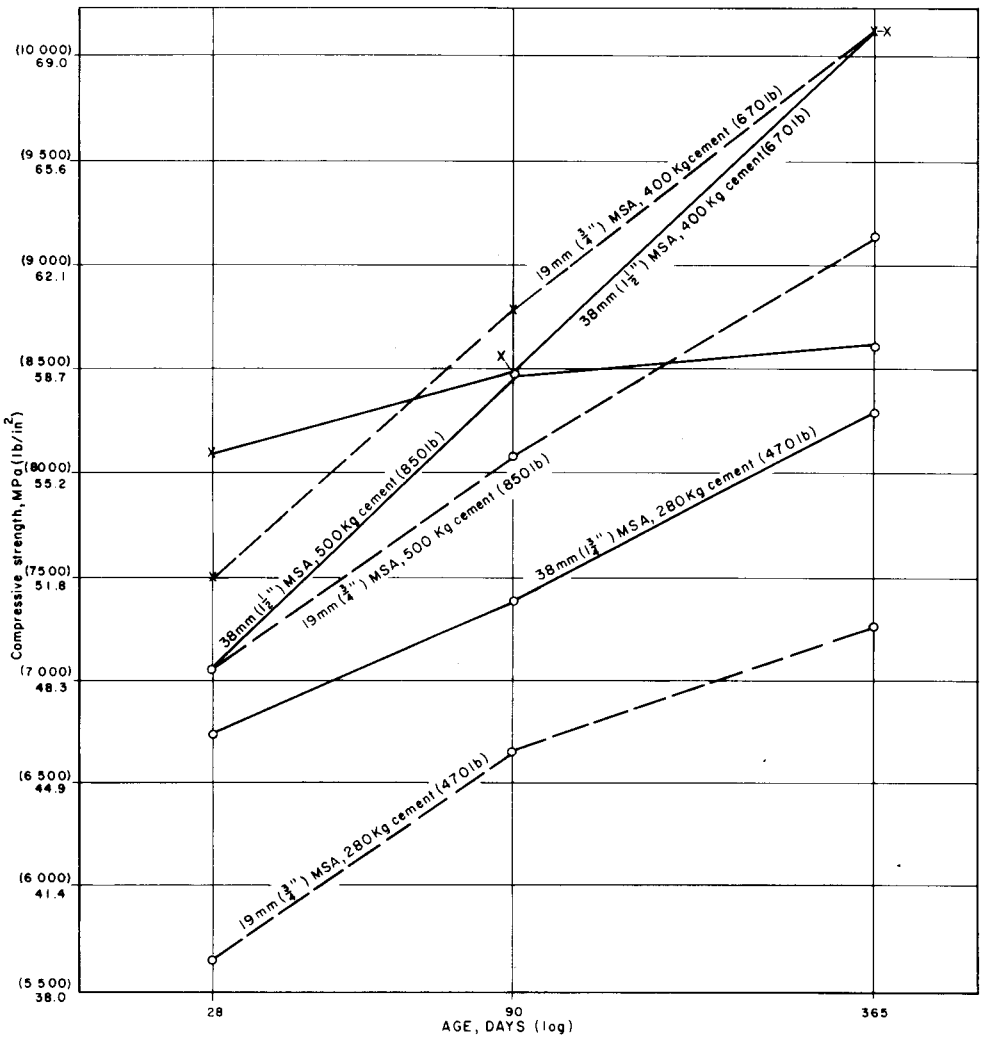


Figure 9. — Compressive strength as affected by cement content, MSA, and age—part I.

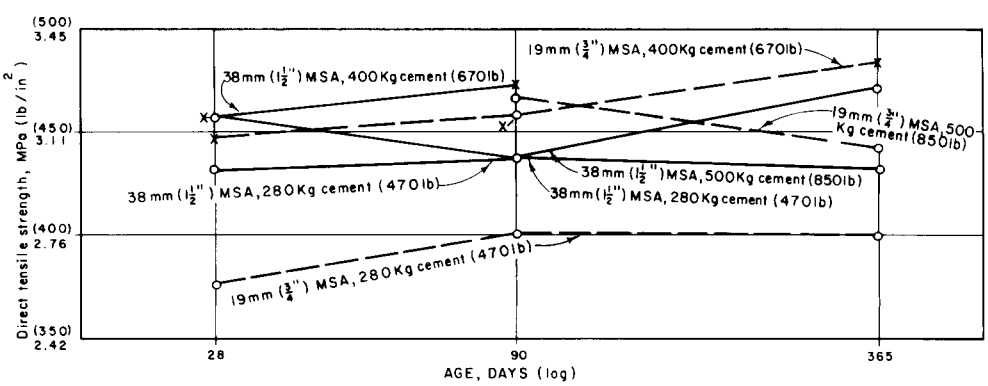


Figure 10. — Tensile strength as affected by cement content, MSA, and age—part I.

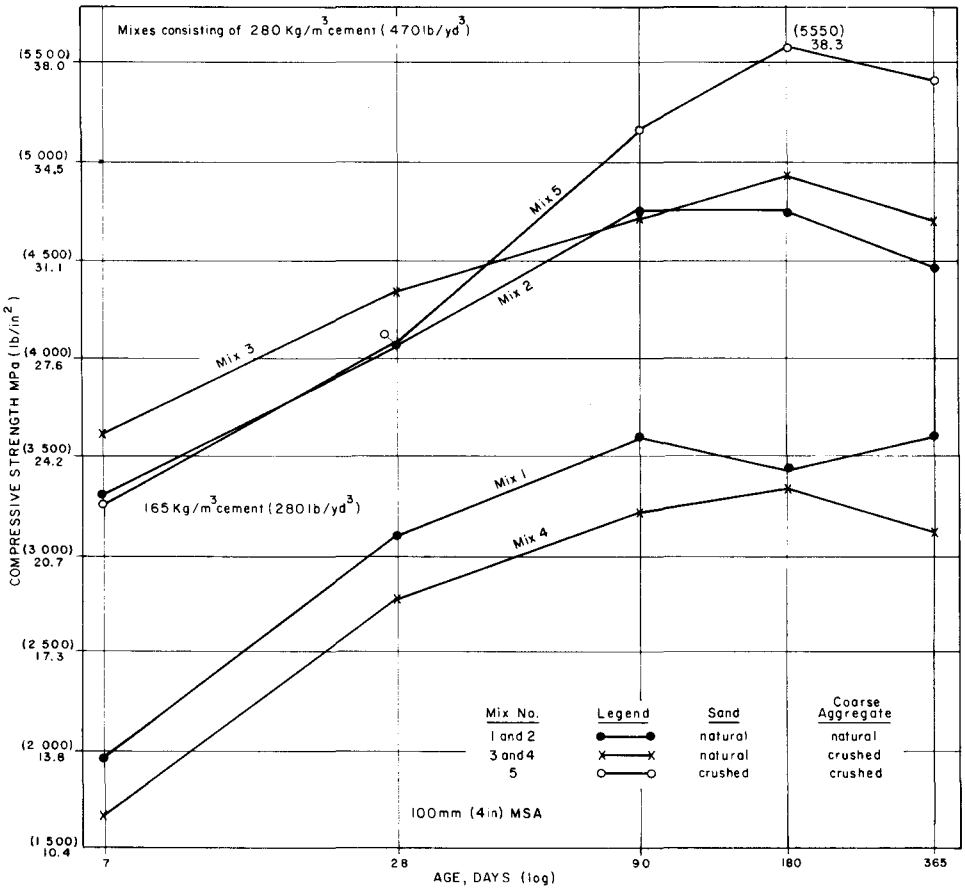


Figure 11. — Compressive strength as affected by crushing sand and aggregate—part II.

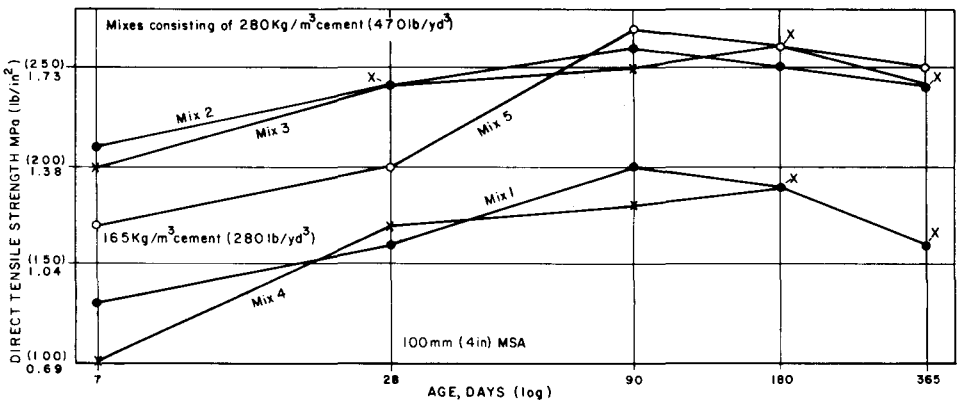


Figure 12. — Direct tensile strength as affected by crushing natural sand and aggregate—part II.

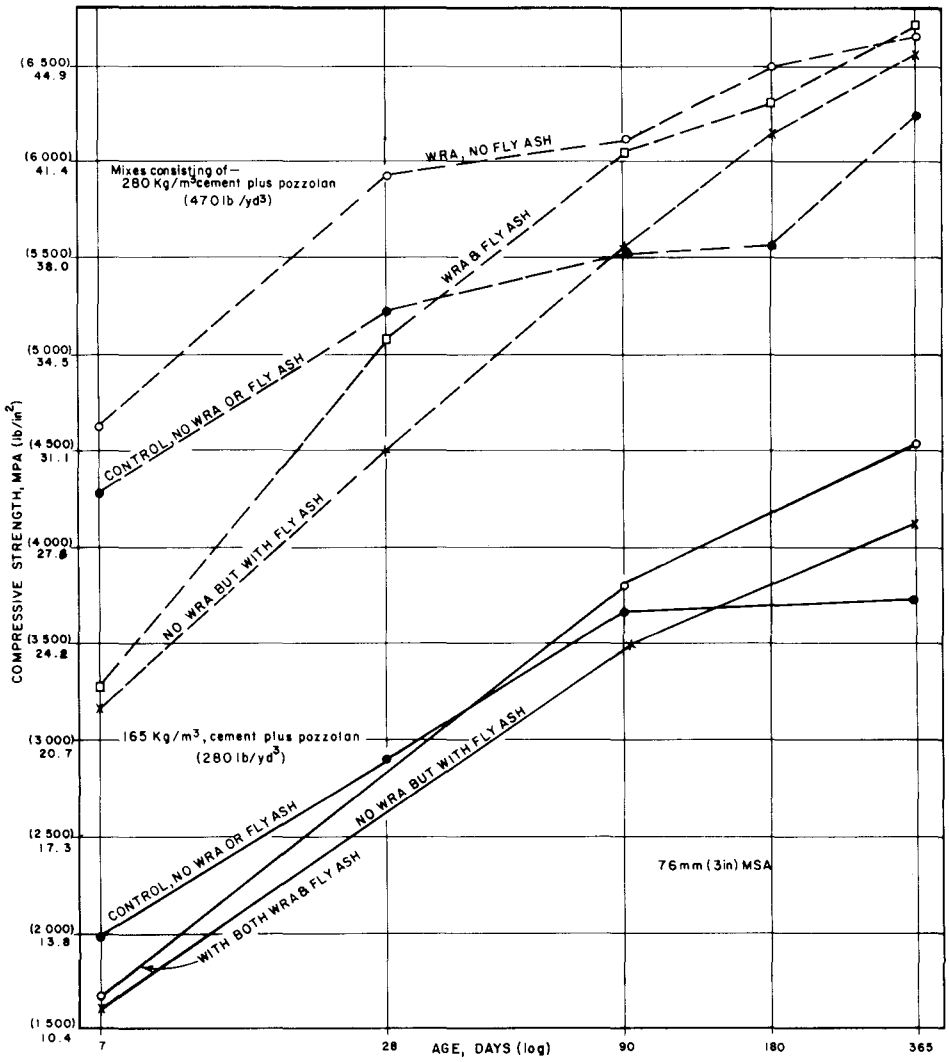


Figure 13. — Compressive strength as affected by additions of fly ash and WRA separately or in combination—part III.

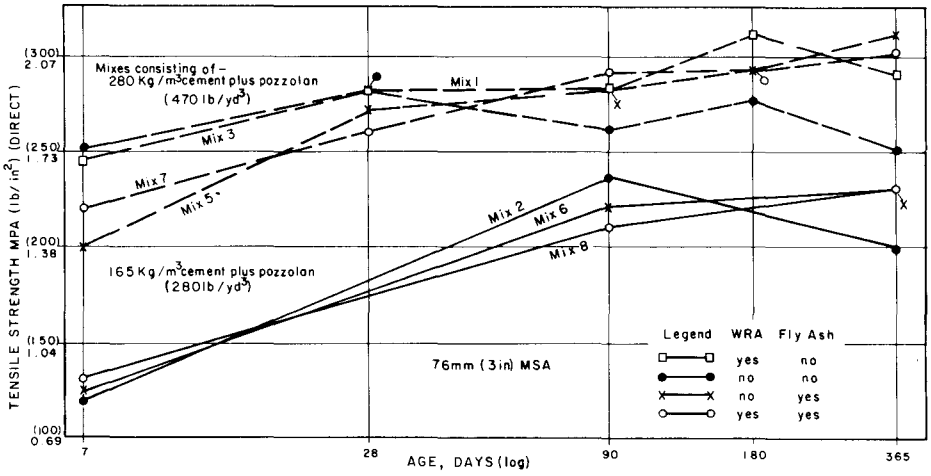


Figure 14. — Tensile strength as affected by additions of fly ash and WRA separately or in combination—part III.

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