Morse Brothers, Inc.
Harrisburg Plant

High-Strength Concrete
Research Study

July, 1987
Study Made By
Oregon State Highway Division
Materials Section

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DOCUMENT NUMBER 983

Specification No. 504	**Report No.**
Report Date	**Type**

Title

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Abstract

Key Words

PCC Strength
Concrete Cylinder Mold
PCC—Steam-Cured
PCC—Moist-Cured
PCC—Prestressed Slabs

Location

ACKNOWLEDGMENTS

The authors gratefully acknowledge assistance from many individuals and organizations who contributed extensively to this research study.

Special thanks are due to Morse Brothers personnel at the Harrisburg plant for their generous contribution of materials and a test site; to Keith Johnston, Structural Materials Engineer for coordinating testing plans and schedules; to the Portland Concrete Inspection Crew and the Eugene Concrete and General Inspection Crew for sampling and testing the plastic concrete; and finally to all other Materials Section personnel involved in handling and testing the concrete cylinders and to the others who made this report possible.

MORSE BROTHERS, INC. HARRISBURG
HIGH-STRENGTH CONCRETE RESEARCH STUDY

INTRODUCTION

This report is the seventh in a series of research studies designed to determine the difference in strength of concrete cylinders cast in steel molds vs. cylinders cast in plastic molds. Prior to this report, six other research studies on the difference in compressive strength of portland cement concrete cylinders cast in steel and plastic molds were conducted by the Oregon State Highway Division (OSHD) Materials Section. The purpose of these reports was to determine the quantity of strength difference for different classes of concrete from different suppliers, as well as the possible cause of the strength difference such as mold flexibility, method of vibration, method of transport, curing conditions, etc. The results of these six studies are summarized in Concrete Cylinder Mold Investigation Summary Report, Oregon State Highway Division Materials Section, March 12, 1987.

This research study was designed to determine which mold (steel, plastic, or tin) produces concrete strength that is most representative of actual strength in a concrete slab structure as determined from concrete cores and tin molds embedded in the slab. In addition, further comparison of the strength difference in mold type and method of field curing were made.

CONCRETE PROPERTIES AND STUDY DESIGN

Two separate batches of concrete were cast seven days apart. Batch No. 1 was used in a steam-cured slab. Batch No. 2 was used in a moist-cured slab. The test slabs and the cylinder molds were fabricated as follows:

1. A total of 45 cylinders (15 each of steel, tin, and plastic molds) were cast, cured, and transported according to AASHTO T23, except that plastic and tin molds were not removed from the cylinders prior to transportation. These 45 cylinders were used to test the difference in strength due to mold type and for comparison with embedded cylinders and cores.

   In Batch No. 1, each set of 15 cylinders corresponding to mold type was fabricated from a single wheel barrow of concrete. Minor variations in concrete strength between wheel barrow loads may account for some systematic differences between mean strength results.

In Batch No. 2, each lift of concrete came from a different wheel barrow to eliminate systematic variations between mold types.

All cylinders were consolidated by vibration.

2. A test slab with approximate dimensions of 4' X 10' X 12" was poured and vibrated, both externally and internally. Embedded within the test slab were 16 tin molds banded together in a 4 X 4 array and treated with bond breaker inside and out. See Figure 1.

   The slab cast from Batch No. 1 was steam cured for the first several hours and then cured under ambient conditions. The slab cast from Batch No. 2 was treated with a liquid membrane curing compound, protected under a polyethylene sheeting and cured under ambient conditions.

   After 27 days of curing, the test slabs were cored and the embedded tin cylinders were released and stripped. A total of 15, 4-inch cores and 16, 6-inch cores were cut from each slab. Four-inch cores were trimmed to a length of 8 inches prior to testing. All cylinders and cores were tested for compressive strength according to AASHTO T22 28 days after batching.

3. A total of 18 additional cylinders (6 each of steel, tin, and plastic molds) were cast and cured in the same manner as the test slab. These cylinders were cast at the request of Morse Brothers, Inc. and were used to compare strengths obtained with AASHTO-cured to strengths obtained with field-cured cylinders.

The compressive strength test results were then analyzed and evaluated to determine which AASHTO-cured mold type most closely represented the strength of the concrete slab as determined by the embedded tin cylinders and the concrete cores. Standard methods for the "t" test of significance between two sample means were used. The 5% significance level was used to test for a significant difference between sample means, i.e., the chance that the means were not significantly different when the sample "t" statistic exceeds the "t" statistic at the 5% level is less than 5 in 100.

The concrete used for this study was a moderate-strength concrete mix design using 7.5 sacks of cement per cubic yard as produced at Morse Brothers, Inc. Prestress Yard, Harrisburg, Oregon. Mix proportions for each batch were approximately the same. The batch proportions and field test results for each batch were as follows:

	April 15 Batch No. 1	April 22 Batch No. 2
Cement (lbs/cy)	708	704
Coarse Agg. 3/4-1/2 (lbs/cy)*	715	710
Coarse Agg. 1/2-#4 (lbs/cy)*	1124	1119
Fine Agg. (lbs/cy)*	1232	1232
Water (lbs/cy)	263	267
MB 100XR (oz/cy)	35.25	35.25
Slump, in.	1.5	2.0
Air content, %	1.7	1.8
Cement content, lbs./yd.	714	702
W/C	0.38	0.37

* All aggregate weights represent saturated surface dry conditions

TEST RESULTS AND DISCUSSIONS

The-28 day compressive strength of the cylinders and cores obtained from each batch are tabulated in Table I and II. For each strength category, the mean, standard deviation, coefficient of variation, and standard error of the mean are presented. Also, the student t statistic at a 5% level of significance, the population mean, and the confidence interval at the 5% level of significance are shown.

Table III, IV, and V summarize the results of comparative tests of mean strength differences between sets of cores and cylinders from Batch No. 1, No. 2, and between batch No. 1 and No. 2 respectively. As previously described, the student "t" statistic is used to determine the significance of the difference of the two means. These test results are summarized individually as follows:

Test 1 - AASHTO Cure: Steel Mold vs. Tin Mold

Batch No. 1 - Steel-molded and tin-molded cylinders produce concrete with a mean strength of 8295 psi and 7400 psi, respectively. The mean difference is 895 psi with a percent mean difference of 10.8%. The mean difference is statistically significant at the 5% level.

Batch No. 2 - The mean strength of the steel-molded cylinders is 7912 psi and the mean strength of the tin-molded cylinders is 6881 psi. The mean difference is 1031 psi with a percent mean difference of 13.0%. The mean difference is statistically significant at the 5% level.

The use of steel molds vs. tin molds results in significantly different compressive strengths. The average mean difference for both batches was approximately 12 percent, with steel molds producing higher strength than tin molds. It is concluded that steel and tin molds should not be used interchangeably in concrete testing.

<u>Test 2</u> - AASHTO Cure: Steel Mold vs. Plastic Mold

Batch No. 1 - Steel-molded and plastic-molded cylinders produce concrete with a mean strength of 8295 psi and 7387 psi, respectively. The mean difference is 908 psi with a percent mean difference of 10.9%. This mean difference is statistically significant at the 5% level.

Batch No. 2 - The steel-molded concrete cylinders have a mean strength of 7912 psi while the plastic -molded concrete cylinders have a mean strength of 7079 psi. The mean difference is 834 psi with a percent mean difference of 10.5%. The mean difference is statistically significant at the 5% level.

The use of steel molds vs. plastic molds results in significantly different compressive strengths. The average mean difference for both batches was approximately 10 percent, with steel molds producing higher strength than plastic molds. These results further confirm findings made by the Oregon State Highway Division and others. It is concluded that steel and plastic molds should not be used interchangeably in concrete testing.

<u>Test 3</u> - AASHTO Cure: Tin Mold vs. Plastic Mold

Batch No. 1 - The mean strength of tin-molded concrete cylinders is 7400 psi. The mean strength of plastic-molded concrete cylinders is 7387 psi. The mean difference is 13 psi with a percent mean difference of 0.2%. This difference is not statistically significant at the 5% level.

Batch No. 2 - The mean strength of tin-molded cylinders is 6881 psi and the mean strength of plastic-molded cylinders is 7078 psi. The mean difference is 197 psi with a percent mean difference of 2.8%. The difference is statistically significant at the 5% level.

It is interesting to note that there is no significant difference at the 95% confidence level for Batch No. 1. There is a significant difference for Batch No. 2. It is concluded that tin and plastic molds could be used interchangeably in concrete testing without substantial error. Additional testing may be warranted for other aggregate sources and classes of concrete.

Test 4 - Steel Mold AASHTO Cure vs. Tin Mold Embedded in Slab

Batch No. 1 - The mean strength of moist-cured steel-molded concrete is 8295 psi while the mean strength of steam-cured tin-molded concrete cast as part of the slab is 8228 psi. The mean difference is 69 psi with a percent mean different of 0.8%. The mean difference is not statistically significant at the 5% level.

Batch No. 2 - The mean strength of moist-cured steel-molded concrete is 7912 psi while the mean strength of moist-cured tin-molded concrete cast as part of the slab is 8542 psi. The mean difference is 630 psi with a percent mean difference of 7.9%. The difference is statistically significant at the 5% level.

Steam-cured concrete as represented by tin molds cast as part of the slab results in mean strength approximately the same as moist-cured steel-molded concrete. Tin-molded concrete cast as part of the moist-cured slab is approximately 8 percent lower in strength than moist-cured steel-molded concrete. The difference in strength results between the two batches may be due to the difference in field cure method. It is concluded that steel cylinders are representative of concrete slab strength as determined by tin-molded cylinders when cast as part of a steam-cured slab, but not when cast as part of a moist-cured slab.

Test 5 - Tin Mold AASHTO Cure vs. Tin Mold Embedded in Slab

Batch No. 1 - The mean strength of moist-cured tin-molded cylinders is 7400 psi while the mean strength of tin-molded cylinders cast as part of the steam-cured slab is 8228 psi. The mean difference is 828 psi with a percent mean difference of 11.2%. The mean difference is statistically significant at the 5% level.

Batch No. 2 - The mean strength of moist-cured tin-molded cylinders is 6881 psi, while the mean strength of tin-molded cylinders cast as part of the moist-cured slab is 8542 psi. The mean difference is 1661 psi with a percent mean difference of 24.1%. The mean difference is statistically significant at the 5% level.

There is significant difference in mean strength of moist-cured tin-molded concrete as compared to tin-molded concrete embedded in either a steam-cured or moist-cured slab. Also, the difference is quite large, ranging from 11 to 24 percent. It is concluded that AASHTO-cured tin-molded cylinders are not representative of concrete slab strength as determined by tin-molded cylinders cast as part of the slab.

Test 6 - Plastic Mold AASHTO Cure vs. Tin Mold Embedded in Slab

Batch No. 1 - The mean strength of moist-cured plastic-molded cylinders is 7387 psi while the mean strength of tin-molded cylinders cast as part of the steam-cured slab is 8228 psi. The mean difference is 842 psi. The percent mean difference is 11.4%. The mean difference is statistically significant at the 5% level.

Batch No. 2 - The mean strength of moist-cured plastic-molded concrete cylinders is 7078 psi while the mean strength of tin-molded cylinders cast as part of the moist-cured slab is 8542 psi. The mean difference is 1464 psi. The percent mean difference is 20.7%. This difference is statistically significant at the 5% level.

There is a significant difference in the mean strength of moist-cured plastic-molded concrete as compared to tin-molded concrete embedded in either the steam-cured or moist-cured slab. Also, the difference is quite large, ranging from 11 to 20 percent. It is concluded that plastic-molded cylinders are not representative of concrete slab strength as determined by tin-molded cylinders cast as part of the slab.

Test 7 - Concrete Cores: 6-inch vs. 4-inch

Batch No. 1 - The mean strength of steam-cured 6-inch cores is 7369 psi and the mean strength of steam-cured 4-inch cores is 6931 psi. The mean difference is 438 psi with a percent mean difference of 5.9%. The mean difference is statistically significant at 5% level.

Batch No. 2 - The mean strength of moist-cured 6-inch cores is 6872 psi. The mean strength of moist-cured 4-inch cores is 6707 psi. The mean difference is 165 psi with a percent mean difference of 2.4%. The mean difference is not statistically significant at approximately the 5% level.

There is a large difference in mean strength associated with the size of the cores from the steam-cured slab. However, for cores obtained from the moist-cured slab, the mean strength results are not significantly different. The mean strength for 4-inch cores is less than 6-inch cores for both batches (slabs). It is concluded that 6-inch cores would be preferable to 4-inch cores when such supplemental concrete testing is feasible and necessary.

Test 8 - Steel Mold AASHTO Cure vs. 6-inch Cores

Batch No. 1 - The mean strength of moist-cured steel-molded concrete cylinders is 8295 psi. The mean strength of steam-cured 6-inch cores is 7369 psi. The mean difference is 926 psi with a percent mean difference of 11.2%. The mean difference is statistically significant at approximately the 5% level.

Batch No. 2 - The mean strength of moist-cured steel-molded concrete cylinders is 7912 psi while the mean strength of moist-cured 6-inch cores is 6872 psi. The mean difference is 1040 psi with a percent mean different of 13.1%. The mean difference is statistically significant at the 5% level.

There is a significant difference in mean strength of moist-cured steel-molded cylinders as compared to steam-cured or moist-cured 6-inch cores. The average difference for both batches is approximately 12 percent. It is concluded that AASHTO-cured steel-molded cylinders are not representative of concrete slab strength as determined by 6-inch cores.

Test 9 - Steel Mold AASHTO Cure vs. 4-inch Cores

Batch No. 1 - THe mean strength of moist-cured steel-molded concrete cylinders is 8295 psi while the mean strength of steam-cured 4-inch cores is 6931 psi. The mean difference is 1364 psi with a percent mean difference of 16.4%. The mean difference is statistically significant at the 5% level.

Batch No. 2 - The mean strength of the moist-cured steel-molded concrete cylinders is 7912 psi while the mean strength of the moist-cured 4-inch cores is 6707 psi. The mean difference is 1205 psi with a percent mean difference of 15.2%. The mean difference is statistically significant at the 5% level.
There exists a significant difference in test results between moist-cured steel-molded cylinders and steam-cured or moist-cured 4-inch cores. The average difference for both batches is approximately 16 percent. It is concluded that moist-cured steel-molded cylinders are not representative of concrete slab strength as determined by 4-inch cores.

Test 10 - Tin Mold AASHTO Cure vs. 6-inch Cores

Batch No. 1 - The mean strength of moist-cured tin-molded concrete cylinders is 7400 psi. The mean strength of steam-cured 6-inch concrete cores is 7369 psi. The mean difference is 3 psi with a percent mean difference of 0.4%. The mean difference is not statistically significant at the 5% level.

Batch No. 2 - The mean strength of moist-cured tin-molded concrete cylinders is 6881 psi while the mean strength of steam-cured 6-inch cores is 6872 psi. The mean difference is 9 psi with a percent mean difference of 0.1%. The mean difference is not statistically significant at the 5% level.

There is no significant difference in strength between moist-cured tin-molded concrete cylinders and steam-cured or moist-cured 6-inch cores. It is concluded that moist-cured tin-molded cylinders are very representative of concrete slab strength as determined by 6-inch cores.

Test 11 - Tin Mold AASHTO Cure vs. 4-inch Cores

Batch No. 1 - The mean strength of moist-cured tin molded concrete cylinders is 7400 psi while the mean strength of steam-cured 4-inch concrete cores is 6931 psi. The mean difference is 469 psi and the percent mean difference is 6.3%. The mean difference is statistically significant at the 5% level.

Batch No. 2 - The mean strength of moist-cured tin-molded cylinders is 6881 psi while the mean strength of moist-cured 4-inch concrete cores is 6707 psi. The mean difference is 174 psi. The percent mean difference is 2.5%. The mean difference is not statistically significant at the 5% level.

There is a significant difference in strength between moist-cured tin-molded concrete cylinders and steam-cured 4-inch cores. But, there is no significant difference (at the 5% level of significance) between moist-cured tin-molded cylinders and moist-cured 4-inch cores. It is concluded that moist-cured tin-molded cylinders are not representative of concrete strength as determined by 4-inch cores.

Test 12 - Plastic Mold AASHTO Cure vs. 6-inch Cores

Batch No. 1 - The mean strength of moist-cured plastic-molded cylinders is 7387 psi while the mean strength of steam-cured 6-inch cores is 7369 psi. The mean difference is 18 psi. The percent mean difference is 0.2%. The mean difference is not statistically significant at the 5% level.

Batch No. 2 - The mean strength of moist-cured plastic-molded cylinders is 7078 psi while the mean strength of moist-cured 6-inch cores is 6872 psi. The mean difference is 206 psi with a percent mean difference of 2.9%. The mean difference is not statistically significant at the 5% level.

There is no significant difference (at the 5% level) in test results between moist-cured plastic-molded cylinders and steam-cured or moist-cured 6-inch cores. It is concluded that moist-cured plastic-molded cylinders are representative of concrete slab strength as determined by 6-inch cores.

Test 13 - Plastic Mold AASHTO Cure vs. 4-inch Cores

Batch No. 1 - The mean strength of moist-cured plastic-molded concrete cylinders is 7387 psi while the mean strength of steam-cured 4-inch cores is 6931 psi. The mean difference is 456 psi with a percent mean difference of 6.2%. The mean difference is statistically significant at the 5% level.

Batch No. 2 - The mean strength of moist-cured plastic-molded cylinders is 7078 psi. The mean strength of moist-cured 4-inch concrete cores from field moist cured slab is 6707 psi. The mean difference is 371 psi with a percent mean difference of 5.2%. The mean difference is statistically significant at the 5% level.

There is a significant difference in strength test result between moist-cured plastic-molded concrete cylinders and steam-cured or moist-cured 4-inch concrete cores. It is concluded that moist-cured plastic-molded cylinders are not representative of concrete strength as determined by 4-inch cores.

Test 14 - Tin Mold Embedded in Slab vs. 6-inch Cores

Batch No. 1 - The mean strength of tin-molded concrete cylinders cast as part of the steam-cured slab is 8228 psi. The mean strength of steam-cured 6-inch concrete cores is 7369 psi. The mean difference is 859 psi with a percent mean difference of 10.4%. The mean difference is statistically significant at the 5% level.

Batch No. 2 - The mean strength of tin-molded concrete cylinders cast as part of the moist-cured slab is 8542 psi while the mean strength of moist-cured 6-inch cores is 6872 psi. The mean difference is 1670 psi. The percent mean difference 19.5%. The mean difference is statistically significant at the 5% level.

There is significant difference in strength test results between tin-molded concrete cylinders embedded in the steam-cured or moist-cured concrete slab as compared to 6-inch concrete cores taken from the same slab. Also, for both curing methods, the difference is quite large. It is concluded that embedded tin-molded cylinders are not representative of concrete strength as determined by 6-inch cores.

Test 15 - Tin Mold Embedded in Slab vs. 4-inch Cores

Batch No. 1 - The mean strength of tin-molded concrete cylinders embedded in the steam-cured slab is 8228 psi. The mean strength of steam-cured 4-inch concrete cores is 6931 psi. The mean difference is 1297 psi. The percent mean difference is 15.8%. The mean difference is statistically significant at the 5% level.

Batch No. 2 - The mean strength of tin-molded concrete cylinders embedded in the moist-cured slab is 8542 psi while the mean strength of moist-cured 4-inch concrete cores is 6707 psi. The mean difference is 1835 psi with a percent mean difference of 21.5%. The mean difference is statistically significant at the 5% level.

There is significant difference in strength test results between tin-molded concrete cylinders embedded in steam-cured or moist-cured concrete slab as compared to 4-inch cores taken from same slab. The average difference for both batches is approximately 19 percent. It is concluded that embedded tin-molded cylinders are not representative of concrete strength as determined from 4-inch cores.

TEST 16 - Steel Mold: AASHTO Cure vs. Field Cure (Steam or Moist Cure)

Batch No. 1 - The mean strength of AASHTO moist-cured steel-molded cylinders is 8295 psi while the mean strength of field-steam-cured steel-molded cylinders is 7840 psi. The mean difference is 455 psi with a percent mean difference of 5.5%. The mean difference is statistically significant at the 5% level.

Batch No. 2 - The mean strength of AASHTO moist-cured steel-molded cylinders is 7912 psi and the mean strength of field-moist-cured steel-molded cylinders is 7385 psi. The mean difference is 527 psi with a percent mean difference of 6.7%. The mean difference is statistically significant at the 5% level.

There is a significant difference between the AASHTO-moist-cured and field-moist-cured steel cylinders. The average difference for both batches is approximately 6 percent, with field-cured cylinder strengths lower than AASHTO cured and transported cylinders. It is concluded that AASHTO curing methods are superior to field curing when steel molds are used.

Test 17 - Tin Mold: AASHTO (Moist) Cure vs. Field Cure (Steam or Moist Cure)

Batch No. 1 - The mean strength of AASHTO moist-cured tin-molded concrete cylinders is 7400 psi while the mean strength of field-steam-cured tin-molded cylinders is 7162 psi. The mean difference is 238 psi with a percent mean difference of 3.2%. This difference is statistically significant at the 5% level.

Batch No. 2 - The mean strength of AASHTO moist-cured tin-molded cylinders is 6881 psi and the mean strength of field-moist-cured tin-molded cylinders is 7222 psi. The mean difference is 341 psi and the percent mean difference is 5.0%. This difference is statistically significant at the 5% level.

There is a significant difference between the AASHTO moist-cured and field-moist-cured tin cylinders. Field steam curing produced cylinder strengths lower than AASHTO curing, while field moist curing produced cylinder strengths higher than AASHTO curing. Because of the conflicting results, no conclusion can be made.

Test 18 - Plastic Mold: AASHTO Cure (Moist) vs. Field Cure (Steam or Moist)

Batch No. 1 - The mean strength of AASHTO moist-cured plastic-molded cylinders is 7387 psi and the mean strength of field-steam-cured cylinders is 6683 psi. The mean difference is 704 psi with a percent mean difference of 9.5%. The mean difference is statistically significant at the 5% level.

Batch No. 2 - The mean strength of AASHTO moist-cured plastic-molded cylinders is 7078 psi and the mean strength of field-moist-cured cylinders is 6755 psi. The mean difference is 323 psi with a percent mean difference of 4.6%. This difference is statistically significant at the 5% level.

There is a significant difference between AASHTO moist curing and field moist curing of plastic cylinders. The average difference for both batches is 7 percent, with field-cured cylinder strengths lower than AASHTO-cured and transported cylinders. It is concluded that AASHTO curing methods are superior to field curing when plastic molds are used.

Test 19 - Between Batch No. 1 and No. 2: Steel Mold AASHTO Cure

The mean strength of moist-cured steel-molded concrete cylinders is 8295 psi and 7912 psi for Batch No. 1 and Batch No. 2 respectively. The mean difference is 383 psi with a percent mean difference of 4.8%. The mean difference is statistically significant at the 5% level.

There is a significant difference between Batch No. 1 and No. 2 in strength of cylinders cast in steel molds and cured according to AASHTO T23. This is likely caused by minor differences in batch proportions, materials, and mixing, placing and testing techniques.

<u>Test 20</u> - Between Batch No. 1 and No. 2: Tin Mold AASHTO Cure

The mean strength of tin-molded concrete cylinders is 7400 psi and 6881 psi for Batch No. 1 and No. 2 respectively. The mean difference is 519 psi and the percent mean difference is 7.5%. The mean difference is statistically significant at about the 5% level.

As with steel molds, there is a significant difference in strength test results.

<u>Test 21</u> - Between Batch No. 1 and No. 2: Plastic Mold AASHTO Cure

The mean strength of moist-cured plastic-molded concrete cylinders is 7838 psi for Batch No. 1 and 6881 psi for Batch No. 2. The mean difference is 309 psi with a percent mean difference of 4.4%. The mean difference is statistically significant at the 5% level.

As with steel and tin molds, there is a significant difference in strength test results. The average strength difference between batches for steel, tin, and plastic molds is 5.5 percent, with Batch No. 2 showing lower strength than Batch No. 1. This overall difference would indicate that the concrete from Batch No. 1 produced higher strengths than the concrete in Batch No. 2.

<u>Test 22</u> - Between Batch No. 1 and No. 2: Tin Mold Embedded in Slabs

The mean strength of tin-molded concrete cylinders embedded in the slabs is 8228 psi and 8542 psi for Batch No. 1 (steam-cured) and Batch No. 2 (moist-cured) slabs respectively. The mean difference is 314 psi with a percent mean difference of 3.7%. The mean difference is statistically significant at the 5% level.

There is a significant difference in strength test results between the steam-cured and moist-cured tin-molded cylinders embedded in the slabs, with Batch No. 2 showing higher strength than Batch No. 1. These results are inconsistent with the results from Test 23 and 24 below. The reason is unknown, however many embedded tin-molded cylinders were out-of-round and may have had lower than actual strength. Also, the strength of cylinders in Batch No. 1 were based on the average area of a few measured cylinders, while the strength of cylinders in Batch No. 2 were based on actual measured area of each cylinder. These differences could account for inconsistent test results.

Test 23 - Between Batch No. 1 and No. 2: 6-inch Cores

The mean strength of 6-inch cores is 7369 psi for the steam-cured slab and 6872 psi for the moist-cured slab. The mean difference is 497 psi with a percent mean difference of 7.2%. The mean difference is statistically significant at the 5% level.

There is a significant difference in strength test results between 6-inch cores taken from the two slabs. Unlike the embedded tin mold results, Batch No. 2 is lower in strength than Batch No. 1.

Test 24 - Between Batch No. 1 and No. 2: 4-inch Cores

The mean strength of 4-inch cores is 6931 psi for the steam-cured slab and 6707 psi for the moist-cured slab. The mean difference is 224 psi with a percent mean difference of 3.3%. The mean difference is not statistically significant at the 5% level.

When taken collectively, there is no consistent pattern in concrete slab strength, since tin-molded cylinders embedded in the steam-cured slab were lower in strength than the same cylinders in the moist-cured slab. Conversely, the 6-inch and 4-inch cores from the steam-cured slab had higher strength than the same cores in the moist-cured slab. Inconsistencies in the placement or vibration of the concrete in the slabs, as discussed above, may have contributed to this result.

CONCLUSIONS AND FURTHER STUDY

Based on the above comparative tests, it can be concluded that concrete cylinders cast in steel, tin, and plastic molds exhibit significantly different 28-day strengths. Steel molds produce the highest compressive strengths, and tin and plastic molds produce similar strengths about 10 percent lower than steel molds. These results confirm previous OSHD studies referenced in the Introduction. There is no significant difference in strength test results between plastic-molded and tin-molded cylinders.

There is a significant difference in strengths produced by tin molds embedded in a slab as compared to 6-inch or 4-inch cores take from the same slab. The embedded tin molds produce strengths approximately 10-20 percent higher than comparable cores.

Steel molds are representative of concrete strengths determined by embedded tin molds, but only in steam-cured slabs. However, these results need to considered in light of the inconsistent strength results for embedded tin molds. Steel molds are not representative of strength determined by 6-inch or 4-inch cores. Tin and plastic molds are representative of concrete strengths determined by 6-inch cores, but not embedded tin molds or 4-inch cores.

Cylinders obtained from tin molds embedded in concrete mass and cured with slab were a little bit out of round shape. The strength of individual cylinders from Batch No. 1 was based only on the average area of <u>some</u> cylinders. The strength of individual cylinders from Batch No. 2 was based on measured average area of each cylinder.

Field moist cured slab generated cores with no significant difference in mean strength between 4-inch and 6-inch cores while field steam cured slab did not. The mean strength of these cores is about eleven to sixteen percent lower than mean strength of moist room cured steel molded cylinders. Six-inch concrete cores from both slabs have insignificant difference in mean strength from tin and plastic molded moist room cured cylinders. This is also true for 4-inch cores from field moist cured slab while it is not for those from field steam cured slab.

ACI 318-83 states that cores tests with an average of 85% of the design strength are entirely realistic. P. Kumar Mehta, author of "<u>Concrete: Structure, Properties, and Materials</u>", mentioned in his book that core strengths are generally lower than those of standard-cured concrete cylinders. Based on this report, these statements would only be true when cores are compared to steel-molded cylinders. Core strengths from our experimental slab are lower than strengths of moist room cured steel molded cylinders. Tin and plastic molded, moist room cured cylinders do not exhibit strengths significantly different from that of cores.

Finally, it can be concluded that there is significant difference between strength of concrete cylinders as well as cores from two batches of concrete of similar proportions and same type of curing. The percent mean strength difference between each group of cylinders and cores from the two experimental batches is between three to seven percent. Although, the difference between mean strength of each group of cylinders and cores in the comparative tests is small, ranging from one and one half to eight times the standard error of the mean difference, it is statistically significant.

Like the previously referenced OSHD studies, this study does not show why cylinders cast in steel, tin or plastic molds have different strengths. Further research should be conducted to determine if the cause is due to physical or chemical interactions of the concrete and mold material.

This study does provide some information on which cylinder mold materials are most representative of in situ concrete strength as determined by cores and embedded tin molds. The authors recommend that the Oregon State Highway Division retain its current policy of using plastic cylinders as the primary means of acceptance. Concrete cores could be used to provide supplemental information when cylinder strengths are not available. If cores are used, 6-inch cores are preferable to 4-inch cores.

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TABLE I

MORSE BROTHERS HIGH-STRENGTH CONCRETE RESEARCH STUDY
SUMMARY OF CYLINDER STRENGTH DATA
BATCH # 1

	STEEL MOLD		TIN MOLD		PLASTIC MOLD		TIN MOLD	CORES	
	AASHTO CURE	FIELD CURE	AASHTO CURE	FIELD CURE	AASHTO CURE	FIELD CURE	EMBEDDED IN SLAB	6" X 12"	4" X 8"
	7730	8050	7430	7340	7250	6610	8290	7490	8020
	7590	7990	6980	7280	7130	7360	8110	7780	6320
	8700	7390	7720	7190	7580	6560	8320	7920	7470
	8280	7570	7250	7090	7480	6510	8190	7880	6720
	8410	8100	7410	7030	7040	6330	8240	7170	7200
	7820	7940	7530	7040	7270	6730	8270	7130	7020
	8310		7460		7170		8230	7630	6480
	8650		7260		7210		8060	6900	7350
	8240		7530		7370		8140	7380	6810
	8440		7380		7510		8020	7030	6930
	8130		7660		7550		8350	7350	6840
	8640		7260		7780		8070	7360	6520
	8350		7440		7660		8340	7350	6610
	8910		7340		7120		8330	7480	6620
	8230		7350		7690		8350	6810	7060
							8340	7250	
SAMPLE SIZE	15	6	15	6	15	6	16	16	15
SAMPLE MEAN	8295	7840	7400	7162	7387	6683	8228	7369	6931
STANDARD DEVIATION	369	290	180	130	236	357	115	325	444
COEFF. OF VARIANCE	4.45	3.7	2.43	1.82	3.19	5.34	1.4	4.41	6.41
STD. ERROR OF THE MEAN	95.28	118.39	46.48	53.07	60.93	145.7	28.8	81.25	114.64
$t_{.05}$	2.145	2.571	2.145	2.571	2.145	2.571	2.131	2.131	2.145
POP. MEAN AT 5% LEVEL OF CONFIDENCE	8295 ±204	7840 ±304	7400 ±100	7162 ±136	7387 ±131	6683 ±375	8228 ±61	7369 ±173	6931 ±246

TABLE II

MORSE BROTHERS HIGH-STRENGTH CONCRETE RESEARCH STUDY
SUMMARY OF CYLINDER STRENGTH DATA
BATCH # 2

	STEEL MOLD		TIN MOLD		PLASTIC MOLD		TIN MOLD	CORES	
	AASHTO CURE	FIELD CURE	AASHTO CURE	FIELD CURE	AASHTO CURE	FIELD CURE	EMBEDDED IN SLAB	6" X 12"	4" X 8"
	7840	7980	6890	7060	7200	6650	8200	6390	6220
	7860	7590	6830	7460	7250	6830	8320	6330	6720
	7480	6940	6940	7540	6980	7010	8160	6950	7690
	8700	7050	6860	7460	6920	6580	8390	6930	6370
	7700	7470	6640	6940	7070	6610	8910	6930	6700
	7810	7280	6990	6870	7070	6850	8770	7590	6990
	7980		7050		7350		9090	7100	7380
	8770		6690		6700		8850	6740	7000
	7710		6890		6730		9670	7760	6780
	7630		6900		6950		8540	7230	6170
	8100		6920		7180		8610	6730	6580
	7530		6690		7310		8540	6760	5880
	7640		6990		7090		8210	6980	6090
	7910		7320		7040		8190	7240	6880
	8020		6620		7330		7950	6430	7150
							8270	5860	
SAMPLE SIZE	15	6	15	6	15	6	16	16	15
SAMPLE MEAN	7912	7385	6881	7222	7078	6755	8542	6872	6707
STANDARD DEVIATION	378	381	180	298	201	169	436	479	503
COEFF. OF VARIANCE	4.78	5.15	2.61	4.13	2.83	2.5	5.11	6.97	7.49
STD. ERROR OF THE MEAN	97.56	155.41	46.43	121.67	51.77	68.88	109.04	119.72	129.78
t.05	2.145	2.571	2.145	2.571	2.145	2.571	2.131	2.131	2.145
POP. MEAN AT 5% LEVEL OF CONFIDENCE	7912 ±209	7385 ±400	6881 ±100	7222 ±313	7078 ±111	6755 ±177	8542 ±232	6872 ±255	6707 ±278

TABLE III

SUMMARY OF STATISTICAL ANALYSIS OF CYLINDER STRENGTH DATA
BATCH # 1

TEST	CYLINDER GROUP	SAMPLE MEAN	STANDARD DEVIATION	MEAN DIFF	% MEAN DIFF	STD ERR OF MEAN DIFF	OBSERVED t VALUE	SIGNIFICANT DIFF AT 5% LEVEL?
1	STEEL MOLD AASHTO	8295	369					
	TIN MOLD AASHTO	7400	180	895	10.79	106.01	8.443	YES
2	STEEL MOLD AASHTO	8295	369					
	PLASTIC MOLD AASHTO	7387	236	908	10.95	113.09	8.029	YES
3	TIN MOLD AASHTO	7400	180					
	PLASTIC MOLD AASHTO	7387	236	13	0.18	76.64	0.17	NO
4	STEEL MOLD AASHTO	8295	369					
	TIN MOLD IN SLAB	8228	115	67	0.81	96.82	0.692	NO
5	TIN MOLD AASHTO	7400	180					
	TIN MOLD IN SLAB	8228	115	-828	-11.1	53.89	15.365	YES
6	PLASTIC MOLD AASHTO	7387	236					
	TIN MOLD IN SLAB	8228	115	-841	-11.3	66	12.742	YES
7	CORES 6"	7369	325					
	CORES 4"	6931	444	438	5.94	139.1	3.149	YES
8	STEEL MOLD AASHTO	8295	369					
	CORES 6"	7369	325	926	11.16	124.69	7.426	YES
9	STEEL MOLD AASHTO	8295	369					
	CORES 4"	6931	444	1364	16.44	149.06	9.15	YES
10	TIN MOLD AASHTO	7400	180					
	CORES 6"	7369	325	31	0.42	95.27	0.325	NO
11	TIN MOLD AASHTO	7400	180					
	CORES 4"	6931	444	469	6.34	123.7	3.791	YES
12	PLASTIC MOLD AASHTO	7387	236					
	CORES 6"	7369	325	18	0.24	102.61	0.175	NO
13	PLASTIC MOLD AASHTO	7387	236					
	CORES 4"	6931	444	456	6.17	129.83	3.512	YES
14	TIN MOLD IN SLAB	8228	115					
	CORES 6"	7369	325	859	10.44	86.19	9.967	YES
15	TIN MOLD IN SLAB	8228	115					
	CORES 4"	6931	444	1297	15.76	114.79	11.299	YES
16	STEEL MOLD AASHTO	8295	369					
	STEEL MOLD FIELD	7840	290	455	5.49	169.04	2.692	YES
17	TIN MOLD AASHTO	7400	180					
	TIN MOLD FIELD	7162	130	238	3.22	81.29	2.928	YES
18	PLASTIC MOLD AASHTO	7387	236					
	PLASTIC MOLD FIELD	6683	357	704	9.53	131.92	5.337	YES

TABLE IV

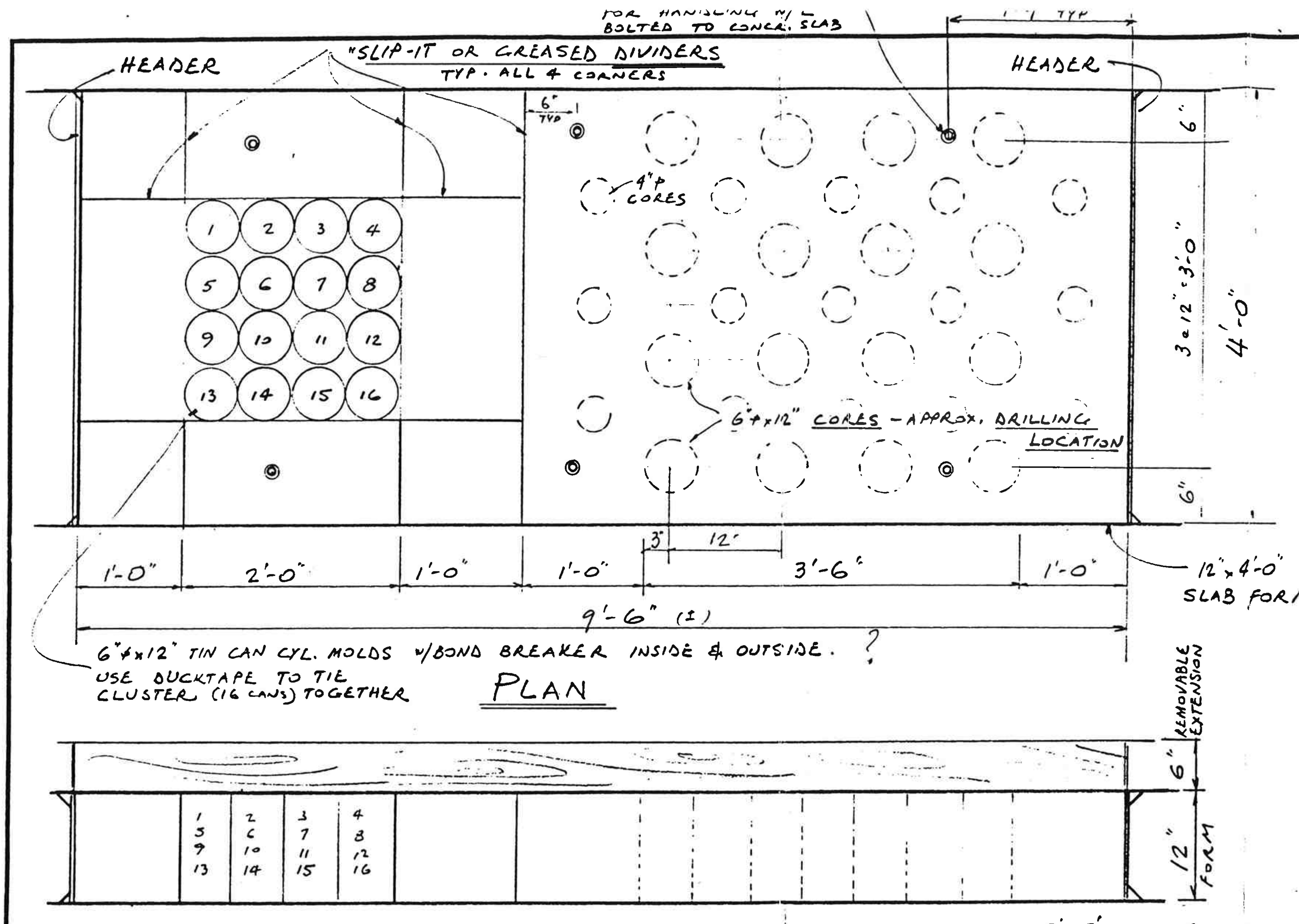
SUMMARY OF STATISTICAL ANAYLYSIS OF CYLINDER STRENGTH DATA
BATCH # 2

TEST	CYLINDER GROUP	SAMPLE MEAN	STANDARD DEVIATION	MEAN DIFF	% MEAN DIFF	STD ERR OF MEAN DIFF	OBSERVED t VALUE	SIGNIFICANT DIFF AT 5% LEVEL?
1	STEEL MOLD AASHTO	7912	378					
	TIN MOLD AASHTO	6881	180	1031	13.03	108.1	9.537	YES
2	STEEL MOLD AASHTO	7912	378					
	PLASTIC MOLD AASHTO	7078	201	834	10.54	110.54	7.545	YES
3	TIN MOLD AASHTO	6881	180					
	PLASTIC MOLD AASHTO	7078	201	-197	-2.86	69.67	2.828	YES
4	STEEL MOLD AASHTO	7912	378					
	TIN MOLD IN SLAB	8542	436	-630	-7.96	147	4.286	YES
5	TIN MOLD AASHTO	6881	180					
	TIN MOLD IN SLAB	8542	436	-1661	-24.1	121.33	13.69	YES
6	PLASTIC MOLD AASHTO	7078	201					
	TIN MOLD IN SLAB	8542	436	-1464	-20.6	123.37	11.867	YES
7	CORES 6"	6872	479					
	CORES 4"	6707	503	165	2.4	176.37	0.936	NO
8	STEEL MOLD AASHTO	7912	378					
	CORES 6"	6872	479	1040	13.14	155.69	6.68	YES
9	STEEL MOLD AASHTO	7912	378					
	CORES 4"	6707	503	1205	15.23	162.46	7.417	YES
10	TIN MOLD AASHTO	6881	180					
	CORES 6"	6872	479	9	0.13	131.72	0.068	NO
11	TIN MOLD AASHTO	6881	180					
	CORES 4"	6707	503	174	2.53	137.94	1.261	NO
12	PLASTIC MOLD AASHTO	7078	201					
	CORES 6"	6872	479	206	2.91	133.6	1.542	NO
13	PLASTIC MOLD AASHTO	7078	201					
	CORES 4"	6707	503	371	5.24	139.86	2.653	YES
14	TIN MOLD IN SLAB	8542	436					
	CORES 6"	6872	479	1670	19.55	161.93	10.313	YES
15	TIN MOLD IN SLAB	8542	436					
	CORES 4"	6707	503	1835	21.48	168.75	10.874	YES
16	STEEL MOLD AASHTO	7912	378					
	STEEL MOLD FIELD	7385	381	527	6.67	182.97	2.88	YES
17	TIN MOLD AASHTO	6881	180					
	TIN MOLD FIELD	7222	298	-341	-4.96	104.99	3.248	YES
18	PLASTIC MOLD AASHTO	7078	201					
	PLASTIC MOLD FIELD	6755	169	323	4.56	93.27	3.463	YES

TABLE V

SUMMARY OF STATISTICAL ANAYLYSIS OF CYLINDER STRENGTH DATA
BATCH # 1 vs BATCH # 2

TEST	CYLINDER GROUP	SAMPLE MEAN	STANDARD DEVIATION	MEAN DIFF	% MEAN DIFF	STD ERR OF MEAN DIFF	OBSERVED t VALUE	SIGNIFICANT DIFF AT 5% LEVEL?
19	STEEL MOLD AASHTO #1	8295	369					
	STEEL MOLD AASHTO #2	7912	378	383	4.84	136.39	2.808	YES
20	TIN MOLD AASHTO #1	7400	180					
	TIN MOLD AASHTO #2	6881	180	519	7.54	65.73	7.896	YES
21	PLASTIC AASHTO #1	7387	236					
	PLASTIC AASHTO #2	7078	201	309	4.37	80.04	3.861	YES
22	TIN MOLD IN SLAB #1	8228	115					
	TIN MOLD IN SLAB #2	8542	436	-314	-3.68	112.73	2.785	YES
23	CORES 6" #1	7369	325					
	CORES 6" #2	6872	479	497	7.23	144.71	3.434	YES
24	CORES 4" #1	6931	444					
	CORES 4" #2	6707	503	224	3.34	173.23	1.293	NO



ELEVATION

APPROX VOLUME: 9.5x1.5' SLAB = 57 cu.ft

3x15 ASTM
3x6 STEAM CYL = 63 CYLINDERS 13" / 70 "

2.59 cu yards + waste SAY 3 cu. YARDS

TEST PROGRAM SEQUENCE

1. SET UP SYSTEM IN 12" SLAB BED.
2. PROVIDE HEADERS DIVIDERS, 16 pcs of 6"⌀x12" TIN MOLDS, AND 6" SLAB DEEPENING FORM
3. PLACE TIN MOLDS IN PRE-DRAWN LOCATIONS. TIE THE CLUSTER TOGETHER W/DUCKT TAPE. SPOT WELD 1, 4, 13, 16 MOLDS TO FORM.
4. PLACE ALL DIVIDERS AND SLAB EXTENSION TO PROPER LOCATION - USE BOND BREAKER
5. USE 7.5 SACK CONC. MIX, NO AIR 2"-3" SLUMP.
6. FILL UP 18" DEPTH IN THREE 6" LIFT. USE EXTERNAL AND INTERNAL VIBRATION STARTING AT SECOND LIFT. ? always done
7. MAKE 15 TEST CYL. STEEL + 15 TIN + 15 " " PLASTIC FROM THE SAME CONC. AS 18" SLAB. ODOT FURNISH CYL. AND CURED BY ASTM METHOD. SEE ALSO ITEM 13.
8. AFTER COMPLETING 18" DEEP SLAB POUR, REMOVE TOP 6" EXTENSION FORM AND TAKE OFF CAREFULLY EXTRA 6" CONC. AT TOP
9. FINISH (SMOOTH TROWEL) TOP SURFACE OF 12" SLAB
10. COVER SLAB, WAIT 3½-4 HRS. SETTING TIME AND STEAM CURE BY PLANT PRACTICE. 4-15- TEST ONL
11. AFTER STEAM CURING SLAB COVER W/VISQUEEN AND INSUL FOR 28 DAYS ? NO
12. ITEM 7. CYLINDERS WILL BE CURED BY ASTM. METHOD
13. MAKE 6 TEST CYL. STEEL + 6 CYL TIN + 6 CYL PLASTIC MOLD

STEAM CURE & STORE WITH SLAB. APR. 15 TEST ONLY, ODOT PROVIDE TIN & PLASTIC MOLDS. MORSE - STEEL MOLDS. ODOT WILL BREAK 28 DAY CYL. 4-15- TEST ONLY

APPROVED	DRAWN: G. L. DATE: 4-6-87	MORSE BROS. PRESTRESS, INC. P.O. Box 181, Harrisburg, Oregon 97446	ODOT CONCRETE VS CYL. MOLDS TEST PROGRAM
	CHECKED: DATE:		

2 TESTS APR. 15 '87 - SLAB STEAM. CURED
APR. 22 '87 - SLAB ASTM. CURED