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Also presented are analyses and discussions on the following related subjects:

1) Prediction of flexural strength from compressive strength;

2) Use of the air meter base for determining unit weight;

3) Use of the K-Meter for measuring concrete consistency.

4) Precision of the cement factor determination.

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DIVISION OF STRUCTURES & ENGINEERING SERVICES
OFFICE OF TRANSPORTATION LABORATORY

November 1976

FHWA No. F-4-20
TL No. 631153

Mr. C. E. Forbes
Chief Engineer

Dear Sir:

I have approved and now submit for your information this interim research project report titled:

PRECISION OF SELECTED
CONCRETE
TEST METHODS

Study made by . . . . General Services Branch

Under the Supervision of . . . . W. H. Ames, P.E.

Principal Investigator . . . . P. E. Benson, P.E.

Co-Investigators . . . . R. R. Trimble, P.E.
C. R. Sundquist, P.E.

Report Prepared by . . . . P. E. Benson, P.E.

Very truly yours,

GEORGE A. HILL, P.E.
Chief, Office of Transportation Laboratory

Attachment

PEB:lb

ACKNOWLEDGEMENTS

Without the facilities and materials found at a modern-day concrete batch plant the controlled experiments described in this report would have been almost impossible to carry out. The author wishes to thank Mr. B. Godfrey (Teichart Aggregates) and Mr. Everett Osgood (Graniterock) for arranging for use of these facilities and coordinating plant operations. Thanks also go to the operators who diligently carried out their testing assignments even though experiments sometimes lasted longer than anticipated. Participants from Translab included Messrs. Don Smith, Dave Nakao and Hideyo Hashimoto. Operators with much field experience were recruited from Districts 4, 6 and the Bridge Department (now Division of Structures).

This project was conducted in cooperation with the Federal Highway Administration under Agreement No. F-4-20. The contents of this report reflect the views of the Transportation Laboratory which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

TABLE OF CONTENTS

INTRODUCTION

During the past two years a series of studies have been made by the California Transportation Laboratory to determine the precision of some of the more common test methods used for controlling the quality of portland cement concrete. Several of these studies were based on available job control records while the others involved detailed field experiments. This report will summarize the procedures followed and results obtained for the test methods studied, thereby promoting better understanding of testing reliability in this field.

The test methods covered by the report are: Air Content (No. Calif. 504-C), Unit Weight of Fresh Concrete (No. Calif. 518-E), Compressive Strength of Molded Concrete Cylinders (No. Calif. 521-C), Ball Penetration (No. Calif. 533-A), and Flexural Strength (AASHTO Des. T97). Precision statements are determined for each of these test methods, and other pertinent findings are also reported. For instance, an analysis on the use of the air meter base for unit weight determinations is made, and the feasibility of predicting flexural strength from compressive strength is evaluated.

The acceptable range of two test results (D2S) is used as the standard measure of test precision. The parameter can be described as the difference between two test results that would be equaled or exceeded by only 1 case in 20 for a given set of conditions. These conditions define the type of precision statement: single-operator or multi-operator.

Single-operator precision considers the acceptable difference between repetitive determinations made on identical portions of material by the same operator. Multi-operator precision is a measure of the same difference, but includes the variabilities introduced by different operators and equipment. Where possible, the total test variability has been resolved into the following components: operator technique, equipment and residual. The residual component includes all errors not accounted for by the systematic effects of operator and equipment. The relative contributions of these components will show whether improved calibration procedures, tighter test method specifications, or better training programs for operators are needed to improve test precision.

FINDINGS AND CONCLUSIONS

Concrete Compressive Strength

The precision of this test method was found to vary linearly with compressive strength over the range studied. This is reflected in Table 1 which lists the single-operator and multi-operator precision statements for different ranges of compressive strength. Also given are the basic statistical parameters of variance and its square root, the standard deviation (see Glossary for definitions).

The coefficient of variation is often used as a measure of concrete compressive strength variability. The concept that this single value can accurately describe the variability of a process throughout its range holds true only if, coincidently, the slope of the variability function, in this case precision versus compressive strength, equals the coefficient of variation in decimal form (see proof in Appendix). Since this was not

TABLE 1

PRECISION STATEMENT TABULATION

COMPRESSIVE STRENGTH OF CONCRETE CYLINDER

Single-Operator Precision

Compressive Strength (psi)	Variance	Standard Deviation	Acceptable Range of Two Results
3500	16860	129.9	367
4000	21310	146.0	413
4500	26270	162.1	458
5000	31760	178.2	504
5500	37770	194.3	550
6000	44290	210.5	595

Multi-Operator Precision

Compressive Strength (psi)	Variance	Standard Deviation	Acceptable Range of Two Results
3500	65890	256.7	726
4000	74430	272.8	772
4500	83490	288.9	817
5000	93060	305.1	863
5500	103160	321.2	908
6000	113780	337.3	954

exactly the case it was felt that a tabular presentation would give a more accurate picture of test precision as a function of compressive strength.

A study of equipment tolerances and results from a cylinder fabrication class revealed the following precision components for cylinders tested at age 28 days. Two cylinders were fabricated by each operator from the same large batch of concrete.

Operator Technique and Sampling	65%
Equipment	5%
Residual	30%

Intrusive sampling errors are the most probable cause of the large operator component of variance. Unfortunately, these sampling errors, caused by the large lot size required for a multi-operator experiment, are inseparable from the between operator error for the available data. The very small amount of equipment induced error indicates that improvements in test precision can best be effected by more tests per sample, not by better equipment.

Concrete Flexural Strength

It should be noted that the flexural strength test method (AASHTO Des. T97) studied in this report involves a third point loading pattern on a 6" x 6" x 20" concrete beam fabricated and tested under laboratory conditions. While certain general comparisons between this test and the common compression test used in the field (No. Calif. 522-B) may be made, the precision estimates should not be considered identical.

As with the compressive strength test, the precision of the flexural strength method was found to be directly proportional to the flexural strength of the concrete. This type of behavior is most likely attributable to the relative abundance of potential failure planes for low strength material as opposed to the unique modes of failure found in high strength material (the former being less sensitive to aberrant specimen properties than the latter). Table 2 shows the single-operator precision for the flexural strength test. Neither multi-operator nor multi-laboratory sources of error were obtainable from the information at hand.

Because cylinders had been made from the same batch of concrete used to fabricate the flexure beams, a correlation between the two related parameters of compressive (f_c) and flexural (f_t) strength was possible. The overall correlation of the two variables yielded the following linear relation: $f_t = 258 + (0.0867)f_c$ (see Figure 1). This result agreed quite closely with a prior study done by Clyde E. Kesler in 1954 (10). It was not considered satisfactory for predicting flexural from compressive strength, however, since the aggregate properties of size, surface texture, strength, coatings and shape, and the mortar properties of bond and cube strength can significantly affect the relation between f_c and f_t (1, 2, 13). Analyses showed that at least 7 and possibly 19 of the 32 sources studied in this project would have had their material's flexural strength predicted incorrectly had the overall equation been used. It is readily apparent from these numbers that any accurate prediction of flexural strength from compressive strength must take into account numerous influencing parameters, a study of which is beyond the scope of this project. Satisfactory results can be obtained for a particular aggregate and cement mixture, however, by correlating 10 cylinder and beam

TABLE 2

PRECISION STATEMENT TABULATION

CONCRETE FLEXURAL STRENGTH

Single Break Precision

Flexural Strength (psi)	Variance	Standard Deviation	Acceptable Range of Two Results
400	445	21.1	60
450	591	24.3	69
500	757	27.5	78
550	944	30.7	87
600	1152	33.9	96
650	1381	37.2	105
700	1630	40.4	114

Average of 2 Breaks

Flexural Strength (psi)	Variance	Standard Deviation	Acceptable Range of Two Results
400	222	14.9	42
450	295	17.2	49
500	379	19.5	55
550	472	21.7	61
600	576	24.0	68
650	690	26.3	74
700	815	28.5	81

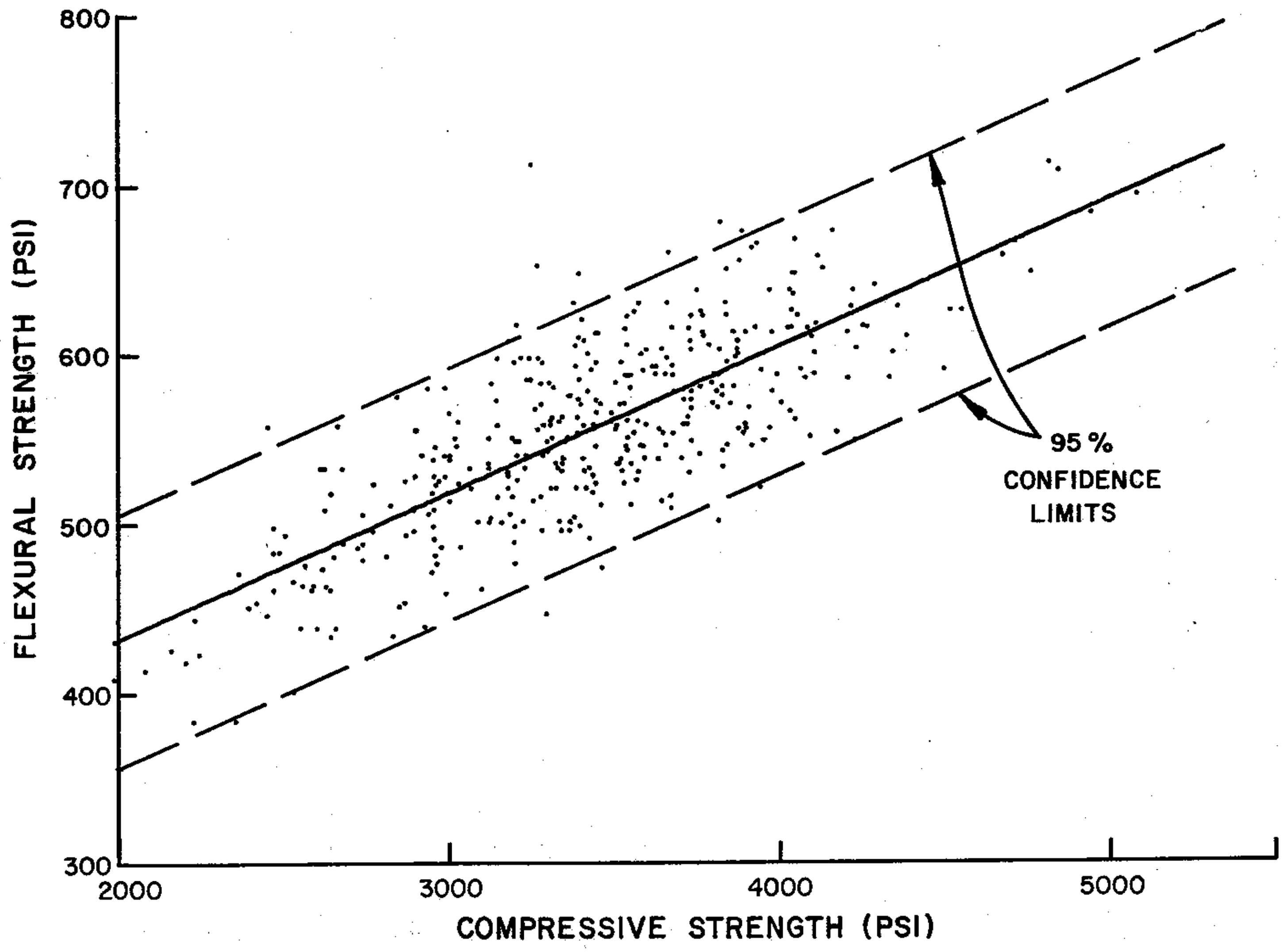

Fig. 1 CORRELATION BETWEEN FLEXURAL AND COMPRESSIVE STRENGTH

pairs over the range of values expected to be encountered. Each result should be the average of 2 replicate cylinder or beam breaks. It is reasonable to expect that subsequent flexural strength predictions made from replicate cylinder breaks will be within ±30 psi of the tested flexural strength 95% of the time. This confidence interval was determined by using the pooled mean square error for regression analyses performed on each source.

Air Content of Fresh Concrete

As has occurred in the previously discussed tests, the precision of the air content test was shown to be directly related to the amount of air being measured. At higher air contents testing errors were magnified. A full tabulation of test precision values at evenly incremented air contents is given in Table 3.

The sources of error for multi-operator precision were distributed as follows:

Operator Technique	30%
Equipment	30%
Residual	40%

Note that the operator and equipment errors are well balanced so that if the precision of this test was found inadequate, no one source of error could be considered at fault without further investigation.

Unit Weight of Fresh Concrete

In analyzing the results from this experiment it was obvious that the precision of the test varied as a function of some parameter. Three possibilities were studied: 1) concrete

TABLE 3

PRECISION STATEMENT TABULATION

% AIR CONTENT OF FRESH CONCRETE

Single-Operator Precision

Air Content	Variance	Standard Deviation	Acceptable Range of Two Results
1.0	.0093	.096	.27
2.0	.0138	.117	.33
3.0	.0191	.138	.39
4.0	.0254	.159	.45
5.0	.0325	.180	.51
6.0	.0405	.201	.57

Multi-Operator Precision

Air content	Variance	Standard Deviation	Acceptable Range of Two Results
1.0	.0238	.154	.44
2.0	.0353	.188	.53
3.0	.0490	.221	.63
4.0	.0650	.255	.72
5.0	.0832	.289	.82
6.0	.1037	.322	.91

consistency (as measured by the penetrometer), 2) air content, and 3) unit weight. Of these three, unit weight correlated best with the observed changes in precision. At low unit weights the precision of the test was significantly better than at high unit weights. Magnification of calibration and tare weight errors as a function of unit weight probably account for this behavior. Table 4 summarizes these findings over the range of materials studied.

The distribution of error types for the unit weight test ran as follows:

Operator Technique	30%
Equipment	40%
Residual	30%

The overall multi-operator error was much smaller than expected. This is attributable to the fact that a single operator using one set of scales calibrated all of the buckets. Considering the limitations of the equipment (scales read to nearest 0.1 lb.), one would expect the multi-operator D2S limits to have been three times larger than measured if each operator had calibrated his own equipment after each test result. Therefore, to maintain the level of multi-operator precision shown in Table 4, tare weights and calibration factors would have to be determined by using scales accurate to the nearest 0.02 lb. If this were done, both the precision and accuracy of the test method would be enhanced.

The experiment to determine the precision of the unit weight and air content tests also gave the opportunity to compare unit weight determinations made by the unit weight bucket and the smaller air meter base (1/4 cu.ft.). The method of placing and rodding the concrete was the same for both containers.

TABLE 4

PRECISION STATEMENT TABULATION

UNIT WEIGHT (1/2 CUBIC FOOT UNIT WEIGHT BUCKET)

Single-Operator Precision

Unit Weight	Variance	Standard Deviation	Acceptable Range of Two Results
140	.04	.19	.5
142	.06	.25	.7
144	.10	.31	.9
146	.14	.37	1.0
148	.18	.43	1.2
150	.24	.49	1.4
152	.30	.55	1.6
154	.37	.61	1.7
156	.44	.67	1.9
158	.53	.73	2.1
160	.62	.79	2.2

Multi-Operator Precision

Unit Weight	Variance	Standard Deviation	Acceptable Range of Two Results
140	.13	.36	1.0
142	.22	.47	1.3
144	.34	.58	1.6
146	.48	.69	2.0
148	.64	.80	2.3
150	.84	.91	2.6
152	1.05	1.03	2.9
154	1.30	1.14	3.2
156	1.56	1.25	3.5
158	1.85	1.36	3.9
160	2.17	1.47	4.2

Results using the air meter base were not as precise as those from the larger unit weight bucket, but did follow the same pattern of better precision at lower unit weights (see Table 5). The difference in precision between the methods was probably caused by two factors: 1) the smaller sample size of the air meter base allowing material inconsistencies to have a greater effect on the test result variability, and 2) the air meter base's higher calibration factor magnifying errors to a greater extent than the 1/2 cubic foot unit weight bucket's calibration factor.

The precision differential between the two methods could be eliminated by making two air meter base determinations for the unit weight and averaging them. This would take little or no additional time if an air content test was going to be made anyway. Since results from the experiment show no significant difference between answers obtained by the two methods on the same concrete there should be no difference in the level of quality obtained by using either method.

The primary use of unit weight results is in the computation of sacks of cement per cubic yard of concrete. This cement factor, as it is called, is a function of unit weight, total batch weight and pounds of cement in the batch. By using the precision of the unit weight test and estimating the precision of the batching scales, an evaluation of the precision of the cement factor can be made. This evaluation will be somewhat lower than expected, however, since a homogeneously mixed batch is assumed.

A generalized presentation of cement factor precision values would be impractical since the unit weight precision, batch weight precision, batch size, unit weight and nominal cement

TABLE 5

PRECISION STATEMENT TABULATION

UNIT WEIGHT (AIR METER BASE)

Single-Operator Precision

Unit Weight	Variance	Standard Deviation	Acceptable Range of Two Results
140	.14	.37	1.0
142	.18	.43	1.2
144	.24	.49	1.4
146	.31	.55	1.6
148	.38	.61	1.7
150	.46	.68	1.9
152	.54	.74	2.1
154	.64	.80	2.3
156	.74	.86	2.4
158	.85	.92	2.6
160	.97	.98	2.8

Multi-Operator Precision

Unit Weight	Variance	Standard Deviation	Acceptable Range of Two Results
140	.37	.61	1.7
142	.50	.71	2.0
144	.66	.81	2.3
146	.83	.91	2.6
148	1.03	1.02	2.9
150	1.25	1.12	3.2
152	1.49	1.22	3.5
154	1.75	1.32	3.7
156	2.03	1.42	4.0
158	2.33	1.53	4.3
160	2.65	1.63	4.6

content all affect the precision of the cement factor. Instead, a typical concrete batch was considered: 6 sacks per cu. yd., 7 cubic yards, 150 lbs./ft^3. Table 6 shows the single-operator and multi-operator cement factor precision for this type of a batch using increasingly less precise batching scales. It is important to note that Case I was designed such that scale errors and unit weight errors contributed equally to the overall error.

Two important conclusions can be made by studing this table. First, that improvements in batch scale sensitivity beyond that shown in Case II have a negligible effect on cement factor precision. Second, that cement factor precision is much more responsive to changes in unit weight precision (i.e. single-operator to multi-operator) than batch scale sensitivity. Therefore, improvements in unit weight precision would have a direct and dramatic effect on the precision of cement factor determination.

Penetration of Fresh Concrete

The precision of the penetration test is given as a function of penetration values in Table 7. These precision values apply to the average of three penetration readings as called for by the test method. Observations indicate that high penetration results tend to be more sensitive to the rate of release of the ball penetration apparatus than low results. This would explain the change in test precision shown in Table 7.

The Ball Penetration Test Method specifies that all three individual readings be within 1" penetration of each other. Using the standard deviations for single-operator precision of individual results shown in Table 8 and the distribution of the relative range for a sample size of 3 (7), the expected

TABLE 6 CEMENT FACTOR PRECISION
(7 YD., 6 SACK MIX, 150 lbs/ft^3)

CASE	BATCH SCALE SENSITIVITY (LBS./DIV.)		CEMENT FACTOR PRECISION* (SK./YD.)	
	AGG. & WATER	CEMENT	SINGLE-OPERATOR	MULTI-OPERATOR
1	5	1	0.0559	0.1049
2	20	3	0.0561	0.1050
3	200	50	0.0775	0.1178

* D2S LIMIT

TABLE 7

PRECISION STATEMENT TABULATION

PENETRATION TEST FOR FRESH CONCRETE (IN.)
AVERAGE OF 3 PENETRATIONS

Single-Operator Precision

Ball Penetration	Variance	Standard Deviation	Acceptable Range of Two Results
.5	.01	.11	.3
1.0	.02	.14	.4
1.5	.03	.17	.5
2.0	.04	.19	.5
2.5	.05	.22	.6
3.0	.06	.25	.7
3.5	.08	.28	.8
4.0	.09	.31	.9

Multi-Operator Precision

Ball Penetration	Variance	Standard Deviation	Acceptable Range of Two Results
.5	.01	.11	.3
1.0	.02	.14	.4
1.5	.03	.17	.5
2.0	.04	.20	.6
2.5	.05	.23	.6
3.0	.07	.26	.7
3.5	.08	.29	.8
4.0	.10	.32	.9

maximum range can be computed. This range would normally be exceeded only 95% of the time. For nominal penetrations of 2 inches or less this range is within the 1 inch tolerance specified. For 4 inch penetration concrete, however, ranges of slightly greater than 1-1/2 inches can be expected to occur under normal conditions. Therefore, a more realistic tolerance might be 1-1/2 inches. The standard deviations in Table 8 reaffirm the appropriateness of measuring ball penetration to the nearest 1/4 inch.

The approximate distribution of error types for the penetration test was as follows:

Operator Technique and Equipment	5%
Residual	95%

The operator and equipment errors were almost immeasurable despite the fact that operators were told not to collaborate on techniques, and ball weights varied over a range of 0.18 lb. This indicates that the test is in good control and that most of the testing error stems from variations in concrete consistency between replicate test sites. The test method specification which calls for ball penetration apparatus not to deviate from their standard weight more than ± 0.1 lb. is obviously quite adequate.

A new device for measuring concrete consistency was included as part of the experiment on the precision of the penetration test. This device, called a K-Meter, is shown in Figure 2. The K-Meter measures the amount of concrete mortar that will flow into its perforated tube in 60 seconds. Results are read directly in inches of slump according to the manufacturer.

TABLE 8

PRECISION STATEMENT TABULATION

PENETRATION TEST FOR FRESH CONCRETE (IN.)
INDIVIDUAL RESULTS

Single-Operator Precision

Ball Penetration	Variance	Standard Deviation	Acceptable Range of Two Results
.5	.03	.17	.5
1.0	.05	.22	.6
1.5	.07	.27	.8
2.0	.10	.31	.9
2.5	.13	.36	1.0
3.0	.16	.40	1.1
3.5	.20	.45	1.3
4.0	.24	.49	1.4

Multi-Operator Precision

Ball Penetration	Variance	Standard Deviation	Acceptable Range of Two Results
.5	.03	.18	.5
1.0	.05	.22	.6
1.5	.07	.27	.8
2.0	.10	.31	.9
2.5	.13	.36	1.0
3.0	.16	.40	1.1
3.5	.20	.45	1.3
4.0	.25	.50	1.4

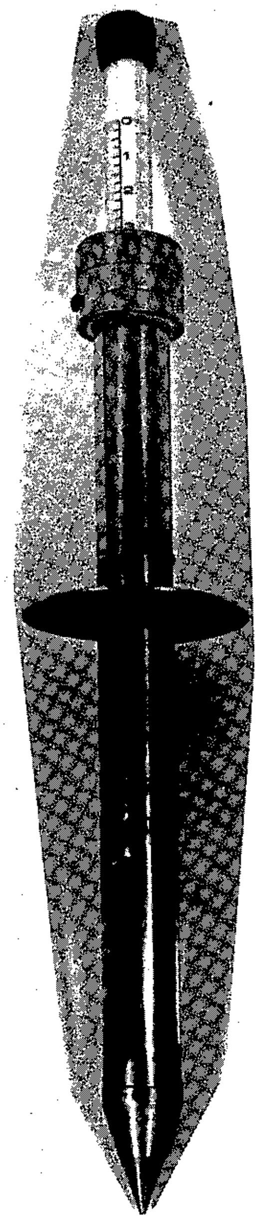

Fig. 2 K-Meter.

Penetration and K-Meter readings were correlated and the precision and sensitivity of the two methods compared. There was a definite correlation established between K-Meter and penetration results for the several methods of using the K-Meter that were tried. Both the precision and sensitivity of the K-Meter Test, however, proved inferior to the penetration test, particularly because 3 penetration readings could be taken and averaged in the amount of time required to run one K-Meter Test.

Other miscellaneous findings regarding the K-Meter Test were as follows: 1) rodding the concrete before inserting the K-Meter gave markedly erratic results, 2) inserting the K-Meter deeply into the concrete gave significantly higher results, 3) small aggregate particles easily clogged the tube perforations, and 4) during insertion large particles sometimes pushed ahead of the tube, creating a void around the perforations. This problem, noted most frequently for 1-1/2" maximum concrete, tended to give erroneously low readings.

The findings of this report show that the K-Meter's overall sensitivity is inferior to that of the ball penetration apparatus. However, other applications for the K-Meter such as measurement of grout consistency and measurement of concrete consistency at test sites inaccessible to the ball penetration apparatus should be investigated.

RECOMMENDATIONS

It is recommended that:

1) An evaluation of overall test result variability (materials, sampling and testing variability) be made for the test methods studied herein. Comparisons between this overall variability and the test precision will tell if improvements in the test should be made.

2) A separate section on test precision be added to the text of each of the test methods studied in this report.

3) A detailed study of test precision be required for new concrete test methods before their adoption.

IMPLEMENTATION

The findings of this report have been conveyed to the Concrete Branch of the Transportation Laboratory. They agree with the recommendations and as funds become available will endeavor to implement them. In particular, as test methods that have been covered by this study come up for review a new section on precision will be added to their text.

DESCRIPTION OF WORK

Precision statements for the test methods studied in this report were obtained in either of two ways: 1) analysis of existing job control and research records, or 2) analysis of data from field experiments designed specifically for the determination of test precision. As expected, the second type of analysis yielded more comprehensive results regarding test precision.

The compressive strength and flexural strength studies were both based on existing records. For compressive strength, most of the data was obtained from replicated 28 day contract control tests. The remainder came from various research projects. A total of almost 2,000 cylinder breaks were compiled and analyzed. All of this data, except a small portion, yielded single-operator precision only. Multi-operator precision was based on relatively few tests (about 60 cylinder breaks) from a certification class in cylinder fabrication conducted in 1970.

Replicated flexural strength breaks were found in good quantity in the records for Test Method No. Calif. 536-A (Cement Content for PCC Pavements). A total of 760 beam breaks performed during the period 1969 to 1974 were studied. Unfortunately, none of the results included multi-operator sources of variation. Corresponding compressive strength results were also part of this data.

Since the data for the flexural and compressive strength precision studies already existed, only compilation and analysis were needed to obtain a precision estimate. For the remaining test methods, however, experiments had to be designed and completed before the compilation and analysis phase was reached.

The initial unit weight and air content experiment was performed in August 1973 at Teichert Aggregates' Perkins Plant in Sacramento. The experiment involved 4 operators using 4 different sets of equipment, and was run over a 3-day period. Each day two 1-yard batches of concrete were prepared and loaded into a small transit mixer. The operators, all experienced personnel, were instructed to run tests according to their normal procedure and not to collaborate in any way. All equipment had been calibrated in the laboratory about a week before the tests began.

An amount of concrete sufficient to run 4 unit weight and 4 air content tests was taken from the mixer and placed into a large tub (see Figure 3). The 4 operators, using the same sets of equipment each time, randomly chose their material from the tub and simultaneously made unit weight determinations (see Figure 4). After completing this test and reporting their results, they filled their air buckets according to test method specifications and weighed bucket, concrete and glass plate for a second unit weight result. The glass plate was then removed

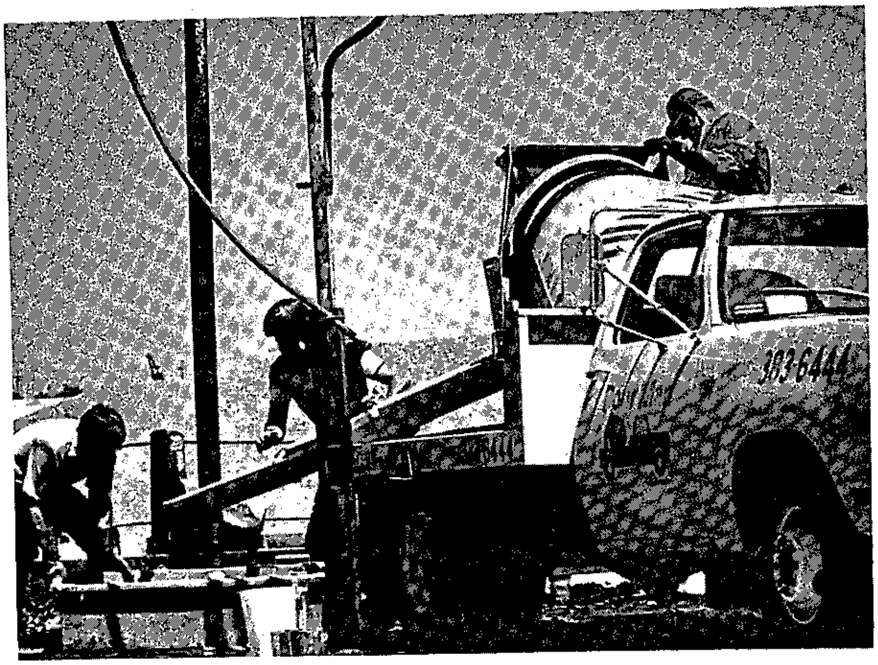

Fig. 3 Filling the Tub with Concrete.

Fig. 4 Four Operators Making Unit Weight Determinations Simultaneously.

and the operators proceeded to determine the air content of the concrete already in the bucket. After this, all equipment was washed, scales were recalibrated and excess concrete was removed from the tub.

The procedure was repeated 2 more times for each truckload batch of concrete. Three mixes with varying air contents were used during the 3-day-testing period: A 1-1/2" maximum aggregate 5 sack pavement mix, a 1" maximum aggregate 6 sack mix, and a 1" maximum aggregate 7-1/2 sack mix. These mixes were all made using river run aggregate.

The experiment was patterned after a specific type of statistical design known as the Randomized Block Method. Results from each tub of concrete were considered an indepenent "block" of data. In all, there were 6 truckloads tested during the 3-day period. Three tubs of concrete were taken from each truckload, resulting in a total of 18 data blocks for each test method.

Preliminary analyses indicated that operator-equipment effects were highly significant, and that unit weight precision was being affected by either air content, concrete consistency or unit weight. Two more phases of the experiment were set up to help clarify these preliminary findings.

The first phase was based on what statisticians call a Latin Square Design. The procedure for this technique is similar to the Randomized Block Method except that operators change equipment from block to block. This allows the analyst to study operator and equipment effects separately.

Again, the work was done at Teichert. A 4 x 4 Latin Square was run using a 1" maximum sized aggregate, 6 sack mix. This meant that 4 separate blocks were performed on one truckload of material. The operators (except for one) and equipment were the same as before.

The second phase involved a continuation of the Randomized Block Method, but using different operators and material. The purpose of this phase was two-fold: 1) find out which relationship affecting unit weight would remain constant under different conditions, and 2) ascertain whether crushed particles would yield a different test precision than rounded particles for either test method.

The tests were conducted at Bakersfield Ready Mix in the same manner as before. Three truckloads (all 1" maximum aggregate, 6 sack mix, but with varying air contents) were used for a total of 9 data blocks. Penetration and concrete temperature were recorded for each block. The two methods of determining unit weight were alternated as the first test for each block, thus minimizing the time factor which had made earlier comparisons between the two methods difficult.

Because of the success of the unit weight and air content experiment, the ball penetration experiment was designed along the same lines. Four experienced operators and four recently calibrated ball penetration apparatuses were used. The apparatus weights were within 0.18 lb. of each other (method specifies $\pm$ 0.1 lb. maximum). Two plants were selected for the tests: Teichert, Sacramento and Graniterock, Santa Cruz. Here again, both rounded and crushed aggregate products were represented.

A large tub measuring 51" x 42" was obtained for the experiment. Its size permitted 12 penetration tests on 10" centers to be run on a single undisturbed sample of fresh concrete. Coordinates defining the 12 testing sites were written on the side of the tub.

The experiment was divided into eight structurally congruent units, each taking about 1-1/2 hours to complete. Four were done at Teichert's plant and four at Graniterock's plant. A test unit began by filling the tub with concrete to a depth of 8", mixing by shovel and leveling off the surface as described in the test method (see Figure 5). Each operator was then called on to run three penetration tests at randomly assigned coordinates. He reported his results to the nearest 0.1" by using a special ruler (this was done to increase the sensitivity of the experiment -- see Figure 6) after all four operators completed their tests, the concrete was remixed by shovel and a level testing surface again prepared. The cycle was repeated a total of six times for 72 penetration readings.

Immediately after this, the same concrete was used to run a 4 x 4 Latin Square. This consisted of four additional runs for which the concrete was remixed and leveled each time. The difference between this procedure and the one previously described was that operators exchanged equipment for each run and that one, not three readings, were taken by each operator. This meant an additional 16 penetration readings, or 88 per unit for a grand total of about 700 tests.

The operators chosen for this experiment were told to follow their normal procedure provided it was within the framework described by the test method. A fifth operator was included to run tests using the K-Meter. For the experimental unit

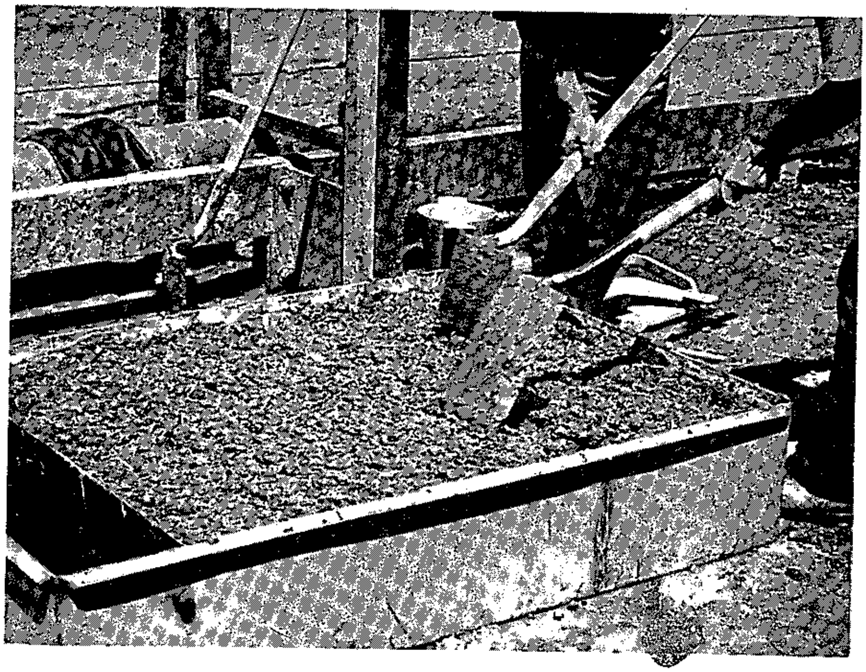

Fig. 5 Preparation of Testing Surface.

Fig. 6 Reading Penetration Results to Nearest 0.1".

previously described, this operator would run three replicate tests for each of the six cycles prior to the Latin Square designed test. These tests were run in the same tub as the penetration tests and at the same time.

Before each test, the K-Meter was washed in a bucket of water. The instrument, retaining some moisture from the washing, was then inserted into the concrete mass up to its flange with a slow, nonrotational motion. It was left undisturbed in the concrete for 60 seconds. Only penetration tests 20 inches or more away from the K-Meter were permitted during this time (see Figure 7). At the end of 60 seconds the plunger tube was slowly lowered and the first reading taken. This reading was intended to correspond to the slump of the concrete. The plunger tube was then raised and the K-Meter was extracted from the concrete with the same slow, nonrotational motion with which it had been inserted. Slowly lowering the plunger tube again immediately after the K-Meter was removed from the concrete yielded a second reading (see Figure 8). The difference between the two readings allegedly measured the workability of the concrete.

Methods of test site selection and preparation for the K-Meter were changed several times during the experiment. Each method strove to ensure that the concrete was consolidated and that the K-Meter test would not interfere with the penetration experiment. The methods are described in Table 9.

Fig. 7 Simultaneous K-Meter and Penetration Test.

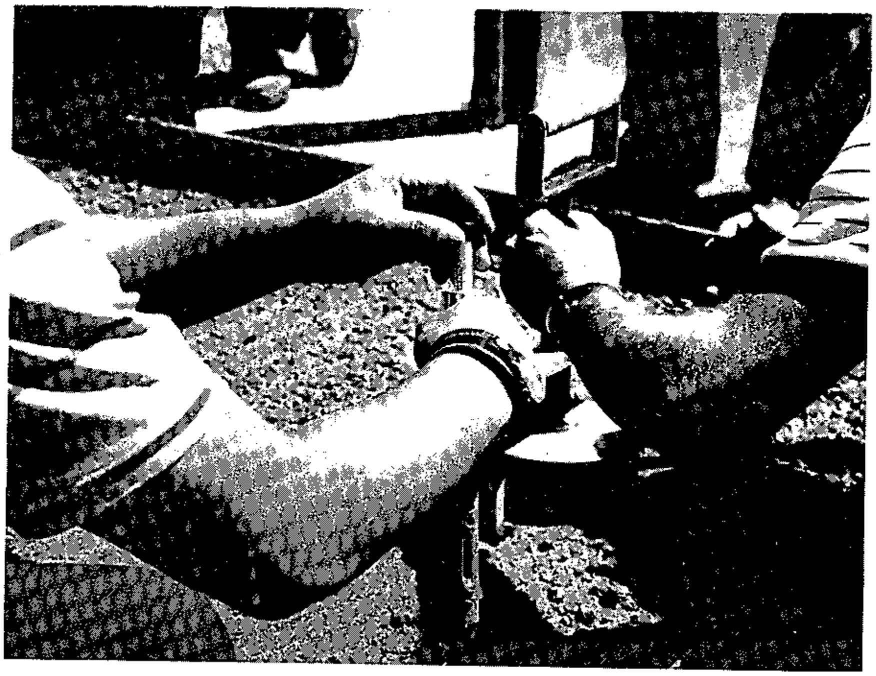

Fig. 8 Second Reading of K-Meter.

Table 9

Description of K-Meter Site Selection and Preparation Procedures

Method	Description
A	Tests performed in three corners of the tub, about 6" from sides. No addition site preparation.
B	Test performed at previously used penetration sites. Prior to inserting K-Meter site was rodded eight times and leveled with a trowel.
C	Tests performed at previously used penetration sites. Test site leveled with trowel.
D	Tests performed at previously used penetration sites. K-Meter thrust deeply into concrete (flange 1/2 to 1" below leveled surface).

DATA ANALYSIS

Concrete Compressive Strength

The first objective of this analysis was to compute an accurate precision statement tabulation. Since precision is measured by the D2S statistic (acceptable range between two results) it was felt best to study replicate breaks consisting of two cylinders only. This was the most common form of results and was most compatible with the D2S statistic. Analyses which included replicates of three or more cylinders resulted in precision estimates that were within 10% of those reported here.

A total of 956 cylinder pairs ranging from 2580 psi to 6970 psi were analyzed. The pairs were first ranked into seven compressive strength ranges. For each range the standard deviation of the differences between replicate breaks and the range mean were computed. A linear regression analysis was then run with the standard deviation of differences as the dependent variable and the mean compressive strength for the corresponding range as the independent variable. Results were weighted according to the number of cylinder pairs contained in each range.

The single-operator precision statement was taken directly from this linear regression equation after adjusting the results to the standard deviation of individual values and not differences.

A similar approach using the available multi-operator precision data was impractical, however. This limited amount of data spanned a relatively narrow range of compressive strengths thereby eliminating the possibility of establishing a separate and independent precision-strength relation. To overcome this difficulty, it was assumed that the relationship between strength and precision for both single and multi-operator conditions followed the same slope. The overall mean and pooled standard deviation of the multi-operator data were then used as the boundary conditions to establish a separate precision-strength relation from which the multi-operator precision statement was taken.

The inherent weakness of this assumption, the small amount of data available, and the lack of information concerning testing procedures all served to lessen the reliability of the compressive strength multi-operator precision statement. The expense of conducting a special experiment was prohibitive, however.

An estimate of equipment induced errors was made subsequent to the analysis of the field data. This estimate took into account the cylinder mold tolerance (diameter = 6" ± 1/16"*) and the testing machine precision (results read to the nearest 500 lbs.). Theorems regarding the distribution of products and quotients were used to estimate the total error contributed by these equipment factors (7).

Concrete Flexural Strength

The data for this analysis consisted of 380 paired beam breaks ranging in flexural strength from 380 psi to 720 psi. To ascertain whether a precision-strength relationship existed the pair means and standard deviations were linearly regressed. The resulting equation was significant, and its slope and intercept were used to logarithmically transform the data for the next stage of analysis. By doing this the data no longer exhibited the precision-strength relation and could be treated as a whole.

*ASTM C470-71T

While the results were transformed, the differences for each pair and the overall standard deviation of the differences were computed. This standard deviation was then retransformed for even intervals of flexural strength according to the rules governing progagation of errors (11). These were the values on which the precision tabulation was based.

This same procedure was followed using the accompanying 380 pairs of compressive strength tests. Precision results agreed within 2% of the previously determined single-operator precision; the different data base and completely different analytical approach notwithstanding.

The next phase of the analysis involved studying the feasibility of predicting flexural from compressive strength. The first step was to perform a regression analysis on the 380 paired flexural and corresponding compressive strength tests. The results are shown in Figure 1. Unquestionably, a relation exists between the two strength parameters. The coefficient of correlation for the analysis was 0.77, a reasonable number, and the regression F-Ratio proved highly significant. The question remained, however, as to whether there were separate linear relations for each source studied.

Two analytical methods were used to answer this question. The first method was based on the T-Paired Test for differences. There were nine data points for each of the 32 sources studied. For each source the differences (d) between the observed and predicted flexural strengths for all nine points were computed (see Figure 9). Then the mean and standard deviation of these differences were determined. If the flexural-compressive strength relation was the same for both the overall and source analyses, the mean of the differences would tend to equal zero. Seven of the 32 sources proved to have significantly different flexural-compressive strength relations by this method. In some extreme cases the flexural-strength prediction errors using the overall results would have been as high as 100 psi. In most cases, however, the error would not have exceeded 50 psi.

The second method involved computation of a 95% confidence zone for each source. The confidence zone was in terms of compressive strength and was computed at a flexural strength of 550 psi (see Figure 9); 550 psi was chosen because it is the flexural strength required of PCC pavement before opening to traffic by the California Standard Specifications. The overall results showed that a compressive strength of 3375 psi corresponded with the 550 psi specification. Therefore, if a source's confidence zone did not encompass 3375 psi it was reasonable to assume that the source required a special compressive strength value to predict a flexural strength of 550 psi. By this method, 19 of the 32 sources were shown inconsistent with the overall analysis.

Air Content of Fresh Concrete

To determine the precision of this test method a technique known as Randomized Block Analysis (RBA) was used (8). The data was made up of eighteen separate blocks (batches) and four treatments (operator-equipment combinations). By regressing block standard deviations and means it was discovered that the test precision and air content range were dependent parameters (see Figure 10). This violated two assumptions of RBA: variance homgeneity and additivity. However, these violations were minimized by using a logarithmic transformation. After the RBA was completed, components of variance were extracted and retransformed. These values were used for the precision statement.

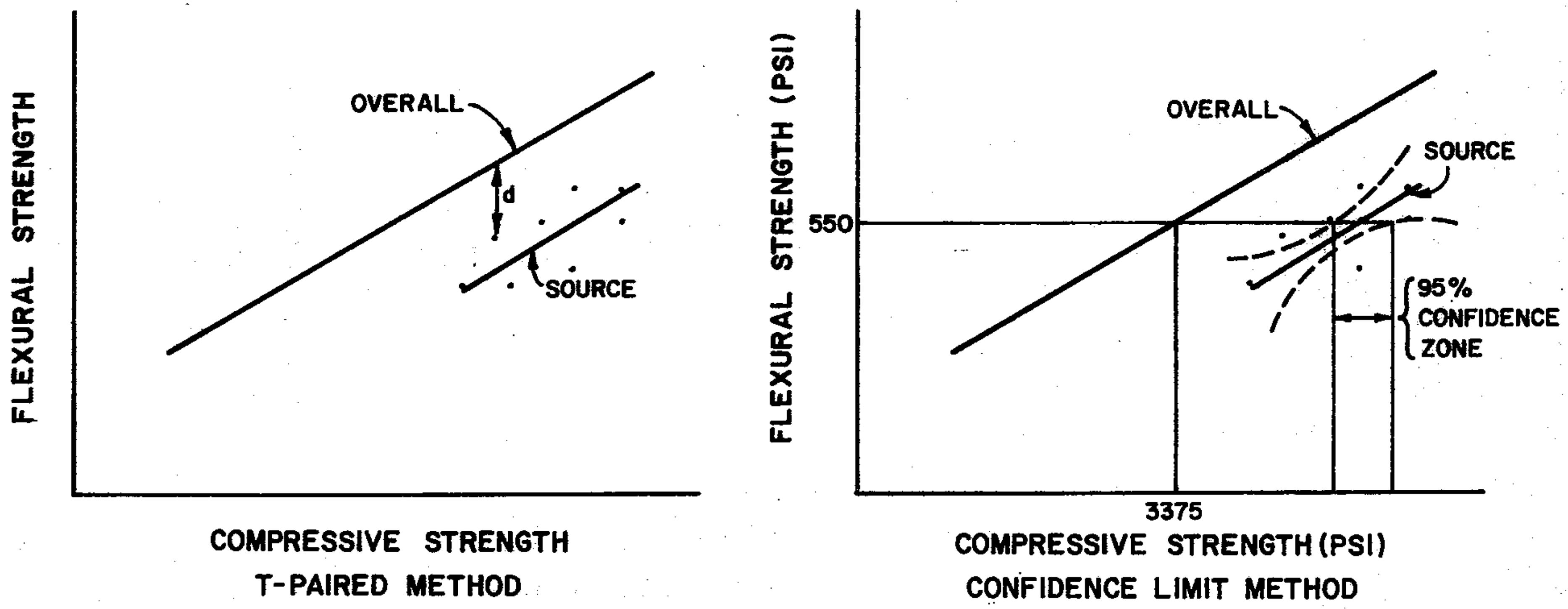

Fig. 9 METHODS FOR COMPARING SOURCE AND OVERALL PREDICTION VALUES FOR CONCRETE FLEXURAL STRENGTH

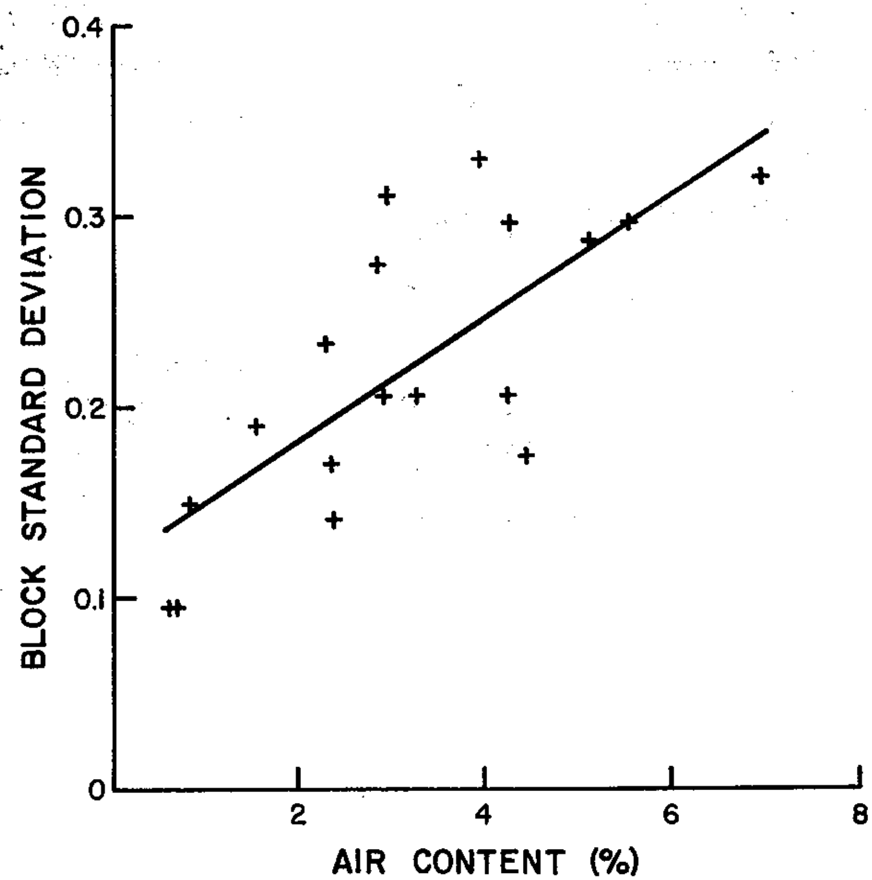

Fig.10 CHANGING PRECISION OF AIR CONTENT TEST

A 4 x 4 Latin Square Analysis (LSA) was also performed (8). No transformation was used for this analysis, however, since tests were run over a narrow range of air contents (4 to 5.4%). The variance components from the LSA were used to partition the total multi-operator variance into its component parts of operator, equipment and residual.

Unit Weight of Fresh Concrete

Before determining the precision of this test method it was necessary to ascertain whether the precision was constant, or varied according to either unit weight, concrete consistency or air content. Regression analyses were performed on block standard deviations versus each one of these parameters. At first, the results were inconclusive though the standard deviation-unit weight analysis had the best correlation coefficient. However, later results from the Bakersfield experiment coincided well with the unit weight analysis, but not with the other two analyses. Because of this, it was decided that unit weight was the best gage of the varying precision of the test method.

There were two sets of unit weight measurements: one using the unit weight bucket and the other using the air meter base. RBA was used to determine the precision of the transformed data for both these sets. As with the air content test, operator and equipment components of error were isolated by using LSA. A T-Paired Test between the two sets of data showed no significant difference in their results, but an F-Ratio on the transformed residual variances did show a significant difference in test precision between the two methods.

An estimate of the expected precision of the unit weight test was made using an assumed standard deviation of the field scales of: $s = 0.025$ lbs. By comparing this with the experimental results a recommended scale accuracy for calibration procedures was determined. Theorems involving distributions of sums and quotients (7) were used to estimate the precision of the cement factor determination for several combinations of batch weight, unit weight, and nominal cement content.

Penetration of Fresh Concrete

The experiment on ball penetration precision was very similar in structure to the unit weight-air content experiment. Independent blocks of data made up the bulk of the results, but latin squares were also included. A regression analysis on block standard deviations versus average penetrations revealed a linear relation between test precision and concrete consistency. Because of this, a logarithmic transformation was used before applying the analytical techniques.

The precision of averages of three penetration readings was determined by using RBA. A full factorial Analysis of Variance yielded the precision of individual results. As with the unit weight and air content tests, LSA separated the error components of operator and equipment.

Least squares linear regression was used to correlate K-Meter and ball penetration results. The precision of the K-Meter Test was determined by simple variance pooling. The comparison between K-Meter and ball penetration precision was based on the "sensitivity" concept (12).

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GLOSSARY OF STATISTICAL TERMS

ACCURACY: The degree of agreement with an accepted reference level (same).

ANALYSIS OF VARIANCE (ANOVA): A numerical technique which computes the variances of a measurable process under the influence of different treatments, and assesses the relative importance of these treatments. Randomized Blocks and Latin Squares are forms of this technique which do not require repeated measurements.

COEFFICIENT OF VARIATION: The ratio of the standard deviation to the mean or average of the variate, usually expressed in the form of a percentage.

CORRELATION: A measure of the interdependence between variables. The stronger this interdependence the closer the absolute value of the correlation coefficient approaches 1.

DIFFERENCE TWO-SIGMA LIMIT (D2S): An index that represents the maximum acceptable difference between two results obtained on test portions of the same material under a well defined set of circumstances. Equal to $2\sqrt{2}$ times and appropriate standard deviation.

ERROR: Used loosely to indicate any deviation from a true or perfect test result. Inherent in any testing procedure.

F-RATIO: A statistic consisting of the ratio of two variances: $F = S_1^2/S_2^2$. May be used to determine whether both variances come from the same population.

PRECISION: The degree of mutual agreement between individual measurements of a repeated process.

REGRESSION ANALYSIS: A method for determining a functional relation between two or more correlated variables. The method used herein is termed the least squares method.

REPEATABILITY: A measure of the difference between two results that could be expected to be exceeded in only 1 out of 20 cases when properly conducted repetitive determinations are made on identical portions of material by a competent operator using one set of equipment.

REPLICATE TESTS: Ideally, two or more tests conducted under identical conditions on identical material by the same operator.

REPRODUCIBILITY: A measure of the difference between two results that could be expected to be exceeded in only 1 out of 20 cases when properly conducted determinations are made by two different operators in different laboratories on identical portions of material.

SENSITIVITY: If M is a measure of some property Q, and σ_M is its standard deviation, the sensitivity of M is defined as $(dM/dQ)/\sigma_M$.

STANDARD DEVIATION: The square root of the variance, also known as the root mean square deviation. This is often a more practical statistic than the variance since it is in the same units as the variate and can be used directly to compute confidence intervals.

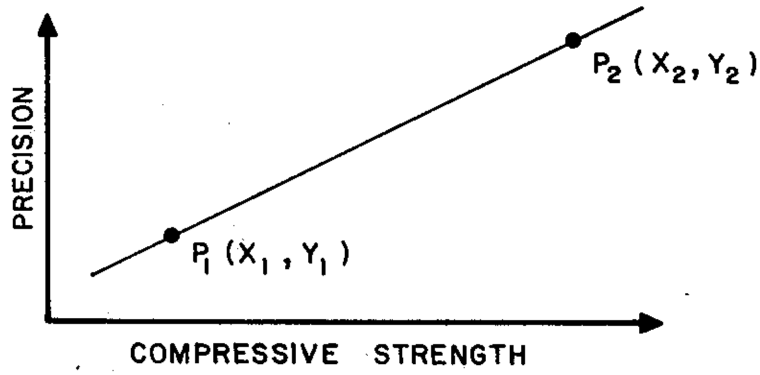
T-PAIRED TEST: Given a set of paired observations from two normal populations with means μ_1 and μ_2, tests the hypothesis: $\mu_1 = \mu_2$.

VARIANCE: A statistical measure of data dispersion defined as the mean of the squares of the deviation of each data point from the arithmetic mean.

APPENDIX

Proof that coefficient of variation must equal slope of variability function to be constant for all compressive strengths.

GIVEN:



TERMS: CV = Coefficient of Variation
M = Slope of Line

PROVE: If $CV_1 = CV_2$ then $CV = M$

(1) $$CV_1 = \frac{Y_1}{X_1}\ ,\quad CV_2 = \frac{Y_2}{X_2}$$

(2) $$M = \frac{Y_2 - Y_1}{X_2 - X_1}\ \left(\frac{1/X_1}{1/X_1}\right)$$

(3) $$= \frac{(Y_2/X_1) - CV_1}{(X_2/X_1) - 1}\ \left(\frac{X_1/X_2}{X_1/X_2}\right)$$

(4) $$= \frac{CV_2 - CV_1(X_1/X_2)}{1 - X_1/X_2}$$

(5) Since $CV_1 = CV_2$

$$M = \frac{CV[1 - X_1/X_2]}{1 - X_1/X_2} = CV$$