# FIELD EVALUATION OF

# VOID SPACING INDICATOR

by

Billy N. Banister

Research Report 504-1F
A Field Evaluation of the Void Spacing Indicator
for Determining the Quality of Air Entrainment
in Plastic Concrete

Research Study 1-9-72-504

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16. Abstract


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This test was developed from research done by Torrens and Ivey[1] at the Texas Transportation Institute. The equipment and procedures were only slightly modified for this field testing.

Projects in each District were selected and VSI tests were performed at the same time as other plastic concrete tests were conducted. Exact locations on the bridge projects were recorded for later coring operations. Cores were lifted and were examined by the linear traverse method and compared with the VSI data.

Statistical analysis was run and no mathematical relationship could be established between the void spacing in plastic concrete to the void spacing in hardened concrete. The test does give the inspector a quick check on the relative size and quantity of air entrainment that is in the plastic concrete prior to the final placement.


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# ABSTRACT

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Key Words: Void Spacing Indicator (VSI), Void Spacing Factor ($\bar{V}$) in plastic concrete, Void Spacing Factor ($\bar{L}$) in hardened concrete, air entrained concrete, entrained air voids, entrapped air voids, coarse aggregate factor, fine aggregate factor, paste content, freeze-thaw rapid testing, linear traverse, durability

# SUMMARY

In earlier research it was found that small air voids, closely spaced in hardened concrete improved the durability against freeze-thaw action. The quantity of air has been measured for many years by the pressure meter, etc., but there has also been a desire to determine the quality of the entrained air system. Various research investigations have been accomplished in the area. The most promising test developed was the Void Spacing Indicator test, yet it needed field testing for further study. The Materials and Tests Division agreed to perform this research.

Inspectors were trained in the VSI test procedure at the Materials and Tests Division in Austin. On returning to their respective Districts, they performed the VSI tests on their District projects. Cores were later lifted from exact locations where the tested concrete was cast. Then the cores were delivered to Austin for examination by the linear traverse method.

The data was examined statistically to determine if some mathematical relationship existed between the void spacing in the plastic and the hardened concrete. From the test data obtained in this research, there is no valid relationship.

The test can be beneficial to the inspector. It can give a visual observation of the relative size and quantity of air voids which are in the plastic state prior to the actual placement. It could be used as a supplemental test to observe the character of the air entrained system.

# IMPLEMENTATION

No plans are being made to implement this test for the Texas Highway Department. The need for this test was not established by this study. All concrete placed in this test program when examined by linear traverse measurements indicated that an adequate void spacing was obtained in the hardened concrete.

If desired, this test could be run as a supplementary test to check the general character of the air entrained system prior to the final placement of the plastic concrete.

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## I. SUBJECT

This report discusses the field testing and procedures used to evaluate the Void Spacing Indicator (VSI) with regard to reliability in determining the void spacing in plastic concrete as mathematically related to the void spacing in hardened concrete.

## II. PURPOSE

Research by Torrens and Ivey[1] at the Texas Transportation Institute reported an instrument which they termed a Void Space Indicator. Based on laboratory data the instrument was intended to be able to predict, from tests on plastic concrete, the bubble size, spacing and quantity of entrained air systems in hardened concrete.

In order to determine the reliability of the VSI under field conditions and therefore its acceptability for implementation, this investigation was undertaken using current projects in six Districts and Departmental personnel from those Districts to evaluate the VSI. If correlation of the test results from VSI could be made with linear traverse analyses of the entrained air systems in the same concrete, then this test could replace or supplement present procedures utilized to control entrained air systems in concrete.

## III. CONCLUSIONS AND RECOMMENDATIONS

The VSI test is only an indicator type test and the data indicates that it cannot be correlated mathematically with the void spacing in hardened concrete.

The test does give the inspector an opportunity to visually observe the approximate quantity and character of air void systems in a test sample. The inspector can see the approximate volume by the area that the air voids cover on the plate. He can also distinguish the general size. Small sizes generally indicate that there will be an adequate void system in the hardened concrete.

This test could be used as a supplemental test to other plastic concrete tests as a check on the size of the air voids being entrained.

The VSI test procedure will not be included in the Manual of Procedures and is not recommended to replace existing standard procedures to control the quantity and quality of entrained systems in concrete.

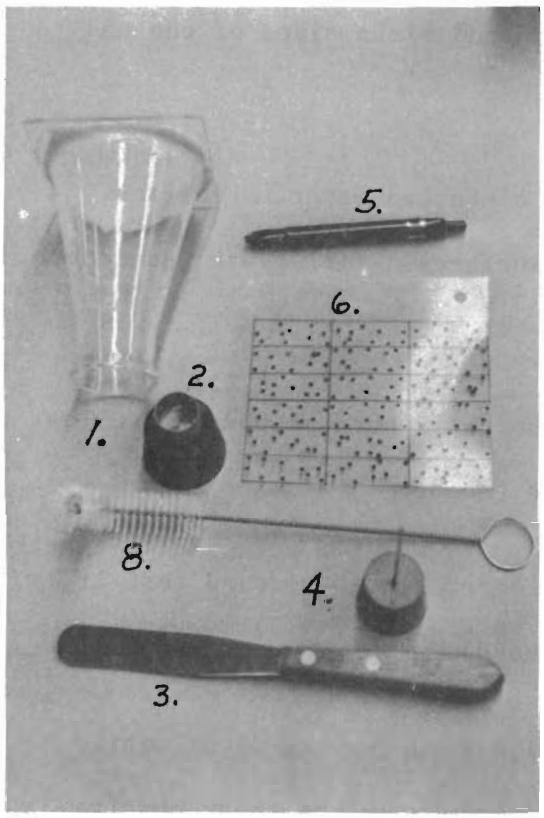
## IV. EQUIPMENT

### A. Void Space Indicator

<u>Test Purpose</u>

The VSI test is a procedure for the measurement of the air voids in plastic concrete for determining the approximate size and character of the air void system.

Equipment




1. VSI Flask.
2. Chace Air Indicator type brass cup in rubber stopper.
3. Spatula.
4. Rodding Tool (a 2-inch size paperclip in cork stopper).
5. Black Grease Pencil (erasable type).
6. Plastic Card Areagraph Plotter.
7. VSI Graphs (Table II).
8. Bristle Bottle brush.

Figure 1

VSI Equipment

Procedure For Testing

1. Fill the brass cup with cement mortar excluding any plus No. 10 size material. Rod the mortar approximately 25 times with a thin stiff wire (2 inch size paperclip wire). Tap sides of cup lightly with spatula to remove any entrapped air. Strike off mortar flush with top of cap and clean sides of cup and stopper.

2. Completely fill VSI flask with clean tap water. Free any bubbles clinging to the glass surfaces. Tilt flask and insert mortar filled cap.

3. Apply a slight downward force on the rubber stopper and allow all the air and excess water to escape.

4. Invert flask and check for entrapped air. (Discard test if large bubbles appear at this phase).

5. Hold VSI flask at $60^{\circ}$ angle while rotating the flask until mortar is dislodged from brass cup. Rock the flask gently to dislodge the entrained air bubbles from the mortar.

6. Hold the inverted flask at approximate $45^{\circ}$ angle and get all the entrained air bubbles to the top.

7. Slowly turn the flask until the bottom plate is passed the horizontal position allowing the bubble to flow upward to form a continuous area of bubbles on a one layer system.

8. Place the areagraph on the plate and trace the outline of the area of the bubbles with a grease-marking pen.

9. Remove and count black dots enclosed. Dots on line count one half each. Divide total number of dots by 10, which is equal to area ($\bar{a}$) in square inches.

10. Measure volume of air (A) by the pressure method.

11. Determine (P) which is the percent of paste in the total volume of concrete excluding the air entrainment.

12. Determine the coarse aggregate factor of the plastic concrete and express as a decimal fraction.

13. With the percent air, the percent paste, the coarse aggregate factor and the VSI reading, enter the VSI Chart (Table II). Follow the direction on the chart and determine the ($\bar{V}$) spacing factor. Record all data on VSI Worksheet (Table III).

14. Clean equipment thoroughly.

B. Linear Traverse Machine

Details of Linear Traverse Study of Field Cores

The cores taken from the field were submitted to the Petrographic Section of the Materials and Tests Division at Austin for microscopic analysis. The cores were sawed with a 24" diamond-blade saw in a longitudional direction giving two flat surfaces for examination.

These faces were polished to a fine surface finish using #600 silicon carbide grit. The surfaces were washed clean of grit, etc. and dried. The polished samples were placed on the linear traverse machine and examined in accordance to ASTM Designation: C 457. (See Figure 2)

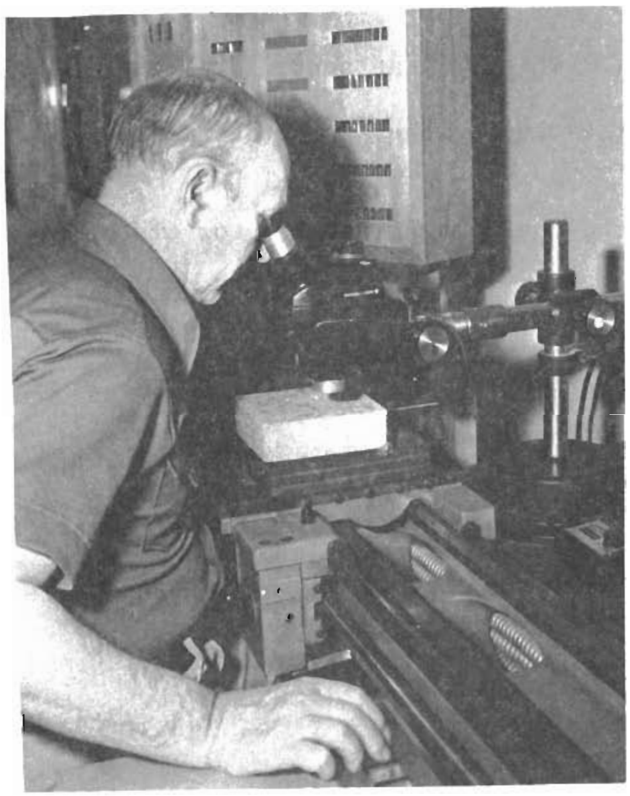


Figure 2

Examination Being Conducted On A Polished Concrete Section
By The Linear Traverse Method

Using a binocular microscope with a magnification range of 100X to 120X, the following features were observed and recorded:

1. The number of air voids (entrapped and entrained).
2. Total length of air voids measured in inches.
3. Total aggregate (sand and gravel) measured in inches.
4. Paste measured in inches.

This data from the linear traverse machine is next programmed for a Hewlett-Packard 9100B calculator which calculates the percent air, percent paste, specific surface area, void spacing and other prime factors (see Table V). From this data a comparison is made with the VSI field data.

## V. PROCEDURES FOR ACQUIRING DATA

### A. Development of the Test Program.

Torrens and Ivey recommended in their Report on the Void Space Indicator,(1) that further research was needed since this report was not sufficient to fully evaluate the VSI test. This report was accepted by the Texas Highway Department Research Advisory Committee (Area II) which requested that the Materials and Tests Division evaluate the procedure to see if this test was feasible. The Materials and Tests Division then developed a research study which was funded by the Federal Highway Administration. The project was divided into seven phases.

Phase 1

This period was used to assemble and manufacture necessary equipment for use in the field testing program.

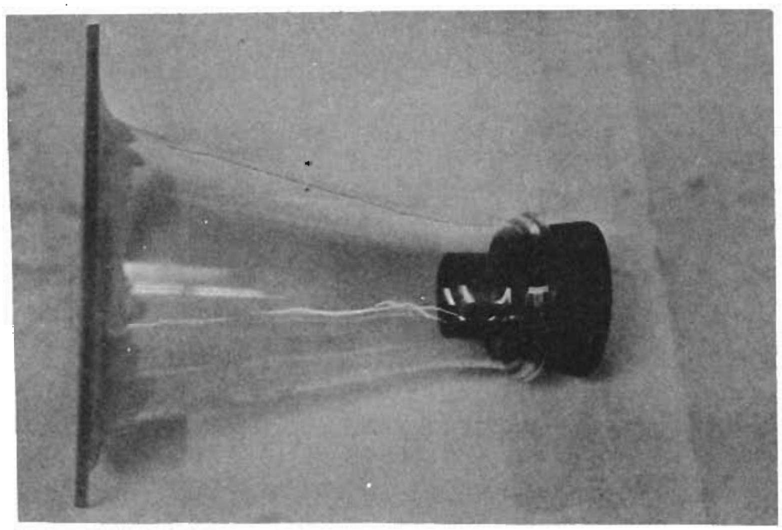


Figure 3

Locally Manufactured VSI Flask

The flat bottom flask (Figure 3) was made in the Materials and Tests Division of the Texas Highway Department. A 250 ml Erlenmeyer flask with a wide mouth was used. By the use of a fine diamond blade saw, the curved bottom was cut off. Then ground to a smooth edge. Epoxy was used to glue a square glass plate, 1/8" thick to the bottom of this flask. Extreme care was used to prevent any epoxy from getting on the glass plate (or flask) on the inside portion. These were more economical than the flat bottom (metal framed) flasks used by Torrens and Ivey.[1]

After satisfactory equipment was made, techniques to improve laboratory and field testing were instigated to check out and test any problem areas that might occur. Air entraining agents were added to a plain mixture of sand and water which was frothed up to develop an air entrained system. Tap water performed equally well as distilled water, thus eliminating the need to carry distilled water to the job. The microscope was used to study the action of these small bubbles in the VSI flask (Figure 4).

The bubbles rose to the bottom of the top plate. There was some stacking of bubbles, some void spacing between bubbles and some variation in size of bubbles. The stacking could partially be eliminated by gently tapping on the side of the flask. This motion also tended to help eliminate the voids between the bubbles. In accordance with the basic theory, all bubbles should be touching

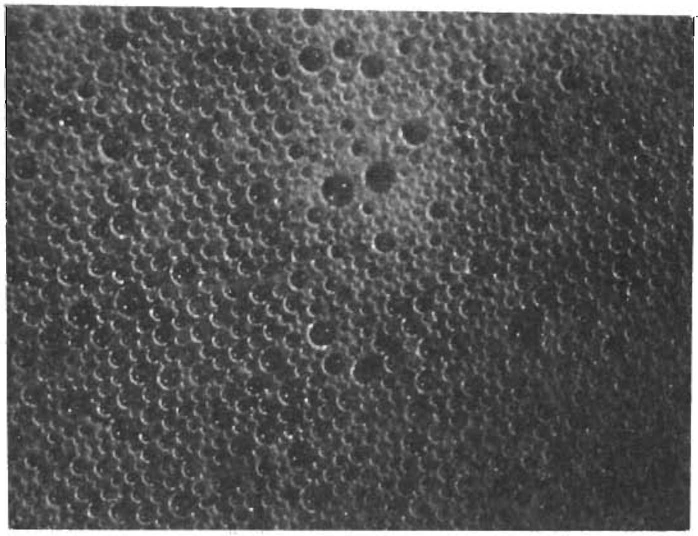


Figure 4

Air Entrained Bubble System
Under Microscopic Examination

other bubbles, thus having no large void space where a bubble could possibly fit in between. Between the problems of stacking and the problems of void areas, compensating errors would reduce the finite errors of each. The coalescence of the bubbles were a possible problem but after microscopic studies were made, there appeared to be no change in over several hours of observation in several different tests performed. This observation was made on regular concrete mortar as well as the sand-water mix, with both using the same type of air-entraining agent.

Phase 2

The Physical Test Section set up a standard concrete mix design, using a Lancaster pan-type batch mixer. Strict controls were maintained. Air content was measured on a calibrated pressure air meter. The author and other qualified personnel performed the VSI testing and determined the void spacing ($\bar{V}$) in the plastic concrete. Concrete cylinders were made from each concrete batch tested.

Repeatability of test results was fairly easy to obtain after several practice tests. Duplication of test results between technicians on the same concrete batch mixture indicated reliability in the test procedure. Variation between individuals was usually less than 0.2 sq. inches. After the operator technique was standardized, cylinders were made from the tested batch and properly handled and cured. The cylinders were later cut on a diamond blade saw, the surface polished and then examined on the linear traverse machine. The air content, the void spacing ($\bar{L}$) and other parameters were measured.

Mathematical charts were developed to reduce calculations required in the field. The original chart developed (Table I) was later replaced by an improved chart (Table II) which further reduced the calculations required. Either chart can be used, but the improved chart is the easiest.

Area measuring devices for an irregular shaped surface area of bubbles was a problem. The planimeter is an excellent way to figure the area but a simpler way was desired. The Bruning Areagraph measuring device (Table IV) was determined the best for field use. This transparent sheet is divided into many one-square inch rectangles in which there are ten dots scientifically spaced

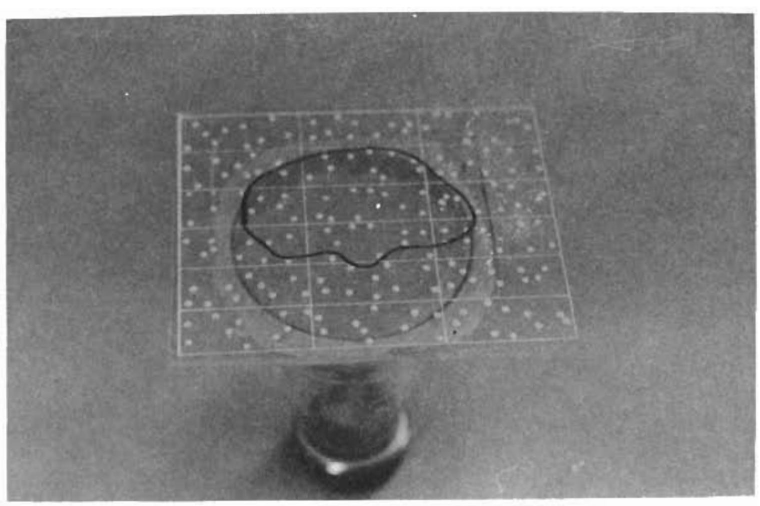


Figure 5

Measuring Bubble Area With A Modified Bruning Areagraph within the lines. By covering the irregular area of the bubbles and then counting the number of dots in this area, this will give you a number. This number divided by ten will give you the square inches of the bubble covered area in the VSI flask (Figure 5).

A training course was developed for instruction of field personnel and necessary plans were made to implement it.

Phase 3

Two inspectors from each of the cooperating Districts attended a training course developed and presented by the Materials and Tests Division. The primary purpose was to standardize the test procedure for all inspectors who would be involved in the field testing.

Phase 4

The field testing was begun in each of the Districts when a new bridge project started. The VSI testing was performed at the same time the rest of the testing on plastic concrete was being accomplished. It was requested that the inspector positively locate the exact position of the deposited concrete on which the tests were made. This was to be recorded on the VSI report form (Table III) for later use in coring operations.

As field testing was progressing beam-ends from the flexural tests were sent in to be examined by the linear traverse method

(Table VI). A question arose as to validity of the beam-ends data, so a decision was made to stop this and accept only data from the cores which were to be examined. Sixty-four cores were lifted and used in the final test data.

Phase 5

This phase included the petrographic examination of the core specimen by the linear traverse method. This data was recorded on work sheets. Basic data was fed into a Hewlett-Packard Computer and the parameters were calculated (see Table V).

Phase 6

All data was collected. Various statistical analyses were computed, and then reviewed. Questionable data was compared to previous research work. It was statistically analysed by various methods. The linear traverse equipment was checked for accuracy. Basic data sheets were checked for mathematical errors. Various investigations of the data were made in order to arrive at a logical conclusion.

Phase 7

The final phase is the writing of this report.

B. Field Testing.

There were seven Texas Highway Department Districts that agreed to cooperate in this field research project. Construction projects using air entrained concrete occurred in only five of the Districts in which cores could be lifted from bridge decks or concrete pavement. This report is limited to results of studies from these Districts. Participating Districts are shown in Figure 6.

Field inspectors planned their testing program for air entrained concrete that was to be used for bridge deck construction or concrete paving. After the flexural tests were run in the field, the beam ends were sent to the Materials and Tests Division for preliminary petrographic examination. Data of the beam ends are recorded in Table VI. The data from the linear traverse and the field tests indicated an increase air content. This was opposite to what was found in research done by Torrens and Ivey(1). A question developed as to the validity of the representation of the beam end to the "in-place" concrete. To eliminate any doubt, beam-end analyses were stopped. Cores were to be the determining factor in this field study.

It was planned to use the pressure meter and the Chace Air Indicator for the measurement of the air content. Through misunderstanding, in a few cases only the Chace was used. Although the precision of the Chace Air Indicator is limited, some data was used due to necessity.

The procedure was to run the VSI tests when the other plastic concrete tests were made. This was done to minimize the work-load on the inspectors. The inspectors took the sample from

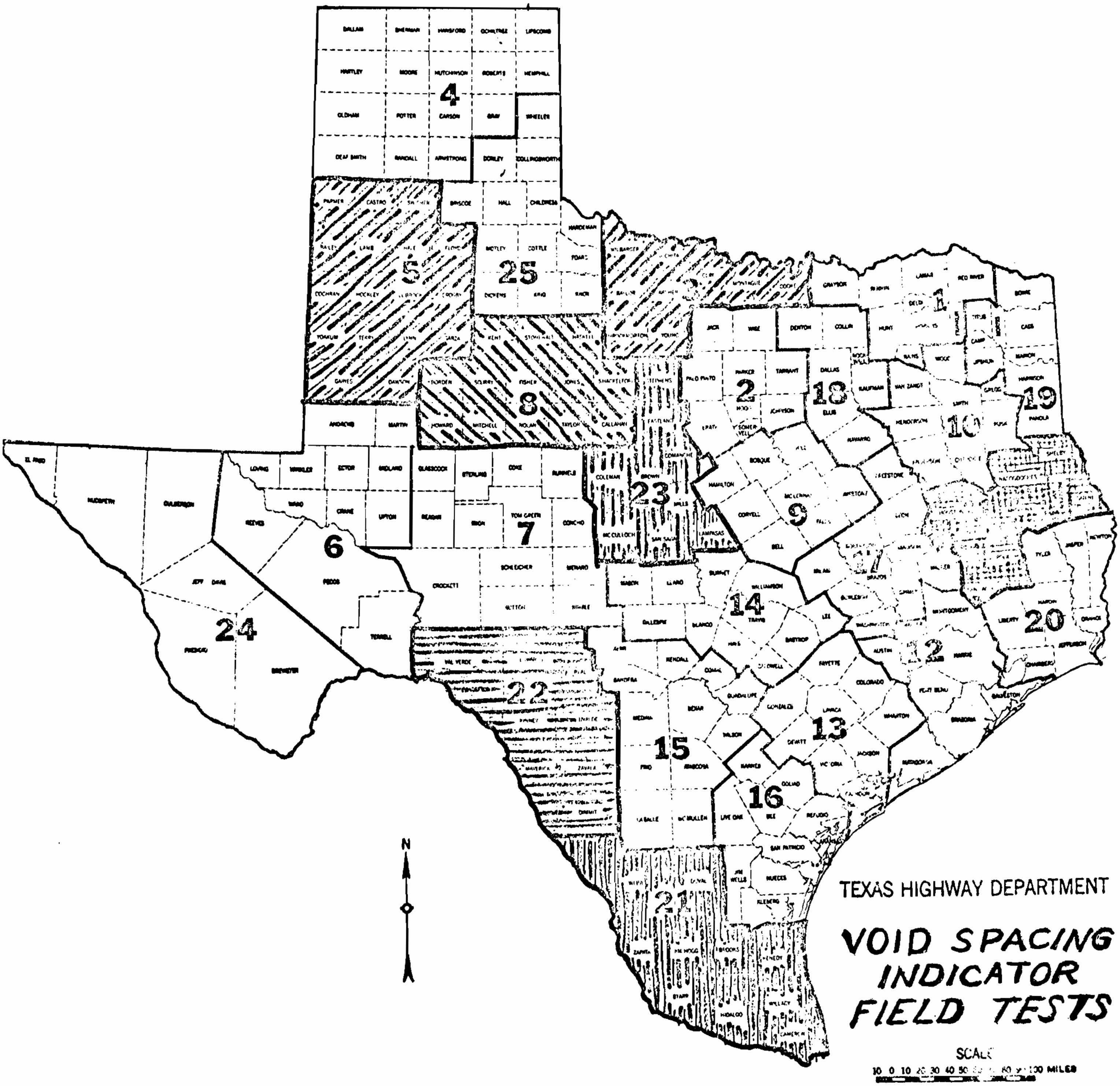



Figure 6

Texas Highway Department Districts involved in the Void Spacing Indicator Field Testing Research ready-mixed concrete trucks in the prescribed methods of sampling. The slump test was made, air content was determined by both the pressure meter and the Chace Air Indicator, beams were cast, and then the VSI test was run. The concrete was placed, with the exact location of the tested load marked on the VSI data sheet (Table III). This was done to be able to obtain a core from the exact same concrete that was tested. One District had their test equipment set up as shown in Figure 7.

Figure 7

Field Setup for VSI Testing

VSI reports were completed and then sent into the Materials and Tests Division for compilation and study. As the field work progressed, recommendations from the field for improving equipment were made. The first was to increase the bottom surface area by going to the next larger size flask. This did not affect the resulting data other than allow for a possibly more accurate reading of the area covered by bubbles where the air content was high. The neck using a larger stopper provided a better means of eliminating possible entrapped air bubbles around the outside of the cap itself. Also it provided more space between the brass cup and the glass neck to prevent flask breakage when sand is wedged in between at the time of stopper removal. The second item was the improvement of the area measuring device (Figure 5). The originals were on heavy sheet film, but the lightness was a detriment, especially in windy weather. It was difficult to find once it had blown away. By the use of the silk screen process, the areagraphs were placed on 1/8" hard plastic plate.

Upon completion of projects, the core drill was sent out to lift cores from these projects (Figure 8). The inspector who made the VSI test was present to pinpoint the exact location of where the tested concrete was placed (Figure 9). The cores were then marked on the side for positive identification (Figure 10). The cores were then delivered directly to the petrographic section of the Materials and Tests Division and logged in.

Figure 8. Core Drilling Operations.
Drilling Bridge Deck for VSI Specimen

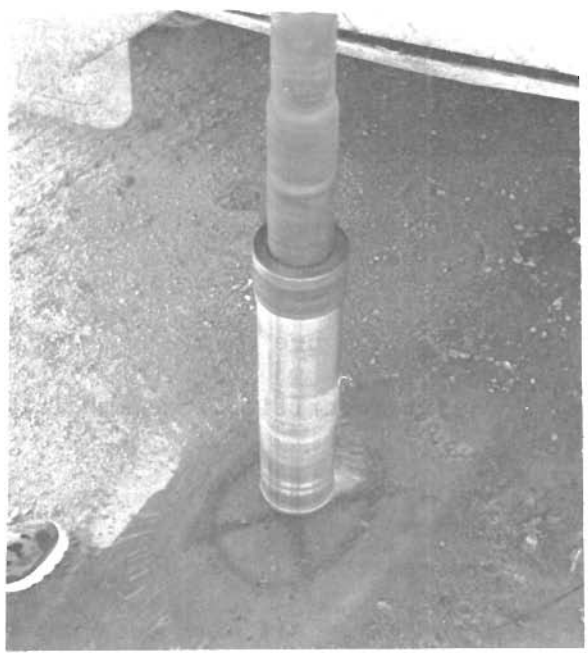


Figure 9. Area of VSI Tested Concrete Marked for Coring.

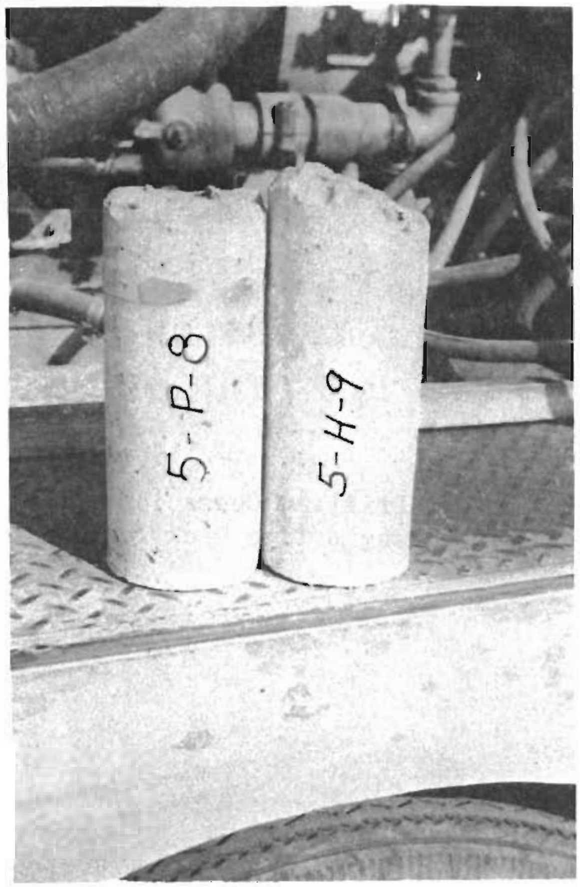



Figure 10

Cores Marked for Positive Identification Immediately After Being Removed From Slab.

Field testing for this report ended on July 1, 1972. Tabulation of results started in August. All beam ends not tested have been discarded. VSI reports are on file of all tested concrete. Not all VSI tested projects were cored for this study due to inaccessability or time limitations.

## VI. TEST DATA

### A. Mathematical Determination of Void Spacing in Plastic Concrete.

Torrens and Ivey[1] derived the mathematical equations for use with the VSI Test to determine ($\bar{V}$).

$$\bar{V} = \frac{0.053P}{\bar{a}\ (1-Vca)} \qquad \text{When } P/A < 4.33 \qquad (1)$$

$$\bar{V} = \frac{.159A}{\bar{a}\ (1-Vca)} \left[ 1.4\left(\frac{P}{A} + 1\right)^{\frac{1}{3}} - 1 \right] \qquad \text{When } P/A > 4.33 \qquad (2)$$

EXAMPLE

From test data:

$\bar{a}$ = 4.1 sq. inches (Area of Bubbles Measured on VSI Flask)

P = .241 (Paste factor of cement and water in decimals)

A = .045 (Air content expressed in decimals)

Vca = .482 (Coarse Aggregate Factor expressed in decimals)

Solution:

1. Check the P/A value to determine formula P/A =

$$\frac{.241}{.045} = 5.4 > 4.33. \quad \text{Use Formula (2)}$$

2. $$\bar{V} = \frac{.159A}{\bar{a}\ (1-Vca)} \left[ 1.4(P/A + 1)^{\frac{1}{3}} - 1 \right]$$

$$= \frac{(.159)(.045)}{(4.1)(1-.482)} \left[1.4(5.4 + 1)^{\frac{1}{3}} - 1\right]$$

$$= \frac{(.159)(.045)}{(4.1)(.518)} \left[1.4(6.4)^{\frac{1}{3}} - 1\right]$$

$$= \frac{.00715}{2.123} \left[1.4(1.852) - 1\right]$$

$$= .0035 \left[1.593\right]$$

$$\bar{V} = 0.0056 \text{ inches}$$

Then checking the VSI Chart, the $\bar{V}$ is 0.0055. This gives a check both ways. The slight variation between the two results are well within tolerance of the expected test results.

Instead of performing the mathematical calculations each time, curves have been placed on a chart (See Table II) for a direct reading of the void spacing. Table I gives the same answer but requires additional calculations so it has now been replaced by Table II which simplifies the testing procedure even further. The test is simple, yet it requires operator technique and practice.

B. Statistical Analysis

The void spacing factors in the plastic concrete ($\bar{V}$) and in the hardened concrete ($\bar{L}$) were examined to determine what mathematical relationships could be determined and what statistical conclusions could be made concerning these relationships. The mathematical relationship was determined by performing a linear regression analysis.

Then the two sets of test values and their variances were studied to determine the validity of this relationship.

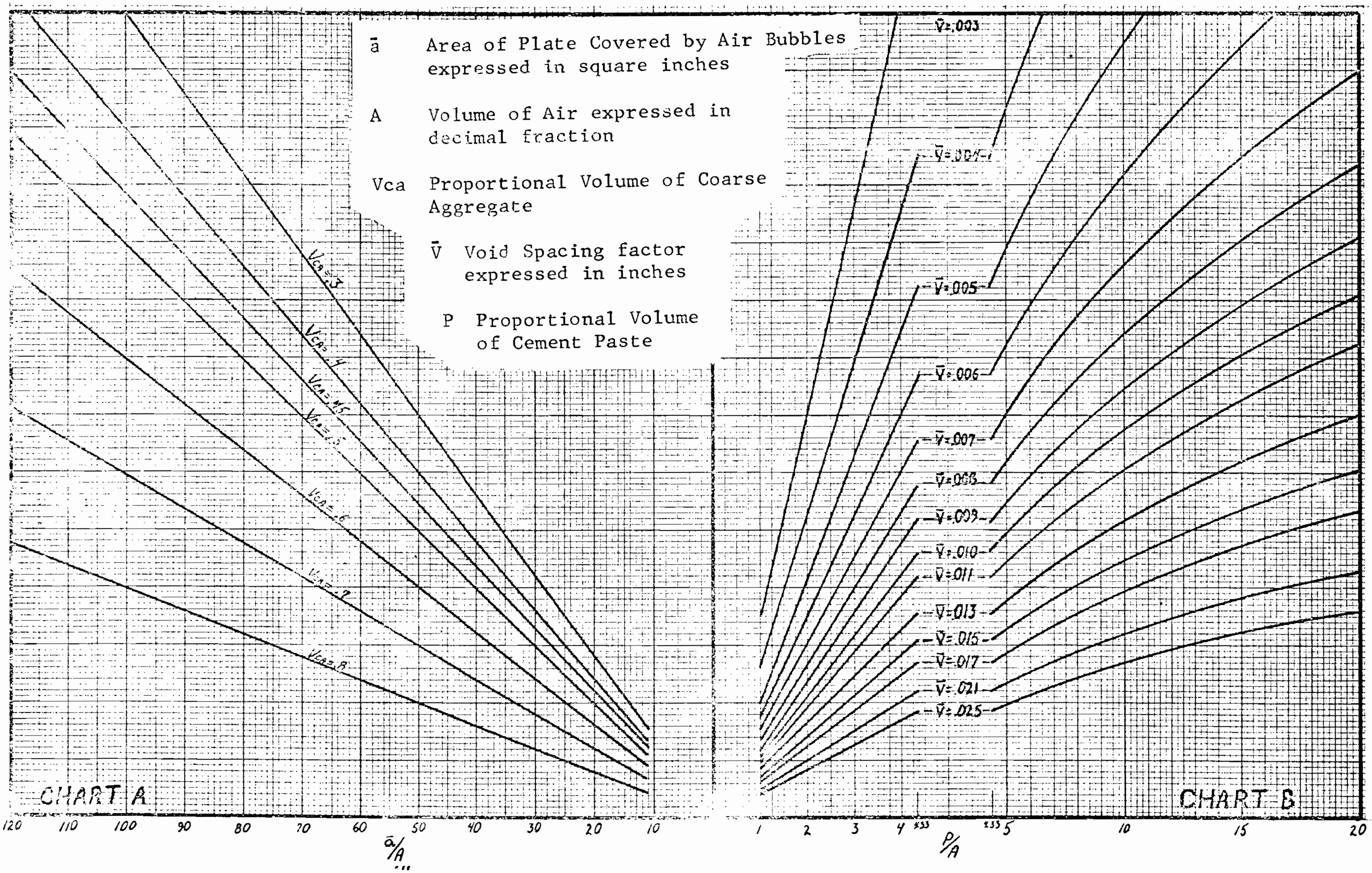
Table XII shows the result of the linear regression analysis. Note that because of scale limitations, not all points are shown on the plot although they were used to derive the equation. The relationship, $\bar{L} = 0.2881\ \bar{V} + 0.0034$, was determined with a correlation coefficient between the equation and data points of only 0.525. This equation accounts for only about 28% of the variation in the data as is indicated by the large scatter of data points. This indicates that either there are other variables involved or that the relationship is not valid.

The sets of data were now studied to determine if the above relationship is valid. This was done in two ways. First the mean of the differences of paired values was determined for 64 pairs, a t-value calculated, and then this value was compared to a maximum t-value determined from a standard Student's-t Distrubution table. The calculated value was $t = 6.53$, the table value was 2.00 at a confidence level of 95%. Since the calculated value is greater than the table value, the hypothesis that the two sets of test values ($\bar{V}$ and $\bar{L}$) are equivalent is rejected. Tests on the District subgroups of data gave similar results.

The equivalence of variances is studied by comparing a calculated F factor with one from standard tables. The F value is equal to the ratio of the variances (square of standard deviation) of the two sets. For $\bar{V}$ and $\bar{L}$, F = 3.50 and from the Table F = 1.67 at a 95% confidence level. The hypothesis that the two groups of variances are related must be rejected.

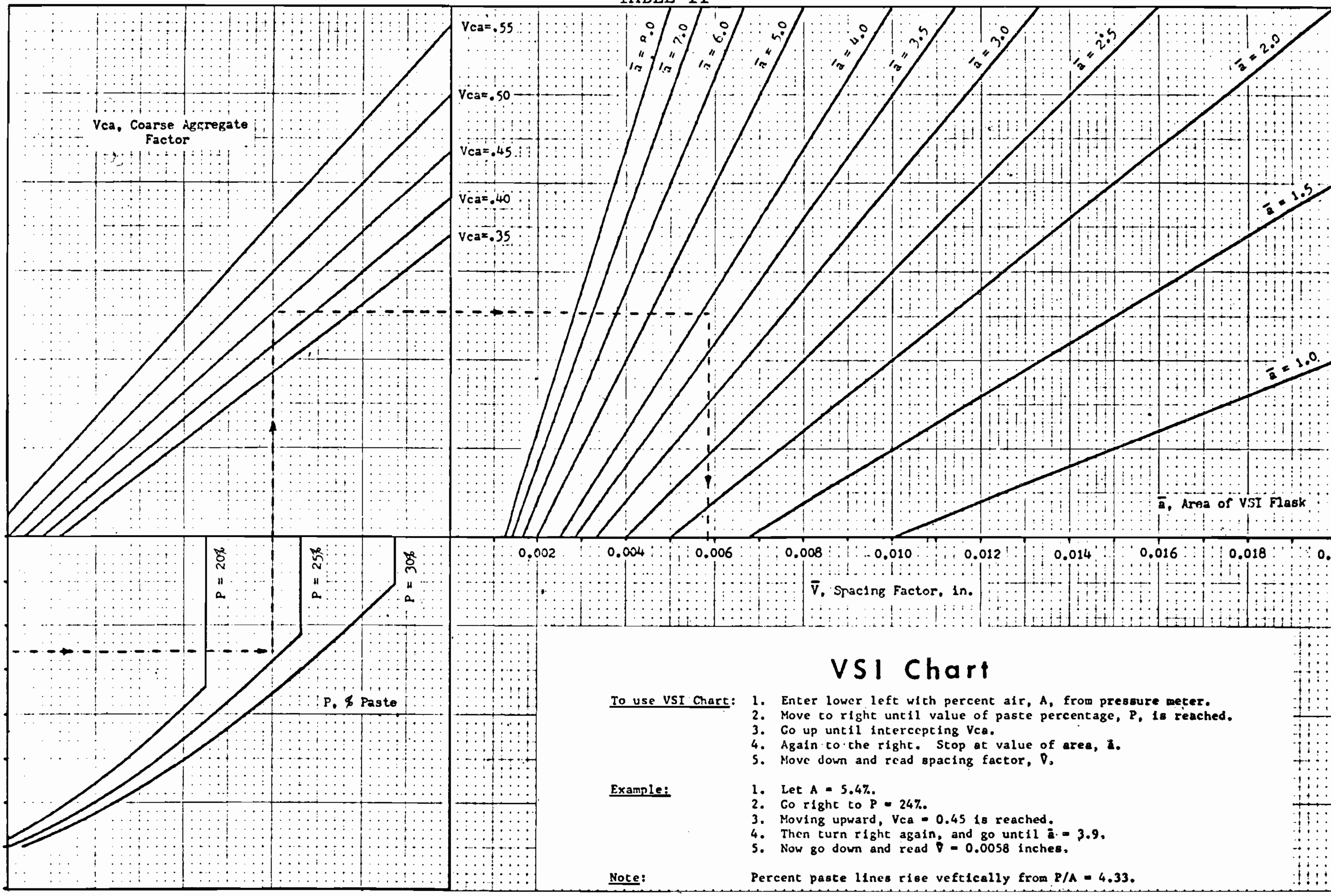
These studies rejected any hypothesis that $\bar{V}$ and $\bar{L}$ represented separate measurements of the same quantity, i.e., air-void spacing. Accordingly, the relationship derived from the regression analysis must be rejected as not being meaningful. This should have been suspected since the correlation coefficient of .525 from the regression accounts for only 28% of the variance in the data.

TABLE I




Original VSI Chart Used For Deriving Void Spacing In Plastic Concrete

TABLE II




Improved VSI Chart For Deriving Void Spacing in Plastic Concrete

A. GENERAL INFORMATION Pd. No.________ Date:________

DISTRICT________ COUNTY________ Hwy. No.________ CONTROL NO.________
PROJECT NO.________ Rdwy. WIDTH________ SLAB THICKNESS________
LOCATION: STATION________ DIST. (L) (R) CENTER LINE________ LANE________
WEATHER: (WET/DRY); TEMPERATURE________ HUMIDITY________ TIME________

B. MATERIALS

DESIGN FACTORS
CAF________
FAF________
C/F________ sk/yd
W/C________ Gal./Sack
AIR________ % TYPE________
W.R.________ % TYPE________

1 SACK DESIGN
COURSE AGG.________ cf
FINE AGG.________ cf
CEMENT________ cf
WATER________ cf
AIR________ cf
YIELD________ #/cf

DESIGN DENSITY________ #/cf
BRAND________

C. TEST RESULTS

VOL. AIR________ % (Pressure)
VOL. AIR________ % (Chace)
SLUMP________ INCHES
VOL. PASTE________ % (Cement + Water)
CONC. TEMP.________ °F

VSI READINGS

1.________ sq. in.
2.________ sq. in.
3.________ sq. in.
Avg.________ sq. in.

VOID SPACING

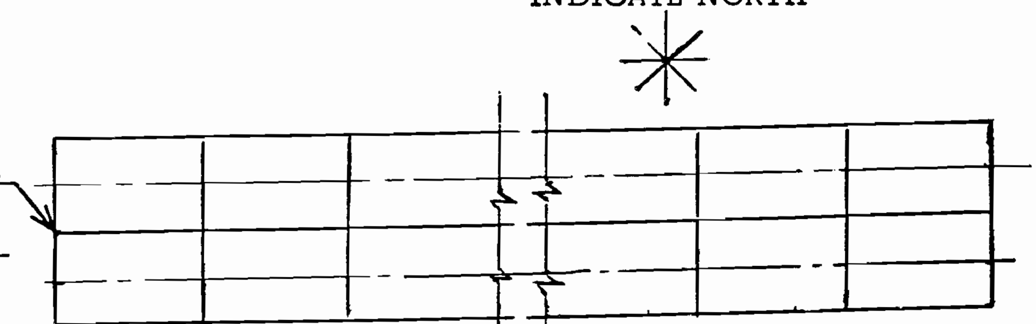
$\overline{V}$ = ________ in.

D. REMARKS:

INDICATE NORTH

STATION NO.

________

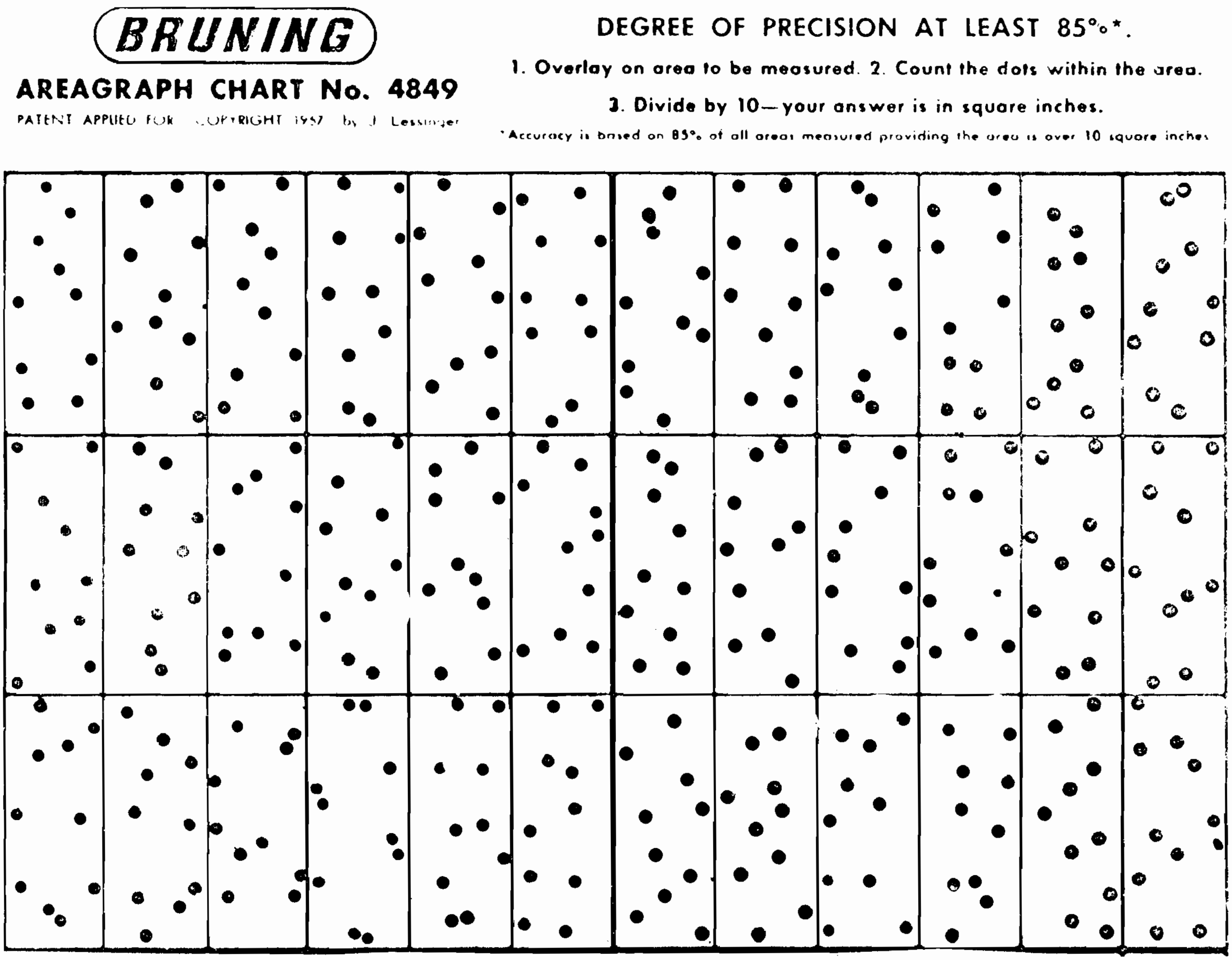


MARK LOCATION WHERE SAMPLE WAS TAKEN.

E. INSPECTOR________

VOID SPACING INDICATOR RECORD DATA SHEET

TABLE IV




An Opaque Reproduction Of A Half Section
Of A Bruning Areagraph Chart

TABLE V

# LINEAR TRAVERSE DATA SHEET

Operator T.S. Patty & W. Jarnagin

District / Lab / Source District 5 VSI Core

Magnification 120X

Specimen No. Core # 5-P-3

Traverse Spacing, Inch 0.2"

Date June 26, 1972

| Traverse Number | Counter Readings | | | | | | % | |
|---|---|---|---|---|---|---|---|---|
| | Voids | Air | Aggregate | Paste | | Total Concrete | Air | Paste |
| 1 | 89 | .3229 | 4.8532 | 2.4236 | | 7.5689 | | |
| 2 | 64 | .5416* | 5.2085 | 1.8514 | | 7.5781 | | |
| 3 | 60 | .3849 | 5.4852 | 1.7488 | | 7.5976 | | |
| 4 | 92 | .4149 | 4.9839 | 2.2241 | | 7.5970 | | |
| 5 | 95 | .3599 | 5.2119 | 2.0552 | | 7.5994 | | |
| 6 | 84 | .3782 | 4.9727 | 2.1932 | | 7.5897 | | |
| 7 | 112 | .7671 | 4.3661 | 2.4916 | | 7.3943 | | |
| 8 | 96 | .5473 | 4.9371 | 1.9756 | | 7.5927 | | |
| 9 | 96 | .4707 | 4.9729 | 2.1870 | | 7.6013 | | |
| 10 | 92 | .4972 | 4.8637 | 2.1942 | | 7.5990 | | |
| 11 | 91 | .4044 | 4.9173 | 2.2412 | | 7.5355 | | |
| 12 | 87 | .4132 | 4.872 | 2.1786 | | 7.5897 | | |
| 13 | | | | | | | | |
| 14 | | | | | | | | |
| 15 | | | | | | | | |
| 16 | | | | | | | | |
| 17 | | | | | | | | |
| 18 | | | | | | | | |
| 19 | | | | | | | | |
| 20 | | | | | | | | |
| Totals | 1058 | 5.5023 | | 25.7665 | | 91.0432 | | |
| | (1) N | (2) Y | (3) | (4) P | | (5) T | | |

Comments & Diagram

A typical linear traverse data sheet used for each separate core examined in this study.

This core has 6.04% air with $\bar{L}$ spacing of .0058 inches.

| | | |
|---|---|---|
| (6) | Air Content, A | 6.04 % |
| (7) | Paste Content, p | 28.30 % |
| (8) | Aggregate Content, G | 65.65 % |
| (9) | Avg. Chord Length, $\bar{l}$ | .0052 in. |
| (10) | Specific Surface, α | 769 $in^2/in^3$ |
| (11) | Voids / Inch, n | 11.62 |
| (12) | P/A | 4.68 |
| (13) | Spacing Factor, $\bar{L}$ | .0058 in. |

**Linear Traverse Data on Concrete Having 6.04% Air**

TABLE VI

Relationship Between The Void Spacing In Plastic Concrete And Hardened Concrete (Beam Ends).

| | Field Data | | | | Laboratory Data | | Conversion Constant $\bar{V}/\bar{L}$* |
|---|---|---|---|---|---|---|---|
| | Volume of Air | | | | Volume of Air | | |
| Beam No. | Pressure % | Chace % | Design % | $\bar{V}$ Inches | Lin. Trav. % | $\bar{L}$ Inches | $\bar{V}/\bar{L}$ |
| 1 | 7.0 | - | 5.0 | .0100 | 9.85 | .0022 | 0.45 |
| 2 | 5.7 | - | 5.0 | .0067 | 9.10 | .0036 | 1.86 |
| 4 | 5.4 | - | 5.0 | .0061 | 7.30 | .0041 | 1.48 |
| 6 | 7.0 | - | 5.0 | .0068 | 11.34 | .0024 | 2.83 |
| 9 | 4.5 | 3.5 | 6.0 | .0088 | 6.68 | .0032 | 2.75 |
| 10 | 3.0 | 3.5 | 5.0 | .0085 | 3.64 | .0082 | 1.04 |
| 17 | 8.0 | 7.5 | 5.0 | .0070 | 9.01 | .0029 | 2.41 |
| 18 | 6.0 | 5.5 | 5.0 | .0090 | 8.66 | .0034 | 2.65 |
| 26 | 2.8 | 2.5 | 5.0 | .0120 | 4.49 | .0091 | 1.32 |
| 29 | 8.2 | 8.0 | 5.0 | .0050 | 9.24 | .0022 | 2.27 |
| 30 | 4.5 | - | 5.0 | .0090 | 4.32 | .0063 | 1.43 |
| 33 | 6.0 | - | 6.0 | .0100 | 4.23 | .0060 | 1.67 |
| 39 | 4.5 | - | 6.0 | .0100 | 4.17 | .0060 | 1.67 |
| 46 | 5.0 | 6.4 | 6.0 | .0060 | 7.50 | .0050 | 1.20 |
| 47 | - | 5.1 | 5.0 | .0067 | 6.50 | .0064 | 1.05 |
| 48 | 5.2 | 6.0 | 6.0 | .0080 | 5.50 | .0047 | 1.70 |
| 50 | - | 4.5 | 5.0 | .0080 | 5.21 | .0064 | 1.25 |

TABLE VI - CONTINUED

| | Field Data | | | | Laboratory Data | | Conversion Constant $\bar{V}/\bar{L}$* |
|---|---|---|---|---|---|---|---|
| | Volume of Air | | | | Volume of Air | | |
| Beam No. | Pressure % | Chace % | Design % | $\bar{V}$ Inches | Lin. Trav. % | $\bar{L}$ Inches | $\bar{V}/\bar{L}$ |
| 58 | 3.0 | - | 5.0 | .0084 | 2.79 | .0105 | 0.80 |
| 59 | 3.5 | - | 5.0 | .0050 | 3.58 | .0099 | 0.51 |
| 65 | 2.5 | - | 5.0 | .0115 | 3.73 | .0103 | 1.12 |
| 71 | 5.2 | 5.4 | 5.0 | .0053 | 4.84 | .0056 | 0.95 |
| | | | | | | Total | 32.39 |
| | | | | | | Average | 1.54 |

* $\bar{V}$ = Void Spacing in Plastic Concrete (by VSI Tests).

$\bar{L}$ = Void Spacing in Hardened Concrete (by Linear Traverse Measurement).

TABLE VII

Test Results From District 3

| Sample No. | $\bar{V}$ Inches | $\bar{L}$ Inches | $\bar{V}/\bar{L}$ | Air Press. Meter % | Air Chace % | Air Linear Traverse % |
|---|---|---|---|---|---|---|
| 3-T-1 | .008 | .0032 | 2.5 | 5.2 | 4.0 | 7.86 |
| 3-T-2 | .008 | .0046 | 1.74 | 5.2 | 4.0 | 7.07 |
| 3-S-1 | .008 | .0077 | 1.04 | 5.2 | 4.2 | 4.13 |
| 3-S-2 | .0124 | .0064 | 1.94 | 4.7 | 4.0 | 5.87 |
| 3-S-3 | .011 | .0078 | 1.41 | 4.5 | 4.0 | 4.66 |
| 3-S-4 | .010 | .0068 | 1.47 | 4.7 | - | 6.5 |
| 3-S-5 | .0118 | .0066 | 1.79 | 4.5 | 4.0 | 5.99 |
| Average $\bar{x}$ | .0099 | .0062 | 1.699 | 4.86% | 4.03% | 6.01% |
| Std. Dev. | .0019 | .0017 | .462 | .33 | .08 | 1.30 |
| Coef. Var. $\bar{V}$ | 19.3% | 27.2% | 27.2% | 6.8% | 2.02% | 21.6% |
| No. of Tests n | 7 | 7 | 7 | 7 | 6 | 7 |

TABLE VIII

Test Results From District 5

| Sample No. | $\bar{V}$ Inches | $\bar{L}$ Inches | $\bar{V}/\bar{L}$ | Air Press. Meter % | Air Chace % | Air Linear Traverse % |
|---|---|---|---|---|---|---|
| 5-H-1 | .0063 | .0079 | .80 | 5.4 | - | 4.50 |
| 5-H-[illegible] | .0061 | .009 | .68 | - | 5.0 | 3.65 |
| *5-H-7 | .0168 | - | - | - | 4.2 | - |
| *5-H-9 | .0053 | - | - | - | 5.7 | - |
| 5-H-11 | .0065 | .0081 | .80 | - | 3.8 | 4.97 |
| 5-H-16 | .0053 | .0062 | .85 | 5.2 | 5.4 | 7.59 |
| Average $\bar{x}$ | .0077 | .0078 | .783 | 5.3% | 4.8% | 5.2% |
| Std. Dev. | .0045 | .0017 | .0723 | .141 | .801 | 1.699 |
| Coef. Var. $\bar{V}$ | 58.0% | 15.0% | 9.2% | 2.7% | 16.6% | 32.8% |
| No. of Tests n | 6 | 4 | 4 | 2 | 5 | 4 |
| 5-P-3 | .0055 | .0058 | .94 | - | 5.0 | 6.04 |
| 5-P-5 | .0076 | .0081 | .94 | 3.0 | - | 2.69 |
| *5-P-8 | .0053 | - | - | - | 5.0 | - |
| *5-P-9 | .0077 | - | - | 4.8 | - | - |
| 5-P-10 | .0084 | .0089 | .94 | 3.0 | - | 2.69 |
| *5-P-18 | .0051 | - | - | 3.6 | 4.5 | - |
| 5-P-23 | .017 | .0096 | 1.77 | 2.8 | 2.8 | 3.3 |
| Average $\bar{x}$ | .0081 | .0081 | 1.00 | 3.4% | 4.3% | 3.68% |
| Std. Dev. | .00415 | .0065 | .415 | .817 | 1.044 | 1.599 |
| Coef. Var. $\bar{V}$ | 51.3% | 20.4% | 36.2% | 23.8% | 24.1% | 43.5% |
| No. of Tests n | 7 | 4 | 4 | 5 | 4 | 4 |

* Linear Traverse Data Not Available On These Cores.

TABLE IX

Test Results From District 21

| Sample No. | $\bar{V}$ Inches | $\bar{L}$ Inches | $\bar{V}/\bar{L}$ | Air Press. Meter % | Air Chace % | Air Linear Traverse % |
|---|---|---|---|---|---|---|
| 21-2 | .0075 | .0051 | 1.47 | 3.7 | - | 5.52 |
| 21-3 | .0060 | .0034 | 1.76 | - | 5.5 | 6.01 |
| 21-4 | .0062 | .0040 | 1.55 | - | 5.0 | 5.06 |
| 21-5 | .0095 | .0056 | 1.70 | - | 4.5 | 7.23 |
| 21.6 | .0075 | .0060 | 1.25 | - | 4.2 | 6.70 |
| 21-6A | .0075 | .0054 | 1.39 | - | 4.2 | 5.46 |
| 21-7 | .0090 | .0056 | 1.61 | - | 4.3 | 5.04 |
| 21-8 | .0100 | .0050 | 2.00 | 4.1 | 3.8 | 5.85 |
| 21-10 | .0066 | .0080 | .75 | 4.2 | - | 6.26 |
| 21-13 | .0107 | .0058 | 1.84 | 3.2 | 3.0 | 6.13 |
| 21-14 | .0085 | .0036 | 2.36 | 5.2 | 4.5 | 8.41 |
| 21-15 | .0081 | .0035 | 2.31 | 3.9 | 4.6 | 6.51 |
| 21-16 | .0081 | .0033 | 2.45 | 5.5 | 5.5 | 9.31 |
| Average $\bar{x}$ | .0081 | .00495 | 1.73 | 4.26% | 4.46% | 6.4% |
| Std. Dev. | .00143 | .00136 | 0.4795 | .818 | .721 | 1.263 |
| Coef. Var. $\bar{V}$ | 17.7% | 27.5% | 27.8% | 19.2% | 16.2% | 19.7% |
| No. of Tests n | 13 | 13 | 13 | 7 | 11 | 13 |

TABLE X

Test Results From District 22

| Sample No. | $\bar{V}$ Inches | $\bar{L}$ Inches | $\bar{V}/\bar{L}$ | Air Press. Meter % | Air Chace % | Air Linear Traverse % |
|---|---|---|---|---|---|---|
| 22-2 | .0048 | .0023 | 2.09 | 8.0 | 7.5 | 9.43 |
| 22-3 | .0048 | .0027 | 1.78 | 8.0 | 7.5 | 9.63 |
| 22-4 | .0090 | .0027 | 2.96 | 6.0 | 5.5 | 8.22 |
| 22-5 | .0100 | .0038 | 2.63 | 4.5 | 4.5 | 7.58 |
| 22-6 | .0110 | .0044 | 2.54 | 4.3 | 4.5 | 7.95 |
| 22-7 | .0200 | .0083 | 2.41 | 4.2 | 4.5 | 4.61 |
| 22-8 | .0200 | .0114 | 1.75 | 3.0 | 3.3 | 4.20 |
| 22-9 | .0060 | .0043 | 1.40 | 5.5 | 4.6 | 6.26 |
| 22-10 | .0070 | .0040 | 1.75 | 4.3 | 4.5 | 8.80 |
| 22-11 | .0090 | .0078 | 1.15 | 2.8 | 3.0 | 3.54 |
| 22-12 | .0120 | .0086 | 1.40 | 2.8 | 2.5 | 4.40 |
| 22-15 | .0050 | .0017 | 2.94 | 8.2 | 8.0 | 11.79 |
| 22-21 | .0060 | .0043 | 1.40 | 5.5 | 4.6 | 6.26 |
| 22-22 | .0070 | .0040 | 1.75 | 4.9 | 4.5 | 9.50 |
| 22-23 | .0060 | .0042 | 1.43 | 4.6 | 5.6 | 8.78 |
| 22-24 | .0050 | .0040 | 1.28 | 5.0 | 4.5 | 10.15 |
| 22-29 | .0060 | .0035 | 1.71 | 4.3 | 4.2 | 9.56 |
| 22-30 | .0050 | .0032 | 1.56 | 5.5 | 5.0 | 9.86 |
| 22-31 | .0090 | .0043 | 2.09 | 4.6 | 5.0 | 8.96 |

TABLE X - CONTINUED

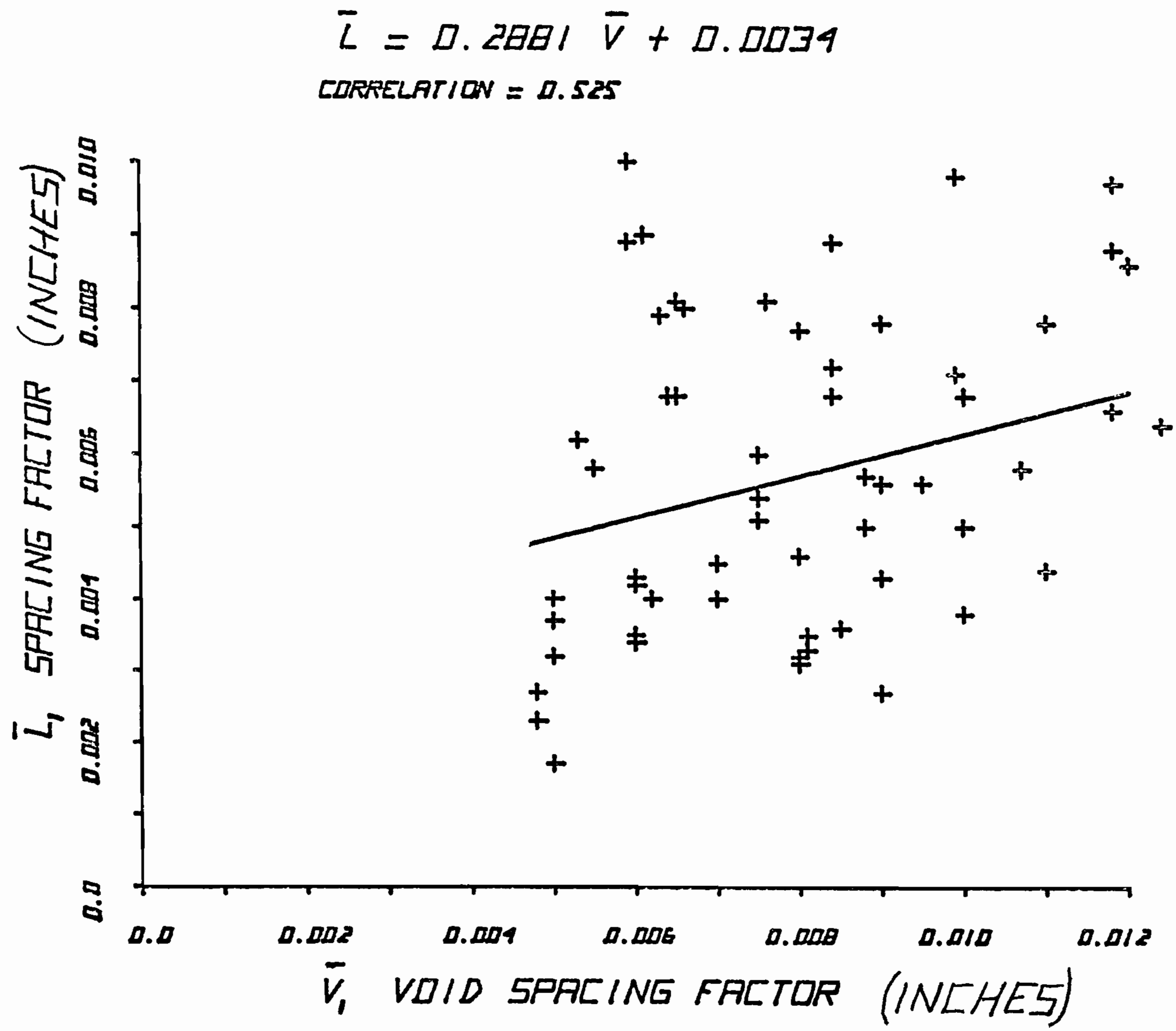
| Sample No. | $\bar{V}$ Inches | $\bar{L}$ Inches | $\bar{V}/\bar{L}$ | Air Press. Meter % | Air Chace % | Air Linear Traverse % |
|---|---|---|---|---|---|---|
| 22-32 | .0070 | .0045 | 1.56 | 4.4 | 4.0 | 7.75 |
| 22-33 | .0050 | .0037 | 1.40 | 4.3 | 4.0 | 7.75 |
| 22-34 | .0080 | .0031 | 2.58 | 4.2 | 5.0 | 10.02 |
| Average $\bar{x}$ | .0083 | .0046 | 1.89 | 4.95% | 4.85% | 7.95% |
| Std. Dev. | .0043 | .0024 | .555 | 1.509 | 1.36 | 2.217 |
| Coef. Var. $\bar{V}$ | 52.2% | 51.2% | 29.4% | 30.5% | 28.2% | 27.9% |
| No. of Tests n | 22 | 22 | 22 | 22 | 22 | 22 |

TABLE XI

Test Results From District 23

| Sample No. | $\bar{V}$ Inches | $\bar{L}$ Inches | $\bar{V}/\bar{L}$ | Air Press. Meter % | Air Chace % | Air Linear Traverse % |
|---|---|---|---|---|---|---|
| 23-T-1 | .0059 | .0089 | .66 | - | 2 | 4.19 |
| 23-T-2 | .0059 | .010 | .59 | - | 2 | 5.53 |
| 23-T-3A | .0118 | .0097 | 1.21 | 3.0 | - | 4.01 |
| 23-T-3B | .025 | .0097 | 2.57 | 3.0 | - | 3.43 |
| 23-T-4A | .0118 | .0088 | 1.34 | 3.0 | - | 4.01 |
| 23-T-4B | .025 | .0088 | 2.84 | 3.0 | - | 3.43 |
| 23-T-7 | .0088 | .0050 | 1.76 | 4.3 | 4.2 | 6.29 |
| 23-T-8 | .0088 | .0057 | 1.54 | 4.3 | 4.2 | 7.22 |
| 23-T-9 | .0084 | .0068 | 1.23 | 4.3 | - | 6.46 |
| 23-T-10 | .0084 | .0072 | 1.16 | 4.3 | - | 7.51 |
| 23-T-11 | .0064 | .0068 | 0.94 | - | 3.0 | 6.60 |
| 23-T-12 | .0065 | .0068 | 0.95 | - | 3.3 | 6.96 |
| 23-T-13 | .0099 | .0071 | 1.39 | 3.9 | 3.5 | 4.59 |
| 23-T-14 | .0099 | .0098 | 1.01 | 3.9 | 3.5 | 6.87 |
| Average $\bar{x}$ | .0109 | .0079 | 1.374 | 3.70% | 3.212% | 5.507% |
| Std. Dev. | .00628 | .00164 | .6494 | .6218 | .8543 | 1.5017 |
| Coef. Var. $\bar{V}$ | 57.6% | 20.7% | 47.2% | 16.8% | 26.6% | 27.3% |
| No. of Tests n | 14 | 14 | 14 | 10 | 8 | 14 |

TABLE XII




Graph of Void Spacing Relationship

## VII. DISCUSSION

Air entrained concrete has shown excellent resistance to freeze-thaw action for many years.[2] The benefits are well known, but often the actual physical process is not understood. Basically, the principal involved is the artificial introduction of a system of closely spaced air voids, evenly distributed throughout the concrete paste.

Water expands approximately 9% when it freezes. Then if the water is confined, the hydraulic pressure increases tremendously as the water begins to freeze. This is the situation encountered with saturated concrete. All of the bleed channels and micro pores are filled with water. As the water begins to freeze on the surface, a hydraulic pressure is exerted inward. The amount of pressure developed depends on the distance the liquid must travel to the nearest air void for pressure relief.

The air void is a small bubble space enclosed by the cement paste in the concrete.[3] It is so small that water will not enter it under normal atmospheric conditions. The surface tension of water is so great that it will not wet the interior of the air void. When the pressure builds up, a small portion of the shell of the bubble will break open, relieving this force. When the pressure starts rebuilding the water flows through the micro pores to the next air void and repeats the same pressure relief as the first one. This continues, so it is necessary to have these air voids closely spaced to prevent such a pressure buildup that would exceed the tensile strength of concrete.[4] When the thaw occurs, the built-up air pressure within the air void forces the water out of the bubble making it ready again for freezing action.

T. C. Powers[2] in 1945 established that smaller size air voids, closely spaced, greatly improve the durability of concrete. He suggested that the spacing between the air voids be no greater than 0.01 inches. He designated this spacing as $\bar{L}$ or the spacing factor in hardened concrete. R. C. Mielenz[5] and others have studied this theory. They have found that reducing this spacing factor ($\bar{L}$) to 0.008 inches or less produces a very noticeable increase in resistance to freeze-thaw damage.

Air entraining admixes became generally acceptable to the construction industry in the early 1950's. But in the latter part of that decade, the deterioration of bridge decks became a major problem all over the U.S.A. In 1961, the Portland Cement Association, in cooperation with the Bureau of Public Roads (now FHWA) and twelve state highway departments, undertook a comprehensive study of concrete bridge deck deterioration.[6] This was an in-depth study conducted in four phases to: first, determine the type and extent of bridge deck problems; second, determine the cause; third, develop methods for ensuring durability in new bridge decks; fourth, develop methods for the retardation of deterioration on now existing bridge decks. Random surveys and some in-depth investigations were made. Many discrepancies were discovered.

One factor that came out of this study was that excellent scale resistance was achieved when the concrete contained a uniform air void system with the spacing factor ($\bar{L}$) not over 0.010 inches.[2] Recommendations were made for further research by each state agency.

An extensive bridge deck deterioration study was made by the Texas Highway Department.[7] Cores were lifted and linear traverse measurements were made. Although generally air entrainment was not required on these bridges, among the observations in the traverse studies, there was evidence of low air content even when specified. Other research was being conducted in air entrained concrete at the Texas Transportation Institute.[8] This led into their study of air voids in ready mixed concrete[9] when the idea for the void spacing indicator was first formulated. Then the research project on the Void Spacing Indicator[1] was developed. Field testing was the recommendation made from that report.

The Void Spacing Indicator test technique is similar to that used in the Chace Air Indicator Test. A brass capful of mortar from the concrete is used for the sample to be tested. The VSI test differs in the fact that the Chace breaks the bubbles down (with alcohol) and consolidates the air to give a volume measurement while the VSI retains them as individual bubbles (in a water solution) to give a visual area of observation of the size and quantity of air bubbles in the sample. A problem of coalescence was observed by Torrens' and Ivey's report[1] so this was checked out thoroughly. None was observed by the author in any of his tests. In fact the test was left in the stage of testing where the bubbles were on the flat plate. The next day the bubbles were observed. No coalescence was observed and the bubbles had maintained their integrity during the hardening process. This was in conflict with Torrens and Ivey's findings.

To correlate between the VSI void spacing ($\bar{V}$) and the linear traverse void spacing ($\bar{L}$), many variables had to be used depending on the reliability of other tests. First from the design mix, the coarse and fine aggregate factors must be determined as well as the paste factor. From the design it must be assumed that the ready-mixed concrete plant made the actual design mix. Then at the construction site, the air content must be accurately determined, preferably by the pressure meter. Then the VSI test is run along with the other tests required. If any of the tests prior to the VSI test are in error then the void spacing factor ($\bar{V}$) will be incorrect, but in this field test it was assumed that all tests were valid. These were the conditions under which the research project was set to run the VSI field tests.

Inspector personnel were instructed in the proper method of running the VSI test at a meeting held in Austin prior to field testing. In the three day program, these inspectors became proficient in running the VSI test.

Later, projects in each District were selected and VSI tests were performed. Originally, it was thought that the broken end of test beam specimens would be sent in for examination. Approximately twenty-one beams were examined by linear traverse (see Table VI). While beams were providing the information on the tested concrete, it did not fully represent the inplace concrete as desired for this test. It was felt that cores lifted from the exact spots where the concrete was cast, would eliminate other variables that might be built in from the flexural beam end specimens. Cores were lifted later from completed projects and then examined by the linear traverse method. Sixty-four cores were examined and data compiled.

On preliminary examination, there was a possibility of some mathematical relationship between the void spacing of ($\bar{V}$) and ($\bar{L}$). A regression analysis was run but no valid relationship was established. The pairs were plotted by the Hewlett-Packard 9100B calculator plotter and the scatter was such that no valid relationship could exist between the two sets of data (Table XII). The correlation coefficient indicated little agreement on a line of best fit. Looking into the deviation from the mean, the figures indicated that they are probably not measurements relating to the same quality. Other statistical analysis were investigated with similar negative results.

Other phases of the test program were reexamined for possible source of errors. There was a variation between the percent of air in the plastic state versus the hardened state. Brown and Pierson(10) in their research found that these two measurements were approximately equal. The data from our research did not follow this theory. Pressure meters are calibrated annually or on special request when calibration is in doubt. The

Districts reported their equipment calibrated so this difference in air measurement became a problem. With this apparent disparity in our input data, a question arose on the possible error in our linear measuring equipment.

To check the reliability of this linear traverse, a request was sent to Portland Cement Association for some standard samples of concrete with known quantities of air. Three different operators ran linear traverse measurement on these standard samples and the following comparison is made:

| | Sample #1 | Sample #2 | Sample #3 | Sample #4 |
|---|---|---|---|---|
| THD Measurement (Average) | 3.05% | 4.28% | 5.55% | 8.38% |
| PCA Measurement | 2.96% | 4.26% | 5.91% | 8.55% |
| Difference | .09% | .02% | -0.36% | -0.17% |

The comparative measurements appeared to be within the tolerance expected among operators. But in order to check their data against ours, PCA was questioned. It was found that the samples they had sent us were not the standard reference samples that had been requested. On those samples sent, only one operator had made one run of approximately 60 linear inches on each of the four samples which is not considered adequate[10] for accurate calibration. Our three operators each ran over 90 linear inches per sample which is the recommended minimum traverse.

There were some minor problems in the field that led to some comments from them. One problem was trying to get the bubbles in a one layer system. Another was the problem of the large bubbles bulldozing their way through the finer bubbles making it difficult and time consuming in getting a proper square area measurement. The light plastic area-graph was changed to heavier plastic to help prevent it from blowing away by gusty winds. But overall, the concrete inspectors liked the test.

Other aspects of the VSI test were appraised and evaluated for benefits that might be derived. The most outstanding was the visual inspection of the bubble system. In the test procedure where the bubbles rise to the top against the glass plate, two items are quickly observed. First is the amount of bubbles and secondly, the individual bubble size. On a one layered system, the area covered is an indication of the quality of the air entraining system. For the same measured volume of air, the finer the division of the air bubbles, the more area will be covered under the flat plate. A frothy or foamy looking bubble system will normally indicate that the entrained air pattern is excellent. Larger size bubbles with only a little foam indicate a less desirable system. Another aspect in the VSI testing when measuring numerous ready-mixed concrete trucks, is to visually determine consistency of air-entrainment between the various loads. This is a cross-check against the slump test which is the normal test for consistency between batches. When there has been a change in the air content, it can be recognized very quickly by the test. This VSI test was hoped to be a method by which the durability against freeze-thaw could be tested and evaluated while the concrete was still in the plastic state. This would provide the inspector with a chance to reject the concrete prior to placement if the anticipated durability factor is low because of an inadequate air system.

While this study did not establish a correlation between the VSI test and the accepted linear traverse methods, it is the author's opinion that this tool would be a useful addition to the concrete technology field. It does give an indication of the type of entrained air system present in the plastic concrete. In those cases where the concrete technician does not have the control of all materials used in the batch and does not have the degree of inspection and testing required and exercised by the Texas Highway Department, the VSI test will be a valuable addition to his quality control tools.

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