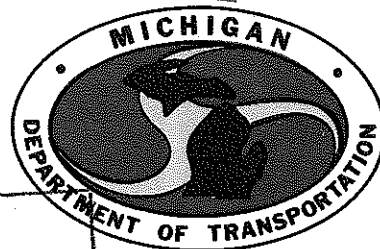


A STATISTICAL ANALYSIS OF POTENTIAL
RELATIONSHIPS BETWEEN SELECTED
CONCRETE AND AGGREGATE PROPERTIES
AND CONCRETE PAVEMENT PERFORMANCE



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MATERIALS and TECHNOLOGY DIVISION

A STATISTICAL ANALYSIS OF POTENTIAL
RELATIONSHIPS BETWEEN SELECTED
CONCRETE AND AGGREGATE PROPERTIES
AND CONCRETE PAVEMENT PERFORMANCE

Wen-Hou Kuo

Research Laboratory Section
Testing and Research Division
Research Project 76 A-26
Research Report No. R-1094

Michigan State Highway Commission
Peter B. Fletcher, Chairman; Carl V. Pellonpaa,
Vice-Chairman; Hannes Meyers, Jr., Weston E. Vivian
John P. Woodford, Director
Lansing, July 1978

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Introduction

The Department has performed freeze-thaw durability tests on coarse aggregate supplied by various aggregate sources since 1954. Moreover, condition surveys of concrete pavements containing coarse aggregate from these sources are also available. Sample preparation procedures and the test report form for the freeze-thaw durability test are included in Appendix A. Each freeze-thaw Test Report Form provides 22 material properties identified as V_1 through V_{22} in this report. Descriptions of these 22 variables can be found in the test report form and are summarized in Table 1. Pavement condition survey data provide the history of pavement cracking and joint deterioration. It is the intent of this study to explore potential relationships between the several material properties and the condition surveys of projects built with aggregate from the corresponding aggregate sources.

In order to establish the relationships between these two sets of data, it is first necessary to investigate intercorrelation among the 22 material properties themselves. If intercorrelation exists, it should be possible to reduce the number of variables needed to statistically predict pavement performance.

We present the detailed analyses in Appendices B (intercorrelation among the 22 variables from the Freeze-Thaw Durability Report Form) and C (relationship between pavement performance and the 22 variables from the Freeze-Thaw Durability Report Form) and summarize the findings below.

Conclusions and Remarks

1) Two hundred and sixty-three freeze-thaw durability tests on aggregate from various sources have been recorded. Each freeze-thaw test provides the 22 variables shown in Table 1. The relationship between any two variables is either very poor (see Figs. B-7 through B-22, Appendix B), or approximately linear (see Figs. B-1 through B-6 and Figs. B-24 through B-29, Appendix B). Those variables demonstrating a good linear relationship are presented in Table B-1, Appendix B.

2) Factor analysis¹ of the material properties from the Freeze-Thaw Durability Test Report Form shows some of the 22 variables appearing to belong to any of three groups, clusters, or factors. Furthermore, those variables which group together seem logically related (Appendix B).

¹ Factor analysis is a statistical method designed to group variables on the basis of their intercorrelations.

TABLE 1
FREEZE-THAW DURABILITY TEST RESULTS

	Variable	Description
Properties of Coarse Aggregate	V ₁	Bulk Specific Gravity (dry basis)
	V ₂	Absorption, percent - 24-hour soak
	V ₃	Absorption, percent - vacuum saturation
	V ₄	Ratio (V ₂ /V ₃)
	V ₅	Deleterious Particles, percent - soft and non-durable
	V ₆	Deleterious Particles, percent - chert
	V ₇	Deleterious Particles, percent - hard absorbent
	V ₈	V ₅ + V ₆ + V ₇
	V ₉	Soundness Loss, percent - 5 cycles MgSO ₄
	V ₁₀	Crushed Material in Sample, percent
Concrete Mix Data	V ₁₁	Sand, percent of total aggregate
	V ₁₂	Slump, in.
	V ₁₃	Weight per cu ft
	V ₁₄	Actual Cement Content, sack/cu yd
	V ₁₅	Net Water, Gps
	V ₁₆	Air, percent
Concrete Strength	V ₁₇	Concrete Strength, psi - compressive, 7-day
	V ₁₈	Concrete Strength, psi - compressive, 28-day
	V ₁₉	Concrete Strength, psi - flexural, 7-day
	V ₂₀	Concrete Strength, psi - flexural, 28-day
Freeze-Thaw Durability	V ₂₁	Freeze-Thaw Durability (cycles to failure) - 30 percent reduction in modulus
	V ₂₂	Durability Factor (300 cycles) - V ₂₁ x 70/300

3) No variable is well related to V₂₁ or V₂₂ as one can see from Figures B-30 through B-49, Appendix B. That is, the freeze-thaw durability (cycles to failure or durability factor) can not be well estimated by any of the other 20 variables (V₁ through V₂₀). The stepwise regression procedures were also used to determine if freeze-thaw durability can be reasonably estimated from linear combinations of V₁ through V₂₀. These procedures failed to find any combination of V₁ through V₂₀ which could adequately predict freeze-thaw durability (V₂₁).

4) The standard deviation and mean, based on nine samples of the freeze-thaw durability (cycles to failure) are plotted in Figure 1. If we define aggregate quality in terms of the number of freeze-thaw cycles to failure, it then follows that high quality aggregate can endure more freeze-thaw cycles before failure than can poor quality aggregate. By this definition, we see from Figure 1 that the variability (standard deviation) of freeze-thaw durability increases with aggregate quality (mean number of cycles) up to about 200 cycles. Beyond this point variability declines. This means that the test results of either good or poor quality aggregate are much more consistent or repeatable than those of mid-range quality. We do not know whether this is inherent in the nature of aggregate or is due to the precision of the freeze-thaw testing procedures.

5) In general, the variance of freeze-thaw durability is high. This could explain the poor relationship between V_{21} or V_{22} and the other 20 variables as concluded in 3) above.

6) Based on past experience², we decided to examine only construction projects that had at least 15 years of condition survey data. We located 50 such construction projects for the preliminary investigation. Unfortunately, the times of freeze-thaw testing were not consistent with the construction dates of these 50 projects. The differences are generally one or two years. This means that the two sets of data, freeze-thaw durability tests and pavement condition surveys, do not match. Moreover, 20 percent of these 50 construction projects were supplied by more than one pit source. Thus, we were forced to use averages of tests obtained from samples taken as close as possible to the time of construction.

7) The quantity of coarse aggregate used for freeze-thaw durability tests is too small to ensure statistical reliability. This means that the test results obtained from a small quantity of aggregate might differ considerably from the value obtained from a large number of samples from the same source.

8) There are many criteria for measuring pavement performance. Primarily because of 5) and 6) above, as well as simplicity of definition, we decided to use the proportion of joints that are spalled as the measure of pavement performance. If this measure relates well to freeze-thaw durability tests, we could then use more refined measures, along with the

² Holbrook, L. F., and Kuo, W. H., "General Evaluation of Current Concrete Pavement in Michigan," Michigan Department of State Highways and Transportation, Research Report No. R-905, 1974.

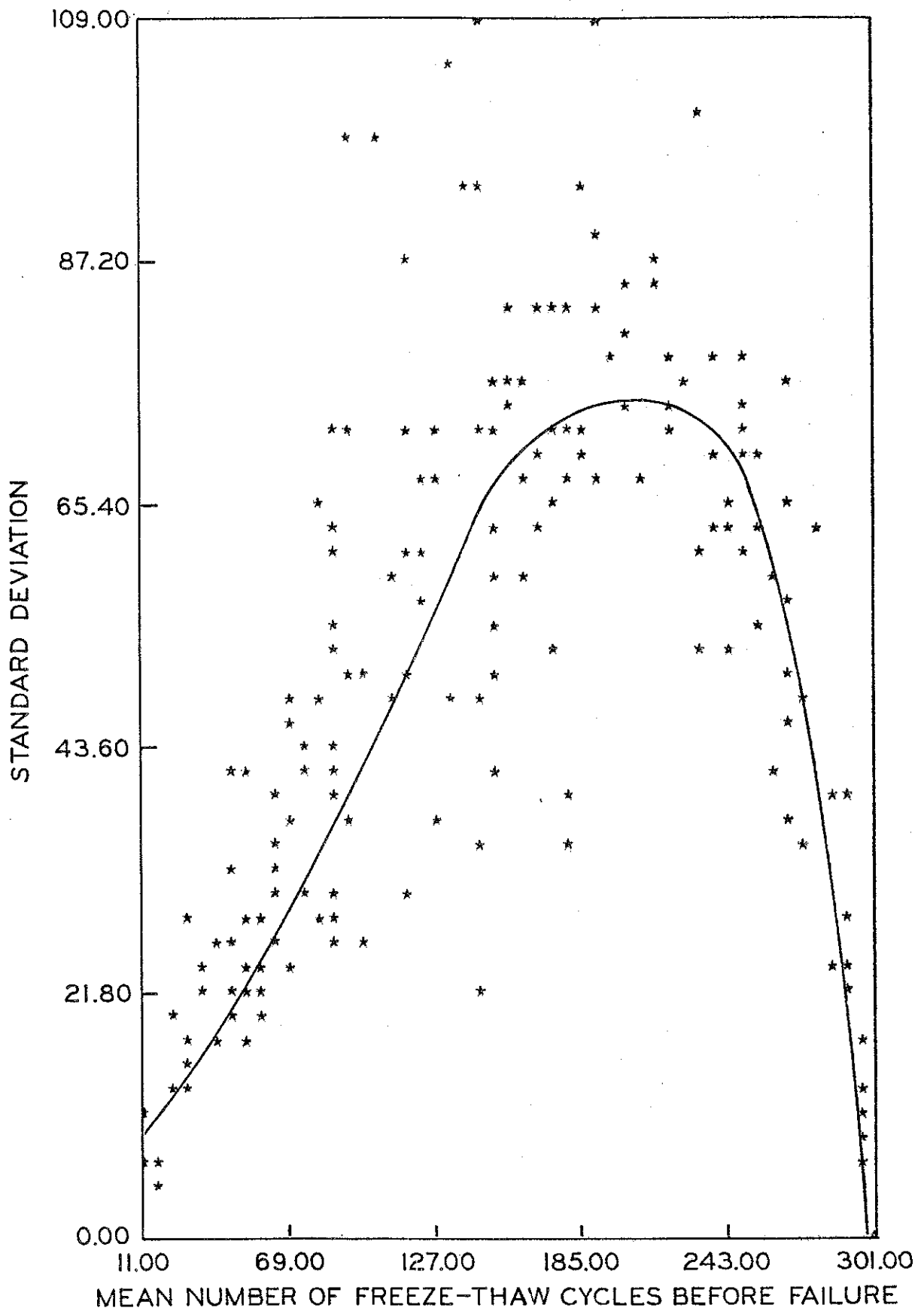


Figure 1. Mean versus standard deviation of the freeze-thaw durability (cycles to failure), based on nine samples.

traffic and weather data, to sharpen the investigation. As stated in Appendix C, no significant relationships were found between the proportion of joints deteriorated by spalling and freeze-thaw durability tests. This finding could be due to the unmatched data problem cited in 6) above or the data reliability problem cited in 7) above, or both.

9) We also sought relationships between freeze-thaw durability (cycles to failure) and the other 20 variables (V_1 through V_{20}) for each aggregate type--gravel and crushed limestone. Again, no significant relationships were found. As mentioned before, the large variation in freeze-thaw durability and the narrow ranges of the other 20 variables could prevent statistical identification of any association which might exist.

10) Research to date indicates that the susceptibility of coarse aggregate to freeze-thaw deterioration when critically saturated with water is the main cause of 'D-cracking.' Thus, weather data such as the number of natural freeze-thaw cycles, freezing rate, total precipitation and the percentage wet time should also be considered in the development of performance estimation procedures. Due to the cost of obtaining adequate weather data and the finding cited in 8) above, we decided not to further investigate potential relationships between weather data and pavement performance.

APPENDIX A
SAMPLE PREPARATION PROCEDURES
AND
TEST REPORT FORM

COARSE AGGREGATES FOR FREEZE-THAW DURABILITY TESTS

In nearly all instances, coarse aggregates for portland cement concrete for freeze-thaw durability testing are, and have been, obtained from trucks or stockpiles at the source of the aggregate. In a few cases, generally undeveloped sources, bank run granular material has been transported to an established plant where it was processed.

The coarse aggregate received for freeze-thaw testing is separated into the following size fractions:

- Passing 1-inch, Retained on 3/4-inch sieve.
- Passing 3/4-inch, Retained on 1/2-inch sieve.
- Passing 1/2-inch, Retained on 3/8-inch sieve.
- Passing 3/8-inch, Retained on No. 4 sieve.

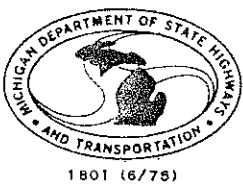
From this sorted material the following samples are taken for laboratory testing:

1. Petrographic Analysis. This sample consists of:
 - 7,500 gm. of 1-inch to 3/4-inch material.
 - 3,000 gm. of 3/4-inch to 1/2-inch material.
 - 1,500 gm. of 1/2-inch to 3/8-inch material.
 - 500 gm. of 3/8-inch to No. 4 sieve material.

From one full bag of each sieve fraction noted above, the following samples are obtained:

2. Los Angeles "B" Abrasion. This sample consists of:
 - 2,500 gm. of passing 3/4-inch, retained on 1/2-inch sieve.
 - 2,500 gm. of passing 1/2-inch, retained on 3/8-inch sieve.
3. Soundness Loss. This sample consists of:
 - 1,500 gm. of passing 1-1/2-inch, retained on 3/4-inch sieve.
 - 1,000 gm. of passing 3/4-inch, retained on 3/8-inch sieve.
 - 300 gm. of passing 3/8-inch, retained on No. 4 sieve.
4. Absorption (two samples). These samples consist of:
 - 1,250 gm. of each sieve size.

(The 24 hour soak absorption sample is returned to the Aggregate Laboratory for determination of deleterious particle content.)



REPORT OF TEST

FREEZE-THAW DURABILITY

Sheet 1 of 2

Project	General
Job No.	
Laboratory No.	55 A-2382
Date	

Report on sample of <u>Coarse Aggregate</u>	
Date sampled <u>February 2, 1955</u>	Date received <u>June 9, 1955</u>
Source of material <u>American Aggregate Corp., Oxford, Pit No. 63-4</u>	
Sampled from <u>Stockpile</u>	Quantity represented <u>---</u>
Submitted by <u>Walter Gula</u>	
Intended use <u>Aggregate Freeze-Thaw Durability</u>	Specification <u>1950 R & B</u>

TEST RESULTS

Properties of Coarse Aggregate

Bulk Specific Gravity (Dry Basis) 2.67

Absorption, percent

24 hour soak 1.25

Vacuum-saturation 1.48

Ratio 0.84

Deleterious Particles, percent

Soft and Non-durable 1.7

Chert 2.2

Hard Absorbent 0.7

Total 4.6

Soundness Loss, percent* (5 cycles $MgSO_4$) 4.2

Crushed Material, percent 34.5

Concrete Mix Data

Date Made 6-16-55

Sand, percent of total agg. 38

Slump, in. 1-1/2

Weight per cu ft, lb 149.2

Actual Cement Content, sk/cu yd 5.59

Net Water, Gps 4.80

Air, percent 4.9

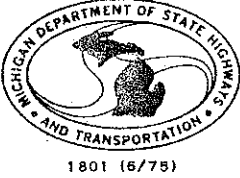
Concrete Strength, psi

Compressive

7 days

28 days

	Batch Number			Average
	1	2	3	
	6-16-55	6-23-55	7-19-55	
	38	38	38	38
	1-1/2	1-7/8	3	2-1/8
	149.2	149.0	147.5	148.6
	5.59	5.56	5.50	5.55
	4.80	5.06	5.10	4.99
	4.9	5.0	7.0	5.6
	2560) 2660	2300) 2280	2460) 2490	2475
	2755)	2260)	2515)	
	3980) 3815	3135) 3090	3215) 3210	3370
	3650)	3040)	3200)	



REPORT OF TEST

FREEZE-THAW DURABILITY

Sheet 2 of 2

Project	General
Job No.	
Laboratory No.	55 A-2382
Date	

Report on sample of <u>Coarse Aggregate</u>	
Date sampled _____	Date received _____
Source of material _____	
Sampled from _____	Quantity represented _____
Submitted by _____	
Intended use _____	Specification _____

TEST RESULTS

	Batch Number						Average
	1		2		3		
Concrete Strength, psi							
Flexural							
7 days	725 755	740	650 640	645	615 610	615	665
28 days	880 810	845	650 690	670	705 695	700	740
Freeze-Thaw Durability							
Cycles to Failure							
(30% Reduction in Sonic Modulus)							
Beam 1	223		66		221		
Beam 2	257		15		119		
Beam 3							
Average	240		41		170		150
Durability Factor (300 Cycles)							
Beam 1	52		15		52		
Beam 2	60		4		28		
Beam 3							
Average	56		10		40		35

REMARKS: * Soundness Test conducted according to ASTM C88-56T (Alternate B)

cc: R. H. Vogler

Signed _____
Engineer of Testing

APPENDIX B
INTERCORRELATIONS AMONG THE MATERIAL
PROPERTIES FOUND ON THE FREEZE-THAW
DURABILITY TEST FORM

After examining plots of each variable pair, we observe that the relationship between every two variables is either very poor or approximately linear. Therefore, we may use Factor Analysis to further analyze these test results (Table 1). It turns out that some of the 22 variables can be expressed by three (unknown) common factors F_1 , F_2 , and F_3 as follows:

$$V_1 = -0.7611 F_1 + 0.2740 F_2 - 0.2519 F_3 \quad (\text{B-1})$$

$$V_2 = 0.7944 F_1 - 0.2465 F_2 + 0.4225 F_3 \quad (\text{B-2})$$

$$V_3 = 0.7965 F_1 - 0.2444 F_2 + 0.4371 F_3 \quad (\text{B-3})$$

$$V_5 = 0.6902 F_1 - 0.2532 F_2 + 0.2248 F_3 \quad (\text{B-4})$$

$$V_6 = -0.0387 F_1 - 0.7025 F_2 - 0.4048 F_3 \quad (\text{B-5})$$

$$V_8 = 0.6891 F_1 - 0.4535 F_2 + 0.0732 F_3 \quad (\text{B-6})$$

$$V_9 = 0.6577 F_1 + 0.0644 F_2 + 0.3516 F_3 \quad (\text{B-7})$$

$$V_{10} = 0.3553 F_1 + 0.7378 F_2 + 0.3685 F_3 \quad (\text{B-8})$$

$$V_{13} = -0.8272 F_1 - 0.1096 F_2 - 0.0935 F_3 \quad (\text{B-9})$$

$$V_{17} = -0.4386 F_1 - 0.2464 F_2 + 0.7908 F_3 \quad (\text{B-10})$$

$$V_{18} = -0.4452 F_1 - 0.2123 F_2 + 0.7855 F_3 \quad (\text{B-11})$$

$$V_{19} = -0.6530 F_1 - 0.1734 F_2 + 0.5838 F_3 \quad (\text{B-12})$$

$$V_{20} = -0.6446 F_1 - 0.1377 F_2 + 0.5635 F_3 \quad (\text{B-13})$$

$$V_{21} = -0.2220 F_1 + 0.7882 F_2 + 0.1916 F_3 \quad (\text{B-14})$$

$$V_{22} = -0.1937 F_1 + 0.7985 F_2 + 0.1972 F_3 \quad (\text{B-15})$$

Variables V_4 , V_7 , V_{11} , V_{12} , V_{14} , V_{15} and V_{16} can not be well described by the three common factors. Coefficients of the above equations reflect the importance of each factor in the composition of each variable. As one can see from these equations, every variable is significantly associated with at least two factors. However, Factor 1 is dominated by variables V_1 , V_2 , V_3 , V_5 , V_8 , V_9 and V_{13} ; Factor 2 is dominated by variables V_6 , V_{10} , V_{21} and V_{22} ; and Factor 3 is dominated by variables V_{17} through V_{20} . By referring to variable definitions in Table 1, it seems reasonable to designate Factors 1, 2, and 3 as the properties of coarse aggregate, freeze-thaw durability, and concrete strength, respectively.

Upon close examination of coefficients in these equations, one would expect that V_1 , V_2 , V_3 , and V_{13} from Factor 1; V_{21} and V_{22} from Factor 2; and V_{17} , V_{18} , V_{19} and V_{20} from Factor 3 to be the only variables that can be expressed in terms of each other (within the same factor). This can

be more readily visualized with the help of Figures B-1 through B-29. Corresponding regression lines are presented in Table B-1. The regression line between V_{21} and V_{22} is not included in Table B-1 because their relationship is exactly specified by $V_{22} = V_{21} \times 70/100$ for $V_{21} \leq 300$ and is, therefore, not statistical.

At this point, we are especially interested in the estimation of freeze-thaw durability (V_{21}) from variables V_1 through V_{20} . From Figures B-30 through B-49, we see that none of these variables can alone estimate V_{21} within a reasonable degree of accuracy. Since factor analysis indicates that every variable is more or less associated with the factor related to V_{21} , stepwise regression analysis was used to obtain the following regression equation.

$$V_{21} = 3533.75 + 147.56 V_1 - 31.61 V_2 + 1.51 V_5 - 23.14 V_6 + 1.90 V_{11} - 12.86 V_{12} - 5.94 V_{14} - 1311.83 V_{15} \quad (B-16)$$

The standard error of estimation is 60.49 and the regression line can only explain 61.44 percent of the total variation. Moreover, the plot of residuals versus actual test results reveals a non-random pattern. For these reasons, we conclude that V_{21} can not be well estimated by linear combinations of variables V_1 through V_{20} . Although we do not know whether V_1 can be expressed by a non-linear function of variables V_1 through V_{20} , this possibility is extremely slim in light of Figures B-30 through B-49 and the large variance of V_{21} .

TABLE B-1
COEFFICIENTS OF THE REGRESSION LINE
 $Y = a + bX$

Variables		Coefficients		Correlation Coefficient of Y and X	Standard Error	No. of Data Points
Y	X	a	b			
V_2	V_1	19.72	-6.91	-0.76	0.48	263
V_3	V_1	27.77	-9.85	-0.77	0.66	263
V_{13}	V_1	101.87	17.31	0.73	1.34	263
V_3	V_2	-0.23	1.35	0.97	0.27	263
V_{18}	V_{17}	442.15	1.20	0.96	213.05	263
V_{19}	V_{17}	400.76	0.095	0.75	51.78	263
V_{20}	V_{19}	159.97	0.97	0.87	43.18	263

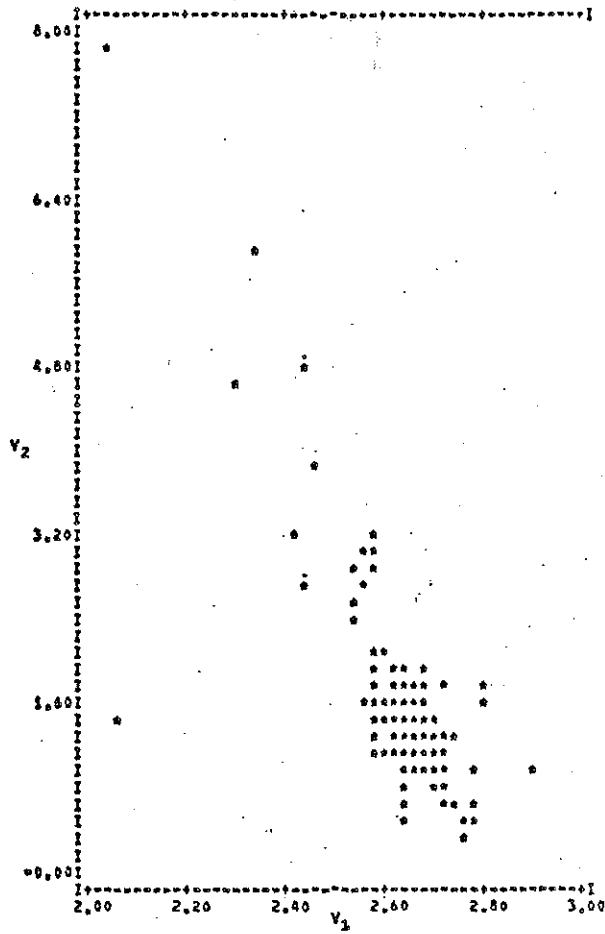


Figure B-1. The relationship between V_1 and V_2 .

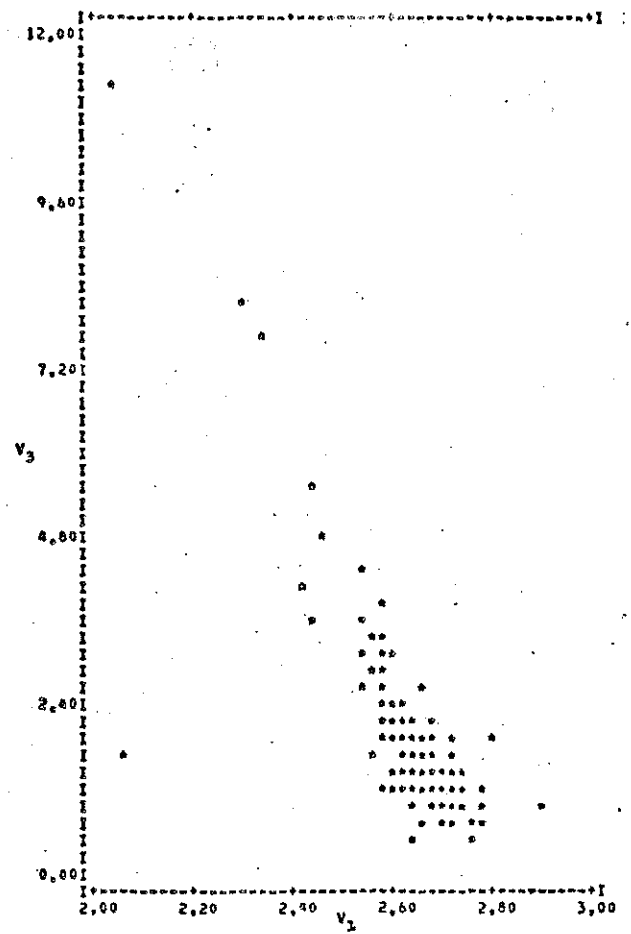


Figure B-2. The relationship between V_1 and V_3 .

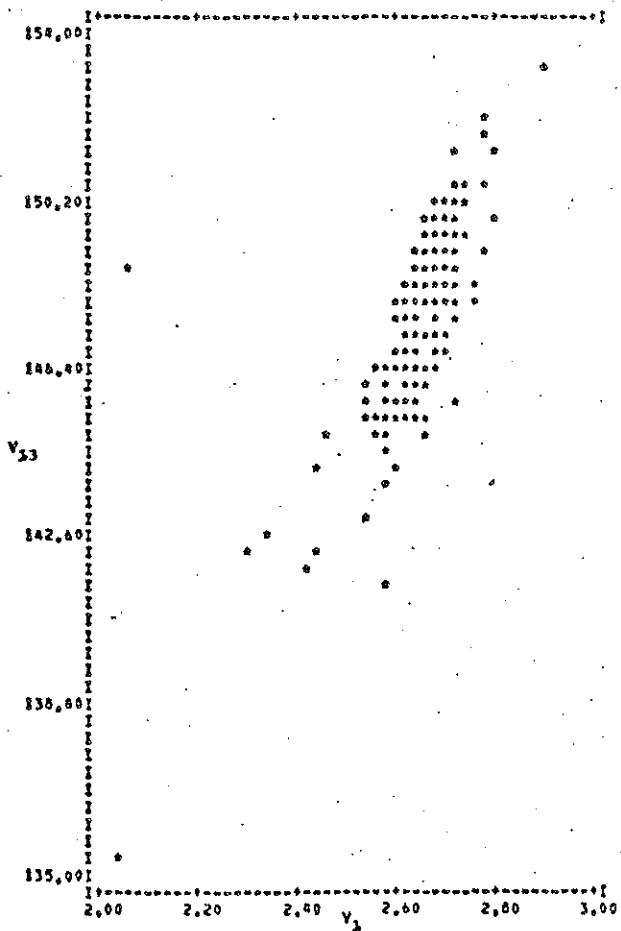


Figure B-3. The relationship between V_1 and V_{33} .

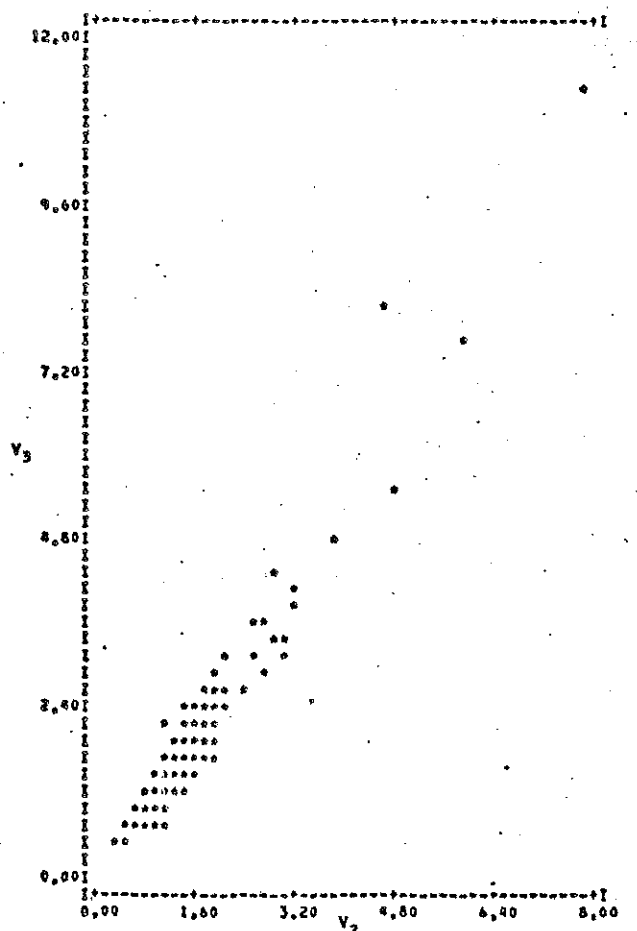


Figure B-4. The relationship between V_2 and V_3 .

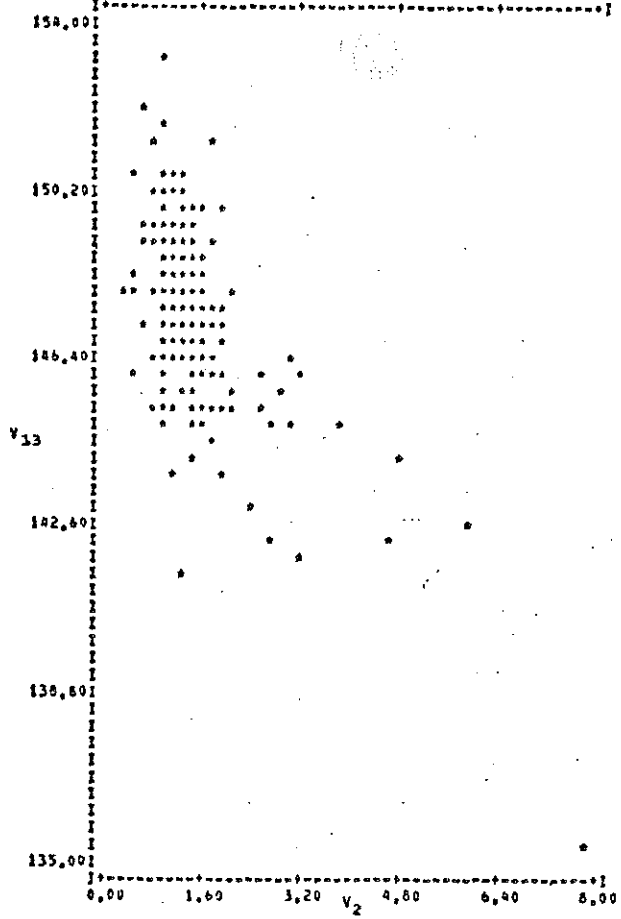


Figure B-5. The relationship between V_2 and V_{13} .

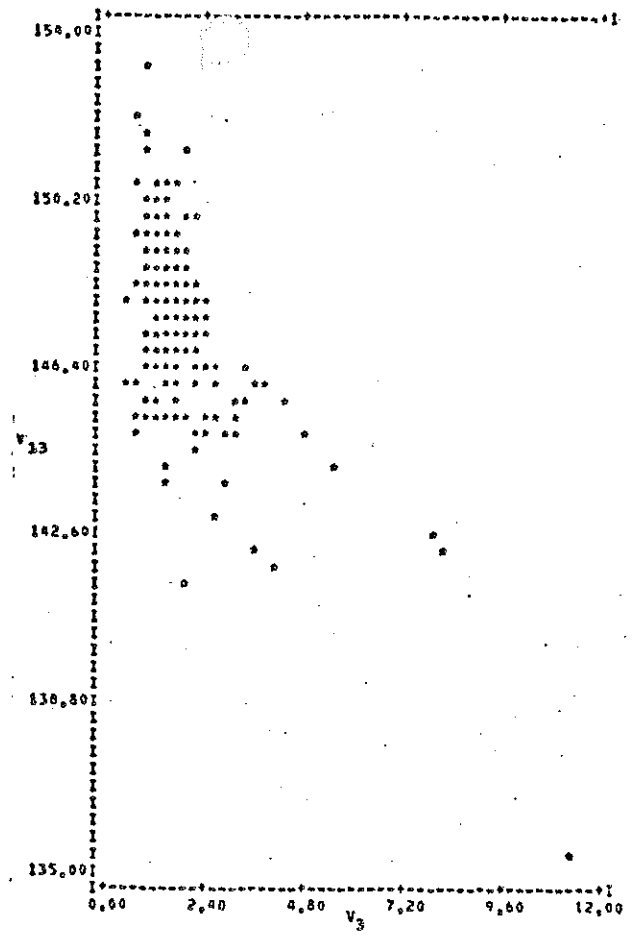


Figure B-6. The relationship between V_3 and V_{13} .

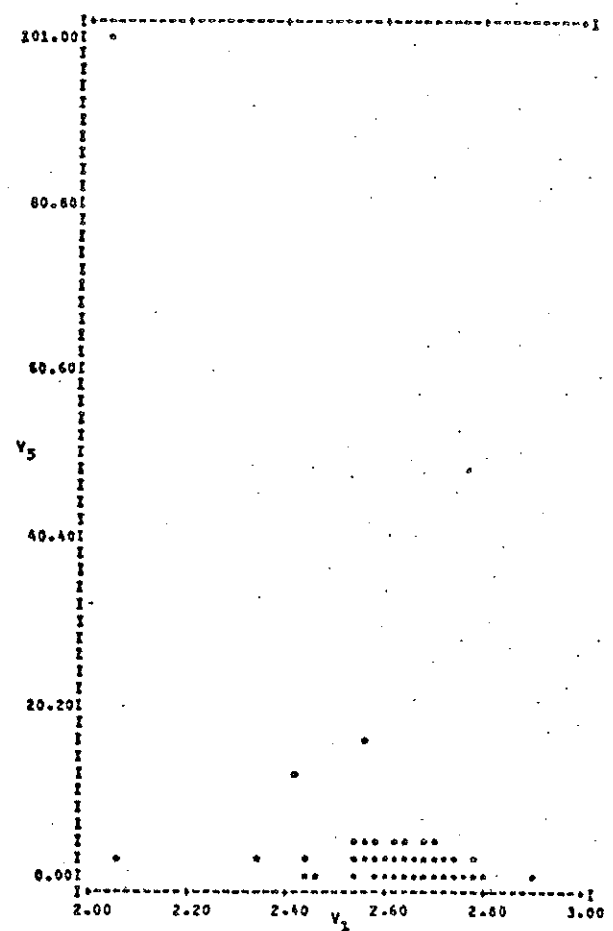


Figure B-7. The relationship between V_1 and V_5 .

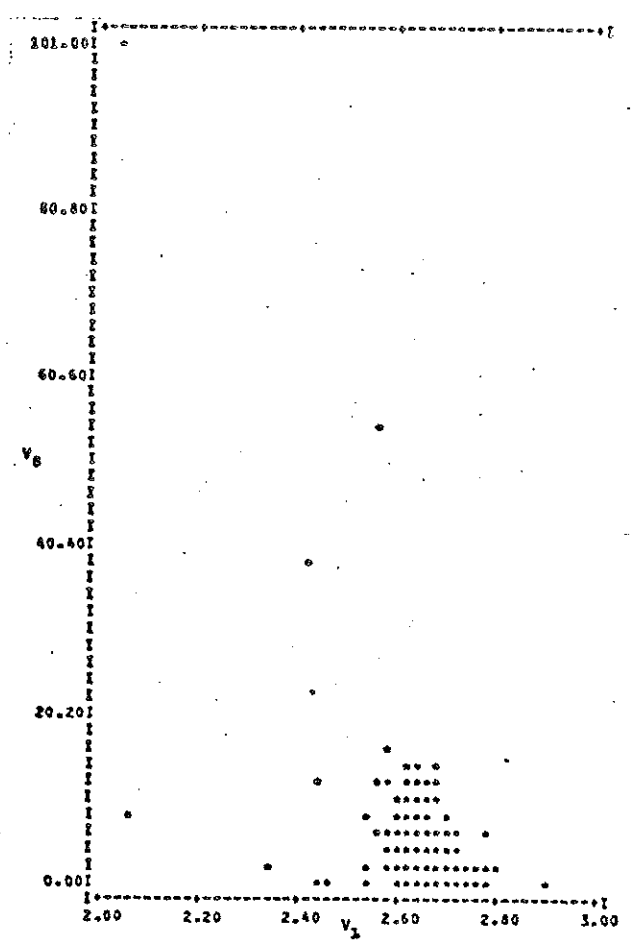


Figure B-8. The relationship between V_1 and V_6 .

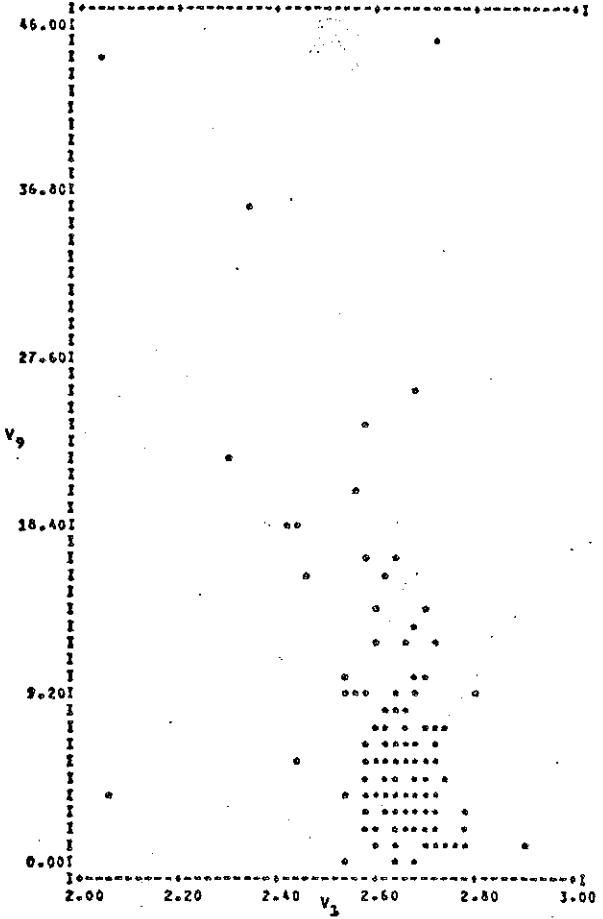


Figure B-9. The relationship between V_3 and V_9 .

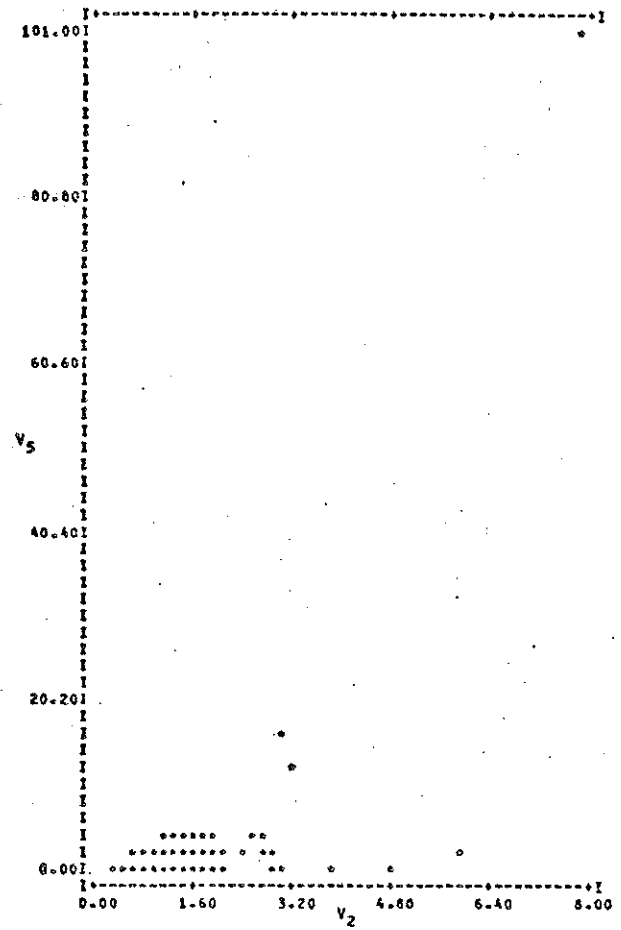


Figure B-10. The relationship between V_2 and V_5 .

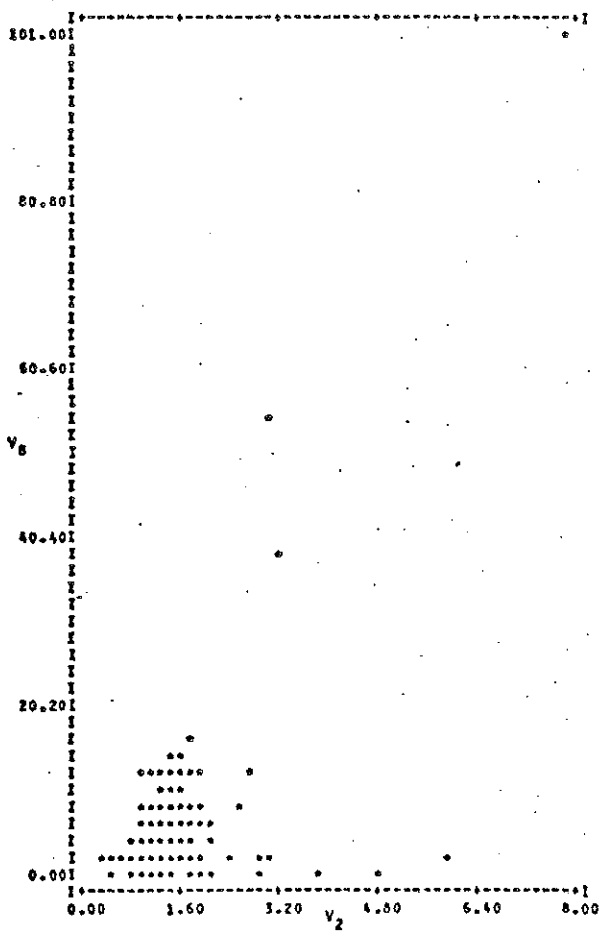


Figure B-11. The relationship between V_2 and V_8 .

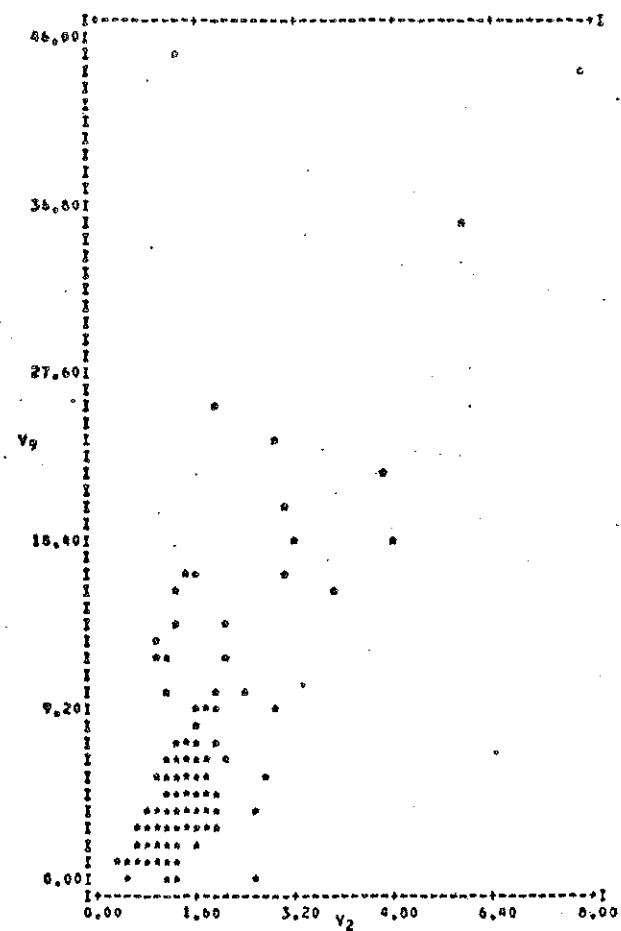


Figure B-12. The relationship between V_2 and V_9 .

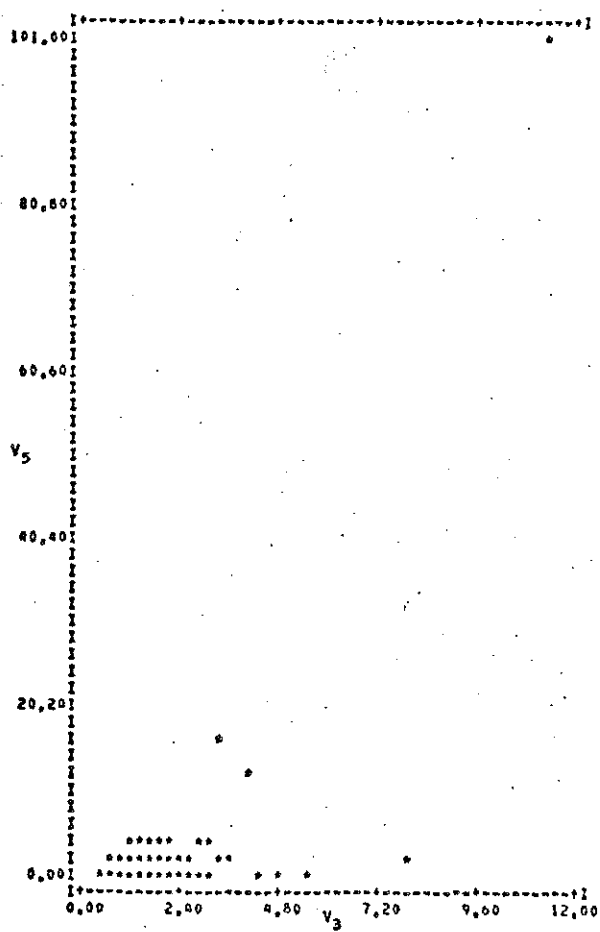


Figure B-13. The relationship between V_3 and V_5 .

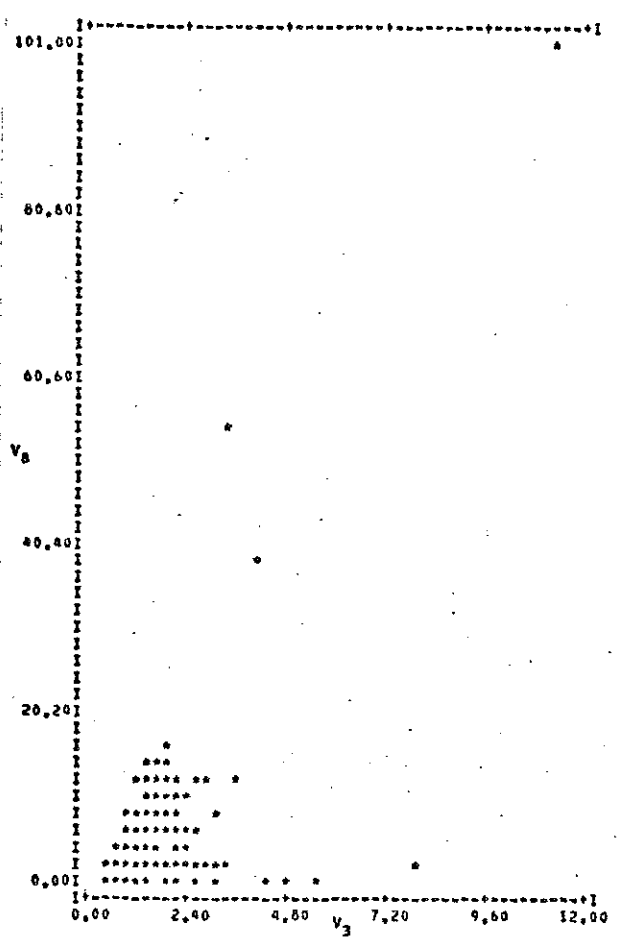


Figure B-14. The relationship between V_3 and V_8 .

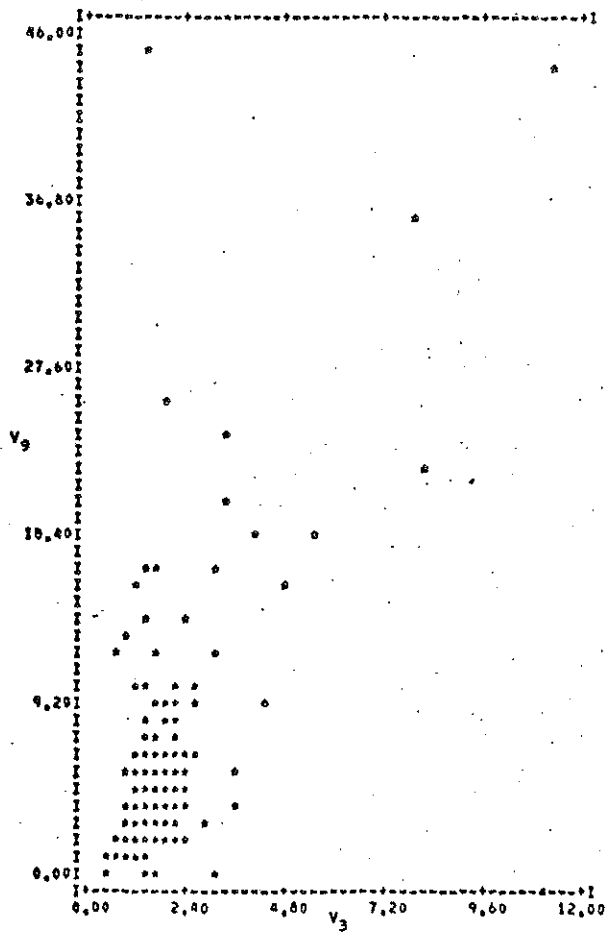


Figure B-15. The relationship between V_3 and V_9 .

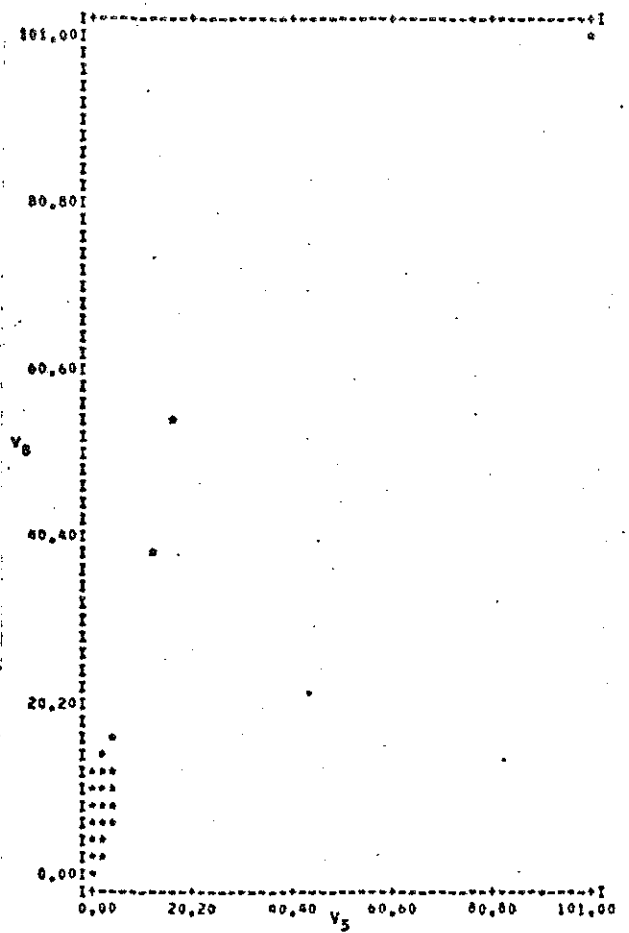


Figure B-16. The relationship between V_5 and V_6 .

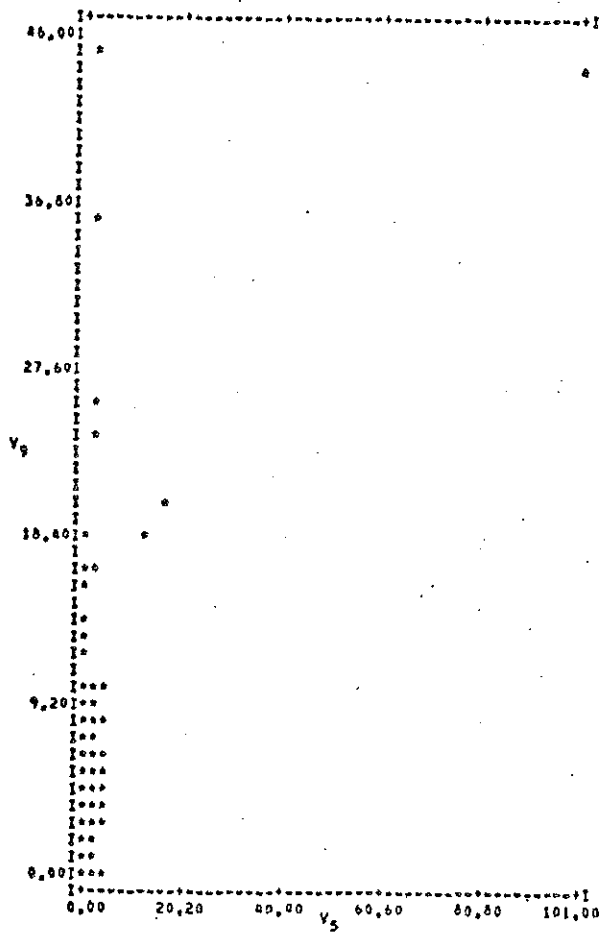


Figure B-17. The relationship between V_5 and V_9 .

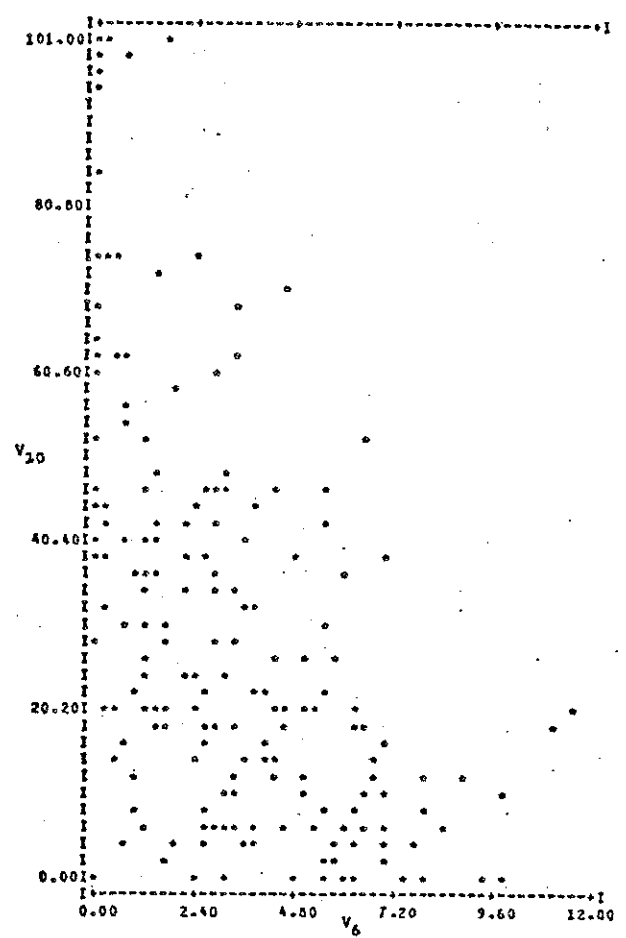


Figure B-18. The relationship between V_6 and V_{10} .

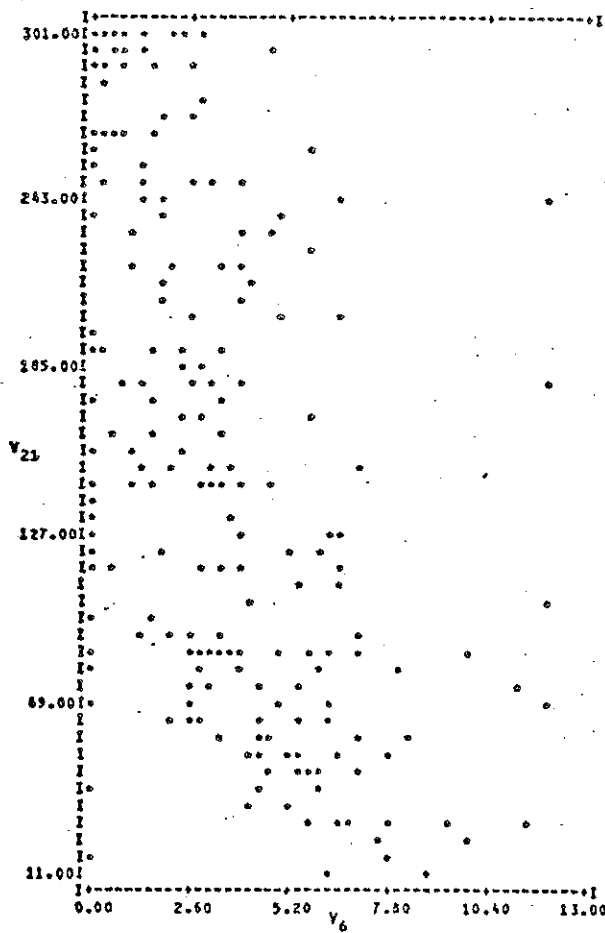


Figure B-19. The relationship between V_6 and V_{21} .

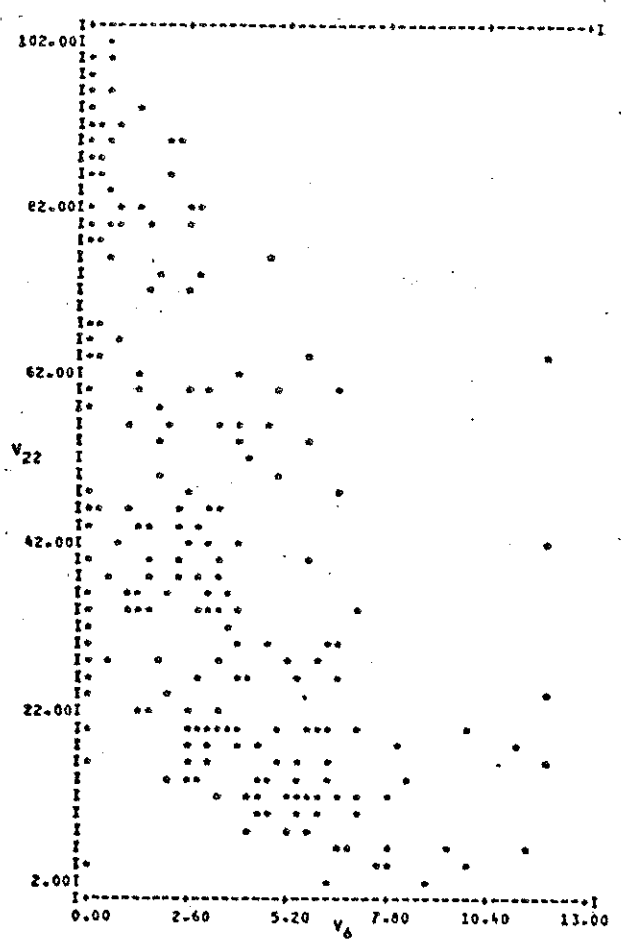


Figure B-20. The relationship between V_6 and V_{22} .

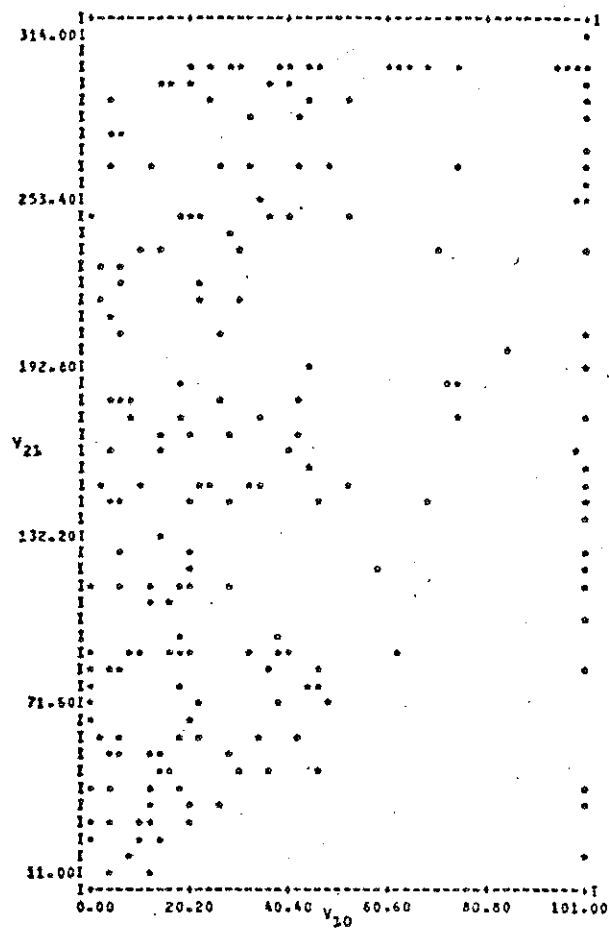


Figure B-21. The relationship between V_{10} and V_{21} .

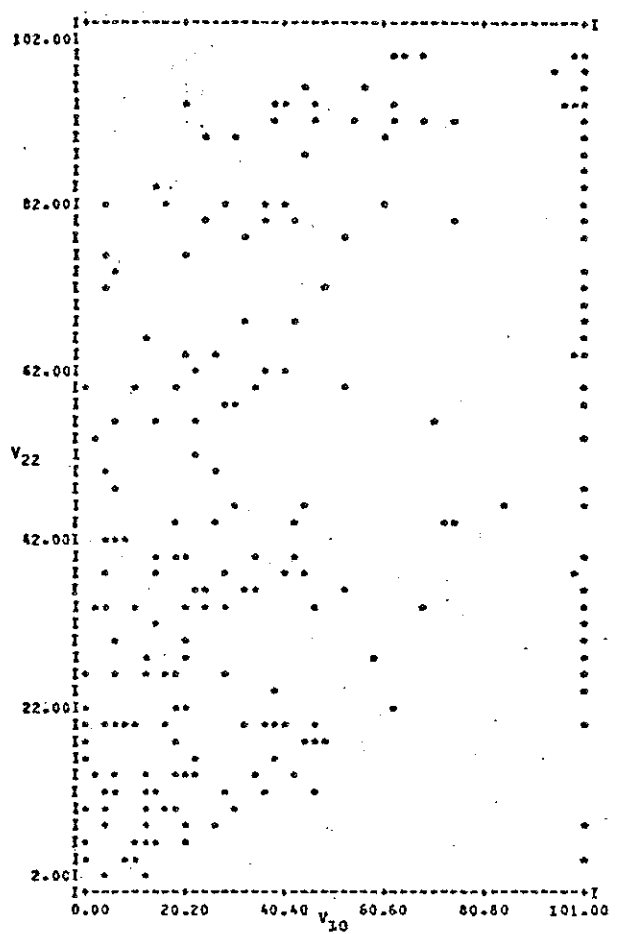


Figure B-22. The relationship between V_{10} and V_{22} .

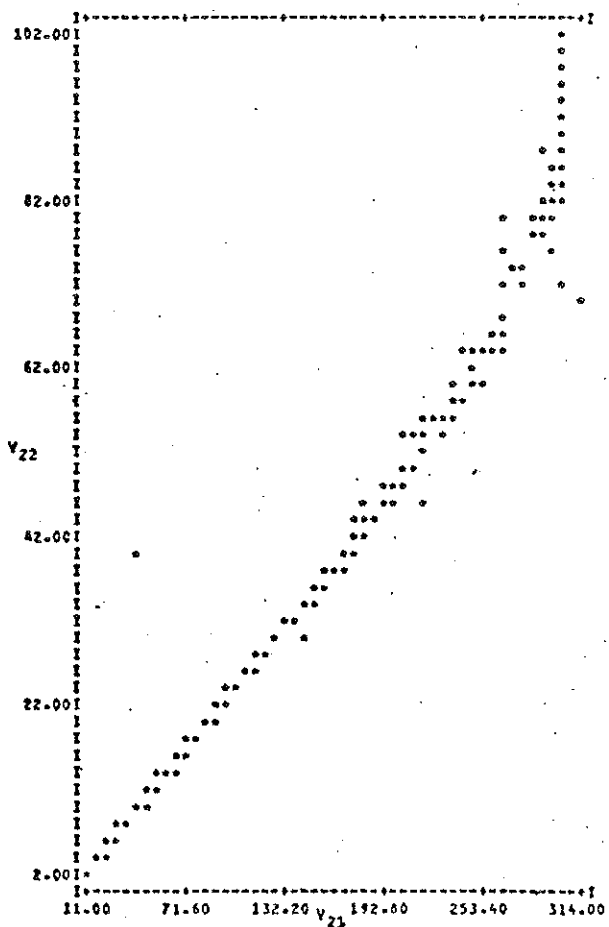


Figure B-23. The relationship between V_{21} and V_{22} .

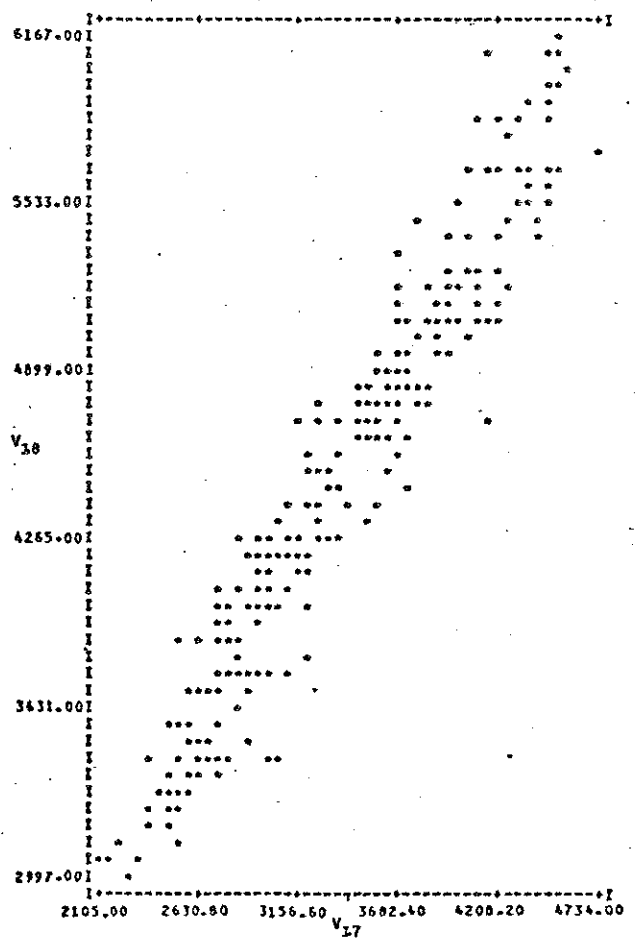


Figure B-24. The relationship between V_{17} and V_{18} .

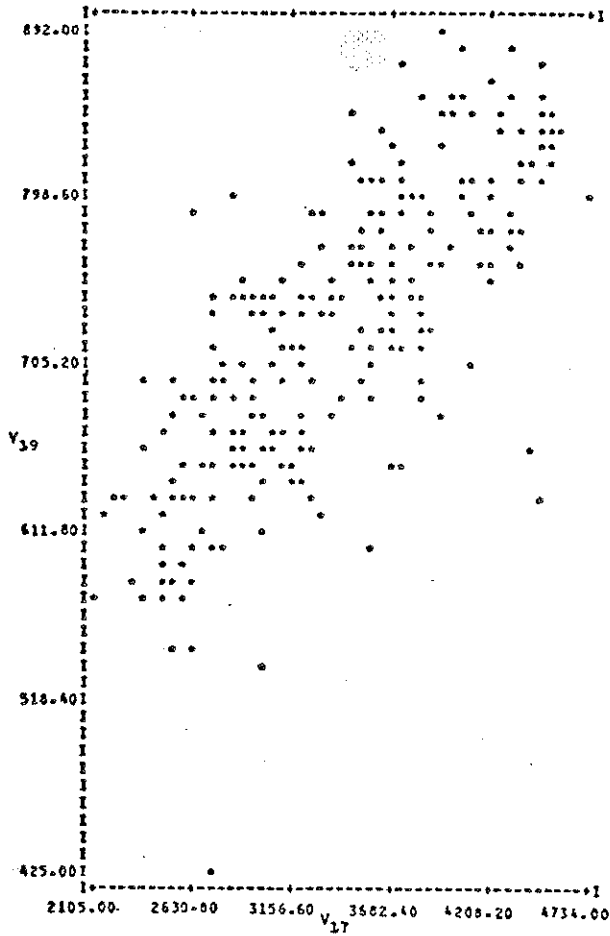


Figure B-25. The relationship between V_{17} and V_{19} .

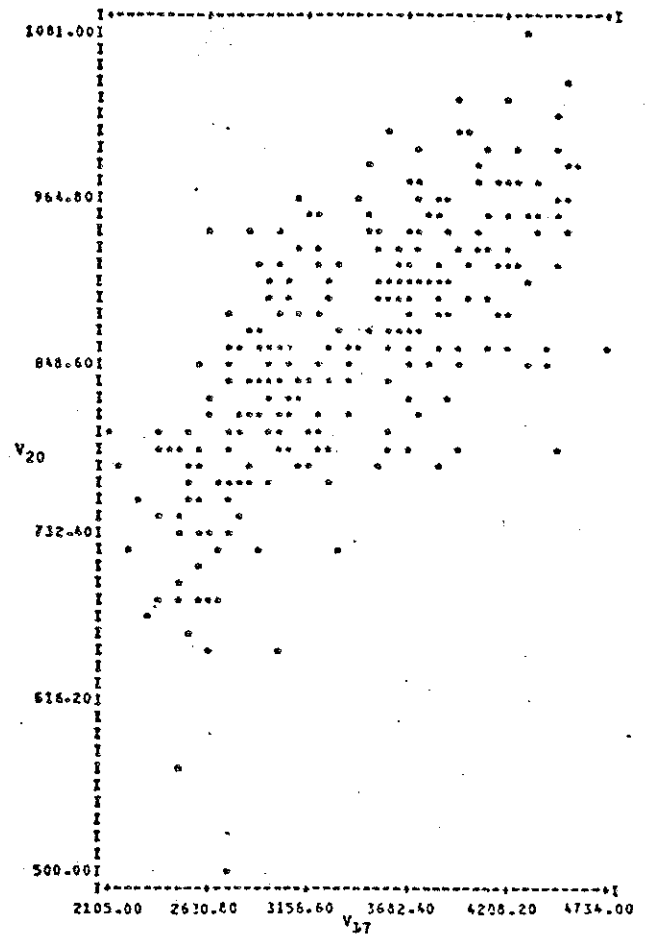


Figure B-26. The relationship between V_{17} and V_{20} .

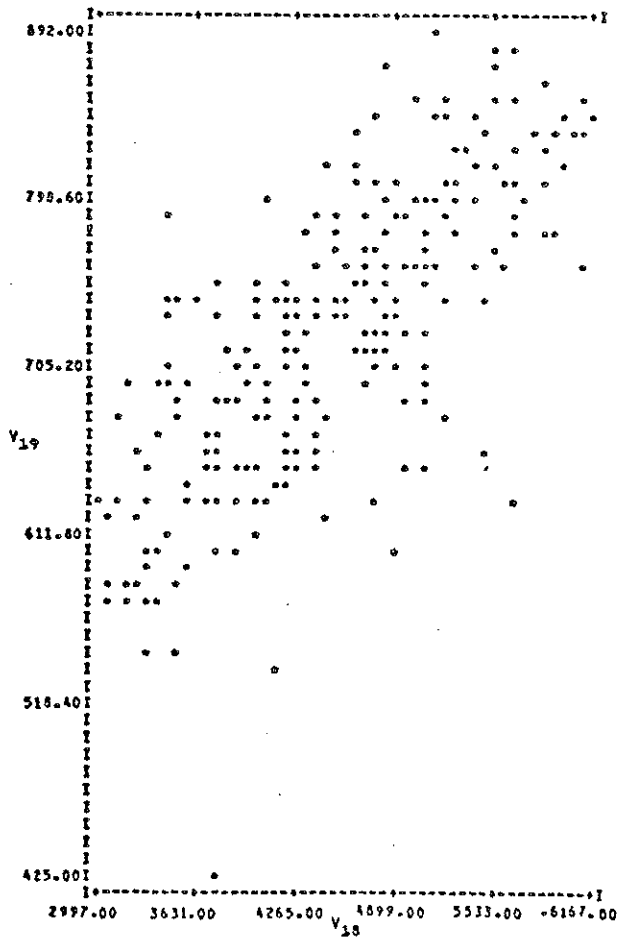


Figure B-27. The relationship between V_{18} and V_{19} .

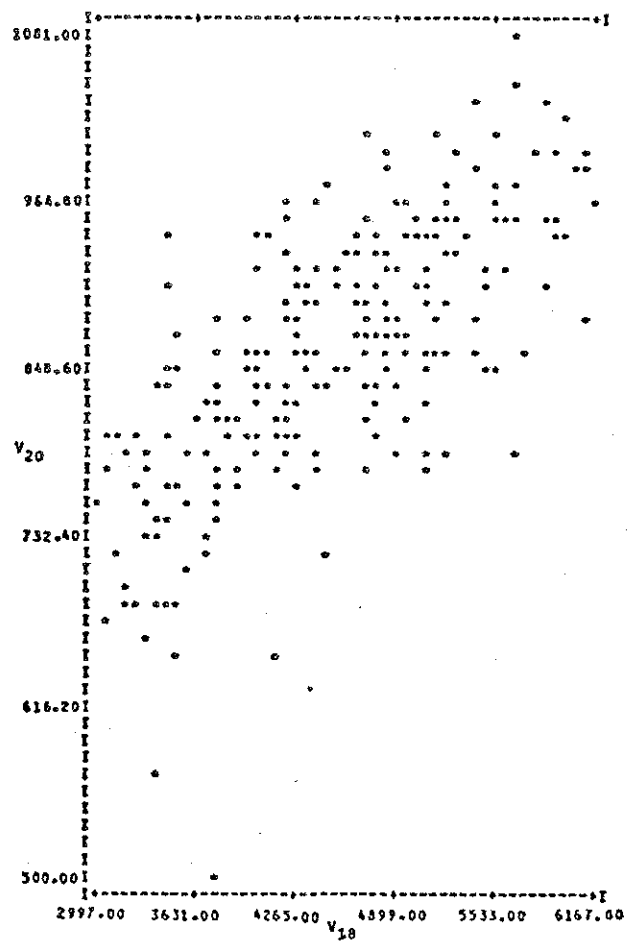


Figure B-28. The relationship between V_{18} and V_{20} .

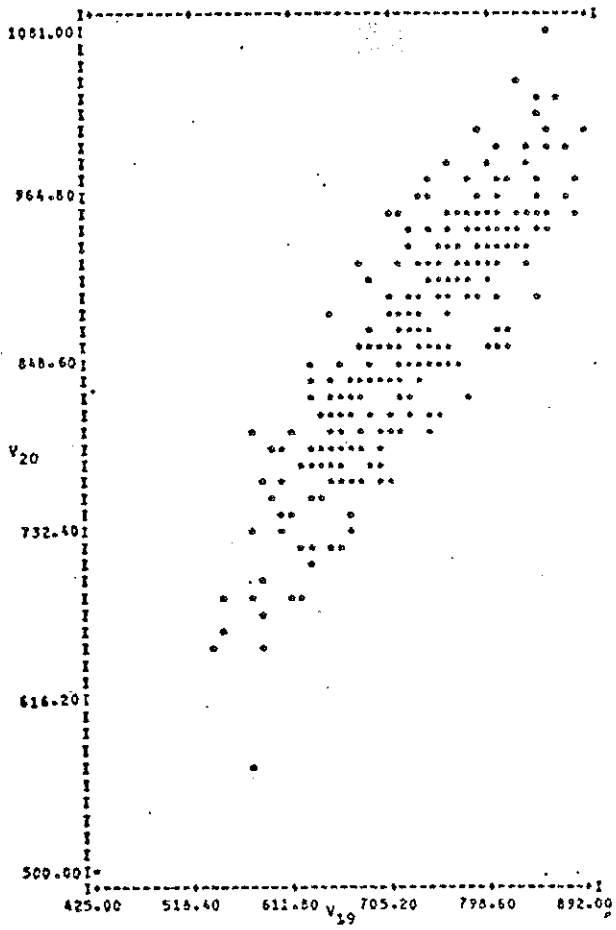


Figure B-29. The relationship between V_{19} and V_{20} .

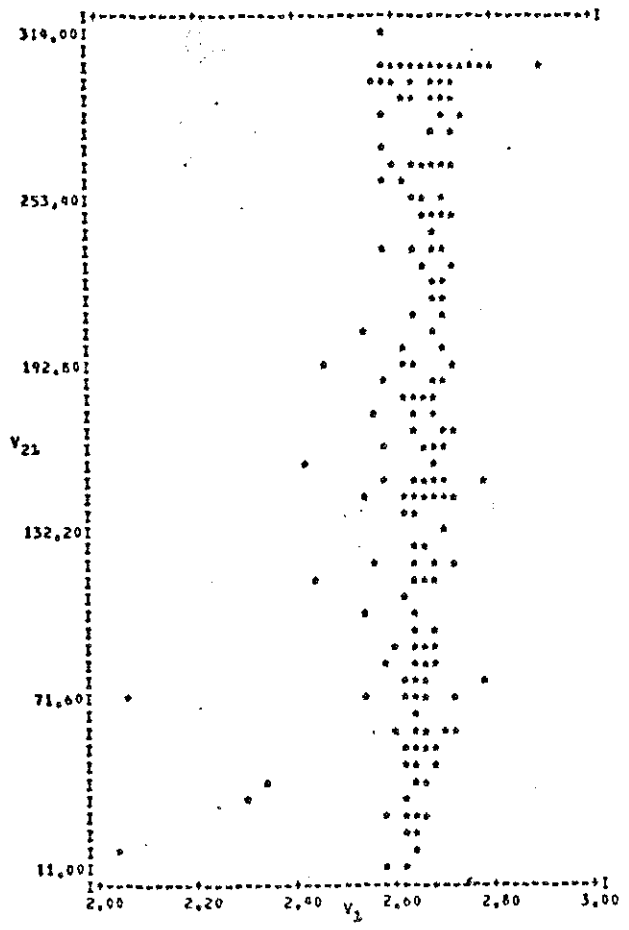


Figure B-30. The relationship between V_3 and V_{21} .

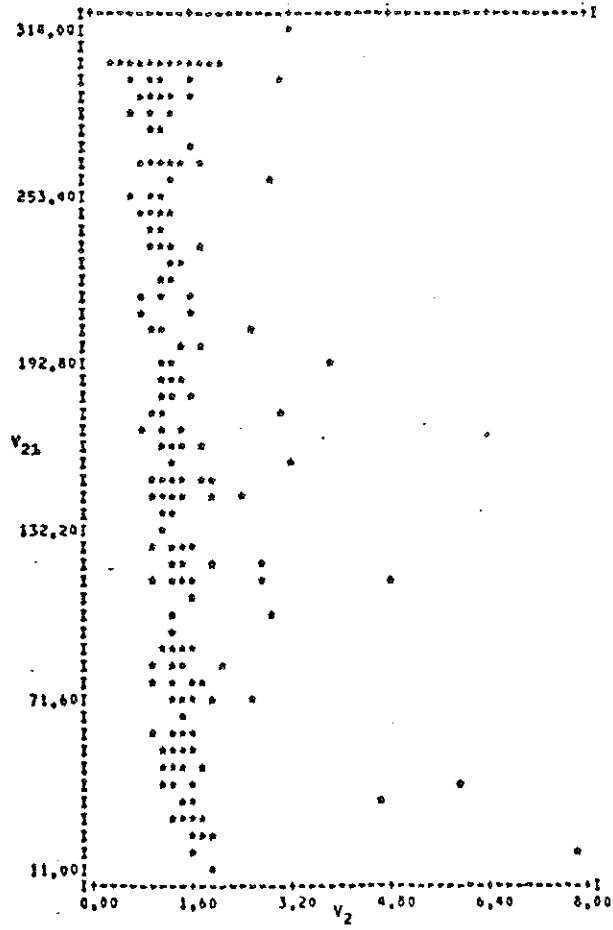


Figure B-31. The relationship between V_2 and V_{21} .

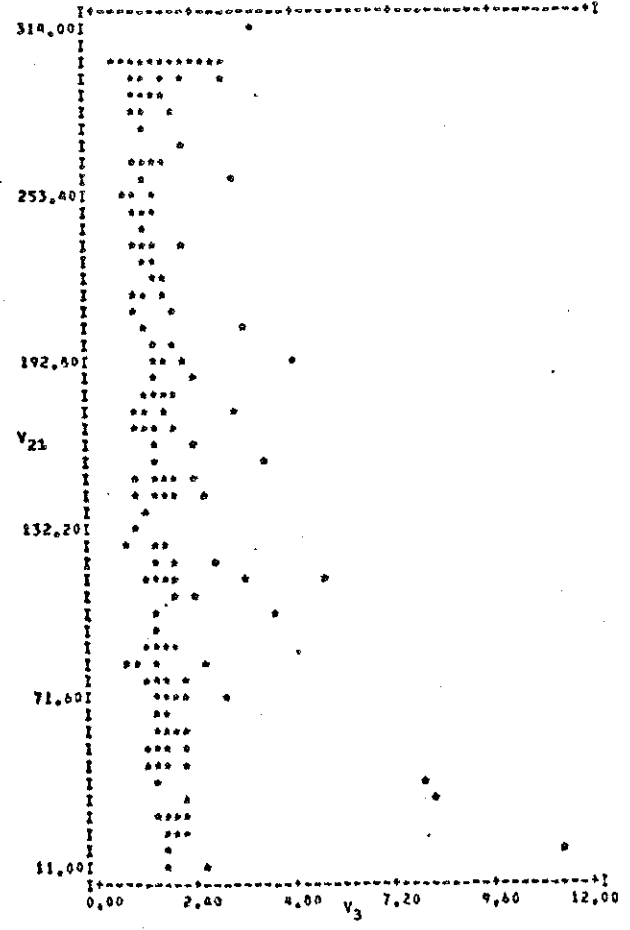


Figure B-32. The relationship between V_3 and V_{21} .

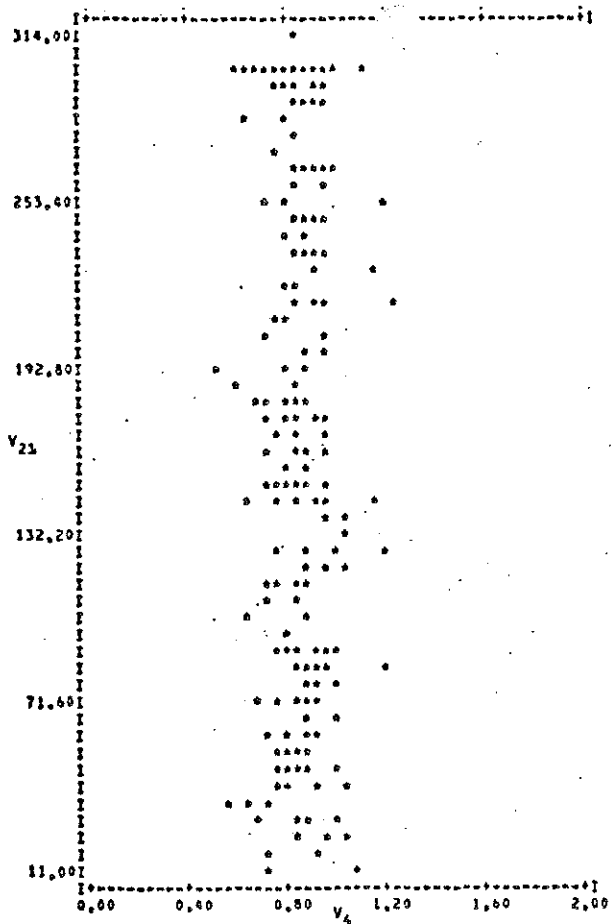


Figure B-33. The relationship between V_4 and V_{21} .

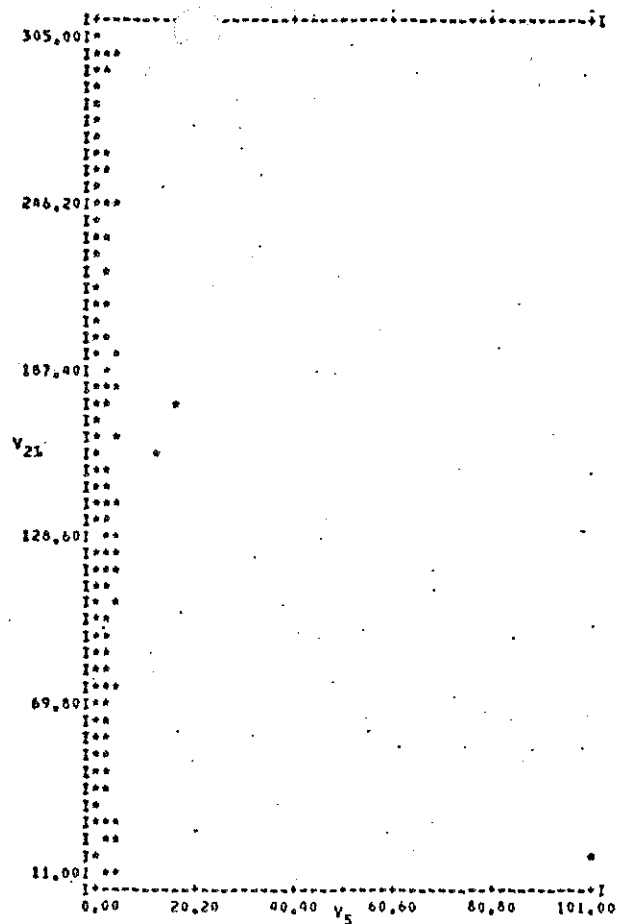


Figure B-34. The relationship between V_5 and V_{21} .

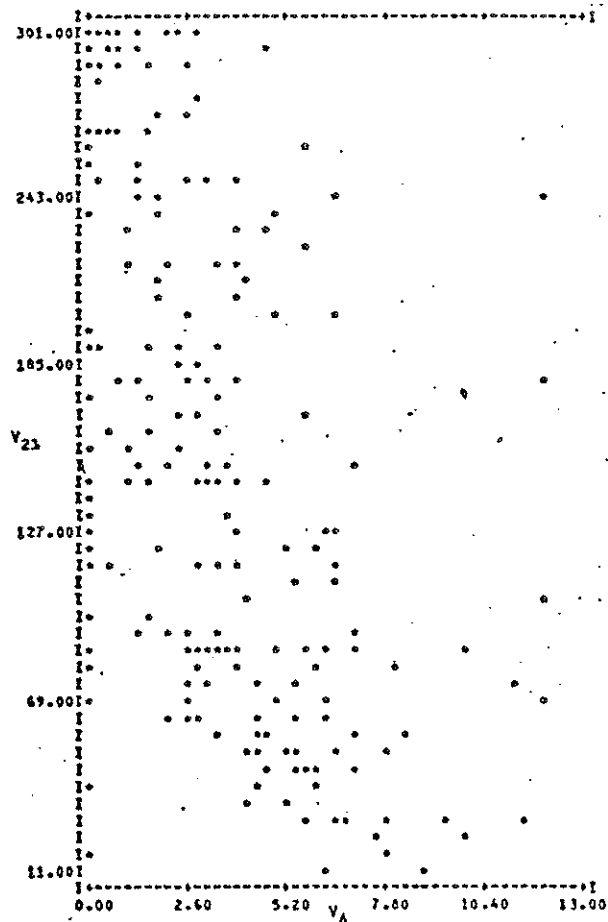


Figure B-35. The relationship between V_6 and V_{21} .

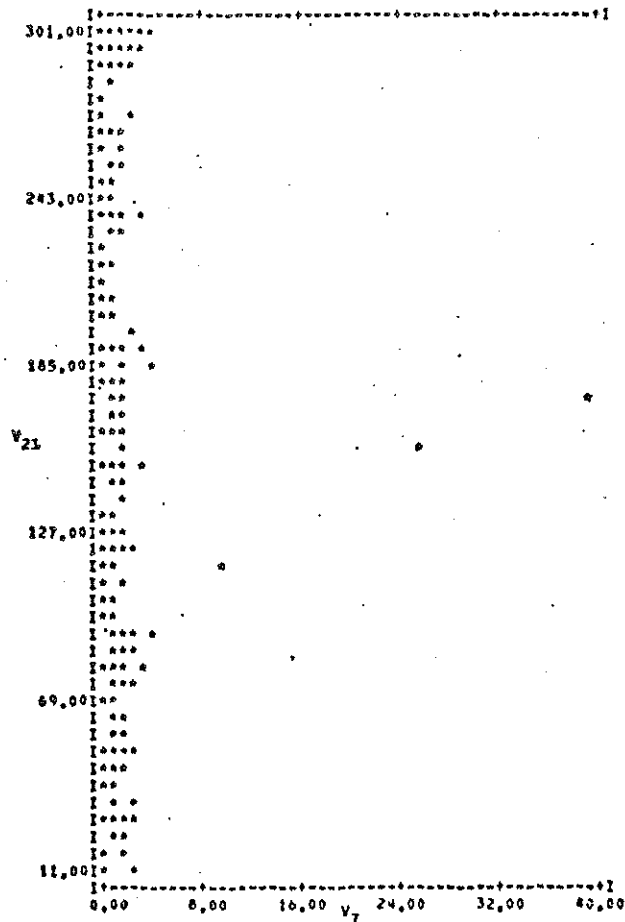


Figure B-36. The relationship between V_7 and V_{21} .

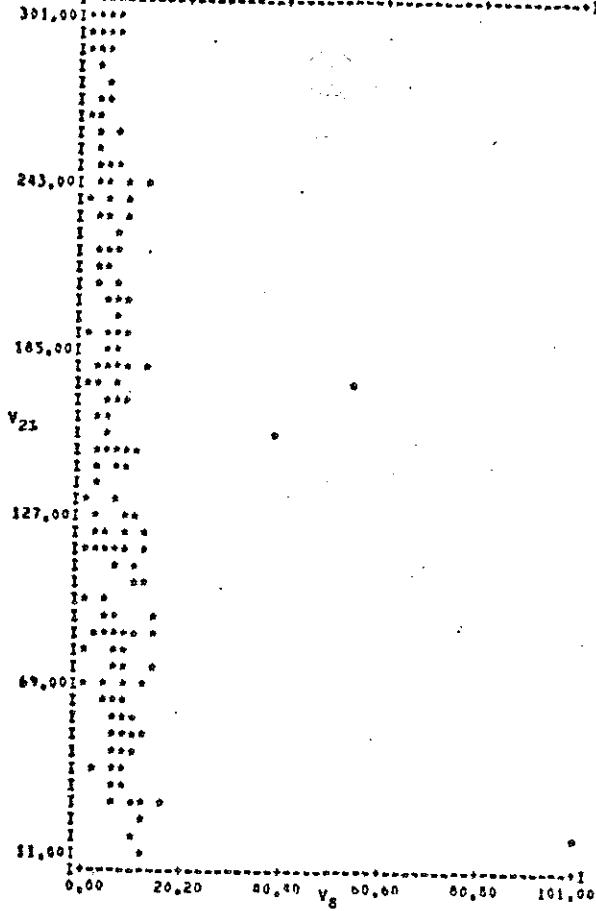


Figure B-37. The relationship between V_8 and V_{21} .

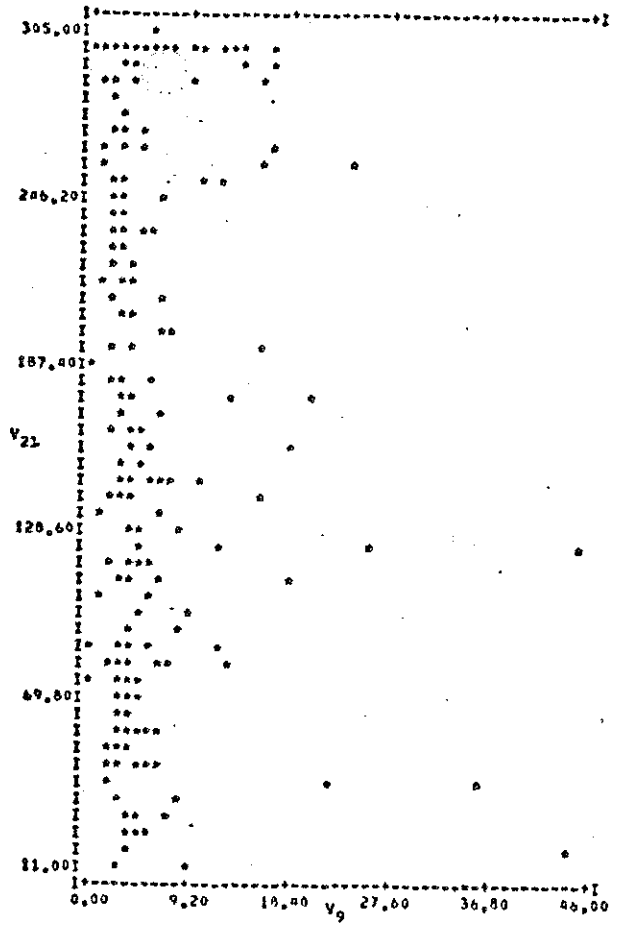


Figure B-38. The relationship between V_9 and V_{21} .

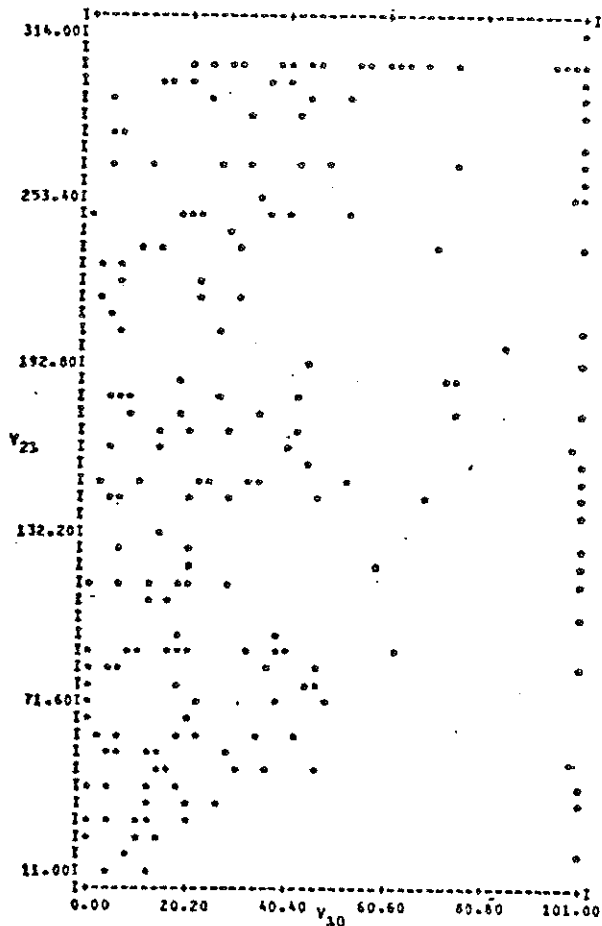


Figure B-39. The relationship between V_{10} and V_{21} .

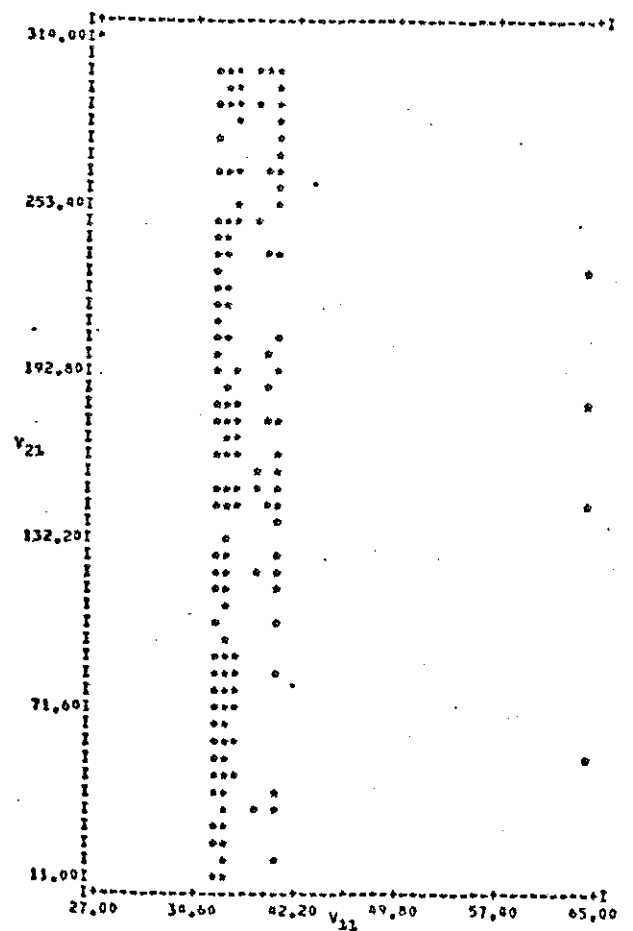


Figure B-40. The relationship between V_{11} and V_{21} .

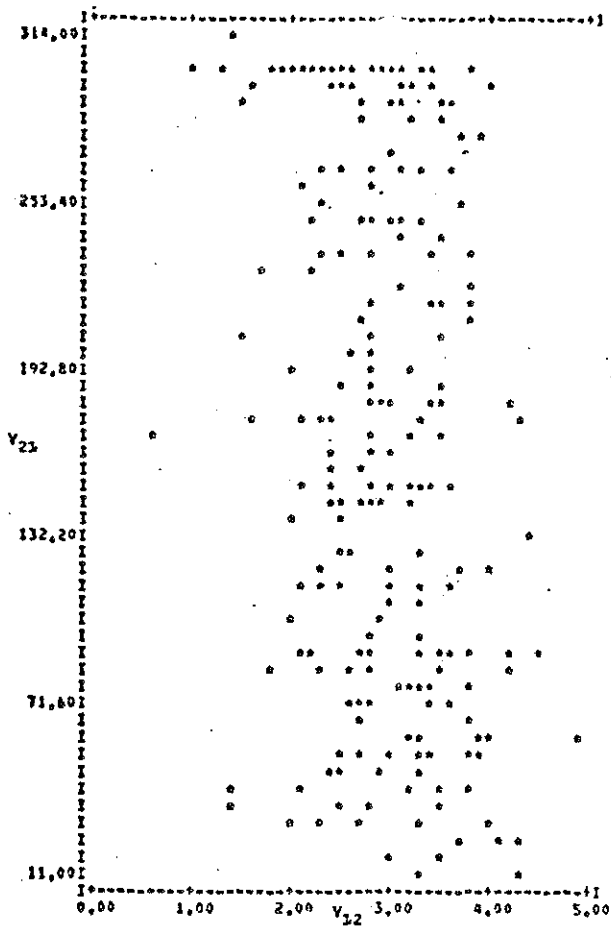


Figure B-41. The relationship between V_{12} and V_{21} .

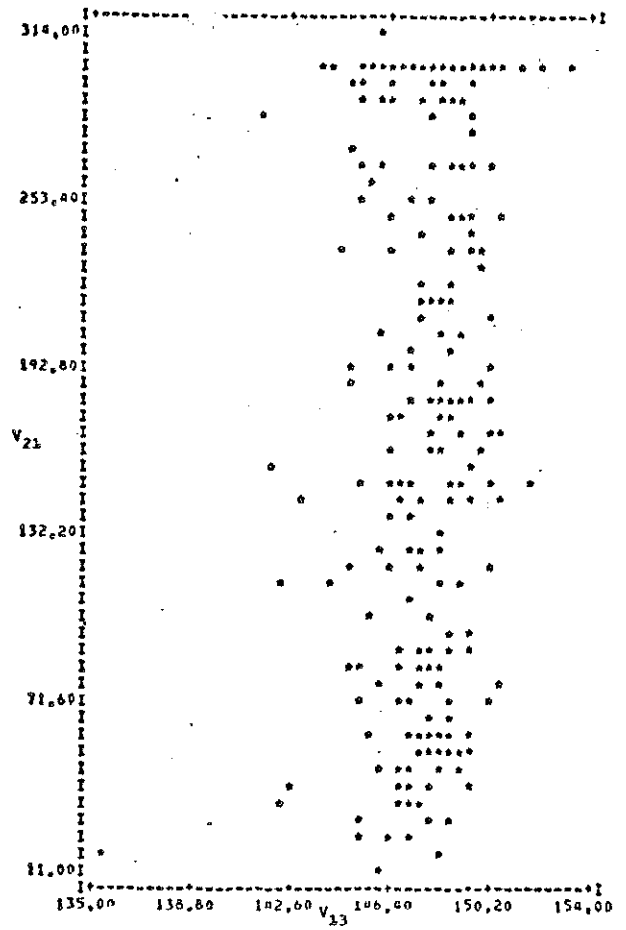


Figure B-42. The relationship between V_{13} and V_{21} .

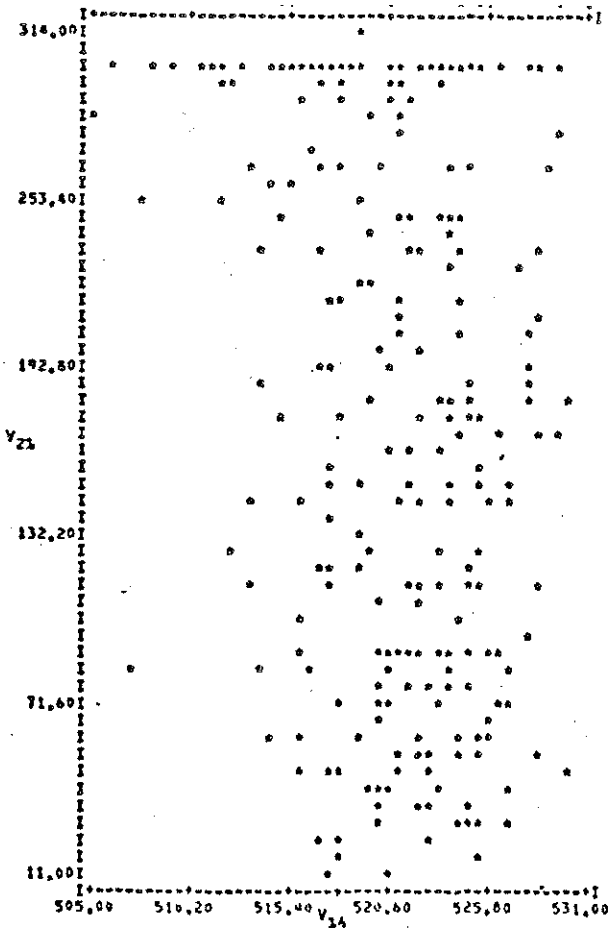


Figure B-43. The relationship between V_{14} and V_{21} .

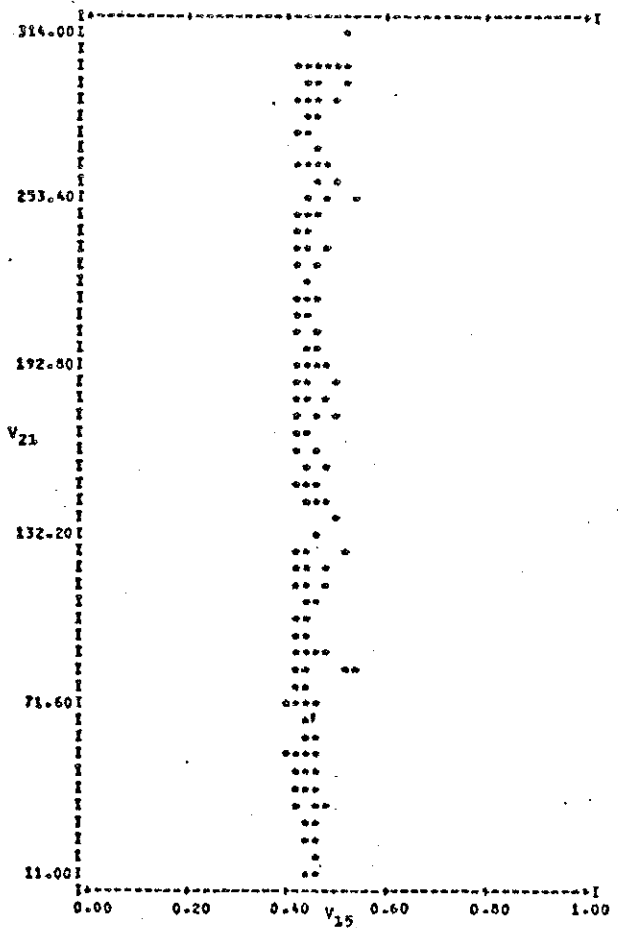


Figure B-44. The relationship between V_{15} and V_{21} .

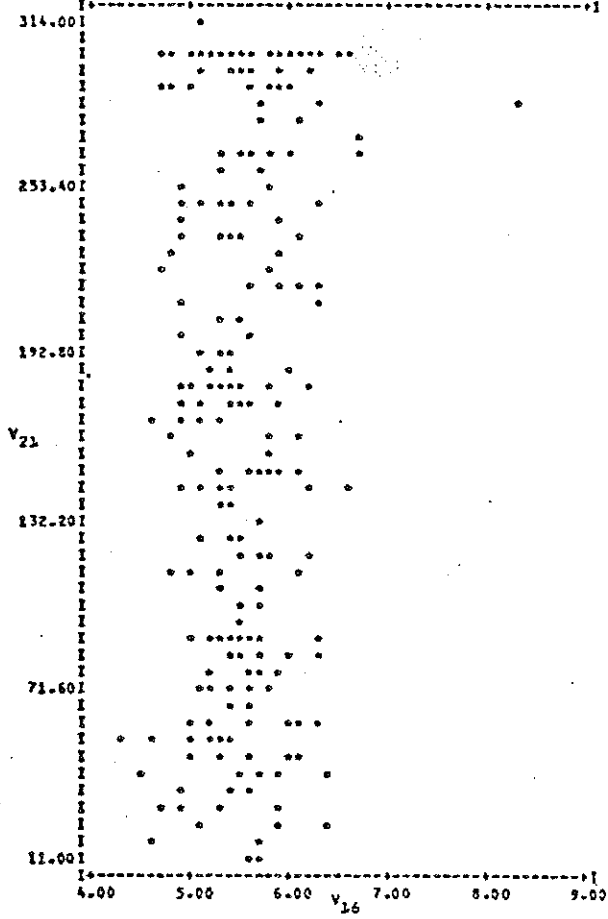


Figure B-45. The relationship between V_{16} and V_{21} .

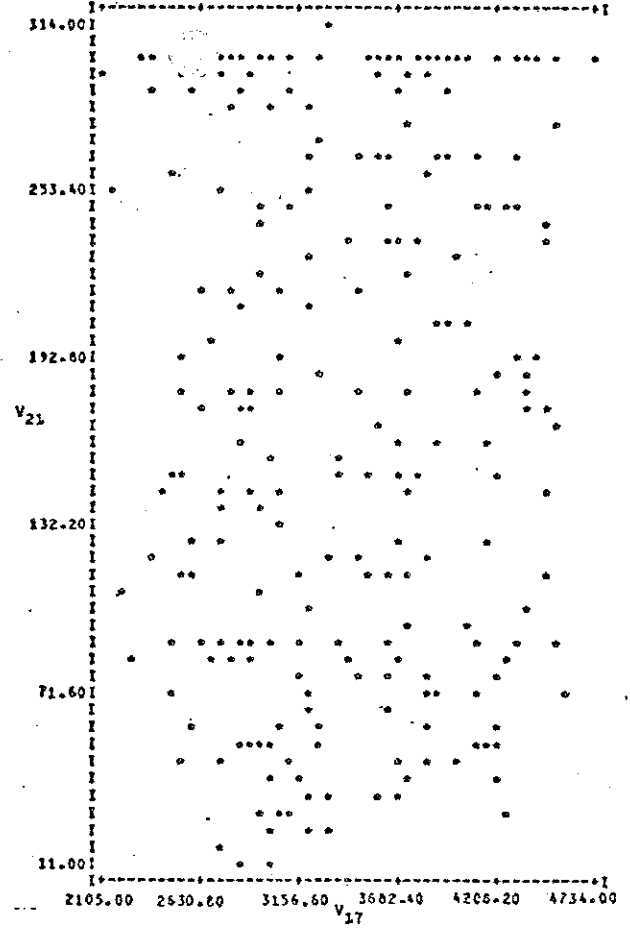


Figure B-46. The relationship between V_{17} and V_{21} .

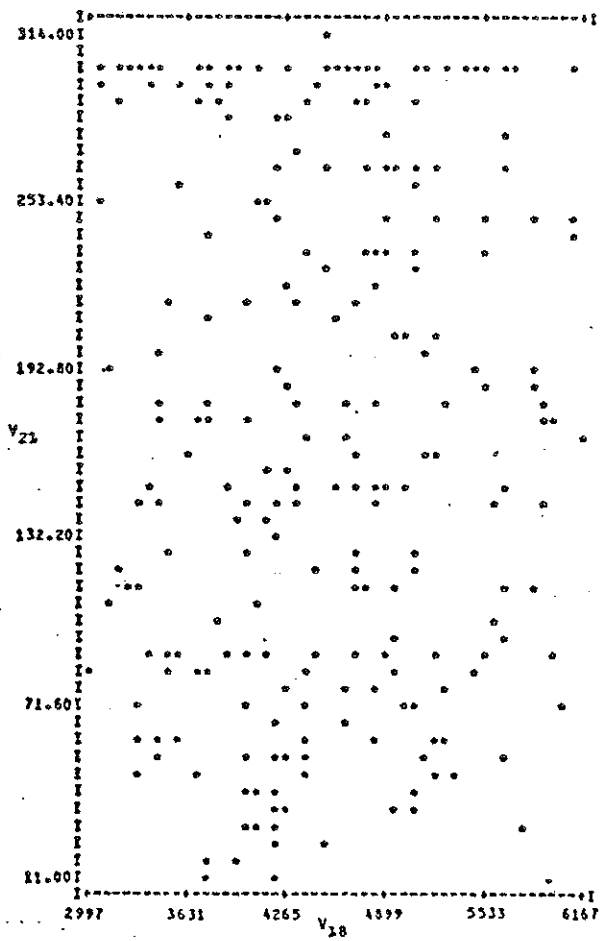


Figure B-47. The relationship between V_{18} and V_{21} .

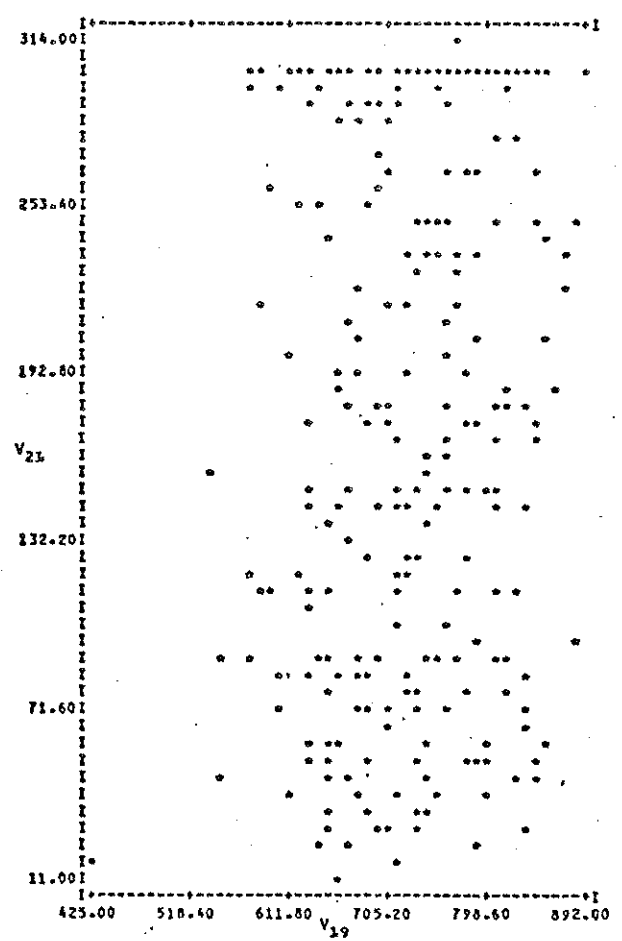


Figure B-48. The relationship between V_{19} and V_{21} .

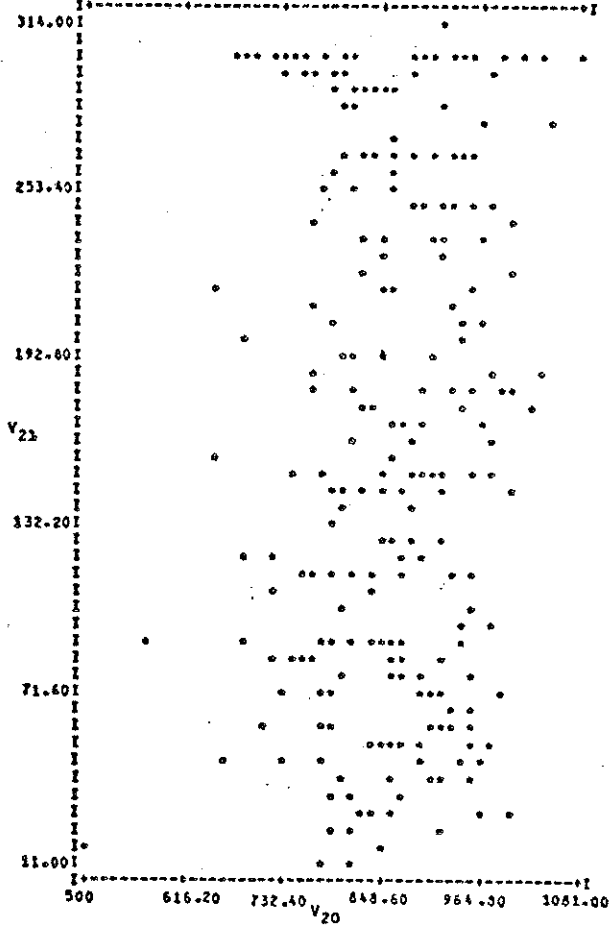


Figure B-49. The relationship between V₂₀ and V₂₁.

APPENDIX C

RELATIONSHIPS BETWEEN PAVEMENT PERFORMANCE
AND THE MATERIALS PROPERTIES FOUND ON THE
FREEZE-THAW DURABILITY TEST FORM

In order to relate the material properties listed on the Freeze-Thaw Durability Test Form (variables V₁ through V₂₂) to pavement performance, one must use projects which provide at least 15 years of condition survey data and were constructed with aggregate from pit sources tested by freeze-thaw durability test procedures. We located 50 construction projects that satisfied these requirements. After examining these 50 projects, we observed the following:

- 1) Twenty percent of the projects used coarse aggregate supplied by more than one pit; and, 2) the test year of the freeze-thaw durability test did not agree with the construction year. It usually differed by about one or two years. This indicates that we might not have time-coordinated data.

Many measures can be used to define pavement performance; e. g., the percent of joint deterioration or the proportion of joints that are spalled. Obtaining percentages of joint deterioration is more time-consuming than obtaining proportions of joints which are spalled.

Due to the possibility of unmatched data problems, we shall use proportions of joints that are spalled within 4 to 6 years and 15 to 16 years for our initial investigation. If these measures relate well to the material properties on the Freeze-Thaw Durability Test Form, we could then use more refined measures to sharpen the investigation.

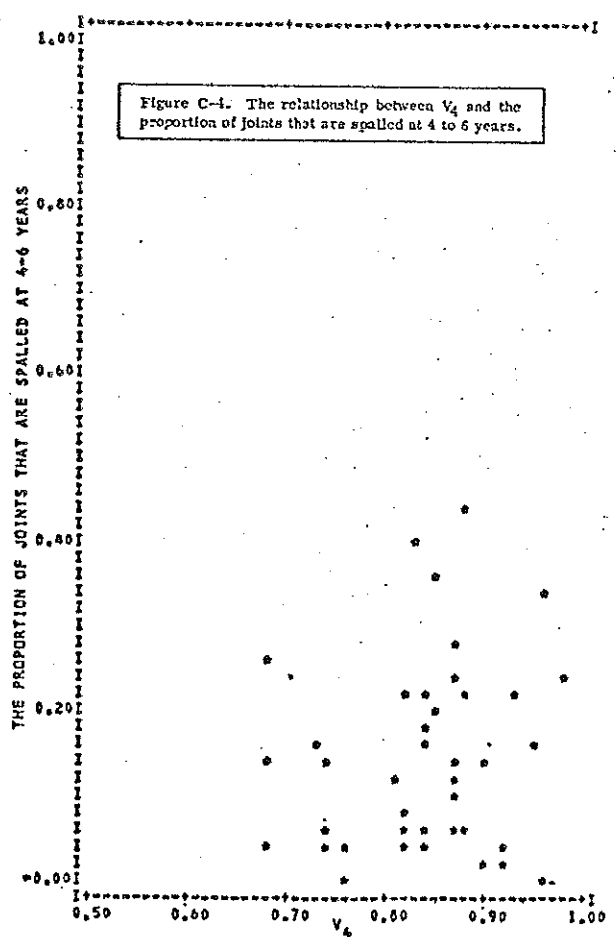
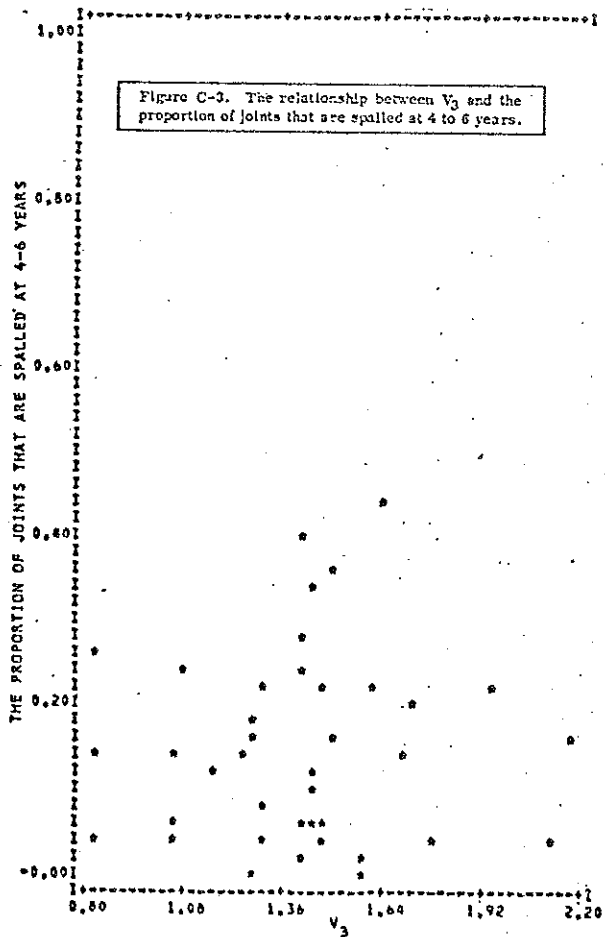
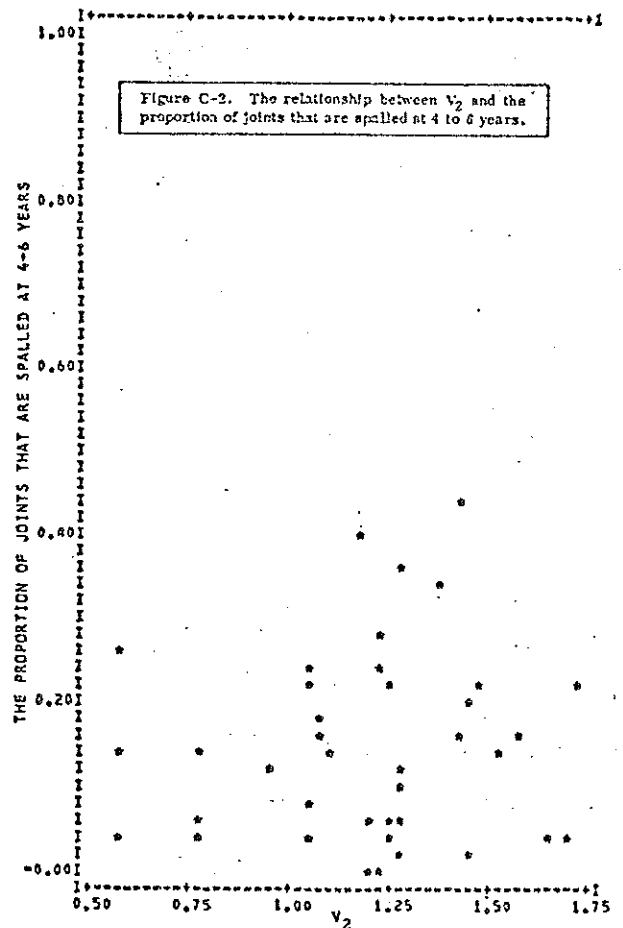
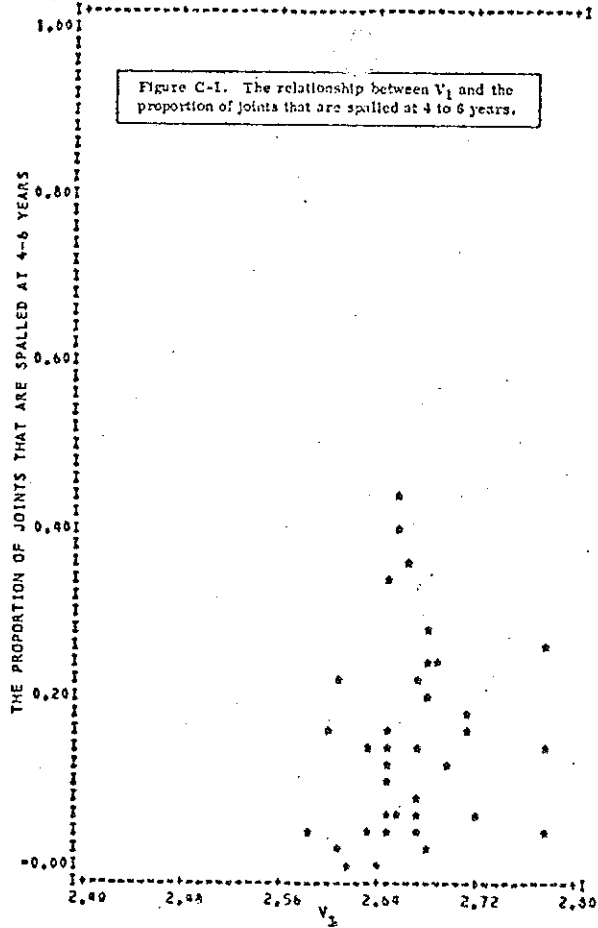
Plots of pavement performance versus each of the 22 materials variables are presented in Figures C-1 through C-42. As can be seen from these figures, correlations are very poor. That is, each of the 22 variables cannot be used alone to estimate the proportion of joints that would be spalled at 4 to 6 years and 15 to 16 years. In this situation, it is unlikely that combinations of freeze-thaw test data can be jointly used to estimate pavement performance within reasonable accuracy. Thus, we must conclude that the poor relationship is due to one or more than one of the following causes:

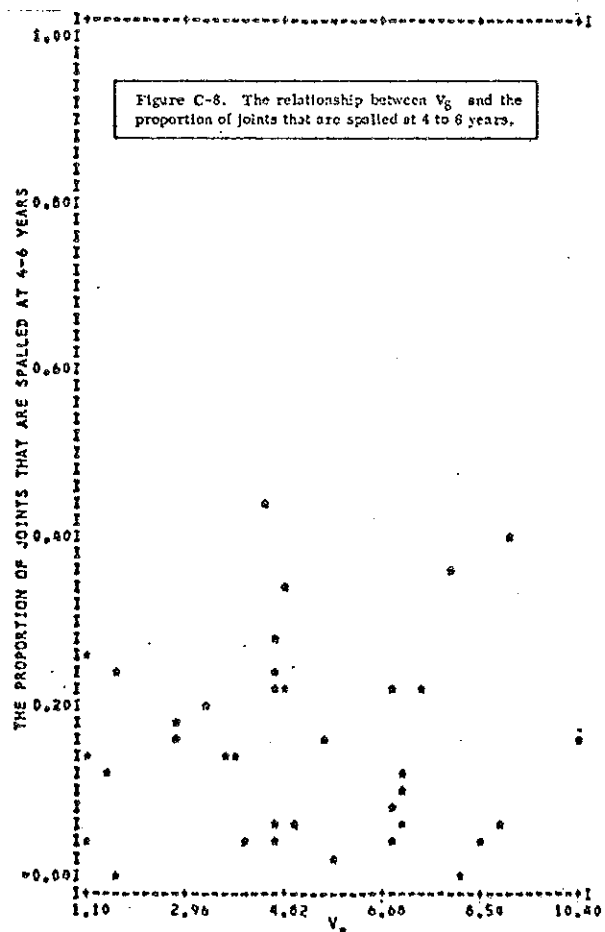
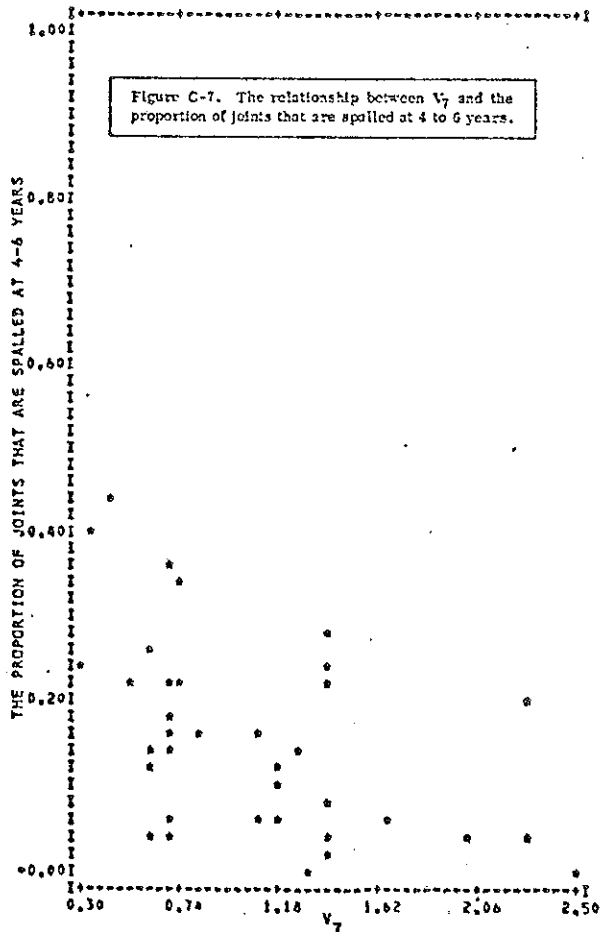
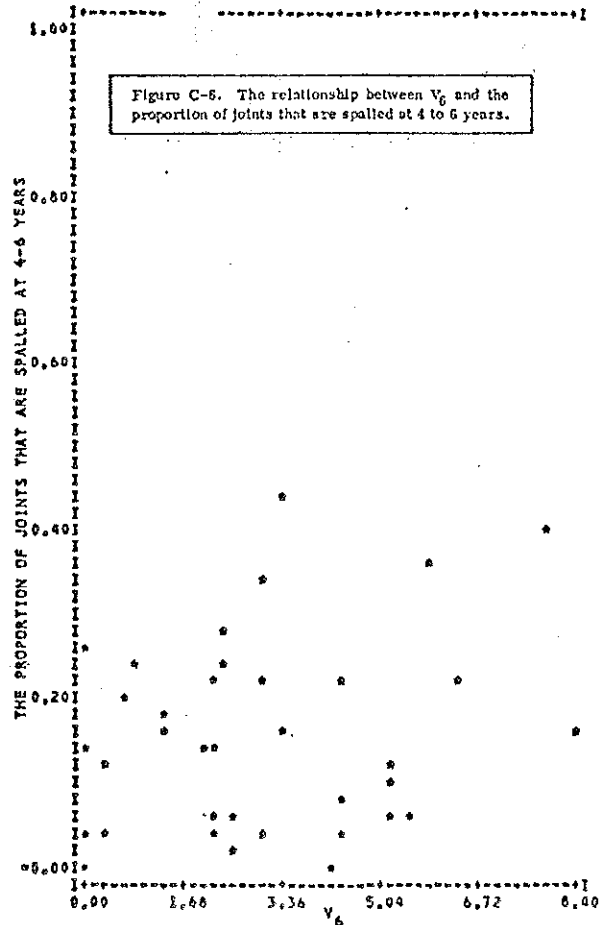
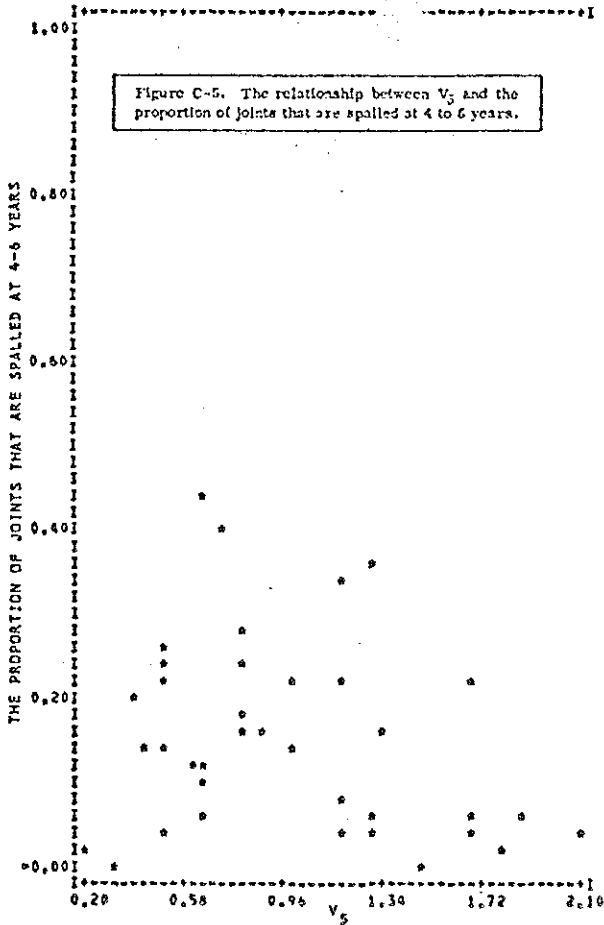
- 1) The material properties listed on the Freeze-Thaw Durability Test Form do not match with the pavement condition survey data as pointed out previously.

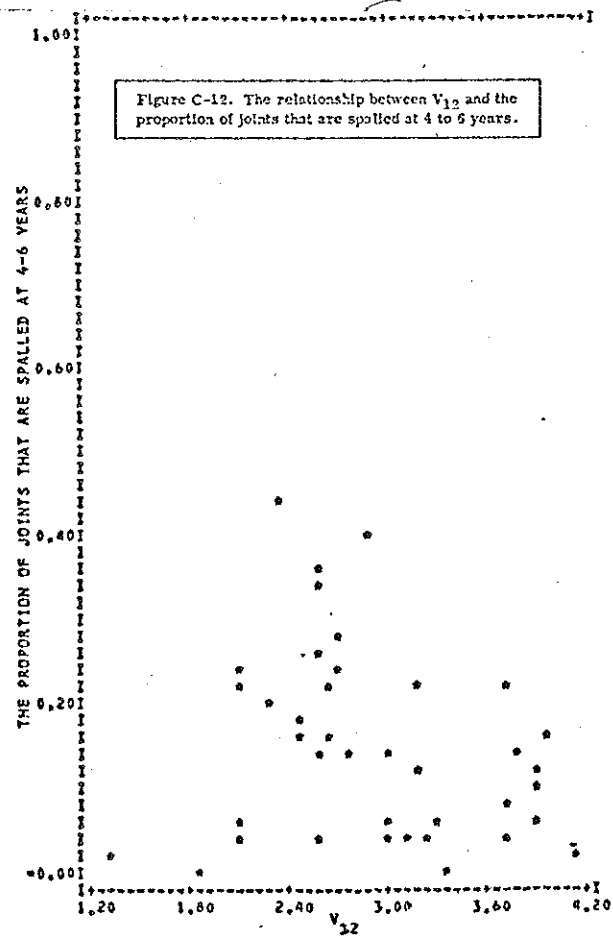
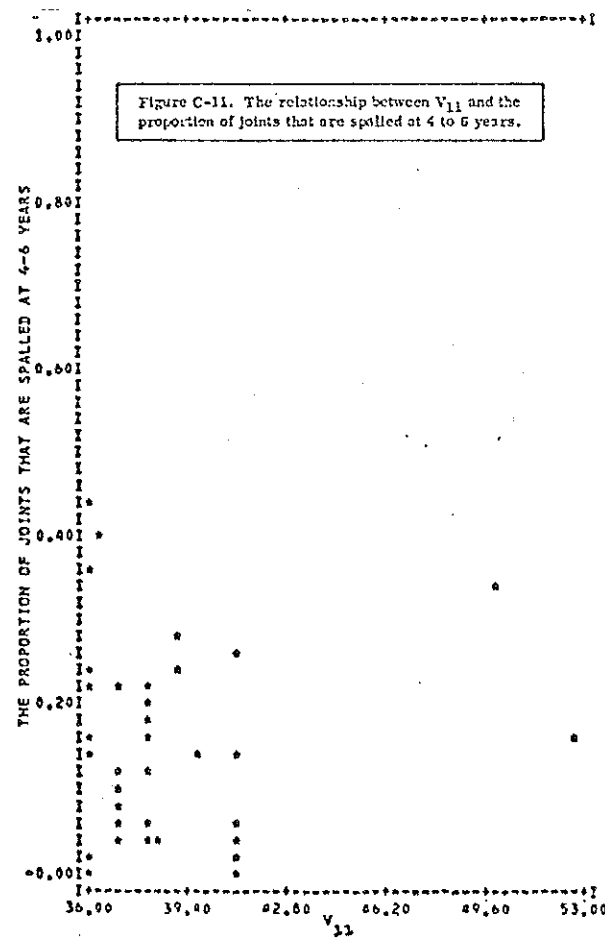
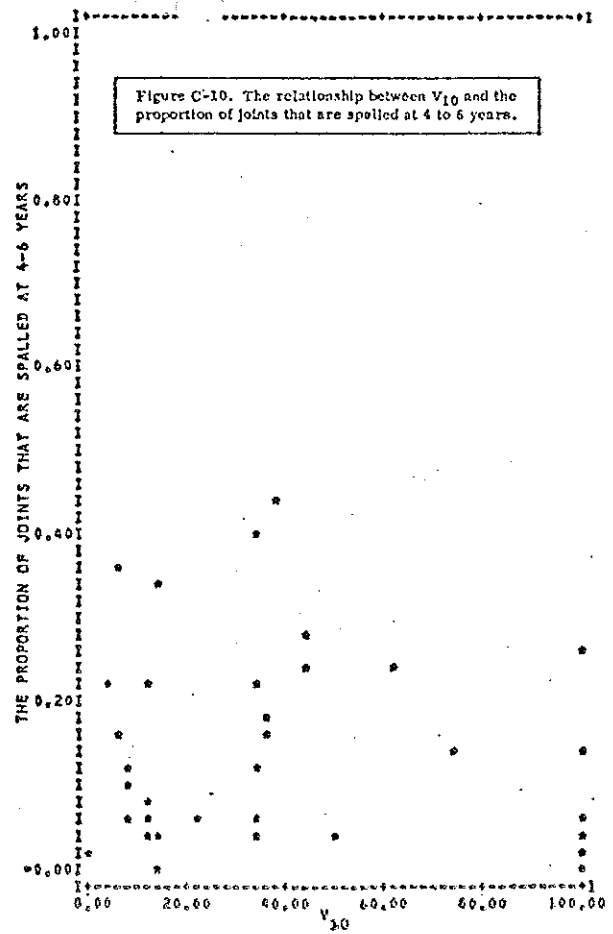
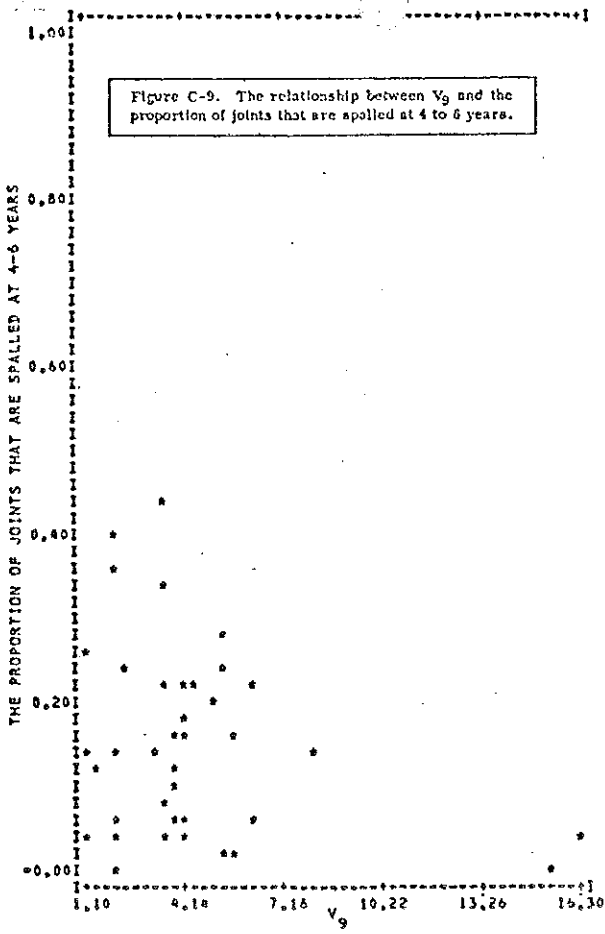
- 2) The small quantity of coarse aggregate obtained from pit sources for the freeze-thaw durability test is too small to adequately represent the entire construction project.

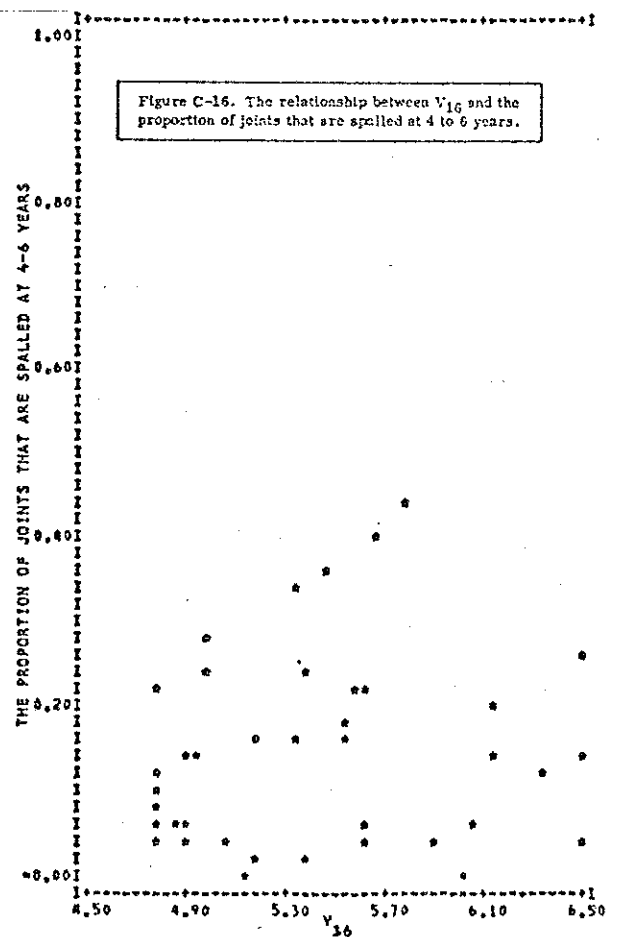
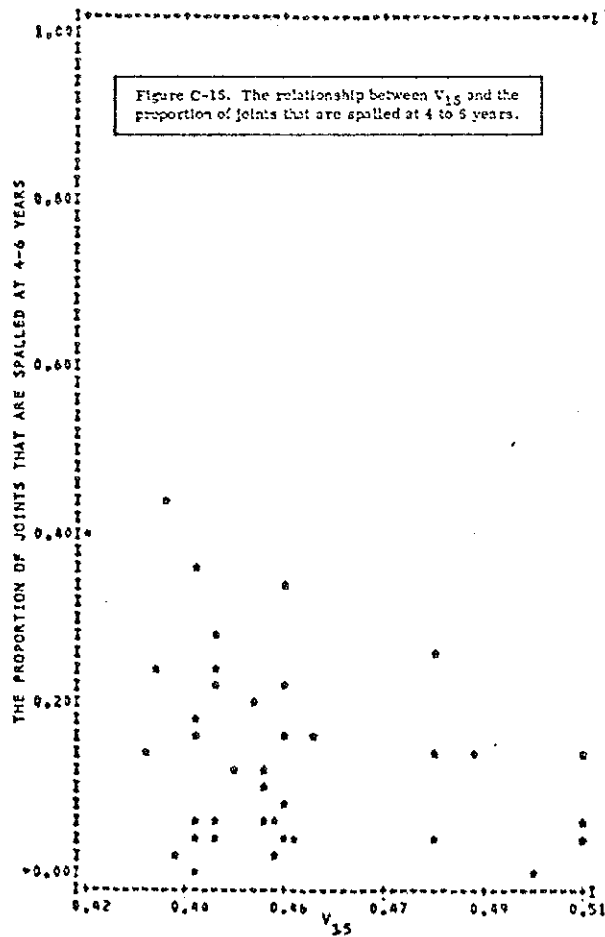
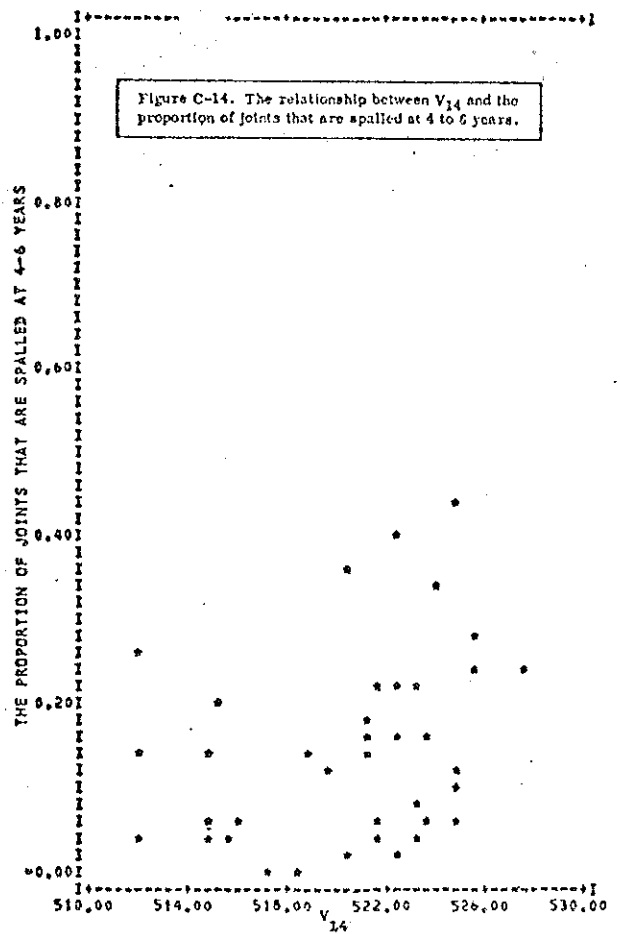
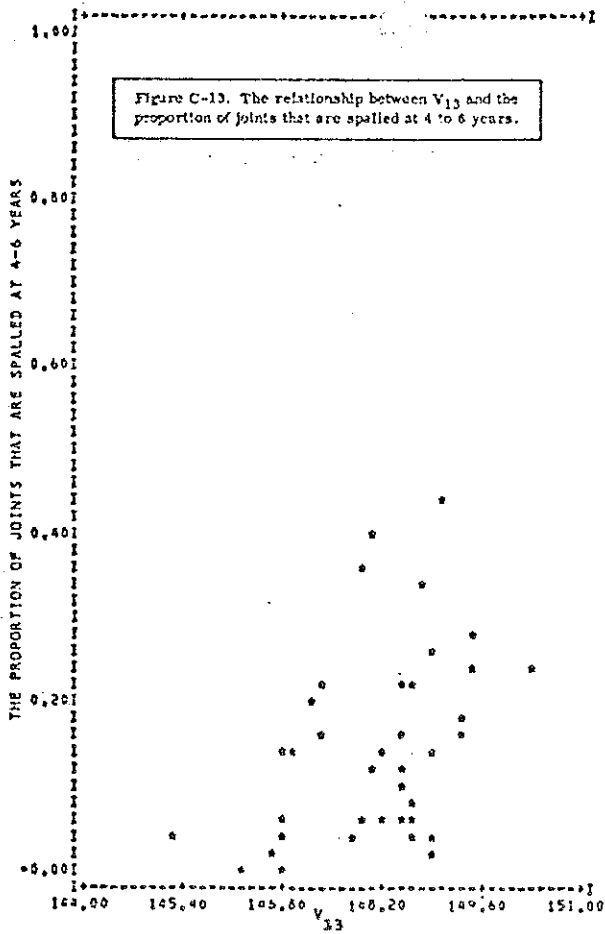
- 3) Data gathered for the freeze-thaw durability tests do not predict pavement performance.

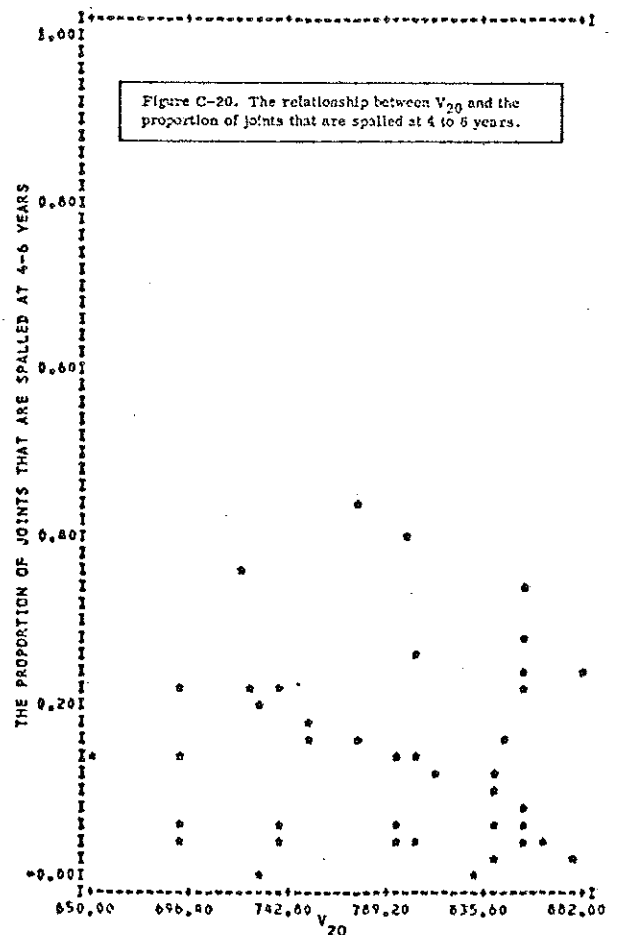
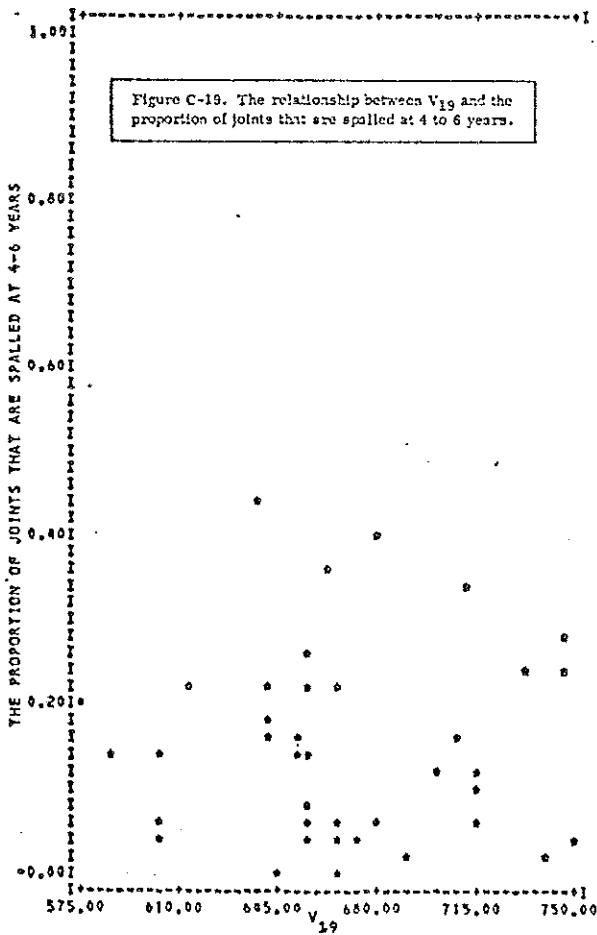
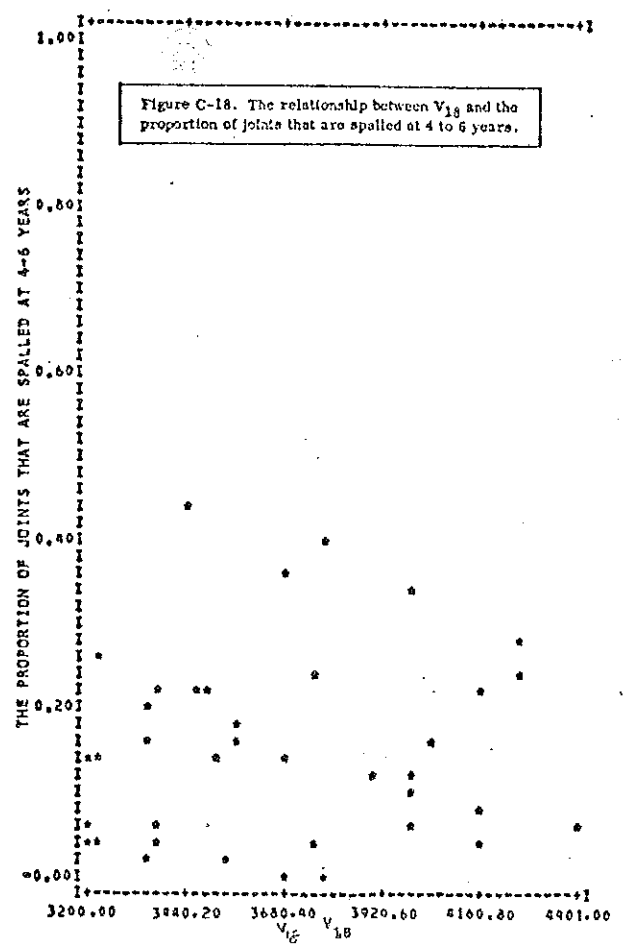
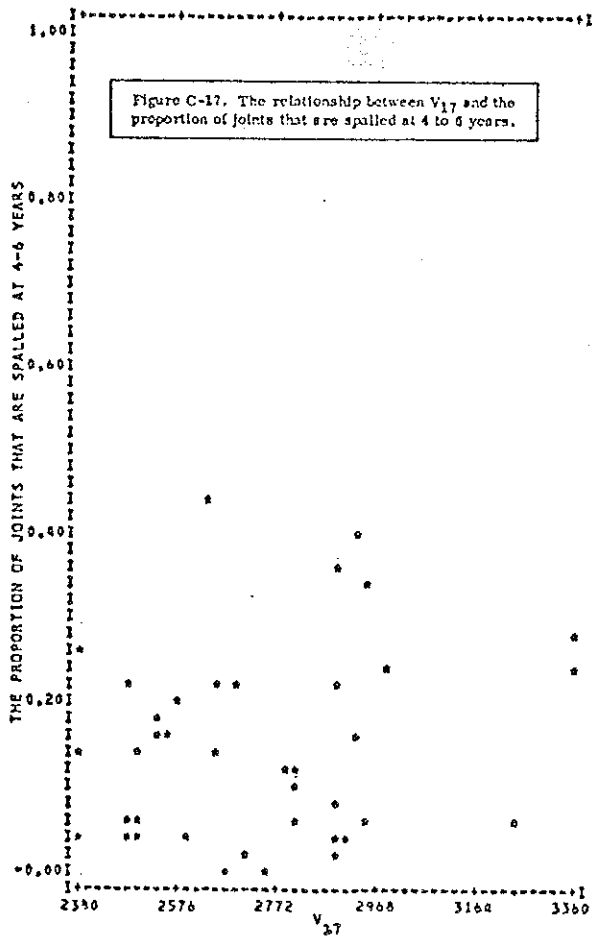
For these reasons, we decided not to investigate potential relationships between these data and pavement performance defined by other means such as percent of joint deterioration, etc.

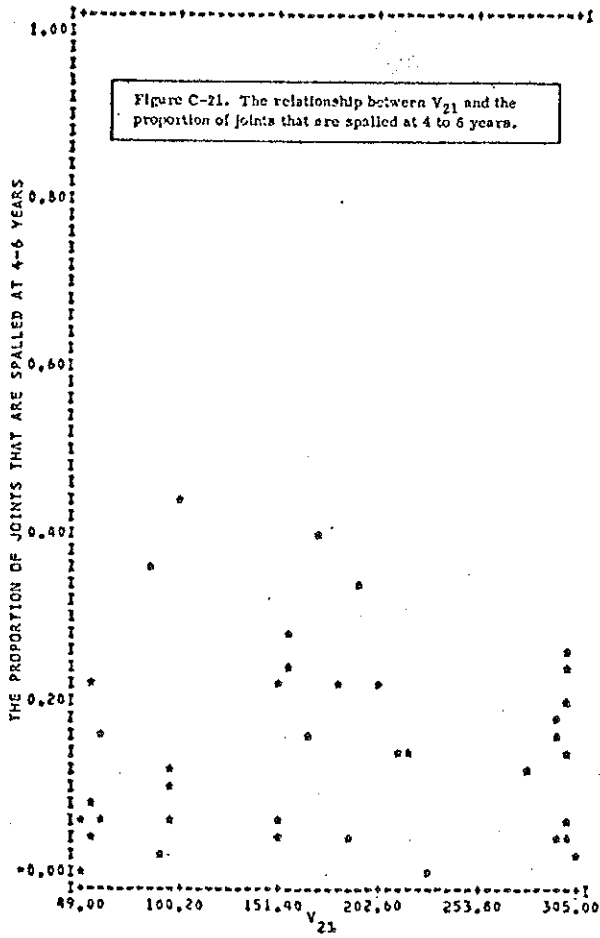


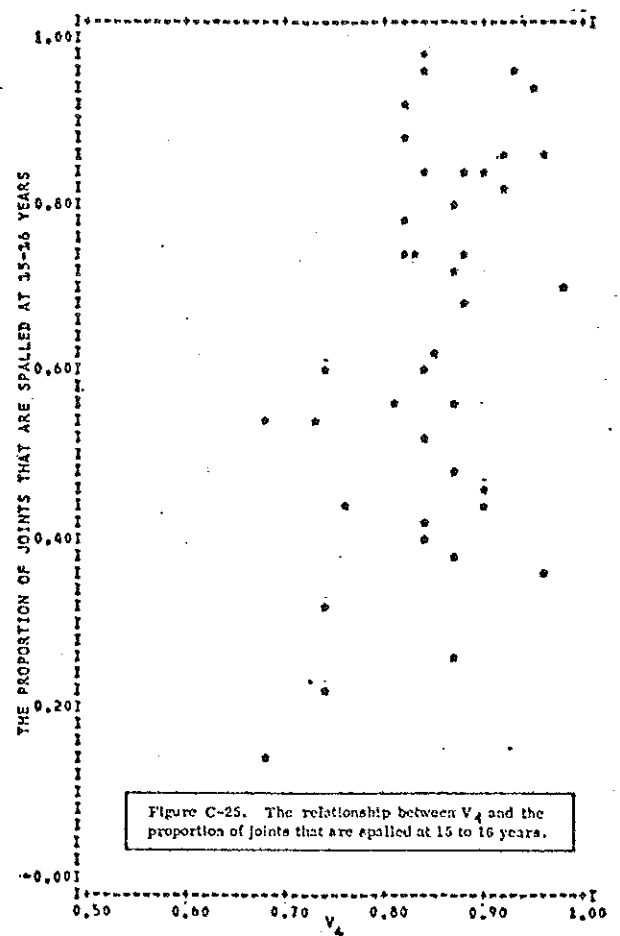
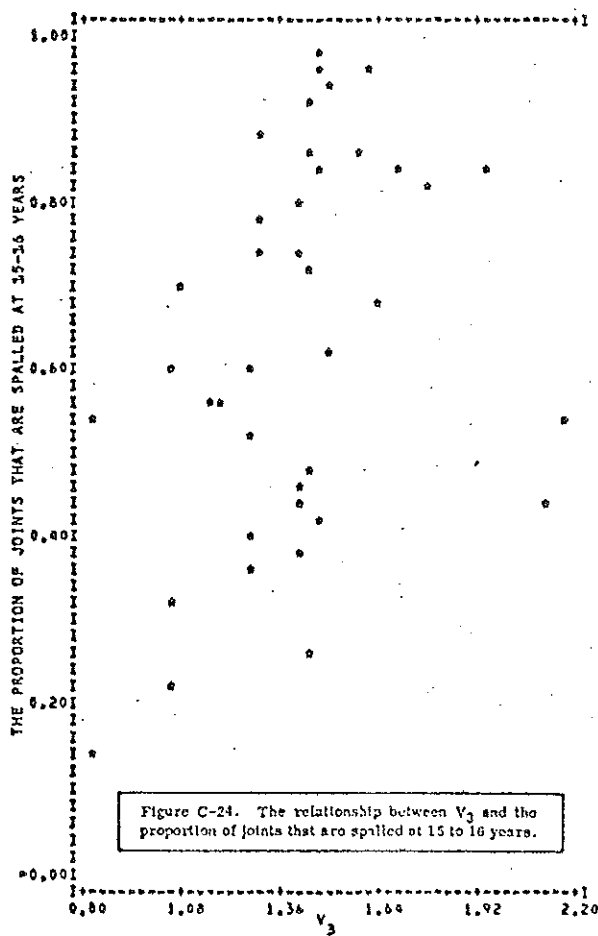
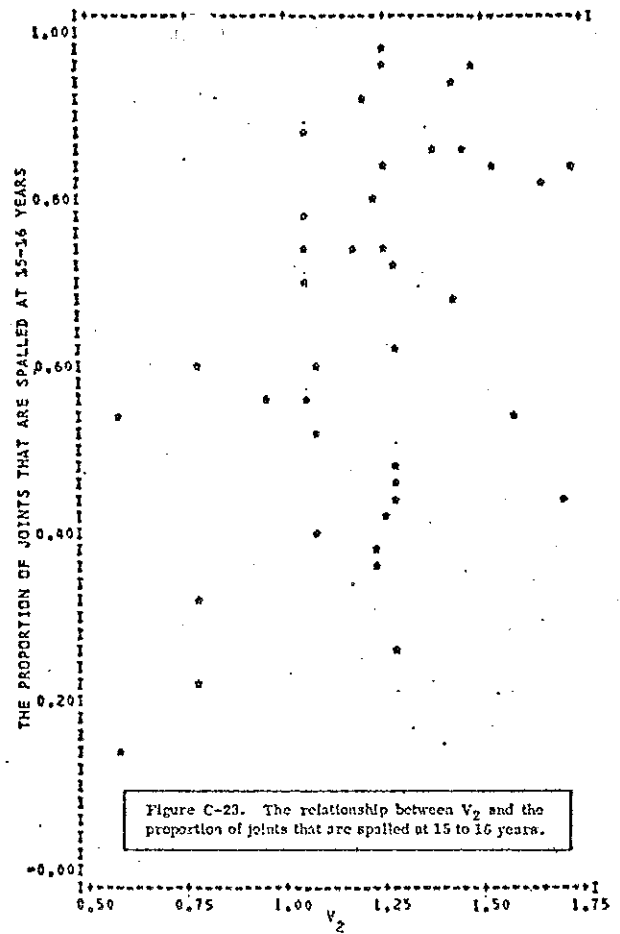
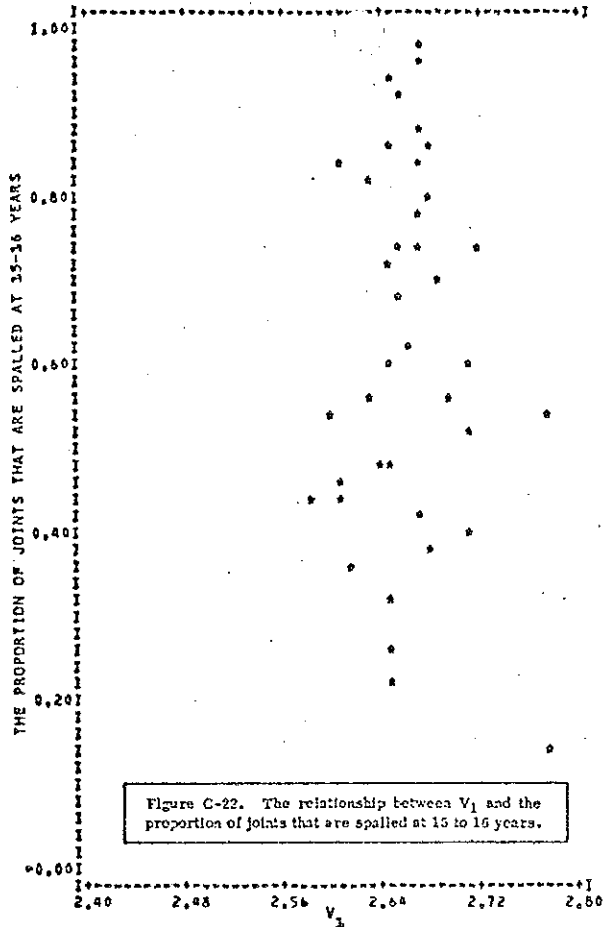


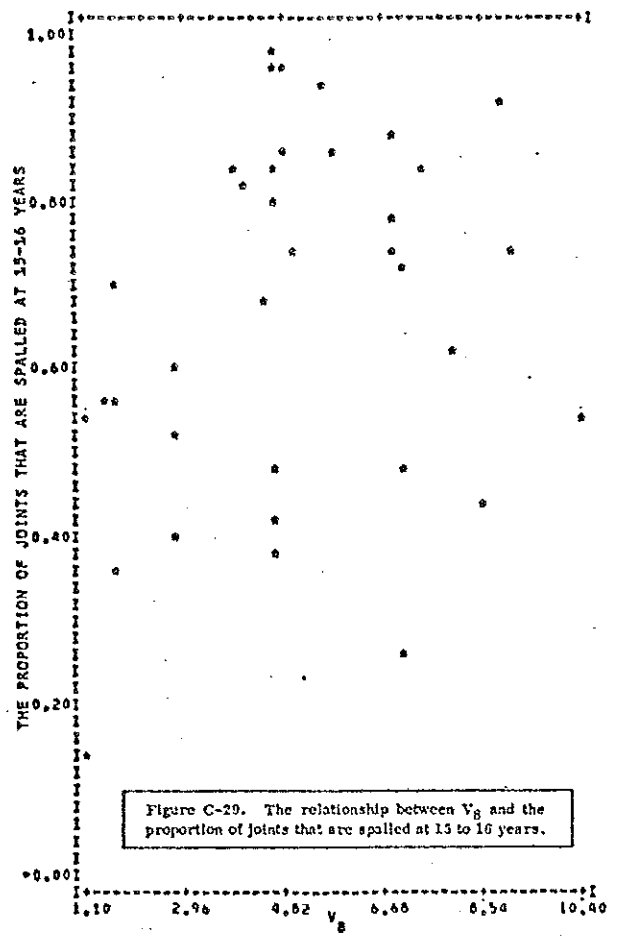
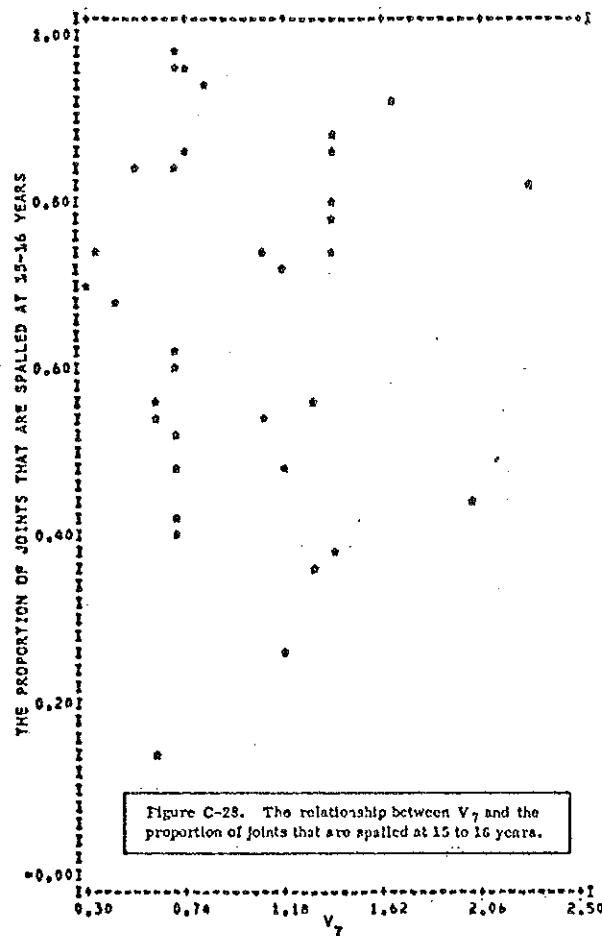
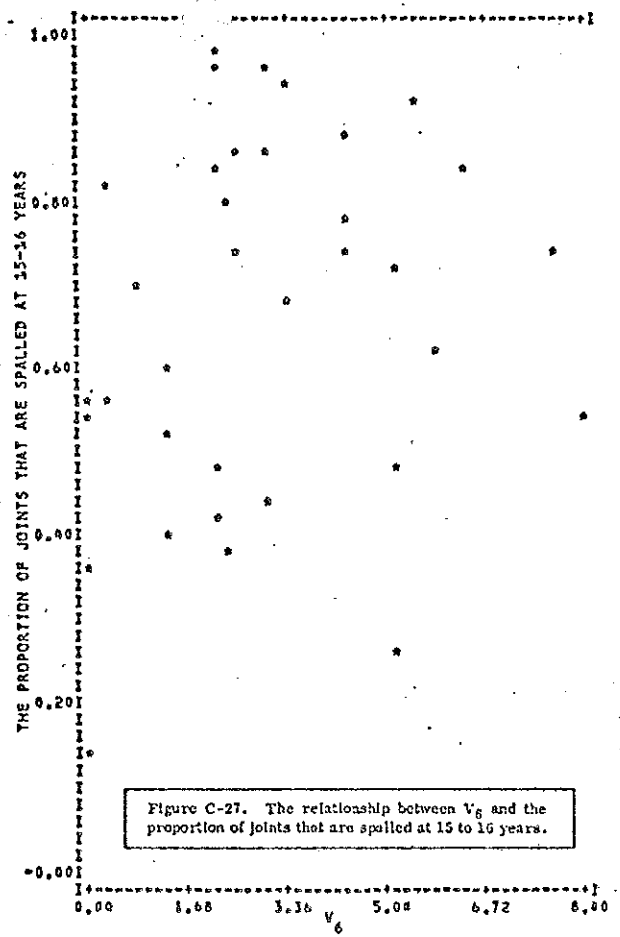
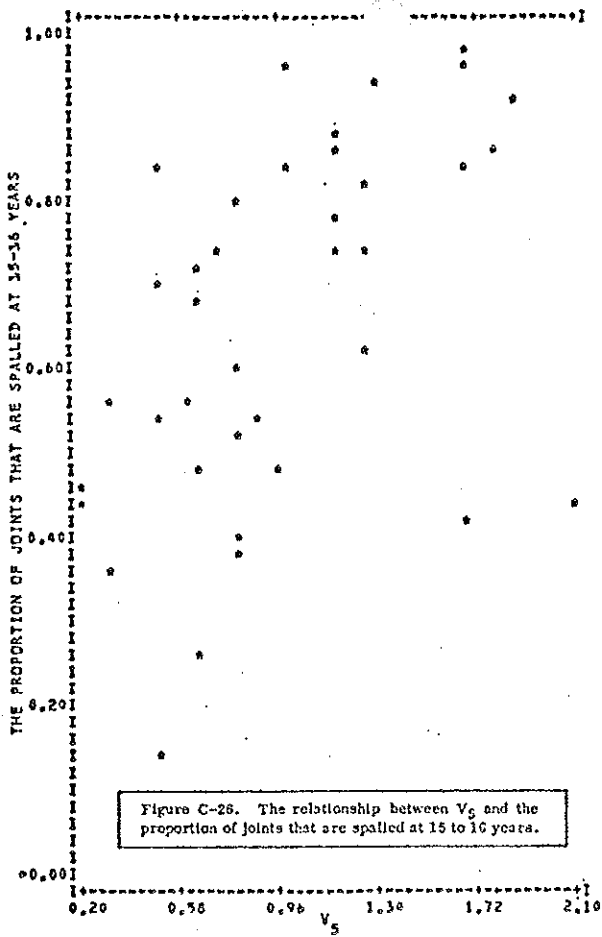












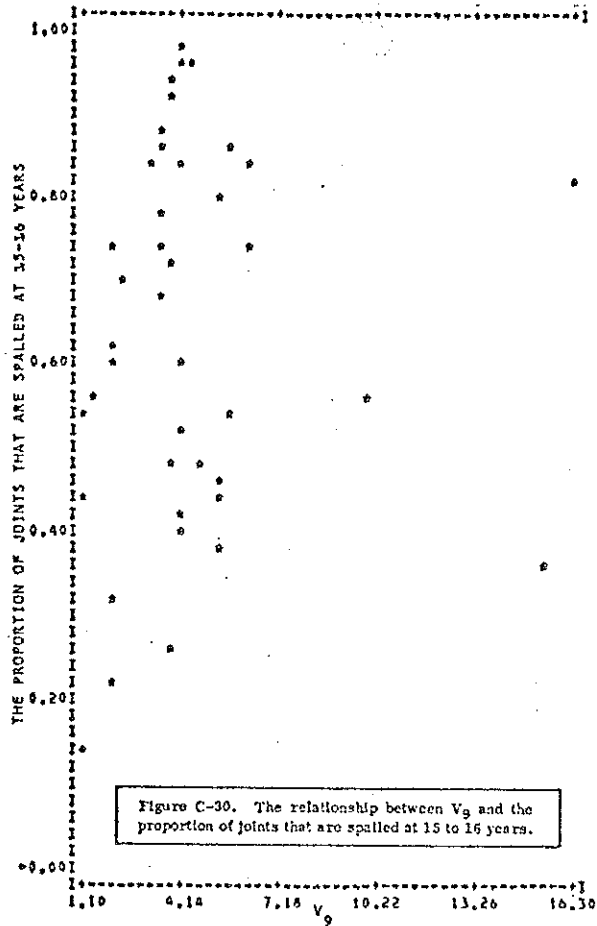


Figure C-30. The relationship between V_9 and the proportion of joints that are spalled at 15 to 16 years.

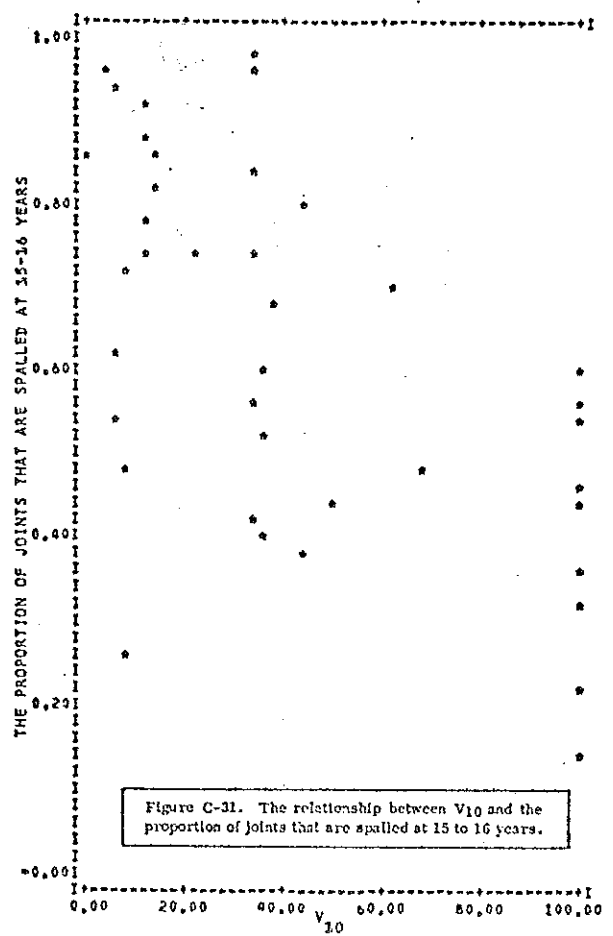


Figure C-31. The relationship between V_{10} and the proportion of joints that are spalled at 15 to 16 years.

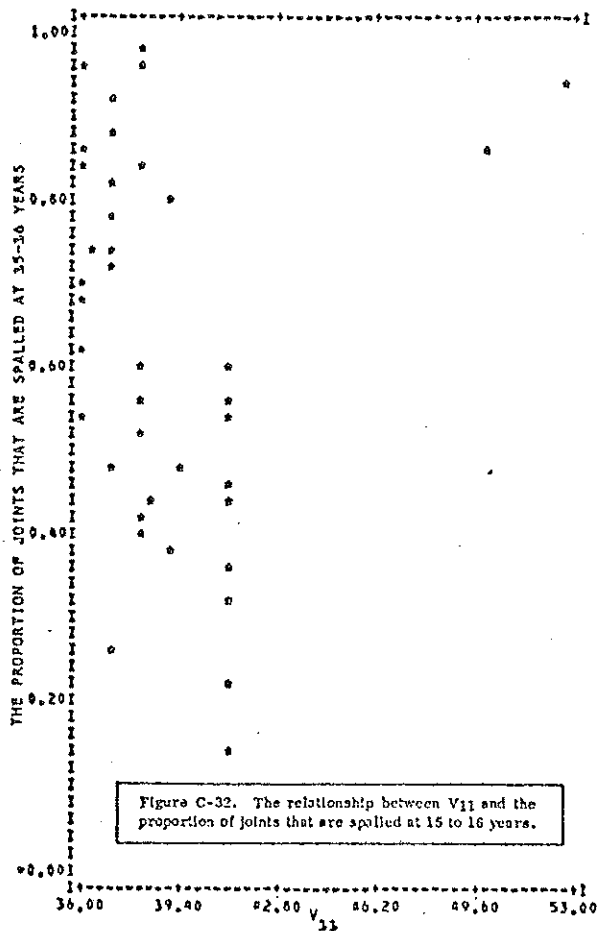


Figure C-32. The relationship between V_{11} and the proportion of joints that are spalled at 15 to 16 years.

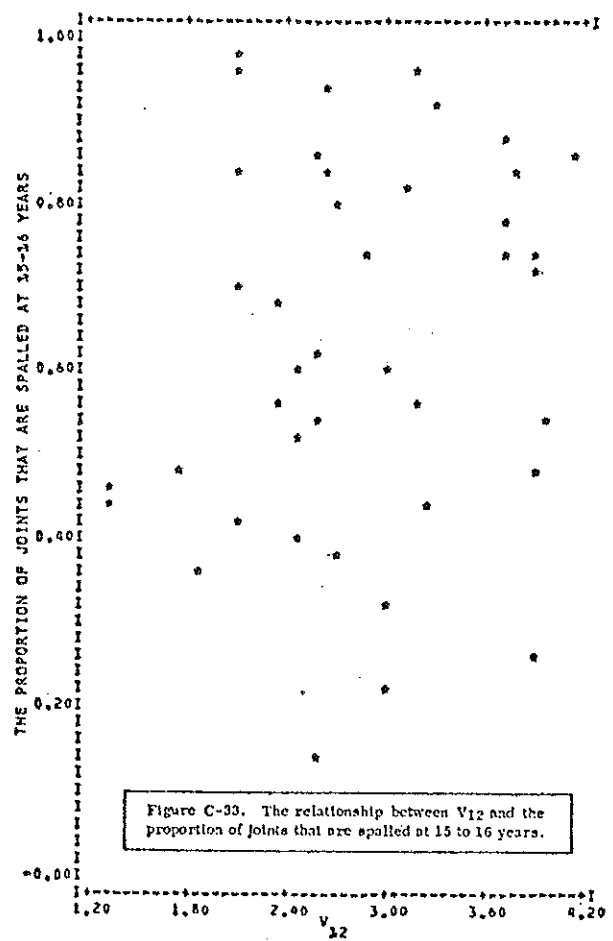


Figure C-33. The relationship between V_{12} and the proportion of joints that are spalled at 15 to 16 years.

