TRANSVERSE CRACKING OF ASPHALT PAVEMENTS IN VERMONT

PROBABLE CAUSE AND A POTENTIAL REMEDY

FINAL REPORT

by

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JANUARY 9, 1970

FOREWORD

This report was instigated through the concern of several engineers in the Vermont Highway Department for the in-service performance of asphalt pavements in Vermont. This was because historically, most pavements developed some degree of transverse cracking within 4 years of their installation.

Due to their combined experience and literature reviews, they felt that through a research project some combination of parameters could be found that would lead to a practical recommendation for increasing the durability of asphalt pavements in Vermont.

This report is the result of their initial concern and presents the practical solution they hoped for. As a result, the Vermont Highway Department is planning to incorporate this solution in its highway construction and maintenance activities.

SUMMARY

This report is concerned with the incidence of transverse cracks, as they are found in asphalt pavements on Vermont's Interstate System. This particular crack pattern is generally conceded to be of thermal tension in nature.

This report recommends the use of higher penetration grades of asphalt cement as a remedy to reduce or eliminate these cracks.

The following are brief discussions of some of the various factors affecting pavement durability and what changes, if any, might be anticipated in them with the adoption of softer penetration grades of asphalt cement.

A.) Bitumen Content

The amount of Bitumen required in a particular mix will not vary because of a change in the grade of Asphalt Cement used. This fact has been borne out by our limited experience as well as a review of the literature. Selection of bitumen content is based on the standard Marshall Method of design for a particular aggregate source. As the aggregate sources vary, so will the bitumen content requirements vary to some degree. The basis of the variance will be applicable regardless of the penetration grade of bitumen selected.

B.) Air Voids

The restrictions imposed on air void content in Vermont's bituminous mixes are controlled by the density requirements. These requirements compare to those recommended by the Asphalt Institute. McLeod (2) in comparing 60/70 penetration asphalt cement with 150/200 penetration asphalt cement showed no difference in percent laboratory compacted density between the two grades for standard 50 blow Marshall samples. From a test road in Proctor, Vermont using 85/100 penetration asphalt cement and 120/150 penetration asphalt cement, no appreciable difference in air voids was noticed.

It is concluded that no appreciable change will occur in the air void content.

C.) Mineral Voids

Mineral voids are a function of the asphalt cement by volume and air voids in the compacted mix. The contribution the asphalt cement gives is measured by volume, therefore, different grades would not significantly effect the end result. From the discussion of air voids and the above, it is concluded no significant change will occur in the mineral voids.

D.) #200 Material

It is not anticipated at this time that any change in the minus #200 material is necessary. As this is a void filling material, it is intimately related to VMA, which was discussed above. When changing from 85/100 to 120/150 penetration asphalt cement in the Proctor test road, no change in the #200 material was required.

E.) Viscosity

The viscosity of an asphalt cement is a function of its crude source. As Vermont's asphalt cement presently comes from a limited number of suppliers, no significant change in viscosity has been recorded for varying penetration grades of asphalt cement. Viscosities increase with age of the pavement which is substantiated by this report and the literature.

F.) Ductility

Loss of ductility in asphalt pavements hastens failure (1,9). A review of the literature (1,2,9) shows that the higher penetration asphalt cements show higher ductilities at any given temperature when compared to lower penetration asphalt cement's. Further, the higher penetration asphalt cement's retain higher in-service ductilities. It is, therefore, deemed beneficial to retain as high a ductility as possible, especially in colder climates, to retain durability.

G.) Overall Review of Mix Gradation

At this time, it is not anticipated that any change will be necessary in the overall mix design now used by Vermont. This is in view of our limited experience to date with softer asphalt cement and from knowledge gained from the literature. There may be some softer asphalt cements that will require minor changes, and the changes necessary have been discussed earlier. The broad limits of these mixes are included in Table VII.

H.) Older Uncracked Pavements

It is our opinion that it is the exception, rather than the rule, to find a pavement made with 85/100 penetration asphalt cement that is more than four or five years old that does not have considerable transverse cracking in Vermont.

A report by this department on cracked and uncracked Interstate sections dated November 1965 states relatively little cracking could be found on the Brattleboro-Dummerston-Putney I 91-1 (9) contract and severe cracking on the I 91-1 (10) C-3. The pavement age in both cases, when the report was written, was four years. As this is our estimated critical age for transverse cracks to occur, it is very possible to have one section cracked and the other uncracked. It is of interest to note, aside from the report's observations of the filler-asphalt ratio, that tests run by Mobile Oil Corporation in 1967 showed the ductility in the uncracked section to be 56 cms at 77°F and in the cracked section to be 5 cms. One could logically expect that this large difference in ductility at least contributes to the severity of the cracking. In fact, after analyzing all the test reports, it is concluded that this big difference in ductility is the only major variable and hence, must be a major cause of two sections cracking before the other two. The I 91-1 (9) contract was cored as part of our research program in July 1969 (core #23). At that time, the transverse crack i... rval after 8 years of service is 33 feet for the passing lane and 67 feet for the travel lane. Therefore, the previously noted uncracked section at 4 years of age has become seriously transverse cracked after 8 years.

I.) Stability

Concern is naturally expressed as to the stability characteristics of mixes made with softer grades of asphalt cement. Lewis and Welborn (1) showed that as the penetration increases, the stability decreases when measured at the same temperature, but also when the temperature decreases the stability increases for the same grade of asphalt cement. Further, the change in stability between 77°F and 40°F is much more dramatic than is the change in stability from a 156 penetration asphalt cement to a 93 penetration. This was illustrated (1) by the Hubbard-Field stabilities measured for these two penetrations. The 156 penetration asphalt cement at 77° had a stability of 2,230, where as at 40°F the stability was 7,450. The 93 penetration asphalt cement had a stability of 2,980 at 77°F, and 8,400 at 40°F. "Tests of the weathered specimens were also made at lower temeperatures to provide a more complete picture of the changes in strength that may occur under normal climatic conditions." (1). Briefly stated, it has been shown that stability increases with pavement age because of the hardening of the contained asphalt cement and that this increase in stability is proportional to the rate of decrease in penetration. McLeod (2) discusses the problem extensively and soundly describes the phenomenon. His basis of argument is that if the compaction obtained on the project is only 95% of laboratory compacted density (Marshall Method) for a 60/70 penetration asphalt cement, it is equivalent to 97% of laboratory density for a 150/200 penetration asphalt cement, and at these two points, these grades of asphalt cement would have the same Marshall stability values. He concludes, "Nevertheless, just how soft an asphalt cement can be selected to minimize transverse cracking in colder weather, and to provide at the same time adequate stability for traffic in hot weather, will be a matter for sound engineering experience and judgement in each region to decide."

The Highway Research Board (8) in a comprehensive report also showed stability increasing with age of asphaltic mixes for various grades of asphalt as "The time required for an asphalt to flow when a stress is applied is increased by aging."

The Asphalt Institute (11), in discussing low stability values and corrective procedures, states "It usually is possible to improve the stability and increase the aggregate void content of a mix by increasing the amount of crushed materials."

We can, therefore, see that stability will be a function of the asphalt cement and the quality of the aggregate as well as the judicial proportioning of the two. Further, stability is dependent on the climatic environment in which the mixture is placed. Considering Vermont's present design procedures and location, it is the author's opinion that usage of 120/150 penetration asphalt cement will not significantly alter the stability characteristics of our asphalt pavements. This again is borne out in the Proctor test road where the stability values for 85/100 penetration asphalt cement and 120/150 penetration asphalt cement using the same aggregate were identical.

J.) Penetration Immediately after Placement

This type of work has been done by others (8,9) who show that the highest initial penetration asphalt cements continue to remain the highest throughout mixing, compaction and in-service age as compared to lower penetration asphalt cements. From the literature, 85/100 penetration asphalt cements appear to drop to about 60 penetration after 1 day in-service and 40 penetration after 2 years, whereas the 120/150 penetration asphalt cements appear to drop to about 90 penetration after 1 day and 60 penetration after 2 years. There is no reason to believe there would be any change in this observation for mixes in Vermont, though the values of the recovered penetrations may be somewhat different from the findings of others due to construction methods. This is borne out in the fact that it takes about four years for 85/100 penetration asphalt cement to reach 40 penetration in Vermont.

K.) We fully concur that research in asphaltic pavement continue with particular attention to their durability characteristics in Vermont's climatic environment.

INTRODUCTION

Vermont's expanded use of hot-mixed asphalt pavements in recent years has developed a definite need for investigation into their in-service performance. Growing concern was expressed as to the durability of these pavements because of certain crack phenomenon occurring after a period of in-service use. It was felt that some of the reoccurring crack patterns could be related to properties of the asphalt cement itself.

Vermont's geographic location imposes climatological factors shared by only a few of the other states along the northern tier of the country. It was felt that because of Vermont's location, it might be necessary to investigate other than the paving grade asphalts normally associated in this area to improve the durability of our pavements.

The findings of this and other reports bear this out. Vermont is not unique with the problem, nor the recommendations. Research has been carried out in various degrees of complexity for over 30 years relating to age-hardening and cracking in asphalt pavements. The reports range from sophisticated chemical analysis of recovered asphalts to simple field evaluations of in-service conditions of pavements made with different grades of binder. The reoccurring theme in many of these reports (1, 2, 3, 4, 6, 7) is that characteristics of the asphalt binder, as measured by one or several standard methods, is of fundamental importance in studying pavement durability. Others (1, 2, 3, 4, 5) have also recognized the need to relate climatic conditions as a most important parameter in relating in-service durability to the particular characteristic of the asphalt. These correlations have been made in enough reports to preclude any doubt as to the validity of such comparisons. It remains only for the author to choose what particular tack he is able to proceed along due to his time and analysis facility limitations.

PROCEDURE

It was felt important to reduce the number of variables used for comparison for clarity of interpretation. The selection of those variables was based on past available data, present analysis facilities, standardized production techniques, identical typical design sections, highway type and a measurable reoccurring crack pattern.

In view of the above considerations, it was felt that the Interstate system in Vermont would provide the longest time span of available standard design and usage characteristics. Project records of the mixes and asphalts were comprehensive and well documented. The Laboratory of the Vermont Highway Department was able to provide a chemist to do Abson recovery tests to obtain the penetration and viscosity of the asphalt in the actual in-service samples taken. The crack pattern that was observed and measured in the field by the author was of the transverse type. Only transverse cracks extending a full 12 foot lane width or greater were counted. The number of cracks were counted and averaged for the transverse crack interval (TCI) in feet on at least two representative 200 foot sections for each project.

The system for coring was established by the year the section of highway was paved. As some sections of Interstate were paved in the northern as well as southern sections of the state the same year, it was decided to core different geographic locations within the state paved the same year. Cores were taken by a mobile rig with a 10 inch diamond bit. Selection of the core location on each project was done at random unless the location chosen was obviously non-representative. All cores were taken 6 feet right of center line for standardization This location has been used by other researchers (12) but is subject to suspect (8) due to oil drippings. However, visual observation showed little discoloration due to this. It is the authors opinion that there has been little effect on the final results because of this potential contamination. Core depth included top and binder course averaging a total of 3 inches of depth. Photographs were taken at each core location.

At the Laboratory, the top was separated from the binder and extracted by a rotarex using a trichlorethylene solvent. The gradation, percent asphalt and density (% theoretical voidless mix) were calculated. The centrifuged solution was taken to the chemist where it was processed according to AASHO T-170 (Abson method) to recover the asphalt. Two tests were performed on the recovered asphalt-the standard penetration test (100 grams 5 seconds, 77°F) and the absolute viscosity at 140°F using the Cannon-Manning Vacuum Viscometer. The same procedure was used for the binder portion of the cores.

DATA

The summary of in-service age, penetrations and TCI for all core locations are presented in Table I. The in-service age was calculated to the time the project was cored, 1969. Average penetrations for the asphalt cement used in the production of both top and binder courses prior to mixing were obtained from project records, and repøresent a great many samples for each average. The recovered penetration was run on both top and binder courses to see if a correlation could be established in this respect. The TCI as measured in feet includes both travel and passing lanes, although only the travel lane was cored. It is an observed phenomenon that in general, the passing lane is more severly transverse cracked than the travel lane (Figure X).

Table II gives the in-service age, the recovered penetration, the TCI and the recovered viscosity by core. As there is much discussion at present about viscosity grading of asphalt cements, it was desired to try to obtain a correlation between age and viscosity.

The average mix gradations for top and binder as used in the projects are presented in Table III. These averages represent many test results as found in the project records.

Table IV is the summary of core gradations as extracted in the Laboratory.

Table V gives other relative information as obtained from the cores.

Table VI summarizes the densities (% theoretical voidless mix) of mix prior to laydown and the density of the cores after in-service life.

Table VII gives the design limits of Vermont's bituminous items.

Figure I illustrates the reduction of penetration as the in-service age of the pavement increases for the top course.

Figure II illustrates the reduction of penetration as the in-service age of the pavement increases for the binder course.

Figure III demonstrates the relationship of recovered penetrations between top and binder courses.

Figure IV gives the relationship of TCI to in-service age.

Figure V gives a correlation to in-service age and viscosity of the top course, travel lane.

The relative decrease in penetration from prior to mixing to coring during the aging process in Vermont is illustrated in Figure VI.

The horizontal line at the top is the average penetration of the asphalt for all projects prior to mixing as obtained from project records. The curved line represents the recovered penetration which decreases with increasing age.

A comparison done by others in Pennsylvania (8) of various penetration grades of asphalts and how they age is illustrated in Figure VII.

Figure VIII illustrates work done by others in Pennsylvania (8) on various grades of asphalt with respect to ductility.

Figure IX is the FI (Freezing Index) of the United States.

Figure X shows photographs of the crackfilling operation prior to overlayment on the Interstate system near Core 1. Note the greater number of transverse cracks filled in the passing lane than the travel lane.

DISCUSSION

Welborn and Lewis of the Public Roads Administration (1) noted in 1948, "The durability of asphaltic pavements, as influenced by the consistency of the asphalt, depends upon the climatic environment in which they are located. The critical penetration of the bitumen at which pavement cracking occurs is higher in cold climates than in warm climates."

McLeod of Imperial Oil Limited reports (2), "This paper indicates that transverse pavement cracking in Canada is caused primarily by low winter temperatures, and that it can be dramatically reduced and even eliminated by the use of softer grades of asphalt cement."

A recent report from South Dakota (3) concluded, "A definite relationship was found to exist between asphalt hardness and pavement cracking. The hardest asphalt used in South Dakota (85-100 penetration) can be expected to develop a crack spacing of 50 feet or less within three years of construction. Nearly two-thirds of the projects using SC-6, the softest asphalt in general use, show little or no cracking after an average of ten years of age. Intermediate hardness asphalts show correspondingly intermediate levels of cracking."

Housel, Professor of Civil Engineering at the University of Michigan and Research Consultant for the Michigan State Highway Department (5) concluded in 1964.

"With full realization that pavement life and serviceability are controlled more by environmental effects than by load application, pavement design practice may be pointed in the future more directly toward compensating for these natural destructive influences. The range of pavement performance covered by the present profile surveys is sufficiently large and the contrast between the best and poorest performance such as to indicate that emphasis in design on these environmental factors may produce substantial improvements."

These and others have demonstrated that a relationship most definitely exists between the asphalt binder, crack phenomenon and climatic environment. This paper presents Vermont's peculiar application to these relationships and is illustrated by data collected on our Interstate system.

It might be suggested that the data presented is insufficient to conclusively state that the relationship does indeed exist. However, it is the intent of this paper to substantiate the findings of others, and to show the correlation of these factors in Vermont. In an unpublished report "Pavement Distress Evaluation" done earlier this year by this author only two relationships were considered, that of climatic environment and pavement cracking. As this report showed a possibility for further study, it was decided to investigate a third parameter, that of the properties of the recovered asphalt. As it appears, little work has been done to investigate "aging gradients" through the depth of the pavement (10) it was hoped by analyzing the surface and binder courses separately some correlation might be obtained.

The main concern was to find what could be done to extend the durability of asphaltic pavements in Vermont. Welborn (1) and others conclude that a measure of durability can be made by tests of the recovered bitumen. Due to the normal work load at our Laboratory, our investigations into the tests of the recovered bitumen were restricted to penetration and viscosity measured at standard temperatures. It was felt that low temperature ductilities would have been of great help in measuring durability, but because of facility limitations these were not run.

Of course, a justification must be made as to the reduction of variables to the exclusion of all except the asphalt cement itself. Of major concern is the void content (8, 11, 13, 14, 15), particularly as it relates to in-service aging of the pavement. Two factors which affect the void content, among others, are mix design and paving techniques. The standard Marshall Method and the Bureau of Public Roads Gradation Chart (Form PR-1115) is utilized for the former and cores relating to the particular mix production for the latter.

Table III shows that the mix gradations and density remain within a relatively narrow range and are considered acceptable by the Asphalt Institute (11) and our Specifications. Table VI shows the densities from the cores remaining within the range of densities of the initial mix. Due to the fact that no wide variations occur with respect to these densities, it is concluded that the relationship between the recovered penetrations and the original penetration is indicative of the aging process due primarily to years in-service in Vermont's climatic environment, and not caused by poor design or paving techniques.

With this established, Figure I illustrates the reduction in penetration for the top course as in-service age increases. From Figure III it is interesting to note the lag in reduction in penetration for the binder course behind the top course. The most logical explanation would be the reduction of the oxidation process on the binder course due to its physical location in the mat. This ~~is~~ has been substantiated (16) by both penetration and ductility values which are the lowest for the surface course and highest for the base course. Lee (6) also showed this in his work, though with viscosities and not penetration. However, the penetration does reduce in both cases though at apparently different rates. With the relationship established between reduction of penetration to in-service age, it became necessary to correlate the transverse crack interval to the in-service age, which Figure IV does. With less than 4 years in-service, the TCI is either extremely large and too random to conclusively measure or nonexistent. After 4 years of service, it is shown that the TCI becomes of severe enough nature to evaluate and continues to deteriorate as the age of the pavement increases. The shortest TCI measured was 12 feet on pavement 6 years old in the north-central part of the state on the Canadian border.

It remained only to correlate these two phenomenon as they occur within Vermont's particular climatic environment to see at what minimum penetration the TCI becomes of reasonably recordable frequency. With the age of 4 years established as producing a TCI of severe nature and going to Figure I, it is seen that a recovered penetration of slightly above 40 in the top course will produce this.

Lee (6) in working on durability tests for asphalts reminds us that, "in reality, asphalt will not last forever, or to infinite time. More likely than not, the asphalt will reach a critical value of penetration or viscosity or ductility or other controlling property and fail before it reaches the limiting valve or infinite time. Therefore, it is this critical valve (or valves) of the controlling property (or properties), and the time the asphalt in question takes to reach this valve is of the utmost practical concern." Lee was working with five 85-100 penetration grade asphalts and one 120-150 penetration grade. It is of interest to note, that of the asphalts Lee tested, the 120-150 grade took the longest time to reach its limiting viscosity at 77°F, and he pointed out that even though others had lower limiting viscosities, they might fail at an earlier time because they would reach the critical viscosity earlier.

To illustrate the drop between recovered penetration from its original penetration, Figure VI is presented. Using penetration as a measure of durability (1) and considering current construction practices as providing proper densities (11), then it is logical to investigate the use of a softer grade of asphalt to substantially boost the curve in Figure VI, thereby prolonging the in-service time required for the penetration to reach 40.

Vermont presently has some 120-150 penetration asphalt in use. One experimental project is only one year old and is much too new to indicate any difference between it and the 85-100 penetration used on the other half of the same project.

Other usage of 120-150 penetration has been in thin ($\frac{1}{2}$ inch to 1 inch) sand-mix overlays for maintenance resurfacing in a few areas. Cores of these overlays give a recovered penetration approximating that of 85-100 penetration used in normal ($2\frac{1}{2}$ to 3 inch) thickness pavements for equivalent in-service age. These values are believed to be caused by the thin overlays oxidizing at a more rapid rate than the normal surface course. Even though these thin overlays reduced in penetration more than was anticipated, there has been little transverse cracking of consequence in projects up to 5 years old, which is the oldest 120-150 penetration asphalt in use in Vermont.

As Vermont has few pavements constructed with other than 85-100 penetration asphalt, Figure VII illustrates work done by Gotolski et all (9), in Pennsylvania using various grades of asphalt cement. Five different initial penetration asphalts were used on test strips and cored periodically. It is noted that the softest grade of asphalt used retained the highest recovered penetration at all ages. Gotolski reported "that a common (70-85 penetration, 3,000±200 viscosity) asphalt was performing as well as any as indicated by the percent retained penetration---." This can be seen in Figure VII because the slopes flatten as the original penetration is reduced. However, two of the line grade asphalts (77 and 59 penetration) possibly would have already produced transverse cracking in Vermont, within 30 months, and three others (110, 94, and 89 penetration) by extrapolation would approach a penetration of 40 considerably sooner than the line 146 penetration asphalt.

It was mentioned earlier that it would have been interesting to measure the ductility of the recovered asphalt at a low temperature as an indication of durability in Vermont's climatic environment. Gotolski (9) did work on this approach in Pennsylvania. Figure VIII illustrates that the softest line grade of asphalt as measured by both initial penetration and initial ductility remained the softest through the coring period as measured by ductility at 39.2°F and 1 cm per minute. Gotolski's work, when correlated with Lee's, strongly indicates that the usage of a higher penetration asphalt substantially increases the time required to reach a particular critical value where failure, such as transverse cracks occur.

How well do our findings compare with work of others? Gietz and Lamb (4) in their Wyoming work showed little or no cracking when the penetration of the recovered asphalt remained near 40 or above. Inspection of the Figure IX shows the Freezing Index of Wyoming comparable to Vermonts. South Dakota (3) concluded that transverse cracking could become a serious problem in 3 years using 85-100 penetration asphalt and that the use of 120-150 penetration asphalt displayed a greater resistance to cracking than did the 100-120 or 85-100 penetration asphalts. The Freezing Index of South Dakota is somewhat greater than Vermont's, thus suggesting that perhaps transverse cracking occurs in South Dakota at a higher recovered penetration than in Vermont due to the colder temperature. This is supported by McLeod (2) in his findings north of the Great Lakes, where the Freezing Index is considerably higher than Vermonts. McLeod found that transverse cracks were not serious as long as the penetration of the recovered asphalt remained above 60 as one of the limiting criteria.

Again, considering current construction practices acceptable in view of density, the practical and most economic way to increase the durability is to select a softer grade of asphalt. Gotolski (9) demonstrated this as shown in Figures VII and VIII. Figures VII and VIII also demonstrate the relative closeness of characteristics between 85-100 and 100-120 penetration
asphalts, as well as the advantages of using 120-150 penetration. Vermont has experienced this when using 85-100 and 100-120 penetration
grades as often the difference in penetration between the two grades is only 10 points. McLeod (2) also demonstrated the concept of skipping at least one grade to obtain appreciable results. To realize any appreciable increase in durability, then it must be concluded that Vermont should go to the 120-150 penetration grade as the initial step in improving the durability of its asphalt pavements.

CONCLUSIONS

1.) There are critical values and times for controlling properties of the asphalt cement to create pavement failure.

2.) Full 12 foot lane width transverse cracks occur in recordable frequency after about 4 years of in-service use.

3.) The average recovered penetration after 4 years of in-service use for 85-100 penetration asphalt in surface course is about 40.

4.) Our findings are comparable with the work of others.

5.) The use of softer asphalts will substantially increase the durability of pavements in Vermont.

6.) It will be necessary to change from 85-100 to at least 120-150 penetration to realize any appreciable increase in durability.

7.) No change in present mix design methods ~~is~~ are anticipated as detailed in the summary.

RECOMMENDATIONS

1.) Vermont adopt the use of 120-150 penetration asphalt as the initial step in increasing the durability of its asphalt pavements.

2.) Limiting requirements other than penetration (as ~~formal~~ found from 4 below) should be included to insure a durable asphalt cement.

3.) With adoption of "3-Stage Construction" on the Interstate system it is suggested more work be conducted in the "aging-gradient" to hopefully establish the optimum time the third stage should be applied to recieve the full durability benefit of each stage of pavement.

4.) Investigation should be conducted into low temperature characteristics of different grades of asphalts.

ACKNOWLEDGEMENTS

The author is indebted to Mr. Edward H. Stickney, Assistant Chief Engineer, and Mr. Frank E. Aldrich, Paving Engineer, Vermont Highway Department, for their continued interest and support of this project.

The author also thanks the Vermont Highway Department Laboratory for its help in compiling data and especially to their chemist, Mr. John H. Townsend.

LITERATURE CITED

1.) Lewis & Welbron. "The Effect of Characteristics of Asphalts on Physical Properties of Bituminous Mixtures", Division of Physical Research, Public Roads Administration. 1948.

2.) N. W. McLeod. "Transverse Pavement Cracking Related to Hardness of the Asphalt Cement." 1968.

3.) South Dakota Highway Department. "Pavement Cracking as Related to Asphalt Hardness." 1968.

4.) Gietz and Lamb. "Age-Hardening of Asphalt Cement and its Relationship to Lateral Cracking of Asphaltic Concrete." 1968.

5.) Housel, W. S. "Evaluation of Pavement Performance Related to Design, Construction, Maintenance and Operation." 1964.

6.) Lee, D-Y. "Development of a Laboratory Durability Test for Asphalts." 1968.

7.) Majidzadch and Schweyer. "Viscoelastic Response of Aged Asphalt Cements." 1968.

8.) HRB, National Co-op Highway Research Program Report #67. "Relation of Asphalt Rheological Properties to Pavement Durability." 1969.

9.) Gotolski et all. "Study of Physical Factors Affecting the Durability of Asphaltic Pavements." 1968.

10.) Haas & Topper. :Thermal Fracture Phenomena in Bituminous Surfaces." HRB Special Report 101. 1968.

11.) The Asphalt Institute. "Mix Design Methods for Asphalt Concrete." 1962.

12.) Maryland Research Report. "Progress Report on Investigation of Base Courses of Flexible Pavements." 1966.

13.) J. York Welborn. "The Fact and Fallacy of Asphalt Hardening." 1969.

14.) L. F. Rader. "Correlation of Low Temperature Tests with Resistance to Cracking of Sheet Asphalt Pavements."

15.) Hubbard & Gollomb. "The Hardening of Asphalt with Relation to Development of Cracks in Asphalt Pavements." 1967.

16.) HRB #321, "Flexible Pavement Design and Performance Studies."

TABLE I

DATA ON RECOVERED ASPHALT CEMENTS AND IN-SERVICE CONDITIONS FOR INTERSTATE SYSTEM

In-Service Age (Yrs.)	Core No.	Average Pen. Prior to Mixing		Recovered Pen.		Transverse Crack Interval-Feet	
		Top	Binder	Top	Binder	Travel	Passing
1	6	90	91	48	48	--	--
1	9	91	92	56	65	--	--
2	5	94	94	56	79	--	--
2	10	92	92	47	37	--	--
3	11	91	91	39	51	--	--
4	12	95	95	39	42	--	--
4	8	94	94	38	38	--	--
4	7	90	90	35	34	70	35
5	2	90	90	36	38	50	50
5	4	89	89	40	63	200	200
6	3	89	89	46	37	100	50
6	13	90	90	22	30	22	20
6	14	88	88	34	53	40	20
7	15	87	87	36	50	20	25
7	21	88	88	74	38	50 to 500	20 to 500
8	1	88	88	29	27	25	33
8	22*	90	90	38	39	20	20
8	23	89	89	29	46	67	33
9	24	93	93	47	29	33	33
10	25	94	94	35	21	25	28
11	26	94	94	29	34	140	70

* Overlayed

TABLE II

DATA ON RECOVERED ASPHALT CEMENTS AND IN-SERVICE CONDITIONS FOR INTERSTATE SYSTEM

In-Service Age (Yrs.)	Core No.	Recovered Absolute Viscosity-Poises		Recovered Pen.		Transverse Crack Interval-Feet	
		Top	Binder	Top	Binder	Travel	Passing
1	6	3,907	------	48	48	--	--
1	9	2,554	2,410	56	65	--	--
2	5	3,349	1,969	56	79	--	--
2	10	3,747	5,791	47	37	--	--
3	11	4,537	3,067	39	51	--	--
4	12	4,405	4,761	39	42	--	--
4	8	7,747	------	38	38	--	--
4	7	------	7,153	35	34	70	35
5	2	5,910	------	36	38	50	50
5	4	5,770	2,203	40	63	200	200
6	3	3,876	------	46	37	100	50
6	13	------	------	19	30	22	20
6	14	8,298	2,869	34	53	40	20
7	15	6,399	3,470	36	50	20	25
7	21	------	11,290	74	38	50 to 500	20 to 500
8	1	13,587	16,540	29	27	25	33
8	22*	12,731	11,137	38	39	20	20
8	23	8,353	3,294	29	46	67	33
9	24	4,810	14,278	47	29	33	33
10	25	9,660	-------	35	21	25	28
11	26	------	-------	29	34	140	70

* Overlayed

TABLE III

AVERAGE PROJECT GRADATIONS

Core No.	Course	Gradation % Passing Sieve 3/4	½	3/8	#4	#10	#40	#80	#100	% AC (Total Mix)	Density (% Theoretical)
1	Top		100	88	58	43	32	17	5	6.4	95.5
1	Binder	100	86	70	48	41	31	16	5	5.9	95.3
2	Top		100	86	58	43	26	16	7	6.6	98.1
2	Binder	100	82	65	46	35	19	11	6	5.7	98.1
3	Top		100	86	60	43	24	15	6	6.6	97.6
3	Binder	100	87	68	49	35	21	12	5	6.0	96.5
4	Top		100	86	60	42	26	16	6	6.5	98.7
4	Binder	100	83	63	50	36	21	13	5	5.6	97.7
5	Top	100	99	87	65	43	22	10	4	5.8	97.1
5	Binder	100	87	74	54	38	22	11	5	5.7	96.7
6	Top		100	89	61	43	23	10	3	6.6	96.1
6	Binder	99	83	72	48	36	23	10	3	5.7	96.0
7	Top		100	87	64	43	19	9	5	6.6	97.2
7	Binder	100	86	72	55	37	19	9	4	5.5	97.1
8	Top		100	88	71	45	22	9	4	6.6	97.3
8	Binder	100	84	71	53	36	18	8	3	6.0	97.9
9	Top	100	99	86	64	46	19	9	4	6.5	96.9
9	Binder	100	83	70	50	36	17	8	4	5.8	96.4
10	Top	100	99	88	61	46	16	9	6	6.5	95.0
10	Binder	100	86	69	44	35	17	8	4	5.7	95.0
11	Top	100	99	89	60	45	18	10	5	6.6	95.8
11	Binder	100	86	71	46	36	16	8	4	5.7	95.0
12	Top		100	87	57	45	25	11	5	6.6	96.7
12	Binder	100	86	66	45	35	19	10	4	5.7	96.2
13	Top		100	86	54	44	25	14	6	6.8	96.9
13	Binder	100	82	68	43	34	20	11	5	5.9	96.6
14	Top		100	87	61	45	29	16	6	6.3	96.5
14	Binder	100	82	64	50	42	27	14	6	5.9	96.0
15	Top		100	84	54	42	27	15	6	6.3	97.8
15	Binder	99	82	62	47	39	25	13	6	5.5	96.7
21	Top		100	82	59	50	20	12	7	6.8	97.0
21	Binder	100	84	74	52	36	14	9	5	5.7	97.5
22	Top		100	88	66	49	21	13	7	6.6	96.6
22	Binder	100	89	69	53	41	17	11	5	5.6	96.1
23	Top		100	89	64	49	27	14	6	6.5	96.0
23	Binder	100	85	69	49	37	21	11	5	5.6	96.3
24	Top		100	87	58	43	23	11	6	6.2	97.4
24	Binder	100	85	--	48	36	20	10	5	5.8	95.9
25	Top		100	85	60	47	20	14	6	6.6	----
25	Binder	100	82	--	51	37	16	11	5	5.4	----
26	Top		100	87	57	44	20	12	6	6.6	97.8
26	Binder	100	86	67	52	38	15	10	5	5.5	97.2

TABLE IV

AVERAGE CORE GRADATIONS

Core No.	Course	3/4	1/2	3/8	4	10	40	80	200	% AC Total Mix	Density (% Theorectical)
		Gradation % Passing Sieve									
1	Top		--	--	--	--	--	--	-	---	----
1	Binder	100	84	64	46	41	36	20	4	6.3	94.6
2	Top		--	--	--	--	--	--	-	---	----
2	Binder	100	85	69	50	37	20	10	5	6.5	95.3
3	Top		--	--	--	--	--	--	-	---	----
3	Binder	100	86	74	52	35	19	11	4	6.5	95.8
4	Top		100	89	59	42	27	18	6	5.9	96.5
4	Binder	100	86	69	53	39	23	14	6	5.9	98.4
5	Top	100	99	90	63	42	23	12	5	6.6	94.8
5	Binder	98	87	72	52	36	19	9	4	5.9	----
6	Top	100	99	89	65	46	23	10	4	6.5	94.5
6	Binder	97	81	71	51	37	25	13	4	5.7	96.5
7	Top	100	98	89	69	45	19	10	5	6.3	94.0
7	Binder	100	92	75	55	37	17	7	4	6.1	96.3
8	Top		100	91	70	49	23	12	5	6.8	96.7
8	Binder	100	90	71	46	33	19	10	4	5.6	95.9
9	Top	100	99	88	65	47	19	10	5	6.9	96.4
9	Binder	100	89	80	58	40	20	11	5	6.2	97.1
10	Top	100	99	90	67	47	20	12	6	6.2	94.8
10	Binder	100	84	75	46	33	22	11	4	5.6	91.7
11	Top	100	99	90	65	50	17	10	6	6.6	96.4
11	Binder	100	85	70	48	37	12	7	4	5.9	93.5
12	Top	100	100	84	56	43	23	10	5	7.0	98.3
12	Binder	100	90	66	43	34	19	9	5	6.2	97.4
13	Top	100	99	84	55	44	26	15	5	6.7	95.8
13	Binder	100	79	64	43	33	20	12	5	6.4	95.8
14	Top		100	90	61	44	30	17	6	6.4	96.9
14	Binder	100	81	66	50	40	28	14	5	6.4	99.0
15	Top		100	85	48	42	28	18	7	6.3	98.0
15	Binder	100	81	62	44	35	22	14	6	5.9	99.1
21	Top	100	99	85	58	50	22	14	8	6.9	97.6
21	Binder	100	84	73	52	38	16	9	5	5.5	96.7
22	Top		100	92	68	51	19	12	5	6.8	96.4
22	Binder	100	87	71	55	41	16	10	5	5.9	96.4
23	Top		100	92	67	50	27	12	5	7.1	96.1
23	Binder	100	93	79	58	41	21	12	6	6.2	98.7
24	Top		100	90	59	44	25	11	5	6.3	98.6
24	Binder	100	84	66	50	39	21	10	5	5.9	96.1
25	Top		100	86	59	46	22	14	6	6.4	----
25	Binder	100	92	77	54	38	20	14	9	6.1	----
26	Top		100	90	60	45	17	10	4	6.7	----
26	Binder	100	87	70	51	38	16	10	5	5.7	----

TABLE V

DATA ON CORES

Core No.	Course	% Asphalt (Total Mix)	Asphalt by Volume	% Voids	% Voids Filled with AC	VMA
1	Top	---	----	---	----	----
1	Binder	6.3	14.5	5.4	72.9	19.9
2	Top	---	----	---	----	----
2	Binder	6.5	15.4	4.7	76.6	20.1
3	Top	---	----	---	----	----
3	Binder	6.5	15.3	4.2	78.5	19.5
4	Top	5.9	13.9	3.5	79.9	17.4
4	Binder	5.9	14.5	1.6	90.1	16.1
5	Top	6.6	15.4	5.2	74.8	20.6
5	Binder	5.9	----	---	----	----
6	Top	6.5	15.3	5.5	73.6	20.8
6	Binder	5.7	13.9	3.5	79.9	17.4
7	Top	6.3	14.2	6.0	70.3	20.2
7	Binder	6.1	14.2	3.7	79.3	17.9
8	Top	6.8	15.9	3.3	82.8	19.2
8	Binder	5.6	13.2	4.1	76.3	17.3
9	Top	6.9	16.2	3.6	81.8	19.8
9	Binder	6.2	14.8	2.9	83.6	17.7
10	Top	6.2	14.8	5.2	74.0	20.0
10	Binder	5.6	13.0	8.3	61.0	21.3
11	Top	6.6	15.8	3.6	81.4	19.4
11	Binder	5.9	14.0	6.5	68.3	20.5
12	Top	7.0	16.6	1.7	90.7	18.3
12	Binder	6.2	14.7	2.6	85.0	17.3
13	Top	6.7	15.2	4.2	78.4	19.4
13	Binder	6.4	14.6	4.2	77.7	18.8
14	Top	6.4	15.3	3.1	83.2	18.4
14	Binder	6.4	15.7	1.0	94.0	16.7
15	Top	6.3	14.9	2.0	88.2	16.9
15	Binder	5.9	14.0	0.9	94.0	14.9
21	Top	6.9	16.2	2.4	87.1	18.6
21	Binder	5.5	13.1	3.3	79.9	16.4
22	Top	6.8	15.9	3.6	81.5	19.5
22	Binder	5.9	13.8	3.6	79.3	17.4
23	Top	7.1	16.7	3.9	81.1	20.6
23	Binder	6.2	15.1	1.3	92.1	16.4
24	Top	6.3	14.8	1.4	91.4	16.2
24	Binder	5.9	13.6	3.9	77.7	17.5
25	Top	6.4	----	---	----	----
25	Binder	6.1	----	---	----	----
26	Top	6.7	----	---	----	----
26	Binder	5.7	----	---	----	----

TABLE VI

COMPARISON OF ORIGINAL MARSHALL DENSITY TO CORE DENSITY AND IN-SERVICE AGE

In-Service Age (Years)	Core No.	Course	Marshall Density	Core Density
1	6	Top	96.1	94.5
1	6	Binder	96.0	96.5
1	9	Top	96.9	96.4
1	9	Binder	96.4	97.1
2	5	Top	97.1	94.8
2	5	Binder	96.7	----
2	10	Top	95.0	94.8
2	10	Binder	95.0	91.7
3	11	Top	95.8	96.4
3	11	Binder	95.0	93.5
4	12	Top	96.7	98.3
4	12	Binder	96.2	97.4
4	8	Top	97.3	96.7
4	8	Binder	97.9	95.9
4	7	Top	97.2	94.0
4	7	Binder	97.1	96.3
5	2	Top	98.1	----
5	2	Binder	98.1	95.3
5	4	Top	98.7	96.5
5	4	Binder	97.7	98.4
6	3	Top	97.6	----
6	3	Binder	96.5	95.8
6q	13	Top	96.9	95.8
6	13	Binder	96.6	95.8
6	14	Top	96.5	96.9
6	14	Binder	96.0	99.0
7	15	Top	97.8	98.0
7	15	Binder	96.7	99.1
7	21	Top	97.0	97.6
7	21	Binder	97.5	96.7
8	1	Top	95.5	----
8	1	Binder	95.3	94.6
8	22	Top	96.6	96.4
8	22	Binder	96.1	96.4
8	23	Top	96.0	96.1
8	23	Binder	96.3	98.7
9	24	Top	97.4	98.6
9	24	Binder	95.9	96.1
10	25	Top	----	----
10	25	Binder	----	----
11	26	Top	97.8	----
11	26	Binder	97.2	----

TABLE VII

VERMONT BITUMINOUS MIX DESIGN LIMITS

Course		Binder Courses				Wearing Courses			
Mix Type		Item 213		Type II		Type III		Type IV	
		Percent by Weight Passing Square Opening Sieves							
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Sieve Designation	1½"	100							
	1"	55	85	100					
	3/4"	45	70	95	100	100			
	1/2"	35	55	72	92	95	100	100	
	3/8"	--	--	62	82	76	94	95	100
	No. 4	15	25	44	62	54	74	50	85
	No. 10	3	10	28	45	34	53	35	70
	No. 40	--	--	11	27	14	32	16	40
	No. 80	--	--	6	17	8	20	8	26
	No. 200	--	--	2	5	3	6	3	6
Total Mineral Aggregate		95.5	96.5	93	95	92	95	92	94
Bitumen (Percent of Total Mix)		3.5	4.5	5	7	6	7	6	8
Total Mix		100		100		100		100	

FIGURE [illegible]

IN SERVICE AGE AND RECOVERED PENETRATION

TOP COURSE

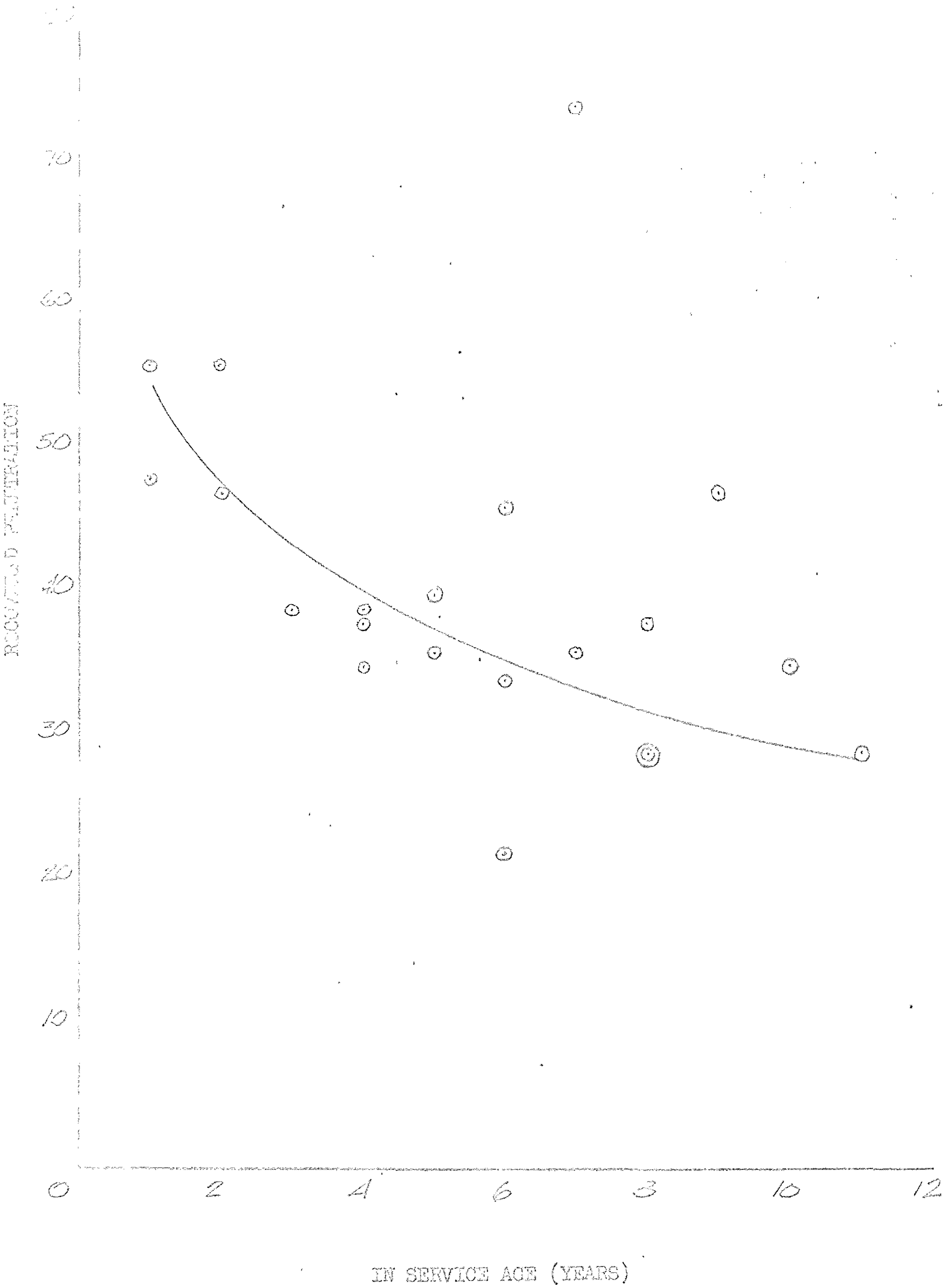


FIGURE II

IN SERVICE AGE AND RECOVERED PENETRATION

BINDER COURSE

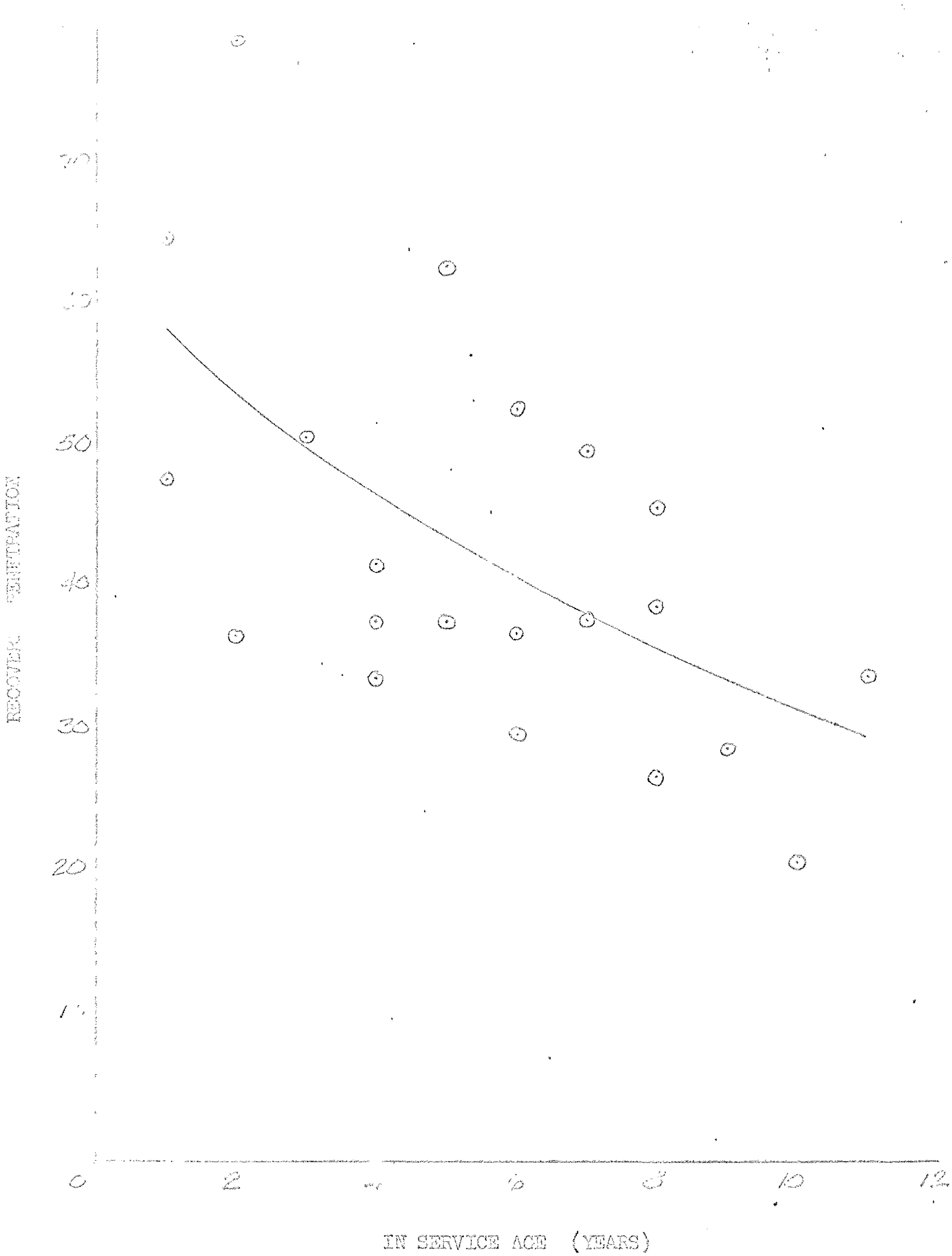


FIGURE III
IN SERVICE AGE AND RECOVERED PENETRATION
TOP AND BINDER COURSES

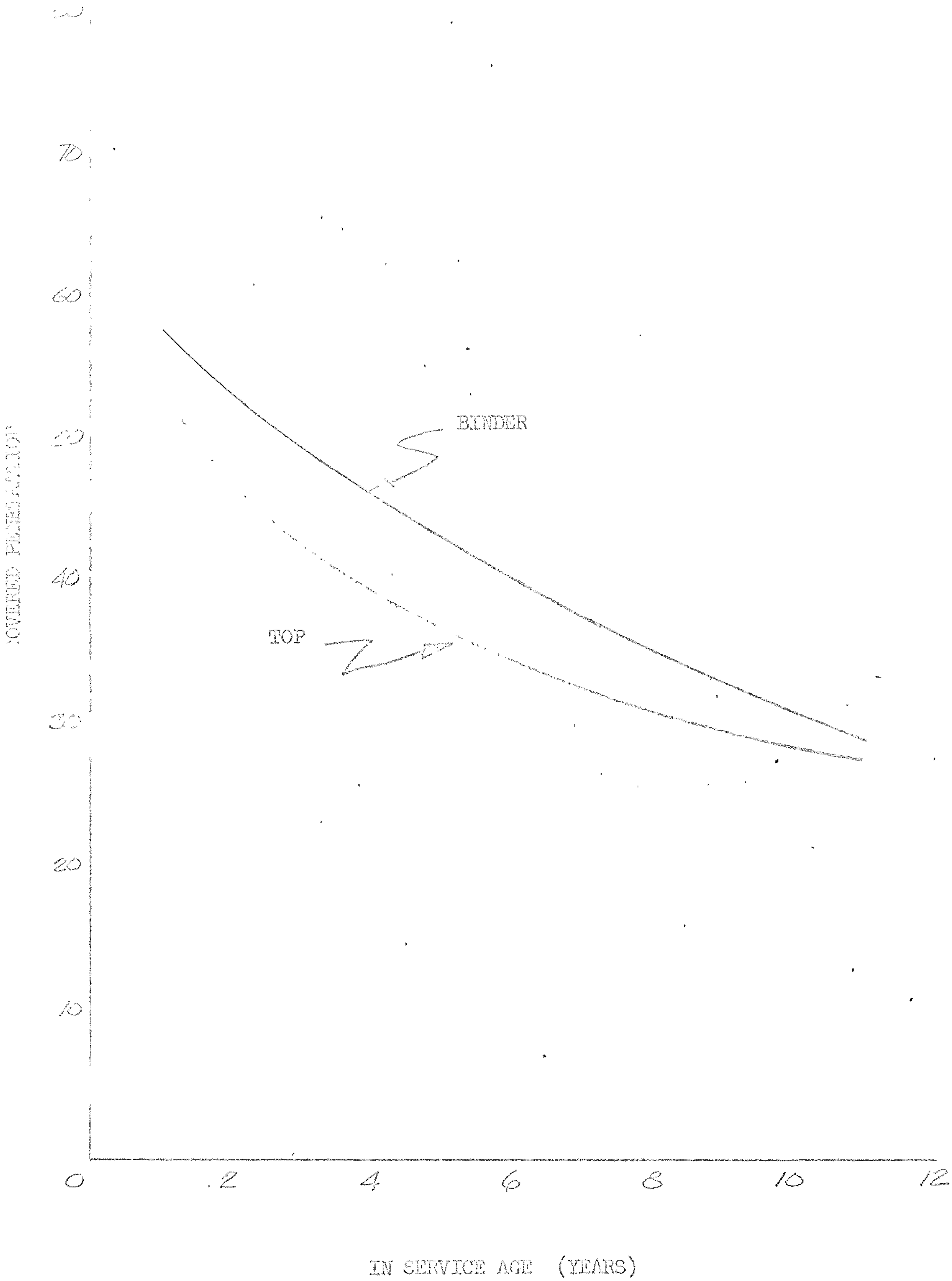
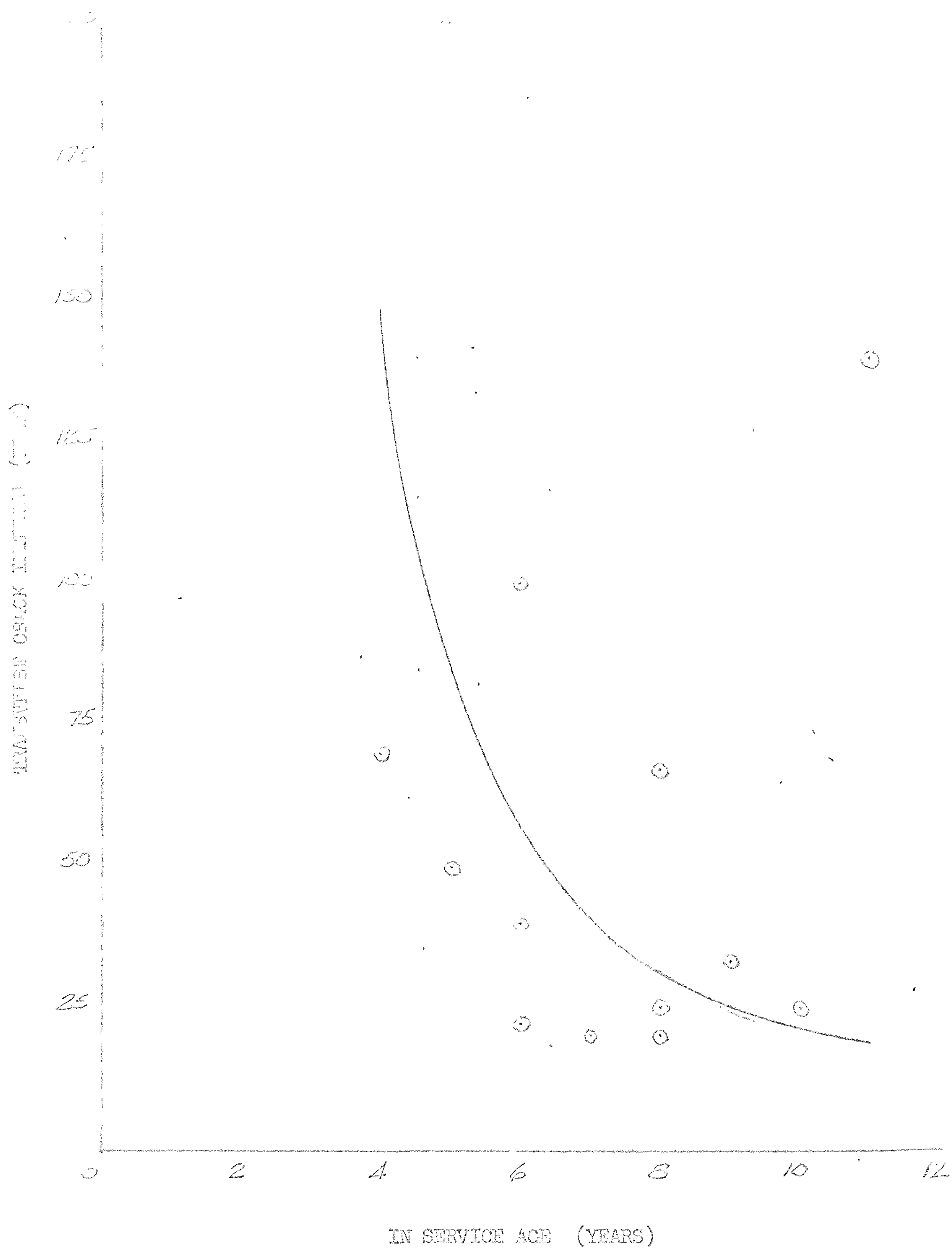
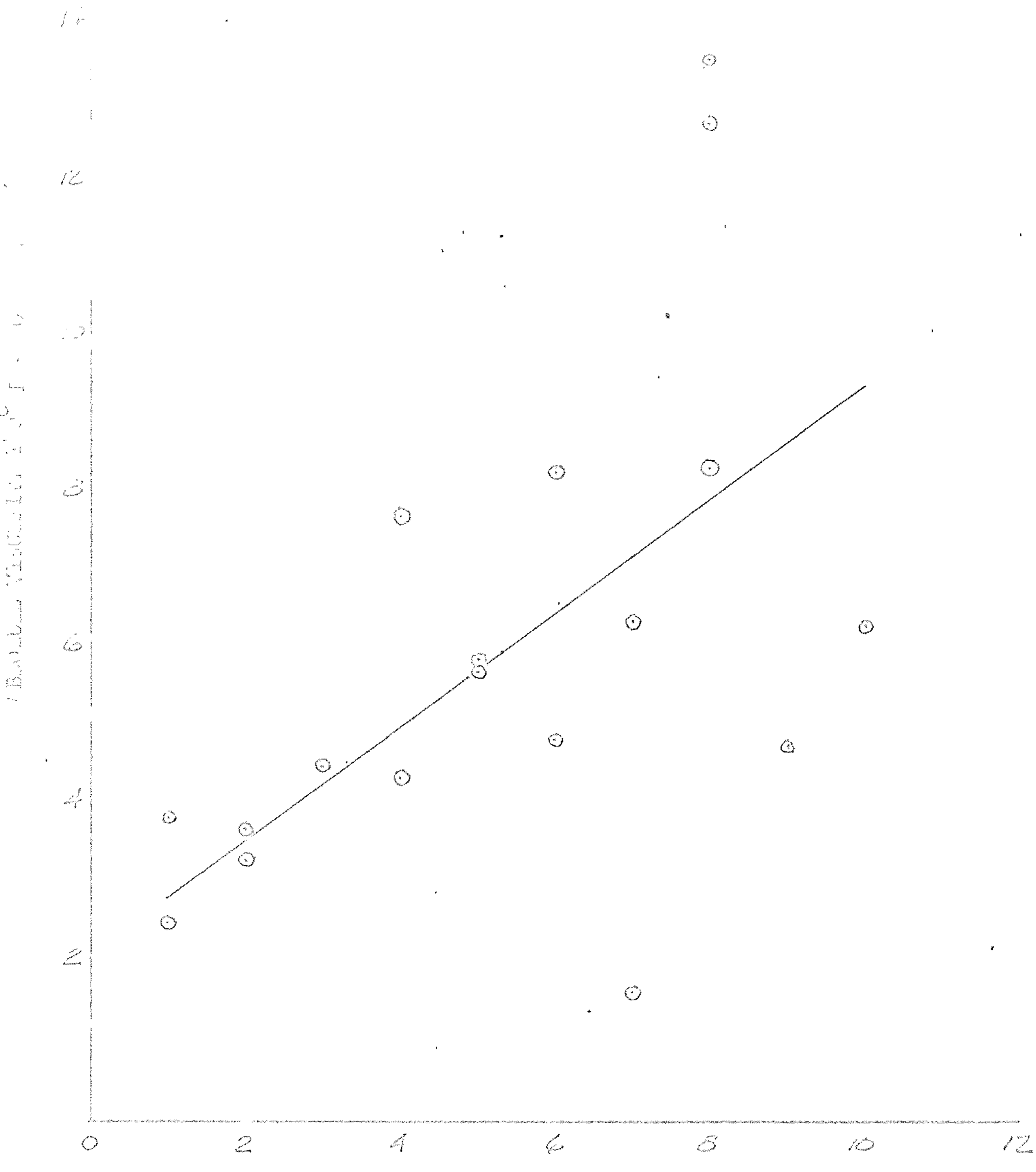


FIGURE IV

IN SERVICE AGE AND TRANSVERSE CRACK INTERVAL, TRAVEL LANE





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8
6
4
2
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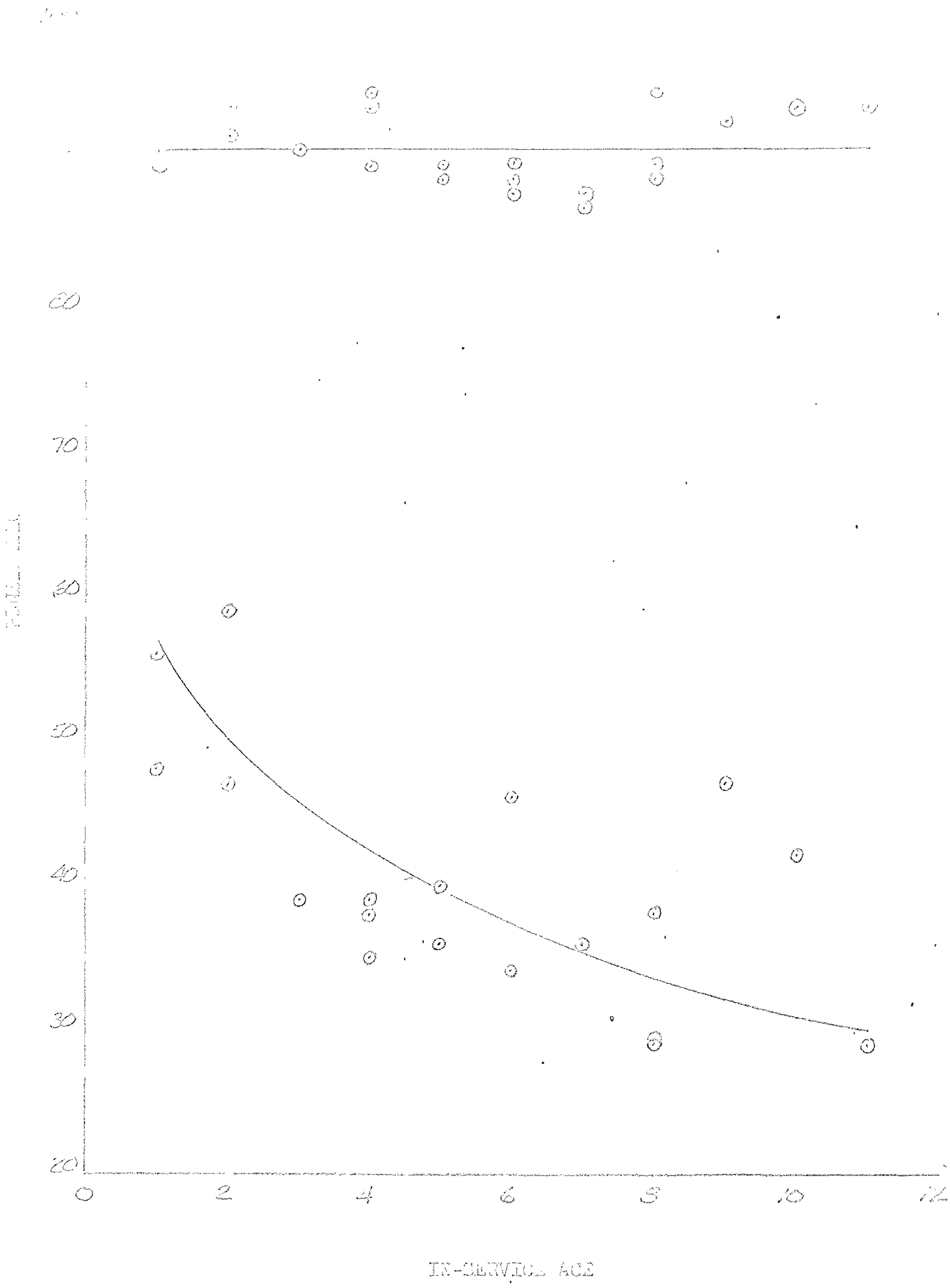
4
6
8
10
12
IN-SERVICE AGE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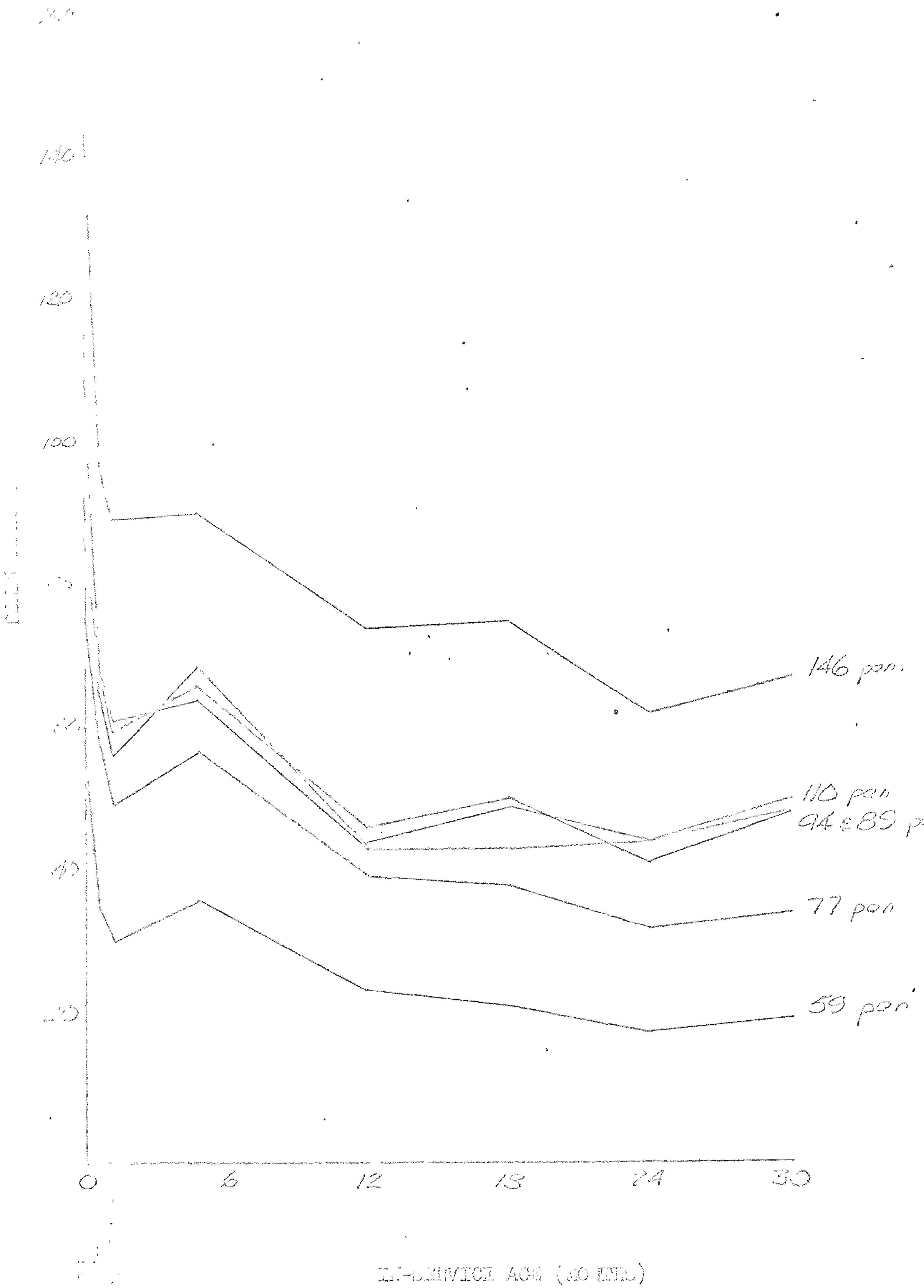
4
6
8
10
12
IN-SERVICE AGE

II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59 pen
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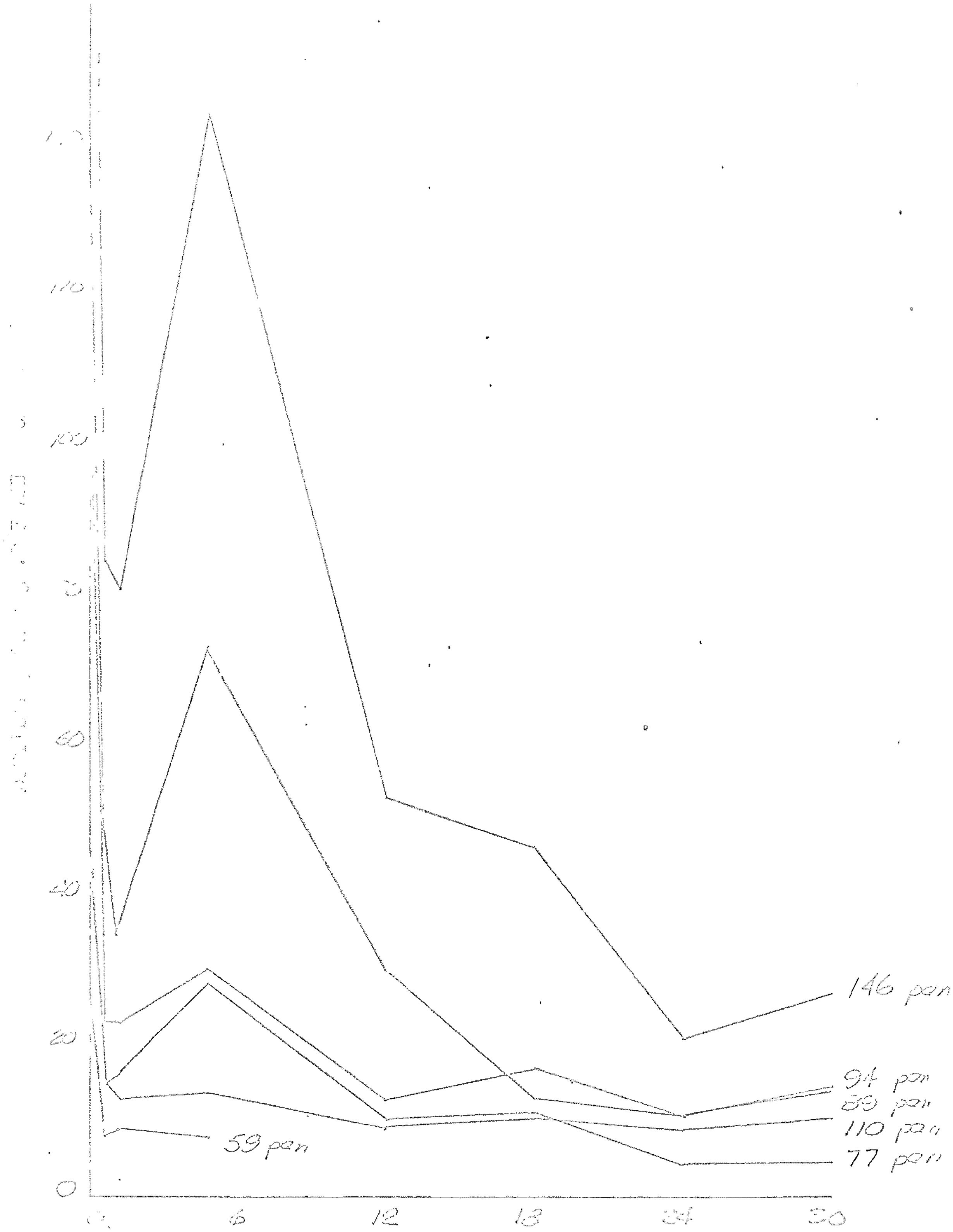
6
12
18
24
30
IN-SERVICE AGE (MONTHS)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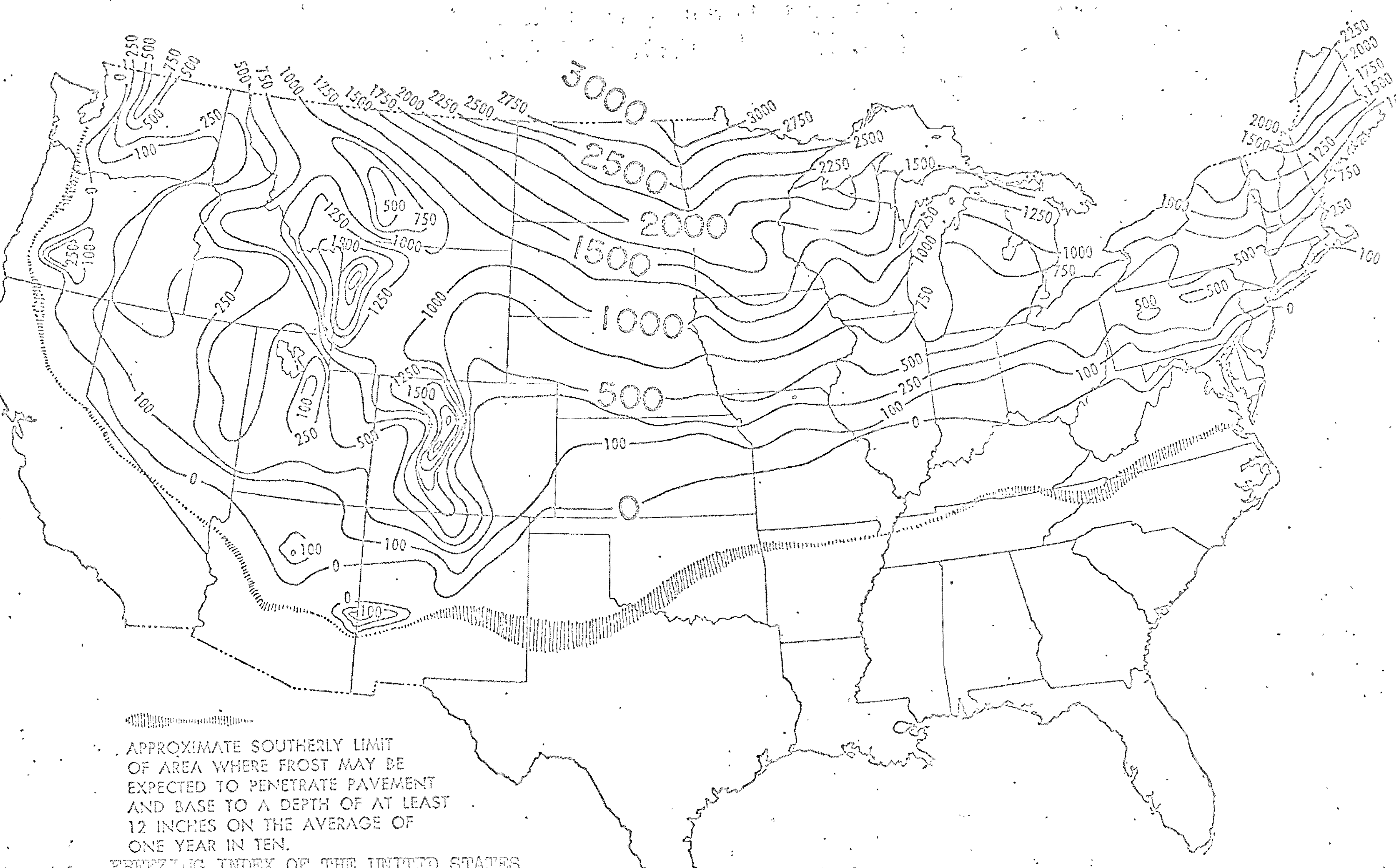

FREEZING INDEX OF THE UNITED STATES

FIGURE IX

FIGURE X

Passing lane more severly transverse cracked than travel