# PAVING ASPHALT PROPERTIES AND PAVEMENT DURABILITY

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Thirteen asphalt concrete pavements built in Pennsylvania were studied from September 1961 to March 1973. As a result of an extensive sampling and analysis program, considerable information has been gained on the durability of asphaltic pavement. Based on physical test data (penetration, viscosity, and ductility) and percentage of asphaltenes, all of the asphalts used in the various pavements hardened with time. The time of year when a pavement is sampled was shown to influence test results among and within test pavements. In experimental pavement studies all test pavements should be sampled at the same time of the year on an annual basis. Inasmuch as conditions appear to be more detrimental in summer than in winter, an additional 5 to 6 months of pavement life may be realized if the pavements are built in the fall rather than in the spring. This allows some pavement compaction to occur before the agents of asphalt hardening become active. The air void volume of an asphalt pavement has been shown to be a major factor in pavement durability and, with deterioration, the safety of those using the pavement. Based on construction results on experimental pavements, air void contents of Pennsylvania highway pavements are on the average too high. Multiple air void specifications should be replaced by a single number—10 percent of maximum theoretical. Field control must become somewhat continuous and totally enforceable. Lower viscosity asphalts, greater field compaction and control, and greater selectivity in design are offered as means of fulfilling lower air void content specifications. The hardening of asphalts in the pug mill should be studied closely. Lower mixing temperatures and shorter mixing times in conjunction with lower viscosity asphalts should provide a paving viscosity similar to that now used but with lower initial hardness.

•EXTENDING the useful life of a bituminous pavement is a problem for both the users and producers of asphaltic materials. During recent years, much research (1, 2, 3, 4) has been performed to determine the factors necessary to evaluate or predict the durability of an asphalt roadway and to gain an understanding of the physical and chemical changes that occur during the age hardening of asphalt. Hardening of an asphaltic pavement is confined to the asphalt cement. Any investigation of the hardening of an asphalt mix should concentrate, therefore, on the changing properties of the asphalt cement. Accordingly, it is important to understand the processes by which an asphalt hardens.

Oxidation is probably the most important factor in the hardening and loss of binding power of asphalt (5). It is a continuous process that occurs at the surface of the pavement and that depends on temperature, time, and rate of oxygen diffusion.

Photooxidation influences the hardening of asphalt at the surface. However, because 99 percent of the light waves can only penetrate to a depth of 10 microns (6), photooxidation does not harden asphalt that is internally situated in the wearing course of an asphaltic pavement. Photooxidation forms a hardened, impermeable film that is soluble in water but insoluble in common asphaltic solvents such as benzene, chloroform, and carbon tetrachloride (7). This exposed film becomes very hard, loses adhesiveness, and erodes away.

Age hardening or steric hardening is a phenomenon that occurs in asphalt at temperatures below the softening point of asphalt. When a sample of asphalt is cooled, a structure forms within the asphalt with the passage of time. As this structure develops, the penetration decreases, thus indicating that the asphalt has hardened. The structure is somewhat thixotropic in nature in that most of the structure is destroyed by the application of heat or mechanical energy (8). Age hardening is not a completely reversible process because some permanent hardening does occur.

There are many other factors that affect the hardening of an asphalt. Traxler (5) summarizes these factors as photochemical, polymerization, syneresis, action of water, absorption by solids, adsorption of components at solid surface, chemical reactions or catalytic effects at interface, and microbiological deterioration.

All of these affect the hardness of the asphalt and in turn the durability of an asphaltic pavement, but there are other properties that contribute as much or more to the durability of an asphaltic pavement. Stability, the ability to withstand loads, is very important to the longevity of an asphaltic pavement, as are also tensile, flexural, and flow properties. An asphaltic pavement must be resilient and able to rebound after an instantaneous load. These properties are affected by the temperature and duration of wet mixing in the pug mill, uniformity in batching, gradation of aggregate, aggregate shape, physical properties of aggregate such as strength and porosity, temperatures during spreading and rolling, segregation during spreading, amount and type of rolling, percentage of asphalt, subsoil and subgrade conditions, shoulder conditions, and so on.

Under the sponsorship and with the cooperation of the Federal Highway Administration and the Pennsylvania Department of Transportation, the Civil Engineering Laboratories of the Pennsylvania State University undertook an investigation of the physical and chemical properties of in-service asphalt concrete material. The principal aim of this investigation was to study the physical and chemical changes of asphalt and asphalt mixtures over time, with a view to gaining an understanding of the factors affecting the durability of asphaltic pavements.

## TEST PROJECTS

This study was concerned with the performance of 13 test pavements designed and constructed by the Pennsylvania Department of Transportation. The pavements were originally studied as three groups of pavements. Group 1 pavements consisted of four road projects that were selected when the Pennsylvania Department of Transportation introduced specifications using the Marshall method for design and control of bituminous paving mixtures in 1961. Initial data, construction data, some in-service data, and the history of the pavements are given in the literature (4, 11). A brief description of the type of surface and aggregate used is given in Table I.

Six additional pavements (group 2) were included in the study in fall of 1963, but evaluation of four of these was discontinued in 1970. Sampling was discontinued because these pavements had characteristics—air voids, average daily traffic density, aggregate type, and transverse pavement location—whose order of importance in asphalt hardening was difficult to determine.

Group 3 consisted of three pavements constructed to determine whether penetration specifications for asphalt should be complemented by specifications for absolute viscosity. Data on the material properties of the asphalt and aggregates are reported in the literature (9, 10). A complete history of the group 3 pavements was reported in 1968 (9, 11). In addition to being constructed from different aggregates, each pavement was built with six different asphalts as described in the literature (9, 10).

## TESTING PROCEDURES

The sampling and construction procedures were formulated for each project before each roadway was constructed. A complete discussion of these procedures was reported in 1967 (11). For this investigation, the testing procedure adopted for penetration was ASTM Designation D 5-65 and for absolute viscosity was ASTM Designation D 2171-63T.

Specific gravity determinations, based on Pennsylvania Department of Transportation

**Table 1. Description of test projects.**

| Group | County | Legislative Route | Type of Surface | | Type of Aggregate | | Date Constructed (overlayed) |
|---|---|---|---|---|---|---|---|
| | | | Wearing | Binder | Coarse | Fine | |
| 1 | Washington | 113 | ID-2 | ID-2 | Slag | Slag | June 1963 |
| | Beaver | 538 | ID-2 | ID-2 | Slag | Slag | October 1961 |
| | Lycoming | 41037 | ID-2 | ID-2 | Limestone | Limestone | September 1961 |
| | Lebanon | 141 | ID-2 | ID-2 | Limestone | Limestone | May 1962 |
| 2 | Allegheny | 652 | ID-2 | ID-2 | Gravel | Sand and gravel | September 1963 |
| | Armstrong-Butler | 387 | FJ-1 | ID-2 | Limestone | Glacial sand | November 1963 |
| | Butler[a] | 75 | FJ-1 | ID-2 | Limestone | Glacial sand and fly ash | October 1963 |
| | Butler[a] | 251 | FJ-1 | ID-2 | Limestone | Glacial sand and fly ash | October 1963 |
| | Clarion[a] | 214 | FJ-1 | ID-2 | Limestone | Glacial sand | October 1963 |
| | Clarion[a] | 66 | FJ-1 | ID-2 | Limestone | Glacial sand and fly ash | October 1963 |
| 3 | Clinton | 219 | ID-2 | ID-2 | Limestone | Limestone | October 1964 |
| | McKean | 101 | ID-2 | ID-2 | Gravel | Sand and gravel | August 1965 |
| | Jefferson | 338 | FJ-1 | ID-2 | Limestone | Sand | September 1965 |

[a]Sampling discontinued in 1970.

**Figure 1. Percentage of retained penetration versus time for group 1 pavements.**

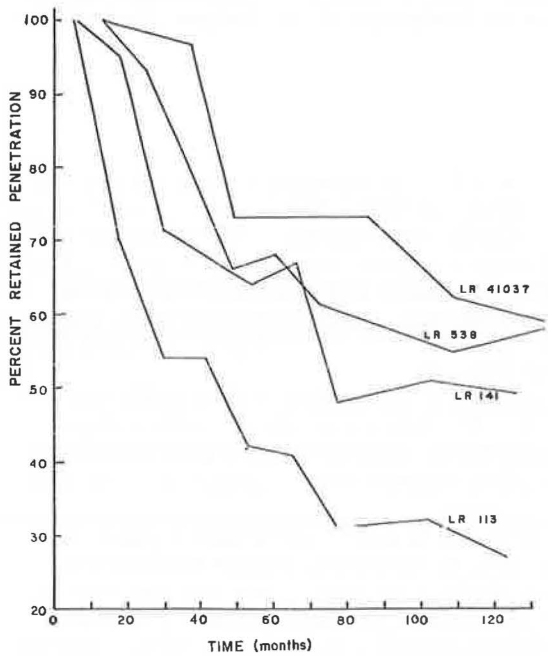
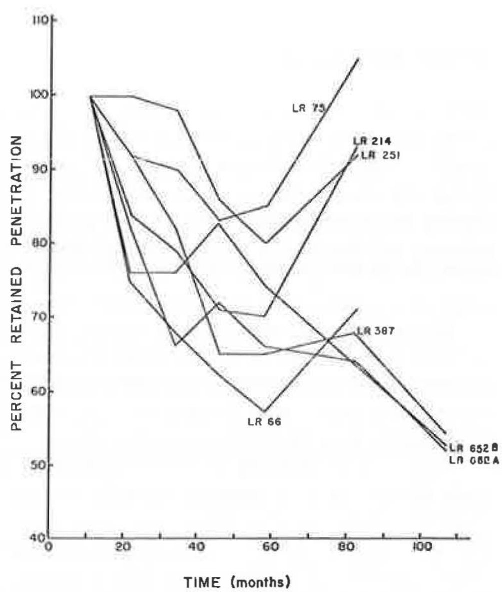



**Figure 2. Percentage of retained penetration versus time for group 2 pavements.**



specifications, were made on the mix samples to ascertain degrees of compaction at construction and during service life.

Asphalt cement samples were obtained from mix and field core specimens by the immersion-reflux method of extraction and the Abson method of recovery (ASTM Designation D1856-65). Benzene was used as the solvent to minimize any chemical reaction between solvent and asphalt during the contact time of the recovery process.

## RESULTS AND DISCUSSION

The specific test values of penetration and absolute viscosity for each asphalt used on each test pavement have been presented elsewhere (9-15). To look at asphalt hardening relative to all other asphalts, graphs were used in place of tabulated data wherever possible. All figures involving changes in penetration with time, viscosity with time, and so on were drawn by using the sample that initiated an annual pattern of sampling on the particular test pavement. In the use of such samples, only the asphalt hardening that occurred after construction was reflected in the figures. The penetration and viscosity of these samples were used as the base (the original values) for determining the percentage of retained penetration and percentage of original viscosity. A research program involving the study of hardening of asphalt pavements should sample all the test pavements at the same time of year. As some of the research pavements begin to reach a limiting value of hardness, these pavements can be switched to biennial or even triennial sampling, but still at the same time of year.

As a result of the above procedure, hardening data collected for a particular asphalt pavement may or may not represent the total hardening that the pavement experienced since the time of construction. The data not useful in pavement comparisons include the hardness incurred from the time of construction to the sampling month. In some cases, this hardening may be quite substantial. As a result, future researchers may wish to secure a sample at the time of pavement construction in order that total pavement hardening may be determined. Of course, the ideal method is to construct all research pavements at the same time of year. All data would then reflect total pavement hardening.

### Penetration

Figures 1 through 5 show the relationship of percentage of retained penetration to time for the 13 pavements under study. Group 1 pavements (Figure 1) reveal that, after 10 years of aging, the retained penetration values ranged from 65 to 28 percent. The change in LR 113 should be noted. Group 2 pavements (Figure 2) reveal the effect of the authors gaining experience. LRs 66, 75, 214, and 251 were discontinued from the study because each pavement differed from the group in some significant fashion (sampling location, aggregate type, traffic density, excessive oil deposition). Group 3 pavements (Figures 3 to 5) permit examination of differences in performance of both the pavements and the asphalts. Comparison of LRs 219, 101, and 338 shows the better performance of LR 101 (as a group) and the very poor performance of asphalt 1 on LR 219. Air void data presented later will explain these differences.

### Absolute Viscosity

Figures 6 through 10 show the relationship of percentage of original absolute viscosity to time for the 13 pavements. Examination of these figures shows differences in the vertical scale. For example, although the six asphalts of LR 101 (Figure 9) first seem to have a typical performance, the highest original viscosity value is only 375 percent. Comparison of all pavements shows that LR 113 and LR 101 (asphalt 1) increased more than 700 percent since first sampling. Again, air void data will explain this performance.

Figure 3. Average percentage of retained penetration versus time for LR 219, group 3.

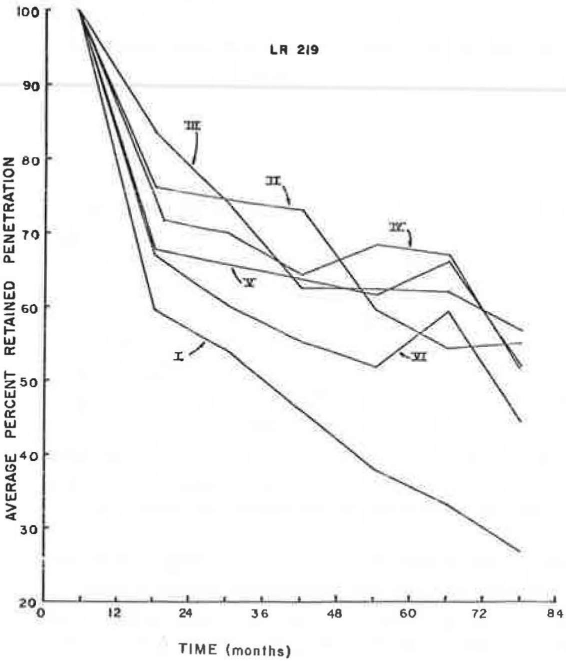



Figure 4. Average percentage of retained penetration versus time for LR 101, group 3.

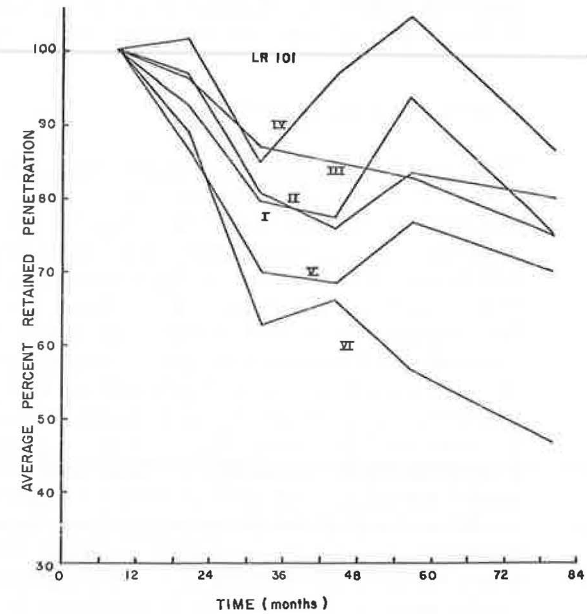



Figure 5. Average percentage of retained penetration versus time for LR 338, group 3.

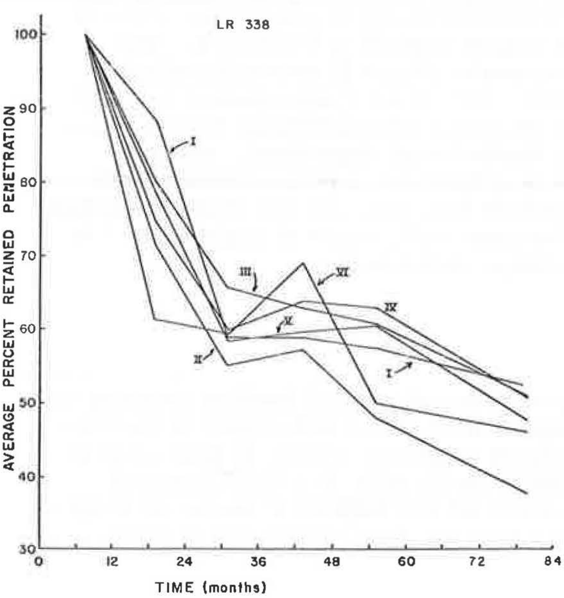



Figure 6. Percentage of original absolute viscosity versus time for group 1 pavements.

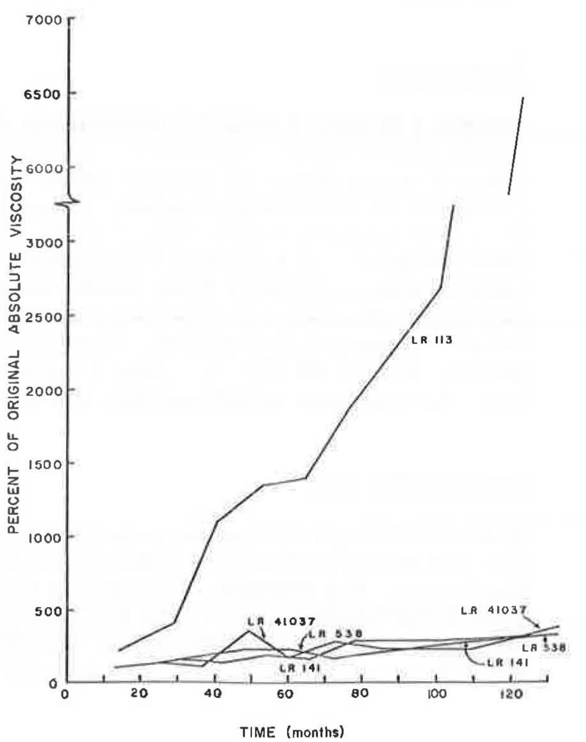


Figure 7. Percentage of original absolute viscosity versus time for group 2 pavements.

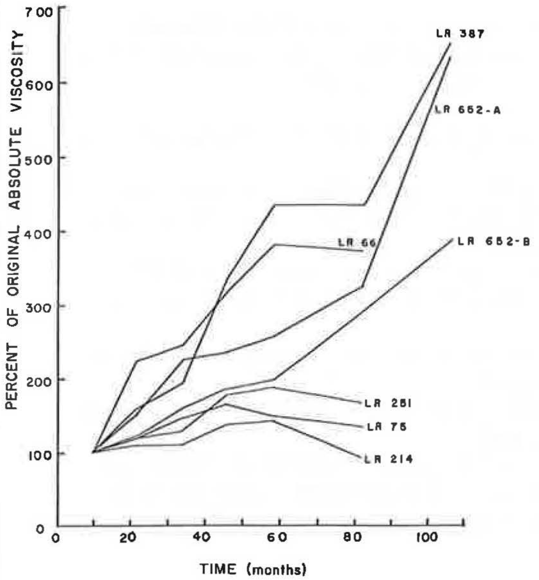



Figure 8. Average percentage of original viscosity versus time for LR 219, group 3.

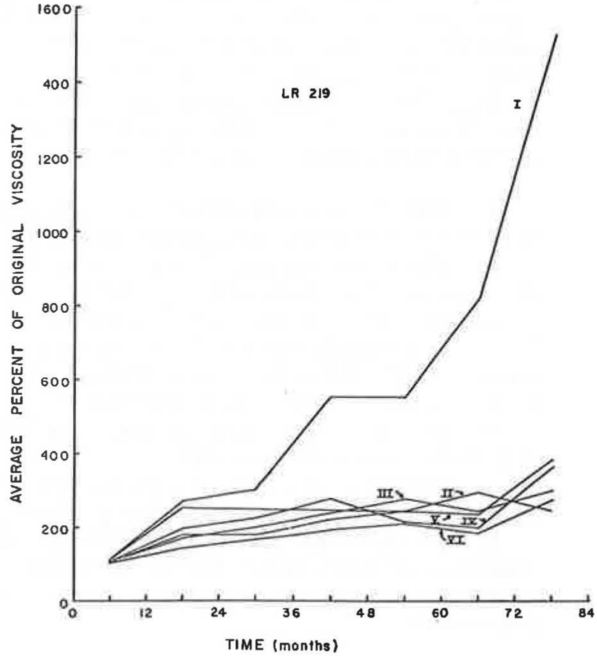



Figure 9. Average percentage of original viscosity versus time for LR 101, group 3.

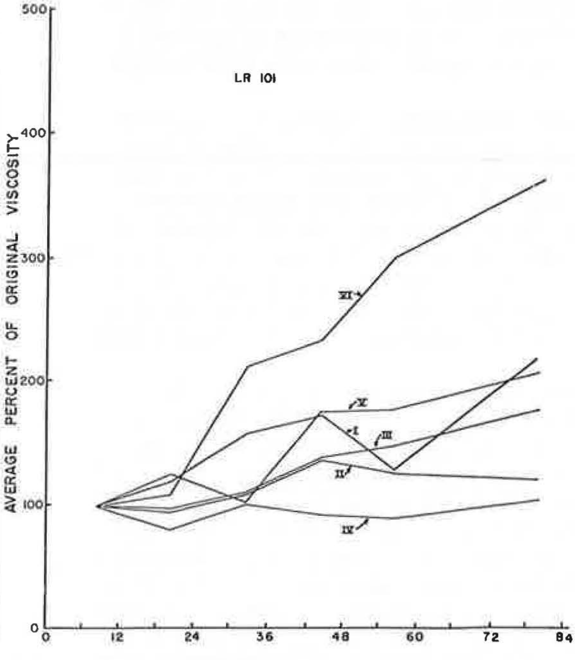
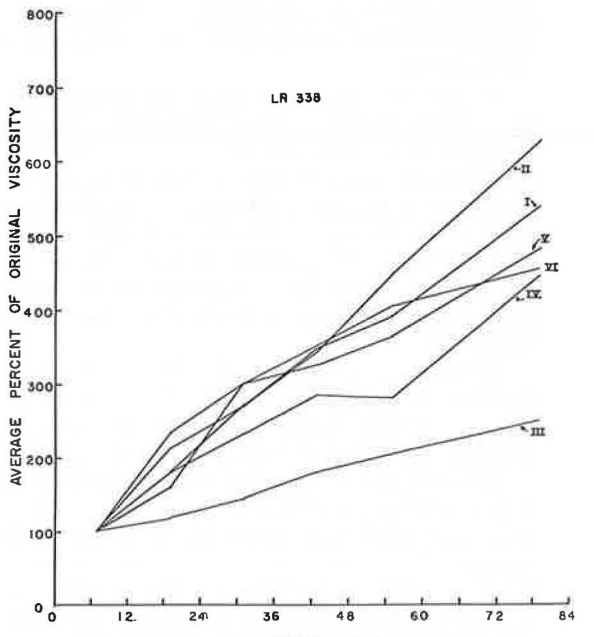



Figure 10. Average percentage of original viscosity versus time for LR 338, group 3.



## Air Voids

Air voids are one, if not the greatest, factor affecting the rate of hardening of an asphalt pavement. The influence of this variable appears to be so pronounced that it completely overshadows the performance of asphalt type, aggregate type, traffic density, and microclimate differences.

Correlating asphalt cement performance with air void content is a very difficult task because of the variability of air voids in an asphalt pavement. The following types of air void variability have been recognized in this research (10, 15):

1. The inherent variability from point to point in a pavement due to varying degrees of aggregate interlock and asphalt content;
2. The gently sloping air void trends in the longitudinal direction of the pavement due to variability in gradation, asphalt content, mixing temperature, compaction temperature, and thickness of lift during the construction day;
3. The steeply sloped air void variability across the transverse direction of the pavement due to the decreasing lateral support of the mixture from the center of the traffic lane to its edges during compaction;
4. The air void variability among asphalt cement types on any one pavement due to differences in asphalt cement viscosity during compaction;
5. The air void variability among pavements due to gradation, aggregate type, and differences in degree of hardening in the pug mill; and
6. The decrease in air voids with time due to traffic, particularly in the wheel or load zone of a pavement, and the variability in decreases in air voids among asphalt pavements due to differing traffic densities and the degree of initial compaction among pavements.

Figures 11 through 15 show the changes in air voids with time for each asphalt on each pavement. As before, any durability comparisons of asphalt cement type and air voids should be based on air void values obtained at the same sampling times each year. Figure 11 clearly shows the atypical performance of LR 113. Of the 13 pavements under study, this pavement has the highest initial and highest residual air void content. Figure 12 shows that LR 387 had considerably higher air void contents than did the remaining pavements of group 2. Figures 13 to 15 show the performance of asphalt 1 on LR 219 and the poorer performance of LR 338, on the whole, when compared to LRs 219 and 101.

Figure 16 shows the relationship between retained penetration and air void percentage. This figure is based on values obtained after approximately 78 months of field aging of group 3 pavements. The differences between the pavements are attributed to the average daily traffic, initial extent of hardness after mixing, air temperatures during compaction, and shape characteristics of the aggregates, which in turn affect the rate of change of the air void percentages. ADT plays a conflicting role in pavement performance. The higher the density is, the greater are the compaction under traffic and the oil deposition, both favorable. On the other hand, the greater the traffic density (and percentage of trucks) is, the quicker will be the failure after the asphalt has hardened.

Hardening in the pug mill is a factor that quickens the hardening process. The greater the initial hardening is, the more rapid will be the rate of hardening due to the exponential nature of the hardening process (1). A close examination of the pug mill mixing process might reveal means for reducing asphalt hardening in the pug mill.

Because the sensitivity of the penetration test decreases as the asphalt approaches a penetration value of 10, the authors believe that a better understanding of the continuing hardening process can be obtained by using absolute viscosity data. Accordingly, Figure 17 is presented to demonstrate that asphalt hardening does not reach a limiting value; rather, it increases exponentially with time. It appears that, when the asphalt has an absolute viscosity of roughly seven times its original viscosity, the rate of asphalt hardening increases rapidly. The problem, of course, is to prevent the asphalt from hardening sevenfold.

**Figure 11. Percentage of total air voids versus time for group 1 pavements.**

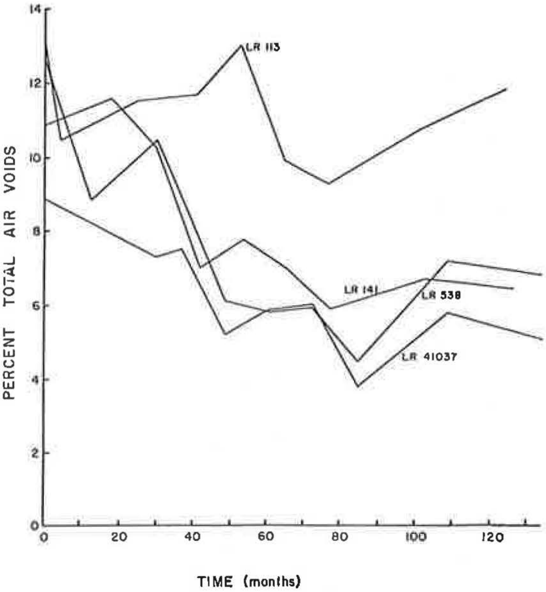



**Figure 12. Percentage of total air voids versus time for group 2 pavements.**

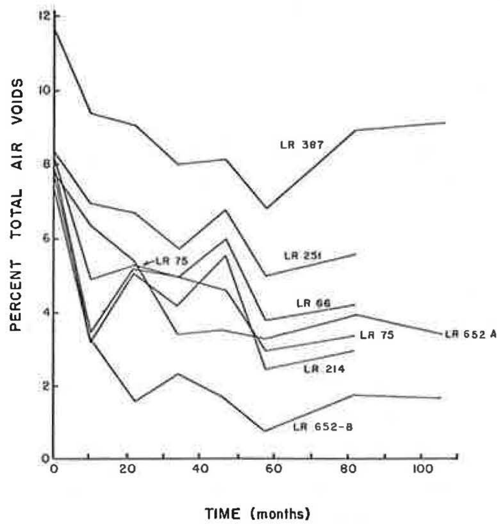



**Figure 13. Average percentage of air voids versus time for LR 219, group 3.**

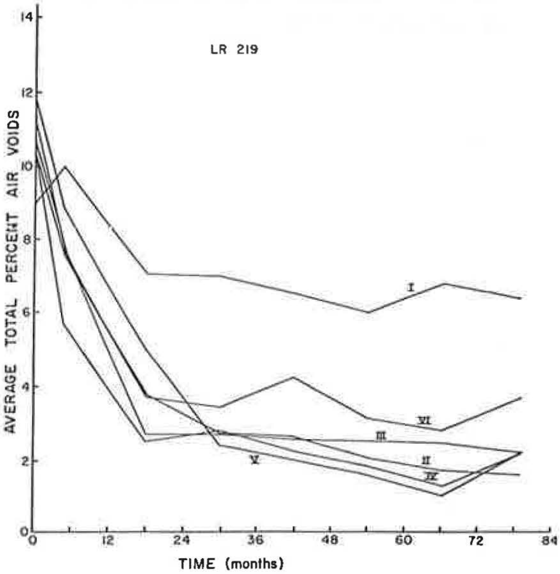



**Figure 14. Average percentage of air voids versus time for LR 101, group 3.**

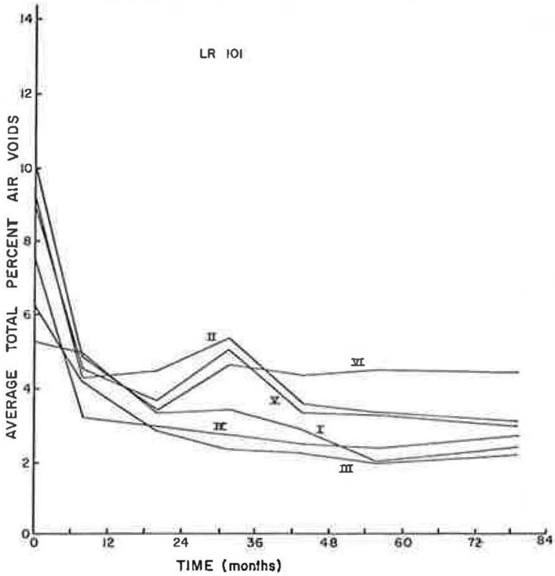


Figure 15. Average percentage of air voids versus time for LR 338, group 3.

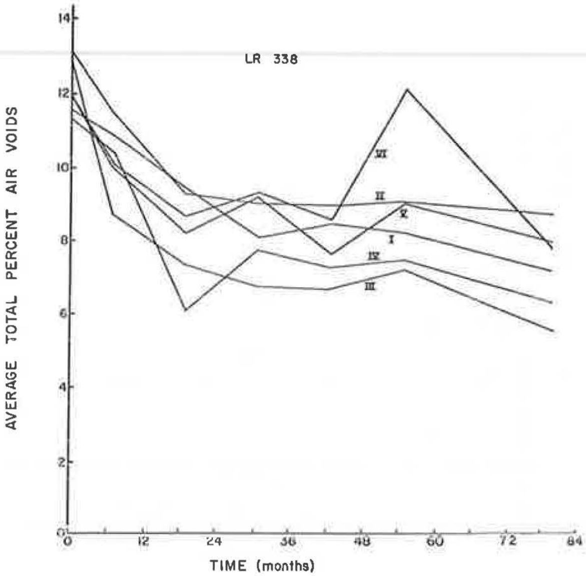



Figure 16. Percentage of retained penetration versus percentage of air voids (78-month values) for group 3 pavements.

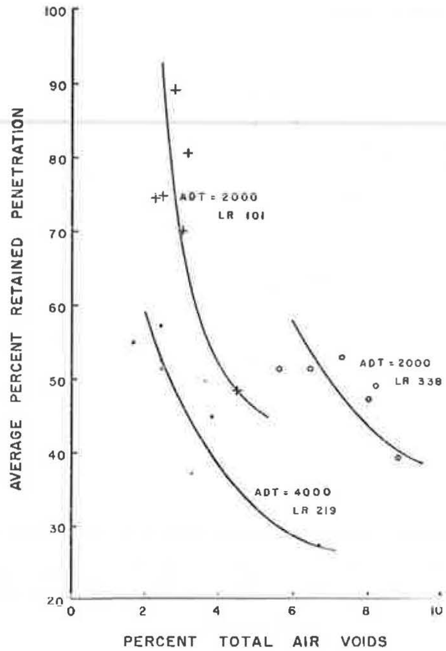



Figure 17. Percentage of original viscosity versus time for all groups.

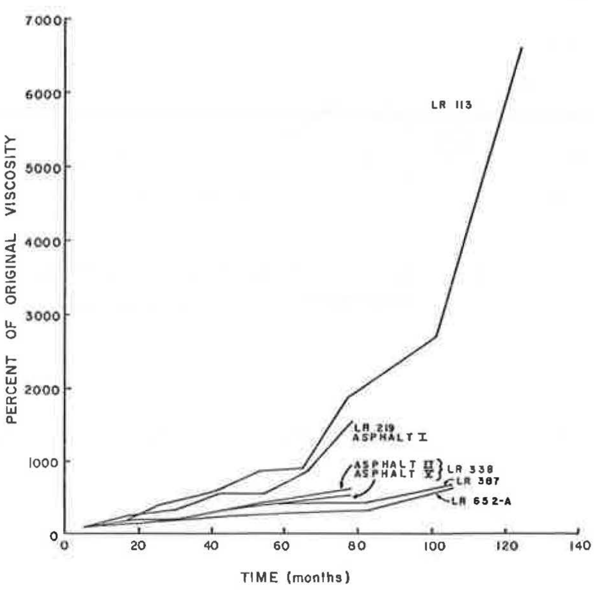
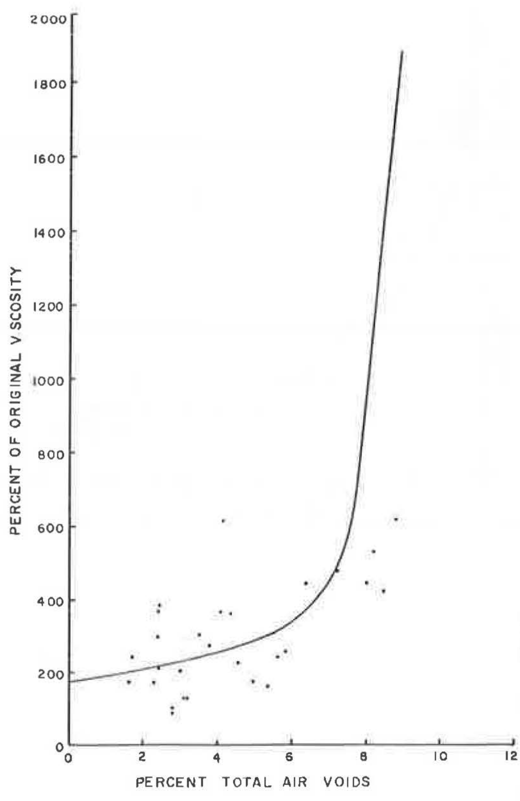



Figure 18. Percentage of original viscosity versus total air voids for all groups.



From Figure 17, one might expect the asphalt 1 pavement section on LR 219 to fail next. LR 387 is not so hard, yet it is more severely cracked than LR 219, asphalt 1. This cracking is most noticeable over the portion of the LR 387 pavement that was constructed on an aggregate base course. The remainder of the LR 387 pavement was constructed over a portland cement concrete base course and is not severely cracked. The LR 219 pavement was constructed entirely on a portland cement concrete base course.

It should be clearly understood that pavement hardness merely sets the stage for pavement cracking and other types of failure. A pavement such as the LR 338 project has a number of test sections that could eventually reach a hardness similar to that of LR 113. The LR 338 pavement, however, consists of 12 in. (305 mm) of asphalt concrete on a portland cement concrete base course. This very thick pavement will most likely never show such severe signs of distress as LR 113, which is just 3 in. (76 mm) of asphalt concrete on a portland cement concrete base course. Base thickness, therefore, is yet another variable confounding any analysis of pavement service.

Figure 18 shows the relationship between percentage of original viscosity and total air voids for all pavement sections after 80 months of service (data points obtained from figures presented earlier at 80 months of service). This figure contains all the variability discussed earlier, due to not only air voids, but also sampling time and location, initial hardness, pavement thickness, asphalt film thickness, asphalt grade, shear susceptibility, etc. Considering all of these factors, Figure 9 presents a significant relationship. There is also an abrupt increase in hardening at the 6 to 7 percent air void content (after 80 months of service). It is essential that this percentage figure be based on the maximum theoretical density and not on the daily plant Marshall density. Under current specifications (23), the daily Marshall density may vary from 94 to 98 percent of the maximum theoretical density (6 to 2 percent voids) and the field density may be as low as 95 percent of daily Marshall density. Combined, these specifications allow a range in total air voids of 2.0 to 10.3 percent. This is excessively high.

The pavements studied received better than average design and field control; yet these pavements were constructed with void contents as high as 13 percent. This underscores the need for more restrictive specifications and closer field control.

As early as 1968 the authors concluded that low void contents that enhanced durability were incompatible with regard to developing high skid resistance. Research work on the Blair County pavement (16) has shown that permeability, increased by high void contents, is lost quickly; thus skid resistance should not be used as an excuse for high air void content pavements.

## SUMMARY AND RECOMMENDATIONS

From the research conducted to date, the following summary statements and recommendations are presented.

1. In general, all the asphalts from the 13 pavements are hardening with time based on physical test data.
2. The time of year when a pavement is sampled influences test results among and within test pavements. All test pavements should be sampled at the same time each year on an annual basis.
3. An additional 5 to 6 months of pavement life may be realized if the pavement is constructed in the fall rather than in the spring. This allows some pavement compaction to occur prior to the time the agents of asphalt hardening become active.
4. The air void content of an asphalt pavement is a major factor in pavement durability and, with deterioration, the safety of those using the pavement.
5. The hardening of asphalts in the pug mill should be studied closely. Lower mixing temperatures and shorter mixing times in conjunction with lower viscosity asphalts should provide an asphalt with similar viscosity but lower initial hardness.
6. Air void contents of Pennsylvania highway pavements are on average too high. Multiple air void specifications should be replaced by a single number—10 percent of

maximum theoretical. Field control must become continuous and totally enforceable. Lower viscosity asphalts, greater field compaction and control, and greater selectivity in design are means of fulfilling lower air void content specifications.

## ACKNOWLEDGMENTS

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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Pennsylvania Department of Transportation or the Federal Highway Administration.

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# DISCUSSION

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The authors have produced a relevant paper of immediate practical significance, and they are to be congratulated for both the paper and their perserverance in following the study for 13 years. However, I feel that they have overextended their data in recommending implementation of fall or cold-weather paving and an end product specification for a maximum of 10 percent voids in the finished pavement.

In 1962, the New York State Department of Transportation undertook a research project to study the physical properties of asphalt concrete. That project, which paralleled much of the research performed by the authors in Pennsylvania, concentrated on the New York State DOT type 1A top course, a mixture quite similar to Pennsylvania DOT ID2 top course. Inasmuch as these two states have similar specifications, materials, and climate, I feel qualified to comment based on my involvement in the New York research (17, 18, 19, 20).

Briefly, the New York State DOT research in asphalt concrete density showed that controlling the density of pavement top course required a concerted effort by the designer in providing a pavement structure of proper stiffness on which to compact the top course mixture, the materials engineer in supplying a uniform mixture of proper gradation and asphalt content to the project, and the project engineer in seeing that the mixture is properly compacted while the mixture is hot. The thruway authority's research (21) confirmed the value of a properly prepared surface in overlaying existing pavement, especially ruts in the existing pavement caused by studded tire wear. Density of the test pavements increased with time with or without traffic but seemed to level off at 100 ± 2 percent of the laboratory (Marshall) density.

Research into asphalt hardening and pavement condition or durability showed that, for the study pavements, condition and percentage of retained penetration at 77 F were synonymous. It also showed that initial properties of the study pavements and their AADTs could be used as predictors of later condition and that they outweigh minor age differences and various environmental factors.

The conclusion was that maximum durability could be achieved by ensuring that the design criteria and specifications be directed to maximizing the level of compaction and thus to minimizing total air voids. The authors' recommendations are not fully consistent with those goals. Specifically, fall paving is very critical considering that low ambient temperatures are not conducive to compacting asphalt concrete. Anything gained by reduced oxidation rates in cold weather could easily be lost by a poor initial level of compaction (higher void content and high permeability). At its worse, cold-weather paving can cause what we call the late season paving syndrome—rapid hardening of the asphalt cement leading to cracking, raveling, and general distress at an early age.

Recognized mix design criteria call for air void contents from 2 to 5 percent, and according to the Asphalt Institute (22) a minimum of 97 percent of the laboratory density should be expected on a properly compacted pavement; therefore, air voids in place should not exceed 8 percent in the worst case, if both standards are applied consecutively. Mix quality assurance should control the potential voids in the mixture; project quality assurance should control compaction. With a single number specification, a maximum of only 5 percent voids would be allowable since compaction level can often equal or exceed 100 percent of laboratory values and the mix itself should compact in the laboratory to 5 percent air void content or less. The multiple specification can take into account that 100 percent densification cannot always be achieved on the project and that some slightly lesser conformance will not necessarily be detrimental considering the positive effects of traffic; a single specification cannot. Therefore an end product specification of 10 percent would give a very poor level of control.

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## AUTHORS' CLOSURE

We are pleased that Clark has shown an interest in our work. We believe it necessary, however, to clarify two points of potential disagreement. We believe the net result will be agreement between us and Clark.

The detrimental effect of cold-weather paving or the late season paving syndrome is mentioned. In citing a desire for fall paving, we did not mean to imply cold-weather paving. We are in agreement with Clark that cold-weather paving is undesirable in terms of the high void contents and high permeabilities that develop. We recommend that fall paving under desirable field temperatures is preferable to similar temperatures during the spring months.

We agree with Clark that air voids in the compacted material should be less than those in the experimental pavements we studied. The debate of the desirability of an end product specification, in our minds, is controlled by the need for a specification that can be easily enforced by field personnel. In our opinion the number of pavements constructed with air voids in excess of a specified value would be fewer in number with an end product specification than with the existing set of specifications. In retrospect, whether the maximum end product air void specification is set at 10 or 8 percent or less remains open for discussion.

In 1973 the Pennsylvania DOT introduced a restricted performance specification for bituminous concrete. The specific gravities of all the materials and the maximum specific gravity of the mixture are determined in accordance with Pennsylvania DOT procedure. The percentage of unfilled voids and the percentage of aggregate voids filled with bitumen are based on the maximum specific gravity and the asphalt content determined for each group of specimens prepared from the same sample.

This approach is being used so that contractors will provide and maintain a quality control system that will ensure that all materials and products submitted for acceptance conform to contract requirements. A new concept of compaction called control strips is also introduced in these specifications. The contractor is afforded the opportunity to proof roll a test area to determine the optimum roller pattern and procedures under existing job conditions. Measurement and control of this strip are achieved by means of a nuclear gauge. The strip is placed and rolled until a maximum density is obtained. Then, the average density of the strip as determined by 10 density measurements should not be less than 92 percent of the theoretical maximum density. Thereafter, each layer or course of the compacted mixture should achieve a target density of at least 96 percent of the control strip density (23).

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