

Role of Pessimum Voids Concept in Understanding Moisture Damage to Asphalt Concrete Mixtures

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On the basis of a hypothesis that voids in asphalt pavements are a major source of water damage, a test system was developed by Oregon State University as part of SHRP Project A-003A to evaluate the major factors that influence water sensitivity. The Environmental Conditioning System (ECS) was used to develop a test procedure that includes measurement of permeability, vacuum wetting (partial saturation), cycling at various temperatures, and continuous repeated loading while monitoring the resilient modulus (M_R) after each conditioning cycle. The development aspects of the ECS conditioning procedure will not be discussed in this paper, as they have been documented elsewhere by Terrel and Al-Swailmi. This paper gives a brief overview of the theoretical aspects of water sensitivity, followed by a more detailed description of the role of air voids and water accessibility of asphalt mixtures in the mechanism of the water sensitivity. If asphalt concrete specimens are water conditioned, the retained strength is typically somewhat lower than that for the original dry mixture. This effect tends to be tempered by the voids in the mixture. Mixtures with minimal voids that are not interconnected are essentially impermeable. When air voids increase beyond some critical value, they become larger and interconnected. The test results show that the worst behavior in the presence of water occurs in the range where most conventional mixtures are compacted. Thus, the term "pessimum voids" can be used to describe a void system (i.e., the opposite of optimum).

The design of asphalt paving mixtures is a multistep process of selecting asphalt and aggregate materials and proportioning them to provide an appropriate compromise among several variables that affect mixture behavior. Consideration of external factors such as traffic loading and climate is part of the design process. Performance goals that are of concern in any design include at least the following:

1. Maximize fatigue life,
2. Minimize potential for rutting,
3. Minimize effect of low temperature or thermal cycling on cracking,
4. Minimize or control the amount and rate of age hardening, and
5. Reduce effect of water.

In many instances, water or moisture vapor in the pavement can reduce the overall performance life by affecting any one

of the goals listed above. The effect of stripping or loss of adhesion is readily apparent because the integrity of the mixture is disrupted. The loss of cohesion is often less obvious but can cause a major loss of stiffness or strength. The introduction of air or moisture into the void system accelerates age hardening, thus further reducing pavement life. This paper is aimed at an evaluation of the role of air void content in the effect of water on asphalt mixtures.

The effect of water on asphalt concrete mixtures has been difficult to assess because of the many variables involved. One of the variables that affects the results of current methods of evaluation is the amount of air voids in the mixture. The very existence of these voids as well as their characteristics can play a major role in performance. Contemporary thinking is that voids are necessary or at least unavoidable. Voids in the mineral aggregate are designed to be filled only to a certain point to allow for traffic compaction. But if one could design and build the pavement properly, allowing for compaction by traffic would be unnecessary. In the laboratory, dense-graded mixtures are designed at, for example, 4 percent total voids, but actual field compaction may result in as much as 8 to 10 percent voids. These voids provide the major access of water into the pavement mixture.

HYPOTHESIS

The existing mixture design method and construction practice tend to create an air void system in asphalt concrete that may be a major cause of moisture-related damage, as shown in Figure 1. If mixtures of asphalt concrete are prepared and conditioned by some process such as water saturation followed by freezing and thawing, it can be shown that the retained strength or modulus is typically somewhat lower than that for the original dry mixture. However, this effect tends to be tempered by the voids in the mixture, particularly access to the voids by water.

If the mixtures shown in Figure 1 are designed for a range of voids by adjusting the aggregate size and gradation and the asphalt content, a range of permeability results. Those mixtures with minimal voids that are not interconnected would be essentially impermeable. When air voids increase beyond some critical value, they become larger and interconnected and water flows more easily through the mixture. Most asphalt pavements are constructed to be between these two extremes

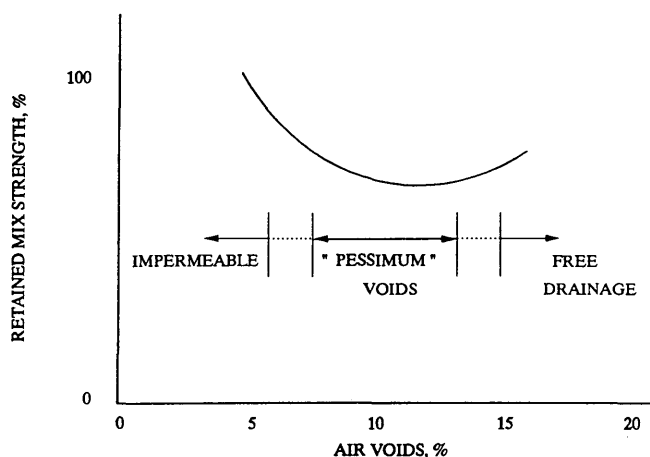


FIGURE 1 Dependence of relative strength of mixtures on access to water in void system.

of impermeable and open or free draining. The voids tend to range from small to large, with a range of permeability depending on their degree of interconnection.

The curve in Figure 1 indicates that the worst behavior in the presence of water should occur in the range where most conventional mixtures are compacted. Thus, the term "pessimism voids" can be used to describe a void system (i.e., the opposite of optimum). Pessimism voids can actually represent a concept of quantity (amount of voids in the mixture) and quality (size, distribution, and interconnection) as they affect the behavior and performance of pavements.

Intuitively, one could describe the three regions in Figure 1 as follows:

1. Impermeable or low-void mixtures are made with high asphalt content or are mastics. To offset the instability expected from high binder content, aggregate gradation is modified (crushed sand, large size stone) and an improved binder containing polymers, fibers, or both can be used.

2. The midrange or pessimism voids system is represented by conventional dense-graded asphalt concrete such as that used in the United States.

3. Free-draining or open-graded mixtures are designed as surface friction courses or draining base courses. With the use of polymer-modified asphalt, these mixtures can be designed with higher binder content (thicker films) to remain open and stable under traffic.

The European community, in an investigation of stone-mastic asphalt and porous asphalt, discovered the advantages of mixtures that fall outside the pessimism voids region (1). The stone-mastic mixtures have high stability combined with good durability, low voids (3 to 4 percent), and increased performance life (20 to 40 percent) compared with conventional dense-graded mixtures. Porous asphalt is also widely used in Europe to improve safety, reduce noise, and lessen water spray from tires. With the use of polymer-modified asphalt, durability and performance life were shown to increase (2).

THEORY FOR WATER SENSITIVITY BEHAVIOR

As indicated earlier, water appears to affect asphalt concrete mixtures through two main mechanisms: (a) loss of adhesion between the asphalt binder and the aggregate surface and (b) loss of cohesion through a gross "softening" of the bitumen or weakening of the mixture.

Voids in the asphalt concrete are the most obvious source of entry of water into the compacted mixture. Once a pavement is constructed, the majority of water and air is taken in through these relatively large voids. Other voids or forms of porosity may also affect water sensitivity. For example, aggregate particles have varying sizes and amounts of both surface and interior voids. Water trapped in the aggregate voids because of incomplete drying plays a role in coating during construction and during the pavement's early service life. Also, there appears to be some indication that asphalt cements may themselves absorb water, allow some water to pass through films at the aggregate surface, or both. The complexity of the water-void system will require a careful and detailed evaluation to better understand its significance.

Although continued study of water sensitivity will very likely result in improved understanding and pavement performance, this discussion begins with the state of the art.

THEORIES OF ADHESION

Terrel et al. (3,4) have provided a good overview of previous research and current thinking on adhesion. Four theories of adhesion have been developed that address several factors appearing to affect adhesion, namely,

1. Surface tension of the asphalt cement and aggregate,
2. Chemical composition of the asphalt and aggregate,
3. Asphalt viscosity,
4. Surface texture of the aggregate,
5. Aggregate porosity,
6. Aggregate cleanliness, and
7. Aggregate moisture content and temperature at the time of mixing with asphalt cement.

No single theory seems to completely explain adhesion; it is most likely that two or more mechanisms may occur simultaneously in any one mixture, thus leading to loss of adhesion. All of the mechanisms discussed may occur to some extent in any asphalt-aggregate system. Research has shown that adhesion can be improved through the use of various commercial liquid antistripping additives or lime. The four theories of adhesion are discussed in the following sections.

Mechanical Adhesion

Mechanical adhesion relies on several aggregate properties, including surface texture, porosity or absorption, surface coatings, surface area, and particle size. In general, a rough, porous surface appears to provide the strongest interlock between aggregate and asphalt.

Chemical Reaction

It is recognized that a chemical reaction may be a mechanism for adhesion between asphalt cement and aggregate surfaces. Many researchers have noted that better adhesion may be achieved with basic aggregates than with acidic aggregates.

Surface Energy

The theory of surface energy is used in an attempt to explain the relative wettability of aggregate surfaces by asphalt, water, or both.

Molecular Orientation

The molecular orientation theory suggests that molecules of asphalt align themselves with unsatisfied energy charges on the aggregate surface. Although some molecules in asphalt are dipolar, water is entirely dipolar, and this may help explain the preference of aggregate surfaces for water rather than asphalt.

THEORIES OF COHESION

In compacted asphalt concrete, cohesion might be described as the overall integrity of the material when subjected to load or stress. Assuming that adhesion between aggregate and asphalt is adequate, cohesive forces will develop in the asphalt film or matrix. Generally, cohesive resistance or strength might be measured in a stability, resilient modulus, or tensile strength test. The cohesion values are influenced by factors such as viscosity of the asphalt-filler system (3). Water can affect cohesion in several ways, for example, through intrusion into the asphalt binder film and through saturation and even expansion of the void system (swelling). Although the effects of stripping may also occur in the presence of water, a mechanical test such as the repeated-load resilient modulus test tends to measure gross effects, and the mechanisms of adhesion or cohesion cannot be distinguished separately.

VOID STRUCTURE

Since air voids play a significant role in water sensitivity, Terrel and Al-Swailmi (5) have recognized that it is necessary to measure air voids qualitatively as well as quantitatively. When aggregate type and aggregate gradation are variables, mixtures may have similar air voids, but different water accessibility. The typical methods of calculating air voids for asphalt concrete mix design (AASHTO T 166, ASTM D 1188, or ASTM D 2726) are not precise because such methods give only the quantity of air voids in the mixture without considering other factors such as size, shape, and distribution of the air voids.

A detailed study of air voids-permeability characterization has been documented by Al-Swailmi and Terrel (6,7). Because of space limitations, only the major finding of that study is pointed out in this paper. The air voids and permeability

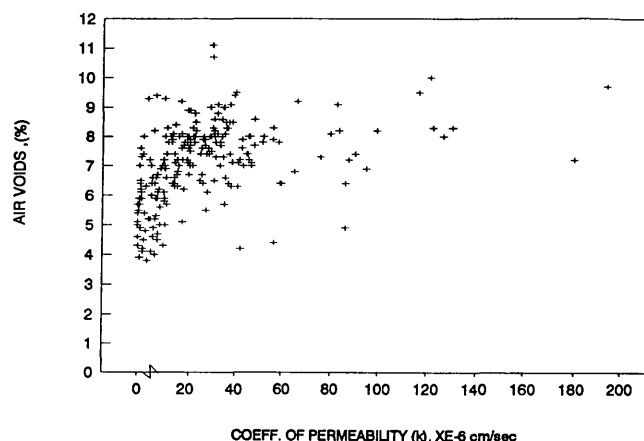


FIGURE 2 Relationship between air voids and permeability.

test results of more than 200 specimens, shown in Figure 2, indicate that the data are scattered and that the air voids-permeability relationship is not as straightforward as one might expect. Therefore, the desirability of including permeability in addition to air voids during the mix design and analysis procedure has been suggested, because permeability accounts for the structure and interconnection of air voids.

In addition, the voids structure was investigated as part of the Water Sensitivity Task in SHRP Project A-003A. Twelve samples composed of four asphalt-aggregate combinations with air void levels of 4 and 8 percent were prepared and sent to the Danish Road Institute, Roskilde, Denmark, which had entered into a contract to conduct a microscopic analysis of vertical and horizontal planes in specimens with different air voids and prepared by different compaction methods (8).

Figure 3 shows the air void distributions for two specimens, one with 3.7 and one with 6.6 percent air voids. By a visual inspection, one can see that the air voids are very unevenly distributed in both specimens. It became evident from the findings of the microscopic analysis and the permeability study that direct comparison of air void contents using traditional methods can lead one to the wrong conclusions.

TEST RESULTS

As explained earlier, the hypothesis of pessimum voids suggests that the water in the void system of asphalt concrete plays an important role in its performance. If mixtures of asphalt concrete are water conditioned, the retained strength is typically lower than the original, unconditioned strength. This effect can be characterized by the voids in the mixture. Mixtures with very low air voids, such as 4 percent, are almost impermeable to water and are essentially unaffected by it. Mixtures designed to have more air voids than some critical value, say 15 percent, do not show significant water damage even though they are very permeable to water because there is free drainage and the mixture does not hold the water for long. Between these two extremes of impermeable and free-draining mixtures is a range in which the air voids are accessible to water but lack free drainage and thus tend to retain the water. In this range the highest water damage is experienced.

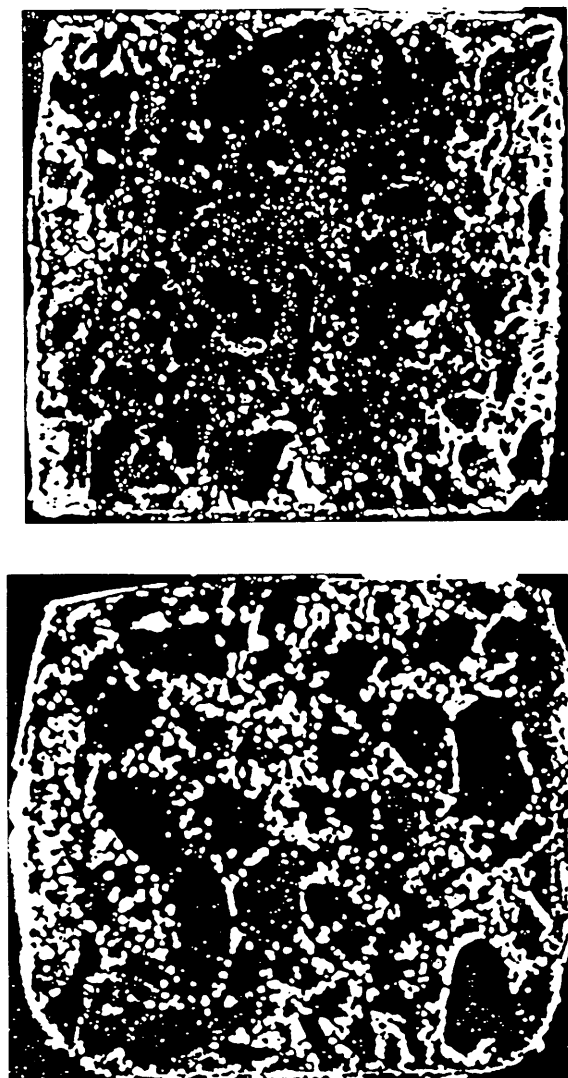


FIGURE 3 Air void distributions of specimens with two air void levels [after Danish Road Institute (8)]: (top) asphalt/aggregate RL/AAK-1; air voids, 3.7 percent; kneading compaction, 20 blows at 300 psi and 150 blows at 400 psi; (bottom) asphalt/aggregate RB/AAG-1; air voids, 6.6 percent; kneading compaction, 20 blows at 150 psi and 150 blows at 150 psi.

In order to prove the foregoing analogy of the pessimum voids concept in the laboratory, a water-conditioning study was conducted in which free drainage was provided and the drying time was included as a variable. Because the Environmental Conditioning System (ECS) was not applicable, a special conditioning setup was constructed to simulate the action of free drainage following wetting (5). Three sets of mixtures were prepared from the same asphalt-aggregate combination (RL/AAK) and compacted at three air void contents: low at 4 percent, pessimum range at 8 percent, and free drainage at 30 percent. The diametral resilient modulus, M_R , was then determined for each specimen. The six specimens were placed in a vacuum container and a partial vacuum of 22 in. Hg was applied for 10 min. The vacuum was removed and the specimens were left submerged in the water for 30 min. This

wetting process was selected by trial and error to provide partial saturation of 70 percent for the specimens with 8 percent air voids. Using the same procedure, open-graded and low-air-void specimens resulted in saturation of 99 and 38 percent, respectively, as shown in Table 1.

The relationship between air voids and level of saturation implies that specimens with high air voids are totally accessible to water, and specimens with very low air voids are not interconnected and essentially not accessible. The wetting mechanism of the specimens with 8 percent air voids falls between the two extremes.

After water conditioning, the specimens were placed in an air bath (environmental cabinet) for 6 hr at 50°C, then for 5 hr at 25°C, and allowed to drain. The diametral resilient modulus, M_R , was determined at the end of each conditioning cycle, and the retained M_R was expressed as the ratio of the conditioned to the original dry M_R . The conditioning temperature chosen was 50°C instead of 60°C because of the tendency of open-graded specimens to deform under their own weight at the higher temperature. In addition, open-graded specimens were enclosed within a 4-in. diametral cylindrical membrane during condition cycles to assist them in retaining their original geometry. This conditioning process (partial saturation, 6 hr at 50°C, then 5 hr at 25°C) was repeated 20 times (cycles). Table 2 is a summary of the test results.

DISCUSSION OF RESULTS

Water Accessibility

A suitable degree of saturation was established on the basis of AASHTO T-283-85 and other previous experience (9) to be between 55 and 80 percent of the volume of air. This target window of saturation was achieved by placing the specimen in a vacuum container filled with distilled water and applying a partial vacuum, such as 20 in. Hg, for a short time. If the degree of saturation was not within the limits, adjustments could be made by trial and error by changing vacuum level, submersion time, or both. This saturating method worked satisfactorily for asphalt concrete mixtures with one air void content, 8 ± 1 percent air voids. However, this is not a good technique to use in water conditioning a wide range of air voids, as in the ECS method. The ECS method attempted to standardize the wetting procedure by controlling water accessibility and vacuum level instead of controlling water volume and degree of saturation as in AASHTO T-283-85.

The ECS method uses a controlled vacuum for saturation by maintaining a 20-in. vacuum level during the wetting stage

TABLE 1 Permeability, Air Voids, and Degree of Saturation

Specimen	Thick. In.	Permeability (cm/s)	Air Voids (%)	Degree of Sat. (%)
1H	4.660	1.26 E-04	32.60	97
2H	4.450	6.69 E-05	30.00	98
1M	4.380	1.51 E-06	8.40	68
2M	4.230	1.23 E-06	8.90	70
1L	4.200	Impermeable	5.50	35
2L	4.180	Impermeable	4.20	41

TABLE 2 Resilient Modulus Test Results

CYCLE NO.	Low Air Voids		Medium Air Voids		High Air Voids	
	M_R Avg, ksi	M_R Ratio	M_R Avg, ksi	M_R Ratio	M_R Avg, ksi	M_R Ratio
D	620.00	1.00	347.25	1.00	33.75	1.00
1	616.00	0.99	277.00	0.80	30.68	0.91
2	644.25	1.04	271.00	0.78	29.00	0.86
3	618.50	1.00	242.25	0.70	29.50	0.87
4	606.50	0.98	213.00	0.61	28.50	0.84
5	630.00	1.02	217.75	0.63	28.75	0.85
6	600.50	0.97	208.00	0.60	28.25	0.84
7	649.75	1.05	198.25	0.57	30.00	0.89
8	617.00	1.00	208.25	0.60	27.75	0.82
9	655.25	1.06	215.25	0.62	30.25	0.90
10	644.25	1.04	194.75	0.56	28.75	0.85
11	608.25	0.98	206.50	0.59	29.25	0.87
12	605.50	0.98	196.50	0.57	29.00	0.86
13	630.00	1.02	197.00	0.57	30.00	0.89
14	599.75	0.97	172.00	0.50	28.25	0.84
15	616.50	0.99	167.75	0.48	29.00	0.86
16	600.75	0.97	171.00	0.49	28.50	0.84
17	615.75	0.99	170.00	0.49	29.00	0.86
18	634.00	1.02	170.50	0.49	28.50	0.84
19	623.75	1.01	164.25	0.47	28.25	0.84
20	629.00	1.01	164.00	0.47	29.25	0.87

(equivalent to the partial saturation stage in AASHTO T-283-85) and a 10-in. vacuum level during the conditioning cycles, whereas some of the current methods (e.g., AASHTO T-283-85) use a controlled degree of saturation by maintaining the degree of saturation between 55 and 80 percent. In the case of similar gradations with one air void level, using the technique for controlled degree of saturation is appropriate. However, the objective of the ECS testing program is to develop a universal water-conditioning procedure for asphalt mixtures with different air voids. Therefore the technique of controlled degree of saturation is not the best because there are dense mixtures in which 60 percent of the air voids are not connected or are inaccessible and it is not possible to achieve the minimum 55 percent saturation with any high vacuum level. At the other extreme, there are open-graded mixtures with air voids of 15 percent or more in which almost all the air voids are interconnected and very accessible to water. By merely soaking or dipping the specimens in the water bath without applying vacuum, they will become more than 90 percent saturated.

In order to illustrate the above concept, the data on degree of saturation from Table 1 were plotted in Figure 4 versus the data on air voids and permeability. The trends confirm that in order to achieve a target saturation level for a specimen with a certain air void level, one may inadvertently destroy the specimen because of the need for the high vacuum level, as in the case of low (4 percent) air voids. In contrast, one may achieve the target degree of saturation before completing an appropriate accelerated wetting process, such as for the mixture with 31 percent air voids.

On the basis of this concept, the water penetration into the mixture achieved by the ECS method, rather than the volume of water, was used as a saturation indicator. This results in using a controlled vacuum, which actually controls the water penetration into the specimen.

Water Damage

The retained strength results from Table 2 are given in Figure 5, which shows the average curve of retained M_R for the three specimen sets throughout 20 cycles. The impermeable set shows no water damage, and the open-graded set shows a slight

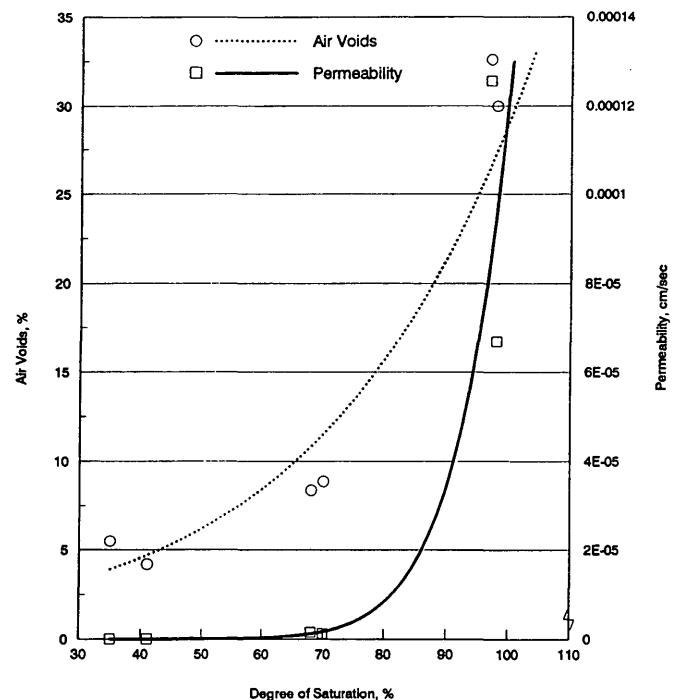


FIGURE 4 Relationship between degree of saturation and air voids.

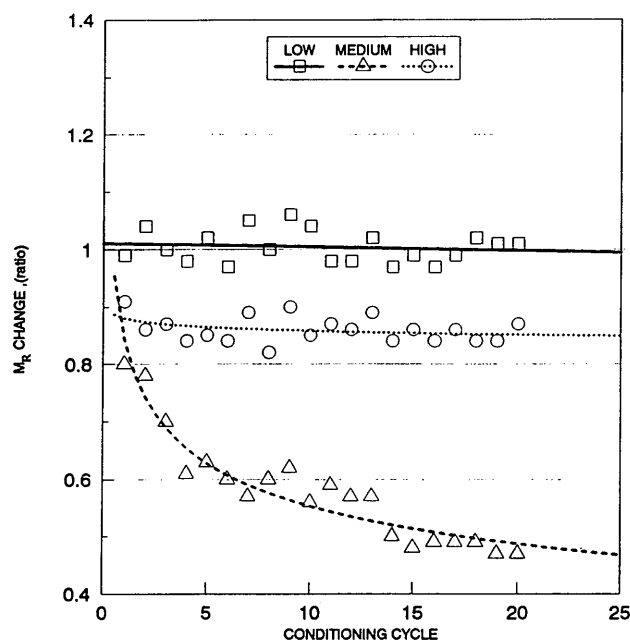


FIGURE 5 Change in M_R after free drainage water conditioning for different void contents.

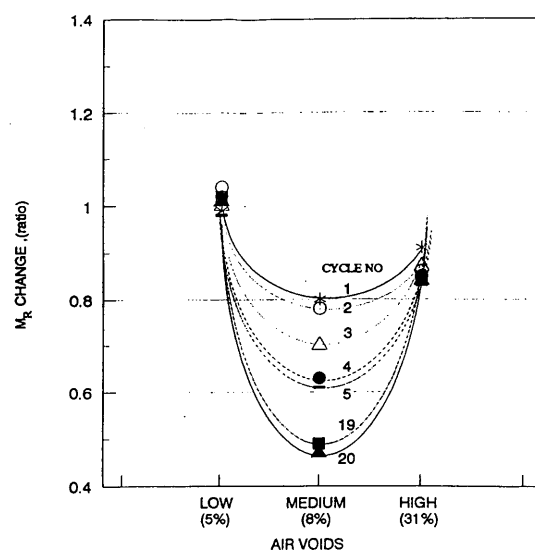
decrease in retained M_R . The set with the middle, or pessimum, range shows considerable water damage. In order to show the behavior trend, each set is represented by a regression formula (see Figure 5). Specimens with 8 percent air voids are expressed by the regression formula $y = 0.8x^{-0.18}$, which gives $R^2 = 0.89$. Open-graded mixture ratios are expressed by $y = 0.8x^{-0.01}$ with $R^2 = 0.91$. Specimens with 4 percent air voids are expressed by a linear regression, $y = 1.0 + x$, and because it is almost a horizontal line, R^2 is not applicable; one can see the low variation around the line, however.

In order to display the test results in a format similar to that used earlier (Figure 1) to introduce the pessimum voids concept, Figure 6 was prepared for selected cycles (Cycles 1 to 5 and Cycles 19 and 20). These results confirm the hypothesis that air voids in the pessimum range play an important role in asphalt concrete performance in the presence of water. Water retained in these voids during service life (as represented by water-conditioning cycles) of the pavement would tend to cause more damage than in mixtures with either more or less voids.

CONCLUSIONS

Analysis and evaluation of the laboratory test data combined with the literature search provided insight into the role played in water damage by air voids and water accessibility of asphalt mixtures. The following conclusions are based on the test results obtained in this laboratory study and their analysis as presented:

1. Air voids are very unevenly distributed in compacted asphalt mixtures.



CYCLE NO.	LEGEND	LOW (5%)	MEDIUM (8%)	HIGH (31%)
1	*—	0.99	0.80	0.91
2	○—	1.04	0.78	0.86
3	△—	1.00	0.70	0.87
4	●—	0.98	0.61	0.84
5	—	1.02	0.63	0.85
19	■—	1.01	0.47	0.84
20	▲—	1.01	0.47	0.87

FIGURE 6 Relationship between M_R change and air void content after free drainage water conditioning.

2. Permeability is a more informative measure of the air void system in a mixture than air void content alone.

3. Water accessibility under controlled vacuum is more representative for the wetting process than water volume of compacted asphalt mixtures (i.e., controlled degree of saturation).

4. The hypothesis on the role of voids in mixture performance was shown to be correct. Specimens with voids either higher or lower than the pessimum range resist water damage more than specimens within the pessimum range.

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