

Effect of Compaction on Asphalt Concrete Performance

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This paper presents information on how compaction (specifically, air voids) influences the performance of dense asphalt concrete pavement surfaces. The information is based on three separate sources: the existing literature on the subject, a questionnaire survey of 48 state highway agencies on compaction practice, and performance data from the Washington State Pavement Management System. All three information sources show some correlation between the degree of compaction and the performance of asphalt concrete pavement. Overall, a 1 percent increase in air voids (over the base air-void level of 7 percent) tends to produce about a 10 percent loss in pavement life.

This paper is the result of research on how compaction—specifically, air voids—affects the performance of dense asphalt concrete pavement. Three information sources support the findings: a literature review; a survey of state highway agencies (SHAs); and data from the Washington State Pavement Management System (WSPMS).

PREVIOUS RESEARCH

Other researchers have found that asphalt concrete performance is in part a function of compaction, and hence air voids, in dense mixtures. Two frequently used terms indicative of performance are fatigue cracking and aging.

Fatigue Cracking

Fatigue cracking (or “alligator cracking”) usually describes cracked pavement that has been repeatedly bent by heavy traffic. Researchers might reasonably ask how air voids affect asphalt concrete fatigue life.

Several authors (1–3) have shown that the fatigue life (time from original construction to substantial fatigue cracking) of asphalt concrete is reduced from 10 to 30 percent for each 1 percent increase over normal in air voids. For example, if 7 percent air voids are achievable for a mix yet 11 percent air voids resulted from construction, one could expect about a 40 percent reduction in pavement surfacing life (11 percent minus 7 percent equals 4, times 10 percent).

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Another way to approach air voids is to ask how they affect the thickness of asphalt concrete. As demonstrated by Finn and Epps (1), the effective thickness of asphalt concrete layers decreases as air voids increase. Finn and Epps evaluated two thicknesses of asphalt concrete, 4 and 6 in., at a starting point of 7 percent air voids (7 percent is generally considered achievable in normal paving construction). The following tabulation summarizes their findings.

Percent Air Voids in Asphalt Concrete	Effective Thickness of Asphalt Concrete (in.)	
	Example 1	Example 2
7	4.0	6.0
8	3.5	5.0
9	3.0	4.5
10	2.5	4.0
12	2.0	4.0

Thus, if the air voids are increased from a desirable level of 7 percent to a very poor compaction level of 12 percent, a 4-in.-thick asphalt concrete layer effectively lasts only as long as a 2-in. layer; a 6-in. layer is reduced to the effectiveness of a 4-in.-thick layer.

Aging

Aging of asphalt concrete can be evaluated in many ways. One way pertinent to this research is to judge aging by considering asphalt penetration and determining how air voids affect that property.

Goode and Owings (4) showed that, for asphalt concrete mixtures 4 years after construction, asphalt penetration is reduced about 6 percent for each 1 percent increase in air voids. They demonstrated, for example, that mixes retain about 75 percent of their original (immediately after construction) asphalt penetration at an air void level of 6 percent. If the air voids immediately after construction are 12 percent, however, the asphalt penetration is only 30 percent of its original level. The lower the asphalt penetration, the more susceptible the mixture is to cracking, as established by Hubbard and Gollomb (5), who showed that asphalt penetration of 30 or less (at 77°F) generally leads to distressed asphalt concrete. High-air-void pavements, as Goode and Owings (4) conclude, can be expected to result in low penetration levels for asphalt cement whose penetration level before mixing was at 85–100.

Air Void Levels

The work of the authors discussed above corroborates the findings of Finn et al. (6) concerning the maximum air void levels desirable for asphalt concrete construction. Those levels are summarized below.

<i>Asphalt Concrete Layer</i>	<i>Maximum Air Voids (%)</i>	
	<i>Light Traffic</i>	<i>Moderate to Heavy Traffic</i>
Upper 1½–2 in. of asphalt concrete pavement	8	7
Asphalt concrete pavement deeper than 2 in.	7	6

Results of the SHA survey also support the levels established by Finn et al.

QUESTIONNAIRE

A questionnaire (7) was prepared and sent in 1987 to the materials engineer in each of the 50 SHAs. The questionnaire's purpose was to review practice and gather opinions of the SHAs on the control of air voids in asphalt concrete pavements. Each agency was asked to respond to eight questions on methods of mix design, construction compaction control and tests, field density limits and average asphalt content, pavement air voids, primary mode of pavement failure, and, finally, the effect of increasing air voids on pavement life. Forty-eight agencies responded to the questionnaire.

It should be noted that some questions are subjective; answers may be based on the respondent's opinion rather than on data.

A sample completed questionnaire is shown in Figure 1. Each question and a summary of agency responses follow. (Percentage figures for number of agencies responding have been rounded to the nearest whole percentage point.)

Question:

- I. Asphalt concrete mix design procedure
 - (a) Marshall method
 - (b) Hveem method
 - (c) Other (please specify)

Analysis:

Responses are summarized in the following table. Two agencies use both Marshall and Hveem methods. Other methods used are aggregate gradation and AASHTO T-167.

<i>Method</i>	<i>No. of Agencies Using Method</i>	<i>Percent of 48 Respondents</i>
Marshall	34	71
Hveem	10	21
Both	2	4
Other	2	4

Question:

2. Are field results used to verify the adequacy of asphalt concrete mix designs? Yes _____ No _____. If yes, what types of field data are considered?

Analysis:

Yes—39 agencies (81 percent)
No—9 agencies (19 percent)

Agencies that responded yes typically use field results to verify air voids, aggregate gradation, asphalt content, and so on.

Question:

3. Construction compaction requirement
 - (i) Percent of laboratory-compacted density
 - (ii) Percent of theoretical maximum density (i.e., zero air voids)
 - (iii) Percent of control strip density (e.g., target = 95% of control strip)
 - (iv) Other (please specify)

Analysis:

- (i) Percent of laboratory compacted density—18 agencies (38 percent)
- (ii) Percent of theoretical maximum density (TMD) (AASHTO T209-82)—21 agencies (44 percent)
- (iii) Percent of control strip density—6 agencies (12 percent)
- (iv) Other—3 agencies (6 percent), which reported percent of field Marshall density

Question:

4. Construction compaction control tests
 - (a) Nuclear densimeter
 - (b) Core samples
 - (c) Other (please specify)

Analysis:

Eighteen agencies indicated use of both nuclear gauge and core samples. The core samples are most likely used to calibrate the nuclear gauge when both methods are specified.

- (a) Nuclear gauge — 18 agencies (38 percent)
- (b) Core samples — 12 agencies (25 percent)
- (c) Other — 18 agencies (38 percent), which reported using both methods

QUESTIONNAIRE ON EFFECT OF AIR VOIDS
ON ASPHALT CONCRETE PERFORMANCE

Please answer the following questions with respect to your agency's procedures or requirements for construction control of asphalt concrete pavement. In this questionnaire "air voids" are defined as the air spaces that occur between the coated aggregate particles in the final compacted asphalt concrete mixture.

1. Asphalt concrete mix design procedure
 - (a) Marshall method _____
 - (b) Hveem method X
 - (c) Other (please specify) _____

2. Are field results used to verify the adequacy of asphalt concrete mix designs? Yes X No _____. If yes, what types of field data are considered?

3. (a) Construction compaction requirement
 - (i) Percent of laboratory compacted density _____
 - (ii) Percent of theoretical maximum density X
(i.e., zero air voids)
 - (iii) Percent of control strip density _____
(e.g. target = 95% of control strip)
 - (iv) Other (please specify) X-Roller passes for peak density
 (b) Compaction specifications - Please include a copy of ^{(non main} your standard specification for asphalt concrete _{line)} compaction with the questionnaire.

4. Construction compaction control tests
 - (a) Nuclear densimeter X
 - (b) Core samples _____
 - (c) Other (please specify) _____

5. Construction compaction control criteria
 - (a) Does the Agency have a maximum field density limit?
Yes _____ No X
If yes, what is the limit (percent) _____ %
 - (b) What do you normally do if a contractor exceeds your maximum compaction requirements?

 - (c) Does the Agency have a minimum field density limit?
Yes X No _____
If yes, what is the limit? (percent) 92 % of Rice
 - (d) What do you normally do if a contractor does not meet ^{Density} your minimum compaction requirements?
Price Adjustment

 - (e) Has the Agency recently changed or is it considering a change in its compaction requirements?
Yes _____ No X Year _____

FIGURE 1 Sample completed questionnaire.

(f) At what minimum compacted course thickness does the agency require compaction control? 1-1/4 (inches)

6. What is the average asphalt cement content you use in your normal asphalt concrete surfacing mixes (% by weight of total mix)? 5.5

7. What is the range and average of field air voids in pavements constructed in the past five years?

Maximum 10
Minimum 5
Average 7

8. (a) What is the typical "life" of an asphalt concrete surfacing in your state? 12-1/2 years. ("Life" is defined as the time between construction and the time when the next overlay or rehabilitation is needed.)

(b) What is the principal mode of failure at the end of an asphalt concrete surfacing life (i.e. fatigue cracking, rutting, etc.) fatigue

(c) What is your experience or opinion of the effect of field air voids on asphalt pavement life?
Directly affects rutting, raveling and
fatigue cracking

(d) In your opinion, what is the effect of increasing air voids on asphalt pavement life, expressed as a percentage of design life, for the following field (as constructed) air void contents: 4% 100% 5% 100%
6% 100% 7% 100% 8% 90% 9% 80%
10% 70% 11% 60% 12% 50%

(Normally, 4 to 6% air voids would constitute 100% of design life)

9. Please make any additional comments you wish to add on this subject.

The results of this questionnaire will be summarized.. Please indicate if you wish to receive a copy of this summary.

Yes X No _____

Person answering this questionnaire:

Name _____
Title _____
Agency _____
Address _____
Telephone () _____

Question:

5. (a) Construction compaction control criteria
Does the Agency have a maximum field density limit?
Yes _____ No _____ If yes, what is the limit (percent) _____

Analysis:

Yes — 12 (25 percent)

No — 36 (75 percent)

The following table shows the limits for maximum field density specified by the 12 agencies that responded yes.

<i>Specification Limit</i>	<i>No. of Agencies</i>
96% of TMD	2
97% of TMD	6
98% of TMD	1
101% of Marshall	1
102% of control strip	1
105% of control strip	1

Question:

5. (b) What do you normally do if a contractor exceeds your maximum compaction requirements?

Analysis:

The 12 agencies that reported taking action did the following if the maximum density limit was exceeded.

<i>Action</i>	<i>No. of Agencies</i>
Price adjustment	2
Price adjustment or remove and replace	2
Penalty system	2
Removal if severe	1
No incentive payment	1
Adjust job-mix formula	1
Adjust rolling procedure	1
New control strip	1
No answer	1

Question:

5. (c) Does the Agency have a minimum field density limit?
Yes _____ No _____ If yes, what is the limit (percent) _____

Analysis:

All 48 responding agencies have a minimum density limit, summarized as follows:

<i>Specification Limit</i>	<i>No. of Agencies</i>
90% of TMD	1
91% of TMD	1

<i>Specification Limit</i>	<i>No. of Agencies</i>
92% of TMD	12
92.5% of TMD	2
93% of TMD	5
93% of Marshall density	1
95% of Marshall density	9
96% of Marshall density	2
97% of Marshall density	1
95% of field Marshall density	2
98% of field Marshall density	1
95% of control strip density	1
97.5% of control strip density	1
98% of control strip density	4
95% of Hveem density	1
95% of other lab density	1
98% of other lab density	1
No answer	2

Question:

5. (d) What do you normally do if a contractor does not meet your minimum compaction requirements?

Analysis:

The agencies reported the following actions when the minimum density limit was not achieved.

<i>Action</i>	<i>No. of Agencies</i>
Price adjustment	17
Price adjustment or remove and replace	13
Penalty system	5
Reevaluate compaction procedure or mix design	3
Require additional compaction	5
Reject below 92% of TMD	1
Assess liquidated damages	1
No answer	3

Question:

5. (e) Has the Agency recently changed or is it considering a change in its compaction requirements? Yes _____
No _____ Year _____

Analysis:

Yes—23 agencies (48 percent)

No—25 agencies (52 percent)

Question:

5. (f) At what minimum compacted course thickness does the Agency require compaction control? _____(inches)

Analysis:

The 48 responses are summarized as follows:

<i>Minimum Thickness (in.)</i>	<i>No. of Agencies</i>
$\frac{3}{4}$	5
1	13
$1\frac{1}{8}$	1
$1\frac{1}{4}$	5
$1\frac{1}{2}$	10
2	2
No minimum	8
No answer	4

Question:

6. What is the average asphalt cement content you use in your normal asphalt concrete surfacing mixes (percent by weight of total mix)?

Analysis:

The range of asphalt content was 4.6 to 6.7 percent, with an average of 5.7 percent. While the spread of asphalt content is 2.1 percent, it is noteworthy that 25 agencies (52 percent) reported an average asphalt content between 5.5 percent and 6.0 percent. Within this band, about as many of the SHAs use the Marshall method as use the Hveem method to determine optimum asphalt content.

<i>Percent by Weight of Total Mix</i>	<i>No. of Agencies</i>
4.6	1
5.0	4
5.1	2
5.2	1
5.3	3
5.4	1
5.5	6
5.6	4
5.7	3
5.8	3
6.0	9
6.1	2
6.2	2
6.3	1
6.4	3
6.5	2
6.7	1

Question:

7. What is the range and average of field air voids in pavements constructed in the past 5 years?

Maximum _____ Minimum _____ Average _____

Analysis:

This question is somewhat subjective, and it was not uniformly interpreted. Some agencies listed the range of field air

voids and others listed only the average. Seven agencies did not answer the question at all for a variety of reasons: "Data unknown"; "Don't know without a lot of analysis"; "Do not test for air void content in the field"; and "Figures are not available."

The averages and ranges that were reported are shown below.

	<i>Pavement Air Void Content (%)</i>	
	<i>Average</i>	<i>Range</i>
Maximum	9.9	5-15
Minimum	3.5	1-6
Average	6.5	2.8-10

Question:

8. (a) What is the typical "life" of an asphalt concrete surfacing in your state? _____ years. ("Life" is defined as the time between construction and the time when the next overlay or rehabilitation is needed.)

Analysis:

Of the 46 responding agencies, 34 (74 percent) reported an average pavement life of 10 to 15 years. Six agencies reported longer life and six reported shorter life. The overall average for all responding agencies was 12.5 years. Naturally, this question is a difficult one in that most SHAs have only an approximate idea of the "typical" life of asphalt concrete.

<i>Average Pavement Life (years)</i>	<i>No. of Agencies</i>
7	1
8	2
9	3
10	10
10.5	1
11	1
12	6
12.5	5
13	1
13.5	3
15	7
17.5	3
20	2
21	1

Question:

8. (b) What is the principal mode of failure at the end of an asphalt concrete surfacing life (i.e., fatigue cracking, rutting, etc.)?

Analysis:

In responding to this question, some agencies reported more than just the principal mode of failure. The several causes of

failure mentioned are summarized below, along with the number of agencies reporting them.

<i>Mode</i>	<i>No. of Agencies</i>
Fatigue cracking	20
Rutting	14
Cracking (non-specific)	12
Thermal cracking	6
Stripping	5
Weathering	4
Raveling	3
Reflective cracking	2
Base failure	2
Shrinkage cracking	1
Wear	1
Variable modes	5
No response	1

Question:

8. (c) What is your experience or opinion of the effect of field air voids on asphalt pavement life?

Analysis:

Forty-six agencies responded to this question. Comments are grouped in three categories.

Air Void Significance

All 46 respondents said that air voids play a significant role in the performance and life of asphalt concrete pavement. Fourteen (30 percent) described the role as

- Critical [to have an acceptable range]
- Significantly influencing life of asphalt pavement
- Playing a tremendous part in performance
- Very critical (four agencies used this description)
- All-important
- Very important
- Having a dramatic effect
- The most important item relative to life
- The single most important property affecting durability
- One of the most important criteria
- Extremely important

Minimum Air Voids

Twenty of the respondents (44 percent) commented that too few air voids cause a reduction in pavement life due to rutting, shoving, and bleeding. Eight of the 20 respondents indicated a minimum field-air-void content to avoid this distress. The specified minimum air-void level and the number of agencies reporting that level are listed below.

- 1–2 percent—1 agency
- 2 percent—2 agencies
- 3 percent—3 agencies
- 4 percent—2 agencies

One agency commented that low air voids in the surface mix are more likely than raveling to cause pavements to fail.

Maximum Air Voids

Of the 46 respondents, 44 indicated that increasing or excessive air voids adversely affect pavement performance and life. Opinions ranged widely, however, on the level of air voids at which performance and life begin to be affected. Fourteen agencies (30 percent) reported the following levels.

- 3 percent—1 agency
- 4 percent—1 agency
- 5 percent—1 agency
- 6 percent—5 agencies
- 7 percent—1 agency
- 8 percent—3 agencies
- 10 percent—1 agency
- 11 percent—1 agency

Question:

8. (d) In your opinion, what is the effect of increasing air voids on asphalt pavement life, expressed as a percentage of design life, for the following field (as constructed) air void contents: 4% _____ 5% _____ 6% _____ 7% _____ 8% _____ 9% _____ 10% _____ 11% _____ 12% _____ (Normally, 4 to 6 percent air voids would constitute 100 percent of design life.)

Analysis:

Twenty-eight respondents (only 58 percent of the whole sample) addressed this question, the most subjective one in the questionnaire. The opinions of those agencies that did respond varied widely, but suggest that air void levels above about 6 percent will decrease asphalt concrete life by about 7 percent for each 1 percent increase in air voids.

<i>Air Void Content (%)</i>	<i>Percent of Design Life</i>	
	<i>Range</i>	<i>Average</i>
4	20–120	97
5	30–120	97
6	70–120	98
7	50–100	93
8	40–100	87
9	30–100	79
10	20–100	73
11	10–95	62
12	0–90	54

AIR VOID EFFECTS ON PAVEMENTS IN WASHINGTON STATE

In Washington State, data from WSPMS support the results of the questionnaire survey. The Washington State Department of Transportation (WSDOT) has conducted visual condition surveys of the entire state system every 2 years since

TABLE 1 SUMMARY OF CONTRACT DATA

State Route	Contract No.	Construction Year	Life to PCR = 40 (years)	Percent Loss
2	8602	1970	7.0	42
82	8672	1971	8.5	29
395	8004	1968	5.0	58
			6.8 (avg)	43 (avg)

1969. Specific performance curves are developed from this data for over 2,600 project-length segments of the complete 7,000-mi centerline system. These segments usually match with past paving projects which represent areas of unique and consistent performance. The survey-and-distress deduct values are weighted toward fatigue cracking. The Pavement Management System thus tracks over time the general fatigue performance of all past paving projects for the entire state.

In addition, the WSDOT conducts a reasonably detailed resurfacing investigation on all resurfacing or reconstruction projects as part of the normal design process. This investigation, which examines the performance of well over 100 projects a year, demonstrates that a combination of factors contributes to the particular performance of each project. Almost never can shortened service life be attributed to a single cause. But of the several factors that can cause reduced performance, air voids is consistently one of the most significant, probably because it is so difficult to achieve the optimal air void levels during construction. The effects of high air voids are well documented in project files, but the data have not been rigorously culled to show clear cause and effect.

The three projects discussed below are typical of those in which high-air-void contents in the wearing and leveling courses caused early fatigue failure. The pavements in eastern Washington were originally constructed in the late 1960s and early 1970s, and the wearing and/or leveling courses were hot-recycled in the early 1980s to correct the problems associated with early fatigue failure. Eastern Washington has a dry, freeze environment, which is more prone to performance problems associated with void content and moisture sensitivity than is a wet, no-freeze environment, such as that in western Washington. In all three cases, the void content of the original pavements was in the 11- to 12-percent range for the wearing or leveling courses. (When the pavements were put down, there was little construction control of air voids and plant production increases were not marked by compaction equipment increases behind the paver.) All three projects were built to similar specifications, shown below.

1.8 in.	Class B ACP (wearing course)
1.2 in.	Class B ACP (leveling course)
4.2 in.	Class E ACP (base course)
3.0 in.	Crushed surfacing top course (unstabilized)
6.0 in.	Gravel base (unstabilized)
16.2 in.	Total

The Class B and Class E ACP are normal, dense-graded asphalt concrete pavement mixes. Class B's maximum size aggregate is $\frac{3}{8}$ in. and Class E's is $1\frac{1}{4}$ in.

A summary of the pertinent data for each contract is shown in Table 1. The first three columns are self-explanatory. The fourth column shows the time it took for each project to reach

a pavement condition rating (PCR) of 40, which represents about 10 percent fatigue cracking, the level at which rehabilitation projects are programmed in the WSPMS. The percent-loss column represents the percent reduction in service life (to PCR = 40), as compared to $12\frac{1}{2}$ years, the average service life of such pavement in Washington State.

For all three projects, fatigue cracking was confined to the wearing and/or leveling courses. No fatigue cracking was found in the Class E base course, which had air void contents in the 6- to 9-percent range. The lower air-void contents in Class E is likely explained by its greater lift thicknesses, which retain heat longer and permit more compaction. To account for greater thickness, contractors often provided more or heavier compaction equipment for the base lift. During the recycling mix design process, the asphalt recovered from the wearing and leveling courses was found to be quite stiff. Tests on the recovered asphalt showed penetrations in the range of 7-16 and 140°F absolute viscosities of 50,000 to 250,000 poise. The asphalt used in the earliest project was 85-100 penetration grade, while the asphalt from later projects was AR 4000w, which registers a penetration range of about 100-115. Personal observation suggested that the effects of the high air voids increased the rate of hardening of the asphalt cement binder and decreased the fatigue resistance of the pavement. State Route 82 experienced the best service life and evidenced the least hardening of the binder, but this project was sand-sealed shortly after construction to reduce the effects of the high air voids on pavement performance.

The three pavements have been in service now for 4 to 6 years after recycling with a more normal void content; the latest condition survey, conducted in the spring of 1988, revealed no signs of any deterioration.

The effects of air voids on pavement life were also studied but not reported in a small FHWA-funded activity on pavement performance equations (8). The 70 projects studied, equally divided between eastern and western Washington, were initially selected based without regard to void content. Enough data on air void content were gathered, however, to allow analysis of the effects of air voids on pavement life (PCR = 40).

Void Content (%)	Loss in Service Life (%)
7	0
8	2
9	6
10	17
12	36

The data are based on only a small sample (less than 5 percent of the state system) and are perhaps somewhat skewed because western Washington's climate is mild, which ameliorates the detrimental effects of high air voids. Nonetheless,

TABLE 2 EFFECT OF COMPACTION ON PAVEMENT PERFORMANCE

Air Voids (%)	Pavement Life Reduction (%)		
	Literature ^a	SHA Survey ^b	WSPMS
7	0	7	0
8	10	13	2
9	20	21	6
10	30	27	17
11	40	38	—
12	50	46	36

^aLower bound of range.

^bAverage.

the data confirm the findings of the previously described SHA survey.

FINDINGS

Table 2 summarizes the findings on the effect of compaction (specifically, air voids) on asphalt concrete pavement performance.

All three sources of information confirm that air void content affects pavement performance. The rule-of-thumb that emerges is that each 1 percent increase in air voids (over a base air void level of 7 percent) results in about a 10 percent loss in pavement life (or about 1 year less).

Of course, the performance of asphalt concrete is affected by more than just air void content. Although the primary goal of the SHA survey was to estimate the effects of air voids, the summary of the responses necessarily addresses current mix design procedures, compaction specifications, and field practice, all of which play a part in performance outcome.

CONCLUSIONS

Results of an examination of the literature, a survey on compaction practice, and performance data from WSPMS lead to the following conclusions.

1. An analysis of the available literature and WSPMS data suggest that both fatigue cracking and age-hardening of dense asphalt concrete mixtures is exacerbated by poor compaction

(high air voids). Further, pavement life is reduced about 10 percent for each 1 percent increase in air voids over a base level of 7 percent. The SHA survey on compaction practice tended to confirm this finding.

2. The survey of the SHAs reveals that compaction specifications, field practice, and asphalt concrete performance vary widely from state to state. Although some questions in the survey were subjective, the responses still tend to show a definite correlation between compaction and pavement life.

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