FIELD VERIFICATION PROCESS FOR OPEN-GRADED HMAC MIXES

Final Report

SPR 304-051

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by

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16. Abstract

The State of Oregon uses significant amounts of open-graded HMAC mixes as primary wearing courses on state highways. The primary materials design system for these mixes relies heavily on laboratory draindown to select the design asphalt content. Subsequent adjustments in the field rely heavily on the visual draindown characteristics as well. Draindown is a limiting characteristic in terms of constructability of open-graded mixes, but adjustments made to mitigate draindown may reduce the long-term performance of the wearing surface.

This research looked at the viability of using conventional film thickness measurements as a means of field verifying the quality of the open-graded mixtures being produced. The findings were that conventional film thickness measurements were too sensitive to the material passing the 75 μm sieve and were therefore not a practical tool.

The authors proposed a simple alternative involving measuring the volume change that occurs when asphalt cement is added to uncoated aggregate. This measurement tool uses readily available field laboratory equipment and provides a simple means of measuring a fundamental mixture property.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

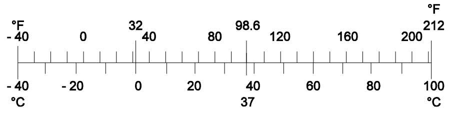
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
In	Inches	25.4	Millimeters	Mm
Ft	Feet	0.305	Meters	M
Yd	Yards	0.914	Meters	M
Mi	Miles	1.61	Kilometers	Km
		AREA		
in^2	Square inches	645.2	millimeters	mm^2
ft^2	Square feet	0.093	meters squared	M^2
yd^2	Square yards	0.836	meters squared	M^2
Ac	Acres	0.405	Hectares	Ha
mi^2	Square miles	2.59	kilometers squared	Km^2
		VOLUME		
fl oz	Fluid ounces	29.57	Milliliters	ML
Gal	Gallons	3.785	Liters	L
ft^3	Cubic feet	0.028	meters cubed	m^3
yd^3	Cubic yards	0.765	meters cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
Oz	Ounces	28.35	Grams	G
Lb	Pounds	0.454	Kilograms	Kg
T	Short tons (2000 lb)	0.907	Megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	Millimeters	0.039	inches	in
m	Meters	3.28	feet	ft
m	Meters	1.09	yards	yd
km	Kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
ha	Hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
mL	Milliliters	0.034	fluid ounces	fl oz
L	Liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	Grams	0.035	ounces	oz
kg	Kilograms	2.205	pounds	lb
Mg	Megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8C + 32	Fahrenheit	°F



***** SI is the symbol for the International System of Measurement

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DISCLAIMER

FIELD VERIFICATION PROCESS FOR OPEN-GRADED HMAC MIXES
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1.0 INTRODUCTION

1.1 PROBLEM STATEMENT

In recent years the Oregon Department of Transportation (ODOT) has moved toward contractors being responsible for developing their own Hot Mix Asphalt Concrete (HMAC) mix designs. These mix designs are developed under the general guidelines established by ODOT, but do allow designs to fit within a set of broad parameters. For dense-graded mixes ODOT has instituted a field mix design verification process to assure the produced mix will meet ODOT design criteria. No such verification is performed for open-graded mixes. Although the open-graded mixes are generally more forgiving than dense-graded mix, there may be differences between the mix design and field conditions affecting mix properties. ODOT needs an objective verification process that will assure open-graded HMAC mixes are receiving adequate liquid asphalt to optimize performance.

1.2 BACKGROUND

Since 1990 open-graded HMAC mixes (12.5 mm and 19.0 mm nominal maximum size aggregate) have played an important role as the primary wearing surface used on many of Oregon's highways. Approximately 2,900 centerline kilometers of open-graded HMAC mixes have been placed on the state highway system for use by all levels of traffic. The significant "splash and spray" reduction as well as improved resistance to rutting has made open-grades an attractive alternative as a primary wearing course material for use in Oregon's wet climate.

While overall performance has generally been quite good, the forgiving nature of open-graded mixes has allowed mixes to be produced with effective asphalt contents (P_{be}) ranging from the lower 3% range to those exceeding 6%. Effective asphalt is the "non-absorbed" asphalt (i.e. the asphalt not absorbed into the aggregate) that is free to bind the aggregate structure together. This range of allowable P_{be} is primarily due to the high Voids in Mineral Aggregate (VMA) contents of these mixtures and the significant draindown problems encountered when designing these mixes.

The high VMA (20-25%) creates a large "surge reservoir" in the aggregate structure that allows a high P_{be} without major negative impacts to the stability of the mix. At the other extreme, the strong aggregate structure appears to allow mixes to be constructed with relatively low P_{be} and still perform adequately, at least initially.

The original laboratory design philosophy was to put as much asphalt into the mix as possible until significant draindown appeared in the laboratory-fabricated samples. Lower viscosity asphalts would inherently have lower design asphalt contents because the asphalt tended to run off the aggregate more readily. Higher viscosity asphalts led to laboratory designs that had significantly higher asphalt contents. In some instances these high asphalt content designs led to significant draindown problems during construction or resulted in mixes with greatly reduced permeability.

Once designed in the laboratory it was still essential to have an expert at the construction site to adjust the asphalt content based on any draindown issues encountered in the field. During mix production and placement, draindown was usually dealt with by lowering plant temperature, by lowering asphalt content or both. While this strategy may have mitigated the constructability issue of draindown, it also may have sacrificed long-term durability. The experts were more apt to lower the asphalt content if a draindown problem existed than to raise the asphalt content if no draindown problem existed.

In the mid 1990's a volumetric criteria was placed on Voids Filled with Asphalt (VFA) to try to modulate the extremes in design asphalt contents for open-graded mixes. The 40 to 50% VFA criteria significantly reduced the occurrence of draindown problems during construction and helped to reduce the range of P_{be} to approximately 4 to 5%. However, this 4 to 5% range of P_{be} can still be considered significant and heuristically most designers would expect a 5% P_{be} to outperform the same aggregate gradation with a 4% P_{be}. Because the vast majority of the open-graded mixes in Oregon have not reached the end of their design lives, the nuances of their failure mechanisms are not fully understood. Therefore, the "more is better" design philosophy, within the VFA limits, is the current state of the practice. With greater training, the field experts are also now more willing to consider increasing the asphalt content if draindown is not an issue in construction.

In an attempt to refine the process, an initial reaction might be to tighten the VFA range. However, VFA is a linear function of VMA and a "one size fits all" approach to VFA would lead to different P_{be} as VMA varied. A better tool would be to identify the optimum volume of asphalt needed to bind a given volume of aggregate together, then assure that the design has adequate VMA to accommodate both the volume of asphalt and the volume of void space desired for permeability.

If a simple field measure of asphalt volume were available, it could be used as a tool by the field decision maker to assure that the optimum mix is being produced. One potential tool is to utilize existing techniques to determine average film thickness of asphalt on aggregates and then apply an average film thickness criteria to both mix design and field production. Another technique, as proposed by the authors, utilizes a measure of the aggregate volume and effective asphalt cement volume as a means of quantifying a fundamental volumetric ratio of the mix, the Volume Increase Ratio (VIR). This method can also lead to establishing objective criteria for mix design and production. This project tests the viability of using these two techniques for field verification of open-graded HMAC mixes. The results are reported in the following chapters.

1.3 OBJECTIVES

The overall objective of the research was to prove or disprove the hypotheses that film thickness or P_{be} can be used to make field adjustments for open-graded HMAC mixes. Specific tasks included:

1. Review literature for information on film thickness related to open-graded HMAC mixes.

2. Select actual to-be-constructed projects for data collection and evaluation. (Approximately 6 projects in fiscal year 2001).

3. Evaluate existing as-constructed open-graded HMAC projects for effective asphalt content, both mix designs and construction quality control data.

4. Collect field samples from previous open-graded HMAC projects if available.

5. Perform laboratory testing including maximum specific gravity of mixes and aggregate specific gravities of cold feed materials to calculate film thickness and volume increase ratio.

6. Determine and analyze film thickness data for all new and existing projects to determine relevance to field control of open-graded HMAC mixes. Evaluate use of film thickness method and proposed VIR method.

7. Develop recommendations for implementation.

This literature review is contained in Chapter 2. Chapter 3 contains the evaluation of 19 existing projects as reported by Dunn et.al. (*1998*) and development of the VIR. Chapter 4 includes an evaluation of the data gathered during the 2001 construction season and Chapter 5 contains the conclusions and recommendations.

2.0 LITERATURE REVIEW

A review was conducted of the literature relating to studies of film thickness in porous asphalt pavements. In general, several studies acknowledge the importance of film thickness, however, there was little in the way of specific studies on quantifying or specifying film thicknesses for open-graded mixtures. A review was also made of studies of film thickness related to dense-graded asphalt mixtures. Because of the higher porosity of open-graded mixtures, it would be anticipated that film thicknesses should not be lower than those generally specified for dense-graded mixtures. There is a significant body of work on film thickness as it relates to quantifying and specifying film thickness for dense-graded mixtures.

2.1 FILM THICKNESS RELATED TO OPEN-GRADED MIXES

Increased film thickness or increased asphalt content are mentioned in several studies as providing greater resistance to aging and or raveling in porous pavements. This general belief that “more is better” is then tempered with discussions on asphalt draindown, which becomes the limiting factor during actual construction of the pavement.

2.1.1 Relationship of Film Thickness to Pavement Performance

Increased asphalt contents (i.e. increased film thicknesses) will improve resistance to aging, but is limited by draindown (*Younger et al 1994*). Excess asphalt (i.e. high film thicknesses) and/or fine mixes contribute to fat spots and rutting (*Dunn et al 1998*). Open-graded mixtures typically fail by raveling due to asphalt binder aging and subsequent embrittlement (*Huber 2000*). Oxidation and hardening of the asphalt cement due to thin film thickness and air and water movement through the voids has caused early failure of the surface by raveling (*Smith 1992*). For open mixtures, resistance to hardening can be achieved by increasing the thickness of the asphalt coating on the aggregate pieces (*Kumar and Goetz 1977*).

2.1.2 Film Thickness Design Requirements

An Open Graded Friction Course (OGFC), another name for open-graded HMAC, has a higher asphalt content than a dense-graded mix and uses an equal or harder grade of asphalt. An OGFC requires a 8 – 11 micron average film thickness (*FHWA 1990*). ODOT is the only U.S. agency that has a volumetric requirement in its design process and specifies voids filled with asphalt (VFA) of 40 to 50% (*Huber 2000*).

2.2 FILM THICKNESS RELATED TO DENSE-GRADED MIXES

Various studies dating back to the 1950's have attempted to establish appropriate film thicknesses for dense-graded mixes. Conclusions of the studies include:

- An average film thickness of 6 – 8 microns is recommended for dense mixtures (*Campen et al 1959*).
- A more recent study involving the Strategic Highway Research Project short and long-term aging process has led to a recommendation of 8 microns for mixtures with 4 – 5% air voids (*Kandhal et al 1998*).
- A dense-graded mixture requires a 4 – 6 micron average film thickness (*FHWA 1990*).

Film thicknesses are typically calculated based on P_{be} and the surface area of aggregates as determined from the aggregate gradation and surface area factors (*Asphalt Institute 1993*). Table 2.1 provides the surface area factors for the various sieve sizes.

Table 2.1: Surface Area Factors

Sieve	Surface Area Factor
4.75 mm	0.41
2.36 mm	0.82
1.18 mm	1.64
600 μm	2.87
300 μm	6.14
150 μm	12.29
75 μm	32.77

3.0 EVALUATION OF EXISTING PROJECTS

This chapter contains an evaluation of the volumetric data of 19 projects listed in ODOT Research Report, "Establishment of QC/QA Procedures For Open-Graded Mixes", as reported by Dunn et.al. (*1998*). The evaluation was based on the mix designs, statistical acceptance reports and field coring data contained in that report and/or obtained from ODOT. Also included is a discussion and evaluation of potential relationships between volumetric properties and performance for the 19 projects.

3.1 DETERMINATION OF MATERIAL PROPERTIES

Film thickness calculations are based on two inputs; the volume of effective asphalt and an estimate of surface area of the aggregate. ODOT did not routinely measure effective asphalt contents during mix production, therefore production effective asphalt contents were estimated for this study based on the mix design properties.

Additionally, while actual mean values for the gradations of each project were available from the statistical acceptance reports, ODOT does not specify the same sieve series as is used in the most common form of the film thickness calculation. For this analysis, estimates were made as to the percent passing on the various intermediate sieves that are required for the surface area calculations.

Maximum specific gravity (G_{mm} or Rice) testing and asphalt content testing were performed on the cored materials. The cores were not randomly sampled and often times represented distressed areas of unknown severity. The gradation results from cored materials were consistently finer than both the mix design and the production quality control tests. This finer gradation had a significant impact on the surface area of the aggregates and subsequent calculations of film thickness.

While some breakdown of the aggregate is expected in the drum, the gradation changes observed in the cores greatly exceeded what would normally be attributed to the action of the drum. Other sources of the gradation change may be migration of fines due to draindown, external debris that has entered the interconnected void system of the mix, raveling and breakdown of the surface due to the action of studded tires, or generation of fines during coring and subsequent transport into the mix by the cooling water of the coring apparatus.

In several instances, comparisons of the mix design effective specific gravity of the aggregate (G_{se}) and the G_{se} obtained from cored samples indicated significant differences. These may be attributed to either differences in the maximum specific gravity testing or the asphalt content testing. In either case, differences in G_{se} have a significant impact on the calculation of P_{be} and subsequent calculations on film thickness.

3.2 ESTIMATING EFFECTIVE ASPHALT CONTENTS

P_{be} are a function of G_{se}, which in turn is a function of G_{mm}. G_{se} is a particularly powerful tool because it is essentially independent of asphalt content. Hence, once G_{se} is established for a mixture then P_{be} can be reasonably estimated for in-place material based on the total mean asphalt content (P_b) as reported in the statistical acceptance data for a project.

The development of an open-graded mix design generally entails fabricating samples at three to five different known asphalt contents. Historically, G_{mm} and bulk specific gravities (G_{mb}) are measured at each of the different asphalt contents and reported on the mix design.

Also required are the aggregate specific gravity (G_{sb}) for the design gradation and the liquid asphalt specific gravity (G_b), however, these values were not routinely reported on the mix design until the mid 1990's. Fortunately for those designs that lacked the necessary information, G_{sb} could be obtained from ODOT's central laboratory databases. Because the calculations are relatively insensitive to G_b, an assumed value of 1.020 was used in cases where it was not otherwise available.

The first step in this process was to establish a reasonable value for G_{se}. G_{se} was calculated for each known asphalt content and G_{mm} reported in the mix design. While in theory they should be the same, in most cases they varied to some degree due to minor testing errors or round off of significant digits. There was a particularly noticeable change in G_{se} at the higher asphalt contents. Most likely this can be attributed to the draindown and subsequent loss of oil from the test specimen when preparing the G_{mm} sample.

The resultant G_{se} were evaluated and those that appeared to be representative of the mixture were averaged to come up with a final mix design value of G_{se}. In addition, because G_{mm} data was not available from actual mix production, the same design G_{se} was also used in calculating P_{be} for in-place material.

Having established a design G_{se}, the next step is to adjust the mix design volumetrics to the design G_{se}. This is a standard practice now used in the ODOT mix design process. It involves using G_{se} to calculate a new G_{mm} for each design point and computing the volumetrics based on these adjusted G_{mm}. The same process was applied to the in-place material using the mean value asphalt content as reported in the statistical acceptance data. The result was that P_{be} could now be calculated for both the adjusted mix design and for the in-place material.

3.3 ESTIMATING AGGREGATE GRADATIONS

Standard surface area sieves versus historical ODOT mix design sieves are listed in Table 3.1.

Table 3.1: Surface Area Sieves vs. ODOT Sieves

Sieves w/Surface Area Factors	Sieves Used by ODOT for Mix Design
Maximum	25 mm
-	19 mm
-	12.5 mm
-	9.5 mm
-	6.3 mm
4.75 mm	-
2.36 mm	-
-	2.0 mm
1.18 mm	-
600 μm	-
-	425 μm
300 μm	-
150 μm	-
75 μm	75 μm

The inconsistency between the two sieve sets necessitated providing either an estimate of surface area for the ODOT sieves or an estimate of percent passing for the Surface Area sieves. The latter alternative was chosen and determined by applying a 0.45 power gradation chart. The 0.45 power gradation chart is an accepted standard graph used in HMAC analysis for plotting and evaluating aggregate gradations. The percent passing for each of the ODOT sieves was plotted on the graph. The percent passing for the sieves necessary to calculate the surface area were then interpolated from each graph generated from the ODOT sieves. All estimates were made to the nearest whole number.

3.4 ESTIMATED FILM THICKNESS ON EXISTING PROJECTS

Using the estimates of P_{be} and aggregate gradation, film thicknesses were calculated according to accepted procedures (*Asphalt Institute 1993*) for each of the projects:

Table 3.2: Film Thickness on Existing Projects

Hwy No.	Name	Year	Asphalt Grade	Design Film Thickness, µm	In-Place Film Thickness, µm
001	Hayesville- Battle Creek	1990	AC-30(tbl II)	13.95	14.41
001	W. Marquam – N. Tigard	1990	AC-30(tbl II)	13.44	12.90
004	Forge Rd. Lobert Rd.	1990	AC-20R	14.66	15.26
001	Jumpoff Joe – N. Grants Pass	1991	PBA-5	13.03	13.67
002	Corbett – Multnomah Falls	1991	PBA-5	16.61	17.57
002	Rufus – Arlington (E. Unit)	1991	PBA-5	13.06	12.62
004	Williamson Riv. – Modoc Pt.	1991	AC-20R	14.55	16.80
006	Baldock Slough – S. Baker	1991	AC-20R	18.16	15.92
006	E. Pendleton – Emigrant Hill	1992	PBA-6	21.23	25.34
002	Rufus – Arlington (W. Unit)	1993	PBA-6	23.60	24.77
002	Umatilla – McNary	1993	PBA-6	21.85	23.59
047	Wolf Cr. – W. Fk. Dairy Cr.	1993	PBA-5	20.31	20.90
001	Azalea – Jumpoff Joe	1994	PBA-6	17.49	18.90
001	Halsey – Lane Co. Line (SB)	1994	PBA-6	18.00	17.67
001	Halsey – Lane Co. Line (NB)	1994	PBA-6	16.66	17.43
144	Sunset Hwy – Pacific Hwy	1994	PBA-6	21.18	19.29
004	Willowdale – Qualle Rd.	1995	PBA-6	19.93	16.99
026	Mt. Hood – Long Prairie	1995	PBA-6	22.74	23.08
041	Prineville – Powell Butte	1995	PBA-6	19.09	20.99

Standard specifications for asphalt materials are included in Appendix A. Detailed film thickness calculations are included in Appendix B.

Using average film thickness to evaluate typical Oregon open-graded HMAC has two major shortcomings. The first is that “Surface Area Factors” are universal and do not account for variation in particle shape. That is to say, the same surface area factor is used for round particles as well as flat or elongated particles. On a mass percent passing basis, these different shapes may have significantly different surface areas.

The other shortcoming of this procedure is that the largest surface area factors are applied to the finest sieves with the largest contribution to surface area (approximately 40% of the surface area) coming from the material passing the 75 µm sieve (P75 µm). Oregon’s open-graded mixes have low targets for P75 µm, typically in the 2 to 5% range. Allowable production ranges for P75 µm are of a similar order of magnitude. Therefore, normal variations in P75 µm cause wide swings in average film thickness due to its large surface area factor.

3.5 VOLUME INCREASE RATIO

A different way to look at film thickness is to recognize that as asphalt coating increases, so should the volume per unit mass of the mixture. If this volume change can be accurately quantified then a less subjective measure of film thickness may be obtained.

Such a measure can be calculated using currently established test methods; the specific gravity test for bituminous materials (*AASHTO T228, 2001*), the aggregate specific gravity tests (*AASHTO T84 and T85, 2001*), and the "Rice" test (*AASHTO T209, 2001*). The aggregate specific gravity tests give us the aggregate contribution to mixture volume and the Rice test gives us the mixture volume. The difference in the two will be the "non-absorbed" asphalt contribution to mixture volume.

The relationship between the specific gravity of the mixture and the specific gravities of the constituents of the mix (effective aggregate and asphalt liquid) is given as follows[1]:

$$\frac{100}{G_{mm}} = \frac{P_s}{G_{se}} + \frac{P_b}{G_b} \qquad \textbf{(3-1)}$$

P_s is the percentage of the mix by mass that is aggregate. The first term on the right hand side of Equation 3-1 represents the effective aggregate contribution to mixture specific gravity and the second term represents the liquid asphalt contribution. What is desired is the "bulk" volume of aggregate and the "non-absorbed" volume of asphalt.

The liquid asphalt contribution is a combination of "absorbed" and "non-absorbed" materials. Only the "non-absorbed" asphalt will contribute to an increase in film thickness. The relationship between "absorbed" and "non-absorbed" asphalt is as follows[2]:

$$\frac{P_{ba}}{100} = \frac{P_b}{P_s} - \frac{P_{be}}{P_s} \qquad \textbf{(3-2)}$$

P_{ba} is the percent by mass of asphalt binder that is absorbed into the aggregate and is unavailable to bind aggregate together. The relationship between "absorbed" asphalt and aggregate specific gravity is also known and is as follows[3]:

$$\frac{P_{ba}}{100} = \frac{G_b}{G_{sb}} - \frac{G_b}{G_{se}} \qquad \textbf{(3-3)}$$

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[1] Asphalt Institute. "Manual Series No. 2 (MS-2)" Sixth Edition. Article 4.07, Eq. (3)

[2] Asphalt Institute. "Manual Series No. 2 (MS-2)" Sixth Edition. Article 4.09, Eq. (5)

[3] Asphalt Institute. "Manual Series No. 2 (MS-2)" Sixth Edition. Article 4.08, Eq. (4)

Equating Equations 3-2 and 3-3 results in the following:

$$\frac{P_b}{G_b} = \frac{P_{be}}{G_b} + \frac{P_s}{G_{sb}} - \frac{P_s}{G_{se}} \qquad \textbf{(3-4)}$$

The first term on the right hand side of Equation 3-4 represents the contribution of “non-absorbed” asphalt to the liquid asphalt portion of mixture specific gravity.   The second and third terms represent the “absorbed” asphalt contribution.

Substituting Equation 3-4 into Equation 3-1:

$$\frac{100}{G_{mm}} = \frac{P_s}{G_{sb}} + \frac{P_{be}}{G_b} \qquad \textbf{(3-5)}$$

Equation 3-5 now establishes the desired relationship between the “bulk” volume of aggregate per unit mass and the volume of “non-absorbed” asphalt per unit mass. The Volume Increase Ratio (VIR) of these two terms represents the increase in volume of the mixture due to the “non-absorbed” asphalt coating.

$$Volume\ \ Increase\ \ Ratio\ \ (VIR) = \frac{\left(P_{be}/G_b\right)}{\left(P_s/G_{sb}\right)} \qquad \textbf{(3-6)}$$

When multiplied by 100, the VIR becomes a percentage increase with the “bulk” aggregate volume as the basis.

This simple ratio gives a dimensionless measure of how the mixture volume is changing as the asphalt liquid is added to the uncoated aggregate. The measure is determined from known laboratory measurements and not from “assumed” surface area factors. It does not require gradation inputs and therefore is insensitive to minor swings in the P75 μm.

3.6 VOLUME INCREASE RATIO (VIR) ON EXISTING PROJECTS

Using the estimates of P_s and P_{be} and design values for G_b and G_{sb} from the mix designs, the VIR were calculated for each of the projects:

Table 3.3: Volume Increase Ratio on Existing Projects

Hwy No.	Name	Year	Asphalt Grade	Design Volume Increase, %	In-Place Volume Increase, %
001	Hayesville- Battle Creek	1990	AC-30(tbl II)	12.78	12.78
001	W. Marquam – N. Tigard	1990	AC-30(tbl II)	11.59	11.77
004	Forge Rd. Lobert Rd.	1990	AC-20R	12.82	12.42
001	Jumpoff Joe – N. Grants Pass	1991	PBA-5	10.93	10.78
002	Corbett – Multnomah Falls	1991	PBA-5	11.78	11.55
002	Rufus – Arlington (E. Unit)	1991	PBA-5	9.58	9.58
004	Williamson Riv. – Modoc Pt.	1991	AC-20R	11.89	11.63
006	Baldock Slough – S. Baker	1991	AC-20R	12.59	12.45
006	E. Pendleton – Emigrant Hill	1992	PBA-6	15.93	17.32
002	Rufus – Arlington (W. Unit)	1993	PBA-6	15.67	15.60
002	Umatilla - McNary	1993	PBA-6	16.66	16.94
047	Wolf Cr. – W. Fk. Dairy Cr.	1993	PBA-5	14.69	14.69
001	Azalea – Jumpoff Joe	1994	PBA-6	14.92	14.79
001	Halsey – Lane Co. Line (SB)	1994	PBA-6	15.46	15.46
001	Halsey – Lane Co. Line (NB)	1994	PBA-6	14.31	14.31
144	Sunset Hwy – Pacific Hwy	1994	PBA-6	14.65	13.47
004	Willowdale – Qualle Rd.	1995	PBA-6	13.71	12.90
026	Mt. Hood – Long Prairie	1995	PBA-6	14.82	14.73
041	Prineville – Powell Butte	1995	PBA-6	13.38	13.38

Detailed volume increase results are contained in Appendix C.

3.7 POTENTIAL RELATIONSHIPS TO PERFORMANCE

The ODOT Pavement Management database was queried to obtain performance data for the 19 projects. A detailed distress survey of ODOT highways designated on the National Highway System (NHS) is completed every two years. Indexes for fatigue cracking, rutting, patching, longitudinal cracking, transverse cracking, block cracking, raveling, and bleeding are calculated and reported for each section of highway. The index for each distress type quantifies the amount and severity of the distress. An "Overall Condition Index" combining all distress factors is calculated and reported for each section of highway. This index is reported on a scale of 0 to 100, with 100 representing a pavement in excellent condition, and other ratings as defined in Table 3.4. The rating system includes the same evaluation processes and condition definitions for open-graded and dense-graded HMAC.

Table 3.4: Condition Index Descriptions

Overall Condition Index	Description
98.1 – 100.0	Very Good
75.1 – 98.0	Good
45.1 – 75.0	Fair
10.1 – 45.0	Poor
0.0 – 10.0	Very Poor

Table 3.5 indicates the project age, condition index in 2001, and the condition index for each project at 6 years of age. Using six-year performance data allowed a common comparison point for all 19 projects. Attempts were made to correlate individual indexes to performance, but the results were no better than comparing the overall condition indexes.

Table 3.5: Pavement Condition

Hwy#	Project Name	Quality Control (QC)			Binder Grade	Age (2001)	Overall Condition Index (2001)	Overall Condition Index @ Age 6
		P_b	Film Thkn	VIR				
1	Hayesville - Battle Creek	5.50	14.41	12.78	AC-30(Tbl II)	11	61.9	73.2
1	W. Marquam - N. Tigard	5.26	12.90	11.77	AC-30(Tbl II)	11	49.8	61.5
4	Forge Rd. - Lobert Rd.	5.86	15.26	12.42	AC-20R	11	80.3	83.1
1	Jumpoff Joe - N. Grants Pass	4.95	13.67	10.78	PBA-5	10	87.9	85.2
2	Corbett Intch. - Multnomah Falls	5.42	17.57	11.55	PBA-5	10	54.2	81.2
2	Rufus - Arlington(E. Unit)	5.30	12.62	9.58	PBA-5	10	76.6	89.0
4	Williamson River - Modoc Point	5.11	16.80	11.63	AC-20R	10	70.0	75.1
6	Baldock Slough - S. Baker Intch.	5.45	15.92	12.45	AC-20R	10	90.6	84.4
6	E. Pendleton - Emigrant Hill	6.46	25.34	17.32	PBA-6	9	80.8	81.8
2	Rufus - Arlington(W. Unit)	5.78	24.77	15.60	PBA-6	8	94.8	94.8
2	Umatilla - McNary	6.29	23.59	16.94	PBA-6	8	85.5	85.5
47	Wolf Cr. - W. Fk. Dairy Cr.	6.00	20.90	14.69	PBA-5	8	91.6	91.6
1	Azalea - Jumpoff Joe	5.56	18.90	14.79	PBA-6	7	92.7	92.7
1	Halsey Intch. - Lane Co. Ln.(SB)	6.00	17.67	15.46	PBA-6	7	87.0	87.0
1	Halsey Intch. - Lane Co. Ln.(NB)	5.80	17.43	14.31	PBA-6	7	94.6	94.6
144	Sunset Hwy - Pacific Hwy	5.20	19.29	13.47	PBA-6	7	73.4	73.4
4	Willowdale - Qualle Rd.	5.22	16.99	12.90	PBA-6	6	97.9	97.9
26	Mt. Hood - Long Prairie	5.97	23.08	14.73	PBA-6	6	80.1	80.1
41	Prineville Airport - Powell Butte	5.20	20.99	13.38	PBA-6	6	95.1	95.1

Plots of overall condition index at age 6 and film thickness and VIR respectively were generated in an effort to establish if a correlation existed between either mix property and performance at the same baseline age. The plots, including a best fit curve and corresponding R^2 value are presented in Figures 3.1 and 3.2.

The R² values are very low, indicating poor correlation of either property with the overall condition index as calculated by the ODOT Pavement Management System. Analysis of the correlation to performance data is inconclusive.

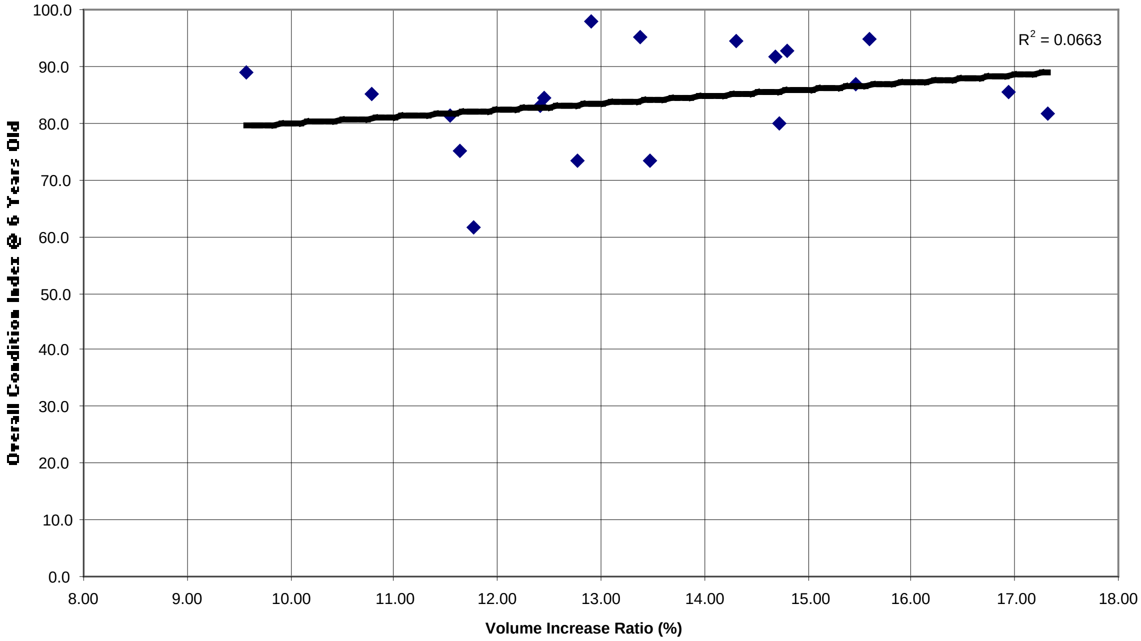

Figure 3.1: Overall Condition Index @ 6 Years Old vs. Volume Increase Ratio

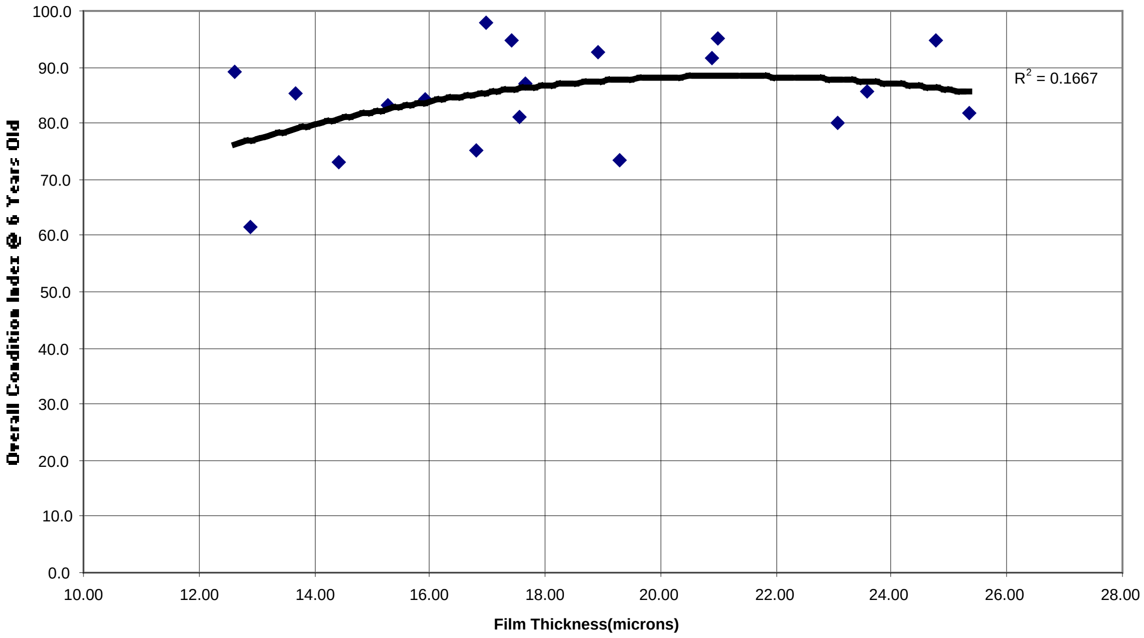

Figure 3.2: Overall Condition Index @ 6 Years Old vs. Film Thickness

Review of the data in Table 3.5 also suggests that there may be some relationship between binder grade and film thickness and VIR. A summary is presented in Table 3.6.

Table 3.6: Binder Grade, Film Thickness and VIR Relationship

Binder	VIR (%)		Film Thickness (μm)	
	Average	Standard Deviation	Average	Standard Deviation
PBA-6	14.9	1.5	20.8	3.2
PBA-5	11.7	2.2	16.2	3.8
AC-30(tbl II)	12.3	0.7	13.7	1.1
AC-20R	12.2	0.5	16.0	0.8

Table 3.6 shows that PBA-6 provides substantially better VIR and film thickness relative to the other binders. PBA-6 is typically polymer modified and is generally more viscous at higher temperatures than the other grades, thus it is more likely to result in thicker films and less likely to draindown during production than the non-modified binders. A change in open-graded HMAC mix design methodology occurred in 1992 that resulted in higher recommended binder contents relative to mixes designed prior to 1992. All of the projects with PBA-6 occurred on or after 1992, and all but one of the projects with other binders occurred prior to 1992. The changes in mix design methodology may have also contributed to the higher VIR noted for projects with PBA-6.

3.8 SELECTION OF TRIAL VIR CRITERIA

The available project data did not identify a specification criteria for volume increase. In a general sense, the poorest performing open-graded surfaced pavements (Overall Condition Index @ Year 6 ≤ 75.1) all occurred at VIR less than 13.5%. None of the projects with a VIR greater than 14% had an Overall Condition Index less than 80. This data suggests that a minimum VIR of 14% may be a reasonable starting point for future evaluations.

One way to develop a VIR criteria is to compare VIR values with current mix design criteria for projects using PBA-6 binder. The PBA-6 binder seems to provide a better VIR and film thickness relative to the non-modified binders as discussed above. The only current volumetric criteria for open-graded HMAC in Oregon is 40 to 50% Voids Filled with Asphalt (VFA), which is based on having a Voids in Mineral Aggregates measure typically in the 20 - 25% range. This range of VFA attempts to achieve a minimum asphalt content on the low end, but preclude localized “fat spots” at the high end.

Six of the ten projects incorporating PBA-6 generally met the current criteria for 40 to 50% VFA. Three of the remaining four PBA-6 projects exceeded the 50% VFA criteria and one didn’t meet the minimum 40% VFA criteria.

The six projects that met the VFA criteria had an average design P_b of 5.6% and an average VIR of 14.3%. This data along with the general trends from performance data discussed above suggest a minimum VIR criteria of 14.0% is appropriate. The three projects that exceeded the

VFA criteria all were in excess of 15.5% VIR, suggesting this value to be an appropriate maximum VIR criteria. The authors recognize the proposed minimum and maximum VIR criteria are based on very limited mixture and performance data, but feel they are appropriate initial values to consider for future work with the VIR concept.

4.0 TESTING OF FIELD MIXES

4.1 FIELD SAMPLES

Field samples of construction materials were obtained from two projects during the 2001 construction season. The purpose of the field testing was to evaluate the sensitivity of film thickness and VIR to changes in mix constituents and to evaluate the practicality of performing the required testing in a field environment.

The samples included coldfeed aggregate samples and HMAC mixture samples. These materials were tested at the ODOT Central Laboratory in Salem. The projects were as follows:

- C12322 – Shogren – Rowena, Phase 2 & W. Mayer State Park – Rowena
- C12511 – Nesika Beach – Rogue River

4.2 LABORATORY TESTING

An incinerator calibration factor was determined for each mixture using the calibration procedure in ODOT TM 323 (*2001*). A portion of each HMAC mixture was then incinerated per AASHTO T 308 (*2001*) and the residue was graded per AASHTO T 30 (*2001*). A separate portion of each mixture was tested per AASHTO T 209 (*2001*) to determine the maximum specific gravity of the mix.

The results were combined with the mix design values for asphalt specific gravity, G_b and combined aggregate bulk specific gravity, G_{sb} to determine the necessary volumetrics.

4.2.1 Shogren – Rowena, C12322

This project involved construction of a 19.0 mm open-graded mix with lime and a PBA-6 binder. The job mix formula (JMF) and project quality control (QC) statistics are included in Appendix D. The JMF and QC results produced the following:

Table 4.1: Shogren – Rowena, C12322 – JMF and QC Results

	JMF	QC
Asphalt Content, P_b	5.30	5.35
% Passing 75 µm Sieve	3.40	3.14
Film Thickness, µm	17.89	18.72
Volume Increase Ratio, %	13.08	13.23

It should be noted that the in-place results are based on the calculated G_{mm} value given the design G_{se} and the mean asphalt content percentage from project data.

Material samples from the project were tested at the ODOT Central Laboratory with the following results:

Table 4.2: Shogren – Rowena, C12322 – Individual Sample Results

	QC 1-2	QC 1-12	QC 1-23
Asphalt Content, P_b	5.34	4.93	5.57
% Passing 75 µm Sieve	3.6	3.0	3.9
Film Thickness, µm	14.84	14.96	15.69
Volume Increase Ratio, %	13.00	11.89	14.29

Details of the film thickness calculations are included in Appendix E and volume increase calculations are included in Appendix F.

4.2.2 Nesika Beach – Rogue River, C12511

This project involved construction of a 19.0 mm open-graded mix with a PG64-22 binder. The project JMF and QC results are included in Appendix D. The JMF and QC results produced the following:

Table 4.3: Nesika Beach – Rogue River, C12511 – JMF and QC Results

	JMF	QC
Asphalt Content, P_b	5.80	5.80
% Passing 75 µm Sieve	2.60	2.13
Film Thickness, µm	17.89	18.72
Volume Increase Ratio, %	13.67	13.67

It should be noted that the in-place results are based on the calculated G_{mm} value given the design G_{se} and the statspec mean asphalt content percentage.

Material samples from the project were tested at the ODOT Central Laboratory with the following results:

Table 4.4: Nesika Beach – Rogue River, C12511 – Individual Sample Results

	QC 1-8	QC 1-13	QC 1-14
Asphalt Content, P_b	6.58	5.60	5.53
% Passing 75 µm Sieve	2.2	1.8	1.7
Film Thickness, µm	20.04	21.63	22.16
Volume Increase Ratio, %	15.01	12.21	12.37

Details of the film thickness calculations are included in Appendix E and volume increase calculations are included in Appendix F.

4.3 ANALYSIS OF FIELD RESULTS

4.3.1 Evaluation of Film Thickness

The field results for both projects show an excessive sensitivity to the P75 µm in the film thickness calculation. In both projects relatively minor changes in P75 µm had a greater impact on the average film thickness than relatively large variations in asphalt content.

As an example, on the Nesika Beach project there was essentially a 1% drop in asphalt content between QC 1-8 and QC 1-13. This is double the normal production tolerance of ±0.5% and would be considered a significant change in asphalt content. Intuitively, it would have been expected that the film thickness for the mix would also have dropped precipitously. In fact the average film thickness went up from 20.04 µm to 21.63 µm. This increase was primarily due to what would be considered an almost insignificant change in P75 µm from 2.2% to 1.8%.

This excessive sensitivity to a non-critical constituent of the mix precludes the use of average film thickness as a practical tool for field control of open-graded mixes.

4.3.2 Evaluation of Volume Increase Ratio (VIR)

In general, volume increase ratios did a much better job of quantifying changes to the mix that could be intuitively tied to changes in the critical constituents, particularly asphalt content. The same change in asphalt content on the Nesika Beach project as noted above resulted in a drop in VIR from 15.01% to 12.21%. This change in VIR is consistent with what would be expected under these circumstances.

The VIR measurement was also able to discern other changes in the mixture beyond change in total asphalt content. Again referring to the Nesika Beach project, the total asphalt content dropped slightly from 5.60% to 5.53% between QC 1-13 and QC 1-14. At first glance, it might be expected that VIR should also have dropped, but in fact, VIR went up slightly from 12.21% to 12.37%. On closer examination of the QC data it is noted that the gradation became measurably coarser on the upper sieves on sublot QC 1-14. As the gradation becomes coarser it would be reasonable to expect the absorption to decrease. However, overall absorption dropped by 0.13% (meaning P_{be} increased and more free oil was available to coat the aggregate). The change in absorption offset any drop in total asphalt and resulted in the slight increase in VIR between QC 1-13 and QC 1-14.

VIR is also a function of G_{sb} and therefore, will be sensitive to changes in aggregate specific gravity. While no changes in aggregate specific gravity were observed on these two projects, it is anticipated that when such a change does occur the resulting VIR will change accordingly.

The ability of VIR to correctly track changes in total asphalt content as well as detect changes in absorption and/or aggregate specific gravity makes it a practical tool for controlling the quality of open-graded mixes.

The authors note that the mix design for neither project fell within the VIR criteria suggested in Section 3.8 and only one of the three field samples from each project met the criteria. The VIR concept was developed after the project mix designs and field testing was completed, so no attempt was made to adjust either mixture to meet the proposed VIR criteria.

4.4 FIELD TESTING CONSIDERATIONS

All of the test procedures to be used for VIR analysis are readily applicable to field testing. All contractor QC and ODOT quality assurance (QA) laboratories and technicians are currently equipped and certified to perform tests required for VIR analysis, including:

- AASHTO T 85 (*2001*) (Specific Gravity of Coarse Aggregates)
- ODOT TM 323 (*2001*) (Determination of Calibration Factors for the Ignition Method)
- AASHTO T 308 (*2001*) (Determining Binder Content of HMA by the Ignition Method)
- AASHTO T 30 (*2001*) (Sieve Analysis of Extracted Aggregates)
- AASHTO T 209 (*2001*) (Maximum Specific Gravity of HMA Mixtures)

No new or special equipment would be required, which makes VIR very attractive as a QC/QA tool for open-graded HMAC.

The biggest obstacle to using VIR as a quality control or assurance tool is obtaining representative and consistent samples. ODOT typically obtains HMAC samples at the discharge of the plant with a mechanical sampling device. The material is transferred via cardboard boxes or stainless steel bowls to a laboratory for splitting and testing. Open-graded mixtures can have a substantial amount of draindown of binder during the transfer of the mix from the plant to the splitting tray. The binder may soak into the cardboard box or coat the steel bowls and not end up in the tested sample. In some cases, the technician may scrape most of the binder from the bowls, but it ends up as globs on top of the sample, and is difficult to evenly distribute through the sample. These difficulties can lead to substantial variability in binder content and maximum specific gravity test results, and ultimately, VIR.

The bulk of the variability in binder content noted in Tables 4.2 and 4.4 can likely be attributed to sampling and splitting issues. Any future work with VIR will need to address procedures for minimizing variability from sampling and splitting of test samples.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

This research looked at the viability of using film thickness as a field measure of mixture quality for open-graded mixes in Oregon. The results of this research lead to the following conclusions:

1. Due to the low amount of material passing the 75 μm sieve in Oregon's open-graded mixtures and the high sensitivity of the film thickness calculation to material passing the 75 μm sieve, conventional film thickness calculations do not provide a practical tool for field management of open-graded mixtures.

2. An alternative procedure developed by the authors involving Volume Increase Ratio (VIR) measurements offers a practical measure of mixture properties for open-graded mixtures. This procedure is simple and uses readily available testing equipment in field laboratories.

3. There is no strong correlation between either VIR or film thickness and performance of open-graded HMAC based on overall condition index from the ODOT Pavement Management System.

4. PBA-6 provided significantly higher VIR and thicker films than the other binders used on the 18 projects evaluated in this study.

5.2 RECOMMENDATIONS

The findings of this research lead to the following recommendations:

1. The Volume Increase Ratio (VIR) measurements should be incorporated into a field mixture verification process for open-graded mixes on a trial basis.

2. A proposed range for the Volume Increase Ratio (VIR) of 14.0% to 15.5%, for both mix design and production, should be used as the initial criteria.

3. The above proposed criteria for both mix design and production should be reviewed periodically as additional long term pavement performance data becomes available for open-graded mixtures in Oregon.

4. ODOT should explore requiring a modified binder (i.e. PG equivalent of PBA-6) for all open-graded mixtures as a means to consistently meet the recommended minimum VIR.

5. Procedures for minimizing variability in test results due to sampling and splitting problems with open-graded HMAC should be investigated and established to improve confidence and repeatability in VIR determination.

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