Study on Mix Design Criteria for Controlling the Effect of Increased Tire Pressure on Asphalt Pavement

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As axle loads have increased, the use of higher tire pressures has become more popular in the trucking industry, and radial tires are predominantly used. However, existing mix design procedures may not produce mixtures capable of withstanding higher tire pressures. They also may not identify potentially highly deformable mixtures. To evaluate the mix design process used by Oregon State Highway Division, aggregate from four different sources was used. One percent lime slurry was added to two aggregates. Six different aggregate gradations, including the Fuller maximum density gradation, were tested. In addition to the routine asphalt mix tests, a simple creep test was run for 3 hr at 40°C, and a compression stress of 0.1 MPa (14.5 psi) was applied. According to the results of creep tests, it is not always true that a mix with a high Hveem stability value resists deformation better than one with low stability. This indicates that current mix design criteria are probably inadequate for producing mixtures capable of withstanding high tire pressures and for identifying potentially highly deformable mixtures. In general, creep stiffness decreases with increases in the percentage of aggregate passing the No. 200 sieve. The effect of the percentage passing the 1/4-in. or No. 10 sieves on creep stiffness is not clear. The results indicate that adding 1 percent lime slurry improves the resistance to deformation of asphalt mixes.

The economics of truck transportation has tended to cause the average gross weight of trucks to increase so that a majority of trucks are operating close to the legal gross loads or axle loads (*1*). In 1982 the federal government permitted 80,000-lb gross vehicle weights, 20,000-lb single axle weights, and 34,000-lb tandem axle weights on Interstate highways. Tandem axle weights of 34,000 lb allowed a potential 12,000-lb load on the steering axle. Many states, including Oregon (*2*), also issue permits for trucks to operate above normal legal load limits.

As axle loads have increased, the use of higher tire pressures has become more popular in the trucking industry. A recent survey in Texas (*3*) indicated that trucks typically operate with tire pressures of about 100 psi in that state. Another study in Oregon (*4*) showed that about 40 percent of radial tires are inflated to more than 110 psi and that the average inflation pressure is 102 psi and 82 psi for radial tires and bias tires, respectively.

Higher tire pressures decrease the contact area between the tire and the pavement, resulting in reduced tire friction or skid resistance and increased potential for pavement damage under the high stress. Higher tire pressures contribute to greater deformation in flexible pavements, manifested as severe wheel track rutting.

In Oregon there have been several occurrences of severe wheel track rutting associated with the high tire pressures that have prevailed in recent years. Rutting is a function of deformation in all layers of a flexible pavement structure, but, with high tire pressures, the deformation in the asphalt concrete mixture is a major contributor. Existing mix design procedures may not produce mixtures capable of resisting high tire pressures. Similarly, they may not identify potentially highly deformable mixtures.

A study of procedures for controlling the effect of increased tire pressure on asphalt concrete pavement damage (*4*) was performed by the Oregon Department of Transportation (ODOT) and Oregon State University (OSU). This paper is about part of this study: the results of mix design evaluation and the results of creep testing to predict rut depth in asphalt pavement. The objectives of this paper are

1. To present and analyze the effectiveness of existing asphalt concrete mix design methods for limiting excessive deformation caused by higher loads and tire pressures and
2. To present and analyze the results of creep testing to predict deformation in asphalt surface layers.

BACKGROUND

Mix Design

The Marshall and Hveem methods of mix design have been widely used with satisfactory results. For each of these methods, criteria have been developed by correlating results of laboratory tests on compacted paving mixes with performance of the paving mixes under service conditions.

However, the limitations of such empirically based methods of pavement mix design have become increasingly apparent in recent years as traffic loads, tire pressures, and numbers of trucks have increased. Increasing demands on asphalt pavements from both higher traffic volumes and higher truck tire pressures have caused highway engineers to examine the foundations of asphalt mix design guidelines and procedures in order to see how best to cope with these challenges.

Existing mix design procedures may not produce mixtures capable of withstanding higher tire pressures. They also may

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not identify potentially highly deformable mixtures. Such a situation was identified by Finn et al. (5) when designing mixtures for heavy-duty airfield pavements on which extremely high tire pressures occur. They used a simple creep test, similar to that developed by Shell researchers (6), to complement Marshall and Hveem mix design procedures and to quantify deformation characteristics of the mix.

Hicks and Bell (7) recently completed a study for the Oregon State Highway Division (OSHD) to evaluate their current specifications and mix design process, which is based on the Hveem procedure. They indicated that gradation of aggregate can be one of the main contributors to producing tender mixes. Many researchers (8) indicate that the potential for constructing tender mix pavements with possible deformation problems increases if gradation values for a 3/4-in. maximum size mix are greater than the following:

Sieve	Percentage Passing
No. 4	55
No. 10	37
No. 40	16
No. 200	3–7

Further, they indicate that gradation curves that cross back and forth over the maximum density curve, especially in the region of the No. 30 to No. 80 sieve, tend to produce tender mixes.

Creep Test

In a major effort to develop rational procedures for the design of asphalt mixes, an attempt has been made to develop a test method suitable for judging the stability properties of asphalt mixes. Van de Loo (9) defined stability of an asphalt mix as its resistance to rutting in an actual pavement (i.e., under varying conditions of climate, traffic volume, and traffic load).

Many researchers have used the creep test (static or repeated mode) as a relatively simple test to predict rutting (or permanent deformation) of an asphalt pavement. In 1973 theoretical deformation models of asphalt mixes were formulated by J. F. Hills (10). It was assumed that any deformations in the mix are the result of sliding displacements between adjacent mineral particles, separated by a thin film of asphalt. He interpreted the results in terms of a mix stiffness (S_{mix}) as a function of bitumen stiffness (S_{bit}). Hills stated that, in addition to the effect of the volume concentrations of the mineral aggregate, the gradation, shape, and surface texture of the aggregate play a role, and the state of compaction exerts a strong influence on behavior.

Grob (11) recommends performance of the unconfined, static creep test that was standardized during Colloquium 1977 in Zürich. The recommended sample size is the same as that of normal Marshall specimens (i.e., 4 in. in diameter and 2.5 in high), and a steady temperature of 40°C should be achieved before the test commences. The constant load of 0.1 MPa (14.5 psi) should be applied without any impact and have a duration of 1 hr. A loading time of 1 hr is arbitrary.

The deformation of an asphalt specimen is measured as a function of loading time at a fixed test temperature. The general equation of the creep curves is

$$\log(\varepsilon) = c + n\log(t) \quad (1)$$

where ε is creep strain at time t and c and n are constants. The constants c and n are related to test conditions such as uniaxial stress and temperature, as well as asphalt cement content and the factors indicated by Hills. The constant n represents the inclination of the straight line. Relatively small n indicates less viscous behavior and relatively large n predominantly viscous behavior (11). It has been found that the level of instantaneous response increases with the amount of filler and bitumen (12). Furthermore, the time dependence of the vertical displacement has been associated with the viscosity of the mortar, which is related to the filler-binder ratio.

DESIGN OF EXPERIMENTS—TESTS ON ASPHALT MIXTURES

Variables Considered

Aggregate from four different sources was used for the laboratory mixture study:

1. Morse Brothers Pit (gravel),
2. Cobb Rock Quarry,
3. Hilroy Pit (gravel), and
4. Blue Mountain Asphalt Pit (gravel).

For the mix with the aggregates from Cobb Rock Quarry and Blue Mountain Asphalt Pit, the aggregates were treated with a 1 percent lime slurry and mellowed for a minimum of 24 hr before they were used in the mix.

The variables considered in laboratory mixture preparation for the creep test were

1. Asphalt cement content:
   A: 4, 5, and 6 percent;
   B: 4.5, 5.5, and 6.5 percent; and
   C: 5, 6, and 7 percent.
2. Aggregate gradations A through F (Table 1):
   A: 65 percent passing 1/4 in., 32 percent passing No. 10, and 5 percent passing No. 200;
   B: 60 percent passing 1/4 in., 29 percent passing No. 10, and 5 percent passing No. 200;
   C: Fuller curve—60 percent passing 1/4 in., 36 percent passing No. 10, and 8 percent passing No. 200;
   D: Same as B except 35 percent passing No. 10;
   E: 60 percent passing 1/4 in., 34 percent passing No. 10, and 5 percent passing No. 200; and
   F: Same as E except 8 percent passing No. 200.

Table 2 gives the aggregate gradations considered for each aggregate source. The properties of asphalt cements used are given in Table 3.

Specimen Preparation and Test Program

Following the standard ODOT procedure (13) of using a kneading compactor, specimens 4 in. (100 mm) in diameter by 2.5 in. (63 mm) high were fabricated from four different aggregate sources.

TABLE 1 PERCENTAGES OF AGGREGATE GRADATIONS PASSING SIEVE SIZES

	Morse Brothers Pit Gradation			Cobb Rock Quarry Gradation				Hilroy Pit Gradation						Blue Mountain Asphalt Pit Gradation				
Sieve	A	B	C	A	B	C	D	A	B	C	D	E	F	A	B	C	D	E
1 in.																		
3/4 in.	–	–	–	–	–	–	–	100	100	100	100	100	100	–	–	–	–	–
1/2 in.	100	100	100	100	100	100	100	99	98	99	99	98	98	100	100	100	100	100
3/8 in.	98	97	82	99	99	86	82	86	85	82	85	85	85	87	87	86	87	87
1/4 in.	86	83	72	82	78	73	72	76	72	72	72	72	72	77	74	73	73	73
No. 10	65	60	60	66	60	60	60	65	60	60	60	60	60	65	60	60	60	60
No. 40	32	30	37	32	29	37	37	33	31	37	37	34	34	32	29	36	36	34
No.	13	11	18	13	11	19	19	14	13	19	19	14	14	14	13	16	16	15
200	4.7	4.3	6.8	6.7	6	9	6.9	4.5	4.2	5.9	4.3	5	6.9	5	4.5	7	5	5.2

TABLE 2 AGGREGATE GRADATIONS CONSIDERED FOR EACH AGGREGATE SOURCE

	Aggregate Gradation					
Aggregate Source	A	B	C	D	E	F
Morse Brothers Pit	X	X	X			
Cobb Rock Quarry (with 1% lime slurry)	X	X	X	X		
Hilroy Pit	X	X	X	X	X	X
Blue Mountain Asphalt Pit (with 1% lime slurry)	X	X	X	X	X	

TABLE 3 PHYSICAL PROPERTIES OF ASPHALT CEMENT

Property	I	II	III	IV
Grade	AR 4000	AR 4000	AR 4000	AR 4000
Original				
Penetration at 77°F	68	68	68	61
Absolute viscosity at 140°F (poises)	1339	1349	1349	2111
Kinematic viscosity at 275°F (cSt)	261	248	248	352
Flash point, open cup (°F)	600	605	605	580
After Rolling Thin Film Oven Test				
Penetration	41	40	40	32
Absolute viscosity at 140°F (poises)	3033	3139	3139	5860
Kinematic viscosity at 275°F (cSt)	367	365	365	562
Loss on heating (%)	0.45	0.52	0.52	0.65

NOTE: I = Morse Brothers Pit, II = Cobb Rock Quarry, III = Hilroy Pit, and IV = Blue Mountain Asphalt Pit.

Figure 1 is a flowchart of the test program followed in this study. The ODOT testing program included the conventional mix tests such as the Hveem stability test (AASHTO T-246), Rice maximum specific gravity test (AASHTO T-209), bulk specific gravity test (AASHTO T-166), and repeated load diametral test for resilient modulus (as compacted and after moisture conditioning). OSU performed the creep test with 54 laboratory-fabricated specimens as described in the following subsection.

Test Methods

After laboratory mixes were prepared, repeated load diametral tests and creep tests were performed. The procedures are outlined next.

Resilient Modulus

The resilient modulus test (*4*) was performed using the repeated load diametral test apparatus. The maximum load applied and the horizontal elastic tensile deformation were recorded to determine the resilient modulus using the following equation:

$$M_R = P(0.2692 + 0.9974\nu)/(\Delta H \times t) \quad (2)$$

where

M_R = resilient modulus (psi),
ΔH = horizontal elastic tensile deformation (in.),
P = dynamic load (lb),
t = specimen thickness (in.), and
ν = Poisson's ratio.

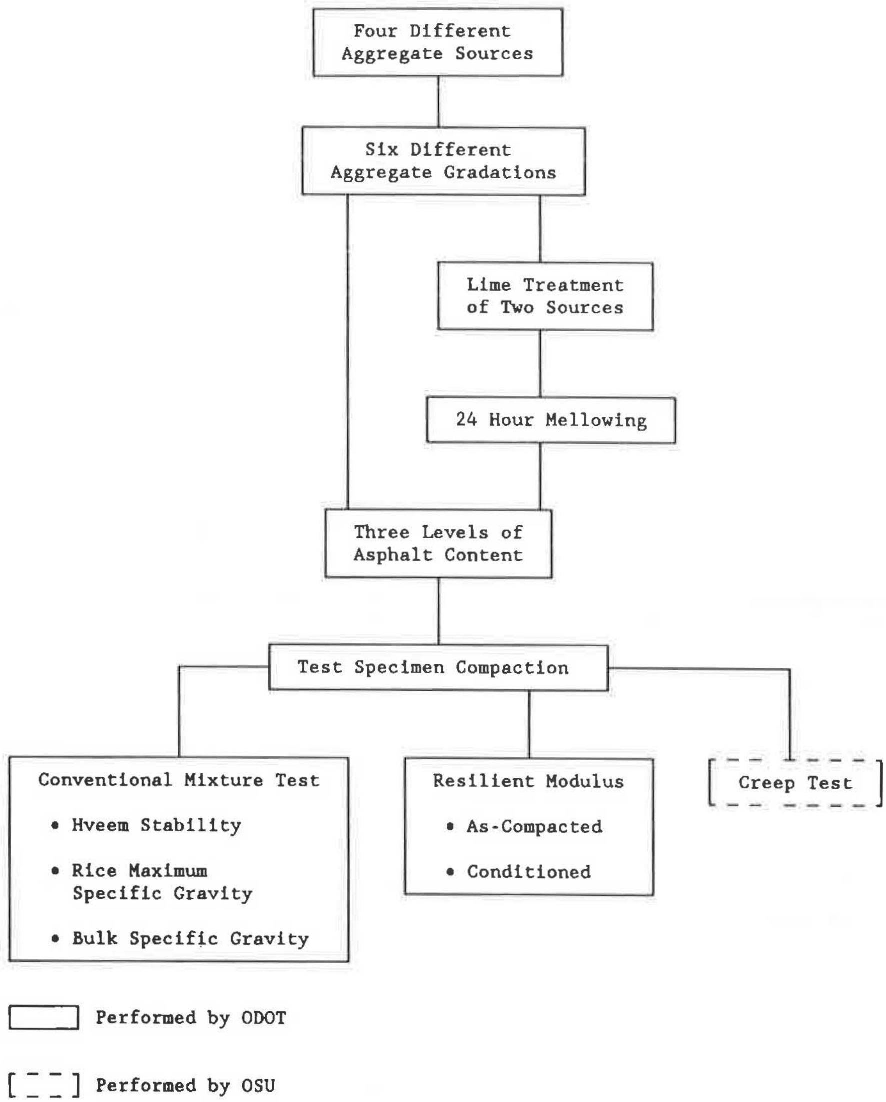

FIGURE 1 Flowchart for test program.

Poisson's ratio was assumed constant and equal to 0.35, which simplified Equation 2 to

$$M_R = 0.6183P/(\Delta H \times t) \quad (3)$$

During the test, the dynamic load duration was fixed at 0.1 sec and the load frequency at 60 cycles per minute. A static load of 10 lb (4.5 kg) was applied to hold the specimen in place. The test was carried out at 77°F (25°C).

Each specimen of each aggregate was tested both before and after conditioning. The specimen-conditioning procedure was based on the moisture damage test defined by Lottman (*14*).

Creep Test

OSU was responsible for developing a simple creep test and running the test. For the creep test, a loading device for soil consolidation and a data acquisition and control unit with a personal computer were used. The creep test was run for 3 hr at 40°C, and a compression stress of 0.1 MPa (14.5 psi) was applied. The creep test procedure is as follows:

1. Put a loading device for soil consolidation in an environmental cabinet and connect to the repeated load test control cabinet. Put the specimens and a dummy specimen with a thermistor in the environmental cabinet. Set the regulator at 0.1 MPa and control the air pressure through the repeated load test control cabinet.
2. Warm the inside of the environmental cabinet to 40°C and check the temperature of the dummy specimen using the data acquisition system and thermistor.
3. After the temperature of the dummy specimen core reaches 40°C, put a specimen on a load plate. Put a linear variable differential transformer on the bottom plate and attach a thermistor to the specimen. Check the level of the bottom plate before running the test.
4. Wait for 5 to 10 min after closing the environmental cabinet door to keep the temperature at 40°C.
5. Apply a pressure of 10 kPa as a preload for 2 min.
6. Apply a pressure of 0.1 MPa and run the computer program.

Kim et al. (*4*) describe the apparatus and the procedure for sample preparation in detail. Also described are the computer programs used to monitor the temperature and measure the deformation of a specimen.

RESULTS

Mix Design

A summary of the mix design for the aggregate from each source with different aggregate gradations is given in Table 4. Table 4 includes the resilient modulus (both as compacted and after conditioning) and the minimum asphalt content for the retained modulus ratio of 0.7. The retained modulus ratio is defined by Equation 4:

$$\text{Retained modulus ratio} = M_R \text{ after conditioning}/M_R \text{ before conditioning} \quad (4)$$

Creep Test

Table 5 gives the creep test results, including the intercept (*I*) and slope (*S*) after regression analysis and creep stiffness at 60 min. The coefficients of determination (R^2) also are given. The regression analysis was performed in the range from 1 to 90 min. Figure 2 shows a typical relationship between creep strain and time.

The intercept and the slope of each sample are obtained by the following equation:

$$\log(\text{strain,\%}) = \log(I) + S*\log(\text{time,sec}) \quad (5)$$

Creep strain and creep stiffness can be determined by the following equations:

$$\varepsilon_c = h/H \quad (6)$$

where

ε_c = creep strain,
h = deformation at time t, and
H = thickness of specimen.

and

$$S_{mix}(T,t) = \sigma/\varepsilon(T,t) \quad (7)$$

where

$S_{mix}(T,t)$ = creep stiffness at temperature T and time t,
σ = compressive stress, and
$\varepsilon(T,t)$ = creep strain at temperature T and time t.

The creep stiffness of each sample presented in Table 5 is the predicted value after regression analysis using the measured stiffness. Figure 3 shows mix stiffness (S_{mix}) as a function of bitumen stiffness (S_{bit}). Bitumen stiffness was obtained by using the Van der Poel bitumen stiffness nomograph with the asphalt properties (PI and softening point) and a range of loading time.

Rut Depth

To predict rut depth due to increased tire pressure, the relationships between S_{mix} and S_{bit} resulting from the creep test were used. Physical properties of the asphalt cement and vertical compressive stress (shown in Figures 4 and 5) for a typical asphalt pavement structure in Oregon (SN = 3.0, Figure 6) were used. The Shell method (*6*) was employed to predict the rut depth in the asphalt layer of the given pavement structure. An 18-kip single axle with dual tires and tire pressures of 80 psi (i.e., assumed tire pressure in previous pavement design) and 125 psi (possible tire pressure for future pavement design) were used.

According to Van de Loo (*15*) the permanent deformation in the asphalt layer can be calculated by the following equation:

$$\delta = C_M H_o \sigma_{avg} / S_{mix} \quad (8)$$

where

δ = reduction in layer thickness;
C_M = correction factor for the so-called dynamic effect, which takes account of differences between static (creep) and dynamic (rutting) behavior (this factor depends on the type of mix and must be determined empirically);
H_o = design thickness of the asphalt layer;
σ_{avg} = average stress in the pavement under the moving wheel; and
S_{mix} = value of stiffness of the mix at $S_{bit} = S_{bit.visc}$.

To determine the vertical compressive stress, ELSYM5 (*16*) was used. Values of the input parameters (modulus, thickness, and Poisson's ratio) of each layer were selected to represent Oregon pavements designed for medium traffic levels. Table 6 gives the average vertical compressive stresses calculated from the output of ELSYM5, and Table 7 gives the predicted rut depth for the asphalt surface layer (thickness is 2 in.). The penetration index is −1.4 (for an AR-4000 grade asphalt cement), and the loading time is 0.0125 sec (corresponding to a speed of 50 mph). The number of load repetitions was 1 million and the correction factor (C_M) was 1.2. According to Equation 8, the rut depth for a tire pressure of 80 psi is 0.022 in., and that for 125 psi is 0.034 in. after 1 million load repetitions.

In this paper only one set of calculations for the C gradation mixes of Morse Brothers Pit is presented for the purpose of demonstration. Because the resilient modulus of the asphalt layer is varied with different mixtures, the modulus value for ELSYM5 should correspond to the resilient modulus test results.

More detailed data on the rut depth calculation are presented elsewhere (*4*).

DISCUSSION

Mix Design

Table 4 gives a summary of the mix design results of laboratory-compacted mixes. Their stability is considered to be most significant in this study. ODOT requires a minimum Hveem stability of 30.

TABLE 4 SUMMARY OF MIX DESIGN DATA

Sample ID[a]	Max Sp. Gr.	Bulk Sp. Gr.	Air Voids (%)	AC Content (%)	VMA[b] (%)	Stability[c]	M_R As Comp.[d] (ksi)	M_R Cond.[e] (ksi)	M_R Ratio[f]	Min. AC to 0.7 MRRT[g] (%)	Optimum A/C (%)
Morse Brothers Pit, Gravel, Chevron AR-4000											
A32	2.484	2.26	9.0	5.0		33	258	146	0.56		
A33	2.455	2.30	6.3	6.0		35	227	197	0.87	5.5	6.6
A34	2.408	2.32	3.6	7.0		31	224	189	0.84		
B29	2.463	2.28	7.4	5.0		35	186	102	0.55		
B30	2.446	2.30	6.0	6.0		32	187	139	0.75	5.8	6.6
B31	2.423	2.33	3.8	7.0		33	194	133	0.69		
C26	2.489	2.34	6.0	4.5		36	492	161	0.33		
C27	2.466	2.37	3.9	5.5		37	447	349	0.78	5.3	5.1
C28	2.440	2.40	1.6	6.5		19	303	237	0.78		
Cobb Rock Quarry, 1% Lime, Chevron AR-4000											
A11	2.514	2.25	10.5	4.5	15.1	41	361	172	0.48		
A12	2.476	2.29	7.5	5.5	14.5	37	320	346	1.08	4.9	6.3
A13	2.433	2.33	4.2	6.5	13.9	37	320	312	0.97		
B09	2.506	2.26	9.8	4.5	14.7	33	312	127	0.41		
B10	2.471	2.30	6.9	5.5	14.1	30	240	120	0.50	6.5	6.2
B11	2.433	2.34	4.2	6.5	13.5	37	266	187	0.70		
C09	2.512	2.33	7.2	4.5	12.0	39	465	301	0.65		
C10	2.471	2.37	4.1	5.5	11.5	31	392	501	1.28	4.6	5.3
C11	2.428	2.41	0.1	6.5	10.9	5	282	374	1.33		
D29	2.541	2.31	9.1	4.0	12.3	45	205	76	0.37		
D30	2.497	2.35	5.9	5.0	11.8	38	404	242	0.60	5.2	5.3
D31	2.459	2.39	2.8	6.0	11.2	33	232	302	1.30		
Hilroy Pit, Gravel, Chevron AR-4000											
A30	2.501	2.27	9.2	4.5	15.3	38	362	94	0.26		
A31	2.465	2.31	6.3	5.5	14.7	38	252	115	0.46	6.4	6.4
A32	2.429	2.34	3.7	6.5	14.5	36	239	180	0.75		
B21	2.493	2.27	8.9	4.5	15.3	36	364	93	0.26		
B22	2.459	2.29	6.9	5.5	15.5	35	280	150	0.54		6.2
B23	2.422	2.33	3.8	6.5	14.9	34	265	176	0.66		
C24	2.523	2.33	7.7	4.0	12.6	39	541	66	0.12		
C25	2.477	2.37	4.3	5.0	12.1	44	438	159	0.36	5.8	5.2
C26	2.437	2.41	1.1	6.0	11.5	35	384	302	0.79		
D27	2.474	2.33	5.8	5.0	13.5	40	391	142	0.36		
D28	2.431	2.37	2.5	6.0	13.0	41	403	260	0.65	6.3	5.6
D29	2.414	2.40	0.6	7.0	12.8	18	329	284	0.87		
E29	2.519	2.29	9.1	4.0	14.1	40	752	175	0.23		
E30	2.482	2.34	5.7	5.0	13.2	37	401	199	0.50	7.0	5.9
E31	2.443	2.35	3.8	6.0	13.7	40	396	239	0.60		
F09	2.519	2.30	8.7	4.0	13.8	37	420	89	0.21		
F10	2.482	2.38	4.1	5.0	11.7	39	429	293	0.68	5.3	5.3
F11	2.452	2.40	2.1	6.0	11.9	36	374	272	0.74		
Blue Mountain Asphalt Pit, Gravel, 1% Lime, Chevron AC-20											
A38	2.583	2.33	9.8	4.5	17.9	29	437	214	0.49		
A39	2.545	2.37	6.9	5.5	17.4	30	404	291	0.72	5.4	5.6
A40	2.504	2.41	3.8	6.5	16.9	30	371	289	0.78		
B32	2.590	2.36	8.9	4.5	16.8	37	465	294	0.63		
B33	2.548	2.40	5.8	5.5	16.3	37	425	346	0.81	4.9	5.9
B34	2.510	2.44	2.8	6.5	15.8	38	374	346	0.92		
C29	2.607	2.37	9.1	4.0	16.0	39	679	339	0.5		
C30	2.565	2.41	6.0	5.0	15.5	38	630	353	0.56	5.4	5.3
C31	2.517	2.45	2.7	6.0	15.0	27	601	536	0.89		
D35	2.617	2.36	9.8	4.0	16.4	40	650	317	0.49		
D36	2.568	2.40	6.5	5.0	15.9	38	592	292	0.49	6.0	5.5
D37	2.530	2.44	3.6	6.0	15.4	33	523	372	0.71		
E37	2.607	2.32	11.0	4.0	17.8	37	836	496	0.59		
E36	2.574	2.39	7.1	5.0	16.2	35	728	737	1.01	4.3	5.7
E35	2.528	2.44	3.5	6.0	15.4	33	753	499	0.66		

[a] A–F = aggregate gradation type.
[b] VMA = voids in mineral aggregate.
[c] Stability = stability at first compaction.
[d] M_R As Comp. = resilient modulus at 25°C, as compacted.
[e] M_R Cond. = resilient modulus at 25°C, after conditioning.
[f] M_R Ratio = Resilient modulus after conditioning/Resilient modulus before conditioning.
[g] Min A/C to 0.7 MRRT = minimum asphalt content for the retained modulus ratio (M_R ratio) of 0.7.

TABLE 5 CREEP TEST RESULTS

Sample ID[a]	S_{mix}[b] (ksi)	I[c]	S[d]	R^2[e]
Morse Brothers Pit, Gravel, Chevron AR-4000				
A32	3.47	0.098	0.177	0.961
A33	3.93	0.132	0.126	0.957
A34	3.14	0.116	0.169	0.996
B29	4.14	0.126	0.124	0.929
B30	6.37	0.084	0.122	0.930
B31	2.83	0.146	0.153	0.983
C26	3.57	0.142	0.129	0.951
C27	4.85	0.117	0.114	0.977
C28	5.24	0.069	0.170	0.973
Cobb Rock Quarry, 1% Lime, Chevron AR-4000				
A11	4.76	0.135	0.099	0.940
A12	3.68	0.171	0.102	0.929
A13	5.40	0.105	0.115	0.997
B09	5.15	0.096	0.134	0.940
B10	3.33	0.206	0.091	0.931
B11	7.33	0.069	0.128	0.948
C09	3.95	0.075	0.194	0.998
C10	2.80	0.114	0.185	0.985
C11	1.47	0.307	0.143	0.962
D29	5.03	0.107	0.121	0.942
D30	3.81	0.093	0.172	0.964
D31	3.73	0.113	0.151	0.985
Hilroy Pit, Gravel, Chevron AR-4000				
A30	5.06	0.127	0.099	0.898
A31	3.50	0.128	0.143	0.929
A32	2.05	0.073	0.227	0.983
B21	6.07	0.058	0.173	0.889
B22	4.85	0.064	0.188	0.944
B23	3.75	0.051	0.247	0.938
C24	4.05	0.101	0.155	0.960
C25	4.62	0.056	0.210	0.979
C26	3.59	0.091	0.182	0.984
D27	5.72	0.058	0.180	0.990
D28	8.06	0.046	0.167	0.945
D29	2.70	0.135	0.169	0.973
E29	5.90	0.027	0.271	0.977
E30	7.56	0.018	0.292	0.964
E31	7.77	0.018	0.283	0.976
F09	4.87	0.025	0.303	0.971
F10	4.70	0.020	0.336	0.980
F11	4.58	0.130	0.109	0.803
Blue Mountain Asphalt Pit, Gravel, 1% Lime, Chevron AC-20				
A38	5.34	0.137	0.084	0.939
A39	4.91	0.182	0.059	0.922
A40	2.31	0.148	0.176	0.991
B32	2.24	0.270	0.107	0.942
B33	2.99	0.188	0.116	0.945
B34	2.57	0.175	0.143	0.984
C29	2.61	0.182	0.137	0.965
C30	2.42	0.243	0.110	0.984
C31	1.48	0.358	0.123	0.970
D35	3.90	0.094	0.169	0.956
D36	2.17	0.206	0.143	0.968
D37	2.88	0.190	0.119	0.967
E38	5.01	0.031	0.273	0.943
E39	5.86	0.027	0.269	0.941
E40	4.25	0.012	0.409	0.952

[a]A–F = aggregate gradation type.
[b]S_{mix} = predicted creep stiffness at 60 min after regression.
[c]I = intercept; strain, percentage at 1 sec.
[d]S = slope; strain, percentage = I*(time,sec)**S.
[e]R^2 = coefficient of determination.

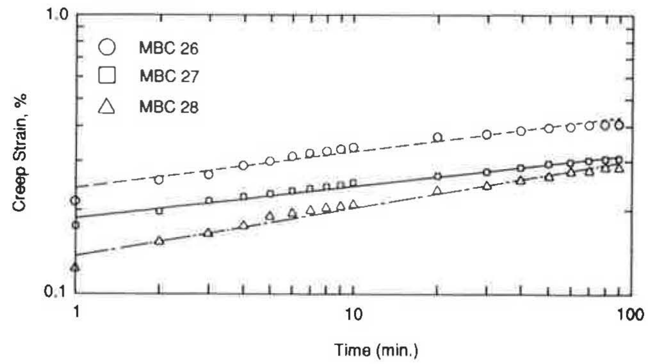

FIGURE 2 Creep strain versus time.

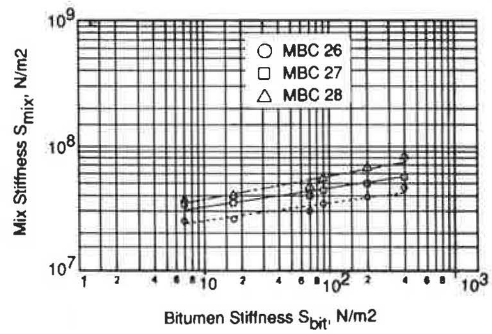

FIGURE 3 S_{mix} versus S_{bit}.

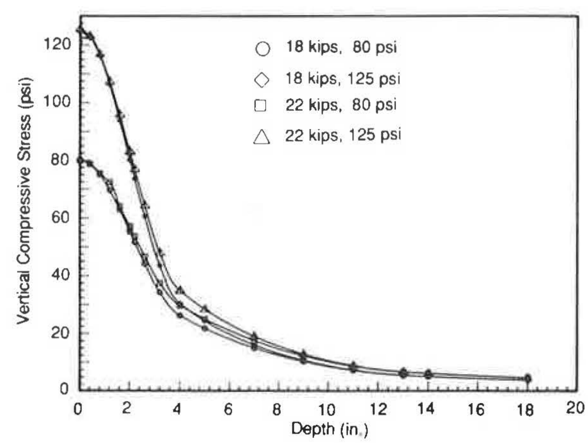

FIGURE 4 Vertical compressive stress: single axle dual tires.

As indicated by the data in Table 8, the correlation between log (Hveem stability) and log (creep stiffness) is not strong except for the Cobb Rock mixes. According to the results of creep tests, it is not always true that a mix with a high stability value resists deformation better than one with low stability. This indicates that the current mix design criteria are probably inadequate for producing mixtures capable of withstanding high tire pressures and for identifying potentially highly deformable mixtures.

It is noted that Gradation C mix (the Fuller maximum density gradation) requires the smallest optimum asphalt content for aggregate from each source according to the existing mix design method. Also, Gradation C has the smallest VMA.

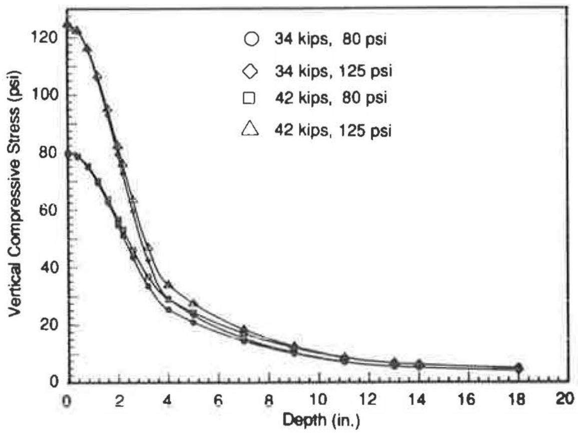

FIGURE 5 Vertical compressive stress: tandem axle dual tires.

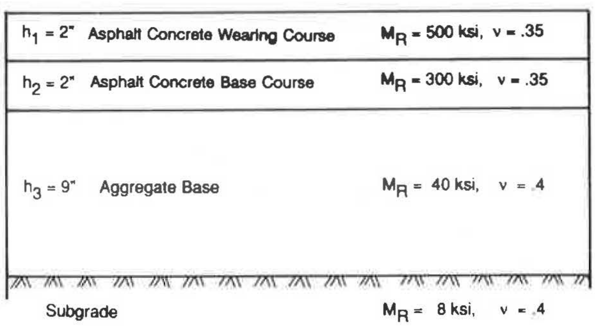

FIGURE 6 Typical asphalt pavement in Oregon (SN = 3.0).

TABLE 6 AVERAGE VERTICAL COMPRESSIVE STRESS

Axle Configuration	Tire Pressure (psi) 80	125
Single axle, dual tires		
18 kips	70.7	108.2
22 kips	71.8	109.4
Tandem axle, dual tires		
34 kips	70.4	107.6
42 kips	71.1	108.8

NOTE: Values are psi.

TABLE 7 PREDICTED RUT DEPTH UNDER GIVEN CONDITIONS

Tire Pressure (psi)	Rut Depth (in.)
80	0.022
125	0.034

NOTE: Conditions are as follows: AR 4000 (PI = −1.4), asphalt pavement (SN = 3.0) shown in Figure 6, H_o = 2.0 in., number of repetitions = 10^6, and MAAT = 20°C.

TABLE 8 CORRELATION ANALYSIS

Variables	Morse Brothers Pit	Cobb Rock Quarry	Hilroy Pit	Blue Mountain Asphalt Pit
Correlations with log (Creep Stiffness, ksi)				
log (stability)	−0.3141	0.8176	0.4878	−0.0482
log (M_R; as comp., ksi)	0.0636	−0.0859	0.5004	−0.2771
log (M_R; cond., ksi)	0.2664	−0.4886	−0.1981	−0.7012
log (M_R ratio)	0.2428	−0.5353	−0.3665	−0.3592
log (AC, %)	−0.0906	−0.2440	−0.4839	−0.3310
log (max sp. gr.)	0.1638	0.2542	0.4825	0.3015
log (air voids, %)	−0.1736	0.7529	0.3890	0.5625
log (VMA)	N/A	0.5805	0.0615	0.7465
log (pass 1/4 in., %)	−0.4197	0.2196	−0.4026	0.5609
log (pass No. 10, %)	0.1970	−0.5034	0.0897	−0.1731
log (pass No. 200, %)	−0.3141	−0.6766	−0.1416	−0.3799
log (intercept)	−0.6955	−0.7780	−0.3532	−0.7038
log (slope)	−0.4395	−0.2410	−0.3908	−0.5329
Correlations with log (Slope)				
log (stability)	−0.5737	−0.1073	−0.0163	0.4056
log (creep stiff., ksi)	−0.4395	−0.2410	−0.3908	−0.5329
log (M_R; as comp., ksi)	−0.1814	0.5060	−0.3602	0.2600
log (M_R; cond., ksi)	−0.0878	0.4838	0.3963	0.2604
log (M_R ratio)	0.0993	0.3077	0.4671	−0.0078
log (AC, %)	0.3817	−0.0476	0.5256	0.0436
log (max sp. gr.)	−0.3476	0.0459	−0.4687	0.0079
log (air voids, %)	−0.3252	−0.2107	−0.2363	−0.2589
log (VMA)	N/A	−0.7506	−0.0819	−0.4468
log (pass 1/4 in., %)	0.4420	−0.5647	−0.2625	−0.4437
log (pass No. 10, %)	−0.0317	0.6751	−0.0743	0.2183
log (pass No. 200, %)	−0.5737	0.6777	−0.0215	0.0439
log (intercept)	−0.3388	−0.4176	−0.5332	−0.2156
Correlations with log (Intercept)				
log (stability)	0.7761	−0.7241	−0.3974	−0.2351
log (creep stiff., ksi)	−0.6955	−0.7780	−0.3532	−0.7038
log (M_R; as comp., ksi)	0.0714	−0.2807	−0.1320	0.1409
log (M_R; cond., ksi)	−0.2211	0.1370	−0.4243	0.5916
log (M_R ratio)	−0.3393	0.3109	−0.2871	0.3855
log (AC, %)	−0.2007	0.2766	−0.1660	0.2983
log (max sp. gr.)	0.0961	−0.2882	0.0705	−0.2930
log (air voids, %)	0.4335	−0.6008	0.1323	−0.4049
log (VMA)	N/A	−0.0696	0.2844	−0.5163
log (pass 1/4 in., %)	0.0795	0.1491	0.5427	−0.3455
log (pass No. 10, %)	−0.1846	0.0341	−0.1375	0.0135
log (pass No. 200, %)	0.7761	0.1812	−0.1531	0.4049
log (slope)	−0.3388	−0.4176	−0.5332	−0.2156
Correlations with log (Stability)				
log (creep stiff., ksi)	−0.3141	0.8176	0.4878	−0.0482
log (M_R; as comp., ksi)	0.0471	0.1153	0.3026	0.0361
log (M_R; cond., ksi)	−0.2101	−0.3435	−0.2735	0.0017
log (M_R ratio)	−0.2987	−0.4685	−0.3810	−0.3332
log (AC, %)	−0.4433	−0.4636	−0.4805	−0.4824
log (max sp. gr.)	0.3579	0.5197	0.4139	0.5657
log (air voids, %)	0.7820	0.9546	0.6501	0.3984
log (VMA)	N/A	0.4529	0.0179	−0.0909
log (pass 1/4 in., %)	0.1302	0.2283	0.0664	−0.6330
log (pass No. 10, %)	−0.2928	−0.2220	0.0104	−0.0017
log (pass No. 200, %)	1.0000	−0.4696	0.2500	−0.1198
log (slope)	−0.5737	−0.1073	−0.0163	0.4056
log (intercept)	0.7761	−0.7241	−0.3974	−0.2351

NOTE: N/A = not available.

In general, the optimum asphalt content from the existing mix design method is higher than that required to achieve the retained modulus ratio (MMRT) of 0.7 except for the mixes with Hilroy Pit aggregate.

It appears to be necessary to study further which mix design criteria, including creep stiffness, should be considered and how to determine the optimum asphalt content of a mix for resistance to rutting and good durability.

Creep Behavior of Mixes

The creep behavior of an asphalt mixture can be determined from the slope obtained after regression analysis and creep strain or creep stiffness. To analyze the effect of some mix variables, including aggregate gradation, on creep behavior, a correlation analysis among the variables (Table 8) was made. In general, creep stiffness decreases with increasing percentage of aggregate passing the No. 200 sieve, as indicated in Table 8.

Because of the limited data, the effect of the percentage of aggregate passing the 1/4-in. or No. 10 sieve on creep stiffness is not clear. With regard to the percentage passing the 1/4-in. or No. 10 sieve, however, the results concerning the creep stiffness of the aggregates from the Morse Brothers Pit and the Hilroy Pit show a similar trend (i.e., negative correlation with the percentage passing the 1/4-in. sieve and positive correlation with the percentage passing the No. 10 sieve). The results on the Cobb Rock Quarry and the Blue Mountain Asphalt Pit aggregates, which were mixed with 1 percent slurry lime, indicate another similar trend (i.e., positive correlation with the percentage passing the 1/4-in. sieve and negative correlation with the percentage passing the No. 10 sieve).

For aggregates from four sources, the creep stiffness has negative correlation with the intercept (which shows the deformation characteristics at the initial stage) or slope (which shows resistance to deformation).

The slope decreases with an increase in the percentage of aggregate passing the 1/4-in. sieve, except for aggregate from the Morse Brothers Pit.

Mixes made with the Morse Brothers Pit aggregate show a trend similar to that of those made with the Hilroy Pit aggregate (i.e., the slope has negative correlations with percentages passing both the No. 10 and the No. 200 sieves), and mixes with the Cobb Rock aggregate have a trend similar to that of the Blue Mountain Asphalt Pit aggregate (i.e., the slope has positive correlations with percentages passing both the No. 10 and the No. 200 sieves).

For the Cobb Rock aggregate and the Blue Mountain Asphalt Pit aggregate mixed with 1 percent lime slurry, the slope increases with increases in the percentage of aggregate passing the No. 10 and the No. 200 sieves.

From the results of the mix design, it can be noted that adding 1 percent lime slurry improves not only the durability of the asphalt mix, as seen by the retained modulus ratio in Table 4, but also its resistance to deformation. This may be due in part to the increased strength imparted to the mix by the addition of the lime. However, the effect of lime slurry on the permanent deformation of asphalt mixes still needs to be investigated.

It should be noted that the creep stiffness of Gradation C mix (Fuller maximum density gradation) is not the highest in the range of asphalt content tested in this study as shown in Figure 7, even though the mix with Gradation C has the smallest VMA (Table 4).

For Hveem stability, the mix with the Cobb Rock aggregate has high correlation between log (stability) and log (creep stiffness).

As can be seen in Figure 7, the relationship between asphalt content and creep stiffness (at 60 min) is not clear. The stiffness of a mix made with aggregate from different sources or of different gradations, or both, is unique.

Rut Depth

The Shell method was employed to predict rut depth in an asphalt surface layer. For the rut depth calculation, the creep test results of C gradation mixes of Morse Brother Pit were used.

The average vertical compressive stress in an asphalt surface layer shown in Figure 6 is about 90 percent of the inflation tire pressure given in Table 6. As the data in Table 7 indicate, the rut depth in the asphalt surface layer increases by 52 percent as the tire inflation pressure increases by 56 percent. Therefore it can be said that the increase in rut depth of an asphalt layer is approximately proportional to the increase in tire inflation pressure.

As indicated by Van de Loo (*17*), it is essential that the creep curve that is used as input in the calculation procedure be representative of the mix that will be present in the pavement. Because the creep behavior (i.e., slope of the curve) of laboratory-prepared specimens may be quite different from that obtained on cores from pavements, because of differences in compaction effort and heating process, core samples should be obtained shortly after construction and used for the creep test. Because of this, the prediction of rut depth with laboratory specimens is meaningless. However, laboratory-prepared specimens can be used to determine the ranking of different mixes.

In this paper emphasis has been mainly on the stability of mixes. For the overall performance of asphalt pavement, however, durability and fatigue characteristics of asphalt mixes as well as their stability should be considered in the mix design process.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The mix design process used by Oregon State Highway Division was investigated to evaluate its ability to minimize damage from higher tire pressure. For this study aggregate from four different sources was used. Six different aggregate gradations, including the Fuller maximum density gradation, were tested.

A simple method of creep testing to predict deformation of an asphalt mixture, which used a loading device for soil consolidation and a data acquisition system with a microcomputer, was used. The major findings and conclusions of this study follow:

1. Gradation C (the Fuller maximum density gradation) requires the least amount of optimum asphalt for aggregate from each source.

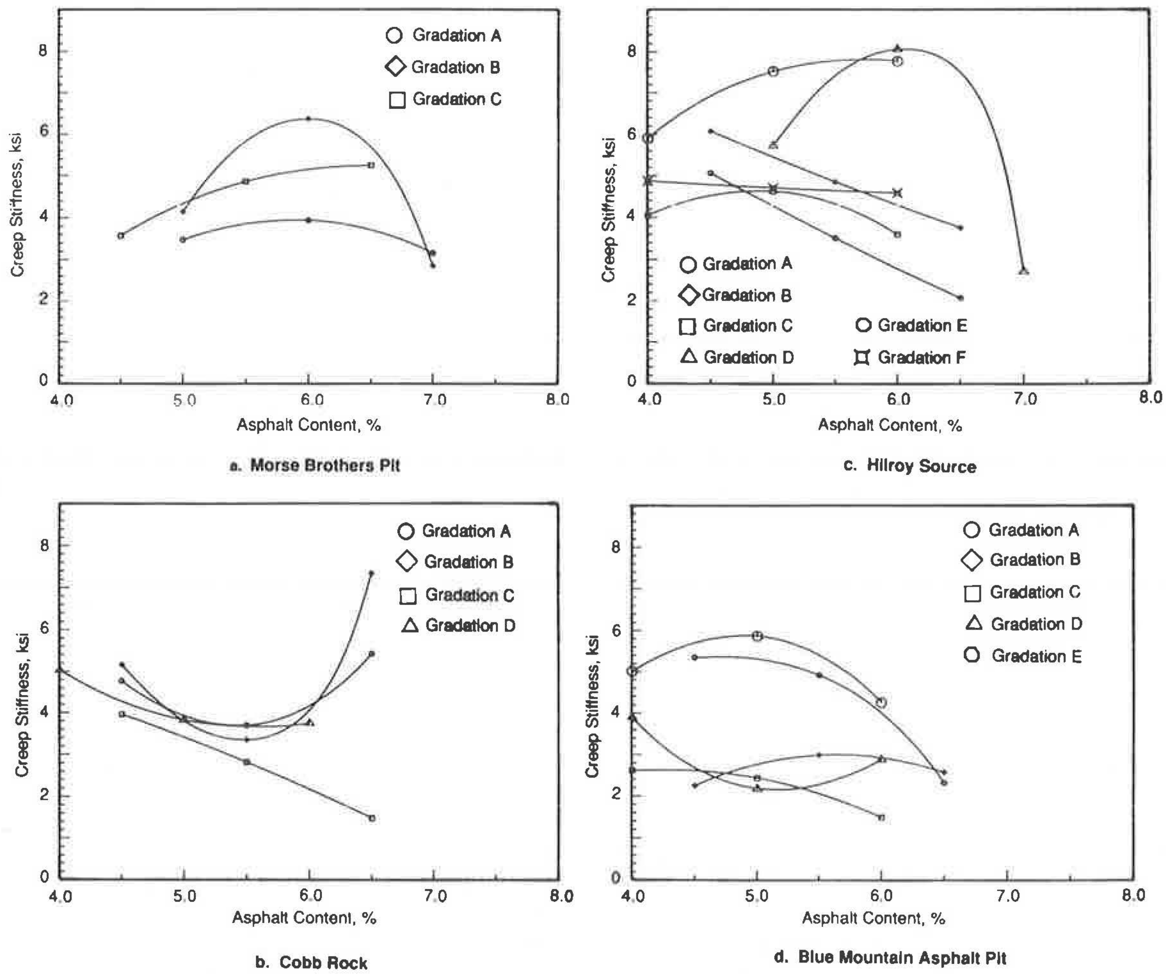

FIGURE 7 Effect of asphalt contents on creep stiffness.

2. Hveem stability has little relationship with creep stiffness. The results of creep tests show that it is not always true that a mix with a high Hveem stability value resists creep deformation better than one with low stability. Therefore, for projects on which deformation is a major concern, the use of creep tests in the mix design process should be of benefit.

3. Creep stiffness decreases with an increasing percentage of aggregate passing the No. 200 sieve. However, the effect of the percentage passing the 1/4-in. or the No. 10 sieve on creep stiffness is not clear. Control of the passing No. 200 material clearly contributes to deformation resistance and should be given more emphasis in mix design and construction.

4. Using 1 percent lime slurry results in some improvement in creep stiffness.

Recommendations

The following recommendations are made for controlling the effect of increased tire pressure on asphalt concrete pavement:

1. Include the creep behavior of a mix in mix design criteria, such as creep stiffness, to predict the rut depth due to increased tire pressure or to rank candidate mixes, or both. As the Shell manual indicates, it is essential that the creep curve that is used as an input in the calculation procedure be representative of the behavior of the mix in the pavement. A study to correlate laboratory mixture stability (i.e., Hveem stability, Marshall stability, and creep stiffness) with field deformation is recommended.

2. More investigation is needed into the effect of lime slurry on the permanent deformation of asphalt mix. The results of this study indicated that there was some improvement in creep stiffness in mixtures that contained lime slurry.

3. The use of other additives to increase creep stiffness of mixtures should be considered.

4. Further study of the process of designing mixes to withstand higher tire pressure is necessary in laboratory and field.

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Results from a Highway Planning and Research study, conducted by the Oregon State Highway Division and Oregon State University in cooperation with the Federal Highway Administration, are presented in this paper. The contribution of the staff of the OSHD mix design unit in obtaining materials and preparing mix designs was invaluable.

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