Development of Asphalt Materials to Mitigate Studded Tire Wear of Pavements

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16. Abstract This study deals with the PacTrans theme of "Developing Data Driven Solutions and Decision-Making for Safe Transport." Currently, all four northwestern states, including Alaska, Idaho, Oregon, and Washington, allow the use of studded tire. Studded tire can dig into asphalt pavement and pick out the small aggregate and eventually result into pavement rutting (*1*). Rutting was reported as one of the most important reasons of vehicle hydroplaning and loss of skid resistance in wet weather and can be closely related with traffic accidents during night and accidents under rain weather conditions (*2, 3*). Each year, millions of dollars are spent to repair/rehabilitate the wear from the studded tire. Developing pavement surface materials that resist studded tire wear will greatly improve the conditions of pavements, and reduce the traffic accidents and repair/rehabilitation costs associated with the studded tire wear. Therefore, the objectives of this proposed study is to determine potential material and mix design variables towards development of a wear-resistant asphalt mix.			
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Chapter 1. Introduction

The use of studded tires is allowed in the cold region states of the United States. These include Alaska, Idaho, Oregon, Washington, Montana, South Dakota, Nebraska, and Colorado. They are used during the winter season to reduce snow- and ice-related accidents. During driving, the studs in these tires progressively punch into the asphalt pavement and displace small aggregates. This raveling process eventually results in pavement rutting, as shown in Figure 1.1 (a). Asphalt pavement rutting can result from deformation of asphalt pavement materials and/or the layers below them under heavy traffic loads or because of raveling from the studded tires that are often mounted on passenger vehicles. Rutting associated with the plastic deformation of asphalt pavement materials has been studied extensively. However, few studies have focused on the reduction or prevention of asphalt pavement rutting related to studded tire wear. Rutting from studded tire wear could be significant and often becomes an engineering concern. It has been reported that rutting from studded tire wear may reach 1 inch within six years, which exceeds the 0.75-inch rutting depth criterion for rehabilitation/repair specified by most highway agencies [1]. In addition, rutting has been reported as one of the most important causes of loss of skid resistance in wet weather and of vehicle hydroplaning (Figure 1.1 (b)). It is closely associated with traffic accidents at night and under rainy weather conditions [2, 3].

(a) (b)

Figure 1.1 (a) Studded tire wear (after WSDOT) and (b) related hydroplaning**.**

Damage due to studded tire wear on asphalt pavement is irreversible, and its repair is costly. On the basis of estimates by the Washington Department of Transportation (WSDOT), the annual cost of asphalt pavement damage due to studded tire wear is between $7.8 million and $11.3 million [4]. The annual cost of studded tire wear damage along the state highways of Oregon is reported to be around $7 million per year [5]. In Alaska, the cost to repair studded tire wear related pavement damage has reached around $5 million each year [6]. Therefore, there is a practical need to reduce studded tire wear to improve pavement performance, provide safer transportation, and save on pavement repair costs.

This study attempted to determine the relevant materials and mix design variables needed to develop a wear-resistant asphalt mix in order to reduce the studded tire wear associated traffic accidents and repair/rehabilitation costs.

Chapter 2. Literature Review

2.1. Background

Studded tires were first used in Finland in 1958 to increase traction on ice and snow [7]. They became popular in the U.S. beginning in the 1960s [8-10]. Originally, studs were fabricated from tungsten carbide cores that had a wear pattern similar to that of rubber tires. Given the positive effects that studded tires have on improving traction, their application has continued to increase in cold region countries. However, the effects of the extensive use of these tires and on pavement wear, noise, and air pollution have prompted many states in the U.S. and other countries to restrict their use [11].

In order to control their protrusion, the weight and depth of studs were modified, e.g. the protrusion of the studs was decreased from 0.087 inches to 0.059 inches and their weight was limited to 0.067 ounces [12]. In the 1980s, Bridgestone in Japan first manufactured stud less winter tires, termed Blizzak. They had microscopic cells that provided better grip on the road. Studies have shown that these tires increase traction comparably to studded tires. In addition, a new type of stud fabricated with lightweight metals and plastic jackets was utilized in Scandinavian countries in the 1990s. They also reduced pavement wear [13].

2.2. Effects of Studded Tires on Pavement

Several studies have been conducted to evaluate the effects of studded tires, with most focusing on pavement wear. The mechanisms of the effects of studded tires on pavement were studied by Angerinos et al. [12]. They found that as the studded tire moves over the pavement, its spikes transfer energy to the pavement through the contact points of the studded tires. These spikes can scratch the pavement, and punching action can occur between the contact points of the studded tires. The punching action leads to rutting and raveling of the pavement, caused by disintegration of the surface layer. One Finnish study in the 1960s showed that a passenger car with four studded tires could ravel about 10 kg of pavement material in a decade [14]. Subsequent studies have shown that with the improvements in the protrusion and weight of studs, this value has decreased to about 2.5 kg. Note, however, that increases in traffic volumes during recent years diminish the net effects of stud improvements.

The rutting caused by studded tire is different from rutting typically caused by heavy traffic loads (permanent deformation) in two ways. First, studded tires cause raveling of the pavement surface material, removing it from the pavement surface layer. This is different from typical rutting, in which materials are displaced and consolidated. Second, studded tire wear is typically caused by passenger cars that have a narrow wheel path (around 60 inches) in comparison to those of heavy vehicles (around 70 inches) [15].

The Oregon Department of Transportation conducted an extensive study on studded tire wear on pavements. This study was conducted in two phases that were completed in 1995 and 2014 [16]. It made use of the Pavement Management Database to extract yearly rutting data for highways that experienced studded tire wear. In addition, studded tire traffic data were collected through a phone survey performed by Portland State University. On the basis of traffic data and studded tire and rut depth measurements, the rate of studded tire depth per studded tire pass was calculated. The results showed that studded tire wear is more severe in asphalt pavements than in Portland Cement Concrete (PCC) pavements. In addition, factors such as protrusion, weight, number of studs per tire, and driving speed were found to have a significant effect on studded tire wear.

2.3. Effect of Mix Design Factors on Asphalt Pavement Wear

Several studies have been conducted to optimize pavement mix design to achieve wear-resistant pavements [7]. The results of these studies showed that stone matrix asphalt (SMA) and mixes with a high percentage of coarse aggregates have better studded wear resistance than conventional hot mix asphalt (HMA) [17]. Fromm et al. [18] conducted a comprehensive study along Hwy 400 in Toronto, Canada. Several types of mixes were used to pave this highway, with the percentages of coarse and fine aggregates and the types of aggregate being the main variables. Rutting was measured after the first winter, and results showed that hard volcanic and synthetic stones were less prone to wear than sedimentary aggregates. In addition, mixes with high percentages of coarse aggregates showed less wear than other mixes. Fromm et al. also observed that studded wear was initiated with fines migration, followed by the loss of coarse matrix support, which led to raveling.

Results from a study conducted by the Alaska Department of Transportation and Public Facilities showed that the use of rubber-modified HMA could reduce both permanent deformation and studded wear of asphalt pavement [19]. Granulated crumb rubber was added to asphalt mixes at 2 percent of the mix by weight, and rutting was measured with a road surface profiler. The results showed that the rubber-modified asphalt pavements performed better than conventional mixes.

2.4. Noise and Air Pollution

An additional concern with the use of studded tires is associated air and noise pollution. Recent studies have shown that studded tires cause noise levels that are 4.8 to 6.4 dB higher than those from conventional tires [6]. In addition, raveling of fine aggregates from pavement that is caused by studded tire wear has a negative effect on air quality near highways.

2.5. Comparisons between Studded Tires and Studless Winter Tires

Three major studies have evaluated the differences in traction among the various types of tires used in wintery conditions. The first one, completed by the Finnish National Road Administration (FinnRA), showed that studded tires had higher friction on ice than studless winter tires. In addition, vehicles with these tires had shorter breaking distances in lock-braking conditions [13].

The second study, by the State of Alaska, compared the starting and stopping distances of vehicles with lightweight studded tires, standard studded tires, and studless winter tires on ice and snow surfaces. The results showed that studded tires (standard and lightweight studs) had better traction for both starting and stopping distances [6].

The results of a study by Scheibe et al. [20] for WSDOT showed that studded tires had the best traction on ice near freezing temperature. However, with a decrease in temperature, the effect was found to decrease. In addition, on dry pavements, studded tires showed less traction than studless winter tires and all-season tires.

2.6. Studded Tire Regulations and Restrictions

Given the detrimental effects of studded tire on pavements, several states have limited their use to specific time periods. Table 2.1 shows the time restrictions in the U.S., based on the results of a survey conducted by the University of Alaska, Anchorage, in 2005 and a follow-up study by the Vermont Agency of Transportation in 2011 [6, 21]. Several countries such as Finland, Sweden, and Canada have also imposed seasonal restrictions. Alternatively, some countries such as Germany and Japan have banned the use of studded tires altogether.

Table 2.1 State regulation on studded tire use [21].

State	Regulation	State	Regulation
Alabama	Prohibited	**Montana**	Oct 1 to May 31
Alaska	Sept 15 to May 1	**Nebraska**	Nov 1 to April 3
Arizona	Oct1 to May 3	**Nevada**	Oct 1 to April 30
Arkansas	Nov 1 to April 1	**New Hampshire**	No Restrictions
California	Nov 1 to April 30	**New Jersey**	Nov 15 to April 3
Colorado	No Restriction	**New Mexico**	No restrictions
Connecticut	Nov 15 to April 30	**New York**	Oct 16 to April 30
Delaware	Oct 15 to April 15	**North Carolina**	No restrictions
DC	Oct 15 to April 15	**North Dakota**	Oct 15 to April 15
Florida	Prohibited	**Ohio**	Nov1 to April 15
Georgia	Safety requirement	**Oklahoma**	Nov1 to April 3
Hawaii	Prohibited	**Oregon**	Nov1 to April 3
Idaho	Oct 1 to April 30	**Pennsylvania**	Nov1 to April 15
Illinois	Prohibited	**Rhode Island**	Nov1 to April 3
Indiana	Oct 1 to May 3	**South Carolina**	Oct 1 to April 30
Iowa	Nov 1 to April 3	**South Dakota**	Oct 1 to April 30
Kansas	Nov 1 to April 15	**Tennessee**	Oct 1 to April 15
Kentucky	No restrictions	**Texas**	Prohibited
Louisiana	Prohibited	**Utah**	Oct 15 to March 31
Maine	Oct 1 to April 30	**Vermont**	No restrictions
Maryland	Prohibited	**Virginia**	Oct 15 to April 15
Massachusetts	Nov 2 to April 30	**Washington**	Nov 2 to March 31
Michigan	Prohibited	**West Virginia**	Nov 1 to April 15
Minnesota	Prohibited	**Wisconsin**	Prohibited
Mississippi	Prohibited	**Wyoming**	No Restrictions
Missouri	Nov 2 to March 31		

Chapter 3. Objectives of Study

The main objective of this study was to determine the mix design properties of asphalt mixes that affect studded tire wear. The effects of those factors on conventional rutting (plastic deformation) of asphalt was also evaluated. A detailed statistical analysis was conducted to study the influence of mix design variables on maximum tire wear depth and mass loss.

The properties that improve studded tire wear resistance while not negatively effecting the plastic deformation resistance of asphalt mixes were identified through statistical analysis. The study considered several mix design factors that could potentially have significant effects on the studded tire wear resistance properties of asphalt materials. These included aggregate gradation (open-dense), aggregate source, nominal maximum aggregate size, and asphalt binder type. Five types of mixes were designed in the first stage to consider the above factors. Subsequently, for each mix, secondary factors that can affect studded tire wear—such as asphalt binder content, rubber modification and the percentage of fine aggregate—were modified. Detailed information on the mix design is presented in Chapter 4. That chapter also presents detailed information on the testing procedure. The studded tire wear resistance of the designed mixes was evaluated by tire wear tests, and mixes were compared in terms of wear depth and mass loss after the tests.

Chapter 5 presents the results of laboratory tests. The results relating to studded tire wear were analyzed by using statistical analysis to identify the effects of mix design properties. In addition, conventional rutting resistance (plastic deformation) was evaluated by using the flow number and dynamic modulus of the mixes.

Chapter 4. Mix Design and Laboratory Tests

This chapter presents the mix design and laboratory test procedures of mixes, including flow number, dynamic modulus, and studded wear tests.

4.1. Mix Design

To evaluate studded tire wear resistance, asphalt mixes were fabricated with local materials from Washington and Idaho. The literature review suggested that aggregate type, aggregate gradation, and asphalt binder are the main factors that affect the studded tire wear resistance of asphalt mixes. To evaluate the effects of gradation, four types of gradation were used to prepare asphalt mix samples. Figure 4.1 shows the gradation of those mixes.

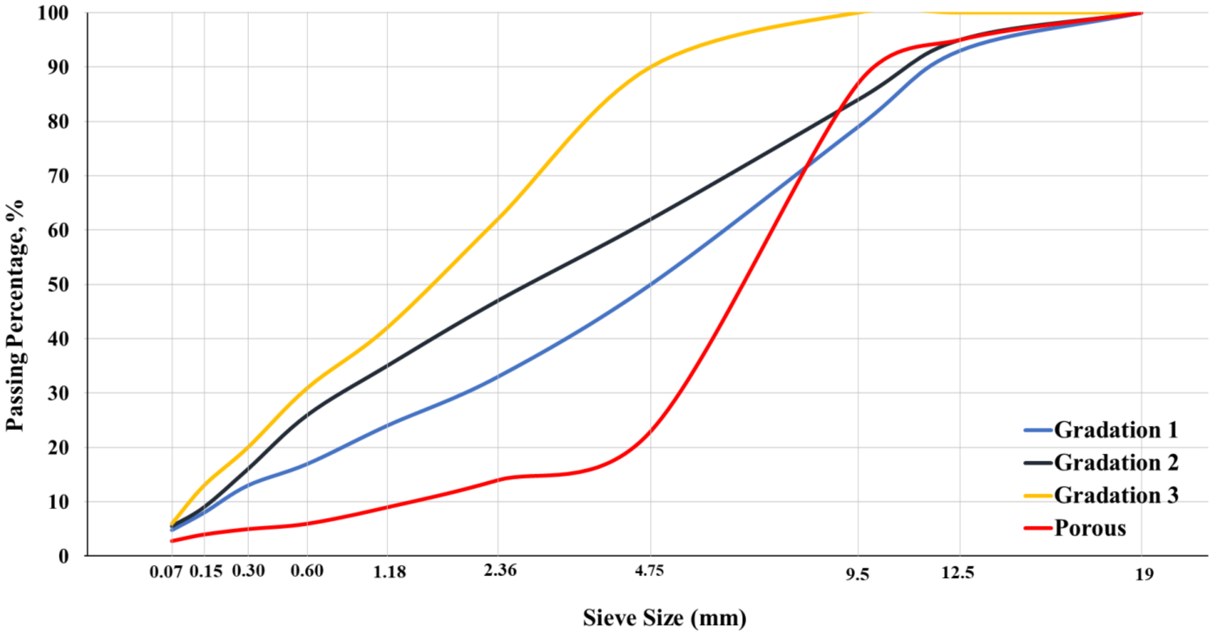

Figure 4.1 Gradation of mixes

Gradation 1 was a coarse dense-graded mix with a nominal maximum aggregate size (NMAS) of 12.5 mm. It complied with WSDOT recommendations for the gradation of dense-graded asphalt mixes. Gradation 2 was similar to gradation 1 but with more fine aggregates (passing the No.4) categorized as a fine dense-graded mix. Gradation 3 was a dense-graded mix with an NMAS of 4.75 mm. In addition, one porous asphalt mix was used as an open-graded mix.

Five groups of mixes, as shown in Table 4.1 were chosen. These mixes included two types of aggregate (local basalt and relatively soft quaternary alluvium), four types of asphalt binder (PG 64-28, PG 64-22, rubber modified PG 64-22, and rubber modified PG 64-28), and four gradations. In addition, for some mixes, higher asphalt content, and/or crumb-rubber asphalt, and/or with more fine aggregate were used for comparison.

4.2. Rutting Performance Tests of Asphalt Mixes

Although rutting and studded wear distresses are measured with the same procedure in the field, rutting is related to the plastic deformation of asphalt mixes, whereas studded wear is caused by the ravelling of aggregates from the surface layer of the pavement. Asphalt materials with good studded tire wear resistance should maintain sufficient rutting performance. Therefore, the rutting resistance of mixes was evaluated by using dynamic modulus and flow number tests. Dynamic modulus is a good indicator of the stiffness of mixes, which has been shown to correlate well with cracking and rutting resistance. In addition, the flow number is a good measure of the plastic deformation of asphalt mixes.

Table 4.1 Test design matrix

	Mix A				Mix B		Mix C	Mix D			Mix E
	I: normal	II: with higher AC%	III: with more fine agg.	IV: with Crumb-rubber	I: normal	II: with more fine agg.	normal	I: normal	II: with higher AC%	III: with Crumb-rubber	Porous HMA
Mix ID	A1	A2	A3	A4	B1	B2	C	D1	D2	D3	Porous
Aggregate Source	Basalt	Basalt	Basalt	Basalt	Basalt	Basalt	Quaternary Alluvium	Basalt	Basalt	Basalt	Basalt
Mixture Gradation	Coarse-Dense	Coarse-Dense	Fine-Dense	Coarse-Dense	Coarse-Dense	Fine-Dense	Fine-Dense	Dense	Dense	Dense	Open-Graded
Gradation	1	1	2	1	1	2	2	3	3	3	Porous
Asphalt Binder Type	PG 64-28	PG 64-28	PG 64-28	PG 64-28 (10% Rubber)	PG 64-22	PG 64-22	PG 64-28	PG 64-22	PG 64-22	PG 64-22 (10% Rubber)	PG 70-22
Binder Content	5.10%	5.60%	5.30%	5.30%	5.10%	5.10%	5.10%	6.80%	7.30%	6.80%	4.10%
Nominal Maximum Aggregate Size (NMAS)	12.5mm	12.5mm	12.5mm	12.5mm	12.5mm	12.5mm	12.5mm	4.75mm	4.75mm	4.75mm	12.5mm
Maximum Thermotical Specific Gravity of HMA (G_{mm}), gr/cm^3	2.614	2.592	2.595	2.600	2.605	2.593	2.472	2.595	2.578	2.590	2.650

5.2.1 Dynamic Modulus and the Flow Number

The dynamic modulus test was conducted in accordance with AASHTO T 378-17. The test was performed on specimens that were fabricated by a Pine-AFG1 Superpave gyratory compactor and were compacted to a target height of 170 mm and a diameter of 150 mm, with an air voids level of 7±0.5 percent for dense-graded mixes and an air void level of 20 ±1 percent for porous asphalt mixes. After compaction, the specimens were cored and cut to a size of 150 mm high and 100 mm in diameter. The theoretical maximum specific gravity (G_{mm}) and bulk specific gravity of specimens were measured in accordance with AASHTO T209 and AASHTO T166, respectively.

The prepared samples were tested by using the Asphalt Mixture Performance Tester (AMPT). The temperatures used for the dynamic modulus test were 40℉, 70℉, 100℉, and 130 ℉, and at each temperature, six different loading frequencies—25, 10, 5, 1, 0.5, 0.1 Hz—were applied. A minimum of two specimens for each mix were fabricated and tested to confirm the results.

The flow number test was performed by using a loading cycle of 1.0 second, which consisted of a 0.1-second haversine load followed by a 0.9-second rest at a testing temperature of 130℉. The flow number is the number of load repetitions when the permanent deformation rate reaches a minimum or strain reaches the tertiary stage after initial consolidation and a secondary constant strain rate. This test is typically conducted after the dynamic modulus test. The flow number is automatically calculated and recorded with the Simple Performance Tester software. This protocol was in accordance with AASHTO TP378-17, the Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT). Note that according to AASHTO standard recommendations, the flow number test should be conducted with high-temperature performance mix grades, but in this study the test was performed at a constant temperature of 54℃ for purposes of comparison.

4.3. Studded Tire Wear Resistance Test

The wear resistance of the mixes was determined by using the Asphalt Pavement Analyzer (APA) Jr., as shown in Figure 4.2 A, at a testing temperature of 5°C. The loading wheels had rubber tires with studs to apply adjustable loads on the asphalt mixture specimen, as shown in Figure 4.2 A. To observe the wear behavior of the asphalt mixture, a loading force of 100lb was applied to the samples to simulate actual traffic loading. The wear depth (in mm) and mass loss (in grams) of each specimen after 8,000 wear cycles were used as the wear resistance performance indicators for the asphalt mixtures. Note that six specimens were tested for each mix.

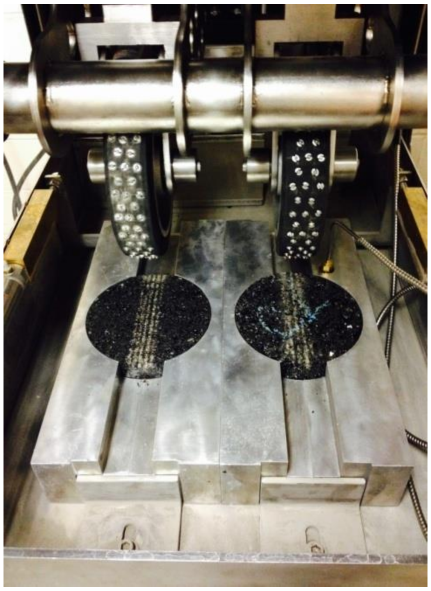

Figure 4.2 Asphalt Pavement Analyzer (APA) Jr. with studded loading wheels

Chapter 5. Test Results

This chapter presents the results of laboratory tests on the different types of mixes.

5.1. Rutting Performance

Figure 5.1 shows the results of the flow number test. As shown, an increase in asphalt binder content (mixes A2 and D2) decreased the flow number and accordingly increased the potential for plastic deformation for both dense-graded mixes with an NMAS of 12.5 mm and 4.75 mm (mix types A and D). In addition, the use of rubber modified asphalt binder (mixes A4 and D3) increased the flow number that correlates with better rutting resistance. The porous HMA showed the lowest flow number, which could have been due to the high air void content of this mix. Moreover, the increase in the percentage of fine aggregates (mixes A3 and B2) resulted in a reduced flow number and an increased potential for plastic deformation. The interlocking potential of the fine aggregate was less than that of the coarse aggregate, and it made the movement of aggregate under destructive load much easier.

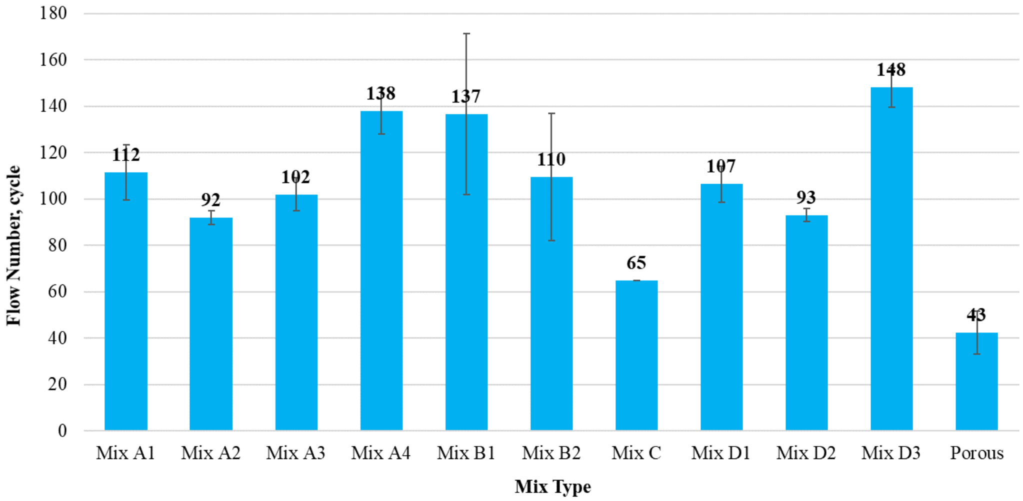

Figure 5.1 Flow number, cycles

Figure 5.2 to Figure 5.4 show the results of the dynamic modulus test at low, intermediate, and high time-temperature levels. As shown, mixes with rubber-modified asphalt binder (mixes A4 and D3) had less stiffness at low time-temperature levels, whereas, those mixes showed high stiffness at high time-temperature levels. This is indicative of the elastic behavior of rubber. In addition, an increase in asphalt binder content decreased the stiffness of mixes (mixes A2 and D2) at all tested levels, and this decrease was prominent at high temperatures. This can be attributed to the dominant effect of the asphalt binder in asphalt mixes at high temperatures. Moreover, the increase in fine aggregate percentage in dense-graded mixes (mixes A3 and B2) increased the dynamic modulus of mixes at intermediate and high time-temperature levels.

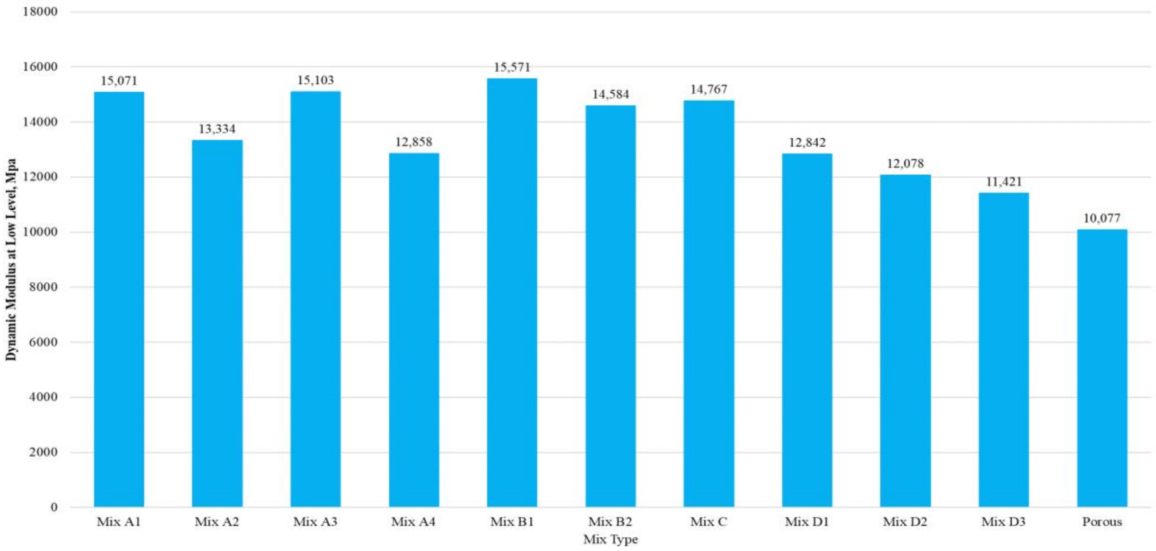

Figure 5.2 Dynamic modulus at low time-temperature level (40°F, 25Hz)

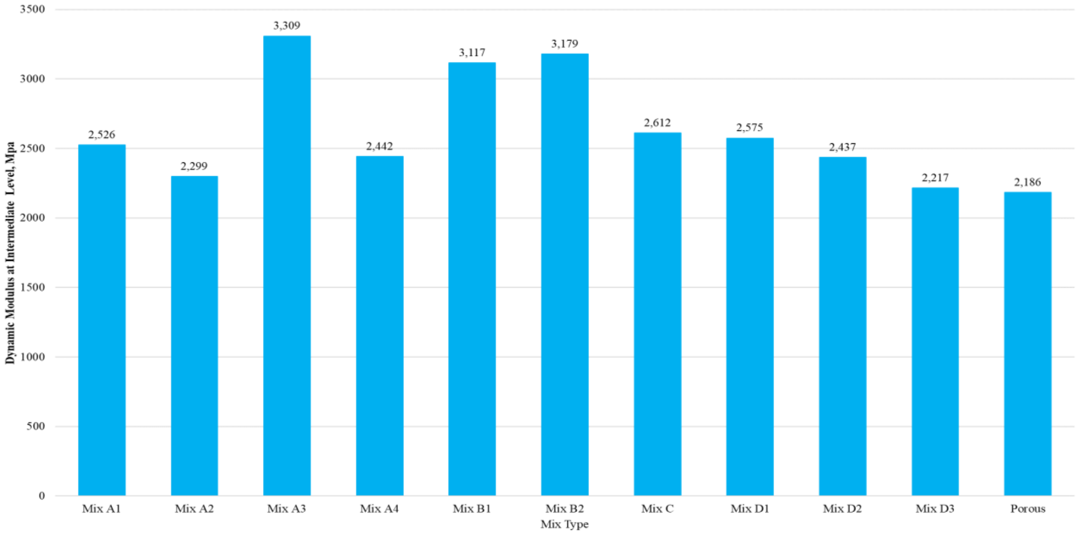

Figure 5.3 Dynamic modulus at intermediate time-temperature level (70°F, 1Hz)

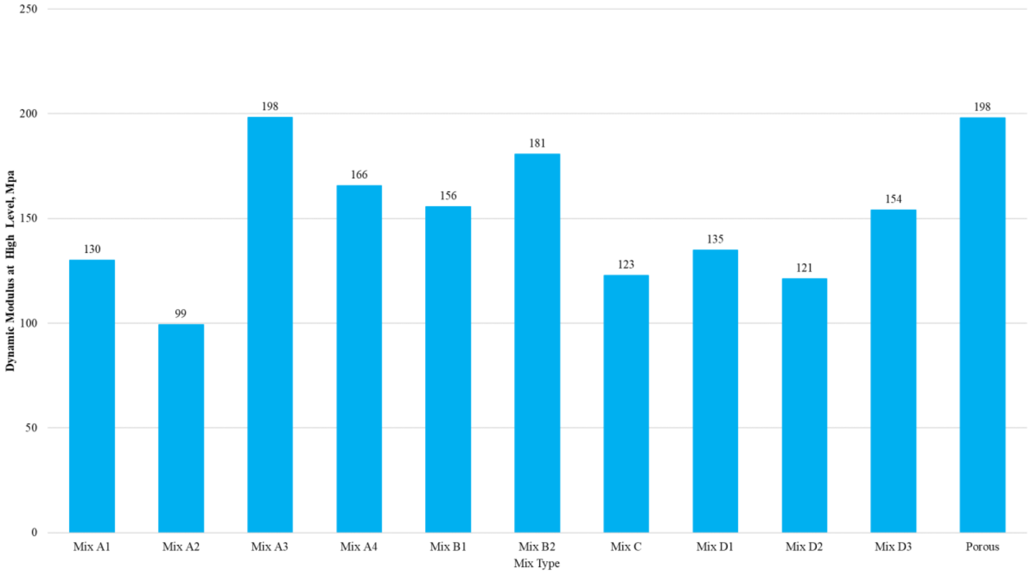

Figure 5.4 Dynamic modulus at high time-temperature level (100°F, 0.1Hz)

5.2. Studded Tire Wear Resistance

Figure 5.5 shows the evolution of wear depth during the studded tire test. The porous HMA had the highest studded tire wear depth among the mixes. Mixes A1, B1, C, and D1 also showed comparable wear depth.

Moreover, the addition of rubber increased the wear depth for the coarse dense-graded mix with an NMAS of 12.5mm (mix A4) and decreased the wear depth for mix type D with a 4.75 mm NMAS (mix D3). The results also showed that an increase in asphalt binder decreased the wear depth for both the coarse dense-graded mix (mix A2) and the dense-graded mix with an NMAS of 4.75 mm (mix D2).

In addition, the results showed high fluctuation, which correlated with the rough surface of the HMA. This fluctuation was greater for porous asphalt with its high porosity on the surface.

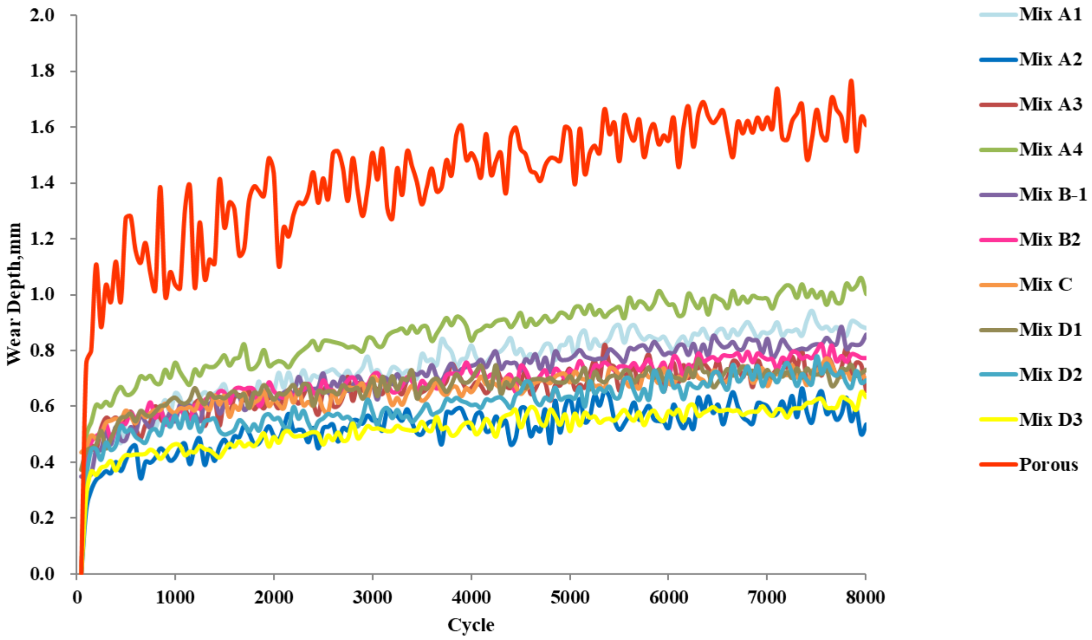

Figure 5.5 Studded wear depth

5.3. Statistical Analysis

An analysis of variance (ANOVA) was performed on the maximum wear depth and mass loss results to evaluate the effects of different mix design properties on the wear resistance of the asphalt mixes. First, an ANOVA test was conducted with a 0.05 significance level to identify the overall differences among mixes. Subsequently, post-hoc tests were performed to extract meaningful differences among the mixes. The results are presented in Appendix A. Sections A.1 and A.2 give the post-hoc results for maximum wear depth and mass loss, respectively.

Figure 5.6 shows the average maximum wear depth from the studded tire tests. Porous HMA had the highest maximum wear depth among the mixes. Although the increase in asphalt binder was observed to decrease the maximum wear depth for the coarse dense-graded mix (mixes A1 and A2), the post-hoc results showed no significant difference between the two. On the other hand, the use of rubber-modified asphalt binder appeared to slightly decrease the wear depth for the dense-graded mix with an NMAS of 4.75 mm (mixes D1 to D3). However, analyses did not show a statistically significant difference. Statistical analyses also showed no significant difference in the maximum wear depth among mix types A, B, C, and D.

Note that for the dense-graded mixes, the maximum difference in wear depth observed was between mix A1 and D3 and was less than 0.5 mm. This value is less than one third the measurable field depth of 1.59 mm (1/16 in). It appears that 8,000 loading cycles may not have been sufficient to induce measurable wear. It would be necessary to increase that number in future studies. Regardless, our study is useful in highlighting the potential of adding crumb-rubber for 4.75 mm NMAS to increase wear resistance.

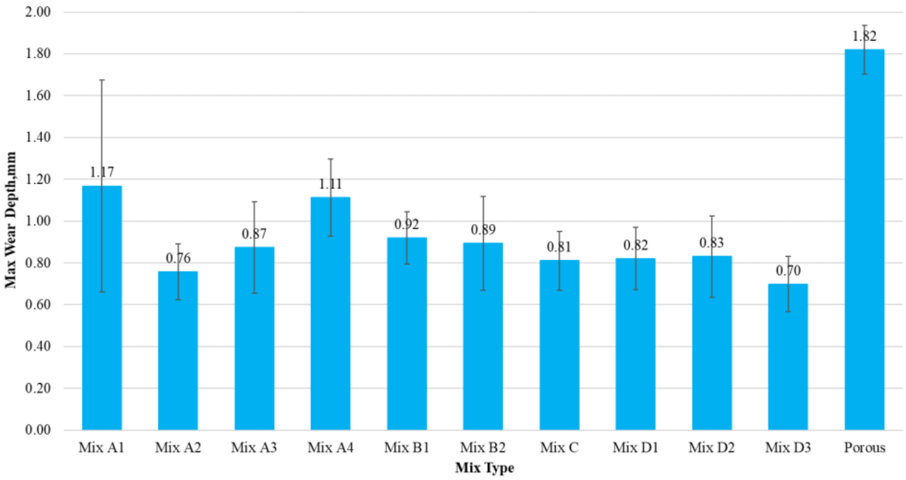

Figure 5.6 Maximum wear depth, mm

Figure 5.7 shows the mass loss results after the studded wear test. The porous HMA had a higher mass loss than the dense graded mixes. Statistical analyses showed no significant difference among mix types A, B, C, and D. This means that asphalt binder type, gradation, and aggregate type were not significant factors in the mass loss of studded wear test.

In addition, post-hoc test results (Appendix A.2) revealed that the utilization of rubber modified asphalt binder (up to 10 percent rubber) did not have a significant effect on studded tire wear mass loss for both coarse dense-graded and dense-graded mixes with an NMAS of 4.75 mm (types A and D). The increase of fine aggregate percentage in coarse dense-graded mixes (mix types A and B) also did not change the mass loss significantly. In addition, a significant difference in mass loss observed between the A1 and A2 mixes indicated that an increase of asphalt binder reduced the mass loss in the coarse dense-graded mixes. However, an increase of asphalt binder content did not show a statistically significant decrease in the mass loss of the dense-graded mixes with an NMAS of 4.75 mm (mixes D1 and D2).

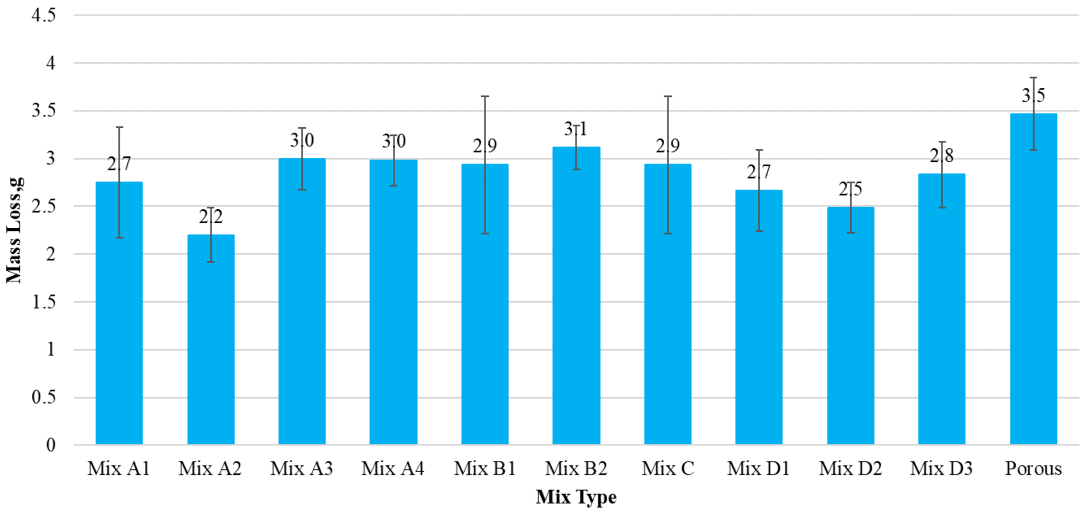

Figure 5.7 Mass loss after the studded tire test

Chapter 6. Summary and Conclusions

Studded tires are used in the United States and many countries to increase traction between the tire and the pavement during winter weather. Although their use has undeniable safety effects, they can cause severe pavement damage. This study evaluated the factors in the mix design for asphalt mixes that can reduce studded tire wear without affecting other performances. Different types of mixes were evaluated in terms of studded tire wear depth, mass loss, and permanent rutting deformation through laboratory tests. The following conclusions can be drawn.

- The porous HMA showed more rutting (permanent deformation) and studded tire wear than dense-graded mixes, which indicates the porous HMA is not an appropriate alternative for regions with no limitation on studded tire use.
- An increase in asphalt binder content reduced studded tire wear, but it can also increase the rutting potential (permanent deformation) of asphalt mixes. Therefore, it can be a good solution to reduce studded tire wear in cold climate regions, where rutting is not the predominant distress.
- Asphalt binder, the percentage of fine aggregate, nominal maximum aggregate size, aggregate type, and rubber modification of asphalt binder did not have a significant influence on the studded tire wear test results.
- In this study, 8,000 cycles of loading were used to evaluate studded tire wear, and results indicated that this number of load repetitions was not adequate to capture significant differences among mixes. Therefore, this number should be calibrated on the basis of the field performance of asphalt mixes in terms of studded wear.

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Appendix A

A.1 Post-Hoc test on Maximum Wear Depth

				95% Confidence Interval	
(I) Mix		Std. Error	Sig.	Lower Bound	Upper Bound
A1	A2	0.08745	0.060	-0.0069	0.5969
	A3	0.08745	0.430	-0.0969	0.5069
	A4	0.08745	1.000	-0.3319	0.2719
	B1	0.08745	0.989	-0.2069	0.3969
	B2	0.08745	0.649	-0.1269	0.4769
	C	0.08745	0.144	-0.0419	0.5619
	D1	0.08745	0.274	-0.0719	0.5319
	D2	0.08745	0.236	-0.0644	0.5394
	D3	0.08745	**0.009**	0.0606	0.6644
	Porous	0.08745	**0.000**	-1.0644	-0.4606
A2	A1	0.08745	0.060	-0.5969	0.0069
	A3	0.08745	0.993	-0.3919	0.2119
	A4	0.08745	**0.026**	-0.6269	-0.0231
	B1	0.08745	0.465	-0.5019	0.1019
	B2	0.08745	0.947	-0.4219	0.1819
	C	0.08745	1.000	-0.3369	0.2669
	D1	0.08745	1.000	-0.3669	0.2369
	D2	0.08745	1.000	-0.3594	0.2444
	D3	0.08745	0.999	-0.2344	0.3694
	Porous	0.08745	**0.000**	-1.3594	-0.7556
A3	A1	0.08745	0.430	-0.5069	0.0969
	A2	0.08745	0.993	-0.2119	0.3919
	A4	0.08745	0.248	-0.5369	0.0669
	B1	0.08745	0.970	-0.4119	0.1919
	B2	0.08745	1.000	-0.3319	0.2719
	C	0.08745	1.000	-0.2469	0.3569
	D1	0.08745	1.000	-0.2769	0.3269

	D2	0.08745	1.000	-0.2694	0.3344
	D3	0.08745	0.771	-0.1444	0.4594
	Porous	0.08745	**0.000**	-1.2694	-0.6656
A4	A1	0.08745	1.000	-0.2719	0.3319
	A2	0.08745	**0.026**	0.0231	0.6269
	A3	0.08745	0.248	-0.0669	0.5369
	B1	0.08745	0.932	-0.1769	0.4269
	B2	0.08745	0.430	-0.0969	0.5069
	C	0.08745	0.069	-0.0119	0.5919
	D1	0.08745	0.144	-0.0419	0.5619
	D2	0.08745	0.121	-0.0344	0.5694
	D3	0.08745	**0.003**	0.0906	0.6944
	Porous	0.08745	**0.000**	-1.0344	-0.4306
B1	A1	0.08745	0.989	-0.3969	0.2069
	A2	0.08745	0.465	-0.1019	0.5019
	A3	0.08745	0.970	-0.1919	0.4119
	A4	0.08745	0.932	-0.4269	0.1769
	B2	0.08745	0.997	-0.2219	0.3819
	C	0.08745	0.721	-0.1369	0.4669
	D1	0.08745	0.894	-0.1669	0.4369
	D2	0.08745	0.858	-0.1594	0.4444
	D3	0.08745	0.121	-0.0344	0.5694
	Porous	0.08745	**0.000**	-1.1594	-0.5556
B2	A1	0.08745	0.649	-0.4769	0.1269
	A2	0.08745	0.947	-0.1819	0.4219
	A3	0.08745	1.000	-0.2719	0.3319
	A4	0.08745	0.430	-0.5069	0.0969
	B1	0.08745	0.997	-0.3819	0.2219
	C	0.08745	0.995	-0.2169	0.3869
	D1	0.08745	1.000	-0.2469	0.3569
	D2	0.08745	1.000	-0.2394	0.3644
	D3	0.08745	0.557	-0.1144	0.4894
	Porous	0.08745	**0.000**	-1.2394	-0.6356
C	A1	0.08745	0.144	-0.5619	0.0419

	A2	0.08745	1.000	-0.2669	0.3369
	A3	0.08745	1.000	-0.3569	0.2469
	A4	0.08745	0.069	-0.5919	0.0119
	B1	0.08745	0.721	-0.4669	0.1369
	B2	0.08745	0.995	-0.3869	0.2169
	D1	0.08745	1.000	-0.3319	0.2719
	D2	0.08745	1.000	-0.3244	0.2794
	D3	0.08745	0.981	-0.1994	0.4044
	Porous	0.08745	**0.000**	-1.3244	-0.7206
D1	A1	0.08745	0.274	-0.5319	0.0719
	A2	0.08745	1.000	-0.2369	0.3669
	A3	0.08745	1.000	-0.3269	0.2769
	A4	0.08745	0.144	-0.5619	0.0419
	B1	0.08745	0.894	-0.4369	0.1669
	B2	0.08745	1.000	-0.3569	0.2469
	C	0.08745	1.000	-0.2719	0.3319
	D2	0.08745	1.000	-0.2944	0.3094
	D3	0.08745	0.904	-0.1694	0.4344
	Porous	0.08745	**0.000**	-1.2944	-0.6906
D2	A1	0.08745	0.236	-0.5394	0.0644
	A2	0.08745	1.000	-0.2444	0.3594
	A3	0.08745	1.000	-0.3344	0.2694
	A4	0.08745	0.121	-0.5694	0.0344
	B1	0.08745	0.858	-0.4444	0.1594
	B2	0.08745	1.000	-0.3644	0.2394
	C	0.08745	1.000	-0.2794	0.3244
	D1	0.08745	1.000	-0.3094	0.2944
	D3	0.08745	0.932	-0.1769	0.4269
	Porous	0.08745	**0.000**	-1.3019	-0.6981
D3	A1	0.08745	**0.009**	-0.6644	-0.0606
	A2	0.08745	0.999	-0.3694	0.2344
	A3	0.08745	0.771	-0.4594	0.1444
	A4	0.08745	**0.003**	-0.6944	-0.0906
	B1	0.08745	0.121	-0.5694	0.0344

	B2	0.08745	0.557	-0.4894	0.1144
	C	0.08745	0.981	-0.4044	0.1994
	D1	0.08745	0.904	-0.4344	0.1694
	D2	0.08745	0.932	-0.4269	0.1769
	Porous	0.08745	**0.000**	-1.4269	-0.8231
Porous	A1	0.08745	**0.000**	0.4606	1.0644
	A2	0.08745	**0.000**	0.7556	1.3594
	A3	0.08745	**0.000**	0.6656	1.2694
	A4	0.08745	**0.000**	0.4306	1.0344
	B1	0.08745	**0.000**	0.5556	1.1594
	B2	0.08745	**0.000**	0.6356	1.2394
	C	0.08745	**0.000**	0.7206	1.3244
	D1	0.08745	**0.000**	0.6906	1.2944
	D2	0.08745	**0.000**	0.6981	1.3019
	D3	0.08745	**0.000**	0.8231	1.4269

A.2 Pos-Hoc Test on Studded Tire Mass Loss

				95% Confidence Interval	
		Std. Error	Sig.	Lower Bound	Upper Bound
A1	A2	0.2308	**0.021**	0.088	1.012
	A3	0.2308	0.283	-0.712	0.212
	A4	0.2308	0.316	-0.696	0.229
	B1	0.2308	0.615	-0.579	0.346
	B2	0.2308	0.118	-0.829	0.096
	C	0.2308	0.430	-0.646	0.279
	D1	0.2308	0.719	-0.379	0.546
	D2	0.2308	0.253	-0.196	0.729
	D3	0.2308	0.719	-0.546	0.379
	Porous	0.2308	**0.003**	-1.179	-0.254
A2	A1	0.2308	**0.021**	-1.012	-0.088
	A3	0.2308	**0.001**	-1.262	-0.338
	A4	0.2308	**0.001**	-1.246	-0.321
	B1	0.2308	**0.006**	-1.129	-0.204
	B2	0.2308	**0.000**	-1.379	-0.454
	C	0.2308	**0.002**	-1.196	-0.271
	D1	0.2308	**0.048**	-0.929	-0.004
	D2	0.2308	0.225	-0.746	0.179
	D3	0.2308	**0.008**	-1.096	-0.171
	Porous	0.2308	**0.000**	-1.729	-0.804
A3	A1	0.2308	0.283	-0.212	0.712
	A2	0.2308	**0.001**	0.338	1.262
	A4	0.2308	0.943	-0.446	0.479
	B1	0.2308	0.566	-0.329	0.596
	B2	0.2308	0.615	-0.579	0.346
	C	0.2308	0.774	-0.396	0.529
	D1	0.2308	0.154	-0.129	0.796
	D2	0.2308	**0.029**	0.054	0.979

	D3	0.2308	0.473	-0.296	0.629
	Porous	0.2308	**0.048**	-0.929	-0.004
A4	A1	0.2308	0.316	-0.229	0.696
	A2	0.2308	**0.001**	0.321	1.246
	A3	0.2308	0.943	-0.479	0.446
	B1	0.2308	0.615	-0.346	0.579
	B2	0.2308	0.566	-0.596	0.329
	C	0.2308	0.829	-0.412	0.512
	D1	0.2308	0.176	-0.146	0.779
	D2	0.2308	**0.035**	0.038	0.962
	D3	0.2308	0.518	-0.312	0.612
	Porous	0.2308	**0.041**	-0.946	-0.021
B1	A1	0.2308	0.615	-0.346	0.579
	A2	0.2308	**0.006**	0.204	1.129
	A3	0.2308	0.566	-0.596	0.329
	A4	0.2308	0.615	-0.579	0.346
	B2	0.2308	0.283	-0.712	0.212
	C	0.2308	0.774	-0.529	0.396
	D1	0.2308	0.390	-0.262	0.662
	D2	0.2308	0.102	-0.079	0.846
	D3	0.2308	0.886	-0.429	0.496
	Porous	0.2308	0.012	-1.062	-0.138
B2	A1	0.2308	0.118	-0.096	0.829
	A2	0.2308	**0.000**	0.454	1.379
	A3	0.2308	0.615	-0.346	0.579
	A4	0.2308	0.566	-0.329	0.596
	B1	0.2308	0.283	-0.212	0.712
	C	0.2308	0.430	-0.279	0.646
	D1	0.2308	0.056	-0.012	0.912
	D2	0.2308	**0.008**	0.171	1.096
	D3	0.2308	0.225	-0.179	0.746
	Porous	0.2308	0.135	-0.812	0.112
C	A1	0.2308	0.430	-0.279	0.646
	A2	0.2308	0.002	0.271	1.196

	A3	0.2308	0.774	-0.529	0.396
	A4	0.2308	0.829	-0.512	0.412
	B1	0.2308	0.774	-0.396	0.529
	B2	0.2308	0.430	-0.646	0.279
	D1	0.2308	0.253	-0.196	0.729
	D2	0.2308	0.056	-0.012	0.912
	D3	0.2308	0.666	-0.362	0.562
	Porous	0.2308	**0.025**	-0.996	-0.071
D1	A1	0.2308	0.719	-0.546	0.379
	A2	0.2308	**0.048**	0.004	0.929
	A3	0.2308	0.154	-0.796	0.129
	A4	0.2308	0.176	-0.779	0.146
	B1	0.2308	0.390	-0.662	0.262
	B2	0.2308	0.056	-0.912	0.012
	C	0.2308	0.253	-0.729	0.196
	D2	0.2308	0.430	-0.279	0.646
	D3	0.2308	0.473	-0.629	0.296
	Porous	0.2308	**0.001**	-1.262	-0.338
D2	A1	0.2308	0.253	-0.729	0.196
	A2	0.2308	0.225	-0.179	0.746
	A3	0.2308	**0.029**	-0.979	-0.054
	A4	0.2308	**0.035**	-0.962	-0.038
	B1	0.2308	0.102	-0.846	0.079
	B2	0.2308	**0.008**	-1.096	-0.171
	C	0.2308	0.056	-0.912	0.012
	D1	0.2308	0.430	-0.646	0.279
	D3	0.2308	0.135	-0.812	0.112
	Porous	0.2308	**0.000**	-1.446	-0.521
D3	A1	0.2308	0.719	-0.379	0.546
	A2	0.2308	**0.008**	0.171	1.096
	A3	0.2308	0.473	-0.629	0.296
	A4	0.2308	0.518	-0.612	0.312
	B1	0.2308	0.886	-0.496	0.429
	B2	0.2308	0.225	-0.746	0.179

	C	0.2308	0.666	-0.562	0.362
	D1	0.2308	0.473	-0.296	0.629
	D2	0.2308	0.135	-0.112	0.812
	Porous	0.2308	**0.008**	-1.096	-0.171
Porous	A1	0.2308	**0.003**	0.254	1.179
	A2	0.2308	**0.000**	0.804	1.729
	A3	0.2308	**0.048**	0.004	0.929
	A4	0.2308	**0.041**	0.021	0.946
	B1	0.2308	**0.012**	0.138	1.062
	B2	0.2308	0.135	-0.112	0.812
	C	0.2308	**0.025**	0.071	0.996
	D1	0.2308	**0.001**	0.338	1.262
	D2	0.2308	**0.000**	0.521	1.446
	D3	0.2308	**0.008**	0.171	1.096