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Effect of Varying Amounts of Sandstone on the Performance of Asphalt Mixtures in Arkansas

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Effect of Varying Amounts of Sandstone on the Performance of Asphalt Mixtures in Arkansas

A thesis submitted in partial fulfillment
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by

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ABSTRACT

There are many different species and subspecies of aggregate used across the state of Arkansas, and across the country. However, it cannot be presumed that each of these aggregates will be compatible with the commonly used asphalt binder of an area; this can lead to performance issues and premature pavement damage. It has been suspected in Arkansas that sandstone may be a culprit of some of these premature pavement damage issues, especially regarding the moisture susceptibility of a pavement. This study aimed to analyze the performance effects of using variable amounts of sandstone in order to determine the relationship between the amount of sandstone in a mixture and the performance of said mixture. This study utilized test methods to analyze the cracking, rutting, and moisture susceptibility specimens with various levels of sandstone. It was found that the most evident issues with increased sandstone usage were specifically detrimental to the cracking and moisture resistance of a mixture.

ACKNOWLEDGMENTS

Firstly, I would like to thank my wife for all of her support, wisdom and guidance throughout this process. I could not have accomplished all of this work without her. I would also like to thank the rest of my family for all of their support and encouragement.

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INTRODUCTION

Aggregates in Arkansas are commonly used from different quarries across the state, and there are several major types of aggregate found depending on the quarry from which the aggregate was gathered. Recent literature has called into question the usage of certain aggregate, sandstone in specific, in asphalt mixtures, especially in regard to moisture susceptibility (McCann et al. 2011, Cala & Caro 2021, Zhang et al. 2015). It is suspected that many of these problems relate to the compatibility that the aggregate has with a binder (Bagchi & Hossain 2020). If an aggregate does not properly form a bond with the binder, it is much more susceptible to moisture damage (Copeland et al. 2007). Certain types of aggregate are thought to heavily influence the long-term performance of an asphalt pavement. Therefore, the aggregate and binder compatibility should inform the choices of types and quantities of aggregate in a pavement design.

Hot mix asphalt is one of the most widely utilized pavement materials because of its availability, ease of installation, and capability to deal with dynamic loads. The typical structure of an asphalt pavement the binder is meant to coat and hold together the mineral aggregate contained in the asphalt mixture. Building off of this, are the main components of an asphalt mixture: the asphalt binder and the mineral aggregate of varying gradations. The resulting bond between the aggregate and binder must be maintained if the pavement is to continue to perform adequately across its design life. Over time as traffic and environmental effects take their toll on the pavement, deterioration will inevitably occur. But, in the case of each designed pavement, this rate of deterioration is heavily dependent upon the selection of materials (the aggregate, binder, and additives).

Moisture damage is one of the most common forms of damage in asphalt pavement. Moisture damage occurs when water weakens the adhesive bond between the aggregate and the binder, or the cohesive bond holding the binder together. This phenomenon is commonly referred to as stripping because it results in the aggregate stripping away from the binder and pavement. Research has shown that the physical and chemical properties of aggregates significantly affect the moisture sensitivity of an asphalt mixture. However, it is very difficult to understand and quantify the level of contribution to this issue from the aggregate, the mineral filler (p200 aggregate), and the binder.

Moisture damage in asphalt pavement is a problem that occurs across the country. However, this problem is very difficult to attribute to a single specific cause because of the amount of variation in different pavement designs. Furthering this complexity, the results of moisture damage can be either an adhesive bond failure, cohesive bond failure, or a combination thereof (Hossain & Roy 2018). Studies in recent years have attributed premature moisture damage to incompatibility between the aggregate and binder in an asphalt mixture (Bagchi & Hossain 2020). From this, it can be deduced that if the aggregate and binder used in a mixture are incompatible, they are more likely to not form a proper bond that will achieve adequate performance. To combat this issue, ARDOT has issued a requirement for all mixes in the state to include anti-stripping agent. However, based on previous studies and pavement performance, it is suspected that sandstone is often the cause of incompatibility in asphalt mixtures in Arkansas. So, the current regulations do not effectively address the likely root cause of many of the premature pavement damage issues in the state.

The hope of this research is to analyze the performance of sandstone in Arkansas and determine a safe limit of sandstone usage in Arkansas. While research has well established that aggregates can be the cause of premature moisture damage in asphalt mixtures, the impact of varying the levels of a problem aggregate is not as well established. It is hoped that in the results of this study, a relationship will be found between the amount of sandstone in an asphalt mixture, and the performance of said mixture.

Much of the notable research in the past few years build off the ideas of the research performed by Copeland et al. (2007). This research was performed on binders to test for their adhesive properties with or without moisture conditioning. The results of this research noted that dry samples tended to fail cohesively, while moisture conditioned samples tended to fail adhesively. In addition to this it is noted that moisture decreases the adhesive properties of binders. From this, it can be determined that the adhesive bond between the aggregate and the binder significantly affects the overall moisture resistance of an asphalt pavement. Other research has also indicated that the binder used in a mixture also significantly affects the bond present in an asphalt mixture. Research performed by Moraes et al (2016) indicated that the binder stiffness directly affects the strength of the bonds in the aggregate-binder system. This concept, while important to keep in mind, does not directly contribute to the idea of aggregate performance.

The adhesive bond is affected by the binder and the aggregate. This research aims to isolate the performance effects of using different species of aggregate. Research performed by McCann et al (2005) utilized a regression model to predict the contribution of ten different aggregate characteristics on the moisture sensitivity of an asphalt mixture. According to the model built in this research, the most significant predictor of the moisture sensitivity is the “acid insolubility.” This is a chemical property that would affect the chemistry of the bond between the aggregate and the binder, thus affecting the bond strength and/or the behavior of the bond in the presence of water. The second most significant predictor of the regression model is the pore ratio of the aggregate (although this was not mutually exclusive in the model). Based off this research we can see that the chemical bond potential and the porosity of an aggregate hugely affect the moisture sensitivity of the final mixture. This indicates that these two properties play a large role in the degree of compatibility between an aggregate and a binder.

Much of the recent research regarding the moisture resistance of asphalt mixtures based on the variations of aggregates has focused on petrographic analysis. This form of analysis helps to better understand the mineral composition of specific aggregates. This research has aimed to isolate and analyze specific minerals present in aggregate that can predict the moisture sensitivity of an asphalt mixture. Research performed by Horgnies et al. (2011) used a peel test and spectrometry equipment to analyze the failure plans from the peel test. This research identified that aggregate containing quartz and alkali-feldspar minerals contribute to weaker bonds with the binder. Further research performed by Zhang et al. (2015) indicated that anorthite and clays are also detrimental to moisture resistance. This research also indicated that aggregate containing calcite minerals tend to be more moisture resistant. Continuing off of this, it was noted that in a more recent study that in general mixtures containing siliceous minerals tend to have lesser moisture resistances (Cala & Caro 2021). Concepts from all of these studies help to give a basis for a preliminary understanding of the possible impacts of sandstone usage in Arkansas.

Arkansas is a very geologically diverse state with access to many different species of aggregate. It should also be noted that there are even different subspecies of aggregate used across the state, so sandstone can originate from several different geological formations across the state. This fact is well described by the Arkansas Geological Survey that can be seen in Figure 1. The goal of gathering materials from different quarries/plants across the state is to better analyze the performance of different aggregates and to recognize that aggregates of the same species, but different origin, may not perform equally. According to this survey, and to ARDOT, the gathered materials consist of Hartshorne formation sandstone (Phs on the figure) and Boone formation, which is typically limestone and/or chert (Mb on the figure).

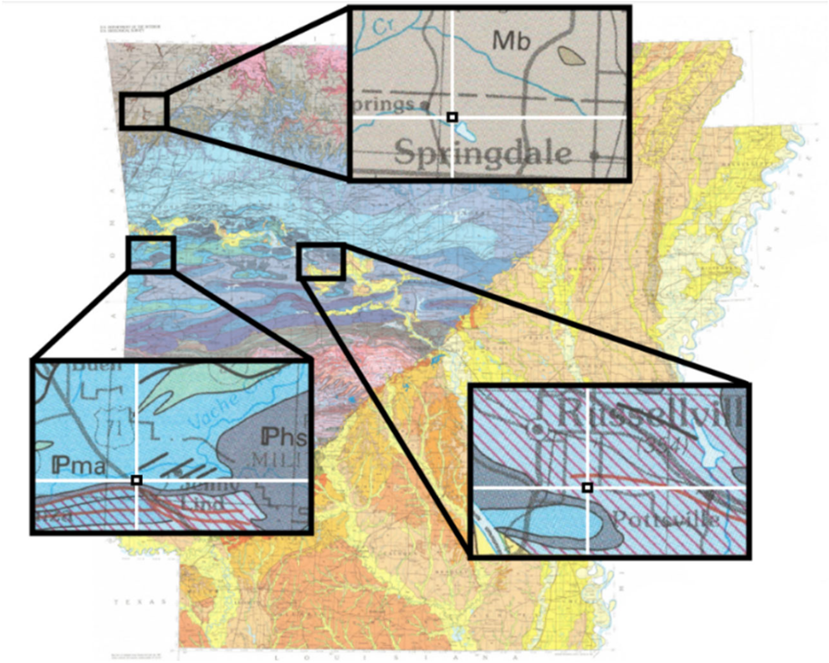

Figure 1. Arkansas Geological Survey

Hartshorne formation has been described as typically having more than 80% quartz and less than 5% feldspars, with the rest comprising of lithic fragments (Yin 2016). Within this composition, the sandstone could be classified as either a quartzarenite or sublitharenite (Folk 1980). Knowing that both quartz and certain feldspars are known to be detrimental to the moisture resistance of an asphalt mixture (Horgnies et al 2011, Zhang et al 2015), there is still possible performance variability within the classification of Hartshorne formation. Boone formation is typically quarried as either chert or limestone. While chert is known to be a harder aggregate, it also has higher silica content, while limestone has a higher calcite content.

Furthermore, how siliceous or calcareous an aggregate is, affects its moisture resistance as well (Cala & Caro 2021). Knowing all of this, there is significant possible variation of aggregate species and performance.

Sandstone is currently a widely utilized aggregate in Arkansas. According to Earle (2015), sandstone can typically be classified by its compositional quantities of quartz (silicon dioxide), feldspar (aluminum tectosilicate minerals), and lithic fragments (eroded fragments from other rock formations). Much of the aforementioned literature has highlighted siliceous minerals such as feldspar and quartz as being detrimental to the moisture resistance of a mixture (Horgnies et al 2011, Zhang et al 2015, Cala & Caro 2021). It should be noted, however, that sandstone can be a highly variable material based on its levels of quartz, feldspar, and lithic fragments, therefore, not all sandstone will have equal performance. Arkansas typically uses sandstones that are classified as either Hartshorne formation or Atokan formation.

Based on the current body of literature, there is reason to believe that sandstone is possibly a poor performing aggregate in asphalt mixtures, especially regarding moisture damage. Research has not however, indicated the relationship between the levels of poor performing aggregate in a mixture and the performance of the overall asphalt mixture. Because of this, it is not known if there is a safe level of sandstone in asphalt mixtures. Another gap in research is indicating established and accessible test methods to identify the degree detriment resulting from the usage of poor performing aggregate (sandstone specifically for this research). This study will aim to deepen the understanding of this subject by performing a wide range of performance testing on mixtures using different species of aggregate; specifically, the performance effects of differing sandstone quantities in a mixture will be analyzed. This information will hope to better inform the professional community on the trends of using different quantities of a suspected poor performing aggregate.

RESEARCH OBJECTIVE

This research aimed to find the relationship between sandstone in Arkansas and the performance of HMA mixtures. This was accomplished by testing mixtures with varying levels of sandstone, then comparing the differences in performance. The testing considered cracking resistance, rutting resistance, and moisture resistance of the asphalt mixtures; the goal in performing such a broad range of tests was to analyze the full effects of sandstone in asphalt mixtures and to identify test methods that could indicate incompatibility present in the mixtures. These results will form a basis for recommending a maximum safe level of sandstone in asphalt mixtures.

MATERIALS AND METHODS

Materials

Asphalt materials used in this research have been gathered from across the state of Arkansas. They consist of asphalt plant mixtures, aggregates, and binders from different plants in the state. The asphalt plant mixtures were reheated in the lab to compaction temperature, split according to AASHTO R 47, and compacted according to AASHTO R 83. The lab mixtures were prepared in two different ways. The first method was to prepare the mixtures while exactly following the given mix design from the plant. The second method was to adjust the level of sandstone in mix. For each of the given mix designs, three mixtures were prepared and tested (One at the base level of sandstone, two with altered levels of sandstone). That method specifies six lab mixtures: 2 with 40% sandstone, 2 with 63% sandstone, and 2 with 86% sandstone. The goal of analyzing the mixtures in such a way was to analyze two different mixtures with high, medium, and low levels of sandstone.

For the mixtures with altered levels of sandstone, limestone was substituted where sandstone was taken away. The different quantities of sandstone served as the basis for the naming of each of the mixtures: ‘L’ refers to low sandstone, ‘M’ refers to medium sandstone, and ‘H’ refers to high sandstone. However, altering a mix design cannot be done like this without first accounting for some of the other factors of a mix, such as the gradation and the binder content. In an attempt to match the base mix design as much as possible, the gradations were selected on the altered aggregate to match the base gradations as closely as possible. The overall gradations for each of these mixes can be seen in Appendix II. For one mix with altered sandstone, ‘Mix AH,’ sandstone had to be added to the blend in order to increase the overall sandstone content to 86%. In this case, limestone and river gravel were removed from the mixture to accomplish this. For each of the other mixes, sandstone chip was able to be replaced by a similar limestone chip while exactly mimicking the gradation. A summary of these mixes can be found in Table 1. In this table, quantities of different aggregate species, nominal maximum aggregate size (NMAS), and the method of preparation (Lab mix lab compacted vs. Plant mix lab compacted) can be found.

Table 1. Summary of tested mixtures

Mix:	NMAS	% Sandstone	% Limestone	% River Gravel	% RAP	PMLC/ LMLC
Mix A	12.5 mm	63 %	18%	19%	N/A	PMLC
Mix AL	12.5 mm	40%	41%	19%	N/A	LMLC
Mix AM	12.5 mm	63%	18%	19%	N/A	LMLC
Mix AH	12.5 mm	86%	8%	6%	N/A	LMLC

Mix B	9.5 mm	86%	N/A	N/A	14%	PMLC
Mix BL	9.5 mm	40%	46%	N/A	14%	LMLC
Mix BM	9.5 mm	63%	23%	N/A	14%	LMLC
Mix BH	9.5 mm	86%	N/A	N/A	14%	LMLC

The other difficulty in preparing mixes with altered levels of a specific aggregate is adjusting the binder content. This should ideally be done by performing a full Superpave mix design, however, this project did not have the time or resources to accomplish this. In order to best mimic this, the binder content estimation equations from the Asphalt Institutes SP-2 document (1996) were used to accomplish this. These equations are represented by Equations (1-5). In regard to Equation (1), the Asphalt Institute mentions that the 0.8 multiplier can be altered at the discretion of the designer to accommodate the absorption of the aggregate blend. In lieu of this, four of the given mix designs were analyzed regarding their binder content and aggregate blend absorptions. Equations (1-5) were analyzed for each of the given mix designs to calculate the actual value of this absorption multiplier (the given 0.8 value in Equation (1)). Using this, a linear trend was developed to accommodate for the absorption of the aggregate blend in the binder content of the mix. The trend was chosen as linear to best accommodate the evident trend as well as the low quantity of data points; it can be seen in Figure 2. The final absorption multipliers and binder contents can be found in Table 2.

$$G_{se} = G_{sb} + 0.8(G_{sa} - G_{sb})$$

Equation (1)

$$V_{ba} = \frac{P_s * (1 - V_a)}{\left(\frac{P_b}{G_b} + \frac{P_s}{G_{se}}\right)} * \left(\frac{1}{G_{sb}} - \frac{1}{G_{se}}\right)$$

Equation (2)

$$V_{be} = 0.176 - 0.0675(S_n)$$

Equation (3)

$$W_s = \frac{P_s * (1 - V_a)}{\left(\frac{P_b}{G_b} + \frac{P_s}{G_{se}}\right)}$$

Equation (4)

$$P_{bi} = \frac{G_b * (V_{be} + V_{ba})}{(G_b * (V_{be} + V_{ba})) + W_s} * 100 \qquad \textit{Equation (5)}$$

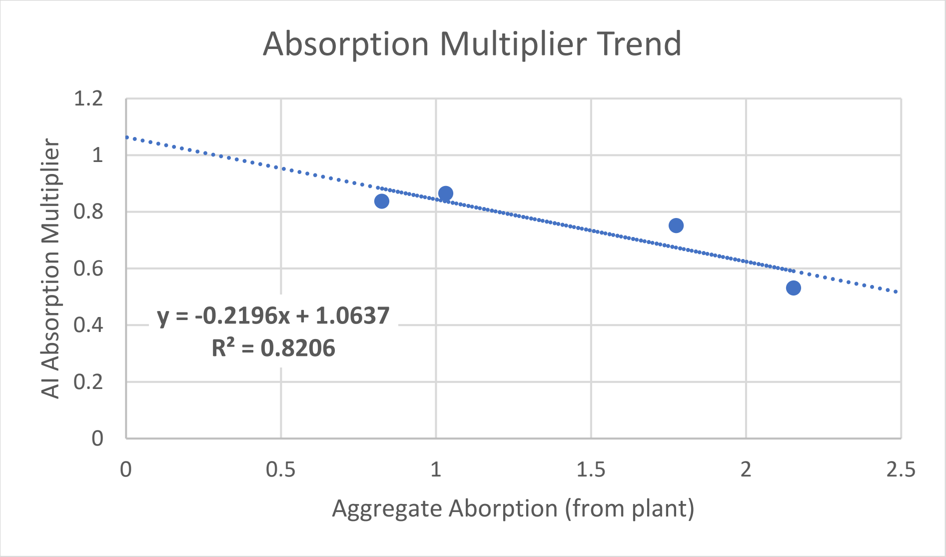

Figure 2. Asphalt Institute "Absorption Multiplier Trend"

Table 2. Asphalt binder contents for lab mixes

Mix:	Aggregate Blend Absorption	% Binder Content
Mix A (Low)	1.334	5.72%
Mix A (Medium)	1.775	5.7%
Mix A (High)	1.781	5.59%
Mix B (Low)	1.832	5.55%
Mix B (Medium)	1.993	5.68%
Mix B (High)	2.154	5.5%

Methods

Each of the different mixtures analyzed in this research, both lab and plant, were subjected to six different performance tests. These tests will help to round out the knowledge of the rutting and cracking potential, as well as the moisture resistance of each mixture. The tests can be seen in Table 3. According to available literature (Copeland et al. 2007), it is most likely that the results of incompatibility between the aggregate and binder will be most evident in the moisture resistance testing. This is because it is well researched and documented that moisture will decrease the adhesive properties of the asphalt binder. However, also based on the current body of research it is difficult to definitively say that the effects of incompatibility will not be seen in any of the other performance testing methods.

Table 3. Summary of test methods

TESTING METHOD	SPECIFICATION
BULK SPECIFIC GRAVITY	AASHTO T 331
DYNAMIC MODULUS & FLOW NUMBER	AASHTO T 378 & R 84
I-FIT	AASHTO TP 124
TENSILE STRENGTH RATIO	AASHTO T 283
HAMBURG-WHEEL TRACK TESTING	AASHTO T 324
IDEAL-CT	ASTM D8225-19

It should be noted that many of these test methods have sensitivities to other factors that are not directly analyzed by this study. Most of these sensitivities deal with the NMAS, presence of RAP, and binder content of a mixture (Zhou 2019, Rafiq et al. 2020, Casillas et al. 2019). So, the analysis for all of this testing should account for these factors. It should also be noted that many of the concerns for the usage of sandstone in asphalt mixtures relate to the high absorption and pore ratio of the aggregate (McCann et al. 2011), so the absorption of the aggregate blend in each mixture will also be analyzed in relation to its performance.

RESULTS AND DISCUSSIONS

The following test methods were performed on all of the LMLC and PMLC mixtures. The results section will focus mostly on the LMLC specimens that do not contain an anti-stripping agent and differing levels of sandstone. This will allow for the analysis of the effects of sandstone content on the performance of these mixtures. This section will often refer to mixes as

‘A’ or ‘B’, these however, will be specifically referencing the LMLC mixes.

Dynamic Modulus

The dynamic modulus test was performed according to AASHTO T 378, in which a 100mm by 150mm specimen is subjected to loading frequencies of 0.1 Hz, 1.0 Hz, and 10 Hz at 4°C, 20°C, and 40°C (at 40°C, the specimens were also tested at 0.01 Hz). The results were then transformed using time-temperature superposition; the final “master curve” can be seen in Figure 3. Previous studies have established that the master curve can be used to rank the cracking potential of a mixture, based on the upper portion of the curve (Park & Kim 2013), and the rutting potential of a mixture, based on the lower portion of the curve (Lacroix & Kim 2014). NCHRP 673 more specifically notes the dynamic modulus as a predictor for alligator cracking and longitudinal cracking. It should also be noted that analyzing the dynamic modulus for the cracking and rutting potential of an asphalt mixture is based on the susceptibility of the mixture to microdamage. This contrasts with other cracking tests that are based on the macrodamage or fracture energy of a specimen (Underwood & Braham 2019).

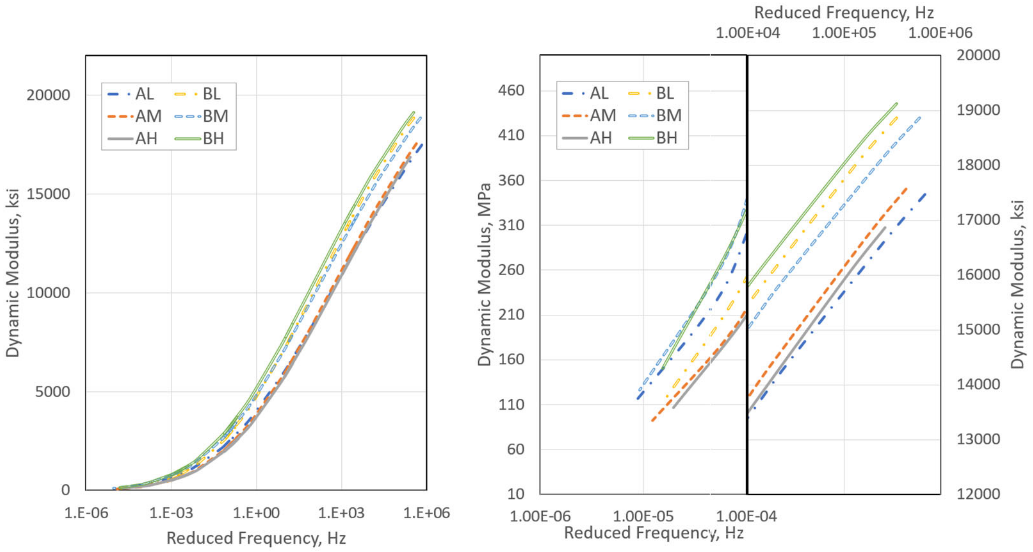

Figure 3. (a.) Dynamic modulus master curve. (b.) Master curve focused on the portions of interest.

Based on the shown master curves, the mixtures show two groupings regarding their cracking potential: Mixes AL, AM, and AH are grouped together, and above that portion, mixes BL, BM, and BH are grouped together. Within these groupings, there is inconsistency as to effects of the altered level of sandstone on the mixture's performance. While it can be seen that the overall worst performing mixture has 'high' levels of sandstone (AH), it can also be seen that the overall best performing mixture has 'high' levels of sandstone. Based on the data seen on the upper portion of the dynamic modulus master curve, it can be inferred that this is not a powerful test method for analyzing the performance effects of sandstone usage in an asphalt mixture.

The lower portion of the dynamic modulus master curve, that is often used to analyze the rutting potential of an asphalt mixture, also shows two clusters of results. The better performing cluster of results includes mixes BH, BM, and AL, while the worse performing cluster includes the mixes AH, AM, and BL. Notably, both of these clusters still include a mixture of 'low', 'medium', and 'high' levels of sandstone. Based off of this, it seems that the lower portion of the dynamic modulus master curve is not a powerful analysis method for discerning the performance effects of sandstone usage in an asphalt mixture either.

Cracking Resistance

In order to further analyze the cracking resistance of the tested asphalt mixture, this study also performed the IDEAL-CT test (ASTM D8225) and the I-FIT test (AASHTO TP-124). Both of these test methods are performed at intermediate temperatures (25°C) and determine the cracking resistance of an asphalt mixture through analysis of the fracture energy found from performing each respective test. The completed test results for these two methods compared to the level of sandstone in each mix can be seen in Figure 4.

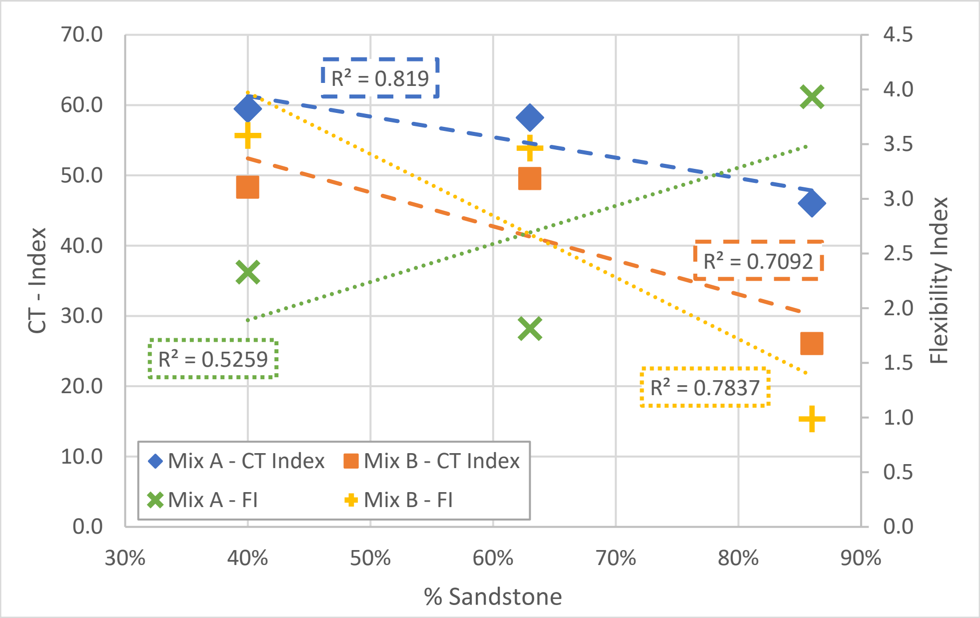

Figure 4. Cracking test results compared to sandstone content

This figure shows that the CT-Index shows a negative trend with the percent sandstone content in a mixture. It should also be noted that the CT-Index should be above 50 for an adequate performing mixture (Camarena-Castillo et al. 2021); NCHRP 195 also noted a range of average CT-Indices from 31 – 255. Based on these results, it can be presumed that BH (Mix B with 86% sandstone), represents an inadequate mixture in regards to the cracking potential, based on the IDEAL-CT test (CT-Index = 28). The poorer performance of the mixes from group B, may be due to the presence of RAP in the mixture; NCHRP 195 also indicated a roughly 70% decrease in CT-Index when RAP/RAS was present.

Meanwhile, the Flexibility Index (FI) showed that the mixtures from ‘A’ developed a higher resistance to cracking with an increase in sandstone present in the mixture. The results for

‘B’ mixtures however, agreed with the Ideal-CT, showing a decrease in cracking resistance with an increase in sandstone in the mixtures. According to the available literature on this test method, a FI of below 2.0 should represent an inadequate mixture regarding cracking performance (Ozer et al 2015). It can be seen that mixtures ‘AM’ and ‘BH’ both fall short of this recommendation. The tabulated results can be seen in Table 4; this table interestingly shows that the higher values for the CT-Index, tend to be linked to a higher variation of test results. We can also see a high variation across all of the Flexibility Index results.

Table 4. Tabulated results for the CT-Index and Flexibility Index

Mixture	CT Index		Flexibility Index	
	AVG.	COV	AVG.	COV
AL	59.47	20.11	2.33	38.20
AM	58.22	17.09	1.81	25.96
AH	46.03	11.36	3.93	33.08
BL	48.32	69.01	3.58	53.91
BM	49.53	29.62	3.46	52.60
BH	26.07	13.57	0.99	63.63

Between these two test methods, it can be seen that in three out of the four shown trends that there is a negative link between the percentage of sandstone and the performance of the mixtures regarding its resistance to cracking. Another interesting thing to note about these results, is that there is consistently the largest change in performance between the mixtures with medium levels of sandstone (63%) and those with high levels of sandstone (86%). This trend carries the implications that somewhere between 63% and 86% sandstone, there is an increase in the impact of sandstone in the mixture, regarding the mixture’s resistance to cracking.

Rutting Resistance

For the rutting resistance of an asphalt mixture, the Flow Number test was performed per

AASHTO T 378. This test is often referred to as the dynamic creep test. In this method, a 100mm x 150mm specimen is subjected to haversine loadings at a frequency of 1 Hz at, until either of the termination conditions are met (10000 cycles or 50000 microstrain). According to AASHTO T 378, this test should be run at the "High Adjusted PG Temperature" at 50% reliability; for the case of this experiment, that temperature was 60.1°C for each mixture. This test yielded a flow number for each specimen, these can be seen in Figure 5. The flow number parameter is defined by the minimum permanent strain rate found during the testing of the sample.

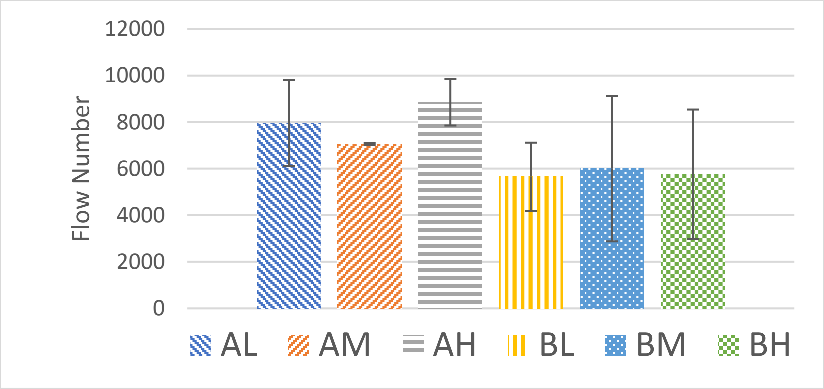

Figure 5. Flow Number Results

NCHRP 673 recommends a minimum flow number of 740 for high-capacity pavements. Knowing this we can see that the each of these mixtures has a high rutting resistance according to this test method. We can also see that all mixes from 'A' exhibit a higher performance than mixes from 'B'. This is likely due to the smaller NMAS within the 'B' mixes, as reported in Bhasin et al 2004. This information leads us to believe that the NMAS of a mixture has more impact on the Flow Number results than the sandstone content.

Moisture Resistance

To analyze the moisture resistance of each of these mixtures, the Hamburg Wheel Tracking Test (HWT) and the Tensile Strength Ratio (TSR) have been analyzed. These tests were performed according to AASHTO T 324 and AASHTO T 273 respectively. It should be noted that based on available literature, the moisture susceptibility of an asphalt mixture is the most likely factor to be impacted by incompatibility between the aggregate and binder (Hossain & Roy 2018, Copeland et al 2007, Horgnies et al 2011, Zhang et al 2015).

The results for the TSR testing can be found below in Figure 6. These results show that the 'A' and 'B' mixtures present a negative trend between the percent of sandstone in the mixture and the final TSR. A study performed by Do et al (2020) also noted the importance of analyzing the moisture conditioned strength of the specimens along with the TSR. Keeping this in mind, it can be seen that the 'A' mixes trend negatively for the moisture conditioned strength and sandstone content. However, we also see that the 'B' mixes have a slight positive trend with this relationship. The other trend to note in this figure is, similarly to the IDEAL-CT and I-FIT tests, the largest drop in TSR occurs between 63% and 86% sandstone content.

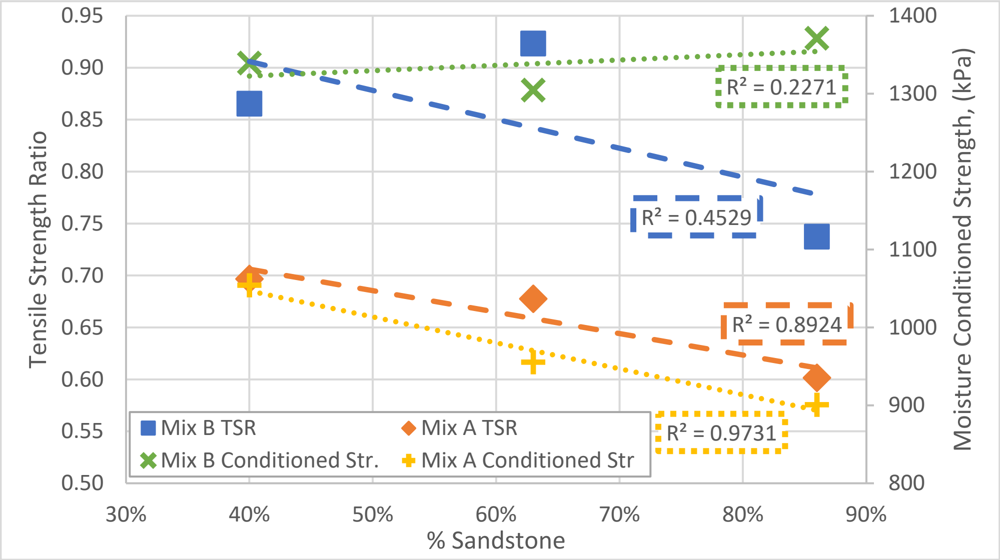

Figure 6. Tensile Strength Ratio and Moisture Conditioned Strength compared to sandstone

content

While the current ARDOT pavement specifications do not require the TSR be performed during the mix design process, a similar test, Retained Stability is required. In these specifications the minimum ratio for the conditioned strength is 80%. It can be seen in Figure 6 that none of the results for the 'A' mixes achieve this limit, and only mix BL and BM do achieve this limit. Following the shown trendline in this figure for the 'B' mixes, a maximum sandstone content of 78% would achieve this limit. It should be noted, however, that the TSR has a harsher moisture conditioning process than the Retained Stability test.

While literature has noted that the HWT test can be an indicator of rutting potential and can show a strong correlation with the Flow Number test (Bhasin et al 2004), it was expected that in this study, the moisture susceptibility of these mixtures would outweigh the rutting susceptibility for this test method. The results of the Hamburg Wheel Tracking test can be seen comparing the different levels of sandstone present in the mixtures to the resulting rut depths in Figure 7.

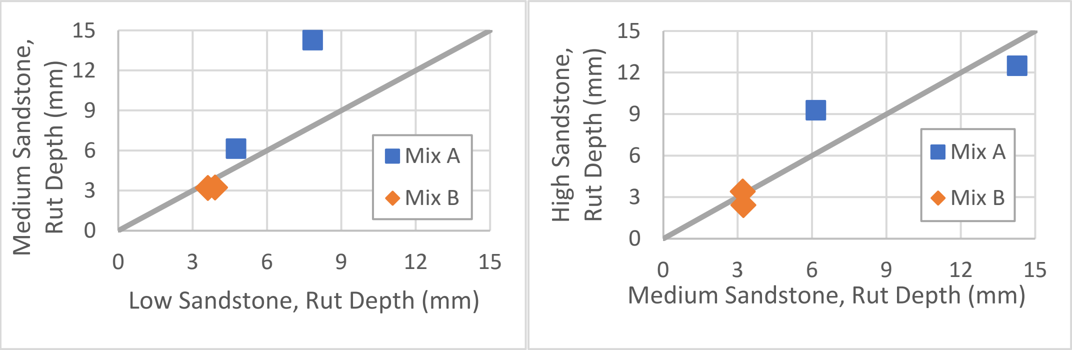

Figure 7. Line graphs displaying the impact of differing sandstone contents

The first thing to note about these results is the overall superior performance of the 'B' mixes when compared to the 'A' mixes. Rafiq et al (2021) notes that the results from the HWT test are very sensitive to RAP; with the presence of RAP being one of the most notable differences between the 'A' and 'B' mixes, this is likely the reason for this difference in performance. Research was not found on the impact of NMAS on the HWT testing results, however it is suspected that the smoother surface often present on smaller NMAS mixtures may have reduced the amplitude of the repetitive loadings from the steel wheel in the HWT device. Another possible cause for this difference is the mineralogical differences between the tested sandstones; based on the Hartshorne sandstone mineral compositional ranges presented by Yin (2017), there could be up to a roughly 30% compositional difference between these two sandstones. Figure 7 also clearly shows that for this method, the largest drop in performance occurs between 40% sandstone and 63% sandstone (primarily for the 'A' mixes). It should also be noted that all 'A' mixes also experienced a stripping point of inflection (SIP), indicating severe moisture damage, as seen in Figure 8.

Figure 8. Hamburg Wheel Track Testing specimen with visible evidence stripping

ARDOT pavement specifications also do not require the HWT test to be performed on mixes. Instead, the Loaded Wheel Tracking (LWT) test is used in place of this method. For this test, mixtures are required to have a maximum rut depth of 8.0mm. The LWT test is also a less harsh method than the HWT, with a rubber casing being used around the loading wheel, instead of just a steel wheel (as in the HWT test). This limit serves as the most appropriate comparison and limit for Arkansas based mixtures. Based on the results of this test, none of the 'B' mixes exceed this limit, however, both the medium sandstone and high sandstone mixtures from 'A' exceed this limit.

Another lens through which to view this data is comparing the results to the absorption of the aggregate blend. This can be seen in Figure 9. While this develops a high r-squared value for the HWT testing results, it also reveals the trend (specifically for the HWT testing) that for 'A' mixes, more absorptive aggregates lead to worse performance, while in 'B' mixes, more absorptive aggregates lead to higher levels of performance. These two trends reveal the fact that the performance of sandstone in asphalt mixtures, especially regarding the moisture resistance, is not solely based on the absorptiveness of the aggregate. Furthermore, the mineralogical composition of these sandstones likely has more impact on the mixture's moisture resistance, as noted in previous studies (McCann et al 2005, Zhang et al 2015).

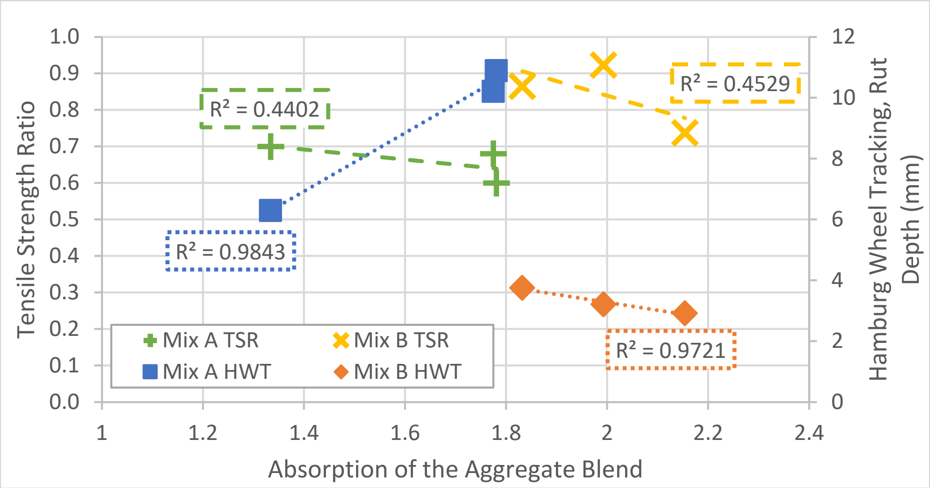

Figure 9. Moisture damage testing compared to absorption

Discussions

A summary of all of the results for both the PMLC and LMLC mixes can be found in Table 5. This table also serves as a visible representation of the adequacy of the mixtures based on each of the respective test methods. Based on this table, we can see that the highest concentration of mixes with inadequate results to the performed test methods occurs in the mixes with higher levels of sandstone; mixes ‘AM’, ‘AH’, and ‘BH’ all fail to meet the previously prescribed limits for at least three of the performed test methods.

Furthermore, numerical values were placed on the performance of each result in this table, assigning the superior performing results with a value of 1.0, adequately performing results with a 0.5, and poor performing results with a value of 0.0. This analysis allows us to apply a numerical performance value to each of these mixtures, The average numerical result for each level of sandstone can be seen in Table 5. This validates two trends. Firstly, mixtures tend to perform poorly with no antistripping agent and higher sandstone percentages, and secondly, the biggest drop in performance occurs between 63% sandstone and 86% sandstone. Furthermore, this drop-off in performance implies that the relationship between sandstone content and asphalt performance may not be best represented by a linear fit, meaning that there is likely a point in this range that the performance drops off steeply with the addition of more sandstone.

Table 5. Summary of test results and prescribed adequacy

Test	Parameter	Mixture							
		A	B	AL	BL	AM	BM	AH	BH
AASHTO T 324	Rut Depth (mm)	3.01	3.08	6.29	3.76	10.21	3.22	9.46	2.92
	SIP	n/a	n/a	14607	n/a	15910	n/a	15589	n/a

AASHTO T 273	**TSR**	83%	85%	70%	87%	68%	92%	60%	74%
	Conditioned STR. (kPA)	1144.8	1435.9	1054.3	1339.5	955.53	1304.7	900.96	1371.3
AASHTO TP 124	**Flexibility Index**	6.93	2.08	2.33	3.58	1.81	3.46	3.93	0.99
ASTM D8225	**CT - Index**	71.6	33.4	59.5	48.3	58.2	49.5	46	26.1
AASHTO T 378	**Cracking Resistance**	18221	18581	17475	18872	17564	18866	16860	19128
	Rutting Resistance	44	77	112	112	92	127	107	151
	Flow Number	2099	1780	7962	5656	7068	6002	8858	5765
Numerical Performance:		0.7		0.58		0.54		0.38	

Results indicative of superior performance

Results indicative of adequate performance

Results indicative of poor performance

CONCLUSIONS

In this study the performance effects of asphalt mixtures containing variable amounts of sandstone were analyzed. The performance of sandstone in Arkansas has been questioned by recent research. To more deeply understand the relationship between sandstone and HMA performance, six widely used test methods were performed on mixtures with varying levels of sandstone. From this, the following conclusions have been drawn:

- Absorption of the aggregate blends did not serve as an overall relevant predictor for the performance of the tested asphalt mixtures. Absorption was able somewhat predict the performance of the mixtures relative to their base mixture (Equal NMAS and RAP content)

- According to this research, there is a link between higher levels of sandstone and poorer performance in the studied test methods.
- Three of the six test methods showed the most severe drop in performance occurring between 63% sandstone content and 86% sandstone content. Conservatively, this would suggest the need in Arkansas for placing a maximum limit of sandstone usage in asphalt mixtures without an anti-stripping agent at 60%. Further research can better define the exact relationship and trend between sandstone and HMA performance in Arkansas.
- In this study, the Tensile Strength Ratio appeared to show the performance effects of sandstone in HMA most reliably. This test method most reliably showed the trends of this data while being less sensitive to NMAS and RAP than other test methods utilized in this study.
- This study also confirmed the ability of mixtures to display adequate levels of moisture resistance without an anti-stripping agent, with up to a certain sandstone content. Overall, we can see there is likely some point between 63% and 86% sandstone in which a severe decrease in performance occurs.

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APPENDIX I – NOTATION:

- G_{se} = *Effective specific gravity*
- G_{sb} = *bulk specific gravity*
- G_{sa} = *Apparent specific gravity*
- V_{ba} = *Volume of absorbed binder*
- P_s = *Percent of aggregate*
- V_a = *Volume of air voids*
- P_b = *Percent of binder*