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Physical Properties and Durability Testing for Calcined Bauxite and Its Alternatives

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Abstract—**Calcined Bauxite (CB) is the most common aggregate used for high friction surface treatment in Missouri. However, CB has very limited sources, which makes it more expensive than locally available aggregates. Consequently, this study evaluated CB's feasible alternatives through physical properties testing and durability testing. Alternative aggregates were Earthworks, Meramec River Aggregate, Steel Slag, Rhyolite, Black Diabase, Quartzite, Flint Chat, and Potosi Dolomite. The physical properties testing contained aggregate gradation, specific gravity and absorption, and uncompacted void content. Durability tests involved Los Angeles (LA) abrasion, Micro-Deval (MD), sodium sulfate soundness, water-alcohol freeze thaw, and acid-insoluble residue. The relationship between LA and MD mass losses was explored. A direct linear relationship was detected between the LA and MD mass losses. The MD was found to be more sensitive for aggregate screening than LA. Based on this study, Meramec River Aggregate was the most favorable alternative to CB followed by Earthworks**

Index Terms—**High Friction Surface Treatment, Calcined Bauxite, High Friction Aggregate, Micro-Deval, Los Angeles.**

I. Introduction

A. *High Friction Surface Treatment*

High friction surface treatment (HFST) applications consist of small size high friction aggregate topping on an epoxy base. High friction surface treatment was used to compensate for the deficiencies of geometric designs tight curves with small radii, small superelevation rates [1, 2], or locations where moving fixed objects to clear the sightline was impossible [2, 3]. The tires of vehicles cause more polishing on the horizontal curved sections compared to the tangent sections as a result of generated shear forces on the pavement surfaces [1, 4]. Crashes on the horizontal curves occur generally due to excess polishing and losing the safety skid friction [4]. Therefore, it was recommended to apply the HFST on horizontal and ramp curves with radii of curvatures less than 1500 ft [5] and apply at the beginning of the horizontal curves—point of curve—till the ending of the curve (point of tangency) [2].

Many studies concluded that using HFST had a considerable impact on reducing the rate of crashes at curves and intersections and wet surface conditions [2, 6–10]. It was concluded that using HFST on curves dropped the crashes by 60 to 90% [7, 9]. Moreover, before/after total crash reduction of 100, 90, and 57% were reported by the Pennsylvania Department of Transportation (DOT), Kentucky DOT, and South Carolina DOT, respectively [2]. It was reported that HFST decreased wet condition crash rates by 30% [7, 10]. Missouri Department of Transportation (MoDOT) has used HFST since 2013 [11] to restore pavement surface friction where traffic has worn down pavement surface aggregates and to improve wet crash locations. In 1976, the use of Calcined Bauxite (CB) in HFST showed significant crash reductions of 31% for 800 intersections in London [6, 8]. Calcined Bauxite is the most common aggregate used in HFST [11–14]. Currently, Calcined Bauxite is the primary aggregate used for HFST in Missouri [12–14].

B. *High Friction Aggregates' Requirements*

The gradation requirements for HFST's aggregates in the other states are demonstrated in Table 1a. These requirements were fairly consistent, with most states requiring the #4 to be analyzed and a few states requiring the #30 to be analyzed. Only Michigan replaced the #6 with the #8. The physical properties of the aggregates were specified in every state. The most common requirements are listed in Table 1b by state. Alaska was the most flexible state for its high friction aggregate requirements according to the retrieved specifications. Table 1c lists some other requirements that were not common among states. Wisconsin was the only state that had an enhanced friction surface treatment (EFST) specification instead of an HFST specification, and it was also the only state to require the fine aggregate angularity to be measured using uncompacted void content (UVC).

High friction surface treatment applications are used to enhance the friction property on special roadways locations, so the aggregates' durability used in these applications is important. Durability testing included Los Angeles abrasion (LAA) and Micro-Deval (MD). The MD device—developed in France in the 1960s—was used to characterize aggregates' durability and resistance to polishing, abrasion, and grinding in the existence of water [1, 4, 15]. Water simulated environmental effects, which were considered better judgments of aggregate durability compared to the LAA test [4, 16, 17]. The existence of the water and the use of smaller steel balls than the steel balls used in the LA test reduced the impact action. Contrarily, surface wear by grinding and abrasion was prevalent [4].

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Table 1. Requirements of high friction aggregates' physical properties by state [18–35]

(a) Aggregate Gradation Requirements

States	Gradation (% passing)					Specification	References
	#4	#6	#8	#16	#30		
Missouri	100% Min.	95% Min.	–	5% Max.	–	AASHTO T 27	[18]
Alabama	100% Min.	95% Min.	–	5% Max.	–	AASHTO T 27	[19]
Florida	100% Min.	95% Min.	–	5% Max.	–	AASHTO T 27	[20]
Georgia	100% Min.	95% Min.	–	5% Max.	–	AASHTO T 27	[21]
Illinois	100% Min.	95% Min.	–	5% Max.	–	AASHTO T 27	[22]
Iowa	100% Min.	95% Min.	–	5% Max.	–	AASHTO T 27	[23]
Kentucky	100% Min.	95% Min.	–	5% Max.	–	AASHTO T 27	[24]
Pennsylvania	100% Min.	95% Min.	–	5% Max.	–	AASHTO T 27	[25]
S. Carolina	100% Min.	95% Min.	–	5% Max.	–	AASHTO T 27	[26]
S. Dakota	100% Min.	95% Min.	–	5% Max.	–	AASHTO T 27	[27]
Tennessee	100% Min.	95% Min.	–	5% Max.	–	AASHTO T 27	[28]
Indiana	100% Min.	95% Min.	–	5% Max.	1% Max.	AASHTO T 27	[29]
Wisconsin	100% Min.	95% Min.	–	5% Max.	1% Max.	AASHTO T 27	[30]
Alaska	–	95% Min.	–	5% Max.	–	AASHTO T 27	[31]
California	–	95% Min.	–	5% Max.	–	AASHTO T 27	[32]
Texas	–	95% Min.	–	5% Max.	–	AASHTO T 27	[33]
Virginia	–	95% Min.	–	5% Max.	–	AASHTO T 27	[34]
Michigan	98% Min.	–	30-70%	5% Max.	1% Max.	AASHTO T 27	[35]

(b) Los Angeles Abrasion and Aluminum Oxide Content Requirements

States	Aggregates	Los Angeles Abrasion		Aluminum Oxide Content		References
		Threshold	Specification	Threshold	Specification	
Missouri	Calcined Bauxite (CB)	20% Max.[a]	AASHTO T 96	87% Min.	ASTM C25	[18]
Alabama	CB	20% Max.[a]	AASHTO T 96	87% Min.	ASTM C25	[19]
Illinois	CB	20% Max.[a]	AASHTO T 96	87% Min.	ASTM C25	[22]
Pennsylvania	CB	20% Max.[a]	AASHTO T 96	87% Min.	ASTM C25	[25]
S. Carolina	CB	20% Max.[a]	AASHTO T 96	87% Min.	ASTM C25	[26]
S. Dakota	CB	20% Max.[a]	AASHTO T 96	87% Min.	ASTM C25	[27]
Florida	CB	10% Max.[b]	AASHTO T 96	87% Min.	ASTM C25	[20]
Indiana	CB	10% Max.[b]	AASHTO T 96	87% Min.	ASTM C25	[29]
Texas	CB	10% Max.[b]	ASTM C131	87% Min.	ASTM C25	[33]
California	Blend of CB	10% Max.[b]	CT 211	–	–	[32]
Alaska	Blend of CB	–	–	–	–	[31]
Tennessee	CB	–	–	87% Min.	ASTM C25	[28]
Michigan	CB	–	–	87% Min.	ASTM C25	[35]
Virginia	CB	20% Max.[a]	AASHTO T 96	–	–	[34]
Iowa	CB	20% Max.[a]	AASHTO T 96	–	–	[23]
Wisconsin	Natural or Synthetic	25% Max.[a] & 10% Max.[b]	AASHTO T 96	–	–	[30]

(c) Finess Modulus, Fine Aggregate Angularity, and Hardness Test Requirements

States	Fineness Modulus	Fine Aggregate Angularity		Hardness test		References
		Threshold	Specification	Threshold	Specification	
Indiana	–	–	–	8 Min.	Mohs Scale	[29]
Michigan	2.28–22.81	–	–	–	–	[35]
Wisconsin	–	45% Min	AASHTO T 304	–	–	[30]

[a] After 500 revolutions.

[b] After 100 revolutions.

Table 2 demonstrates the high friction aggregates' durability testing by state. It is worth noting that there was significantly less agreement between states on which durability tests are important for the aggregates than the required physical properties. Wisconsin is the only state that was found to have an EFST standard rather than an HFST standard.

Table 2. High friction aggregates' durability testing by state [28–30, 32–34]

States	Micro-Deval		Acid Insolubility		Magnesium/ Sodium Sulfate Soundness		References
	Threshold	Specification	Threshold	Specification	Threshold	Specification	
Tennessee	5% Max.	ASTM D7428	–	–	–	–	[28]
Virginia	5% Max.	AASHTO T-327	–	–	–	–	[34]
Wisconsin	15% Max.	ASTM D7428	–	–	–	–	[30]
California	–	–	90% Min.	ASTM D-3042	30% Max.	ASTM C88	[32]
Indiana	–	–	–	–	12% Max.	AASHTO T 104	[29]
Texas	–	–	90% Min.	Tex-512-J	30% Max.	Tex-411-A	[33]

Calcined Bauxite has very limited sources, which makes it more expensive than locally available aggregates. Thus, this study evaluated CB's feasible alternatives—through a testing program—for use in HFST applications. The study focused on the physical properties testing and durability testing of aggregates. These tests were run to classify the aggregates and identify the routine tests that investigate the performance of the proposed aggregates as HFST materials. Therefore, physical properties (e.g., aggregate gradation, specific gravity and absorption, and UVC) and durability tests (e.g., LAA, MD, sodium sulfate soundness, water-alcohol freeze thaw, and acid-insoluble residue) were conducted. Comparisons between aggregates were achieved through analyzing the physical properties testing and durability testing results.

II. MATERIALS AND METHODS

A. Materials

Calcined Bauxite and eight alternative aggregates were selected for testing. These aggregates were selected as possible alternatives to CB. Table 3 presents the received sizes.

B. Methods

Table 3 illustrates the aggregate testing matrix that shows a summary of the experimental design that was detailed in the following sections. Two categories of testing were followed in the testing program: the first category was for the physical properties testing and the second category was for durability testing. See Table 3 for more details. Each category of testing included testing subdivisions. Physical properties testing was divided into aggregate gradation, specific gravity & absorption, and UVC of fine aggregates. Durability testing contained LAA, MD, sodium sulfate soundness, water-alcohol freeze thaw, and acid-insoluble residue.

B.1. Aggregate Physical Properties Testing

The aggregate physical properties were tested for each source of the aggregate to classify the aggregates. Aggregate physical property tests are normally quick and simple. They are also routinely performed on aggregates being used for a variety of purposes.

B.1.1. Aggregate Gradation

The test was conducted following ASTM C136/C136M-19 on #6 to #16 (#6 - #16). See Table 3. The main purpose of the gradation test was to check if the aggregates matched the current MoDOT requirements for HFST (NJSP-15-13B) [18].

B.1.2. Specific Gravity and Absorption of Aggregates

This test was conducted following ASTM C128 – 15 for fine aggregates' gradations passed from #6 and retained on #16 [(#6 - #16), see Table 3 and Table 4]. Specific gravity was expressed as bulk specific gravity (G_{sb}) and bulk specific gravity saturated surface dry (G_{sb} SSD).

B.1.3. Uncompacted Void Content of Fine Aggregate

The UVC test was conducted following ASTM C1252 − 17. The test was used as an indirect measure of fine aggregate's angularity. Test method B (#6 - #8) and test method C [(#6 - #16), note Table 3 and Table 4] were used.

B.2. Aggregate Durability Testing

The aggregates used in the HFST application were exposed to outside weather, de-icing, and snowplowing, so the durability of the aggregates is important to be tested.

B.2.1. Los Angeles Abrasion Test

The LAA test was conducted following ASTM C131/C131M – 20 using grading D, note Table 3. The LAA test was carried out to evaluate the quality, hardness, and durability of tested aggregates subjected to impact and abrasion. The test provided information about aggregate toughness and degradation characteristics because the aggregates were subjected to heavyweights during compaction and after construction under traffic. The number of steel spheres (charges) and the number of revolutions were selected based on the selected grading according to the ASTM C131/C131M − 20.

B.2.2. Micro-Deval Test

The aggregates were tested for their degradation/polish resistances in the MD apparatus. The MD test was utilized to explore aggregates' durability and resistance to polishing, abrasion, and grinding in the existence of water [1, 4, 15]. Coarse aggregate and fine aggregate samples were tested. The coarse aggregate MD test was run following ASTM D6928 – 17 on aggregate size (3/8″ - #4), note Table 4. The samples were prepared according to the ASTM D6928 – 17 (Section 8.4). A total sample weight of 1500g was prepared by combining two portions. The first portion's weight was 750g that had (3/8″ - 1/4″) gradation. The second portion's weight was 750g that had (1/4″ - #4) gradation. The test was run for 105 and 180 minutes.

The fine aggregate MD test was run following ASTM D7428 – 15 with a sample weight of 500g. It was run on the CB gradation [(#6 - #16), see Table 4] for all nine aggregates for 5-, 15-, and 30-minutes run times. All of the weights for this test were reflected oven-dried aggregates.

B.2.3. Sodium Sulfate Soundness

The soundness of the aggregates using sodium sulfate was tested according to AASHTO T 104-99 (2011). Aggregates with a size (#4 - #6) were tested. The aggregate samples were put through 3 cycles of immersion and drying, then washed over #8 in running water for 30 minutes. The samples were then oven-dried at a temperature of 110 °C overnight and sieved over #8 for 15 minutes. Finally, the percentages of mass loss were calculated for aggregates.

B.2.4. Water-Alcohol Freeze Thaw

The water-alcohol freeze thaw resistance of the aggregates was tested following the MoDOT standard (106.3.2.14 TM-14). The test aimed to evaluate the soundness of the aggregates. Aggregates with size (#6 - #8) were tested, note Table 3. The tested aggregate samples were put through 10 cycles of freezing and thawing, then they were oven-dried at a temperature of 110 °C. The samples were sieved over #8 for 15 minutes. To evaluate the aggregates' soundness, the percentages of mass losses were calculated.

B.2.5. Acid-Insoluble Residue

The Aggregates were tested for their acid-insoluble residues. The test was run following ASTM D3042 – 17 on aggregates with (#6 - #8) size, see Table 3. The test estimated the percentages of insoluble residues in carbonate aggregates using a hydrochloric acid solution to investigate the carbonates' reactions. Calculating percentages of insoluble residues aimed to delineate the carbonate aggregates that polish excessively.

Table 3. Aggregate testing matrix [14]

Aggregate Testing	Aggregates Type (Commercial Name & Size)								
	Calcined Bauxite (GRIP Grain)	Earthworks (#6 × #16)	Meramec River Aggregate (Coarse Manufactured Sand)	Steel Slag (1″ × 0)	Rhyolite (#6 × #16)	Black Diabase (1/4″)	Quartzite (1″ × 0)	Flint Chat (#6 × #16)	Potosi Dolomite (9/16″ Clean)
Aggregate Gradation	#6 - #16	#6 - #16	#6 - #16	#6 - #16	#6 - #16	#6 - #16	#6 - #16	#6 - #16	#6 - #16
Specific Gravity & Absorption	#6 - #16	#6 - #16	#6 - #16	#6 - #16	#6 - #16	#6 - #16	#6 - #16	#6 - #16	#6 - #16
Uncompacted Void Content (UVC)	#6 - #8 #6 - #16	#6 - #8 #6 - #16	#6 - #8 #6 - #16	#6 - #8 #6 - #16	#6 - #8 #6 - #16	#6 - #8 #6 - #16	#6 - #8 #6 - #16	#6 - #8 #6 - #16	#6 - #8 #6 - #16
Los Angeles Abrasion (LAA)	Grading D		Grading D	Grading D	Grading D	Grading D			Grading D
Micro-Deval (MD)	3/8″ - #4 #6 - #16	3/8″ - #4 #6 - #16	3/8″ - #4 #6 - #16	3/8″ - #4 #6 - #16	3/8″ - #4 #6 - #16	3/8″ - #4 #6 - #16	3/8″ - #4 #6 - #16	3/8″ - #4 #6 - #16	3/8″ - #4 #6 - #16
Sodium Sulfate Soundness	#4 - #6		#4 - #6	#4 - #6	#4 - #6				#4 - #6
Water-Alcohol Freeze-Thaw	#6 - #8	#6 - #8	#6 - #8	#6 - #8	#6 - #8			#6 - #8	#6 - #8
Acid-Insoluble Residue	#6 - #8	#6 - #8	#6 - #8	#6 - #8	#6 - #8	#6 - #8	#6 - #8	#6 - #8	#6 - #8

Table 4. Specific aggregates' percentages/weights used in uncompacted void content, specific gravity, and Micro-Deval testing [14]

Gradation	Testing	Passing from - Retaining on					
		3/8″ - 1/4″	1/4″ - #4	#6 - #8	#8 - #10	#10 - #12	#12 - #16
3/8″ - #4	Micro-Deval (MD)	750g	750g				
#6 - #16	Specific Gravity, uncompacted void content (UVC), & MD			53.0%	21.1%	13.7%	11.9%

III. RESULTS AND ANALYSIS

In this section, the results of the physical properties testing and durability testing were discussed.

A. *Aggregate Physical Properties Testing Results*

The investigated aggregates in this study included CB and eight alternatives. The following tests results were discussed to evaluate and differentiate between the proposed aggregates.

A.1. Aggregate Gradation

The proposed aggregates were sieved as delivered from their respective sources into different sizes (#6 - #16) and then remixed in controlled manners to prepare specimens for the other physical and durability tests. An average of two replicated samples was computed and plotted in Figure 1. The gradation test was implemented to check if the aggregates matched the current MoDOT requirements for HFST (NJSP-15-13B) [18].

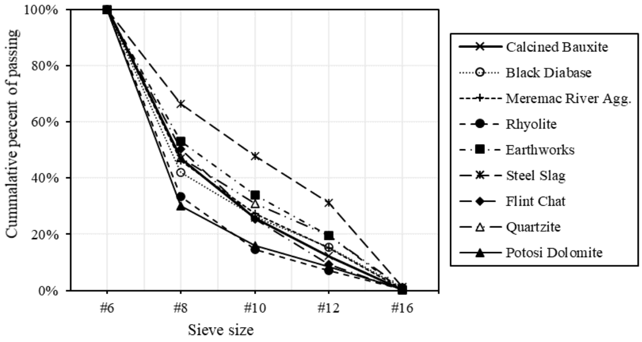

Figure 1. Particles' size distribution

A.2. Specific Gravity and Absorption

The specific gravity was tested on aggregates with (#6 - #16) size. The values of the specific gravities and water absorption percentages of the investigated materials are demonstrated in Table 5. The specific gravity values were the highest for CB. Steel Slag had the highest specific gravity values among the alternative aggregates, followed by Black Diabase. Meramec River Aggregate and Earthworks had the lowest specific gravity values. Steel slag had the highest absorption percentage, followed by Meramec River Aggregates, and then CB. The lowest absorption percentage was recorded for Rhyolite, followed by Black Diabase.

Table 5. The absorption and specific gravity results

Aggregate type	G_{Sb}	$G_{Sb\ SSD}$	Absorption (%)
Calcined Bauxite	3.271	3.354	0.187
Black Diabase	2.912	2.934	0.168

Meramec River Agg.	2.414	2.502	0.197
Potosi Dolomite	2.658	2.706	0.180
Rhyolite	2.544	2.573	0.167
Steel Slag	2.944	3.056	0.206
Earthworks	2.452	2.495	0.179
Flint Chat	2.522	2.569	0.179
Quartzite	2.598	2.569	0.170

A.3. Uncompacted Void Content

The UVC of fine aggregates was used as an indirect measure of the fine aggregates' angularities. The UVC percentages were calculated for CB and alternatives using test method C [CB gradation: (#6 - #16)] and test method B (#6 - #8). Test method C and test method B were discussed in the ASTM C1252 – 17. The test was conducted on two different gradations to assess the impacts of aggregates' gradations on the uncompacted void percentages. Figure 2 shows the UVC percentages before MD polishing. Flint Chat had the highest uncompacted void percentages, followed by Black Diabase, Potosi Dolomite, and Steel Slag. Meramec River Aggregate had the lowest UVC percentages.

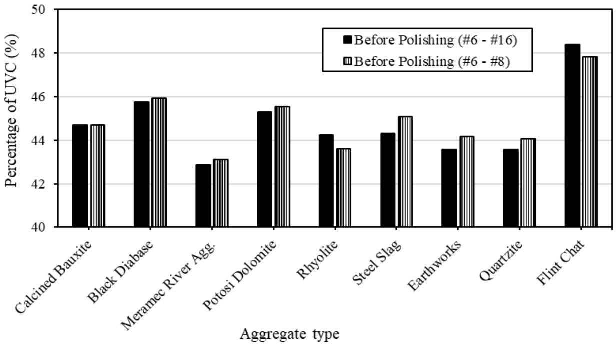

Figure 2. Percentages of UVC using two aggregates' sizes

Figure 3 shows the percentages of UVC for aggregates using (#6 - #16) gradation and (#6 - #8) size. The percentages were calculated for the aggregates using before Micro-Deval polishing (BMD), after 5-minutes of Micro-Deval polishing time (AMD 5), after 15-minutes of Micro-Deval polishing time (AMD 15), and after 30-minutes of Micro-Deval polishing time (AMD 30). The percentages of UVC decreased and reached the lowest values after 30-minutes of MD polishing time. Flint Chat had the highest percentages of UVC before and after polishing. Meramec River Aggregate showed the lowest percentages of UVC before and after polishing. For Meramec River Aggregate with (#6 - #16) gradation, it showed steady low percentages of UVC after polishing.

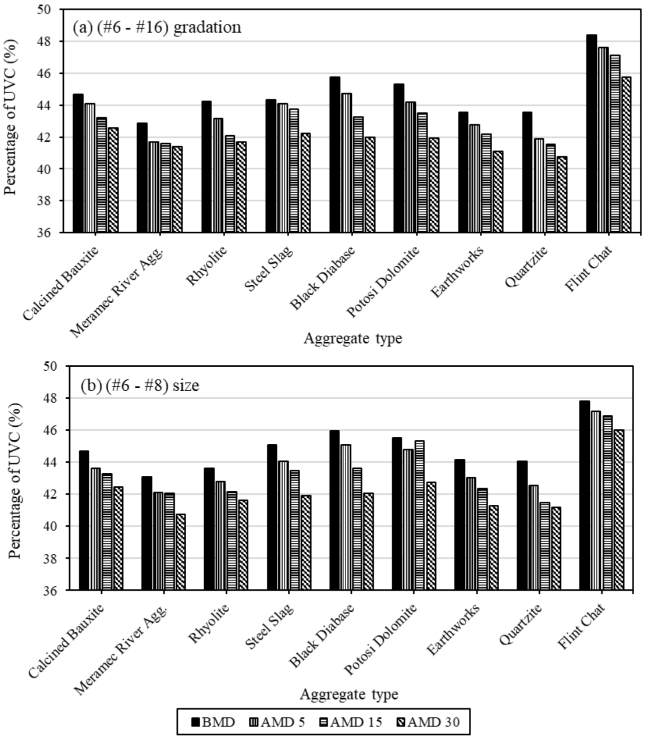

Figure 3. Effect of MD polishing times on the UVC percentages with two sizes

Figure 4 presents the effect of the aggregate size [(#6 - #8) size and (#6 - #16) gradation] on the UVC percentages regarding BMD, AMD 5, AMD 15, and AMD 30. There was an inconsiderable change in the percentage of UVC with changing the size of the aggregates.

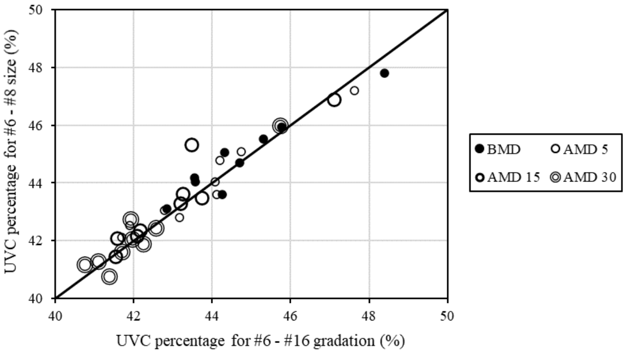

Figure 4. Relationship between UVC percentages for two sizes

B. Aggregate Durability Testing Results

The HFST aggregates experience direct exposure to outside weather, like repetitive cycles of being wet and dry, de-icing, and snowplowing. Therefore, investigating the durability of the aggregates is essential. The test specimens were prepared and mixed with different gradations based on the tests' specifications.

B.1. Los Angeles Abrasion

The aggregate samples were tested for their degradation resistances, using the Los Angeles machine, with grading D. The LAA percentages represented the quality of various aggregates. Figure 5 presents the results of the Los Angeles test. Potosi Dolomite had the highest LAA (33.27%), followed by Black Diabase (23.26%) and then Rhyolite (17.87%). By contrast, Meramec River Aggregate had the lowest LAA (14.06%). The LAA percentages for Potosi Dolomite and Black Diabase exceeded the maximum allowable LAA percentage (20%), as discussed in NJSP-15-13B document [18]. Earthworks, Flint Chat, and Quartzite were tested using grading D for their LAA percentages [14]. These percentages were 20%, 25%, and 29% for Earthworks, Flint Chat, and Quartzite, respectively. This reflected that the LAA percentages for Flint chat and Quartzite surpassed the maximum allowable LAA percentage (20%), as mentioned in NJSP-15-13B document [18].

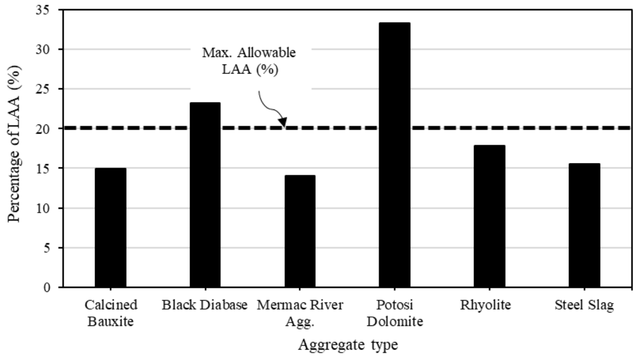

Figure 5. Percentages of LAA

B.2. Micro-Deval Results

In this section, the MD results were discussed for coarse and fine aggregates. The MD results were indicators of the best alternative aggregates rather than CB by analyzing the mass losses after different polishing times. The polishing times were 105 and 180 minutes for the coarse aggregates. Contrarily, the polishing times for the fine aggregates were 5, 15, and 30 minutes. The following subsections explained the MD results.

B.2.1. Coarse Aggregate

The MD test was run for the coarse aggregates with (3/8″ - #4) gradation. The percentages of masses lost after 105- and 180-minutes of Micro-Deval polishing times (AMD 105 and AMD 180) are presented in Figure 6. The highest percentages of mass loss were recorded for Potosi Dolomite. Black Diabase presented the highest percentages of mass loss after Potosi Dolomite. Contrarily, the lowest percentages of mass loss were noted for Meramec River Aggregate. Calcined Bauxite, Quartzite, and Steel Slag had approximately the same percentages of mass losses regarding AMD 105 and AMD 180. Rhyolite and Earthworks showed the same percentages of mass losses for AMD 105 and AMD 180, and they had lower percentages of mass losses than CB, Quartzite, and Steel Slag. Flint Chat aggregate showed a lower percentage of mass loss for AMD 105 than Earthworks, Rhyolite, and Steel Slag. However, for AMD 180, Flint Chat reflected a higher percentage of mass loss than Rhyolite and Earthworks. According to the MD mass losses regarding 105 minutes, Meramec River Aggregate had the lowest mass loss’s percentage followed by Flint Chat, Earthworks, Rhyolite, CB, Quartzite, Steel Slag, and Black Diabase. The highest percentage of mass loss was for Potosi Dolomite. Based on the MD mass losses after 180 minutes, Meramec River Aggregate had the lowest mass loss’s percentage followed by Earthworks, Rhyolite, Flint Chat, CB, Quartzite, Steel Slag, and Black Diabase. The highest percentage of mass loss was for Potosi Dolomite.

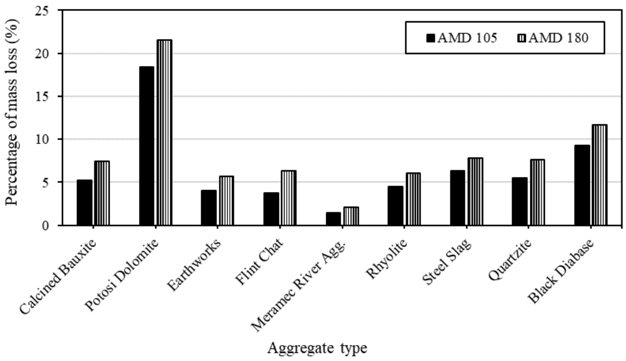

Figure 6. Micro-Deval mass losses’ percentages with (3/8″ - #4) gradation

B.2.2. Fine Aggregate

Figure 7a shows the percentages of mass losses for aggregates with (#6 - #16) gradation; the mass losses were calculated for #6 - #16. The MD polishing times were 5, 15, and 30 minutes. Increasing the MD polishing time from 5 minutes to 30 minutes increased the mass loss percentages. Calcined Bauxite had the lowest mass loss percentage for AMD 30 followed by Meramec River Aggregate, Earthworks, Rhyolite, Steel Slag, Flint Chat, Quartzite, and Black Diabase. However, Potosi Dolomite showed the highest mass loss percentage for AMD 30. Meramec River Aggregate had the same mass loss percentage as the Black Diabase and Quartzite for AMD 5; however, Meramec River Aggregate had less than the half the percentage of mass loss in reference to Quartzite and Black Diabase for AMD 30. Figure 7b depicts the percentages of mass losses for aggregates with (#6 - #16) gradation; the mass losses were estimated for #6 - #8. Increasing the MD polishing time from 5 minutes to 30 minutes increased the mass loss percentages. The mass losses calculated for #6 - #8 were higher than the mass losses calculated for #6 - #16. This indicated that the larger aggregates’ sizes had higher mass losses than the smaller aggregates’ sizes. Meramec River Aggregate had the lowest mass loss percentage for AMD 30 followed by CB, Earthworks, Steel Slag, Black Diabase, Rhyolite, Flint Chat, and Quartzite. However, Potosi Dolomite showed the highest mass loss percentage for AMD 30. Meramec River Aggregate had the same mass loss percentage as the Black Diabase for AMD 5; however, Meramec River Aggregate had less than the half the percentage of mass loss in reference to Black Diabase for AMD 30.

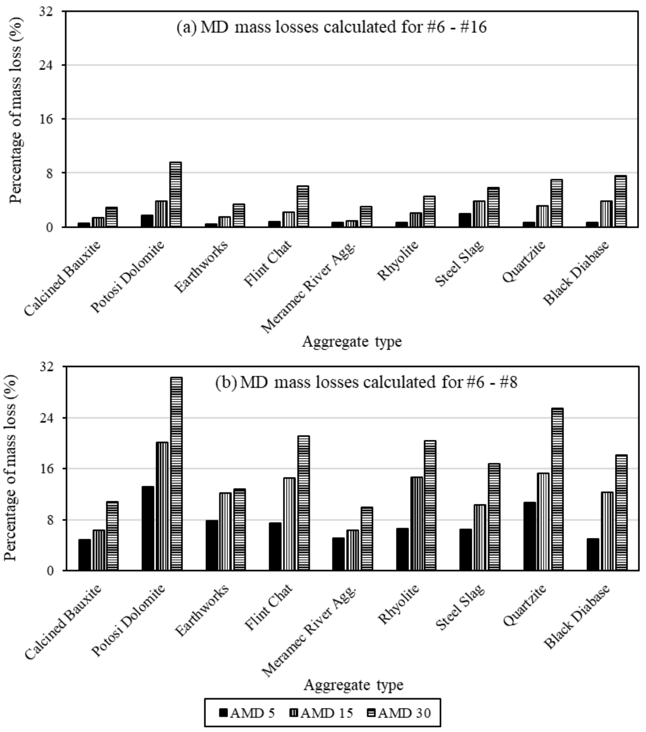

Figure 7. Micro-Deval mass losses' percentages with (#6 - #16) gradation

B.3. Sodium Sulfate Soundness

The sodium sulfate soundness test was conducted to evaluate the aggregates' resistances to disintegration through repeated immersion in sodium sulfate solutions, followed by oven drying. The tests were conducted on (#4 - #6) sized aggregates. The average of two replicates' results was demonstrated in Figure 8. Calcined Bauxite had the lowest percentage lost, followed by Meramec River Aggregate, Rhyolite, and then Steel Slag. The highest percentage lost was noted for Potosi Dolomite.

B.4. Water-Alcohol Freeze Thaw

The water-alcohol freeze thaw resistances of the aggregates were tested on (#6 - #8) size. The tests were conducted to assess the soundness of coarse aggregates. The results shown in Figure 9 demonstrated that CB had the highest percentage of loss (7.24%), followed by Meramec River Aggregate (6.7%). Contrarily, Earthworks had the lowest percentage of loss (2.56%). All aggregates had percentages of losses lower than CB.

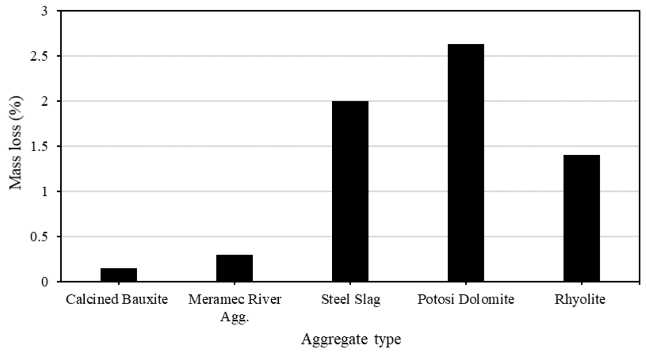

Figure 8. Sodium sulfate soundness test results

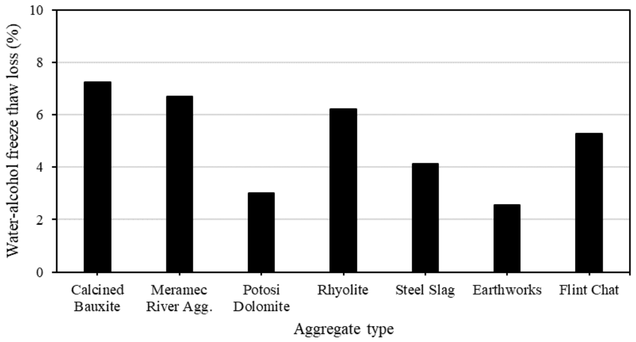

Figure 9. Water-alcohol freeze thaw test results

B.5. Acid-Insoluble Residue

Calcined Bauxite and alternatives were tested for their acid-insoluble residues. The tests were run on the aggregates with (#6 - #8) size. The percentages of noncarbonate (insoluble) residue in carbonate aggregates were determined to identify the polishing susceptibility of the proposed aggregates using a hydrochloric acid solution to cause carbonates reactions. The percentages of insoluble residue are displayed in Figure 10. Potosi Dolomite had the lowest residue percentage, followed by Steel Slag. These percentages were under the minimum allowable residue level (80%). Quartzite had the highest residue percentage, followed by CB and then Rhyolite. The other aggregates were above the acceptable level but lower than Quartzite, CB, and Rhyolite.

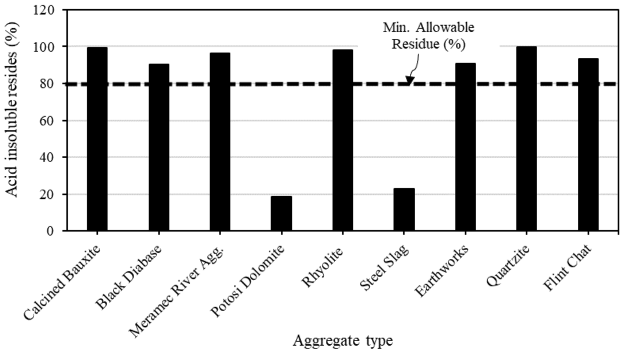

Figure 10. Acid-insoluble residue percentages

C. Relationships between Micro-Deval and Los Angeles Mass Losses

The relationships between the LAA for aggregates with grading D and MD mass losses for (3/8″ - #4) size are illustrated in Figure 11. Two MD polishing times were used for the coarse gradation [105 minutes (Figure 11a) and 180 minutes (Figure 11b)]. According to the maximum allowable LAA percentage [NJSP-15-13B requirements [18]], Potosi Dolomite and Black Diabase were out of the requirements. The MD mass losses increased with increasing the polishing time from 105 minutes to 180 minutes. There were direct linear relationships between the LAA and MD test results. Aggregates with the highest LAA percentage had the highest MD mass losses (e.g., Potosi Dolomite). Meramec River Aggregate had the lowest LAA percentage and MD mass losses. The MD mass losses percentages were observed to be much lower than the LAA percentages. The MD mass losses were more sensitive than the LAA percentages. For instance, Steel Slag and Meramec River Aggregate had similar LAA percentages (14.06% for Meramec River Aggregate and 15.53% for Steel Slag). However, the MD mass losses for the two aggregates were completely different. The MD mass losses for Meramec River Aggregate and Steel Slag after 105 minutes of polishing were 1.4% and 6.3%, respectively. Furthermore, the MD mass losses for Meramec River Aggregate and Steel Slag after 180 minutes of polishing were 2.1% and 7.8%, respectively.

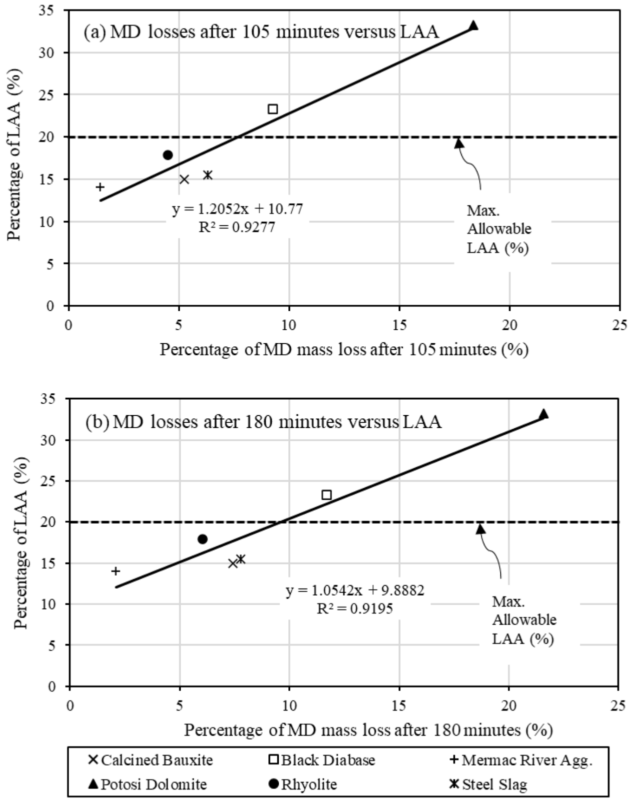

Figure 11. Relationships between the MD mass losses and LAA

IV. CONCLUSIONS

This study discussed the physical properties testing and durability testing results for Calcined Bauxite (CB) and eight alternatives. Alternative aggregates involved Earthworks, Meramec River Aggregate, Steel Slag, Rhyolite, Black Diabase, Quartzite, Flint Chat, and Potosi Dolomite. The physical properties testing included aggregate gradation, specific gravity and absorption, and uncompacted void content (UVC). Durability testing contained Los Angeles abrasion (LAA), Micro-Deval (MD), sodium sulfate soundness, water-alcohol freeze thaw, and acid-insoluble residue. Based on this study, the following points were concluded:

1. The specific gravity results deemed that CB had the highest specific gravity values, followed by Steel Slag, and then Black Diabase. However, Earthworks and Meramec River Aggregate had the lowest specific gravity values.
2. The UVC results showed that Flint Chat had the highest UVC percentages followed by Black Diabase, Potosi Dolomite, Steel Slag, and CB.
3. Calcined Bauxite, Steel Slag, and Meramec River Aggregate showed the lowest LAA percentages. Black Diabase and Rhyolite had the highest percentages.
4. Meramec River Aggregate had the lowest mass losses—regarding sodium sulfate soundness test results—among the alternative aggregates followed by Rhyolite and then Steel Slag. The highest percentage lost was noted for Potosi Dolomite.
5. All alternative aggregates had lower percentages of water-alcohol freeze thaw mass losses when compared to CB; the lowest percentage of mass loss was recorded for Earthworks and then for Potosi Dolomite.
6. Based on the acid-insoluble residue results, Quartzite, Rhyolite, Meramec River Aggregate, and Flint Chat had comparable residues percentages with CB.
7. Meramec River Aggregate, CB, and Earthworks had the lowest MD mass losses' percentages after 180-minutes polishing time for the coarse gradation (3/8″ - #4) or 30-minutes polishing time for the fine gradation (#6 - #16).
8. The MD results for aggregates with fine gradation (#6 - #16) showed that the mass losses calculated for (#6 - #8) were higher than the mass losses calculated for (#6 - #16). This indicated that the larger aggregates' sizes had higher mass losses than the smaller aggregates' sizes.
9. There was a direct linear relationship between the Los Angeles (LA) and MD mass losses. The MD was found to be more sensitive for aggregate screening than LA.
10. Increasing the MD polishing times decreased the UVC percentages.
11. It was concluded that Meramec River Aggregate was the most favorable alternative to CB followed by Earthworks, based on the physical properties testing and durability testing results.

V. RECOMMENDATIONS

1. It is recommended to evaluate the CB and alternatives' performance. Performance testing can include but is not limited to the British pendulum test, dynamic friction test, and aggregate image measurement system test.
2. It is recommended to construct high friction surface treatment field sections using CB and the selected alternatives. This will evaluate the field performance of the selected aggregates.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: M. Abdelrahman, E. Deef-Allah, and Korrenn Broaddus; data collection: M. Abdelrahman, Korrenn Broaddus, and E. Deef-Allah; analysis and interpretation of results: E. Deef-Allah and M. Abdelrahman; draft manuscript preparation: E. Deef-Allah and M. Abdelrahman. All authors reviewed the results and approved the final version of the manuscript.

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