Use of Recycled Brick in Aggregates

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16. Abstract (Limit: 250 words)

Conservation and reuse of resources is a necessity in achieving sustainability across the globe. In recent years, construction and demolition debris including bricks has appeared in stockpiles around Minnesota. The objective of this research project was to investigate the possibility of putting the brick to beneficial use as aggregates for base courses in pavements. This would help to conserve natural stone aggregate and also recycle the brick instead of dumping it as waste in a landfill. In addition, contractors could save money by being able to reuse locally available material. MnDOT is already quite progressive in its use of recycled materials and allows the use of recycled concrete aggregates, recycled asphalt pavement, and recycled glass in base and surface courses. Based on current literature review, Minnesota may become a pioneer in the use of recycled brick aggregate as well.

There are many different types of clay bricks including structural bricks (both commercial and residential), pavers, and refractory bricks. The structural bricks and pavers will also vary from region to region. The bricks used in Minnesota are of the highest quality available because they have to meet severe weathering requirements. Structural brick accounts for the largest amount of brick manufactured. In this project, samples of various types of bricks were tested. The main tests conducted were the Los Angeles Rattler to assess abrasion properties and the magnesium sulfate soundness to evaluate freeze-thaw durability. In addition, basic engineering properties such as specific gravity and absorption were determined.

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EXECUTIVE SUMMARY

Conservation and reuse of resources is a necessity in achieving sustainability across the globe. In recent years, construction and demolition debris including bricks has appeared in stockpiles around Minnesota. The objective of this research project was to investigate the possibility of putting the brick to beneficial use as aggregates for base courses in pavements or for shouldering. This would help to conserve natural stone aggregate and also recycle the brick instead of dumping it as waste in a landfill. In addition, contractors could save money by being able to reuse locally available material. MnDOT is already quite progressive in its use of recycled materials and allows the use of recycled concrete aggregates, recycled asphalt pavement, and recycled glass in base and surface courses. Based on current literature review, Minnesota may become a pioneer in the use of recycled brick aggregate as well.

There are many different types of clay bricks including structural bricks (both commercial and residential), pavers, and refractory bricks. The structural bricks and pavers will also vary from region to region. The bricks used in Minnesota are of the highest quality available because they have to meet severe weathering requirements. Structural brick accounts for the largest amount of brick manufactured. In this project, samples of various types of bricks were tested. The main tests conducted were the Los Angeles Rattler to assess abrasion properties and the magnesium sulfate soundness to evaluate freeze-thaw durability. In addition, basic engineering properties such as specific gravity and absorption were determined.

The majority of the brick tended to have excellent to fair performance often meeting or being close to meeting MnDOT requirements for virgin aggregates. Some of the bricks, however, most notably the refractory ones, had poor performance. Based on the test results, probability and statistics, and the rule of mixtures, it is recommended that a maximum of 10% by total mass of aggregate should be allowed for the brick aggregate. It is predicted that about 98% of all brick aggregate when used in a blend with virgin aggregate at this mass fraction will meet MnDOT specifications for virgin aggregate. If it is desired to check that aggregate blends do not contain more than 10% brick, a bulk specific gravity test for both the virgin aggregate and blended aggregate could be required.

Because of the limitations of the testing program and several assumptions made together with the well-known fact that lab tests do not always predict field performance correctly, it is suggested that MnDOT first conduct some pilot field tests using various amounts of blended brick and virgin aggregates before including a provision for brick aggregate in MnDOT Specification 3138 Aggregate for Base and Surface Courses. Also, a lower risk application could be the use of brick aggregate in shoulders. The estimated annual usage of aggregate for shouldering in Minnesota is 800,000 tons. Ten percent of this number would be 80,000 tons. The estimated annual amount of brick in the waste stream is around 88,000 tons; therefore, shouldering can consume the bulk of the waste brick. As experience is gained with this material and its performance in the field is tested the 10% number could be increased or decreased in the future.

Chapter 1. INTRODUCTION

1.1 Problem Statement

Conservation and reuse of resources is a necessity in achieving sustainability across the globe. In recent years, construction and demolition debris including bricks has appeared in stockpiles around Minnesota. The objective of this research project was to investigate the possibility of putting the brick to beneficial use as aggregates for base courses in pavements. This would help to conserve natural stone aggregate and also recycle the brick instead of dumping it as waste in a landfill. Additionally, some contractors indicated that they could potentially save significant amounts of money if waste bricks on a jobsite could be recycled as aggregates in their current projects. Interest in the project was also shown by Associated General Contractors (AGC) and Minnesota Asphalt Pavers Association (MAPA).

1.2 Current Minnesota Specifications for Base Aggregate

The typical cross-section of an asphalt concrete pavement is shown in Fig. 1. The purpose of the base course in an asphalt pavement is to reduce the effective vertical stress in the subbase and subgrade so that they do not deform. This is achieved primarily by virtue of its thickness. The base course also provides positive drainage and protects the main pavement from frost damage. The aggregates used must conform to gradation and fines content requirements, and also be durable against wear and freeze-thaw.
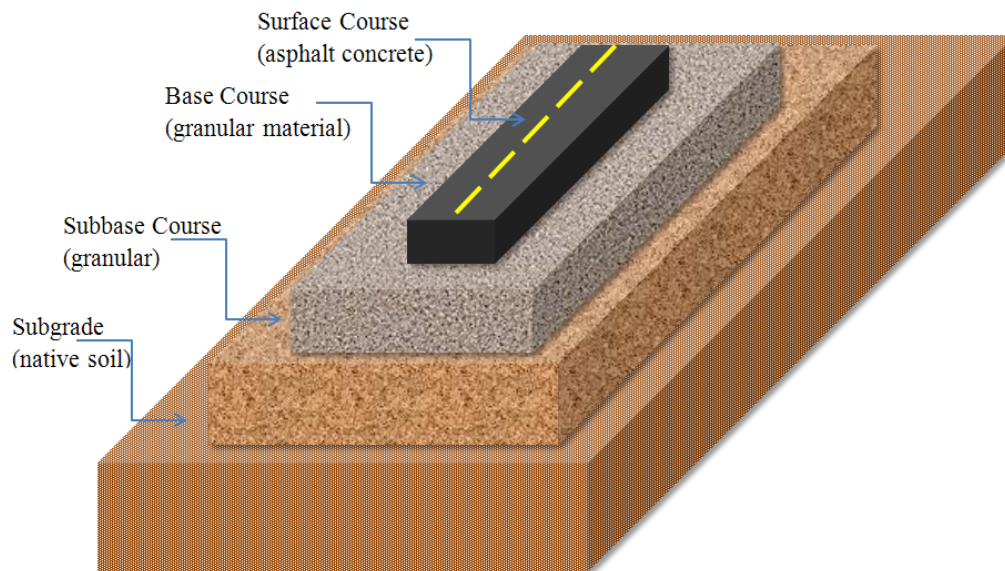
Figure 1. Typical Cross-Section of an Asphalt Pavement.

The 2014 draft version of the MnDOT Standard Specification for Construction 3138 – Aggregate for Surface and Base Courses is included in the Appendix. Seven different classes of aggregates are described: 1, 2, 3, 4, 5, 5Q, and 6; however Class 2 must consist of 100% crushed quarry rock. The quality requirements for virgin materials are summarized in Table 3138-1 which is reproduced here as Table 1. It can be noted that shale, which is a very weak rock, may be included up to 10% by mass in some cases. The maximum Los Angeles Rattler (LAR) is specified as 40% except for Class 6 where it is 35%. The maximum insoluble residue for the portion of carbonate aggregate passing the No. 200 sieve is 10%.

Table 1. Quality Requirements for Virgin Materials.

Requirement	Class			
	1 and 2	**3 and 4**	**5 and 5Q**	**6**
Max Shale, if No. 200 ≤ 7 % by mass	NA	10%	10%	7%
Max Shale, if No. 200 > 7 % by mass	NA	7%	7%	7%
Minimum Crushing Requirements *	NA	NA	10%	15%
Maximum Los Angeles Rattler (LAR) loss from carbonate quarry rock	40%	40%	40%	35%
Maximum Insoluble residue for the portion of quarried carbonate aggregates passing the No. 200 sieve	10%	10%	10%	10%
* Material crushed from quarries is considered crushed material.				

Three types of recycled materials are allowed: recycled asphalt pavement (RAP), recycled concrete materials, and certified recycled glass. The requirements for recycled materials are summarized in Table 3138-2 and reproduced here as Table 2. It can be seen that there are no overall maximum percentage limits set on RAP or concrete, but glass is limited to 10%. The "masonry block" in the specification refers to concrete masonry units (or concrete blocks or cinder blocks) and is limited to 10% of the concrete portion.

Table 2. Quality Requirements for Recycled Materials.

Requirement	Classes 1, 3, 4, 5, 5Q and 6
Maximum Bitumen Content of Composite	3.5%
Maximum masonry block % of the concrete portion	10%
Maximum percentage of glass *	10%
Maximum size of glass *	¾ in [19 mm]
Crushing (Class 5, 5Q and 6) ‖	10% for Class 5 and 5Q †, 15% for Class 6 †
* Glass must meet certification requirements on the Grading and Base website. Combine glass with other aggregates during the crushing operation. † If material ≥ 20% (RAP + Concrete), Class 5 and 5Q crushing requirements are met. † If material ≥ 30% (RAP + Concrete), Class 6 crushing requirement is met. ‖ Material crushed from quarries is considered crushed material.	

While there are no specified requirements for soundness in MnDOT Specification 3138 (Aggregate for Surface and Base Courses), the following requirements for Magnesium Sulfate Soundness can be found in the 2014 draft version of MnDOT Standard Specification for Construction 3139 – Graded Aggregate for Bituminous Mixtures:

"Maximum loss after 5 cycles on the coarse aggregate fraction (material retained on No. 4 [4.75 mm] sieve for any individual source within the mix) as follows:

(1) Percent passing the ¾ in [19 mm] sieve to percent retained on the ½ in [12.5 mm] sieve, ≤ 14%,
(2) Percent passing the ½ in [12.5 mm] sieve to percent retained on the ⅜ in [9.5 mm] sieve, ≤18%,
(3) Percent passing the ⅜ in [9.5 mm] sieve to percent retained on the No. 4 [4.75 mm] sieve, ≤ 23%,
(4) For the composite if all three size fractions are tested, the composite loss ≤ 18%, and acceptance will be granted if:
(4.1) If the Contractor meets the composite requirement, but fails to meet at least one of the individual components, the Engineer may accept the source if each individual component is no greater than 110 percent of the requirement for that component.
(4.2) If the Contractor meets each individual component requirement, but fails to meet the composite, the Engineer may accept the source if the composite is no greater than 110 percent of the requirement for the composite.

Coarse aggregate that exceeds the requirements in this section for material passing the No. 4 [4.75 mm] sieve cannot be used."

1.3 Types of Bricks
This research focused only on *clay* bricks. In the early 1900s in the US, street pavements were often made with bricks, but as they became inadequate for traffic they were replaced. The most common use is in building construction with an estimated 65% of all bricks produced worldwide being used for this purpose [1]. About 35% of all bricks are used in commercial, industrial, and institutional buildings [1]. *Clay pavers* are bricks used for light-duty paving e.g. driveways and sidewalks. Another application is *refractory* brick or *fire* brick which is often used in lining furnaces, kilns, fireboxes, and fireplaces. In this research project, the majority of bricks tested were of the structural types used in building construction, but some clay pavers and refractory brick were also tested as well as brick from a 1900s street pavement. Most likely, potential stockpiles of brick that could be used for recycled aggregates will mainly contain structural bricks but to a lesser extent, some of the other types may appear.

The basic process of brick-making can be described as follows [1, 2]. Raw clay is obtained by digging, mining etc. The raw clays are often blended to obtain a more uniform consistency. In many cases the material is ground to reduce large rocks or clumps of clay to usable size. In the *stiff-mud* process of forming, the clay is mixed with water to render it plastic, after which it is forced through a die that extrudes a column of clay. The column gives two dimensions of the brick and the third dimension is obtained by cutting to size. The bricks are then dried to get rid of excess water. The bricks are then fired and cooled in a kiln capable of temperatures around 1600°F to 2000°F (870°C to 1100°C).

In the making of refractory brick, fireclay which is different than that used in ordinary brick-making, is fired in the kiln until it is partly vitrified, and for special purposes may also be glazed. Refractory bricks have very high (50-80% typical) aluminum oxide content and correspondingly less silica content.

There are several ASTM standards covering various types of bricks. For example ASTM C62 covers building brick, ASTM C216 covers facing brick, and ASTM C652 covers hollow brick which are all types of structural bricks. ASTM C902 covers pedestrian and light traffic paving brick, and ASTM C1261 covers firebox bricks and residential fireplaces. The minimum compressive strength, maximum water absorption and maximum saturation coefficient are used in combination to predict the durability of the bricks in use. Some of the physical property requirements in the specifications are presented in Table 3 [3]. For durability classifications, the letter S indicates severe weathering, M indicates moderate weathering, and N indicates negligible or no weathering. The bricks used in Minnesota should be the most durable available, i.e. for severe weathering conditions. The requirements for refractory brick are quite different from those for the structural brick and clay pavers. For example, the strength requirement in ASTM C1261 is a minimum modulus of rupture of 500 psi (3.5 MPa).

Table 3. Physical Properties in Brick Specifications

		Minimum Compressive Strength, psi (MPa)		Maximum Cold Water Absorption, %		Maximum 5-hr Boiling Absorption, %		Maximum Saturation Coefficient	
		5 brick average	Individual	5 brick average	Individual	5 brick average	Individual	5 brick average	Individual
ASTM Specification and Classification									
C62 (building brick)	SW	3000 (20.7)	2500 (17.2)			17.0	20.0	0.78	0.80
	MW	2500 (17.2)	2200 (15.2)			22.0	25.0	0.88	0.90
	NW	1500 (10.3)	1250 (8.6)			No Limit	No Limit	No Limit	No Limit
C216 (facing brick)	SW	3000 (20.7)	2500 (17.2)			17.0	20.0	0.78	0.80
	MW	2500 (17.2)	2200 (15.2)			22.0	25.0	0.88	0.90
C652 (hollow brick)	SW	3000 (20.7)	2500 (17.2)			17.0	20.0	0.78	0.80
	MW	2500 (17.2)	2200 (15.2)			22.0	25.0	0.88	0.90
C902 (pedestrian & light traffic paving)	SX	8000 [4000][1] (55.2) [(27.6)][1]	7000 [3500][1] (48.3) [(24.1)][1]	8.0 [16.0][1]	11.0 [18.0][1]			0.78	0.80
	MX	3000 (20.7)	2500 (17.2)	14.0	17.0			No Limit	No Limit
	NX	3000 (20.7)	2500 (17.2)	No Limit	No Limit			No Limit	No Limit

[1]Numbers in bracket are for molded brick and apply provided the requirements for saturation coefficient are met

1.4 Estimate of Amount of Waste Brick

It was desired to obtain an estimate of the annual amount of brick that might potentially be available in the waste stream in Minnesota. This proved to be a difficult task because of the limited amount of data that is collected. The Minnesota Pollution Control Agency (MnPCA) did not have this number available at the time of writing this report. The major source of waste brick

should be from building-related construction and demolition. The US Environmental Protection Agency published reports on studies conducted about construction and demolition materials first in 1998 [4] and then again in 2003 [5]. The activities that generated waste were construction, demolition, and renovation. The estimated total amount of building-related construction and demolition waste in the US in 2003 was 170 million tons [5].

The US Census Bureau tracks construction spending in the US. The 2003 value was around $891 billion and the 2012 value was $854 billion [6]; therefore it will be assumed that the values reported in [5] can be used without adjustment.

The total amount of construction and demolition waste reported in [5] includes many different materials such as wood, drywall, concrete, glass, masonry etc. and a breakdown between the materials is not available. It is estimated that bricks comprise only 1 to 5 percent of construction and demolition waste [7]. Using an estimated average value of 3%, the estimated annual amount of brick waste in the US is 5.1 million tons.

In order to estimate the amount of waste brick available in Minnesota, it will be assumed that construction is roughly proportional to population. The population of Minnesota in 2010 was 5.304 million while that of the US was 308.746 million [8]; therefore, the state accounts for 1.72% of the country's population. Assuming that the amount of brick waste in the US is proportional to population, then the estimated amount of annual brick waste in Minnesota is approximately 88,000 tons.

Chapter 2. REVIEW OF LITERATURE

A review of literature on the topic of recycled brick aggregate did not reveal any studies conducted in the US, however several international studies were found. In China, a series of lab tests on chemically stabilized brick-stone aggregate was performed by Wu et al [9]. They studied brick aggregates stabilized with lime-fly ash, cement, and cement-fly ash. Mechanical tests included brushing, compressive strength, modulus of resilience, freeze-thaw and splitting strength. Three experimental test sections were reported to be performing well after two years in service. Mazumder et al. have reported on the possible use of overburnt bricks in pavement base and subbase courses in Bangladesh [10]. These are bricks that are overburnt due to poor temperature distribution in the kiln. Lab tests included LAR, absorption, specific gravity and unit weight. The overburnt bricks were found to have better properties than higher grade bricks. Khalaf and DeVenny studied brick aggregates for use in concrete in the U.K [11]. They found that most of the clay-brick aggregates were suitable for low level concrete applications, while a few could be used in high quality concrete. Tests included compressive strength of parent brick, gradation, aggregate crushing value, relative density, absorption, and porosity. In a second study by Khalaf [12] it was found that concrete made with crushed clay brick aggregate often exceeded that of similar concrete made with granite aggregate while having an 8 to 15% reduction in density. Bazaz and Khayati [13] in Iran also reported that in spite of high porosity and absorption of recycled crush brick, using this material as aggregate results in a semi-lightweight, durable, and low permeability concrete.

Another study conducted in Denmark examined the use of construction and demolition (C&D) waste as aggregates in base or subbase courses [14]. Although serious efforts are made in selective demolition to keep separate concrete, asphalt and masonry rubble, mixed C&D rubble remains a problem. A blend of 55% bricks and 45% concrete is recognized in Denmark and outperforms pure brick. Recycling of C&D waste can be made economical by imposing a fee for disposal at landfills.

Arulrajah et al. [15] investigated the use of recycled crushed brick for use as pavement subbase material in Australia. The experiments included particle size distribution, modified Proctor compaction, particle density, water absorption, California bearing ratio, Los Angeles abrasion loss, pH, organic content, static triaxial, and repeated load triaxial tests. California bearing ratio values were found to satisfy the local state road authority requirements for a lower subbase material. The Los Angeles abrasion loss value obtained was just above the maximum limits specified for pavement subbase materials. The repeated load triaxial testing established that crushed brick would perform satisfactorily at a 65% moisture ratio level. At higher moisture ratio levels, shear strength of the crushed brick was found to be reduced beyond the acceptable limits. The geotechnical testing results indicated that crushed brick may have to be blended with other durable recycled aggregates to improve its durability and to enhance its performance in pavement subbase applications.

Chapter 3. SAMPLING OF BRICKS

3.1 Sampling of Bricks
One of the most critical aspects of the research project was obtaining the samples to be used in the experiments. It was decided that sampling should be done at various levels:

- Level 1: New bricks obtained from a brick plant or distributor. The type of brick *should* be known and the age *should* be known.
- Level 2: Samples obtained during demolition of a site. The type of brick *may* be known and the age *may* be known.
- Level 3: Samples obtained from C&D debris stockpile. Both the type of brick and the age will be *unknown*.

A total of sixteen different sample types of bricks were gathered. These ranged from brand new to more than 100 year old bricks. At level 1 (new brick) *eight* sample types were collected of which three were commercial building brick, three were residential brick, and two were clay pavers. At level 2 (old brick) *five* samples were gathered from demolition sites; and at level 3 (old and unknown brick) *three* samples were obtained from C&D debris stockpiles.

A minimum of about 240 lb (109 kg) of each sample was collected. Acme-Ochs Company in Springfield, MN donated bricks for six of the eight new types. At the time of the sampling, Acme-Ochs was the only remaining brick manufacturer in Minnesota. Three were commercial types and three were residential types. Commercial production is about 65% of their plant output, while residential is about 35%. The samples were labeled from 1 through 16. More details of each type follow:

Number: 1
Description: Sequoia commercial brick (about 16.7% of all Acme-Ochs commercial production)
Color: Red
Markings: "Ochs Brick 717"
Size (in): 11 $^{11}/_{16}$ x 3 $^{7}/_{16}$ x 3 $^{5}/_{8}$
Weight per brick: 8.4 lb
Source: Acme-Ochs, Springfield, MN
Manufacturer: Acme-Ochs
Age at test: 8 months

Figure 2. Sample 1: Sequoia Commercial Brick.

Number: 2
Description: Stanton commercial brick (about 16.7% of all Acme-Ochs commercial production)
Color: Red
Markings: "Ochs Brick 712"
Size (in): 11 $^9/_{16}$ x 3 $^7/_{16}$ x 3 $^5/_8$
Weight per brick: 8.2 lb
Source: Acme-Ochs, Springfield, MN
Manufacturer: Acme-Ochs
Age at test: 8 months

Figure 3. Sample 2: Stanton Commercial Brick.

Number: 3
Description: Montclair commercial brick (about 16.7% of all Acme-Ochs commercial production)
Color: Reddish brown
Markings: None
Size (in): 11 $^9/_{16}$ x 3 $^7/_{16}$ x 3 $^5/_8$
Weight per brick: 7.9 lb
Source: Acme-Ochs, Springfield, MN
Manufacturer: Acme-Ochs
Age at test: 8 months

Figure 4. Sample 3: Montclair Commercial Brick.

Number: 4
Description: New Bedford residential brick (about 25% of all Acme-Ochs residential production)
Color: Red
Markings: "55"
Size (in): $7\,^5/_8$ x $3\,^1/_2$ x $2\,^1/_4$
Weight per brick: 3.5 lb
Source: Acme-Ochs, Springfield, MN
Manufacturer: Acme-Ochs
Age at test: 8 months

Figure 5. Sample 4: New Bedford Residential Brick.

Number: 5
Description: Summit residential brick (about 7% of all Acme-Ochs residential production)
Color: Tan red
Markings: None
Size (in): $7\,^5/_8$ x $3\,^1/_2$ x $2\,^1/_4$
Weight per brick: 3.3 lb
Source: Acme-Ochs, Springfield, MN
Manufacturer: Acme-Ochs
Age at test: 8 months

Figure 6. Sample 5: Summit Residential Brick.

Number: 6
Description: Glenwood Mills residential brick (about 7% of all Acme-Ochs residential production)
Color: Brownish
Markings: None
Size (in): 7 $^5/_8$ x 3 $^1/_2$ x 2 ¼
Weight per brick: 3.3 lb
Source: Acme-Ochs, Springfield, MN
Manufacturer: Acme- Ochs
Age at test: 8 months

Figure 7. Sample 6: Glenwood Mills Residential Brick.

Number: 7
Description: Pine Hall Brick Clay Paver
Color: English edge red
Markings: "495 552478 020"
Size (in): 8 x 4 x 2 $^3/_8$
Weight per brick: 5.4 lb
Source: North Star Stone Masonry, Mankato, MN
Manufacturer: Pine Hall, Iowa
Age at test: 8 months

Figure 8. Sample 7: Pine Hall Clay Paver.

Number: 8
Description: Glen Gery Clay Paver
Color: Rustic red
Markings: None
Size (in): 8 x 3 $^{15}/_{16}$ x 2 $^{1}/_{4}$
Weight per brick: 5.8 lb
Source: North Star Masonry, Mankato, MN
Manufacturer: Glen Gery, North Carolina
Age at test: 8 months

Figure 9. Sample 8: Glen Gery Clay Paver.

Number: 9
Description: Commercial brick obtained from stockpile
Color: Red
Markings: None
Size (in): 12 x 3 $^{3}/_{4}$ x 3 $^{3}/_{4}$
Weight per brick: 9 lb
Source: Dem Con Landfill, Shakopee, MN
Manufacturer: Unknown
Age at test: Unknown

Figure 10. Sample 9: Commercial Brick from Stockpile.

Number: 10
Description: Refractory brick from stockpile. The fact that this brick was used with mortar joints and subsequent performance results hint that it is refractory brick.
Color: Salmon pink
Markings: None
Size (in): 8 x 3 $^3/_4$ x 2 $^1/_4$
Weight per brick: 4.1 lb
Source: Dem Con Landfill, Shakopee, MN
Manufacturer: Unknown
Age at test: Unknown

Figure 11. Sample 10: Refractory Brick from Stockpile.

Number: 11
Description: Residential style brick from stockpile
Color: Red
Markings: None
Size (in): 7 $^1/_2$ x 3 $^1/_2$ x 2 $^1/_8$
Weight per brick: 3.9 lb
Source: Spirit Lake, IA construction debris stockpile
Manufacturer: Unknown
Age at test: Unknown

Figure 12. Sample 11: Residential Brick from Stockpile.

Number: 12
Description: Old 1900s street paver brick from demolition of street at a university campus
Color: Red
Markings: "Purington"
Size (in): 8 $\frac{1}{2}$x 4 x 2 $\frac{1}{2}$
Weight per brick: 7 lb
Source: University of Minnesota, Minneapolis, MN
Manufacturer: Purington. A historical brickyard in East Galeburg, IL, shutdown in 1949.
Age at test: 110 years (estimated)

Figure 13. Sample 12: 1900s Street Paver Brick.

Number: 13
Description: Residential style brick from dorm demolition
Color: Red
Markings: None
Size (in): 7 $\frac{1}{2}$ x 3 $\frac{1}{2}$ x 2 $\frac{1}{4}$
Weight per brick: 3.7 lb
Source: Minnesota State University, Mankato, MN
Manufacturer: Unknown
Age at test: 50 years (estimated)

Figure 14: Sample 13: Residential Brick from Dorm Demolition.

Number: 14
Description: Refractory brick from demolition of old cold storage building. The insulation
properties and subsequent performance indicate that this is a refractory brick.
Color: Orange
Markings: "Stewart"
Size (in): 8 x 3 $^1/_2$ x 2 $^1/_4$
Weight per brick: 3.3 lb
Source: Cold storage building, Elm & Maple St, Mankato, MN
Manufacturer: Stewart. This could be from the Stewart Firebrick Works which was established in
1879 in Mahoning Township in Pennsylvania.
Age at test: 130 years (estimated)

Figure 15. Sample 14: Refractory Brick from Cold Storage Building.

Number: 15
Description: Residential style brick from abandoned house
Color: Brown
Markings: None
Size (in): 7 $^3/_4$ x 3 $^1/_2$ x 2 $^1/_4$
Weight per brick: 3.6 lb
Source: Sioux Valley, MN abandoned home
Manufacturer: Unknown
Age at test: 30 years (estimated)

Figure 16. Sample 15: Residential Brick from Abandoned Home.

Number: 16
Description: Residential style brick from demolition of building
Color: Cream
Markings: None
Size (in): 8 x 3 $^3/_4$ x 2 $^1/_4$
Weight per brick: 4.3 lb
Source: Spirit Lake, IA
Manufacturer: Unknown
Age at test: 15 years (estimated)

Figure 17. Sample 16: Residential Brick from Building Demolition.

3.2 Crushing and Screening

All of the sampled bricks were then crushed in a Bico jaw crusher with an opening of 5 in (127 mm) by 7 in (178 mm). The large opening size allowed whole bricks to be fed in the machine. The crushed brick was then sieved into different sizes using a mechanical testing screen with the following screen sizes: 1.5 in (38.1 mm), 1 in (25.4 mm), 0.75 in (19.1 mm), 0.5 in (12.7 mm), 0.375 in (9.5 mm) and #4 (4.75 mm). The jaw crusher and the mechanical screen on the side can be seen in Fig. 18.

Figure 18. Jaw Crusher and Screen used to Crush Brick and Separate Sizes.

It should be noted that 100% of the material passed through the 1.5 in (38.1 mm) screen, in other words the largest size aggregate that could be obtained was between 1 in (25.4 mm) to 1.5 in (38.1 mm). An example of the crushed product to be used as aggregate can be seen in Fig. 19.

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Figure 19. Crushed Brick Aggregate.

The screened material was stored in separate buckets and appropriately labeled. Enough material was crushed and sieved to be able to conduct three LA abrasion tests, three magnesium sulfate soundness tests, and two specific gravity and absorption tests on each of the 16 brick samples.

The tested size fractions and mass quantities for each LA abrasion test in accordance with AASHTO T96 and ASTM C131 are given in Table 4.

Table 4. Size Fractions and Mass Quantities for LA Abrasion Test

Size Fraction	Mass
3/4 – 1/2 in (19.1 – 12.7 mm)	5.5 lb (2500g)
1/2 – 3/8 in (12.7 – 9.5 mm)	5.5 lb (2500g)

The tested size fractions and mass quantities for the magnesium sulfate soundness test in accordance with AASHTO T104 and ASTM C88 are given in Table 5.

Table 5. Size Fractions and Mass Quantities for Magnesium Sulfate Soundness Test

Size Fraction	Mass
2 1/2 – 2 in (63.5 – 50.8 mm)	6.6 ± 0.66 lb (3000 ± 300g) (unable to obtain)
2 – 1 1/2 in (50.8 – 38.1 mm)	4.4 ± 0.44 lb (2000 ± 200g) (unable to obtain)
1 1/2 – 1 in (38.1 – 25.4 mm)	2.2 ± 0.11 lb (1000 ± 50g)
1 – 3/4 in (25.4 – 19.1 mm)	1.1 ± 0.066 lb (500 ± 30 g)
3/4 – 1/2 in (19.1 – 12.7 mm)	1.5 ± 0.022 lb (670 ± 10g)
1/2 – 3/8 in (12.7 – 9.5 mm)	0.73 ± 0.011 lb (330 ± 5g)
3/8 in – #4 (9.5 – 4.75 mm)	0.66 ± 0.011 lb (300 ± 5g)

Chapter 4. RESULTS

Experiments on the 16 different samples were conducted in random order to avoid any possible experimental bias.

4.1 Specific Gravity and Absorption

Basic engineering properties including specific gravity and absorption were measured in accordance with AASHTO T85 and ASTM C127. These properties have numerous applications. For example specific gravities are useful for estimating quantities in terms of both weight and volume, for surcharge loads, for determining weight-to-volume relationships, estimating voids, etc. Absorption may be an indicator of aggregate durability with higher values generally being detrimental. Absorption can also be used to estimate the volume of asphalt binder that an aggregate is likely to absorb. Similarly, for portland cement concrete the aggregate absorption is necessary to determine the correct water content of the mix.

The specific gravity and absorption tests were conducted on the crushed aggregate prior to separating the size fractions. The minimum sample weight for a nominal maximum aggregate size of 1 in (25.4 mm) is 8.8 lb (4 kg), so a value of approximately 9.9 lb (4.5 kg) was used.

The basic test procedure is to obtain the oven-dry weight by placing in an oven at about 230ºF (110ºC). After cooling the aggregate for 1 to 3 hrs it is soaked under water for 15 hours. The absorption can be determined at this stage. The weight of the aggregate is then measured while submerged in a tank of water. Finally, the excess water is decanted and the aggregates are towel dried to obtain the saturated surface dry (SSD) state.

The apparent specific gravity (ASG) considers the mass of the solid particle divided by the volume of the solid particle (not including permeable voids). The bulk specific gravity (BSG) uses the mass of the solid particle only divided by the overall volume (solid plus permeable voids). The bulk specific gravity saturated surface dry (SSD) considers the total mass (solid plus water in permeable voids) divided by the overall volume (solid plus permeable voids).

Two tests were performed for each brick sample. The average results from the two tests are given in Table 6. A summary of results is provided in Table 7. The overall average bulk specific gravity is 2.13. As a comparison, most rocks have BSG between 2.5 to 2.8 with 2.7 being a typical value for limestone. Some lightweight shales have BSG around 1.05. The brick aggregate having roughly 80% of the bulk specific gravity of limestone could be considered a lightweight aggregate.

The average absorption value for the brick aggregate was 7.7%. Absorption values vary widely for different aggregates and different limits may be acceptable for it depending on the application for which the aggregate is being used. A high absorption may be a predictor of poor freeze-thaw capabilities or abrasion resistance. Measured absorptions typically range from less than a percent for granite and crystalline rocks up to 10-12% for more porous sedimentary rocks (like sandstones and limestones). Some lightweight shales may have absorption as high as 30%.

It could be noted that older bricks had slightly lower specific gravities and higher absorptions than newer bricks. The variability among the older bricks, as seen by the standard deviation, is much higher than the variability among newer bricks as might be expected. Two of the older brick sources, 10 and 14 (both refractory bricks) had very high absorptions more than twice the standard deviation away from the mean.

Table 6. Average Results for Specific Gravity and Absorption

	Sample															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Bulk Specific Gravity	2.13	2.14	2.10	2.16	2.13	2.12	2.18	2.31	2.01	1.81	2.34	2.38	2.08	1.61	1.94	2.17
Bulk Specific Gravity (Saturated Surface Dry)	2.28	2.29	2.26	2.30	2.27	2.27	2.31	2.41	2.13	2.12	2.40	2.43	2.23	1.92	2.14	2.27
Apparent Specific Gravity	2.51	2.52	2.51	2.51	2.48	2.49	2.52	2.57	2.30	2.62	2.50	2.51	2.46	2.33	2.44	2.41
Absorption (%)	7.3	7.0	7.8	6.5	6.7	7.0	6.2	4.4	6.1	17.0	2.6	2.3	7.5	19.1	10.6	4.6

Table 7. Summary of Results for Specific Gravity and Absorption

	Overall average	Overall Standard deviation	Avg. for new bricks (1-8)	Std. Dev. for new bricks	Avg. for old bricks (9 -16)	Std. Dev. for old bricks	Avg. for new commercial brick (1-3)	Avg. for new residential brick (4-6)	Avg. for new pavers (7-8)
Bulk Specific Gravity	2.10	0.19	2.16	0.07	2.04	0.26	2.12	2.14	2.24
Bulk Specific Gravity (Saturated Surface Dry)	2.25	0.13	2.30	0.05	2.21	0.17	2.28	2.28	2.36
Apparent Specific Gravity	2.48	0.08	2.51	0.03	2.45	0.10	2.52	2.49	2.55
Absorption (%)	7.7	4.5	6.6	1.0	8.7	6.4	7.4	6.7	5.3

4.2 Los Angeles Abrasion
The crushed aggregate was tested in the Los Angeles Rattler to determine loss due to abrasion in accordance with AASHTO T 96 and ASTM C 131. Aggregates are subjected to substantial wear and tear throughout their life. Ideally, they should be hard and tough enough to withstand crushing, degradation, and disintegration from a variety of activities such as manufacturing, stockpiling, placing, and compaction. In addition, they must be able to adequately transmit loads from the pavement surface to the underlying layers and eventually the subgrade. The LAR is often used as a measure of the abrasion resistance of the aggregate.

In the LAR test, the coarse aggregate together with a specified number of steel spheres is placed in a rotating steel drum which also contains an interior steel shelf. A total of 500 revolutions are performed during which the aggregate is subjected to abrasion, impact and grinding. At the end of the test the percentage of mass loss due to some of the aggregate being ground finer than the #12 (1.70 mm) sieve is recorded.

Three tests were performed for each brick sample. The results of each test as well as the average are given in Table 8. A summary of results is provided in Table 9. The overall average percent mass loss after the LAR test is 41.6. As a comparison, typical values for some common types of rock are: basalt 10-17, dolomite 18-30, gneiss 33-57, granite 27-49, limestone 19-30, and quartzite 20-35. The MnDOT specification for virgin aggregates is a maximum of 40% loss for all aggregates and 35% for Class 6. The overall average for the brick sources is very close to the MnDOT cutoff point of 40%.

One of the sources (sample 14) had a LAR value of 78 which is roughly 3 standard deviations above the average. These bricks had been gathered from the demolition of a cold storage building and it is suspected that these bricks were of the refractory type because of their insulation value for a cold storage application. A second refractory brick (sample 10) also had a high LAR value of 52 which is almost 2 standard deviations above the average. The average percent loss for new bricks is slightly less than for the old bricks and there is less variability (i.e. lower standard deviation).

Table 8. Average Results from LAR Tests (% Loss) on Brick Samples

	Source															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
LAR test 1	39.6	36.3	42.9	36.3	41.5	41.9	44.4	33.0	35.1	51.6	38.5	31.8	29.9	78.3	38.4	46.4
LAR test 2	40.0	34.7	43.7	36.3	41.6	42.1	44.4	32.2	35.6	52.4	38.0	32.0	29.9	78.2	38.2	46.1
LAR test 3	39.5	36.7	43.7	35.7	42.0	41.8	44.4	33.6	35.3	52.5	38.0	31.8	29.5	77.5	38.1	47.7
Average	39.7	35.9	43.4	36.1	41.7	42.0	44.4	32.9	35.3	52.2	38.2	31.9	29.8	78.0	38.2	46.7

Table 9. Summary of Results from LAR

	Overall average	Overall Standard deviation	Avg. for new bricks (1-8)	Std. Dev. for new bricks	Avg. for old bricks (9 -16)	Std. Dev. for old bricks	Avg. for new commercial brick (1-3)	Avg. for new residential brick (4-6)	Avg. for new pavers (7-8)
LAR	41.6	11.3	39.5	4.1	43.8	15.7	39.7	39.9	38.7

4.3 Magnesium Sulfate Soundness
The crushed aggregate was tested for resistance to weathering using the magnesium sulfate soundness test in accordance with ASTM C88 and AASHTO T104. Aggregates in climates such as Minnesota are subject to weathering effects, particularly freeze-thaw, throughout their service life. Ideally, they should not be subject to excessive degradation from weathering effects. Since actual freeze thaw tests are lengthy, a common test is to use a magnesium or sodium sulfate solution to simulate the effects in a shorter period of time. This is accomplished by repeated immersion in saturated solutions of magnesium sulfate followed by oven drying to dehydrate the salt precipitated in permeable pore spaces. The internal expansive force, derived from the rehydration of the salt upon re-immersion, simulates the expansion of water on freezing.

The basic test procedure is to thoroughly wash and oven dry the sample, sieve into the recommended size quantities, place in containers (#8 mesh (2.36 mm)), immerse the samples in magnesium sulfate solution for 16-18 hours at 68.5 to 71.5ºF (20.3 to 21.9ºC), and oven-dry to constant mass. This is repeated for 5 cycles. After the last cycle, perform a thorough washing to remove the salt. To test when the aggregate is clean enough, a few drops of barium chloride are applied. If the water turns cloudy, additional rinsing is required. Once the aggregates are clean, they are oven dried and the recommended sieve number in AASHTO T104/ ASTM C88 is used to determine the loss.

White et al. [16] suggested that a maximum limit of 20% loss could be used to differentiate poor aggregate from good aggregate (for use in bituminous mixtures) for all climates and traffic loading conditions. MnDOT 3139 Specifications for graded aggregate for bituminous mixtures were discussed in Chapter 1. For the composite loss it specifies 18%.

Three tests were performed for each brick sample. Note that in the case of Brick 1, only two tests were finished because of accidental spillage and the high cost of magnesium sulfate. The results of the average of three tests (but only two for Brick 1) for each brick source are given in Table 10. A summary of results is provided in Table 11. When looking at new bricks, it appears that they all perform admirably for freeze-thaw behavior and could pass the Specification 3139 on their own. When looking at old bricks, the average for #4 to 3/8 is 21.4 and the MnDOT limit is 23%. Two brick sources (14 and 15) exceed this value. For 3/8 to 3/4 in the average is 11.1 and the MnDOT limit is 14%. Once again brick sources 14 and 15 exceed these values. The composite average for #4 to 3/4 in is 13.5 and the MnDOT limit is 18%. Once again, only brick sources 14 and 15 exceed these values. The overall averages for the brick samples are less than the MnDOT cutoff points.

One of the sources (sample 14) also had high LAR value of 78% as well as a high absorption. These bricks had been gathered from the demolition of a cold storage building and it is suspected that these bricks were of the refractory type because of their insulation value for a cold storage application. There may be some correlation of poor freeze-thaw performance with high absorption. Another refractory brick (sample 10) had high absorption and high LAR but fell within MnDOT limits for the magnesium sulfate testing.

Table 10. Average Results from Magnesium Sulfate Soundness (% Loss) on Brick Samples

	Sample															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
#4 to 3/8	10.0	2.8	2.8	1.5	2.3	4.4	1.9	2.6	9.2	19.5	1.5	2.5	6.0	91.1	39.1	1.9
3/8 to 3/4	2.7	1.2	0.8	0.6	0.8	1.4	0.9	1.3	3.7	8.1	1.1	1.1	1.3	54.8	17.5	1.1
3/4 to 1.5	0.7	0.7	0.5	0.5	0.6	1.1	0.5	0.7	1.3	4.6	0.2	0.7	0.9	30.3	6.5	0.4
Composite (#4 to 3/4)	4.4	1.6	1.3	0.8	1.2	2.1	1.1	1.6	5.0	10.7	1.2	1.4	2.4	63.2	22.5	1.3

Table 11. Summary of Results from Magnesium Sulfate Soundness

	Overall average	Overall Standard deviation	Avg. for new bricks (1-8)	Std. Dev. for new bricks	Avg. for old bricks (9-16)	Std. Dev. for old bricks	Avg. for new commercial brick (1-3)	Avg. for new residential brick (4-6)	Avg. for new pavers (7-8)
#4 to 3/8	12.5	23.1	3.6	2.8	21.4	30.9	5.2	2.8	2.3
3/8 to 3/4	6.1	13.7	1.2	0.7	11.1	18.5	1.6	0.9	1.1
3/4 to 1.5	3.1	7.4	0.7	0.2	5.6	10.2	0.6	0.7	0.6
Composite (#4 to 3/4)	7.6	15.8	1.8	1.1	13.5	21.4	2.4	1.3	1.4

Chapter 5. SETTING A LIMIT FOR PERCENTAGE OF BRICK

A general assessment of the brick aggregate shows that the majority of the brick can satisfy MnDOT requirements for virgin (natural) aggregate. The problem is that there are so many types of bricks and a few perform poorly. Table 12 shows the overall performance of each brick sample. If they meet the performance limit it is denoted by Y otherwise it is N. For the case of LAR, the MnDOT 3138 Specification limit is 40% for most aggregates and for bricks that fell between 40 and 44 they are denoted as "close". The MnDOT 3138 Specification limit for LAR for Class 6 is 35% and for bricks that fell between 35 and 39 they are denoted as "close". The MnDOT 3139 specification limits for magnesium sulfate soundness are 14% for 3/8-3/4, 23% for 3/8-#4, and 18% for composite. Although there are no MnDOT specifications regarding the absorption it is generally accepted that high absorptions may be detrimental. The brick aggregates have higher absorptions than virgin aggregates. Recycled concrete aggregate (RCA) also has high absorption but is allowed by MnDOT to be used up to 100% as aggregate; therefore a reasonable limit for absorption may be 9% which is on the high end of absorption for RCA.

Although the majority of brick can satisfy or are close to satisfying the specification limits, a few perform poorly therefore 100% brick aggregate cannot be allowed. The most objectionable type seems to be the refractory brick. It is impractical to specify exclusion of these types of bricks. One option for excluding poorly performing bricks would be to specify a physical test requirement e.g. LAR; however this would be cumbersome and not in line with the simplicity of the current MnDOT 3138 Specification which does not have any test requirement for the other recycled aggregates (concrete, asphalt pavement, and glass). The second approach would be to place an upper limit on the percentage of brick aggregate based on probability and statistics.

Assumptions were made that the samples tested in this study are representative of the population of bricks that are available for recycling, and that the distribution of performance follows a Gaussian (normal) distribution. The equation for a standard normal distribution is given by

$$f(z) = \frac{1}{2\pi} e^{-\frac{1}{2}x^2} \qquad\qquad \text{Equation (1)}$$

The z value in Eqn. 1 is commonly referred to as the *z-score*. It is calculated using

$$z = \frac{x - \bar{x}}{s} \qquad\qquad \text{Equation (2)}$$

where x = particular data point within a set of data (random variable)
$\bar{x}$ = mean of all x values
s = standard deviation

Table 12. Check of Brick Performance versus Specification Limits

Sample	Type	MnDOT 3138 LAR (35%)	MnDOT 3138 LAR (40%)	MnDOT 3139 mag. sulf. 3/8-3/4	MnDOT mag. sulf. 3/8 - #4	MnDOT mag. sulf. composite	Absorption < 9%
1	Commercial (new)	N	Y	Y	Y	Y	Y
2	Commercial (new)	Close	Y	Y	Y	Y	Y
3	Commercial (new)	N	Close	Y	Y	Y	Y
4	Residential (new)	Close	Y	Y	Y	Y	Y
5	Residential (new)	N	Close	Y	Y	Y	Y
6	Residential (new)	N	Close	Y	Y	Y	Y
7	Paver (new)	N	Close	Y	Y	Y	Y
8	Paver (new)	Y	Y	Y	Y	Y	Y
9	Commercial (age unknown)	Close	Y	Y	Y	Y	Y
10	Refractory (age unknown)	N	N	Y	Y	Y	N
11	Residential (age unknown)	Close	Y	Y	Y	Y	Y
12	1900s street paver (110 yrs)	Y	Y	Y	Y	Y	Y
13	Residential (50 yrs)	Y	Y	Y	Y	Y	Y
14	Refractory (130 yrs)	N	N	N	N	N	N
15	Residential (30 yrs)	Close	Y	N	N	N	N
16	Residential (15 yrs)	N	N	Y	Y	Y	Y

Since the Gaussian distribution is symmetric about the mean the area under half of the curve will be 0.50. Therefore to find a 90th percentile value of the random variable the z-score corresponding to an area under the curve of 0.40 is needed which can be found to be 1.28. In a similar manner, the z-score for a 95th percentile value is 1.64 and the z-score for a 99th percentile value is 2.33. Using the z-score, the mean and standard deviation in Equation 2, the corresponding quantile value can be found. The results are shown in Table 13. The information in the table is to be interpreted as follows: 90% of all bricks will have LAR *less than* 56.1; 95% of all bricks will have LAR *less than* 60.2; and so on.

Table 13. Different Percentile Values of Tested Properties

Percentile	LAR	Magnesium Sulfate Soundness (composite)	Absorption
90	56.1	27.8	13.5
95	60.2	33.5	15.1
99	68.0	44.4	18.2

In order to find the required percentage of brick needed in a blend of virgin aggregate and brick aggregate the Rule of Mixtures was utilized. This can be stated mathematically as

$$m_{virgin}y_{virgin} + m_{brick}y_{brick} = y_{composite}$$ Equation (3)

where m_{virgin} = mass fraction of the virgin aggregate
m_{brick} = mass fraction of the brick aggregate
y_{virgin} = virgin aggregate's value of property y (e.g. LAR)
y_{brick} = brick aggregate's value of property y
$y_{composite}$ = composite's value of property y

Since the sum of mass fractions must equal to 1.0, Eqn. 3 can be rewritten as

$$(1 - m_{brick})y_{virgin} + m_{brick}y_{brick} = y_{composite}$$ Equation (4)

Solving Eqn. 4 for m_{brick} we obtain

$$m_{brick} = \frac{y_{composite} - y_{virgin}}{y_{brick} - y_{virgin}}$$ Equation (5)

The values of $y_{composite}$ were set to their maximum allowable values. For LAR this was 40% for most aggregates and 35% for Class 6 aggregates per MnDOT 3138, and for the magnesium sulfate soundness this was 18% per MnDOT 3139. For absorption, there is no specified MnDOT limit; however excessive absorption in an aggregate may be detrimental. Attempts were made to correlate absorption with LAR loss (Fig. 20) and magnesium sulfate soundness (Fig. 21). Although the coefficients of correlation are only around 0.62, there does appear to be a trend of increased LAR mass loss and soundness loss with high absorptions. It was decided to use the upper bound of absorption values for recycled concrete aggregates as a limit since this is a material allowed for use by MnDOT. This value for RCA is about 9% [17].
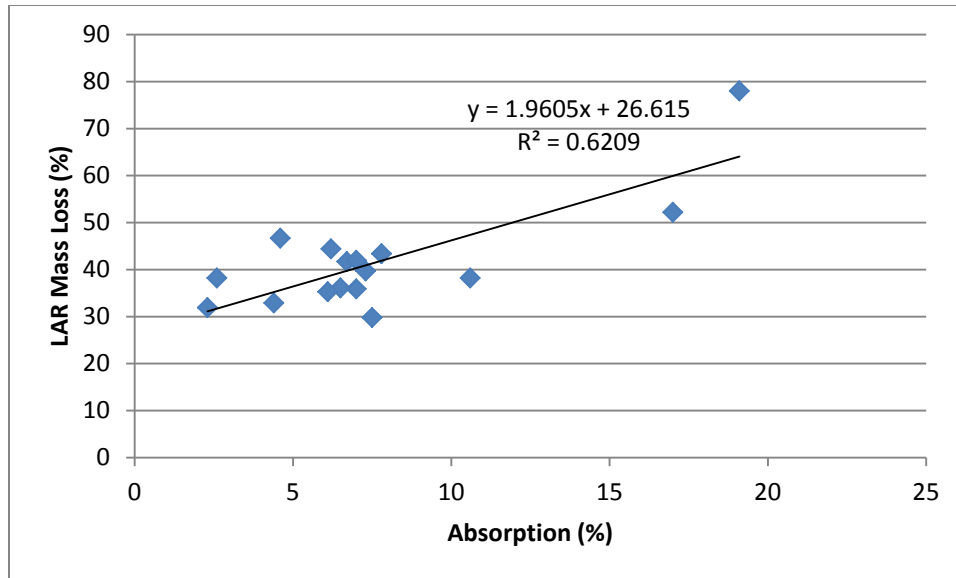
Figure 20. LAR Mass Loss versus Absorption.
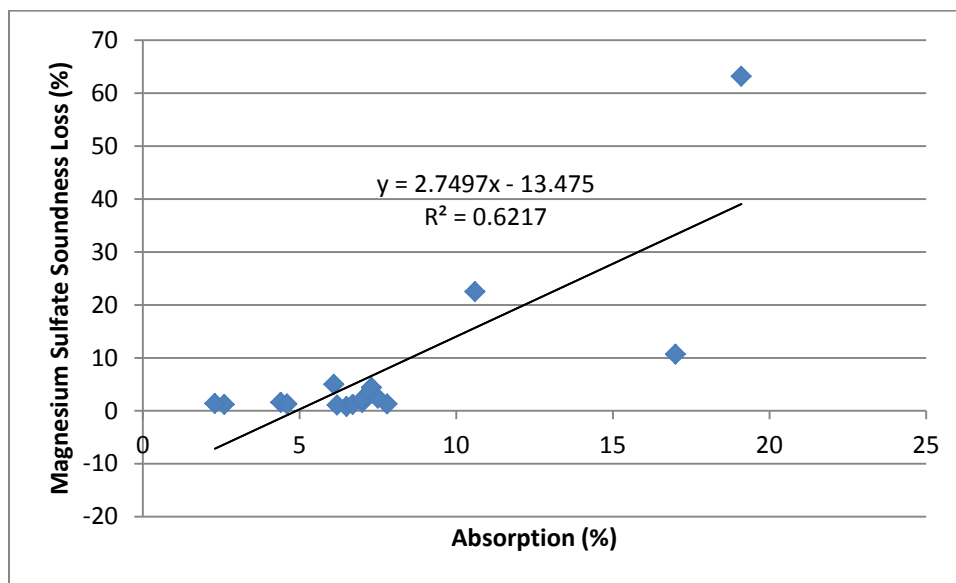
Figure 21. Magnesium Sulfate Soundness Loss versus Absorption.

In order to determine what values of y_{virgin} to use, it was necessary to look at values for a typical aggregate that would be used in Minnesota. This was quite a difficult task since mechanical and durability properties of aggregate can vary significantly. The mean LAR value for natural gravel aggregate for a seven-county area around the Twin-Cities was found to be 21.1% and for magnesium sulfate soundness was 17.3% in a study conducted in 1984 [18]. A similar study conducted more recently in 2000 also found for bedrock (dolostone) aggregates a LAR of 31.7, magnesium sulfate soundness of 12.6% and average absorption of 2.4% [19]. Since natural gravel aggregate resources near the Twin Cities are dwindling significantly, it was decided to use the bedrock aggregate values. In summary, the values used for $y_{composite}$ and y_{virgin} in Eqn. 5 are given in Table 14, while the values of y_{brick} at different percentiles are given in Table 13. The mass fractions of brick aggregate m_{brick} obtained using Eqn. 5 are summarized in Table 15.

Table 14. Values used for Composite Properties and Virgin Aggregate Properties

$y_{composite}$				y_{virgin}		
LAR (35%)	LAR (40%)	Mag. Sulfate	Absorption	LAR	Mag. Sulfate	Absorption
35	40	18	9	31.7	12.6	2.4

Table 15. Mass Fraction of Brick Aggregate to be used in Blended Aggregate

Percentile	LAR (35%)	LAR (40%)	Magnesium Sulfate Soundness (composite)	Absorption
90	0.14	0.34	0.36	0.59
95	0.12	0.29	0.26	0.52
99	0.09	0.23	0.17	0.42

From Table 15 it can be seen that absorption is not a controlling criterion. The controlling criteria are LAR and magnesium sulfate soundness. Based on the evaluation of Table 15, a final recommendation to allow a maximum of 10% of brick aggregate by mass blended with virgin aggregate is made. This value is at the 98th percentile controlled by the LAR limit of 35% and expected to be reasonably conservative.

As a quality control measure to check that contractors are not adding more than 10% of brick aggregate, tests of bulk specific gravity of the virgin aggregate and bulk specific gravity of the blended aggregate can be performed. Since BSG of limestone is about 2.7 for example and BSG of brick aggregate is about 2.13, an excessive amount of brick aggregate should be detectable. A blend of 10% brick and 90% limestone would have a theoretical BSG of about 2.6.

Chapter 6. CONCLUSIONS

Conservation and reuse of resources are becoming ever increasingly important for sustainability. In this research project the possibility of utilizing recycled crushed clay brick as aggregate was studied. MnDOT is already quite progressive in its use of recycled materials and allows the use of recycled concrete aggregates, recycled asphalt pavement, and recycled glass in base and surface courses. Based on current literature review, Minnesota may become a pioneer in the use of recycled brick aggregate as well.

There are many different types of clay bricks including structural bricks (both commercial and residential), pavers, and refractory bricks. The structural bricks and pavers will also vary from region to region. The bricks used in Minnesota are of the highest quality available because they have to meet severe weathering requirements. Structural brick accounts for the largest amount of brick manufactured. In this project, samples of various types of bricks were tested. The main tests conducted were the Los Angeles Rattler to assess abrasion properties and the magnesium sulfate soundness to evaluate freeze-thaw durability. In addition, basic engineering properties such as specific gravity and absorption were determined.

The majority of the brick tended to have excellent to fair performance often meeting or being close to meeting the MnDOT requirements for virgin aggregates. Some of the bricks, however, most notably the refractory ones, had poor performance. Based on the test results, probability and statistics, and the rule of mixtures, the author recommends that a maximum of 10% by total mass of aggregate be allowed for the brick aggregate. It is predicted that 98% of all brick aggregate when used in a blend with virgin aggregate at this mass fraction will meet MnDOT specifications for virgin aggregate.

Because of the limitations of the testing program and several assumptions made together with the well-known fact that lab tests do not always predict field performance correctly, it is suggested that MnDOT first conduct some pilot field tests using various amounts of blended brick and virgin aggregates before including a provision for brick aggregate in MnDOT Specification 3138 Aggregate for Base and Surface Courses. Also, a lower risk application could be the use of brick aggregate in shoulders.

According to Terry Beaudry, grading and base engineer at MnDOT, the estimated annual usage of aggregate for shouldering in Minnesota is 800,000 tons (about 400,000 tons each for MnDOT and counties and cities combined). Ten percent of this number would be 80,000 tons. The estimated annual amount of brick in the waste stream in Minnesota is around 88,000 tons; therefore, shouldering can consume the bulk of the waste brick. As experience is gained with this material and its performance in the field is tested the 10% number could be increased or decreased in the future.

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Appendix
2014 Draft Version of MnDOT Specifications 3138 and 3139

3138 AGGREGATE FOR SURFACE AND BASE COURSES

3138.1 SCOPE
Provide certified aggregate along with Form G&B-104 for 2118, 2211 and 2221.

Note that 5Q is a new gradation, which a designer may designate for use as a base, and would most commonly be produced at a quarry.

3138.2 REQUIREMENTS
A   General
Use aggregate sources meeting the requirements of 1601, "Source of Supply and Quality."

Provide certified aggregate materials that have uniform: appearance, texture, moisture content and performance characteristics.

Provide binder soils from sources meeting the requirements of 3146, "Binder Soil." Add binder soils during the crushing and screening operations.

B   Virgin Materials
Provide virgin aggregates meeting the following requirements:

(1)   Comprised of naturally occurring mineral materials, and contains no topsoil, organics or disintegrating rock as defined in Laboratory Manual section 1209,
(2)   Class 2 must be composed of 100% crushed quarry rock and
(3)   Conforms to the quality requirements of Table 3138-1.

Table 3138-1 Quality Requirements for Virgin Materials				
Requirement	**Class**			
	1 and 2	**3 and 4**	**5 and 5Q**	**6**
Max Shale, if No. 200 ≤ 7 % by mass	NA	10.0%	10.0%	7.0%
Max Shale, if No. 200 > 7 % by mass	NA	7.0%	7.0%	7.0%
Minimum Crushing Requirements *	NA	NA	10%	15%
Maximum Los Angeles Rattler (LAR) loss from carbonate quarry rock	40%	40%	40%	35%
Maximum Insoluble residue for the portion of quarried carbonate aggregates passing the No. 200 sieve	10%	10%	10%	10%
* Material crushed from quarries is considered crushed material.				

C Recycled Materials

The Contactor may substitute recycled aggregates for virgin aggregates, if meeting the following requirements:

(1)   Recycled aggregates contain only recycled asphalt pavement (RAP), recycled concrete materials, recycled aggregate materials, or certified recycled glass, and
(2)   Must meet the requirements of Table 3138-2.

Table 3138-2 Quality Requirements for Recycled Materials	
Requirement	**Classes 1, 3, 4, 5, 5Q and 6**
Maximum Bitumen Content of Composite	3.5%
Maximum Masonry block %	10%
Maximum percentage of glass *	10%
Maximum size of glass *	¾ in [19 mm]
Crushing (Class 5, 5Q and 6) ‖	10% for Class 5 and 5Q † 15% for Class 6 †
* Glass must meet certification requirements on the Grading and Base website. Combine glass with other aggregates during the crushing operation. † If material ≥ 20% (RAP + Concrete), Class 5 and 5Q crushing requirements are met. † If material ≥ 30% (RAP + Concrete), Class 6 crushing requirement is met. ‖ Material crushed from quarries is considered crushed material.	

D Surfacing Aggregates

Provide surfacing aggregates in accordance with 3138.2.A, "General," 3138.2.B, "Virgin Materials," and 3138.2.C, "Recycled Materials," and meeting the following requirements:

(1)   100 percent of the material passes the ¾ in [19.0 mm] sieve,
(2)   Does not use glass,
(3)   Recycled concrete materials may only be used for the roadway shoulders and
(4)   There is no restriction on the bitumen content, if used for shouldering.

Note: Class 2 must be composed of 100% crushed quarry rock per 3138.2B3.

E Gradation Requirements

(1)   For products containing less than 25 percent recycled materials, conform to Table 3138-3.
(2)   For products containing 25 percent or more recycled materials and less than 75% recycled concrete, conform to Table 3138-4.
(3)   For products containing 75 percent or more recycled concrete, conform to Table 3138-5.

(4)   Perform gradation tests prior to bituminous extraction.

Table 3138-3
Base and Surfacing Aggregate
(containing less than 25 percent recycled aggregates)
Total Percent Passing

Sieve Size	Class 1	Class 2	Class 3	Class 4	Class 5	Class 5Q	Class 6
2 in	—	—	100	100	—	100	—
1½ in	—	—	—	—	—	—	—
1 in	—	—	—	—	100	65 – 95	100
¾ in	100	100	—	—	90 – 100	45 – 85	90 – 100
⅜ in	65 – 95	65 – 90	—	—	50 – 90	35 – 70	50 – 85
No. 4	40 – 85	35 – 70	35 – 100	35 – 100	35 – 80	15 – 45	35 – 70
No. 10	25 – 70	25 – 45	20 – 100	20 – 100	20 – 65	10 – 30	20 – 55
No. 40	10 – 45	12 – 30	5 – 50	5 – 35	10 – 35	5 – 25	10 – 30
No. 200	8.0–15.0	5.0–13.0	5.0–10.0	4.0–10.0	3.0–10.0	3.0–10.0	3.0–7.0

Table 3138-4
Base and Surfacing Aggregate
(containing 25% or more recycled aggregates & less than 75% recycled concrete)
Total Percent Passing*

Sieve Size	Class 1	Class 3	Class 4	Class 5	Class 5Q	Class 6
2 in	—	100	100	—	100	—
1½ in	—	—	—	100	—	100
1 in	—	—	—		65 - 95	
¾ in	100	—	—	90 – 100	45 – 85	90 – 100
⅜ in	65 – 95	—	—	50 – 90	35 – 70	50 – 85
No. 4	40 – 85	35 – 100	35 – 100	35 – 80	15 – 45	35 – 70
No. 10	25 – 70	20 – 100	20 – 100	20 – 65	10 – 30	20 – 55
No. 40	10 – 45 † 5 – 45	5 – 50	5 – 35	10 – 35	5 – 25	10 – 30
No. 200	5.0 – 15.0 † 0 – 15.0	0 – 10.0	0 – 10.0	0 – 10.0	0 – 10.0	0 – 7.0

*Add letters in parentheses for each aggregate blend designating the type of recycled products included in the mixture.
(B) = Bituminous, (C) = Concrete, (G) = Glass
(BC) = Bituminous and Concrete, (BG) = Bituminous and Glass
(CG) = Concrete and Glass, (BCG) = Bituminous, Concrete and Glass

† Note: For Class 1, if the bitumen content is ≥ 1.5%, the gradation requirement is modified to 5 – 45% for the #40 Sieve and 0 – 15.0% for the #200 Sieve.

Table 3138-5 Base and Surfacing Aggregate (containing more than 75 percent recycled concrete) Total Percent Passing*						
Sieve Size	Class 1	Class 3	Class 4	Class 5	Class 5Q	Class 6
2 in	—	100	100	—	100	—
1½ in	—	—	—	100		100
1 in	—	—	—		65 – 95	
¾ in	100	—	—	90 – 100	45 – 85	90 – 100
⅜ in	65 – 95	—	—	50 – 90	35 – 70	50 – 85
No. 4	40 – 85	35 – 100	35 – 100	35 – 80	15 – 45	35 – 70
No. 10	25 – 70	20 – 100	20 – 100	20 – 65	10 – 30	20 – 55
No. 40	10 – 45	0 – 8	0 – 8	0 – 8	0 – 8	0 – 8
No. 200	5.0 – 15.0	0 – 3.0	0 – 3.0	0 – 3.0	0 – 3.0	0 – 3.0
* Add letters in parentheses for each aggregate blend designating the type of recycled products included in the mixture. (B) = Bituminous, (C) = Concrete, (G) = Glass, (BC) = Bituminous and Concrete, (BG) = Bituminous and Glass, (CG) = Concrete and Glass, (BCG) = Bituminous, Concrete and Glass						

3138.3 SAMPLING AND TESTING
Report the No. 200 sieve results to the nearest 0.1 percent and all other sieve results to the nearest 1 percent.

A.........................Sampling, Sieve Analysis and Crushing Tests Grading and Base Manual

B.........................Los Angeles Rattler Loss Laboratory Manual Method.. 1210

C.........................Shale Tests Laboratory Manual Method.. 1207 & 1209

D.........................Bitumen Content Laboratory Manual Method... 1852

E.........................Insoluble Residue Laboratory Manual Method.. 1221

F ....Reclaimed Glass AGI Visual Method .... (AGI Data sheet 15.1 and 15.2)

3139   GRADED AGGREGATE FOR BITUMINOUS MIXTURES

3139.1 SCOPE
Provide graded aggregate for use in bituminous mixtures.

3139.2 PLANT MIXED ASPHALT REQUIREMENTS
A   Composition
Provide graded aggregate composed of any combination of the following sound durable particles as described in 3139.2B.

Do not use graded aggregate containing objectionable materials including:

(1)   Metal,
(2)   Glass,
(3)   Wood,
(4)   Plastic,
(5)   Brick, or
(6)   Rubber.

Provide coarse aggregate free of coatings of clay and silt.

Do not add soil materials such as clay, loam, or silt to compensate for a lack of fines in the aggregate.

Do not blend overburden soil into the aggregate.

Feed each material or size of material from an individual storage unit at a uniform rate.

Do not place blended materials from different sources, or for different classes, types, or sizes together in one stockpile unless approved by the Engineer as a Class E aggregate.

B   Classification

B.1   Class A
Provide crushed igneous bedrock consisting of basalt, gabbro, granite, gneiss, rhyolite, diorite, and andesite. Rock from the Sioux Quartzite Formation may contain no greater than 4.0 percent non-Class A aggregate. Do not blend or add non-Class A aggregate to Class A aggregate.

B.2   Class B
Provide crushed rock from other bedrock sources such as carbonate and metamorphic rocks (Schist).

B.3   Class C
Provide natural or partly crushed natural gravel obtained from a natural gravel deposit.

B.4   Class D
Provide 100 percent crushed natural gravel produced from material retained on a square mesh sieve with an opening at least twice as large as Table 3139-2 allows for the maximum size of the aggregate in the composite asphalt mixture. Ensure the amount of carryover, material finer than the selected sieve, no greater than 10 percent of the Class D aggregate by weight.

B.5   Class E
Provide a mixture consisting of at least two of the following classes of approved aggregate:

(1)   Class A,
(2)   Class B, and
(3)   Class D.

B.6   Steel Slag
Steel slag cannot exceed 25% of the total mixture aggregate and be free from metallic and other mill waste.

The Engineer will accept stockpiles if the total expansion is no greater than 0.5 percent as determined by ASTM D 4792

B.7   Taconite Tailings
Obtain taconite tailings from ore mined westerly of a north-south line located east of Biwabik, Minnesota (R15W-R16W) or from ore mined in southwestern Wisconsin.

B.8   Recycled Asphalt Shingles (RAS)
Provide recycled asphalt shingles manufactured from waste scrap asphalt shingles (MWSS) or from tear-off scrap asphalt shingles (TOSS). Consider the percentage of RAS used as part of the maximum allowable Recycled Asphalt Pavement (RAP) percentage. See Table 3139-3.

B.8.A   RAS Gradation..........MnDOT Laboratory Procedure 1801

Provide RAS in accordance with the following gradation requirements:

Table 3139-1 RAS Gradation	
Sieve size	Percent passing
½ in [12.5 mm]	100
No. 4 [4.75 mm]	90

B.8.B   Binder Content
Determine the binder content using chemical extraction meeting the requirements of MnDOT Lab Procedure 1851 or 1852.

B.8.C   Bulk Specific Gravity
The Contractor may use an aggregate bulk specific gravity (Gsb) of 2.650 in lieu of determining the shingle aggregate Gsb in accordance with MnDOT Lab Procedure 1205.

B.8.D   Waste Materials
Do not allow extraneous materials including metals, glass, rubber, nails, soil, brick, tars, paper, wood, and plastics greater than 0.5 percent by weight of the graded aggregate as determined by material retained on the No. 4 [4.75 mm] sieve as specified in MnDOT Laboratory Procedure 1801.

B.8.E   Stockpile
Do not blend an RAS stockpile with other salvage material. Do not blend MWSS and TOSS. The Contractor may blend virgin sand material with RAS to minimize agglomeration if the Contractor accounts for the blended sand in the final mixture gradation.

B.8.F   Certification
Ensure the processor provides RAS certification on the following Department form "Scrap Asphalt Shingles from Manufacture Waste" or "Tear-Off Scrap Asphalt Shingles" at www.dot.state.mn.us/materials/bituminous.html

B.9   Crushed Concrete and Salvaged Aggregate
The Contractor may incorporate no greater than 50 percent of crushed concrete and salvaged aggregate in non-wear mixtures. Do not use crushed concrete in wearing courses.

B.10   Ash
Sewage sludge ash and waste incinerator ash are allowed as an aggregate source at a maximum of 5% of the total weight of the mixture. Sewage sludge ash for use as an aggregate source in wear or non-wear courses must be approved by examination with the Hazard Evaluation Process by MnDOT's Office of Environmental Stewardship.

B.11   Recycled Asphalt Pavement (RAP)

B.11.A Aggregate Angularity
Provide combined RAP and virgin aggregates that meet the composite coarse and fine aggregate angularity for the mixture being produced.

B.11.B Objectionable Material
Do not use RAP containing objectionable materials including metal, glass, wood, plastic, brick, or rubber.

B.11.C Asphalt Binder Content
Determine the asphalt binder content using the MnDOT Lab Manual Method 1851 and 1852.

B.11.D Bulk Specific Gravity
Determine the bulk specific gravity in accordance with MnDOT Laboratory Procedure 1205 or 1815.

C   Quality

C.1   Los Angeles Rattler Test MnDOT Laboratory Procedure 1210
Ensure a coarse aggregate loss no greater than 40 percent.

C.2   Soundness (Magnesium Sulfate) MnDOT Laboratory Procedure 1219
Maximum loss after 5 cycles on the coarse aggregate fraction (material retained on No. 4 [4.75 mm] sieve for any individual source within the mix) as follows:

(1)   Percent passing the ¾ in [19 mm] sieve to percent retained on the ½ in [12.5 mm] sieve, ≤ 14%,
(2)   Percent passing the ½ in [12.5 mm] sieve to percent retained on the ⅜ in [9.5 mm]sieve, ≤18%,
(3)   Percent passing the ⅜ in [9.5 mm] sieve to percent retained on the No. 4 [4.75 mm] sieve, ≤ 23%,
(4)   For the composite if all three size fractions are tested, the composite loss ≤ 18%, and acceptance will be granted if:
    (4.1)   If the Contractor meets the composite requirement, but fails to meet at least one of the individual components, the Engineer may accept the source if each individual component is no greater than 110 percent of the requirement for that component.
    (4.2)   If the Contractor meets each individual component requirement, but fails to meet the composite, the Engineer may accept the source if the composite is no greater than 110 percent of the requirement for the composite.

Coarse aggregate that exceeds the requirements in this section for material passing the No. 4 [4.75 mm] sieve cannot be used.

C.3   Spall Materials and Lumps MnDOT Laboratory Procedure 1219
Stop asphalt production if the percent of spall or lumps measured in the stockpile or cold feed exceeds the values listed in Table 3139-3. Determine lump compliance by dry batching.

C.4   Insoluble Residue Test MnDOT Laboratory Procedure 1221
Use Statewide (except for District 6)

If using Class B carbonate materials ensure the portion of the insoluble residue passing the No. 200 [75 µm] sieve is no greater than 10 percent.

Use for District 6 ONLY.

If crushed carbonate quarry rock (limestone or dolostone) is used, the minus #200 [75 µm] sized portion of the rock insoluble residue shall not exceed 10% by weight.

Blending of sources and/or beds with an insoluble residue up to 15% is allowed to meet the 10% insoluble residue requirement. Individual beds thinner than 6 inches [150 mm] or up to 5% of the total face height, are exempt from the 15% maximum insoluble residue requirement. However, the aggregate producer shall practice good quality control at all times and exclude poor quality stone to the extent practical, regardless of the bed thickness and/or pocket size and location.

No carbonate quarry rock from the Platteville Geological Formation is allowed.

D   Gradation
Ensure the aggregate gradation broad bands meet the following requirements in accordance with AASHTO T-11 (passing the No. 200 [75 µm] wash) and AASHTO T-27.

<table>
<tr><td colspan="5">**Table 3139-2**
Aggregate Gradation Broad Bands (percent passing of total washed gradation)</td></tr>
</table>

Sieve size	A	B	C	D
1 in [25.0 mm]	—	—	100	—
¾ in [19.0 mm]	—	100*	85 – 100	—
½ in [12.5 mm]	100*	85 – 100	45 – 90	—
⅜ in [9.5 mm]	85 – 100	35 – 90	—	100
No. 4 [4.75 mm]	60 – 90	30 – 80	30 – 75	65 – 95
No. 8 [2.36 mm]	45 – 70	25 – 65	25 – 60	45 – 80
No. 200 [0.075 mm]	2.0 – 7.0	2.0 – 7.0	2.0 – 7.0	3.0 – 8.0

* The Contractor may reduce the gradation broadband for the maximum aggregate size to 97 percent passing for mixtures containing RAP, if the oversize material originates from the RAP source. Ensure the virgin material meets the requirement of 100 percent passing the maximum aggregate sieve size.

Table 3139-3
Mixture Aggregate Requirements

Aggregate Blend Property	Traffic Level 2	Traffic Level 3	Traffic Level 4	Traffic Level 5
20 year Design ESAL's	<1 million	1 - 3 million	3 - 10 million	10 – 30 million
Min. Coarse Aggregate Angularity (ASTM D5821) (one face / two face), %- Wear (one face / two face), %- Non-Wear	30/- 30/-	55 / - 55 / -	85 / 80 60/ -	95 / 90 80 / 75
Min. Fine Aggregate Angularity (FAA) (AASHTO T304, Method A) %- Wear %-Non-Wear	40 40	42 40	44 40	45 40
Flat and Elongated Particles, max % by weight, (ASTM D 4791)	-	10 (5:1 ratio)	10 (5:1 ratio)	10 (5:1 ratio)
Min. Sand Equivalent (AASHTO T 176)	-	-	45	45
Max. Total Spall in fraction retained on the #4 [4.75mm] sieve – Wear Non-Wear	5.0 5.0	2.5 5.0	1.0 2.5	1.0 2.5
Maximum Spall Content in Total Sample – Wear Non-Wear	5.0 5.0	5.0 5.0	1.0 2.5	1.0 2.5
Maximum Percent Lumps in fraction retained on the #4 [4.75mm] sieve	0.5	0.5	0.5	0.5
Class B Carbonate Restrictions				
Maximum% -#4 [-4.75mm] Final Lift/All other Lifts	100/100	100/100	80/80	50/80
Maximum% +#4 [+4.75mm] Final Lift/All other Lifts	100/100	100/100	50/100	0/100
Max. allowable scrap shingles–MWSS[1] Wear/Non Wear	5/5	5/5	5/5	5/5
Max. allowable scrap shingles –TOSS[1] Final Lift/All other Lifts	5/5	5/5	0/5	0/0

(1) MWSS is manufactured waste scrap shingle and TOSS is tear-off scrap shingle.

3139.3 PERMEABLE ASPHALT STABILIZED STRESS RELIEF COURSE (PASSRC) AND PERMEABLE ASPHALT STABILIZED BASE (PASB) REQUIREMENTS

A   Restrictions

Do not use recycled materials including glass, concrete, bituminous, shingles, ash, and steel slag.

B   Gradation

The Gradation limits are also considered the Job Mix Formula (JMF) limits.

B.1   PASB

Table 3139-4 PASB Aggregate Gradation	
Sieve Size	Percent Passing
1 ½ inch [37.5 mm]	100
1 inch [25.0 mm]	95 - 100
¾ inch [19.0 mm]	85 – 95
3/8 inch [9.5 mm]	30 – 60
No. 4 [4.75 mm]	10 – 30
No. 8 [2.36 mm]	0 – 10
No. 30 [600 µm]	0 – 5
No. 200 [75 µm]	0 – 3

B.2   PASSRC

Table 3139-5 PASSRC Aggregate Gradation	
Sieve Size	Percent Passing
5/8 inch [16.0 mm]	100
1/2 inch [12.5 mm]	85 – 100
3/8 inch [9.5 mm]	50 – 100
No. 4 [4.75 mm]	0 – 25
No. 8 [2.36 mm]	0 – 5

C   Quality

Will meet all requirements of 3139.2.C.1 through 3139.2.C.3.

3139.2.C.4 changes to: If using Class B carbonate materials ensure the portion of the insoluble residue passing the No. 200 [75 µm] sieve is no greater than 10 percent.

D   Mixture Quality Requirements

Table 3139-6 Mixture Aggregate Requirements for PASSRC & PASB	
Aggregate Blend Property	
Coarse Aggregate Angularity (ASTM D5821) (one face/two face) % PASSRC [1] PASB [1]	95/- -/65
Fine Aggregate Angularity (FAA) (AASHTO T304, Method A) %	NA
Flat and Elongated Particles, max(2) % by weight, (ASTM D 4791)	NA
Clay Content (2) (AASHTO T 176)	NA
Total Spall in fraction retained on the 4.75mm [**#4**] sieve	3.0
Maximum Spall Content in Total Sample	5.0
Maximum Percent Lumps in fraction retained on the 4.75mm [**#4**] sieve	0.5

Note (1) Carbonate Restrictions: If Class B (as defined in 3139.2.B.2), crushed carbonate quarry rock (limestone or dolostone), is used in the mixture, or if carbonate particles in the material retained on the 4.75 mm [**No. 4**] sieve exceeds 55 percent, by weight, the minus 0.075 mm [# **200**] sieve size portion of the insoluble residue shall not exceed 10 percent.

3139.4   ULTRA THIN BONDED WEARING COURSE (UTBWC) REQUIREMENTS.

A   Restrictions
Do not use recycled materials including glass, concrete, bituminous, shingles, ash, and steel slag.

B   Quality
Will meet all requirements of 3139.2.C.

C   Coarse Aggregate
Provide a Class A aggregate, as defined in 3139.2.B.1, in accordance with the following requirements:

Table 3139-7 UTBWC Coarse Aggregate Requirements		
Tests	**MnDOT Laboratory Manual Method**	**Limit, %**
Flat and elongated ratio at 3:1	1208	≤ 25
Los Angeles Rattler Test (LAR)	1210	≤ 40
Bulk Specific Gravity	1204	

D   Fine Aggregate
Provide fine aggregate, passing the No. 4 [4.75 mm] sieve in accordance with the following requirements:

Table 3139-8 UTBWC Fine Aggregate Requirements		
Tests	**Method**	**Limit, %**
Sand equivalent*	AASHTO T 176	≥ 45
Uncompacted void content	MnDOT Laboratory Manual 1206	≥ 40
Bulk Specific Gravity	MnDOT Laboratory Manual 1205	