PAVEMENT MATERIALS

Pavements are typically constructed in distinct layers, with each layer serving a purpose in the overall pavement structure. This section discusses these materials and their properties.

CLASSIFICATION

Pavement materials are classified according to their use and type within a pavement system. Thus, one level of classification is subbase, base, and surface. This classification scheme describes the location of the materials within the pavement system. However, it also provides information about the purpose of the materials. For example, the surface layer is intended to provide a smooth, safe, and durable layer upon which vehicles can travel as well as being a major contributor to the pavement’s structural capacity. The base course also contributes significantly to the pavement capacity, particularly when treated with a stabilizing agent, and it also provides positive drainage and protection against frost. Generally, a subbase or series of subbases are included in a pavement cross section to increase structural capacity, raise pavement layers above the frost line, or provide a leveling course for the placement of base layers.

As noted above, materials are also categorized by type. There are two common types of pavement surfacings: bituminous and Portland cement concrete (PCC). A wide variety of base and subbase materials underlie these surfacings. Common to all of the pavement materials is the use of some sort of aggregate, either with or without a binder.

AGGREGATE BASE

High-quality aggregate bases are constructed with high quality aggregates. The seven classes of aggregates used for base courses are described in Mn/DOT’s Specification 3138. Classes 1 through 6 consist of 100 percent virgin aggregate materials. These materials consist of durable particles of gravel and sand, crushed quarry, or mine rock. Class 7 consists of salvaged or recycled aggregate materials that may or may not be blended with virgin aggregate. The salvaged and recycled aggregates that are permitted include bituminous mixtures, crushed concrete, and reclaimed glass. These materials are subject to specific limitations relative to their application; i.e. reclaimed glass is limited to a maximum of 10 percent by mass.

There are three different approaches to the design and construction of aggregate bases. The base courses resulting from these approaches may be either permeable (drainable) or densely graded (relatively impermeable). Aggregates for both types are discussed below.

1. Permeable Bases. Permeable or drainable base courses are designed to rapidly drain moisture from the pavement structure. The combination of base thickness and material permeability should be such that moisture rapidly flows through the base, preferably draining the layer in fewer than two hours following a precipitation event. An FHWA study showed that the presence of a permeable base course enhanced the performance of the pavement, especially in areas where the pavement materials were affected by the presence of moisture. Essential to the good performance of such permeable bases, however, was the design and construction of adjacent layers, the design and placement of outlet drains, and the presence of a properly designed filter layer between the permeable layer and the subgrade soils beneath it.

Permeable aggregate bases should consist of a hard, durable, crushed, angular aggregate with fewer than 3% fines (material passing the 0.075mm (No. 200) sieve). The LA abrasion index of the aggregate must be 40 or less and the aggregate must contain less than 10 percent minus 0.075mm (No. 200) sieve size insoluble residue (Mn/DOT’s laboratory manual test method No. 1221). Permeable bases may be unstabilized (Open Graded Aggregate Base (OGAB)), or stabilized with either asphalt or Portland cement.
Table 3-3.1 gives the aggregate gradation specified by the Department for permeable aggregate bases.

Table 3-3.1. Gradation for permeable aggregate bases (PAB).

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Unstabilized Percent Passing</th>
<th>Stabilized Percent Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1/4 in.</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>1 in.</td>
<td>95 - 100</td>
<td>95 - 100</td>
</tr>
<tr>
<td>3/4 in. 65 - 95</td>
<td>85 - 98</td>
<td>85 - 98</td>
</tr>
<tr>
<td>3/8 in. 30 - 65</td>
<td>50 - 80</td>
<td>50 - 80</td>
</tr>
<tr>
<td>No. 4 10 - 35</td>
<td>3 - 20</td>
<td>20 - 50</td>
</tr>
<tr>
<td>No. 10</td>
<td>0 - 20</td>
<td>0 - 20</td>
</tr>
<tr>
<td>No. 40</td>
<td>0 - 8</td>
<td>0 - 5</td>
</tr>
<tr>
<td>No. 200</td>
<td>0 - 3</td>
<td>0 - 3</td>
</tr>
</tbody>
</table>

* Typically stabilized with two to three percent asphalt.

The aggregate is required to have a uniformity coefficient ($D_{60}$ divided by $D_{10}$) equal to or greater than 4.0 for unstabilized base and 2.5 for stabilized base, where $D_{60}$ is the diameter of the soil particle of which 60 percent is smaller by weight and $D_{10}$ is the diameter of the soil particle of which 10 percent is smaller by weight. A minimum of 85 percent two-face crushing is required for unstabilized bases and 65 percent for stabilized bases. See standard Special Provision for detailed specifications.

Unstabilized permeable aggregate bases are more susceptible to deformation from construction equipment and care must be exercised to not damage them during construction.

As previously noted, the placement of a well-designed filter layer is essential to the performance of the permeable base layer. The purpose of this layer is to prevent fines from working their way into the voids in the drainage layer, thereby clogging the voids and reducing the permeability of the base. The cost of permeable aggregate bases in new design is generally more than conventional dense-graded materials.

The placement of a permeable base layer must be accompanied by the inclusion of longitudinal edge drains. The purpose of these drains is to remove the moisture collected in the drainage layer away from the pavement structure. There are a number of different types of edge drain designs, but the basic principle remains the same - to quickly remove the moisture that is collected in the drainage layer. In new designs this is most easily done with a properly designed longitudinal trench collector system, which includes the use of collector pipes, geotextiles, and properly sized backfill material. Geocomposite (fin) drains are not recommended for use with permeable bases.

Detailed information on the design and construction of the filter layer, edge drains, and other aspects of providing subsurface drainage is provided in the FHWA’s Technical Paper 90-01, Subsurface Pavement Drainage and in FHWA’s Pavement Subsurface Drainage Design Reference Manual, January 1999, ERES Consultants, Inc. In addition, the FHWA has developed a Windows-based program called Drainage Requirements in Pavements (DRIP). Its applications of interest include the hydraulic design of permeable bases, design of separation layers, and longitudinal edge drains. See Chapter 5 for further discussion concerning permeable bases.
2. Dense-graded Aggregate Bases. The other type of aggregate base is a dense-graded granular material. Granular materials meeting Mn/DOT's Specifications for Classes 3, 4, 5, 6, and 7 may meet the definition of a dense-graded material. These materials will provide adequate support to the pavement structure provided that they have the proper gradation and are not saturated. A saturated base may lose fines due to pumping when subjected to loading, which can reduce the support it provides to the surface layer. In general, saturated bases lose stiffness: modulus reductions of more than 50% have been reported in the literature. In order to reduce or eliminate the moisture-related damage and increase the overall pavement service life, permeable bases and/or edge drains have been incorporated into some designs.

3. Pavement Reclamation. In addition to the previously discussed aggregate base types, in which aggregate materials are imported to the project site, pavement reclamation techniques have become common in recent years. These techniques involve processing in-place pavement surfacing and base materials into a dense-graded base for incorporation in a new pavement structural design. These techniques reduce or eliminate the need to import additional aggregate materials. Two techniques are discussed below.

   a. Bituminous Pavement Reclamation. This process consists of in-place pulverizing and mixing of the existing bituminous pavement structure and a predetermined portion of the underlying aggregate base materials to produce a dense-graded aggregate base. The processed material usually meets Mn/DOT’s Specification 3138, Aggregate Base, Class 5.

   b. Concrete Pavement Rubblizing. This technique consists of rubblizing the in-place pavement into a dense-graded base. The resulting processed material is somewhat variable in size; however, it is more permeable than other types of dense-graded bases. This technique results in a dense base with excellent supporting capabilities.

3-3.01.02 TREATED BASE

Treated bases consist of a granular material to which a stabilizing agent has been added. The most commonly used stabilizing materials in Minnesota are asphalt cement used in permeable asphalt stabilized base and asphalt emulsion used in cold mix recycling. The information that follows is intended to serve as a general introduction to the treatment of granular materials.

1. Bituminous-treated Base. Aggregates may be treated with a bituminous product, resulting in a bituminous-treated base. This treatment can either be done "in-place" with existing materials or at a mix plant. The function of the bituminous treatment is to coat the granular particles with bituminous binder, enhancing the mixture strength and waterproofing characteristics.

   a. Cold Mix Recycling. This process includes the milling of the in-place pavement, the addition of asphalt emulsion, the placement of the new mixture, and a hot-mixed surface overlay. This procedure provides a sound base for a plant-mixed pavement without transporting the millings back to the plant.

   b. Permeable. As with granular bases, bituminous-treated bases may be either permeable or dense graded. When properly constructed, permeable bituminous-stabilized bases have characteristics similar to permeable unstabilized bases and they are better able to withstand construction traffic. Permeabilities for drainable bituminous-treated bases are typically 0.35 cps (1,000 fpd) or more.

   Most often, asphalt cement (such as PG 64-22) is used as the binder for drainable bituminous-treated bases. Typical quantities are from two to three percent asphalt cement (by weight) for a very open-graded aggregate. The
intent is to provide just enough asphalt to coat the particles and bind them
together without filling the voids.

c. Bituminous-treated Base. This work consists of constructing a bituminous-
treated base course on a prepared subgrade as defined in Mn/DOT’s
Specification 2204. Mn/DOT is not currently using this process.

2. Cement, Lime, and Lime-Fly Ash Treatments. Aggregate bases may also be treated with
a number of different cementitious products, including Portland cement, lime, and lime-
fly ash. With any of the treatment materials, it is recommended that trial mixes be
constructed with the stabilizing agent to make sure that the desired reaction will take
place. Many of the reactions are highly dependent upon the nature of the fines and their
mineralogy, and there is no other fail-safe means of determining whether a treatment
method will work without producing the necessary trial mix designs and performing the
correct tests.

a. Portland Cement. Portland cement can be used for the treatment of both fine-
grained and coarse-grained materials to produce a wide variety of cement-
treated base mixtures. Such mixtures include soil stabilized by small amounts of
cement, although there may or may not be specific quality requirements in terms
of volume stability, freeze-thaw and wet-dry durability, strength, and
impermeability.

There are two applicable specifications that govern the design and construction
of cement-treated bases. Mn/DOT’s Specification 2206 covers soil-cement
bases, which are a combination of Portland cement and either in-place soil or
imported soil with the specified qualities. Some soil-cement bases have
performed poorly in the past, due to the appearance of cracks in the asphaltic
concrete pavement surface that have reflected through from shrinkage cracks in
the base. Mn/DOT’s Specification 2201 details the requirements for concrete
bases. This is a higher quality base material that is typically mixed in concrete
batch plants and placed with concrete placement machinery. This base has
significant load carrying capacity, but the development of reflection cracks in
the surface layer from cracks in the base course can still be a problem.

Mn/DOT is not currently using these two specifications in pavement
construction.

b. Lime. Lime can be used to modify fine-grained soils and the fine-grained
portion of granular soils. It is most effective in the treatment of plastic clays,
with a minimum clay content of 10 percent and a plasticity index (PI) greater
than 10.

The effect of the addition of lime is dependent upon such factors as soil type,
lime type, lime percentage, curing conditions (time and temperature), and the
interactions between these variables. The immediate benefits of the lime
treatment of soils include a decreased PI, improved workability, reduced volume
change characteristics, and increased strength. These benefits are the result of
immediate reactions between the lime and the soil (cation exchange followed by
floculation and agglomeration). Over time, the treated soil may also show
enhanced strength and durability properties because of the continued pozzolanic
reaction that is occurring between the lime and the soil. However, this may not
always happen, as the reaction is heavily influenced by the soil conditions and
mineralogical properties. In addition, the lime treatment has the potential to
make the soil more frost susceptible. A lime mix design is based on the results
that are desired, but it is generally suggested that two to four percent lime be
used. At present, the Department has no established specifications for lime-
treated bases.
c. Lime-Fly Ash. Lime-fly ash may be used to treat fine-grained materials, especially silty soils, with the lime reacting with the fly ash in a pozzolanic reaction. The quantity of lime used in lime-fly ash mixtures ranges from two to eight percent, with 2-1/2 to four percent typical, while the fly ash quantity ranges from eight to 36 percent, with 10 to 15 percent typical. The Department does not have established specifications for lime-fly ash/soil mixtures, and they are not currently used in pavement construction in the state.

3. Chemical and Other Treatment Agents. Other agents have been used to treat pavement materials, including calcium chloride and sodium chloride. These have seen some use as dust palliatives; however, they have not seen widespread use as treatment agents in base courses. Sulfur, rice-husk ash, and various forms of slags have also been used, either by themselves or in combination with the other treatment agents discussed above, for treating highway materials. The Department does not currently use any such stabilizing agents.

3-3.01.03 PAVEMENT SURFACINGS

The pavement surface must be constructed to a higher standard than other layers in the pavement structure. It is subjected to both direct loadings from the applied traffic and greater wear from environmental factors. The surface layer is designed to provide a smooth riding surface while maintaining adequate friction. Because of its importance to the overall pavement structure, materials used in the construction of the surface are generally of higher quality. The materials most commonly used for pavement surfacings are aggregates, asphalt mixtures, and Portland cement concrete (PCC).

1. Aggregates. Aggregates may be used as a wearing course (placed directly on the subgrade) on some low-volume roads. Aggregates used for such purposes should conform to Mn/DOT's Specification 3138. A good aggregate material consists primarily of gravel and coarse sand with finer particles to fill the voids and a small portion of clay to act as a binder.

The primary concern regarding the selection of the aggregate relates to the stability of the aggregate mix, which should be stable enough to resist shoving or rutting from the anticipated loadings. The effect of moisture on the layer must also be considered, as it is desirable that the surface shed water.

Other considerations for an aggregate-surfaced road include dust generation, ride quality, and tire wear. It is also desirable that such a surface be easy to maintain. Additional information on the design and rehabilitation of aggregate-surfaced roads can be found in FHWA's *Surface Design and Rehabilitation Guidelines for Low-Volume Roads*. Design guidelines are provided in Section 5-5.0, Aggregate-Surfaced Road Design.

2. Bituminous. Section 5-693.100 of Mn/DOT's Bituminous Manual provides information on the materials used for bituminous surfaces, as well as sampling and testing methods for their construction.

A number of bituminous mixes may be employed as a pavement surface. These are briefly described below.

a. Plant-mixed Bituminous Pavement. Mn/DOT's Specification 2360 covers the use of plant-mixed bituminous pavement and includes several different types. Specification 2360 is the combined 2360/2350 Gyratory/Marshall Design Specification. This specification has strict quality control/quality assurance requirements. In 2006, Mn/DOT's Bituminous Office recommended the use of gyratory bituminous mixtures for all state projects. While the 2360 specification still contains Marshall designed mixtures, it is the intention of the Department to move away from Marshall mixtures towards exclusively gyratory mixtures.
The mixture designations are based on predicted traffic. Gyratory mixtures levels 2, 3, 4, & 5 are used relative to increased traffic levels (20-year design bituminous ESALs), in that order. Higher traffic level mixtures have a higher percentage of crushed aggregate plus tighter aggregate quality specifications. Mn/DOT’s Specifications 3139 and 2360 lists gradation, crushing, and quality requirements.

The Contractor, in accordance with the respective Mn/DOT specifications, may provide recycled asphaltic pavement materials (RAP), scrap asphalt shingles, crushed concrete, sewage sludge ash (SSA) and salvaged material into bituminous mixtures. See table 3-3.2 for the allowable salvage materials for recycling.

<table>
<thead>
<tr>
<th>Mixture Type / Traffic Level</th>
<th>Wear Layers</th>
<th>Non-Wear Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP+: SP – Level 2</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>RAP+: SP – Level 3</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>RAP+: SP – Level 4</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>RAP+: SP – Level 5</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Crushed Concrete</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>Salvaged Aggregate</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Sewage Sludge Ash (SSA)²</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Scrap Asphalt Shingles³</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

1) Wear course is the top 100 cm (4 in.) of the bituminous pavement.
2) Non-Wear course is equal to or greater than 100 cm (4 in.) from the surface of the pavement.
3) RAP containing any objectionable material will not be permitted for use.
4) Only SSA that meets Tier II hazard evaluation criteria as approved by Mn/DOT’s Office of Environmental Services.
5) The percentage of scrap shingles used will be considered part of the maximum allowable RAP.

The Department has instituted a Quality Management plan for bituminous pavements. Section 5-693.400 of Mn/DOT’s Bituminous Manual provides the background information for the administration of this plan.

b. Bituminous Seal Coat. Mn/DOT’s Specification 2356 and the latest Special Provisions cover the materials and procedures for the proper placement of a bituminous seal coat over an in-service bituminous pavement. The process consists of the application of a bituminous material followed by the spreading of an aggregate. The following bituminous materials have been used for the seal coat:

- MC Liquid Asphalt MC 800, 3000
- Emulsified Asphalt
  - Anionic HFMS-2, HFMS-2p and
  - Cationic CRS-2, CRS-2p.
- Asphalt Cement PG Graded as specified.

Mn/DOT’s current position is to use emulsified asphalt, primarily the CRS-2p asphalt, and discourages the use of MC liquid asphalts.
There are many reasons to place a seal coat, but the primary benefits are as follows:

- Waterproofing the surface
- Improvement in surface friction and drainage
- Retarding pavement weathering
- Improvement in surface appearance

It should be noted that seal coats provide no structural contribution to the overall performance of the pavement.

3. Portland Cement Concrete. Portland cement concrete (PCC) is a commonly used surfacing material composed of Portland cement, aggregates, and water. Concrete pavements are covered under Mn/DOT's Specification 2301.

Different types of cements and aggregates may be specified, depending on the anticipated use of the concrete. Several admixtures may also be used in the construction of concrete pavements to alter certain characteristics of the mix. Both batch plant and ready-mix concretes may be used for pavement construction, provided that they are in accordance with the requirements of Mn/DOT's Specification 2461.

Two types of PCC obtained from each of the sources are used for construction in the state. Type 1 concrete is produced using Type I Portland cement, and Type 3 air-entrained concrete is produced by using either Type IA air-entrained Portland cement or Type I Portland cement with an approved air-entraining agent added. Type 1 concrete is not used for pavements because of its lack of air entrainment. Additional information on the different types of cement used by the Department is given in Section 3-3.02.03.

Mn/DOT's Concrete Manual provides a great deal of information on the materials, mix design, batching and mixing, testing, placing, and inspection of concrete used in pavement construction.

The concrete may be placed on a prepared subbase course, which generally consists of either a dense graded base (Class 5) or a permeable aggregate base (treated or non-treated). Concrete also may be placed over an existing concrete pavement, which is referred to as an unbonded concrete overlay, or over an existing bituminous pavement in which case it is referred to as whitetopping, or ultra-thin whitetopping, depending on its thickness. The requirements for concrete pavement constructed in this manner are given in Mn/DOT's Specification 2301. It is the normal practice in the state to construct concrete pavements that are jointed plain (non-reinforced). Transverse joints are dowelled and generally sealed with an approved joint sealant.

3-3.02 ENGINEERING PROPERTIES

The materials discussed in the preceding section are used in pavement structures because they possess desirable engineering properties that contribute to the overall performance of pavements. These properties are discussed in this section, along with the test methods that are used to quantify them.

3-3.02.01 AGGREGATES

Controls are placed on the quality of aggregates used in both aggregate bases and surface courses. The requirements are identical for the most part; the few differences that exist are discussed herein. Mn/DOT's Specification 3138 covers all aspects of aggregate properties.

1. Base. The properties of aggregates used in base courses are specified in order to obtain the desired level of quality. The significance of each of the relevant properties is discussed below in relation to their overall contribution to the performance of the aggregate.
a. Gradation. The gradation of the aggregate is important for several reasons. A dense-graded aggregate includes particles of many different sizes. It will generally compact in a tighter matrix, as the smaller particles fill the voids between larger particles. The result is a base course that has comparatively higher strength and is more impervious to moisture than a more open-graded layer. An open-graded material is used in order to promote drainage, so the large voids between aggregate particles is, in this case, desirable.

Under Mn/DOT's Specification 3138, the aggregate classes shown in Table 3138-1 are generally considered dense graded aggregate materials. The Class 5, 6, and 7 aggregates are normally used as base course aggregates placed directly under the pavement surfacing (concrete and bituminous), whereas Classes 3, 4, and 7 are used as subbase course aggregates beneath the Class 5, 6, and 7 base. It should be noted that these base materials have a limit of 10% passing the 0.075mm (No. 200) sieve. Higher amounts of minus 0.075mm (No. 200) sieve material can have a detrimental effect on the shear strength of the material.

In order to promote pavement drainage, open-graded aggregates are sometimes used in place of dense-graded aggregates. The gradations used for this type of application were discussed in section 3-3.01.01.

b. Crushing. Crushing of aggregates may be necessary for two reasons. Crushing is necessary if the largest aggregate exceeds gradation requirements. However, crushed aggregate is often stronger than the original aggregate because it may break along existing planes of weakness, resulting in smaller stronger pieces. Crushing aggregate also gives a rounded aggregate a more angular shape, which is desirable when greater surface-to-surface contact is needed. Such contact is typical of densely packed aggregates and will increase the strength of the pavement structure.

Some degree of crushing is required for Class 5 and 6 aggregates. Class 5 aggregate should have no less than 10 percent crushed material and Class 6 aggregate should have no less than 15 percent crushed material.

c. Moisture/Density. The relationship between moisture and density in an aggregate base is determined by the Proctor test (AASHTO T 99, Method C). The test method, described in Section 5-692.222 of Mn/DOT's Grading and Base Manual, is used to identify the maximum density and optimum moisture content of the soil. The optimum moisture content (OMC), the value of interest, is defined as the moisture content at which the material can be compacted to its maximum density. The relationship is of engineering interest because an aggregate layer with a moisture content lower than the OMC will require greater compactive effort to achieve the desired density. Conversely, if the moisture content is much greater than the OMC the layer is likely to be very unstable. Lastly, the moisture density state of a compacted soil is an important factor affecting the strength and deformation characteristics of the soil in the pavement, which are related to its structural capacity.

d. Permeability. The permeability of an aggregate mixture is defined as its capacity to conduct or discharge water under a given hydraulic gradient. It is commonly represented by the coefficient of permeability, k, which is the rate at which water passes through a unit area of material in a given amount of time under a given hydraulic gradient. Permeability of a pavement course is often discussed in units of centimeters per second (cps) (feet per day (fpd)).

For a densely graded aggregate, the permeability should be such that the OMC of the material does not vary by more than a few percentage points over the life
of the pavement. The goal is to maintain the moisture content at a fairly low level so that the aggregate material is not adversely affected. It should be noted that this is not an applicable concept for highly permeable granular materials, as their degree of permeability is such that moisture content should not have an effect on layer compaction.

There are two laboratory tests available for determining permeability. The constant head permeability test is performed in accordance with AASHTO T 215, and the falling head permeability test is performed in conjunction with the U.S. Army Corps of Engineers method as described in Engineering Manual EM 1110-2-1906, Appendix VII. Permeability may be measured in the field using the field permeability-testing device, which produces permeability coefficients that correlate well with laboratory values, or by a field percolation test, which is a subjective test that only provides an indication as to whether or not a material is permeable.

Permeable aggregate layers should have a coefficient of permeability of at least 0.1 cps (300 fps), although a minimum value of 0.35 cps (1,000 fps) is desirable. The permeability of dense-graded materials varies widely according to the gradation, quantity, and type of fines. (The permeability of Class 5 base is about 1.4 x 10^-4 cps (0.4 fps).)

e. Strength. Strength is the engineering property of greatest importance for an aggregate layer. Therefore, several different methods for determining aggregate strength have been developed.

(1) R-Value. The R-Value is an important value in pavement design in Minnesota. Section 5-3.05.02 of this manual provides recommendations on the determination of the R-Value. While it is possible to obtain an R-Value for a base material, the Department currently performs this test only on subgrade soils with more than 15 percent passing the 0.075mm (No. 200) sieve. However, based on the Department’s past experience in testing, well-graded aggregate base course materials generally have R-Values in excess of 75.

The test result is empirical and does not represent an intrinsic property of the aggregate sample.

(2) California Bearing Ratio. The California Bearing Ratio (CBR) is a widely used measure of the strength of aggregate base materials. This test is also empirical in nature. CBR is a measure of the load required to produce a 2.5mm (0.1-inch) penetration in a standard aggregate base sample, and is actually a relative indication of the sample’s strength compared to that of a well-graded crushed stone aggregate. The CBR of a well-graded crushed stone aggregate will typically be close to 100.

The Department does not use the CBR to characterize the strength of aggregate bases.

(3) Triaxial Test for Shear Strength. Standard samples are loaded in a compression cell at different confining pressures to produce a Mohr failure envelope, which provides the cohesion (c) and angle of internal friction (Φ) of the material. The relative values of these parameters may be used to estimate the shear strength of the material.
While a few states have developed flexible pavement design procedures based on the results from the triaxial test, Minnesota does not currently use the triaxial test for determining pavement design parameters.

(4) Granular Equivalency. The granular equivalency (G.E.) factor is a means of equating the structural performance of an aggregate course to the structural performance of a high-quality aggregate base, such as a Class 6. As such, the G.E. is also an empirical approach to classifying the strength characteristics of an aggregate material.

The G.E. concept was developed in Mn/DOT's Investigation No. 183 and provides a value, in inches, of material required to obtain the same structural performance as the high-quality aggregate base. Section 5-3.05.02 Bituminous Pavement Design further describes the concept, as well as providing the G.E. of granular materials corresponding to some of the commonly used specifications found in Minnesota.

While the G.E. concept is only used in Minnesota, it has been related to AASHTO's structural coefficients for layers in a bituminous pavement. The structural coefficient is roughly equal to the G.E. value divided by seven. However, such correlations must be applied with great care, as the G.E. and AASHTO's layer coefficients are indicators of different empirical aggregate properties. While they can loosely be used as an indicator of "strength," they are not measurements of an inherent material strength property.

f. Elastic Modulus and Poisson’s Ratio. These values are intrinsic to a particular material under constant moisture, loading, and other conditions. Due to this, they are commonly used in the mechanistic and mechanistic-empirical design procedures that the pavement industry is moving towards.

(1) Resilient Modulus (Mr). The elastic modulus of unbonded bases and subbases is characterized in terms of resilient modulus (Mr). These types of material are stress dependent, meaning that they become stiffer as the confining state of stress is increased. This property can be determined through correlation with other properties (i.e. CBR and R-Value, DCP, etc.) or backcalculated from FWD or laboratory tests. Typical values range from 150 – 300 MPa (20,000 – 40,000 psi). Section 3-2.03.06 provides additional discussion.

(2) Poisson’s Ratio (µ). Poisson’s ratio is an important material property required in mechanistic pavement analysis and design. This property is defined in Section 3-2.03-06. A typical value for aggregate base is 0.35.

g. Quality. The quality of an aggregate base course is an indication of the material's ability to retain its properties over time. Aggregates in Classes 1 through 7 should conform to Mn/DOT's Specification 3138, which includes several quality requirements.

(1) Los Angeles Rattler Test. The Los Angeles (LA) Rattler test (AASHTO T 96) provides a means of measuring the toughness and durability of an aggregate. In the test, a sample of aggregate is placed in a hollow steel drum with steel ball bearings and rotated for 500 revolutions. The aggregate's resistance to wear is determined by measuring the material that is broken off of the original aggregate samples.
(2) Shale. Shale is a poor quality material that, when present in significant quantities, may cause performance problems. A test procedure to determine the presence of shale and other lightweight materials in an aggregate is described in Mn/DOT's Laboratory Manual, Test Method No. 1207.

(3) Micro-Deval.

(4) Other. It should be noted that other factors (namely gradation, composition, and crushing) also contribute to the overall quality of the aggregate. These factors must be strictly observed to ensure maximum performance.

2. Surfacing. The engineering properties of aggregates normally used for surfacing low volume roads and shoulders are discussed briefly below.

a. Aggregate Gradation. Mn/DOT's Specification 3138 provides gradation requirements for the seven different classes of aggregates. Classes 1, 2, 5, 6, and 7 are typically used for aggregate surfacing.

b. Quality. Aggregates used in a surface course should be of suitable quality to serve their intended purpose. The tests described in the previous section for the LA Rattler and presence of shale are applicable.

3-3.02.02 BITUMINOUS MIXTURES (VIRGIN AND RECYCLED)

The properties of bituminous materials used in pavements are discussed in this section. These include the bituminous materials themselves, the mixtures made with the bituminous materials, and the properties of the bituminous mixtures as used in different layers within the pavement system.

1. Bituminous Materials. Bituminous materials consist of a variety of products in different types and grades. Bituminous materials are discussed in Mn/DOT's Specification 3151.

Two broad types of bitumens are used in pavements - asphalt cement, conforming to AASHTO M 20 and emulsified (or modified) asphalts (AASHTO M 140 and M 208, modified). The asphalt binder acts as a binding agent to glue aggregate particles into a dense mass and to waterproof the mixture. When bound together, the mineral aggregate acts as a stone framework to impart strength and toughness to the system. The performance of the mixture is affected both by the properties of the individual components and their combined reaction in the system.

In the late 1990's, Mn/DOT adopted the Strategic Highway Research Program (SHRP) Superpave™ system. The Superpave™ system incorporates performance-based asphalt material characterizations designed to improve pavement performance by controlling rutting, low temperature cracking, and fatigue cracking. Therefore, Mn/DOT currently specifies asphalt binders using the Performance Graded (PG) Asphalt Binder Specification resulting from the Superpave™ project. The PG specification differs from the previous specification in that the tests used to measure physical asphalt properties can be directly related to field performance by engineering principles.

Performance graded (PG) binders are defined by a term such as PG 64-22. The first number (in this case 64) is the “high temperature grade.” This means that the binder possesses adequate physical properties up to at least 64°C. This is intended to correspond with the high temperature in the climate in which the binder is expected to serve. Likewise, the second number (-22) is the “low temperature grade”, which indicates that the binder possesses adequate physical properties down to at least -22°C.
Three asphalt binder characteristics are important in asphalt mixture performance: temperature susceptibility, viscoelasticity, and aging.

a. Asphalt’s properties are temperature susceptible: asphalt is stiffer at colder temperatures. That is why a specified test temperature must accompany almost every asphalt cement and mixture test. Without specifying a test temperature, the test result cannot be effectively interpreted. Similarly, asphalt cement behavior is also dependent on the duration of loading: asphalt is stiffer under a shorter load duration. The dependence of asphalt cement behavior on temperature and load duration means that these two factors can be used interchangeably. That is, a slow loading rate can be simulated by high temperatures and fast loading rate can be simulated by low temperatures.

b. Asphalt cement is a viscoelastic material because it simultaneously displays both viscous and elastic characteristics. At high temperatures (e.g. > 100°C), asphalt cement acts almost entirely as a viscous fluid, displaying the consistency of a lubricant such as motor oil. At very low temperatures (e.g., < 0°C), asphalt cement behaves mostly like an elastic solid, rebounding to its original shape when loaded and unloaded. At the intermediate temperatures found in most pavement systems, asphalt cement has characteristics of both a viscous fluid and an elastic solid.

Because asphalt is organic, it reacts with oxygen from the environment. Oxidation changes the structure and composition of the asphalt molecules. Oxidation causes the asphalt to become more brittle, leading to the term oxidative, or age, hardening. Oxidation occurs more rapidly at higher temperatures. A considerable amount of hardening occurs during HMA production, when the asphalt is heated to facilitate mixing and compaction. That is also why oxidation is more of a concern when the asphalt cement is used in a hot, desert climate.

2. Bituminous Mixtures. The bituminous mixtures used for pavement construction by the Department are listed in Section 3-3.01. The engineering properties of these bituminous mixtures are discussed in this section.

a. Bituminous-treated Base. Mn/DOT’s Specification 2204 provides for construction of bituminous-treated bases; however, the Department is not currently using this specification.

b. Plant-mixed Bituminous Pavement. The various bituminous mixtures used above a prepared subgrade or base were introduced in Section 3-3.01.03. They consist of a combination of a wearing course and non-wearing course. The total bituminous pavement thickness is a function of forecasted 20-year design traffic loadings (in terms of ESALs or load spectrum) and subgrade soil support value (in terms of R-Value or resilient modulus (Mr)).

1. Aggregate Gradation. The aggregate gradation requirement for bituminous mixtures depends on their use and the bituminous mixture in which they are incorporated. Gradation requirements are listed in Mn/DOT’s Specifications 3139 and 2360.

2. Important Properties. Bituminous wear and non-wear course mixtures have to meet certain minimum criteria in regards to certain key properties. The properties include stability, resistance to low temperature cracking, stiffness durability, fatigue resistance, impermeability, and workability. Although the requirements for these properties are not addressed directly, the Department is able to meet
these standards through quality management. Tests can be conducted to determine such key variables as the asphalt content, percent air voids, percent voids in mineral aggregate, aggregate gradation, and inplace density of the compacted mixture. All of these have an impact on the performance of the bituminous pavement.

Stability and resistance to low-temperature cracking are of particular interest for bituminous wear courses. A bituminous pavement with good stability will resist rutting, shoving, and other surface distortion. A bituminous pavement also needs adequate resistance to low-temperature cracking. However, the achievement of these two desirable properties is often in conflict because a mixture may be made more stable by using a stiffer asphalt with a low asphalt content and high air voids, whereas a mixture with a resistance to low-temperature cracking may need to be designed with a softer asphalt, low air voids, and high asphalt content. A satisfactory compromise between the two properties must be obtained in order to control the resulting distress.

(3) Friction. A very important requirement of the wearing course bituminous mixtures is that they provide a pavement surface with adequate friction so that the tire is able to maintain contact with the aggregate particles in the mixture and thus prevent skidding.

3-3.02.03 PORTLAND CEMENT MIXTURES

The Department commonly uses Portland cement mixtures as paving materials. The engineering properties of Portland cement and its concrete mixtures are discussed in this section.

1. Cement. The Department uses various types of Portland cement that conform to AASHTO M 85 and Mn/DOT’s Specification 3101. In general, there are five types of Portland cement available. Three of these have air-entraining subtypes, which brings the total number of distinct cement types to eight.

Type I cement is normal Portland cement without any of the special qualities of the following types. A subtype, Type IA, is air-entrained cement used in place of normal Portland cement when air entrainment is desired. Type II is moderate heat of hydration and moderate sulfate-resistant cement. Type IIA is the air-entrained subtype of Type II cement. Type III cement is for high early-strength concrete mixtures, and Type IIIA is its air-entrained version. The last two types are Type IV, a low-heat of hydration cement; and Type V, a high-sulfate-resistant cement. The Department uses regular Type I cement for most applications, although the use of air-entraining agents is common for some structures.

Two procedures are followed by the Department to obtain high early strength Portland cement mixtures. The first is the addition of calcium chloride to the standard mix; the second is an increase in the cement content of 30% with a reduction of the amount of fine aggregate, with or without the addition of calcium chloride. The details are outlined in Section 5-694.214 of Mn/DOT’s Concrete Manual.

2. Concrete Mixtures. The two primary uses of Portland cement in paving are to stabilize base materials and produce concrete. The engineering properties of cement-treated mixtures and PCC are discussed in this section.

a. Cement-treated Mixtures. The engineering properties of the cement-treated mixtures used in practice depend on their purpose. There are cement-treated mixtures that are nothing more than soils with a small amount of cement added to produce a slightly hardened material that continues to act as a soil. Others are
soil-cement mixtures that are compacted at their optimum moisture content and cured to obtain specific properties. The soil-cement base used by the Department is of the latter kind. However, apart from the requirement to compact the soil-cement to at least 98 percent of its maximum density during placement, there are no other restricted properties. The density is determined as described in Mn/DOT’s Grading and Base Manual.

b. Portland Cement Concrete Pavements. As indicated previously, PCC pavements in Minnesota are either non-reinforced or reinforced and generally constructed on a Class 5 aggregate base. Some important considerations in the design of Portland cement concrete mixtures are discussed below.

(1) Aggregate Gradation. The aggregates in the PCC used for pavement construction make up between 70 and 80 percent of the total volume; consequently, it is important to ensure that the aggregates used are of the right quality and gradation.

Generally, aggregates from a wide variety of sources can be used for Portland cement concrete provided they are strong, clean, and free of friable materials and impurities such as silt, clay, and organic material. The general requirements for the aggregates used for PCC in Minnesota can be found in Mn/DOT’s Concrete Manual. The specific requirements that must be met with respect to the type and quality of aggregates that can be used for PCC are provided in Mn/DOT’s Specifications 2301, 2461, 3126, and 3137. Carbonate aggregates may be susceptible to D-cracking (a common form of pavement distress) and use of such material must be carefully evaluated.

An aggregate gradation is a measure of the grain-size distribution in a particular aggregate stockpile. The gradation requirements for the coarse and fine fractions of the aggregate for PCC are given in Mn/DOT’s Specifications 2461 and 3137, and 3126, respectively. Further information can also be found in Mn/DOT’s Concrete Manual.

(2) Admixtures. Admixtures are any materials (other than cement, water, and aggregate) added to the concrete mixture immediately before or during its mixing to modify the properties of the concrete. Admixtures are commonly used to (1) adjust setting time or hardening, (2) reduce water demand, (3) increase workability, (4) intentionally entrain air, and (5) adjust other concrete properties.

Admixtures may be mineral admixtures, blended cements, or chemical admixtures. Mn/DOT Specifications 3102, 3103, 3113, 3115, and 3911 identify the most commonly used admixtures, described as follows:

**Ground Granulated Blast Furnace Slag (Spec 3102)**
- Grade 100 = Moderate Activity Index
- Grade 120 = High Activity Index

**Blended Cements (Spec 3103)**
- Type IP = Portland-Pozzolan Cement
- Type IP-a = Portland-Pozzolan Cement, Air Entraining
- Type IS = Slag Modified Portland Cement
- Type IS-A = Slag Modified Portland Cement, Air Entraining

**Fly-Ash (Spec 3115)**
- Class C = Fly Ash with pozzolanic and cementitious properties
- Class F = Fly Ash with pozzolanic properties

Silica Fume (Microsilica)
- Available in either powder or liquid form. Used in low permeability applications such as bridge decks and high strength concrete.

Chemical Admixtures (Spec 3113)
- Class I. Water-reducing Admixtures.
  - Type A. Water-reducing,
  - Type A (MR). Water-reducing (Mid Range)
  - Type B. Retarding,
  - Type C. Accelerating,
  - Type D. Water-reducing and retarding,
  - Type E. Water-reducing and accelerating,
  - Type F. Water-reducing and high-range,
  - Type G. Water-reducing, high-range, and retarding.

- Class II. Air-entraining Admixtures.

- Class III. Calcium Chloride. (Spec 3911)
  Mn/DOT Specification 2646.2E precludes the use of calcium chloride in prestressing steel and bridge superstructures.

(3) Durability. Durability is the most important property of concrete. To ensure a high degree of durability, it is essential to use well-mixed, clean, sound materials with the lowest possible water content. Good consolidation during placement of the concrete is important, as are proper curing and protection of the concrete during the early hardening period.

Another property that helps ensure durability is the water to cementitious ratio (w/c). A low w/c ratio is a good indicator of durable concrete. An acceptable strength is usually inherent to a low w/c mix.

A good air-void system is also essential to having a durable concrete when the concrete is exposed to freeze-thaw conditions. Concrete having a total air void content of about 7.0% has been proven to perform optimally. Concrete with entrained air will have a lower strength than the same mix without entrained air, but the concrete can attain strengths required for most purposes by an increase in the cementitious factor of the mix or by reducing the water content.

(4) Strength. The strength of concrete is the next important property to consider. With a fixed amount of cement in a unit volume of concrete, the strongest and most impermeable concrete is one that has the greatest density, i.e. which in a given unit volume has the largest percentage of solid materials. The use of the absolute minimum quantity of water required for proper placement ensures the greatest strength from the concrete. The strength attained is dependent on a wide range of factors, chief among which are the composition of the
concrete mix, the method of preparation of the mix, and the curing methods used.

There are two fundamental rules, which, when followed, will lead to high-strength concretes. The first is the achievement of the highest cement content possible in a unit volume of concrete with all other conditions remaining the same. The second is the attainment of the maximum density for a given unit volume of concrete.

The ratio of the amount of water to the amount of cement is the single most important principle in controlling the quality of concrete. Mn/DOT commonly expresses w/c ratio in pounds of water divided by pounds of cementitious. The lower the w/c ratio, generally, the higher the quality of concrete. Modern day concrete uses a number of ‘cement-like’ materials. Fly ash, slag, and silica fume, etc. They are considered as ‘cementitious’ materials and are treated as cement in calculations for the w/c ratio.

Compressive strength tests are required for one or both of the following purposes:

- To check the potential strength of the concrete under controlled conditions against the desired strength
- To establish a strength-age relationship for the concrete under job conditions as a control for construction operations or the opening of the work.

Quality. Strength is not the only important property of concrete. The workability, durability, volume change, air entrainment, and density of concrete have an enormous influence on good performance. The best possible concrete can be obtained only if all of the properties are carefully monitored to ensure minimum standards are met. The specific details of the requirements with regards to workability, durability, volume change, air entrainment, and density can be found in Mn/DOT’s Concrete Manual.
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