Superpave/Gyratory Mixture Design Guidelines for Local Agencies in Minnesota

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Preface

The purpose of this course is to provide training and guidelines for the use of Superpave/Gyratory mix designs by local agencies in Minnesota. Local agencies need to understand what Superpave is and is not; what it is designed to do; how it works, particularly for low volume roads; what impacts it will have on pavement and mixture design, construction, maintenance, performance and cost; and how to implement Superpave/Gyratory mixtures under Mn/DOT’s specifications. This course will provide focused, state-specific information on traffic, materials, design, construction, quality management, performance and specification issues.

When the term “agency” is used in these guidelines, it should be understood to refer to either a local agency or a consultant performing design work on behalf of that agency.

These guidelines frequently refer to the 2004 Mn/DOT 2360 Combined specification. Specifications continually evolve and improve. The reader should be certain to use the appropriate year’s specifications for a given contract, preferably the most recent.
Introduction

The asphalt paving industry in Minnesota, as in many other parts of the country, has a long history of continually making improvements in technology and the resulting product. Superpave/Gyratory mix designs are the latest and one of the most significant improvements in many years. This long history was highlighted at the 2003 Minnesota Association of Asphalt Paving Technologists (MAAPT) meeting, the 50th meeting of that group (1).

Over the last 50 years, Minnesota has evolved from using cutbacks and road tars in the 1950's to using Performance Graded (PG) binders beginning in the 1990's. Along the way, emulsions were introduced in the 1950's with cationic emulsions being added to the toolbox in the 1960's, along with penetration graded asphalt cements. High float emulsions were implemented and road tars were eliminated in the 1980's. PG binders represented a big step forward in the late 1990's because the PG specifications provide the tools needed to select the right binder for particular climatic and traffic conditions, mixture type, and location within the pavement. The use of PG binders, which are one component of the Superpave system, is now routine in Minnesota.

Asphalt mixture production and paving equipment has also evolved and improved over the years. In the 1950's, road mix was still used, though the transition to hot plant mixes was beginning. Hot screening was eliminated in the 1960's, and drum mix plants were introduced in the 1970's. Drum mix plants also facilitated implementation of hot mix recycling. Tandem steel wheeled and pneumatic rollers were commonly used in the 1960's, but were overtaken by vibratory rollers in the 1970's. Pneumatics started to reappear in the 1990's with Superpave/Gyratory mixes.

Density control improved along with the ability to compact the mix and the technology to measure density during compaction. Prior to 1958, there was no density control. In the late 50's, a minimum percentage of the Hveem density, then the Marshall density, was required. Beginning in the 1970's, nuclear gauges and control strips were implemented for density control.

Other quality management aspects have also improved over the years, especially in the last two decades. The first Quality Management (QM) projects were implemented in the 1980's. This improvement was accompanied by development of the certified technician training program and volumetric training. Literally thousands of agency and industry technicians are now certified at various levels. Certified PG binder sources were introduced in the 1990's after suppliers demonstrated that they could reliably produce binders meeting the required PG grade and had implemented quality control procedures. Certified
hot mix plants have also been developed. The industry has been increasingly involved in Quality Management and working with the Department to improve hot mix asphalt. The current QM program places the responsibilities for mix design, mixture production and placement, and field compaction on the contractor. The contractors’ tests are also used as part of the agency’s acceptance process.

These are just a few highlights of the continual process to improve asphalt pavements in Minnesota. Every year, the specifications and procedures are reviewed and refined to improve the final product.

The implementation of Superpave/Gyratory mixes is a major step in improving the final product by improving the mixtures themselves. The goal of Superpave/Gyratory mixtures is to select, design and produce the right mix for the job. The process takes climate, traffic, type of roadway/mixture and depth in the pavement into account to provide an appropriate mixture. The appropriate mixture is not necessarily a premium mixture. The system is designed to call for premium mixtures only in those situations that require the highest quality materials. The next chapter describes the general concepts behind Superpave/Gyratory mix designs and how they help get the right mixture for the job. Later chapters describe in detail how to use the Mn/DOT specifications to implement Superpave/Gyratory mixtures for local agencies in the state.
1. What is Superpave/Gyratory Mixture Design?

The name "Superpave" conjures up many different interpretations. It is important to understand what Superpave is and how it works to fully appreciate how Superpave mixtures can be used for all types of roadways. This chapter describes, in general terms, what Superpave is and what it is not. It also highlights the similarities and differences between Superpave/Gyratory and Marshall mixes.

The name "Superpave" was coined as an abbreviation of "Superior Performing Asphalt Pavements." The goal of the Superpave system is to improve asphalt pavement performance. Superpave was admittedly designed with an emphasis on high traffic levels and critical roadways. However, the system was also designed with an eye towards lower traffic levels and less demanding applications. The ultimate goal is to select, specify, design and produce the right mixture for the particular application.

Because Superpave mixes are not necessarily premium mixes in all applications, many states are using the term "Gyratory" mixes instead. This term describes how the mixes are designed, but does not imply that the mixes are "Super" in all cases. This terminology perhaps more appropriately emphasizes that Superpave/Gyratory mix design is an evolution – an improvement over Marshall mix designs – not a revolutionary change.

Superpave/Gyratory mixtures, as specified in Minnesota, are based on national research conducted under the Strategic Highway Research Program (SHRP) and on national specifications from the American Association of State Highway and Transportation Officials (AASHTO). Mn/DOT has developed local specifications for use in the state that take local materials and conditions into account. The national specifications are necessarily broader so that they can cover the wide range of materials and climates across the country.

To ensure good performance, an asphalt pavement needs to be designed to safely and effectively carry the traffic that will be using that roadway. The numbers of heavy trucks that will pass over the roadway need to be accounted for to ensure the pavement can carry those loads without rutting in hot weather or failing structurally under load. Flexible pavements are specifically designed to distribute traffic loads by bending slightly under traffic. For good long term performance, the pavement needs to be able to withstand repeated flexing without cracking. In other words, the pavement needs to have resistance to fatigue cracking. In climates such as Minnesota’s, thermal cracking is also an issue. Selecting a mix that can handle low temperatures without cracking can lead to lower life cycle costs by eliminating the need to saw and seal cracks or
maintain sealed cracks. The bottom line is — we want a pavement that will last under the climatic and traffic conditions of that particular application.

Of course, we also need for the pavement to be economical. Agency budgets are limited, and the need to get the "most bang for the buck" is stronger than ever. No agency can afford to put the highest quality, premium mixture on every roadway. If fact, that would not be the best way to ensure good performance, even if the budget allowed. Mixes designed for high traffic applications, with stringent aggregate requirements and modified binders, are designed primarily to resist rutting. These mixtures are not appropriate for lower traffic roadways where durability is a greater concern than rutting. The beauty of the Superpave/Gyratory system is that one system can be used to design appropriate mixes for all traffic levels, climatic regions and type of use (layer in pavement, recycled, etc.), resulting in improved performance and lower life cycle costs overall. The rest of this chapter will briefly describe the concepts behind the Superpave/Gyratory system that help us get the performance we need.

Table 1 is a very simplified summary of the performance that we desire from asphalt pavements and some of the means to achieve that desired performance through material selection, pavement design, mixture design and construction. Superpave/Gyratory mixes can help avoid some distress types, but are no substitute for proper pavement design, mixture production and construction practices. In other words, a Superpave/Gyratory mixture is not a cure-all. That is why adequate pavement design and Quality Management are necessary. Chapter 5 will focus on Quality Management of Superpave/Gyratory mixtures under the 2360 Combined specification.

Table 1 Simplified Summary of Desired Performance and Means to Achieve It

<table>
<thead>
<tr>
<th>Desired Performance</th>
<th>How to Achieve Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance to Rutting</td>
<td>Good aggregate structure</td>
</tr>
<tr>
<td></td>
<td>Appropriate volumetrics</td>
</tr>
<tr>
<td></td>
<td>Proper mix design</td>
</tr>
<tr>
<td></td>
<td>Binder selection</td>
</tr>
<tr>
<td>Resistance to Fatigue Cracking</td>
<td>Pavement design and drainage</td>
</tr>
<tr>
<td></td>
<td>Resilient materials, to a lesser extent</td>
</tr>
<tr>
<td>Resistance to Thermal Cracking</td>
<td>Binder selection</td>
</tr>
<tr>
<td></td>
<td>Adequate field compaction</td>
</tr>
<tr>
<td>Durability</td>
<td>Adequate film thickness/volumetrics</td>
</tr>
<tr>
<td></td>
<td>Proper mix design</td>
</tr>
<tr>
<td></td>
<td>Designing for appropriate traffic level</td>
</tr>
<tr>
<td>Smoothness, resistance to other</td>
<td>Good construction practices</td>
</tr>
<tr>
<td>distresses</td>
<td>Adequate compaction</td>
</tr>
<tr>
<td></td>
<td>Avoiding segregation, etc.</td>
</tr>
</tbody>
</table>
The Superpave/Gyratory system includes two major components: the Performance Graded binder specifications and the Superpave/Gyratory mix design procedure. A third component, performance testing of the designed mixture to predict performance under particular conditions, is still under development. This third component will likely be more suitable for high volume, critical facilities and will not be routinely used on all types of roadways.

\textit{PG Binders}

Prior to the implementation of Performance Graded binders in the 1990’s, asphalts were typically tested and specified using either penetration or viscosity. There were serious shortcomings in these methods, as summarized below. Because of these shortcomings, a significant amount of research in the 1990’s was geared towards establishing a new way to test and specify asphalt binders. The resulting Performance Graded binder specification was one of the primary products of the asphalt research conducted under the Strategic Highway Research Program (SHRP).

The penetration test has been used since the 1800’s. The test is conducted by placing a sample of asphalt in a tin. A 100-gram load is applied through a specified needle that just touches the surface of the binder at the beginning of the test. The depth to which the needle penetrates in five seconds is the penetration value. The test is conducted at 25°C (77°F), or about room temperature.

Viscosity testing became popular in many states in the 1960’s and 1970’s as an improvement over penetration testing. (Mn/DOT never adopted viscosity specifications for binders, but stayed with penetration until implementing PG binders.) Viscosity testing is based on measuring how fast a binder will flow through a small capillary tube. The faster the binder flows, the more fluid, or less viscous, it is. Viscosity tests are performed at either 60°C (140°F) or 135°C (275°F).

The behavior of asphalt binders varies depending on the temperature. At low temperatures, asphalt binders act like elastic solids, that is, they will rebound after loading like a rubber ball or a rubber band. At very low temperatures, however, they can become brittle and break or crack like a rubber band that is stretched too far. As the temperature increases, asphalt acts more like a viscous fluid. That is, it will flow like motor oil or pancake syrup. At intermediate temperatures, asphalts exhibit behavior that is partly elastic and partly viscous. In general, elastic behavior is what we want from an asphalt binder. More elastic binders will rebound after loading, helping to resist rutting and cracking.
Some viscous behavior is also desirable, however, since this can help a binder flow to heal itself before it cracks.

The penetration test is an empirical measure of both the viscous and elastic properties of a binder, but it does not allow separate determination of how elastic or viscous a binder is. Also, it is only measured at an intermediate temperature, which is not typically where our greatest problems occur. Viscosity measures only the viscous properties of the binder at high temperatures. Elastic behavior is not quantified at all. Neither system allows testing the low temperature properties of a binder or considers long-term aging of the material. These tests do not capture the effects of modified binders either and do not provide a means of specifying modifiers generically, without using proprietary names. With either penetration or viscosity, or even with both tests together, a wide range of properties or behavior could be observed in binders that all met the same grade.

In part because of all of these problems with penetration and viscosity specifications, many states attempted to improve the system on their own by adding tests or combining test results in different ways. The required specification tests, then, varied state-by-state. This caused difficulties for the binder suppliers who would have to test binders differently, and in some cases formulate them differently, depending on which state they were shipping to. This was especially difficult in refineries or terminals that served multiple states.

As of the 1980’s then, we did not have the tools needed to specify the right binder for a particular application. For example, we could not reliably specify a more elastic binder to resist rutting. Pavement rutting and cracking were prevalent problems across the country. Specifications varied state-by-state, making it impossible to compare experiences and learn from each other’s mistakes, as well as complicating testing for suppliers. Also, we had no objective way to determine the need for or to specify a modified binder.

The industry needed a better system.

Research under SHRP led to the development of the Performance Grading (PG) specifications and test methods. The PG system evaluates binder performance over the entire range of temperatures at which the binder is expected to perform, from the very high temperatures during construction, through hot summers down to very cold winters. Binders are selected specifically for the temperatures expected in the field. The change in binder performance with aging is also accounted for under the PG specifications, so that the impacts of aging on binder cracking, for example, can be considered. Binders can be selected to resist rutting, fatigue cracking and thermal cracking. In summary,
the PG specifications give us the tools to select the right binder for particular applications.

PG binders are now routinely used in Minnesota and have been since 1997. In fact, most states in the Midwest adopted PG binders in 1997. As of 2002, 47 states and the District of Columbia have implemented the PG specifications. Performance to date has been very good, with reduced cracking being one of the primary benefits attributable directly to binder selection.

**Mix Design Practices**

As with the asphalt binder specifications, there is room for improvement in the mix design procedures as well. Minnesota used the Marshall mix design system for decades, as did most other states in the Midwest and over half of the states across the country. The Marshall mix design system was developed in the late 1930’s and 1940’s. It served well for decades, but as traffic increased and technology advanced some shortcomings became obvious. A high stability value, for example, did not ensure that the mix would not rut. Premature rutting was the most prevalent hot mix asphalt problem nationwide in the 1980’s. With only three compaction levels (25, 50 or 75 blows), Marshall mix designs were not very sensitive to changes in traffic. In addition, the Marshall compaction hammer did not simulate field compaction using vibratory, pneumatic or other rollers. This disconnect between the lab and the field sometimes caused problems with producing realistic mix designs and achieving compaction. In Minnesota, there were a number of instances of low binder contents and raveling in the field with the 2340 mixes in particular. In fact, for low volume roads in particular, raveling is perceived to be a greater problem in Minnesota than rutting. The 2360 Combined specification better accounts for absorption and helps prevent raveling by ensuring there is enough binder in the mixture to satisfy the absorption.

*Again, we needed a better system.*

A new mix design system, dubbed Superpave, was developed under SHRP that builds on the advantages of previous mix design procedures. For example, one of the strong suits of the Marshall mix design procedure was its emphasis on mixture volumetrics. That aspect was incorporated in the new mix design process, and it was improved by the implementation of a more realistic method of compacting lab specimens.

The new compaction device, the Superpave gyratory compactor, was designed based on two existing gyratory compactors – one used in Texas, Oklahoma and Colorado and another used in France. The device uses a downward compaction force coupled with gyration of the mold through a slight angle to yield samples
with densities and aggregate orientations similar to those observed in the field. Traffic level is accounted for by using varying numbers of gyrations for compaction. Higher traffic levels require higher gyrations to design a mix to withstand the traffic loadings without rutting. Lower traffic levels use fewer gyrations, which in turn allow more room between the aggregate particles to provide a thicker binder film for durability.

**Superpave/Gyratory Mix Designs**

So, what is Superpave? It is a mix design system for selecting the right materials and designing an asphalt mixture that is appropriate for the traffic level, climate and location in the pavement. The goal of Superpave/Gyratory mix design is to design long lasting, cost effective mixtures with improved resistance to rutting, fatigue cracking and low temperature cracking as appropriate for the particular application. The system was developed to consider the fact that mixes for lower volume applications need greater resistance to cracking and durability problems, such as raveling, than resistance to rutting. Mixes for high volume roadways, on the other hand, need more resistance to rutting than to cracking.

How does the system account for traffic? All Superpave/Gyratory mix designs require traffic level as an input. The traffic level defines the number of gyrations used to compact mix design specimens in the lab and some quality management specimens in the field during construction. The traffic level also establishes the aggregate properties required; higher traffic levels have more stringent aggregate requirements. The depth of the mix in the total pavement structure also affects aggregate properties; the requirements for base mixes are more lenient since the stresses in the pavement are reduced. Very high traffic levels can even influence the binder grade selection to provide some extra protection against rutting at high traffic levels.

The climate is factored into mix design through the binder grade selection. The anticipated high and low temperatures that the binder will have to withstand in service are estimated and used to determine which binder grade can provide the required level of service.

Lastly, the gyratory compactor is used in design and field control to produce more realistic specimens that better simulate the effects of field compaction. More details on material selection, mix design and Minnesota's specifications will be provided in Chapters 2, 3 and 4.
Superpave/Gyratory Mix Design vs. Marshall Mix Design

In summary, then, the Marshall mix design process is not very sensitive to changes in traffic level and uses an unrealistic compaction method, although its emphasis on mixture volumetrics is good. Under Mn/DOT’s 2340 specification, however, absorption can sometimes lead to low binder contents, which can cause raveling of the mix. The 2360 Combined specification better accounts for absorption, providing higher binder contents and less raveling.

Superpave/Gyratory mix design, on the other hand, is a system for selecting and designing asphalt mixtures considering the climate, traffic and depth in the pavement. Superpave/Gyratory mix designs use a more realistic compaction method for mix design and field control. Superpave/Gyratory mix design builds on the strong points of previous mix design procedures while adding improvements to better account for factors that were not adequately considered before.

Superpave/Gyratory mixtures, then, require:

- the use of PG binders, which are already the norm in Minnesota,
- some higher crushed aggregate requirements, especially for higher traffic levels, and
- the use of the gyratory compactor, which most contractors already have.

These three factors mark the major differences between Marshall and Superpave/Gyratory mix designs in Minnesota. There are a number of factors that are similar between the two types of mix design, such as:

- mix design, testing and construction equipment, with the exception of the compactor;
- structural design;
- best practices for mix production and construction;
- pavement selection policies; and
- normal suppliers and contractors.

There are a number of advantages to implementing Superpave/Gyratory mixes for local agencies in Minnesota. The primary advantages are better pavement performance, longer service live and lower life cycle cost. These can be accomplished by using better tools for selecting materials, accounting for traffic and climate, and designing mixtures for particular applications. There is also an advantage in using one system statewide so that experience can be shared across agency lines. Contractors and suppliers have only one system to deal with on a routine basis, leading to less confusion, expense and error. Lastly,
since Mn/DOT has been working with Superpave/Gyratory mixes for over seven years now, contractors and suppliers around the state are well up the learning curve with Superpave. They have experience with the system, for the most part, and can implement it readily.

There are also, of course, legitimate concerns about implementing Superpave/Gyratory mixes on a local level. While these concerns are valid, the evidence suggests that the benefits far outweigh the risks.

- There is a perception that Superpave/Gyratory mixes are for high traffic volumes only. This is probably due in part to the name “Superpave,” which seems to imply a super mix. Keep in mind, however, that the goal is to improve performance while designing a mix that is appropriate for the traffic, climate and type of roadway. Not every Superpave mix is a premium mix. In fact, the Superpave system gives us the tools to better account for traffic and climate to get the right mix for the job. Traffic figures into the mix design system at several key points so that mixtures are not over-designed. For example, for lower traffic levels, the aggregate requirements are minimal and local materials can be used. The volumetrics incorporated in Mn/DOT’s 2360 Combined specification better account for absorption and VMA to help avoid dry mixes and raveling, as were sometimes seen with the 2340 specifications.

- There is also a perception that Superpave/Gyratory mixes are expensive. This was certainly true in the early days of implementation. Any time major changes are made in specifications, contractors understandably increase their bid prices to help counter their increased risk. Since the early days, however, costs have decreased substantially so that now the bid prices are quite similar to Marshall mixes and are even lower in some cases. For low volume roads in particular, the aggregate and binder requirements do not call for premium materials, which helps to moderate the prices. The bottom line, though, is that the improved performance of Superpave/Gyratory mixes leads to longer service lives and lower life cycle costs. More details are provided in Chapter 7, Case Histories.

- Another common perception is that Superpave/Gyratory mix design is complicated. While the process does allow for more traffic levels than Marshall and includes more variables than typically included in the past (such as climate and some aggregate properties), the process itself is only slightly more involved. The Mn/DOT specifications have been written to clarify mix selection and specification. It is hoped that these guidelines will also help agencies adapt to the new specifications. One key advantage of the 2360 Combined specification is that it shifts much of the responsibility for mix design, testing and production to the contractors. Through certification
training and experience, the contractors are, for the most part, ready for that responsibility.

- Superpave/Gyratory mixes are perceived to be hard to compact. It is true that there were some problems with compaction in the early days of implementation, but contractors have learned, through trial and error, how to deal with compaction problems. Having more rollers on the project, rolling while the mix is hot and sometimes using pneumatic rollers are approaches that have helped to alleviate these problems and produce a better-compacted mat. Compaction problems are more typical on high volume roadways with coarse, angular aggregates and stiff modified binders. There have been few compaction problems noted on low volume roads.

- Lastly, there is a perception that Superpave is not fully developed. It is true that the mix analysis and performance tests are not finalized yet, but these are tools that are intended for use on high volume roadways to verify that the mix designed will perform as desired. It is highly unlikely that these sophisticated tools will be used on low volume roadways in the foreseeable future; there is no need for such elaborate testing. The framework for the mix design procedure is sound and is not expected to change substantially. There will no doubt be refinements in the future as the process of continuous improvement goes on, but again these are more likely to affect high traffic volume mixes than low traffic ones.

Superpave/Gyratory mixes offer a number of advantages to local governments in Minnesota. The mixes provide better durability, resistance to rutting and cracking, and less raveling than the 2340 mixes. The 2360 Combined specifications also put more of the burden of design, production control and testing on the contractor, as did the 2350 mixes. Contractors do their own mix designs according to the specification requirements. Mn/DOT district labs are available to assist with quality assurance testing, if desired. There is no additional burden on the local agency, but they get a better, higher quality product.

It is important to remember, however, that Superpave/Gyratory mixes are not cure-alls. They cannot solve base, subgrade or drainage problems; bad mix design or poor construction practices. Best practices in the past still hold true for controlling pavement design, base and subgrade preparation, drainage, segregation reduction, placement and compaction, etc. Attention to detail is required to ensure that the mix is properly designed, produced and placed.
2. Material Selection: Binders and Aggregates

The first step in any asphalt mixture design is to select the materials to be used. Under the Superpave/Gyratory mix design system, there are some changes in the requirements for binders and aggregates. Although now contractors usually design their own mixtures and select the materials they choose to use, how the agency sets up and specifies the contract can affect material selection and in turn the price and performance of the hot mix. It is important for local agencies and consultants to appreciate the factors that influence material selection and how those factors can be set appropriately to meet the demands of different projects. This chapter describes, in general terms, what properties are required of binders and aggregates for Superpave/Gyratory mix designs and why. This is intended to introduce the concepts that guide gyratory mix design. The mix design process is described in Chapter 3 and specific Minnesota specification requirements are outlined in Chapter 4.

Binder Behavior

The use of Performance Graded binders is an integral part of the Superpave/Gyratory mix design system that helps to achieve the desired performance. Since PG binders have been routinely used in Minnesota for many years now, their implementation with gyratory mixes does not mark a significant change. Nonetheless, we will review the binder grading principles to reinforce the principles that should guide selection of the appropriate binder grade for a particular application. More details on binder behavior and the PG specifications and tests are available in several references, including the Asphalt Institute Manual SP-1, Superpave Asphalt Binder Specification (2).

First, a note on terminology. Throughout this manual, and the Mn/DOT specifications, the term binder is used to refer to the liquid asphalt component in hot mix. This term has replaced “asphalt cement” in the context of PG binders. The reason for this is that the PG binder specification is intended to be an end-result type of specification. We specify the performance we want in terms of the high and low temperatures the binder will likely experience during its service life. In order to cover that range of temperatures, a modifier may or may not be necessary. The term “asphalt cement” implies an unmodified material. The term “binder” (or “asphalt binder”) is more generic, and may or may not include a modifier.

The behavior of an asphalt binder depends on the temperature, time of loading and the aging of the binder. The effects of temperature are obvious. We know that we have to heat a binder in order to make it fluid enough to flow. At elevated temperatures, we can pump the binder into a hot mix plant and coat
aggregate particles with it. At high temperatures, then, asphalt binders act like
viscous materials—they flow. As the temperature cools, the binder solidifies and
holds the aggregate particles in place. At low temperatures, the binder acts like
an elastic solid. If a load is applied to the binder, it will deform, then it will
"spring back" to its original shape when the load is removed, like a basketball or
rubber band. At intermediate temperatures, the behavior of a binder includes
some elastic and some viscous effects. This is illustrated in Figure 1.

![Stiffness Response to Load](image)

Figure 1 Behavior of Asphalt at Different Temperatures

The effect of time of loading (duration) is a little less obvious, but is similar to
the effects of temperature. When a load is applied to a binder for a longer time,
there is more time for the binder to slowly deform. When the load is applied
quickly, there is little time for deformation to occur. Essentially, under rapid
loading, the binder acts more like an elastic solid, or it acts "stiffer," than under
slow loading. A good analogy for this is slowly dipping your toe in a swimming
pool; the water feels soft. If you do a belly flop from the high dive, however, the
water feels very stiff when you hit it at a high rate of speed. In other words, you
can get the same behavior by applying a load slowly as you can by applying a
higher temperature. This is illustrated in Figure 1, which shows that you can get
the same amount of flow of binder from a tin in a short time at a high
temperature as you can get in a longer time at a lower temperature. This is
sometimes called time-temperature equivalence, since time and temperature
produce the same effects.
Figure 2 Time-Temperature Equivalence

The effect of aging may be the least obvious, but it can have great impact. Asphalt binders can react with oxygen in the air through a process called oxidation. This oxidation causes the binder to become stiffer and more brittle over time, so it is also sometimes called age hardening. Different binders age at different rates; some are more susceptible to age hardening than others. Age hardening can occur throughout the life of a pavement. Like many chemical reactions, it occurs faster at high temperatures and when there is a lot of oxygen available to react. During mix production and placement, the binder is heated and oxygen is available, so there can be significant aging of the binder. At pavement service temperatures, the reaction proceeds more slowly, but it can still occur. So the binder can become increasingly stiff over its service life; over many years, this in-service aging can become significant.

The behavior of the binder with temperature, duration of loading and age in turn affects the behavior of the hot mix in which it is used. At high temperatures the binder in an asphalt pavement can "soften" and start to act more like a viscous liquid. The softened binder cannot hold the aggregate particles in place as effectively and can even act as a lubricant. This can allow the aggregate particles to slide past one another producing rutting in the wheelpaths. The same thing can happen under slowly moving loads, which is why rutting tends to be worse at intersections, on hills and in other places where the traffic moves...
slowly. Selecting a binder that is stiffer at high temperatures can help to control rutting to some extent, but the best way to control rutting is by building a strong aggregate skeleton to carry the loads.

At low temperatures, the binder becomes stiffer. If the temperature gets too low, the binder can crack. The thermal stresses that build up in the pavement can exceed the tensile strength of the binder, causing a crack. There are some binders that can “relax” under stress and thereby avoid cracking. Relaxation can occur when a binder remains stretched for some time. This is like a rubber band that is stretched around a shoebox for a long time. The rubber can relax and assume the stretched state as its new length; when removed from the box, it may not spring to its original shape. Some binders can similarly relax under load without cracking.

Selecting a binder that remains flexible and elastic, or that can relax under stress, can help to prevent thermal cracking. Since the cracks almost always propagate through the binder, not through the aggregate, this type of distress is primarily a binder problem. The aggregates used in the mixture have little effect, in most cases. (There are some relatively rare aggregates that can selectively absorb some parts of the binder. This can cause stiffening of the binder that remains in the film coating the aggregates and accelerate cracking.)

At intermediate temperatures, repeated bending of the asphalt pavement can cause what is known as fatigue cracking. This is the same type of cracking that occurs if you repeatedly bend a paper clip back and forth. Eventually you will exceed the fatigue limit of the metal, and the clip will crack. The same thing can happen with an asphalt pavement, if it bends too much or too often. The best prevention for fatigue cracking is at the pavement design stage. Steps can be taken to ensure that the pavement does not flex too much, including providing drainage to keep the subgrade dry and strong, making the pavement thick enough to prevent excessive deflections, and compacting the pavement adequately during construction. Selecting binders that are resilient enough to withstand repeated flexing can also help, but cannot prevent the problem entirely if pavement design issues are not adequately addressed.

Age hardening can worsen the cracking behavior of a pavement. As the binder ages, it becomes more brittle and therefore more prone to thermal and fatigue cracking. Aging can actually help to prevent rutting by stiffening the binder. This is why asphalt pavements that rut tend to do so in the first year or two or service. Continued stiffening of the binder makes rutting less likely. Cracking, on the other hand, tends to happen later in the life of the pavement as the binder becomes more brittle.
Binder Selection

The PG binder specifications are set up to help choose binders that are resistant to rutting, fatigue cracking and thermal cracking. Specification tests are conducted at high, intermediate and low temperatures to check for resistance to the distresses that occur at those temperatures. In addition, the binder is artificially aged in the laboratory to simulate the type of aging that occurs during production and throughout the service life of the pavement.

At high construction temperatures, the binder is checked using a rotational viscometer to ensure it will be fluid enough to pump into the hot mix plant and coat the aggregate particles. At high service temperatures, a device called a Dynamic Shear Rheometer (DSR) is used to apply a shear load to the binder to check its resistance to rutting. We want the binder to be stiff enough to resist rutting, so minimum stiffness limits have been established. This test is conducted on unaged binder and on binder that has been aged in a Rolling Thin Film Oven (RTFO) to simulate the aging that occurs during construction. We expect the binder coming out of the plant to be similar to the RTFO-aged material, but we check the unaged binder too just in case the binder does not age as much in the plant as we expect. We still want the binder to have some resistance to rutting.

The RTFO is also used to check whether the binder contains a high percentage of volatile fractions that may be vaporized and lost during production in the plant. This can age the binder prematurely and increase cracking and durability problems in the field. The weight of binder before and after aging is measured to calculate the mass loss, which is limited to less than 1% of the original weight to avoid this problem. Some of the RTFO-aged binder is then aged further in a device called a Pressure Aging Vessel (PAV) to simulate long-term service aging. After PAV-aging the binder is then tested for its resistance to fatigue and thermal cracking, which tend to happen later in the pavement life.

To resist fatigue cracking, the binder needs to remain flexible or resilient at intermediate temperatures, where this distress tends to occur. The binder's resistance to fatigue cracking is checked using the DSR again. Since we do not want the binder to be too stiff, a maximum stiffness value is established in the specifications.

For low temperature cracking resistance, the binder needs to be soft or elastic enough to stretch or to relax under stress so that cracks do not develop. The binder stiffness (S) and relaxation (m-value) are tested at low temperatures in a Bending Beam Rheometer (BBR). A maximum stiffness and minimum m-value are specified to ensure thermal cracking resistance. We do not want the binder to be too stiff, so we limit S. A high m-value indicates a greater ability to relax.
The ability of the binder to stretch without cracking can be checked in a Direct Tension Tester (DTT), but this test is not yet widely used. A minimum percent elongation of 1.00% is the AASHTO specification limit to help resist thermal cracking; this may not sound like much elongation, but at very low temperatures, this does represent a significant amount of stretching.

When selecting the binder for a given project, then, we want to select a binder that is stiff enough to resist rutting at high temperatures and elastic enough to resist cracking at low temperatures. We also want to be sure the binder is resilient enough to resist fatigue cracking at intermediate temperatures. We can do this by looking at the climatic conditions for the project location to determine the high and low service temperatures that the binder will need to withstand over its lifetime. We check for rutting resistance near the high service temperature and for thermal cracking resistance near the low service temperature. Fatigue resistance is checked at intermediate temperatures.

The National Oceanic and Atmospheric Agency (NOAA) maintains a system of weather stations that collect the needed temperature data daily. The Federal Highway Administration (FHWA) has reviewed these weather stations and pulled out the necessary information from over 8,000 weather stations in North America that have at least 20 years of climate data. They then converted from the air temperatures collected by NOAA to pavement temperatures, which are what the binders feel. The database and binder selection software called LTPPBind is available to download from the FHWA (3). (LTPP stands for Long Term Pavement Performance, the study that developed the database.)

Since rutting typically does not happen with one pass of a truck on a hot day, but rather slowly accumulates over time, the high temperature grade selection is based on the average temperature over a seven-day “hot spell.” The LTPPBind data summarizes the seven hottest days in row over twenty years or more. The average and standard deviation of this “hot spell” over time are calculated and used to estimate the high temperature reliability. (Reliability is the probability that the temperatures reached during a summer hot spell or winter cold snap will not exceed our design temperatures.)

Thermal cracking can happen with one “cold snap,” so LTPPBind contains the average and standard deviation of the single lowest temperature recorded each year for at least twenty years. Again, these values are used to estimate reliability.

In general, the wider the range of temperatures that we want to cover, the more likely it will be that a modifier will need to be added to the asphalt cement. Most neat asphalts cannot cover a wide temperature range. Modifiers typically work by increasing the high temperature stiffness. They can be added to a soft base
asphalt, which provides the low temperature elasticity, to extend the overall temperature range of the binder. As a rough rule of thumb, if the total range of temperatures we want to cover is greater than 90°C, the chances are greater that a modifier will be needed.

Modified asphalts can be more expensive than unmodified materials, however. They should only be used where they are justified. The cost of high reliability cannot be justified on all projects, as it would be much too expensive. For major interstates, we want to be pretty confident that we will not get rutting and cracking, so high reliability is called for. For low traffic volume roadways, however, rutting is not likely a major concern and some cracking can probably be tolerated. A lower level of reliability is called for in this case. We may see a hotter summer or a colder winter than our binder grade was selected for, but we can tolerate the risk. The reliability levels that Mn/DOT recommends are detailed in Technical Memorandum No. 02-06-MRR-01 (5).

Standard binder grades have been established at six-degree increments. This was done to yield a reasonable number of different binder grades while still allowing enough “resolution” to fine tune the binder grade selection for particular locations and applications. Grades are expressed in terms of degrees Celsius. The high temperature grades are PG46, 52, 58, 64, 70, 76 and 82. The low temperature grades range from -46 to -10, also in six-degree increments.

The grades typically used in Minnesota range from PG52 to PG70 on the high temperature side and from -22 to -40 on the low side. PG58-28 is most common. More details are provided in Chapter 4.

**Aggregate Selection**

The aggregates in a hot mix asphalt carry the loads from traffic and distribute them over the base or subgrade. They fill up space in the mixture and help make it more economical; aggregates are much less expensive than binder. Aggregates need to be coated with a film of asphalt binder, though, to help hold the particles together and provide a durable pavement. The aggregate framework needs to provide enough space between the particles to allow for a thick enough binder film; this is discussed in more detail in Chapter 3.

The aggregates themselves need to be strong enough to resist degradation during construction and to carry the traffic. They need to be somewhat angular so that they lock together to help resist displacement or deformation under traffic. Higher levels of angularity are needed for higher traffic levels.

The aggregates also need to be relatively clean so that the asphalt film can bond to the aggregate surface. A clay or dust coating on the aggregates can interfere
with the bond and lead to stripping problems later. Other properties, such as frictional resistance, low absorption, etc., may be needed or desirable in some cases.

To keep the mixtures as economical as possible, the use of locally available aggregates is preferred. Importing aggregates can increase the cost significantly. When considering economics, however, it is important to realize that initial construction costs are not the only concern. If an imported aggregate can help to prevent pavement rutting or improve surface friction, for example, the added initial cost may be justifiable. Lower life cycle costs overall can result from reduced maintenance, a longer service life and better pavement performance. A longer service life can also extend the time between overlays or reconstruction, allowing limited resources to be used over more pavement miles in the long term. As with binder selection, then, we'll keep economics in mind as we make selections based primarily on good engineering.

How do Superpave/Gyratory mix designs help us get the right aggregates for a given application? On a national level, properties related to aggregate shape and cleanliness are specified. During the SHRP research, a panel of experts reached consensus on limits for four properties that are critical for good performance of hot mix asphalt. These so-called consensus properties apply equally to all types of aggregates. They include coarse aggregate angularity, fine aggregate angularity, flat and elongated particles, and the sand equivalent value.

The panel of experts acknowledged that there are other aggregate properties that are equally important, but acceptable values vary too much depending on the type of material to set national standards. These "source properties" are determined on a state-by-state basis based on knowledge of local materials. Source properties can include such things as Los Angeles abrasion, sodium or magnesium sulfate soundness, spall, acid insoluble residue and others. In the case of Minnesota, Mn/DOT has incorporated the consensus properties into the 2360 Combined specification along with pre-existing aggregate source requirements.

Three of the consensus properties relate to particle shape:

- Coarse Aggregate Angularity (ASTM D5821)
- Fine Aggregate Angularity (AASHTO T304, Method A)
- Flat and Elongated Particles (ASTM D4791)

The last consensus property, the sand equivalent value, relates to aggregate cleanliness. Limits are placed on the shape of the aggregates to help to achieve a strong, stable mix by locking the aggregate particles together. Angular
materials have better interlock than rounded particles. Fine aggregate angularity is also related to the surface texture of the aggregates, which affects mixture strength and workability. The cleanliness of the aggregates affects the binder-aggregate bond and helps prevent stripping.

Coarse Aggregate Angularity is basically the crushed aggregate content. It is measured on the coarse aggregate that is retained on a 4.75mm (No. 4) sieve. The test is conducted by visually examining a sample of the coarse aggregate and determining the percentages of particles having one or more crushed faces and the percentage with two or more crushed faces. Because strength and stability are of more concern for heavily trafficked roads and for surface (wear) courses, the coarse aggregate angularity requirements are higher for higher traffic levels and for wear courses. Figure illustrates the difference between uncrushed and crushed particles.

![Figure 3 Uncrushed (Left) and Crushed (Right) Aggregate](image)

Fine aggregate angularity is another measure of aggregate shape that relates to the strength and stability of the mixture. Angular fine aggregate contributes to rut resistance too. The fine aggregate angularity value is also affected by the surface texture of the fine aggregate particles. Surface texture can impact strength and workability of the mix. A rough texture can make for a stronger mixture, but it can also make the mix harsh and hard to work.
The fine aggregate angularity test involves letting a sample of fine aggregate flow freely into a cylinder of known volume, as shown in Figure 4. The shape and surface texture of the particles determine how closely they pack together in the cylinder. The weight of fine aggregate that just fills the cylinder is measured, and the aggregate specific gravity is used to calculate the weight of sand in the cylinder. The air void content between the uncompacted aggregates is an indirect measure of the aggregate shape and texture. Smooth, rounded aggregates will pack more closely together, or have a lower uncompacted void content, than rough, angular aggregates. The consensus standards put minimum void content limits on fine aggregate angularity depending on traffic and depth in pavement. The requirements are higher for high traffic and for courses closer to the surface, just as with coarse aggregate angularity.

Figure 4 Fine Aggregate Angularity Test

The limits on flat and elongated particles were included to restrict the usage of sliver-shaped aggregates. Particles that are long compared to their minimum
dimension tend to show one of two problems. If the aggregate is fairly weak, it may break during compaction or under traffic, yielding uncoated aggregate faces in the mixture. These could be the starting points for stripping. If the aggregates are fairly strong, a high percentage of flat and elongated particles may make a mixture harsh and hard to compact. A special proportional caliper, shown in Figure, is used to measure the relative maximum and minimum dimensions. The specifications place an upper limit on the percentage of coarse aggregate particles (retained on a 4.75mm (No. 4) sieve) that are flat and elongated. Since each lift of the pavement must be compacted, the limits depend on the traffic level only. For low traffic levels, there is no restriction on the flat and elongated content.

Figure 5  Proportional Calipers Used to Determine Flat and Elongated Particles

The sand equivalent value, or clay content, is used to assess the cleanliness of the fine aggregate fraction passing a 4.75mm (No. 4) sieve. Past experience has shown that a coating on the fine aggregate is particularly detrimental to formation of a good bond between the binder and aggregate. This test is conducted by mixing a sample of the fine aggregate in a graduated cylinder with a solution that helps to hold small silt or clay particles in suspension. After thorough mixing, the sample is allowed to sit, and the sand particles settle to the bottom of the cylinder. The silt or clay floats in solution above the sand. The height of the sand column is compared to the height of the clay column to determine the relative proportions of sand and clay. A high sand equivalent value implies a cleaner material. Since stripping can happen in any layer of the pavement, the clay content limits vary depending on traffic level only. Higher traffic levels require cleaner fine aggregate.
It is important to note that the consensus properties apply to the total blend of aggregates, not to each individual stockpile. It is possible to use some aggregates that do not meet the requirements on their own as long as they are blended with enough “good” material that the combination meets the specification limits. This helps to limit the amount of high quality material that might have to be imported if locally available materials do not meet the consensus properties. It is also important for local agencies to note that the aggregate requirements for low volume roads and non-wear courses are minimal, as will be defined in detail in Chapter 4.

There are other aggregate properties that are important to consider in mix design. The aggregate specific gravity is a key piece of information, as shown in Chapter 3. Absorption is another important factor for mix designers to consider, since highly absorptive aggregates can lead to dry mixes that are prone to raveling, if the absorption is not satisfied. This problem has been observed with some of the 2340 mixes used in Minnesota in the past. When enough binder is provided to satisfy absorption, the high total binder content causes the mix to be relatively expensive to produce. Mixes with highly absorptive aggregates can be difficult to design as well.

Reclaimed asphalt pavement can be used to supplement the virgin aggregates in a hot mix asphalt. This certainly helps make the mixes more economical. Past experience shows that recycled mixes can perform well, when properly designed and constructed. Mn/DOT places upper limits on the amount of RAP that can be used based on traffic level and wear/non-wear. For higher RAP contents, the binder grade may need to be adjusted to counteract the stiffening effect of the aged RAP binder. More information is provided on this issue in Chapter 4.

To summarize the differences between Marshall and Superpave/Gyratory mixtures in Minnesota, then, there are some new aggregate properties to consider for gyratory designs. The flat and elongated, fine aggregate angularity and clay content requirements are new. Somewhat higher crushed coarse aggregate contents may be necessary to meet the required mixture volumetrics (described in Chapter 3) in some cases, although the aggregate specification limits are the same for both mix types. This is due mainly to the difference in the compaction method used.

Marshall and Superpave/Gyratory mixes use the same aggregate types and have the same limits on other properties, such as total spall, maximum spall content, percent lumps and Class B carbonate restrictions. Locally available aggregates can be used in both mix types, though sometimes Superpave/Gyratory mixes will require a different blend of materials and/or more imported aggregate to meet the consensus and mixture properties. RAP can also be used in both mix types.
3. The Superpave/Gyratory Mixture Design Process

Beginning with the 2340 specification in 1988, contractors have been doing their own mix designs in Minnesota as part of the Quality Management program. Nonetheless, it is helpful for local agencies to understand the basics of Superpave/Gyratory mixture design so that they can appreciate the potential impacts of, and considerations required for, their implementation. A review of the mix design process also helps to reinforce the importance of some of the specified parameters. This can also help local agencies appreciate some of the costs and benefits of specifying Superpave/Gyratory mixes.

In this chapter, then, we briefly review the mix design process step by step. We also review mixture volumetrics, which are the basis for Superpave/Gyratory mix design and are critically important for assuring pavement performance. More detailed information on state-specific specifications is provided in Chapter 4.

There are four basic steps in the Superpave/Gyratory mix design process.

1. Select materials – select the binder and aggregates as described in Chapter 2.
2. Design the aggregate gradation – compare different blends of the desired aggregates to optimize the mixture requirements for gradation and volumetrics.
3. Optimize the binder content – after selecting a design aggregate blend, fine-tune the binder content to provide good durability and stability.
4. Verify the final mix properties and check moisture sensitivity – after the mix design has been tentatively developed, check that the mixture does meet the volumetric and compaction requirements and that it will be resistant to moisture damage.

These steps were essentially performed for Marshall mix designs as well, but some of them are more formalized now. For example, Step 2 was not required for Marshall mix designs, though many savvy contractors would evaluate various aggregate blends to find an economical mix to produce. Now the Asphalt Institute's SP-2, *Superpave Mix Design Manual* (4) and AASHTO PP28, *Standard Practice for Superpave Volumetric Design for Hot Mix Asphalt (HMA)*, (5) require the evaluation of different aggregate blends. In addition, some of the requirements have changed from previous mixture specifications, such as some of the volumetric properties.

Step 1 was discussed in Chapter 2, so this chapter will focus on the last three steps in the Superpave/Gyratory mix design process.
Designing the Aggregate Gradation

Once aggregates have been selected that meet the source properties, they can be blended in any combination that meets the consensus properties and the gradation requirements. Different trial blends are then mixed with binder and analyzed to determine if they yield a mixture that meets the mixture volumetric requirements. Smart designers will also consider the economics of the designed mixture. It is possible to produce an acceptable mix design with a high binder content, for example, that would be very expensive to produce. Another perfectly acceptable mix design might be possible that would have a lower asphalt demand, and therefore a lower price, but would still perform well.

When selecting aggregate gradations to evaluate, the use of RAP should also be considered. Reusing RAP reduces disposal costs, reuses a valuable resource, reduces material costs, and can lead to good performance, if properly designed and constructed. The RAP aggregate gradation should be included in the overall blend when evaluating compliance with the broadband gradation limits described later. The blend, including the RAP aggregate, must also meet the coarse and fine aggregate angularity requirements.

First, some terminology needs to be defined. The nominal maximum sieve size retains between 0 and 10% of the aggregate. This is the sieve size that is used to designate or name the mix size, such as a 12.5mm or 19.0mm mix. The maximum size is one sieve size larger than the nominal maximum, and 100% of the aggregate will pass this sieve. For example, in a 12.5mm mix, 100% of the aggregate will pass a 19.0mm sieve. Mn/DOT uses three mix sizes as summarized in Table 2.

Table 2 2004 Mn/DOT Superpave/Gyratory Mixtures

<table>
<thead>
<tr>
<th>Size Designation</th>
<th>Nominal Max Size (mm)</th>
<th>Maximum Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (SP 9.5)</td>
<td>9.5</td>
<td>12.5</td>
</tr>
<tr>
<td>B (SP 12.5)</td>
<td>12.5</td>
<td>19.0</td>
</tr>
<tr>
<td>C (SP 19.0)</td>
<td>19.0</td>
<td>25.0</td>
</tr>
</tbody>
</table>

Superpave/Gyratory mix design aggregate gradations are typically plotted on a 0.45 power gradation chart, as shown in Figure. A 0.45 power chart is plotted by taking the sieve size in millimeters and raising it to the 0.45 power. This point on the x-axis is where the percent passing that sieve size is recorded. A maximum density line is plotted by connecting the origin to 100% passing the maximum sieve size. The national standards (SP-2 and AASHTO MP2 and PP28) also include control points on key sieve sizes and a restricted zone. An acceptable aggregate blend must pass between the control points. The restricted zone marks an area where mix tenderness is sometimes observed;
mixes that pass through this area are not recommended unless there is evidence that tenderness will not be a problem. Mn/DOT uses broadband gradations instead of the control points and does not consider the restricted zone. (See Chapter 4 for more detailed information.)

Figure 6 0.45 Power Gradation Chart

**Mixture Volumetrics and Other Properties**

When asphalt binder is added to aggregates to produce hot mix asphalt, part of the binder is typically absorbed into the aggregates and the remainder coats the surface of the aggregates and holds them together. To provide a durable asphalt mixture that will resist raveling, it is important to have enough binder to provide an adequate film thickness around the aggregates, but not to have too much binder, which can reduce the stability of the mix. In a compacted hot mix asphalt sample, then, the space between the aggregate particles is filled with either asphalt binder or air voids. The presence of sufficient air voids is critical to the performance of the pavement. If there are inadequate voids, when the binder expands as the pavement heats up in the summer, the binder will be forced out of the mix causing bleeding or flushing. Insufficient air voids can also reduce the stability of the mix by over-asphalting or over-lubricating the mix, as shown in Figure.
The relative proportions of asphalt binder, aggregate and air, especially in terms of their volumes in a compacted mix, are critical factors affecting the performance of hot mix asphalt. Most mix design procedures rely to some extent on ensuring adequate volumetric properties. Both the Marshall and Superpave/Gyratory procedures place a strong emphasis on volumetrics; the Hveem procedure is not as rigorous. In fact, the Superpave/Gyratory volumetric properties are based on the earlier Marshall properties. However, the Superpave/Gyratory volumetric analysis represents an improvement over the Marshall design because it uses a more realistic compaction procedure and places renewed emphasis on some properties that were previously overlooked in many states.

The volumetric properties that are included in Superpave/Gyratory mix design include:

- Air Void content ($P_a$)
- Voids in the Mineral Aggregate (VMA)
- Fines to Effective Asphalt (F/E)
- Voids Filled with Asphalt (VFA)

Determining these properties requires knowledge of:

- The aggregate effective, bulk and apparent specific gravities
- The aggregate absorption
- The mixture bulk and maximum theoretical specific gravities
This section provides a brief review of these properties and why they are important. More detailed information is available in the Asphalt Institute manual SP-2 (4). A summary of the equations used to calculate the volumetric properties is included in Appendix A. A summary of the conventions for defining volumetric properties is shown in Appendix B.

The density of an object is its mass divided by its volume. Density has units like pounds per cubic foot or kilograms per cubic meter. The specific gravity is the density of the object divided by the density of water. Specific gravity is a unitless quantity that indicates how many times heavier than water an object is.

When the term “bulk” is used in reference to density or specific gravity, it implies that there are different materials contained within the volume of the sample. So, the bulk specific gravity \( G_{sb} \) of an aggregate includes the solid aggregate and the pores and crevices on the surface. The effective specific gravity \( G_{se} \) of the same aggregate, however, includes the solid aggregate particle, but excludes the volume of the pores in the aggregate that will absorb binder. A comparison of the bulk and effective aggregates, then, helps us determine how much binder the aggregate will absorb.

Similarly, in a sample of hot mix asphalt, the bulk specific gravity \( G_{mb} \) includes aggregate, binder and air. The theoretical maximum specific gravity \( G_{mm} \) excludes the air voids from the volume of the sample. In other words, the theoretical maximum specific gravity is the specific gravity of the mix if you could squeeze out all of the air voids. Comparison of the bulk and theoretical maximum gravities, then, lets us calculate the air void content of a mixture.

There are also different binder contents to consider. (Binder contents are not actually volumetric properties. They are expressed in terms of mass rather than volume, but they can be converted to volumes using the specific gravity of the binder.) The total binder content \( P_b \) is the total amount of binder added to the mixture. \( P_b \) is expressed based on the total mass of binder as a percentage of the total mass of the mixture. The mass of the binder absorbed into the aggregate is the absorbed binder content, \( P_{ba} \). Since the amount of binder an aggregate will absorb is really a property of the aggregate and its pore structure, the absorbed binder content is expressed as a percentage of the mass of the aggregate. The effective binder content \( P_{be} \) is the mass of the total binder that is not absorbed into the aggregate. The effective binder is the binder that coats the aggregate particles. It is calculated as a percentage of the mass of the mixture.

It is very important to properly account for binder absorption in the mix design phase. If absorption is not taken into account, the resulting mixture will be under-asphalted once the absorption occurs. Dry mixes are prone to raveling. A
two hour aging period is required by Mn/DOT during mix design to allow absorption to occur before the mixture volumetrics are determined.

The air void content is the volume of air voids in a compacted mix as a percentage of the total volume of the mix. As mentioned above, it is calculated by comparing the bulk specific gravity of the mix, which includes the air voids, to the theoretical maximum specific gravity of the mix, which excludes the air voids. In order to accommodate both the air voids needed and a thick enough binder coating on the surface of the aggregates (the effective asphalt), there has to be enough space between the aggregate particles. This space between the aggregates is called the Voids in the Mineral Aggregate, or VMA. VMA is a critical parameter relating to the durability of the mixture. If the VMA is too low, there will not be enough room to provide a good binder film thickness. This can lead to a dry mixture that may suffer raveling and durability cracking. If the VMA is too high, the mixture can be over-asphalted and may lose stability. It may also be an expensive mix due to the high binder content. Currently, most specifications only include a minimum VMA to ensure durability, but smart designers will try to avoid VMAs that are more than about 2 or 2.5% above the minimum to avoid over-asphalted mixes.

Since the VMA is intended to provide space for a film coating around the aggregate particles, the surface area of the aggregates must be considered. Smaller aggregates have a greater surface area for a given volume, so more room is needed to provide an adequate film thickness. That is why the minimum VMA varies depending on the nominal maximum aggregate size in the mix. Using the nominal maximum size alone, as in SP-2 (4), is a simplification that does not consider the overall gradation of the aggregate blend. Mn/DOT takes this a step further by requiring different minimum VMAs for fine versus coarse aggregate blends. Finer blends will have higher surface areas and need higher VMAs.

Another volumetric property of interest is the Voids Filled with Asphalt (VFA). VFA is the percentage of the space between the aggregate particles, the VMA, that is filled with asphalt. It is analogous to a percent saturation in a soil. VFA is somewhat redundant since it depends only on the VMA and the design air void content, which are both specified. VFA is commonly specified to help ensure adequate binder film thickness.

One last volumetric property is the fines to effective asphalt content. This property compares the percentage of fines passing the 75μm (No. 200) sieve to the percentage of effective binder. The fine material in a mixture can act in one of two ways, depending on how fine it is. Fines have a high surface area and thus a high binder demand. This can make the mix act dry because so much binder is taken up by the fines. If the fines are very small, however, they can
actually fit within the binder film thickness and extend the asphalt, or make the mix seem over-asphalted. For this reason, the ratio of fines to effective asphalt binder is controlled.

In addition to these volumetric properties, Superpave/Gyratory mixes must also meet certain compaction properties that provide a rough idea of how the mixes might behave in the field. For example, a mixture that compacts very quickly to a high level of compaction has very little internal strength. It is a “weak” mix. This type of mixture could be hard to compact in the field and likely would not hold up well under traffic. To prevent use of such weak mixes, there is a limit on how much compaction can be achieved in a few gyrations, called $N_{\text{initial}}$. $N_{\text{initial}}$ ranges between 6 and 8 gyrations in Minnesota depending on the traffic level.

The gyratory compactor can also be used to get some indication of how the mixture might perform late in its life after undergoing repeated traffic loadings. In order for the mix to perform well late in its life, we need to be sure traffic does not squeeze out all of the air voids in the mix. Experience shows that mixtures typically need to retain at least 1 to 2% air voids to prevent bleeding or loss of stability. The gyratory compactor is used to apply a large number of gyrations, between 60 and 160, to a designed mixture to ensure that it retains at least 1-2% air voids. The number of gyrations and required air void content vary depending on traffic.

One other mixture property of interest is resistance to moisture damage. After a mixture design is completed, it is checked for this resistance. ASTM D4867 Mn/DOT Modified is used to measure how much strength a mixture loses due to moisture damage. The tensile strengths of three wet and three dry specimens are measured. The tensile strength ratio (TSR) is the ratio of the average wet strength to the average dry strength. The mix must retain at least 75-80% of its dry strength to be acceptable in Minnesota. If the mix fails to meet the TSR requirement, anti-strip additives may be needed or a different combination of binder and aggregates may be needed.

**Completing the Mix Design**

What does a contractor actually do when completing a Superpave/Gyratory mix design? What information does he need to get started? Let’s review the entire process.

The contractor needs to know the traffic level, binder grade required, layer in the pavement (wear or non-wear) and the nominal maximum aggregate size. The agency determines these factors following recommendations from Mn/DOT that are described in Chapter 4.
The designer then identifies the available aggregates, as described earlier in this chapter. The individual aggregates must meet the source properties. The designer then prepares three or more blends of aggregates to satisfy the broadband gradation limits and the consensus properties. The goal of looking at multiple blends is to try to optimize the aggregate proportions to provide the best volumetrics and most economical mix.

To evaluate the volumetrics of the different blends, the designer needs to prepare mixture samples using the trial blends. The designer estimates a binder content for each blend based on experience or on an estimation procedure outlined by the Superpave/Gyratory method (4). The idea is to get a binder content that comes close to meeting the design air void requirement at the design number of gyrations, \( N_{\text{design}} \). If the air void content is too high or too low, the mix design method provides ways to estimate how the volumetric and compaction properties would change if the binder content were adjusted to yield the design air void content. It is beyond the scope of this manual to describe the process in detail. More details are available in SP-2 (4). A brief summary of the required steps is provided below:

- **Determine the Trial Binder Content**
  - Estimate the effective specific gravity of the combined aggregate blend based on the measured bulk and apparent specific gravities (AASHTO T84 and T85).
  - Estimate the volume of binder the aggregate blend will absorb based on the effective and bulk specific gravities.
  - Estimate the volume of effective binder needed to cover the aggregate surface area.
  - Estimate the total binder content needed to satisfy absorption and coat the aggregate particles. This is the trial binder content.

- **Prepare and Compact Mixture Samples**
  - Estimate the mass of aggregate needed to prepare a gyratory sample.
  - Using the trial aggregate blend and trial binder content, prepare two samples for each trial blend. Also prepare samples to measure the theoretical maximum specific gravity (AASHTO T209).
  - Short-term age the samples for two hours.
  - Compact the samples in the gyratory compactor to \( N_{\text{design}} \).
  - Measure the bulk specific gravity of the compacted specimens and compute the density achieved at \( N_{\text{initial}} \) and \( N_{\text{design}} \).

- **Evaluate Mixture Volumetrics**
  - Determine the air void content in the compacted samples at \( N_{\text{design}} \).
  - Determine the VMA at \( N_{\text{design}} \).
  - If the air void content does not match the design air void content, adjust the binder content accordingly. If the air voids are lower than the design value, estimate how much binder should be removed to
increase the air voids. If the air voids are too high, estimate how much binder to add to fill the voids. This is the estimated binder content.

- Estimate how the VMA would change if the estimated binder content had been used instead of the trial binder content. Also estimate the VFA, compaction at $N_{\text{initial}}$, and fines to effective binder content based on the estimated binder content.

- Now all of the trial blends can be evaluated on an equal basis. They have all been adjusted to meet the design air voids. Select the trial blend that provides the best volumetrics and compaction parameters. (Economics can also be considered.)

- If none of the trial blends meet the mixture requirements, either try a different blend of aggregates or try a different aggregate.

**Optimize Binder Content**

- After an acceptable trial gradation has been selected, the binder content should be optimized. This step is analogous to designing the binder content for a Marshall mix.

- The aggregate blend is mixed and compacted at three different binder contents, the estimated optimum, 1% below optimum and 1% above optimum. Additional points can be evaluated if desired. Two specimens should be mixed and compacted at each binder content.

- Measure the bulk specific gravity of the compacted specimens and evaluate the volumetric and compaction parameters.

- The design binder content is that which produces the design air void content at $N_{\text{design}}$. All of the other volumetric and compaction parameters are checked at the design binder content to verify that they comply with the specifications.

**Verify Mixture Properties**

- Once a mix has been designed, it must be checked to ensure it will not densify too much under traffic and that it has adequate resistance to moisture damage.

- Prepare two samples of the design mix and compact to $N_{\text{maximum}}$. Determine the air void content at $N_{\text{maximum}}$ and ensure it meets the requirements.

- Prepare at least six specimens of the designed mix and test according to ASTM D4867 Mn/DOT Modified. Determine the tensile strength ratio (TSR). If the TSR passes, the mix design is complete. If the mix fails the TSR test, the designer may try using an antistrip additive (and evaluate the effects of the additive on the binder and mixture properties) or may try a different combination of binder and aggregate.

When written out as above, the process seems somewhat complicated. For experienced designers, however, the process is quite familiar. Most of the steps
are similar to what was previously done with Marshall mixes. Some of the steps are more formalized under Superpave, and there is more guidance provided to assist inexperienced mix designers. For example, the Superpave/Gyratory system provides ways to estimate the trial binder content to get you in the right ballpark if you are not experienced with the aggregates being used. If you have experience with those aggregates, you can estimate a trial binder content without using the estimation technique.

This, then, summarizes the steps a contractor needs to follow to complete a Superpave/Gyratory mix design. From an agency point of view, it is important to understand that this process is familiar to most contractors now. They have developed expertise in the process through work for Mn/DOT. The additional burden on agencies is minimal. The steps and decisions an agency must make to select and specify a gyratory mix are described in Chapter 4.

The last important point is that the volumetric and compaction parameters used in Superpave/Gyratory mix design help us get better performing pavements than with previously used mix designs. The process of continual improvement is on going.
4. Selecting and Specifying a Superpave/Gyratory Mixture

The last chapter described the process a mix designer goes through to complete a Superpave/Gyratory mix design. Before a designer can begin the process, however, the agency must make some decisions to specify particular details about the gyratory mixture they want to use. The mix design process was presented first to clarify some of the impacts of the decisions the agency makes. This chapter describes those decisions and how an agency can specify a gyratory mix under Mn/DOT's 2360 Combined specification.

Please remember that this manual refers to the 2004 version of the 2360 Combined specification to illustrate certain points. When specifying a mix, however, it is important to use the most recent specification available – or the specification called out in the contract.

**Required Inputs to a Superpave/Gyratory Mix Design**

After an agency decides to use a Superpave/Gyratory mix design for the hot mix asphalt on a project, the following steps must be taken:

- The agency determines the traffic level,
- The agency designs the pavement structure/layer thicknesses
- The agency defines the mixture(s) to be used in the pavement structure, including specifying the mix type, binder grade, aggregate size and design air void content.

Once these inputs are determined, the contractor can then design the mixture, produce and place the mix, and perform Quality Control testing. Mn/DOT assists by maintaining the specifications, providing technical support and performing Quality Assurance testing, if desired. Quality Management under the 2360 Combined specification is described in Chapter 5.

**Traffic Level**

Determination of the design traffic level is necessary for both pavement thickness design and for Superpave/Gyratory mix design. In the mix design phase, traffic is used to select the appropriate binder grade, determine the aggregate requirements and determine the number of gyrations to use in design ($N_{\text{initial}}$, $N_{\text{design}}$ and $N_{\text{maximum}}$). Existing procedures can be used to develop the traffic estimates needed for mix design. The same estimates are used for thickness design.
One important note, however, is that Superpave/Gyratory mix designs are always specified based on a 20-year design life, regardless of the actual intended design life. The reason for this is that national research has shown that the rate of traffic loading is as important as the total amount of traffic. For example, 10,000 truck passes in one year is more severe than 10,000 truck passes in 20 years. By using a 20-year traffic estimate for all pavements, the difference in rate of loading can be taken into account.

For Superpave/Gyratory designs, traffic is expressed in terms of Equivalent Single Axle Loads (ESALs). (For annual average daily traffic (AADT) volumes below 6000 vehicles per day, Mn/DOT allows traffic level to be estimated on the basis of AADT rather than ESALs. See Table 3, reproduced here from 2360.1-A in the 2004 Mn/DOT specifications.) An ESAL is a measure of the damage done to a pavement by a load. ESALs are expressed in terms of an 18,000 pound (80 kN) load on an axle. The scale is not linear. A 36,000 pound (160 kN) load does far more damage than two 18,000 pound loads. In fact, a load of only 22,000 pounds (100 kN) does about 2.2 times the damage of an 18,000 pound load. Large trucks cause far more damage than passenger cars.

<table>
<thead>
<tr>
<th>Traffic Level</th>
<th>20-year Design ESALs (1 \times 10^6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2(^1)</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>3(^2)</td>
<td>1 to &lt; 3</td>
</tr>
<tr>
<td>4</td>
<td>3 to &lt; 10</td>
</tr>
<tr>
<td>5</td>
<td>10 to ≤ 30</td>
</tr>
<tr>
<td>6</td>
<td>SMA</td>
</tr>
</tbody>
</table>

\(^1\) AADT < 2300  
\(^2\) 2300 < AADT < 6000

Agencies should use the existing procedures to develop traffic estimates. These procedures are explained in *Best Practices for Design and Construction of Low Volume Roads* (7). MnPAVE and MnESALS also provide guidance on estimating traffic. MnPAVE is available on-line from MnDOT (8). The MnESALS spreadsheet is available from the Traffic Forecast and Analysis Section of Mn/DOT.

**Pavement Thickness**

After the traffic is estimated, the agency uses standard procedures to design the pavement layer thicknesses. The MnPAVE Mechanistic-Empirical design procedure is preferred, but other techniques can also be used.

There are no changes to the thickness design procedure. The only thing to keep in mind is that there are minimum layer thicknesses for different aggregate size
mixtures, as there were with Marshall mixes. These minimum layer thicknesses are needed to ensure that there is adequate depth to facilitate mix compaction. If the layer thickness is not greater than the maximum aggregate size, field compaction will be difficult at best. So the layer thickness design and maximum aggregate sizes must be compatible. The minimum layer thicknesses are shown in Table 4, reproduced here from section 2360.1B (2004 specification).

Table 4 2004 Mn/DOT Minimum Layer Thicknesses

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Min. Lift Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP 9.5 Wear</td>
<td>40 mm (1.5 in.)</td>
</tr>
<tr>
<td>SP 12.5 Wear or Non-Wear</td>
<td>40 mm (1.5 in.)</td>
</tr>
<tr>
<td>SP 19.0 Non-Wear</td>
<td>65 mm (2.5 in.)</td>
</tr>
</tbody>
</table>

Wear courses can be either SP 9.5 mm or SP 12.5mm mixes, and non-wear courses can be either SP 12.5 mm or 19.0 mm mixes. The choice of a given size is based on the required layer thickness and past experience.

**Binder Grade Considerations**

To complete specifying the mixture(s) to be used, the agency must select the binder grade, which varies according to type of construction, traffic, speed of traffic and depth in the pavement. Selection of a binder grade is summarized in Technical Memorandum No. 02-06-MRR-01 (5).

As described in Chapter 2, the primary basis for binder grade selection is the climate. There are other considerations, however, that can impact the selection and alter the grade selected based on the climatic conditions alone. Mn/DOT considered the typical climate in Minnesota and the additional factors below to develop binder grade selection recommendations.

The type of construction, whether it is new construction or an overlay, affects the grade selection. (New construction also includes reconstruction, rubblization, cold in-place recycling and full depth reclamation.) As mentioned before, the Superpave parameters were set up to help control rutting, fatigue cracking and thermal cracking. In an overlay situation, rutting is certainly a concern, but fatigue and thermal cracking are less of a concern. Reflective cracking is the major cracking distress observed on overlays; this distress is not specifically addressed under Superpave. New constructions are the ones where thermal cracking may be a greater concern. In general, then, for a given traffic level, the low temperature binder grade is higher (less negative) for an overlay than for new construction.
The traffic level is also a factor that influences binder grade selection. For higher traffic levels, the risk of rutting at high temperatures is increased. For this reason, many states increase the binder grade for higher traffic levels over what is selected based on climate alone. For binder grade selection purposes, Mn/DOT uses three traffic levels: below 3 million ESALs, 3 to 10 million ESALs, and greater than 10 million ESALs. As the traffic level increases, the high temperature grade tends to increase, especially for the highest traffic level. The low temperature grade is unaffected by traffic since thermal cracking is predominantly an environmental, not a load-related, distress.

The speed of the traffic is also a consideration when selecting a binder grade. As described in Chapter 2, the time of loading can influence the binder behavior, making it act more like a viscous liquid just as if the temperature increased. Under slow moving traffic, then, the time of loading is longer and a stiffer binder is needed to prevent rutting. Mn/DOT’s current guidelines generally recommend higher high temperature grades for slower moving traffic.

Fast traffic is defined as traffic having average speeds in excess of 70 kph (45 mph), such as found on rural trunk highways and free-flowing interstates. Slow traffic has average speeds between 20-70 kph (15-45 mph) as seen on metro and urban trunk highways or interstates, or in other areas with stop and go traffic. Standing traffic, the worst category, has average speeds below 20 kph (15 mph). Intersections are also included in the Standing Traffic category.

The last consideration is the depth in the pavement. Flexible pavements carry loads by spreading the load over a larger area as you go deeper into the pavement so that the stress (load divided by area) applied to the subgrade is low. Also as you go deeper into the pavement, the temperatures become more moderate. The lower pavement layers are insulated by the ground below and the pavement layers above. Wear courses, then, generally require a wider range of temperatures than non-wear courses. Wear courses are considered to be the top 100mm (4 in.) of the pavement, and non-wear courses are below 100mm (4 in.) deep. If the 20-year design traffic is below 3 million ESALs, the non-wear courses can be considered to be below 75mm (3 in.). This allows use of a lower binder grade closer to the surface since the traffic loads will not be great.

Given the type of construction, traffic level, traffic speed and depth in pavement, then, the Mn/DOT Guidelines can be used to select a binder grade. There is still room for engineering judgment in the grade selection, however, and the grade choices can be modified due to other considerations. When making changes to the recommendations, it is important to consider whether the changes are likely to lead to use of an expensive modified binder and whether that is justified. Modified binders may be needed for high traffic levels or critical facilities, but they are rarely needed in low volume situations.
Some other considerations that may help make the binder, mixture and project more economical include keeping the number of grades to a minimum, using realistic temperature and traffic estimates, and using RAP.

The more binder grades used on a project, the more tanks a contractor may need to store the separate grades. There are also more chances for accidentally using the wrong binder grade. Switching grades frequently is a hassle and will likely increase bid prices. It is recommended, therefore, to use a single binder grade in the top 100mm (4 in.) and a single grade below 100mm (4 in.). A PG 58-28 is routinely used below 100mm (4 in.) in Minnesota regardless of traffic, speed or type of construction.

If RAP is used in a mixture, the binder grade may need to be adjusted to take into account the stiffening effect of the hardened RAP binder. This adjustment can be done by the contractor at the mix design stage following the guidelines in section 2360.2 G1, shown in Table 5.

<table>
<thead>
<tr>
<th>Overlay</th>
<th>Specified PG Asphalt Binder Grade</th>
<th>Virgin Asphalt Binder Grade to be used with RAP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>≤ 20% RAP</td>
<td>&gt; 20% RAP</td>
</tr>
<tr>
<td>64-22</td>
<td>64-22</td>
<td>64-28</td>
</tr>
<tr>
<td>Other PG Grades</td>
<td>No grade adjustment</td>
<td>No grade adjustment</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>New Construction¹</th>
<th>Specified PG Asphalt Binder Grade</th>
<th>Virgin Asphalt Binder Grade to be used with RAP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>≤ 20% RAP</td>
<td>&gt; 20% RAP</td>
</tr>
<tr>
<td>52-34</td>
<td>52-34</td>
<td>Not allowed*</td>
</tr>
<tr>
<td>58-28</td>
<td>58-28</td>
<td>58-28</td>
</tr>
<tr>
<td>58-34</td>
<td>58-34</td>
<td>Not allowed*</td>
</tr>
<tr>
<td>64-28</td>
<td>64-28</td>
<td>64-28</td>
</tr>
<tr>
<td>64-34</td>
<td>64-34</td>
<td>Not allowed*</td>
</tr>
<tr>
<td>Other PG Grades</td>
<td>No grade adjustment</td>
<td>Not allowed*</td>
</tr>
</tbody>
</table>

* When approved by the Engineer, the virgin asphalt binder grade can be selected by using the blending chart procedure on file in the Bituminous Office. Mn/DOT may take production samples for information/verification of compliance with a specified asphalt binder grade.

¹ Includes cold in-place recycle, reclaiming, and reconstruction.
Designating a Superpave/Gyratory Mix

All of the necessary factors have now been addressed. The 2004 Mn/DOT 2360 Combined specifications provide an easy method to convey this information to the contractor so that he can proceed with designing the desired mixtures. A nine character code summarizes all of the pertinent factors affecting the mix design. This section describes the mixture designations and some additional considerations for mixture selection.

The mixture designation succinctly summarizes the following:

- Superpave/Gyratory Design
- Course in the Pavement
- Maximum Aggregate Size
- Traffic Level
- Binder Grade

The first two letters, SP, specify that a Superpave/Gyratory mix is required. (Gyratory designs for SMAs are designated SM.)

The third and fourth letters indicate the depth in the pavement. WE indicates wear courses and shoulder wear courses. NW indicates non-wear courses. Again, wear courses are in the top 100 mm (4 in.) except for low traffic levels where they can be the top 75mm (3 in.).

The fifth letter indicates the maximum aggregate size. This determines the mixture size and minimum layer thickness.

\[
\begin{align*}
A &= 12.5\text{mm (1/2 in.) maximum size for a 9.5mm mix} \\
B &= 19.5\text{mm (3/4 in.) maximum size for a 12.5mm mix} \\
C &= 25.05\text{mm (1 in.) maximum size for a 19.0mm mix}
\end{align*}
\]

The next character (the sixth) indicates the traffic level in ESALs based on a 20-year design life.

\[
\begin{align*}
2 &= \text{under 1 million ESALs (AADT < 2300 vpd)} \\
3 &= \text{1 to under 3 million ESALs (2300 vpd < AADT < 6000 vpd)} \\
4 &= \text{3 to under 10 million ESALs} \\
5 &= \text{10 to under 30 million ESALs} \\
6 &= \text{SMA}
\end{align*}
\]
The seventh and eighth characters indicate the design air void content required. Superpave and SMA wear courses have a design air void content of 4.0%, designated by 40. Superpave non-wear and shoulder courses have a design air void content of 3.0%, designated 30.

Lastly, the ninth letter indicates the binder grade to be used based on the recommendations and considerations described earlier. The binder grade designations are as follows:

A = PG 52-34
B = PG 58-28
C = PG 58-34
D = PG 58-40
E = PG 64-28
F = PG 64-34
G = PG 64-40
H = PG 70-28
I = PG 70-34
L = PG 64-22

So, for example, SPWEB240B, calls out a Superpave/Gyratory Wear Course with a maximum aggregate size of 19.0mm (3/4 in.) for a traffic level below 1 million ESALs with a design air void content of 4.0 (as required for a wear course) and using a PG 64-22. This designation gives the contractor the information needed to design the mixture.

This mixture will have a minimum lift thickness, based on the aggregate size, of at least 40mm (1.5 in.). In addition, the aggregate size determines the Aggregate Gradation Broad Bands, as shown in Table 6 below, reproduced here from 2360.2-E, and the minimum VMA required, as shown in Table 7 below, reproduced here from 2360.3-B2c. The minimum VMA also varies for fine and coarse mixes, but the shape of the gradation curve is not known until the mix design is completed.
Table 6 2004 Mn/DOT Aggregate Gradation Broad Bands

<table>
<thead>
<tr>
<th>Sieve Size (mm [in.])</th>
<th>A or 4*</th>
<th>B or 3*</th>
<th>C or 2*</th>
<th>5*</th>
<th>E (SMA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.0 [1 in.]</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td>See SMA Provisions</td>
</tr>
<tr>
<td>19.0 [3/4 in.]</td>
<td>100</td>
<td>85-100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.5 [1/2 in.]</td>
<td>85-100</td>
<td>85-100</td>
<td>45-90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.5 [3/8 in.]</td>
<td>85-100</td>
<td>35-90</td>
<td>-</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>4.75 [#4]</td>
<td>25-90</td>
<td>20-80</td>
<td>20-75</td>
<td>65-95</td>
<td></td>
</tr>
<tr>
<td>2.36 [#8]</td>
<td>20-70</td>
<td>15-65</td>
<td>15-60</td>
<td>45-80</td>
<td></td>
</tr>
<tr>
<td>0.075 [#200]</td>
<td>2.0-7.0</td>
<td>2.0-7.0</td>
<td>2.0-7.0</td>
<td>2.0-7.0</td>
<td></td>
</tr>
</tbody>
</table>

* Marshall designation

Table 7 2004 Mn/DOT Minimum VMA Requirements

<table>
<thead>
<tr>
<th>Gradation</th>
<th>Fine Mixture % Pass 2.36 mm [#8]</th>
<th>VMA Minimum</th>
<th>Coarse Mixture % Pass 2.36 mm [#8]</th>
<th>VMA Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>A or 4*</td>
<td>&gt; 47</td>
<td>15.0**</td>
<td>≤ 47</td>
<td>14.5*</td>
</tr>
<tr>
<td>B or 3*</td>
<td>&gt; 39</td>
<td>14.0</td>
<td>≤ 39</td>
<td>13.5</td>
</tr>
<tr>
<td>C or 2*</td>
<td>&gt; 35</td>
<td>13.0</td>
<td>≤ 35</td>
<td>12.5</td>
</tr>
<tr>
<td>5*</td>
<td>-----</td>
<td>15.0**</td>
<td>-----</td>
<td>-----</td>
</tr>
</tbody>
</table>

* Marshall designation
** For LV 4 and LV 5 mixes lower VMA requirements by 0.5%

The designated traffic level also defines the aggregate requirements for the mixture. The properties are described in Chapter 2. The 2004 Mn/DOT specifications are listed in 2360.3-B2a, and shown in Table 8. This table shows that for low volume mixes, the coarse aggregate angularity is only 30% with one crushed face, the fine aggregate angularity requirement is 40, and there are no limits on flat and elongated particles or clay content. In other words, the requirements for low volume roadways are pretty minimal.

The mixture requirements are also determined based on traffic level, as summarized in 2360.3-B2b and shown in Table 9. This table summarizes the gyration levels, the design air void contents for wear and non-wear courses, the maximum density at N_initial and N_maximum, the minimum TSR, the range of fines to effective asphalt binder, and the range of VFA.
Table 8  2004 Mn/DOT Aggregate Requirements Based on Traffic Level

<table>
<thead>
<tr>
<th>Aggregate Blend Property</th>
<th>Traffic Level 2 &amp; LV</th>
<th>Traffic Level 3 &amp; MV</th>
<th>Traffic Level 4</th>
<th>Traffic Level 5</th>
<th>SMA T. Level 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 year Design ESALs</td>
<td>&lt;1 million</td>
<td>1 - 3 million</td>
<td>3 - 10 million</td>
<td>10 – 30 million</td>
<td>See SMA Provisions</td>
</tr>
<tr>
<td>Coarse Aggregate Angularity (ASTM D5821)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(one face/two face), % Wear</td>
<td>30/-</td>
<td>55 / -</td>
<td>85 / 80</td>
<td>95 / 90</td>
<td></td>
</tr>
<tr>
<td>(one face/two face), % NonWear</td>
<td>30/-</td>
<td>55 / -</td>
<td>60 / -</td>
<td>80 / 75</td>
<td></td>
</tr>
<tr>
<td>Fine Aggregate Angularity (FAA) (AASHTO T304, Method A) % Wear % Non-Wear</td>
<td>40(2)</td>
<td>42(1)</td>
<td>44</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Flat and Elongated Particles, max(2) % by weight, (ASTM D 4791)</td>
<td>-</td>
<td>10</td>
<td>(3:1 ratio)</td>
<td>(3:1 ratio)</td>
<td></td>
</tr>
<tr>
<td>Clay Content(2) (AASHTO T 176)</td>
<td>-</td>
<td>-</td>
<td>45</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Total Spall in fraction retained on the 4.75mm [#4] sieve</td>
<td>5.0</td>
<td>2.5</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Maximum Spall Content in Total Sample</td>
<td>5.0</td>
<td>5.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Maximum Percent Lumps in fraction retained on the 4.75mm [#4] sieve</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Class B Carbonate Restrictions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum% -4.75mm [-#4] Final Lift/All other Lifts</td>
<td>100/100</td>
<td>100/100</td>
<td>80/80</td>
<td>50/80</td>
<td></td>
</tr>
<tr>
<td>Maximum% +4.75mm [+#4] Final Lift/All other Lifts</td>
<td>100/100</td>
<td>100/100</td>
<td>50/100</td>
<td>0/100</td>
<td></td>
</tr>
<tr>
<td>Gyratory</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. allowable RAP % Wear/Non Wear</td>
<td>30/40</td>
<td>30/30</td>
<td>30/30</td>
<td>30/30</td>
<td></td>
</tr>
<tr>
<td>Marshall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. allowable RAP % Wear/Non Wear</td>
<td>30/40</td>
<td>30/30</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 For Marshall design, the Contractor may determine –4 crushing by either FAA of uncompacted voids or calculation of crush from the composite blend. The choice must be made prior to start of production. Manufactured crushed fines requirement is 25%. RAP sand will be considered 50% crushed if the angularity index equals or exceeds 40, and 100% crushed if the angularity index equals or exceeds 45.

2 Not applicable under Marshall design.
Table 9 2004 Mn/DOT Mixture Requirements Based on Traffic Level

<table>
<thead>
<tr>
<th>Mixture Requirements</th>
<th>Traffic Level 2</th>
<th>Traffic Level 3</th>
<th>Traffic Level 4</th>
<th>Traffic Level 5</th>
<th>SMA T. Level 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 year Design ESALs</td>
<td>&lt; 1 million</td>
<td>1 - 3 million</td>
<td>3 - 10 million</td>
<td>10 - 30 million</td>
<td>See SMA Provisions</td>
</tr>
<tr>
<td>Gyratory Mixture Requirements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gyration for N&lt;sub&gt;initial&lt;/sub&gt;</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>Gyration for N&lt;sub&gt;design&lt;/sub&gt;</td>
<td>40</td>
<td>60</td>
<td>90</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>Gyration for N&lt;sub&gt;maximum&lt;/sub&gt;</td>
<td>60</td>
<td>60</td>
<td>140</td>
<td>160</td>
<td>-</td>
</tr>
<tr>
<td>Air Voids, % -- Wear</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>-</td>
</tr>
<tr>
<td>Air Voids, % -- Non-Wear &amp; All Shoulder</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>-</td>
</tr>
<tr>
<td>% G&lt;sub&gt;mm&lt;/sub&gt; at N&lt;sub&gt;initial&lt;/sub&gt; -- Wear</td>
<td>-</td>
<td>≤ 91.5</td>
<td>≤ 90.5</td>
<td>≤ 90.0</td>
<td>-</td>
</tr>
<tr>
<td>% G&lt;sub&gt;mm&lt;/sub&gt; at N&lt;sub&gt;initial&lt;/sub&gt; -- Non-Wear &amp; All Shoulder</td>
<td>-</td>
<td>≤ 92.5</td>
<td>≤ 91.5</td>
<td>≤ 91.0</td>
<td>-</td>
</tr>
<tr>
<td>% G&lt;sub&gt;mm&lt;/sub&gt; at N&lt;sub&gt;maximum&lt;/sub&gt; -- Wear</td>
<td>≤ 98.0</td>
<td>≤ 98.0</td>
<td>≤ 98.0</td>
<td>≤ 98.0</td>
<td>-</td>
</tr>
<tr>
<td>% G&lt;sub&gt;mm&lt;/sub&gt; at N&lt;sub&gt;maximum&lt;/sub&gt; -- Non-Wear &amp; All Shoulder</td>
<td>≤ 99.0</td>
<td>≤ 99.0</td>
<td>≤ 99.0</td>
<td>≤ 99.0</td>
<td>-</td>
</tr>
<tr>
<td>Tensile Strength Ratio (1), min%</td>
<td>75&lt;sup&gt;(2)&lt;/sup&gt;</td>
<td>75&lt;sup&gt;(2)&lt;/sup&gt;</td>
<td>80&lt;sup&gt;(3)&lt;/sup&gt;</td>
<td>80&lt;sup&gt;(3)&lt;/sup&gt;</td>
<td>-</td>
</tr>
<tr>
<td>Fines/Effective Asphalt</td>
<td>0.6 - 1.2</td>
<td>0.6 - 1.2</td>
<td>0.6 - 1.2</td>
<td>0.6 - 1.2</td>
<td>-</td>
</tr>
<tr>
<td>Voids Filled with Asphalt, VFA%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wear</td>
<td>65 - 78</td>
<td>65 - 78</td>
<td>65 - 76</td>
<td>65 - 76</td>
<td>-</td>
</tr>
<tr>
<td>NonWear</td>
<td>70 - 83</td>
<td>70 - 83</td>
<td>70 - 82</td>
<td>70 - 82</td>
<td>-</td>
</tr>
<tr>
<td>Marshall Mixture Requirements</td>
<td>LV</td>
<td>MV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marshall Blows</td>
<td>50</td>
<td>50</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Air Voids, %</td>
<td>3.0</td>
<td>3.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Tensile Strength Ratio (1), min%</td>
<td>70&lt;sup&gt;(4)&lt;/sup&gt;</td>
<td>70&lt;sup&gt;(4)&lt;/sup&gt;</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Stability, minimum N [lb f]</td>
<td>5000 [1125]</td>
<td>6000 [1350]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fines/Effective Asphalt</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wear</td>
<td>0.6 - 1.30</td>
<td>0.6 - 1.30</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Non-Wear</td>
<td>0.6-1.40</td>
<td>0.6-1.40</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<sup>1</sup> See Section 2360.4 E9. Use 150mm [6 in.] specimens for gyratory and 100mm [4 in.] specimens for Marshall design.
<sup>2</sup> Mn/DOT Min = 65, <sup>3</sup> Mn/DOT Min = 70, <sup>4</sup> Mn/DOT Min = 60

Summary

To summarize selecting and specifying a Superpave/Gyratory mix using the 2360 Combined specifications, the agency estimates traffic and designs the pavement layer thicknesses using existing procedures. The agency also selects the binder grade, using guidelines from Mn/DOT and engineering judgment.

The traffic estimate influences the binder grade selection and determines the aggregate requirements, maximum allowable RAP content, numbers of gyrations to use, and the mixture volumetric and densification parameters.
The maximum aggregate size must be compatible with the minimum lift thicknesses, as determined based on the thickness design. The maximum aggregate size determines the minimum VMA and range of VFA.

The type of mixture, Wear vs. Non-Wear, impacts the binder grade selection, aggregate requirements and maximum allowable RAP content.

The Mn/DOT specifications and mixture designations provide a simple, concise method for communicating the pertinent mixture information to the contractor for mix design.
5. Quality Management of Superpave/Gyratory Mixtures

As indicated in the Introduction, Minnesota started its Quality Management program in 1988. The program has grown steadily since then. Now, the 2360 Combined specifications afford local agencies a means of implementing the new and improved mix designs without increasing the agency's testing and acceptance burden. Contractors assume more responsibility for their product under the program and perform testing to ensure that required quality is achieved. Mn/DOT's District Labs are available to conduct quality assurance testing, if the local agency chooses not to do the testing themselves. This chapter reviews the Quality Management features of the 2360 Combined specification and how local agencies can use QM to get a quality product for their applications. (Again, recall that this chapter refers to the 2004 specifications. For best results, use the most up-to-date specifications available.)

Quality Management is an overall system for ensuring product quality that includes Quality Control testing by the producer, Quality Assurance testing by or on behalf of the agency and Independent Assurance sampling and testing to verify the accuracy of the test results. Or,

\[ QM = QC + QA + IAST \]

Quality Control is testing performed by the contractor to ensure that the production process is in control. Quality Assurance testing is required by the specifying agency to accept the product. In Minnesota, QA testing is performed by the agency, except on warranty projects, where some contractor tests are being used for QA. Mn/DOT District labs will perform QA testing for local agencies on request. Independent Assurance Sampling and Testing is performed by Mn/DOT’s IA tester to verify test results on companion samples.

**Quality Control**

Under the 2360 Combined specifications, the contractor is required to develop and follow a QC program at the plant. The program must cover mix design, process control inspection, sampling and testing, and how adjustments will be made to the mix to control the quality.

The specifications also require that the hot mix plant be inspected and certified by the agency or Mn/DOT. Certified plants test all mixes produced and document the results. This provides a “track record” to show that the plant can consistently produce quality materials. Certified technicians are also required for process control testing, mix design or adjustment of mixes, and laydown operations. Calibrated equipment for production and testing is required. All of
these features help to ensure that the materials and pavements produced meet the quality requirements.

Sampling and testing is done at random locations at a specified minimum frequency of testing. (Additional samples can be taken at any time.) Mixture samples are taken behind the paver, unless an alternate location is specified. Behind the paver sampling tests the mixture as it exists in the pavement, helping to detect changes in the mix, such as segregation or additional binder absorption during transit.

Tests are required on the following properties:

- Bulk Specific Gravity ($G_{mb}$)
- Maximum Specific Gravity ($G_{mm}$)
- Air Voids ($P_a$)
- VMA
- Binder Content ($P_b$)
- Binder Properties
- Gradation
- Coarse Aggregate Angularity
- Fine Aggregate Angularity
- Moisture Sensitivity (TSR)
- Aggregate Specific Gravity ($G_{sb}$, $G_{se}$)
- Mix Moisture Content

In addition, if a liquid antistrip additive is used in the mixture, the contractor is required to perform additional tests to ensure that the addition of the antistrip does not alter the binder grade.

Control charts are plotted to show how the properties vary over time. Contractors plot their test results and show moving averages of the most recent test results. In other words, control charts graphically illustrate how well the production process is being controlled. If a control chart shows that a property is starting to go out of the specification tolerances, corrections can be made before substandard material is produced. The agency's QA results are also plotted on the control chart to show how closely the contractor's and agency's results compare. Control charts are required for:

- Blended Aggregate Gradation
- Binder Content
- Maximum Specific Gravity of the Mix ($G_{mm}$)
- Production Air Voids
- VMA
Job Mix Formula (JMF) limits on these properties are established in the specifications in terms of plus or minus tolerances from the production targets listed on the Mixture Design Report. Corrective action is required if the moving averages tend towards or exceed the JMF limits. The requirements for remedial action are detailed in the specification. The specification also enumerates the pay factor reductions that apply for materials that fail to meet the production tolerances. (See section 2360.4L.)

**Quality Assurance and Verification Testing**

The engineer or plant monitor is primarily responsible for QA testing and verification sampling. Mn/DOT or agency laboratories conduct the testing on samples taken by the engineer/plant monitor. The engineer/plant monitor is also responsible for observing the contractor's QC sampling and testing, reviewing QC summary sheets and control charts, and verifying equipment calibration.

Verification testing is used to evaluate the contractor's compliance with the QC program. When the agency's verification sample is taken, a companion sample is taken and given to the contractor for testing. The contractor is required to test all verification samples. The contractor and agency results must agree within specified tolerances for particular tests.

**Pavement Quality Testing**

Quality Management does not only apply to the materials produced, but also to the pavement itself. Three pavement properties are measured and assessed: density, thickness and smoothness.

Adequate density is essential for good pavement performance. Achieving the proper compaction in the field helps to reduce later densification under traffic (rutting) and helps to reduce aging, stripping and cracking by limiting the intrusion of air and water into the pavement. Under the 2360 Combined specifications, the density of the compacted pavement layers can be measured and controlled.

The 2004 minimum density requirements, shown in Table 2360.6-B2, must be met to achieve full pay. The contractor is responsible for taking cores from each lot and repairing the core locations. Some of the cores are tested by the contractor, and companion cores are provided to the agency for testing. The pay factors are adjusted based on the lot density and may result in bonuses or penalties.
Thickness of the individual lifts is also assessed to ensure that an adequate amount of material is being placed in the field. The density cores are examined and measured to verify the layer thicknesses. The thickness must be within 6mm (1/4 in.) of the planned thickness. If the lift is too thin, it must be removed and replaced. If too thick, payment is denied for the excess material. This restriction helps to control unnecessary overruns while ensuring that adequate pavement thickness is provided. The 2004 thickness provisions are shown in 2360.7B.

Pavement smoothness is another quality factor that is assessed under the 2360 Combined specifications. Research has shown that smoother pavements last longer, perform better and improve ride comfort for the traveling public. Rough pavements induce vehicle dynamics (bounce) that are uncomfortable and stress the pavement by applying impact loadings.

Smoothness is controlled by use of a profilograph or inertial profiler provided by the contractor. The contractor is also responsible for providing an operator, traffic control and profile index results for the final wear course. Penalties and bonuses are specified for different types of construction, depending on the number of lifts placed. Generally, placing more lifts provides more opportunities to improve the smoothness. Remedial actions for unacceptable smoothness are also specified. See 2360.7 C for more details.

**Summary**

The 2360 Combined specifications provide a means to ensure quality without placing as additional burden for testing and inspection on local agencies. The contractor takes responsibility for testing his own product to control the production process. The contractor also takes samples and provides some test results to the agency. Mn/DOT labs are available to assist with quality assurance testing, if desired.

Local agencies benefit by getting what they want and what they are paying for. Increased material and pavement quality leads to better performance, longer service lives and overall reduced life cycle costs.
6. Case Histories

Usage of Superpave binders and mixtures has increased steadily nationwide since the first mixes were placed in 1992 and 1993. The PG binder specifications are now fully implemented in 47 states and the District of Columbia. Two additional states are in the process of implementing PG grades. Some 34 states have implemented the mix design system, with 13 more in progress of implementing. The number of Superpave projects nationwide has increased from 95 in 1996 to nearly 5000 in 2001. (9)

In Minnesota, the PG binder specifications were fully implemented in 1997, along with most of the states in the North Central region. The first Mn/DOT project with Superpave mix was placed in 1996. The number of tons of Superpave mix placed in the state increased from 807,000 tons in 1998 to more than 1.7 million tons in 2002 (10). Over that time period, over 11% of that tonnage has been designed for traffic volumes below 1 million ESAL's, and nearly 5% has been for traffic volumes below 300,000 ESAL's. Most of that low volume material, however, has been placed on shoulders, not on mainline low volume roads (10).

There have been a number of applications of Superpave/Gyratory mixes for low volume roads in Minnesota since 1995. Several counties have used the system, and more are trying it every year. This chapter briefly reviews three examples of Superpave/Gyratory mix design implementation. More details on these projects are available in references cited below.

**Stearns County**

Stearns County placed an early Superpave mix in 1996. CSAH 75 is a four lane divided highway with a design traffic level of 3 million ESAL's. This project included eight different test sections to compare Superpave/Gyratory mixes to typical Minnesota mixes. The test sections include Superpave wear courses over Superpave binder and base mixes and over conventional binders and bases. A conventional base, binder and surface section is included as a control. There are sections with and without sawing and sealing as well. All of the sections have a total of 150mm (6 in.) of new bituminous mix. Some have 38mm (1.5 in.) on 38mm (1.5 in.) of binder and 75mm (3 in.) of base. Other sections have 50mm (2 in.) of surface on 50mm (2 in.) of binder on 69mm (2.5 in.) of base (11).

The project was a reconstruction of CSAH75 that was necessary due to stripping, thermal cracking, poor ride quality and high maintenance costs. The design, construction and performance of the project are detailed in a LRRB report.
The mix designs for the project used a local granite in all mixtures. A PG58-28 was used in all of the base courses, but the surface and binder courses used PG58-34 and PG58-28 for comparison purposes. The Superpave wear course with the PG58-28 cost the same as the 47A wear course. The Superpave mixes with PG58-34 were significantly more expensive than the corresponding 47A or 47B courses with PG58-28 (11). The cost differential is due to the binder grade. Only the long-term performance will show if this added initial expense led to better performance and lower life cycle costs.

Minimal construction problems were encountered in the field, and the mixtures met the quality requirements. In order to compact the mixes, the breakdown roller followed closely behind the paver. The mixes were reportedly stiff and very stable.

As of 2004, the Superpave mixtures are reportedly outperforming the Marshall mixes. One area in a Marshall mix began to ravel in less than one year. The Superpave mixes also reportedly look blacker, probably due to a thicker binder film. The Superpave mixes are performing better in terms of raveling and durability. No significant rutting has been observed in any of the sections except for minor rutting at intersections. Both sections have some cracking, but there is less cracking and no cupping in the Superpave sections. The conventional mixes (2347) do show cupping at the cracks (11).

The project has been deemed a success and Stearns County has constructed two more Superpave/Gyratory projects since. They report that they will continue using Superpave on the county’s higher volume roads (12).

**MnROAD**

At MnROAD, two cells on the mainline were paved with Superpave and PG58-28 in 1997. One cell’s gradation went through the restricted zone and the other was a coarse grading. Three cells on the Low Volume Road were paved with Superpave. These sections compared PG58-28, PG58-34 and PG58-40 binders. The performance of these sections was summarized in the 2002 Superpave Report (10) and more information is available at the MnROAD website (13).

The mainline MnROAD cells were performing very well in 2002 with minimal rutting, no cracking and good ride quality. Some stripping has started to appear in both sections. No major differences between the gradations have been reported to date. The mainline pavement structure consists of 100mm (4 in.) of Superpave mix over an existing milled 230mm (9 in.) bituminous pavement (10).
The Low Volume Road cells also have good ride quality. The rutting is minimal 9mm (3/8 in.) and very little cracking has been observed. These sections consist of 100mm (4 in.) of Superpave on 300mm (12 in.) of aggregate base (10).

**I-35 at Owatonna**

One last case study is offered for consideration. This is not a low volume roadway, but it is informative nonetheless. I-35 near Owatonna was reconstructed in 1995 and 1996. The Southbound lanes, constructed in 1995, used a 75-blow Marshall mix design. Part of the Southbound lanes used PG58-34 and the rest used 85/100 penetration grade asphalt. The Northbound lanes were paved in 1996 with a Superpave mix and a PG58-34. Both directions include sections with sawed and sealed joints. This study offers an excellent comparison of Marshall and Superpave mixes on new construction.

Again, the Superpave sections are outperforming the Marshall mixes. The Marshall lanes have transverse cracking both with and without sawing and sealing. No transverse cracking had been observed in the Superpave sections as of 2002. The pavement serviceability ratings (PSR) for the two directions show that the Northbound lanes have a PSR of 3.5, and the Southbound lanes have a PSR of 3.25. Based on these ratings, it is anticipated that the Marshall sections will need maintenance in 2007, and the Superpave sections will not need maintenance until 2010. This shows that Superpave is extending the service life of the pavement by at least two to three years (10).

**Other Applications**

Some other counties have begun using the Superpave/Gyratory specifications since these early applications. In 2003, Kandiyohi and Lyon counties implemented the new specifications. In 2004, Clay, Goodhue and Hennipin counties all planned projects as well. Usage of the 2360 Combined specifications is expected to continue increasing as experience builds on the local level and the system's advantages are more widely recognized.
Summary

These case studies and other experience in Minnesota and elsewhere show that Superpave mixes are applicable to local and low volume roadways. Their performance has been very good to excellent. Resistance to environmental distresses like raveling and cracking, which have major problems for local agencies in the past, is significantly improved with Superpave/Gyratory mixes. Initial costs may be, but are not always, higher than Marshall mixes, but the service life before major maintenance or reconstruction, is extended resulting in lower life cycle costs. Superpave/Gyratory mixes offer significant benefits to local agencies in Minnesota with little to no increased cost or risk.
7. Impacts of Superpave/Gyratory Mixtures

Implementing change is never easy, but when the risks and benefits are clearly understood it is easier to make a decision. This chapter reviews some of the possible positive and negative impacts of implementing Superpave/Gyratory mixes at the local level in Minnesota. Impacts on material selection, design, construction, quality management, pavement performance and cost are briefly reviewed.

**Material Selection and Mix Design**

Material selection was discussed in general terms in Chapter 2 and mix design in Chapter 3. This section summarizes some of the potential impacts of implementing Superpave/Gyratory designs by local agencies in Minnesota. It also summarizes some considerations the local agencies should keep in mind.

Performance Graded binders are standard in Minnesota now, and have been since the late 1990's, so implementing the 2360 Combined specifications will not impact binder supplies or selection. Local agencies and consultants are, for the most part, familiar with PG binders now. Mn/DOT has provided guidelines for binder selection in Technical Memorandum 02-06-MRR-01 (5).

As discussed in Chapter 2, the climate is the primary consideration when selecting a binder grade, but the choice can be tempered by considerations of traffic, speed of traffic, depth in the pavement, type of construction and required level of reliability. Mn/DOT’s guidelines take these factors into account.

It is important to select the binder grade appropriately. Over-designing the binder can lead to high costs and may not necessarily lead to improved performance. For local roads, durability and thermal cracking are frequently of greater concern than rutting, so increasing the high temperature grade of the binder will not necessarily improve performance.

The impact of implementing Superpave/Gyratory mixes on use of local aggregates varies depending on the quality of the locally available material. In some cases, the aggregates required for Superpave/Gyratory mixes may require more crushed aggregate. Higher quality aggregates may need to be imported so that the final blend of aggregates satisfies the consensus properties and produces a mixture with the necessary volumetric properties. This will not always be the case, however. It is more often true for higher volume roadways. The aggregate requirements for lower volume roadways are minimal, so most local agencies will be able to use local materials for most projects. Local
materials can almost always be used to some extent, though sometimes in lesser quantities than with Marshall mixes.

From an agency viewpoint, the impacts of Superpave/Gyratory mixes on the mix design process itself are relatively inconsequential. The contractors do the mix designs, and most of them are comfortable with the process. The only real impact on the county may be that meeting the mixture volumetric properties, particularly VMA, may require higher percentages of high quality aggregate than required just to satisfy the consensus properties. If so, this can have an impact on the initial mixture cost.

The mix design procedure, especially the compaction procedure, is more realistic and produces a better mixture. The procedure also takes climate and traffic into account in a more rigorous way than with previous mix designs. The mixes are specifically designed to resist rutting, cracking, moisture damage and environmental distress. The emphasis on volumetrics, coupled with the improved compaction technique, better accounts for absorption, producing thicker binder films and better resistance to raveling than the 2340 mixes.

RAP can be used in Superpave/Gyratory mixtures, which has both environmental and economic benefits.

**Pavement Design, Construction and Quality Management**

In terms of pavement design, there are no substantive changes related to implementing Superpave/Gyratory mix designs. The traffic level is estimated using existing procedures. The pavement thickness is determined using existing procedures. As mentioned in Chapter 4 the mechanistic-empirical structural design procedure in MnPAVE is preferred, but any design procedure can be used. The recommended minimum lift thicknesses in section 2360.1B should be used to facilitate field compaction.

The mix designations described in the 2360 Combined specifications provide a simple, concise way to communicate all of the required information to the mix designer.

From a construction standpoint, Superpave/Gyratory mixtures can sometimes be stiffer and harder to compact. This is more often true for high volume roadways where large proportions of crushed aggregate and modified binders are more frequently used. The high crushed aggregate content can produce a harsh mix. Modified binders tend to be stickier and harder to work. Contractors have learned how to deal with these stiffer mixes through their Mn/DOT high volume work. They are typically better prepared now to deal with construction challenges than in the early days of implementation. When a minimum density
requirement is specified, contractors routinely bring more rollers to the job and roll the mix immediately behind the paver to avoid compaction problems. They are also making more use of pneumatic rollers, which have been successfully used with many stiff mixes. Construction difficulties with mixes designed for lower traffic volumes have been minimal.

The 2360 specifications include a number of Quality Management provisions to encourage the contractor to produce a quality pavement. The contractor tests his product to control the production process. The agency or Mn/DOT performs quality assurance and verification testing to ensure that the contractor is providing a quality product. Material and mixture testing, along with density, thickness and smoothness requirements, help to ensure the pavement meets minimum quality requirements.

Normal attention to detail is needed to avoid segregation, achieve compaction, produce consistent mix, etc. Superpave/Gyratory mixes cannot compensate for poor structural design, bad drainage, improper production or placement, but if properly produced and placed will provide better performance and a longer service life.

**Pavement Performance and Cost**

Minnesota experience summarized in Chapter 6 shows that the Superpave/Gyratory mixtures placed to date typically exhibit:

- Significantly less raveling and oxidation
- Reduced thermal cracking
- Less stripping
- Less cupping at joint
- Very little rutting
- Good ride quality

Some data also seems to suggest that PG binders may be more effective than sawing and sealing at controlling cracking. If sawing and sealing is not necessary, there could be a significant cost savings with no loss of quality.

In short, the Superpave/Gyratory mixes are performing well; they have better durability and fewer distresses. What's more, there is compelling evidence to suggest that Superpave/Gyratory mixes will indeed have longer service lives than Marshall mixes.

Initial costs may be somewhat higher for Superpave/Gyratory mixes in some cases, but not in all. Local conditions, aggregate availability, binder grade, traffic levels and other factors have a great impact on the initial material costs.
Properly estimating and reasonably accounting for these variables can go a long way towards controlling costs.

The price per ton has decreased as contractors have become accustomed to the new system. Statewide costs for Superpave/Gyratory mixes have decreased from $30.58 per ton in 1998 to $26.34 per ton in 2002 over all categories and traffic levels. Over the same time period, the costs of 2350 mixes increased by 16% from $21.70 per ton to $25.14. Superpave/Gyratory mixes are now more economical than many 2350 mixtures (10).

**Summary**

In summary, Superpave/Gyratory mixes have demonstrated improved pavement performance and indicate they will have longer service lives. The initial costs are sometimes slightly higher, but in many cases are comparable to or even more economical than Marshall mixes. Longer service lives will allow more time between major maintenance or rehabilitation efforts. The longer service lives, coupled with marginally higher or equivalent initial costs mean lower life cycle costs overall.
8. Summary and Conclusions

The asphalt industry in Minnesota has a long history of making improvements to its product and the technologies and equipment used to produce it. Improvements have been made over the last fifty years in materials, design, construction, equipment, testing and more. Superpave/Gyratory mix design is one of the most significant improvements in several decades.

Gyratory mix design is rooted in past best practices and solid engineering principles. It marks a major improvement over previous mix design procedures by using a more realistic compaction technique and by better accounting for traffic, structural and climatic conditions. Superpave/Gyratory mixes are an evolution, not a revolution.

Superpave/Gyratory mix designs incorporate:

- Performance Graded binders,
- Some higher crushed aggregate contents and quality requirements, depending on the traffic level, and
- The gyratory compactor to produce compacted specimens that more closely represent field compaction.

Superpave/Gyratory mixtures also incorporate some of the same features as Marshall mixes, including:

- The equipment used for testing, production, placement and field compaction, except for the gyratory compactor,
- The same structural design procedures,
- The same best practices for mix production and construction,
- The same pavement selection process, and
- The same suppliers and contractors.

The Superpave/Gyratory mix design system is designed to get the right materials and mixtures for a given project, considering climate, traffic, speed of the traffic, type of construction, depth in the pavement and more. Superpave/Gyratory mixtures are designed to resist rutting, fatigue and thermal cracking. The PG binder specifications help specify a binder that can perform well over the range of temperatures expected for that material in that location. The binder grade selection process includes traffic volume and speed, depth in pavement, use of RAP and other parameters to get the right binder for the job. Selecting the grade appropriately can help to get better pavement performance while also controlling costs.
Some Superpave/Gyratory mixes require higher quality aggregate blends to produce adequate mixture volumetrics. This is more often true for higher traffic volumes than for low traffic. Aggregate shape restrictions help to get good aggregate interlock to help resist rutting. The aggregate cleanliness is also controlled to help ensure a good bond between the aggregate and asphalt binder to resist stripping. The aggregate requirements for low volume roads and non-wear courses are minimal. Also, the aggregate quality requirements apply to the total blend of material, not the individual stockpiles. If local aggregates do not meet the quality requirements, they can still be used as long as they are blended with some higher quality material.

The Mn/DOT 2360 Combined specifications make it simple to designate a Superpave/Gyratory mixture and communicate the mix requirements to the contractor. Mn/DOT provides guidelines and recommendations to simplify the implementation while still leaving room for engineering judgment to fine tune the requirements for specific projects. The specifications also put much of the burden for producing a quality mix on the contractor. Mn/DOT is available to assist with technical support, maintenance and refinement of the specifications, quality assurance testing and more.

Experience in Minnesota to date shows that Superpave/Gyratory mixtures are outperforming Marshall mixes for low volume and high volume applications. The gyratory mixes exhibit minimal rutting, significantly less cracking and greatly reduced raveling and durability problems. Initial costs are comparable to or slightly higher than Marshall mixes in most cases; sometimes they are lower. Given the longer performance life and better pavement quality of Superpave/Gyratory mixes, then, they are more economical from a life cycle cost standpoint.

Where to Go for Assistance

For more information or assistance with questions about Superpave/Gyratory mix implementation, several Mn/DOT offices are available to assist, including:

- Bituminous Office at the Materials and Road Research Division
- State Aid for Local Transportation
- Mn/DOT District State Aid Offices

Other organizations are also potential sources of information. These organizations include:

- Minnesota Asphalt Pavement Association
- University of Minnesota
- Local Road Research Board
• North Central Superpave Center
• Federal Highway Administration
• Asphalt Institute and
• National Asphalt Pavement Association

All of these organizations have websites with valuable information. See Appendix C for contact information.
References


13. Mn/DOT (Internet), Minnesota Road Research, *MnRoad Website*, http://www.mrr.dot.state.mn.us/research/Mnresearch.asp
Appendices

A  Volumetric Equations
B  Conventions and Definitions of Volumetric Property Abbreviations
C  Contact Information
A. Summary of Volumetric Equations

These are the equations used during the mix design process, as outlined in detail in other resources, such as the Asphalt Institute SP-2 Manual. They are included here for reference and to show how the various volumetric properties are related to each other.

**Bulk Specific Gravity of Aggregate Blend**

\[ G_{sb} = G_{sb\text{combined}} = \frac{100}{\frac{P_{s1}}{G_{sb1}} + \frac{P_{s2}}{G_{sb2}} + \frac{P_{s3}}{G_{sb3}} + ...} \]

**Effective Specific Gravity of Aggregate Blend**

\[ G_{se} = \frac{100 - P_b}{G_{mn}} \]

**Maximum Theoretical Specific Gravity of Mix @ Other Asphalt Contents**

\[ G_{mn} = \frac{100}{\frac{P_s}{G_{se}} + \frac{P_b}{G_b}} \]

**Air Void Content**

\[ P_{ar}, \% = \frac{G_{mn} - G_{mb}}{G_{mn}} \times 100 \]

**Voids in Mineral Aggregate**

\[ VMA, \% = 100 - \frac{G_{mb} \times P_s}{G_{sb}} \]

**Voids Filled with Asphalt**

\[ VFA, \% = \frac{VMA - P_{ar}}{VMA} \times 100 \]
Asphalt Content

\[ P_{b, \%} = \frac{\text{mass of binder}}{\text{mass of mix}} \times 100 \]

Absorbed Asphalt Content

\[ P_{\text{bar}, \%} = \left( \frac{G_{sc} - G_{sb}}{G_{sc} \times G_{sb}} \right) \times G_b \times 100 \]

Effective Asphalt Content

\[ P_{\text{be}, \%} = P_b - \frac{P_{\text{bar}} \times P_t}{100} \]

Fines/Effective Asphalt Content

\[ \frac{F}{E} = \frac{P_{0.075}}{P_{\text{be}}} \]

where \( P_{0.075} \) = percent passing 0.075 mm (No. 200) sieve
B. Summary Of Definitions And Conventions

Naming Convention

![Diagram of naming convention]

Definitions

- $V_{ba}$ = volume of binder absorbed
- $V_{be}$ = volume of effective binder
- $G_b$ = specific gravity of binder
- $G_{sb}$ = bulk specific gravity of stone
- $G_{se}$ = effective specific gravity of stone
- $G_{sa}$ = apparent specific gravity of stone
- $G_{mb}$ = bulk specific gravity of mix
- $G_{mm}$ = maximum theoretical specific gravity of mix
- $P_a$ = percent air (sometimes called $V_a$ for percent air by volume.)
- $P_s$ = percent stone ($100 - P_b$)
- $P_b$ = percent binder
- $P_{ba}$ = percent binder absorbed
- $P_{be}$ = percent effective binder
- $P_{0.075}$ = percent passing 0.075 mm sieve
C. Contact Information

Mn/DOT Offices
Mn/DOT Bituminous Office (651)779-5577
www.dot.state.mn.us/pavement/bituminous/bituminous.asp
Mn/DOT Office of Materials (651)779-5592
www.mrr.state.mn.us/index.asp
Mn/DOT State Aid for Local Transportation (651)296-3011
www.dot.state.mn.us/stateaid/

District 1 – Duluth (218)723-4960, ext 3004
District 2 – Bemidji (218)755-3808
District 3 – Brainerd (218)828-2475
District 4 – Detroit Lakes (218)847-1556
Metro District (651)582-1351
District 6 – Rochester (507)285-7377
District 7 – Mankato (507)389-6870
District 8 – Marshall (507)537-6146

Other Resources
Mn/ROAD
http://www.mnroad.dot.state.mn.us/research/mnresearch.asp

Minnesota Asphalt Pavement Association
http://www.asphaltisbest.com/

North Central Superpave Center
http://bridge.ecn.purdue.edu/~spave/

University of Minnesota Civil Engineering
http://www.ce.umn.edu/index.html

Local Road Research Board
http://www.lrrb.gen.mn.us/

National Asphalt Pavement Association
http://hotmix.org/

Federal Highway Administration, Turner-Fairbank Highway Research Center
http://www.tfhrc.gov/

Asphalt Institute
http://www.asphaltinstitute.org/