Quality Improvement Series 123

NATIONAL ASPHALT PAVEMENT ASSOCIATION

Design & Construction of Heavy-Duty Pavements

Second Edition

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NATIONAL ASPHALT
PAVEMENT ASSOCIATION

NAPA Building ▪ 5100 Forbes Blvd. ▪ Lanham, MD 20706-4407
Tel: 301-731-4748 ▪ Fax: 301-731-4621 ▪ Toll free 1-888-468-6499
www.AsphaltPavement.org ▪ NAPA@AsphaltPavement.org

Audrey Copeland, Ph.D., P.E.
President & CEO

J. Richard Willis, Ph.D.
Vice President for Engineering, Research, & Technology

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Design & Construction of Heavy-Duty Pavements

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By
Harold L. Von Quintus, P.E.
Applied Research Associates Inc.

Charles S. Hughes, P.E.

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Tel: 301-731-4748 ▪ Fax: 301-731-4621 ▪ Toll free 1-888-468-6499
www.AsphaltPavement.org ▪ NAPA@AsphaltPavement.org

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9. Abstract

A revised and updated version of *Design, Construction, and Performance of Heavy-Duty Mixes* (QIP-123), originally published by the National Asphalt Pavement Association in 2002.

Heavy duty mixes are needed in any pavement structure subjected to severe loading conditions as evidenced by the number and weight of heavy loads, heavy static loads, and/or high tire pressures. As pavements meeting these conditions increase, heavy-duty mixes designed to withstand these loads are being used more frequently. Integrating the pavement structural and mixture designs is essential to provide a long-lasting, durable pavement under severe traffic conditions.

This publication provides a state-of-the-practice of the material selection, mixture design, structural design, and construction of asphalt mixtures and pavements used under heavy truck traffic or specialized loading conditions, including discussing the use of large-stone mixtures, polymers, and other additives commonly used to provide higher strengths for heavy-duty asphalt mixtures.

Because the aggregate skeleton must carry much of the load, it is important that a good quality crushed aggregate is used and that the gradation meets the appropriate requirements. The gradation requirements typically require large nominal maximum size aggregate. Although segregation of the large stone can be a problem, using good production and construction practices can minimize this.

Three principal problems that may arise when using large maximum size aggregate are segregation, aggregate fracture, and a slight increase in equipment wear. These problem areas are discussed with an emphasis on the causes of, and steps that can be taken to overcome, segregation.

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CONTENTS

List of Abbreviations Used

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway & Transportation Officials
AI	Asphalt Institute
BMD	balanced mix design
CAA	coarse aggregate angularity
DOT	Department of Transportation
DSR	dynamic shear rheometer
EAPA	European Asphalt Pavement Association
ER	elastic recovery
ESAL	equivalent single axle load
FAA	Federal Aviation Administration
FEL	fatigue endurance limit
FHWA	Federal Highway Administration
FPS	Flexible Pavement System
HMA	hot-mix asphalt
HMAC	high-modulus asphalt concrete
IRI	International Roughness Index
JMF	job mix formula
LDPE	low-density polyethylene
MEPDG	Mechanistic-Empirical Pavement Design Guide
MSCR	Multiple Stress and Creep Recovery
NAPA	National Asphalt Pavement Association
NCAT	National Center for Asphalt Technology
NCHRP	National Cooperative Highway Research Program
NMAS	nominal maximum aggregate size
OGFC	open-graded friction course
PATB	permeable asphalt-treated base
PG	performance grade
PMA	polymer-modified asphalt
PMTP	paver-mounted thermal profiling
PPA	polyphosphoric acid
RAP	reclaimed asphalt pavement
RAS	recycled asphalt roofing shingles
RTFO	rolling thin-film oven
RTR	recycled tire rubber
SBR	styrene-butadiene rubber
SBS	styrene-butadiene-styrene
SHA	state highway agency
SHRP	Strategic Highway Research Program
SMA	stone-matrix asphalt
TAC	time available for compaction
VCA	voids in coarse aggregate
VFA	voids filled with asphalt
VMA	voids in mineral aggregate
WMA	warm-mix asphalt

Notice

1 Introduction

Truck traffic on highways has evolved significantly in terms of weight and axle configuration over the decades. With an ever-increasing volume of trucks on the nation's highways, increasing truck legal load limits, higher tire pressures and use of "super single" wide-base tires, there is a growing emphasis on using strategies that mitigate pavement deterioration to retain pavement smoothness over a longer period of time. One of the design strategies to meet this goal is to use heavy-duty asphalt pavements and mixtures.

Material selection, mixture design, structural design, and construction practices are important for the efficient design of heavy-duty asphalt mixtures and pavements. In addition, a realistic assessment of current and future truck loadings is essential to achieve the desired performance from the asphalt mixture and pavement. Specifications and methodology for designing mixtures for heavy-duty, high-stress applications vary among agencies in the United States.

For the asphalt mixtures to perform as desired, they must be properly designed and constructed. The design should include proper material selection, aggregate sizing and gradation, mixture design, and structural design. More importantly, the mixture and structural design processes must be compatible or integrated to ensure the asphalt mixture and pavement structure can withstand the high-stress application imposed by increasing vehicle weights, tire pressures, and truck volumes.

Definition of Heavy-Duty Mixes

Following are two definitions of heavy-duty pavements:

- The Asphalt Institute (AI) defines heavy-duty pavements as those that carry heavy vehicles (like log-hauling trucks, dump-body haulers, forklift trucks, etc.) with large wheel loads and unique tire configurations that cannot be designed using standard pavement design procedures (AI, 2007).
- The European Asphalt Pavement Association (EAPA) definition of heavy-duty pavements also encompasses facilities that carry static loads of over approximately 1 N/mm^2 (145 psi), such as

A railway freight yard, such as the CSX Total Distribution Services Inc. (TDSI) facility in Birmingham, Alabama, is typical example of an area that requires a heavy-duty pavement. *(Photo courtesy Dunn Construction)* container terminals, airfields, industrial sites, and parking areas (van der Heide, 1995).

The Superpave mixture design system defines asphalt mixtures for heavy-duty applications as dense-graded, asphalt paving mixtures containing a nominal maximum aggregate size (NMAS) between ¾ inch (19 mm) and 1.5 inches (37.5 mm). This definition focuses on specific aggregate size because the size of the aggregate relative to the asphalt lift thickness was considered as a major contributor to mixture strength, particularly at slow loading rates (Davis, 1988).

However, more recent research and experience has shown that aggregate gradation is more important than aggregate size in ensuring stone-on-stone contact of the larger aggregate particles.

For example, Kandhal & Cooley Jr. (2002) tested both fine- and coarse-graded asphalt mixtures for their resistance to rutting. Both the 9.5 mm and 19 mm mixtures exhibited good resistance to rutting. Similarly, Greene & Choubane (2016) tested different thicknesses of a 4.75 mm mixture at the Florida Department of Transportation (DOT) accelerated test facility. The 4.75 fine-graded mixture exhibited less rutting and cracking than the 12.5 mm control mixture.

As a final example, Christianson & Bonaquist (2007) reported on the mixture design and performance of an asphalt overlay placed at the Coors Brewing Co. packaging facility in Elkton, Virginia, in 2003. Assessed 2.5 years later, the fine-graded 19 mm asphalt overlay was exhibiting good performance under 150 heavy trucks per day moving at speeds less than 5 mph.

Heavy-duty asphalt mixes are used in pavements subjected to severe loading conditions. Severe loading conditions include heavy wheel loads, a large number of heavy load repetitions, slow-moving or static loads, and/or high tire contact pressures. As such, the definition of heavy-duty asphalt mixtures and pavements for this document is:

Heavy-duty asphalt mixtures and pavements are those that can withstand high stress imposed by large wheel loads (greater than 7,000 lbs. (3,175 kg) per tire), high contact pressures (greater than 140 psi (965 kPa)), and/or high truck volumes (greater than 50 million trucks) without exhibiting load- and non-load-related pavement deterioration within the design period.

Need for Heavy-Duty Mixes

Heavy-duty asphalt mixes are needed in any pavement structure that is subjected to severe loading conditions or high stresses (Acott, 1986). Heavy-duty roads include pavements subjected to a large number of repetitions of heavy vehicles, such as industrial haul roads, major arterial roads, and most roads in the interstate highway system. Due to the greater use of super single and radial tires, average truck tire pressures now exceed 120 psi (828 kPa) and, in some cases, 150 psi (1,035 kPa) tire pressures have been reported. A higher tire pressure means the load is distributed over a smaller contact area.

Asphalt mixtures and layers are designed to resist these higher stresses and to reduce those stresses to an acceptable level for the underlying layers. Pavements supporting extremely heavy loads must have a well-designed asphalt–aggregate mixture, especially in the surface course and intermediate asphalt layers, that meets the requirements of higher compaction levels, as well as have sufficient layer thickness to protect all unbound layers and the subgrade from over-stressing those layers.

In addition to high design traffic values, there are certain areas of the road network that deserve special attention. These include facilities subject to heavy, slow-moving, channelized traffic and areas where severe braking or lateral stresses are applied. These locations can include truck climbing lanes, approaches to traffic lights and intersections, off-ramps, bus terminals, truck stops, port facilities, and designated specialized haul routes, such as Critical Commerce Corridors.

Airports also require heavy-duty asphalt mixtures and pavements. Airfield pavements require a strong, smooth, skid-resistant, and durable surface free of debris or other particles that can be blown or picked up by propeller wash or jet blast (FAA, 2016). Material specifications for dense-graded asphalt mixtures used for airfield pavement surfacing are provided by the Federal Aviation Administration (FAA) in Advisory Circular No. 150/5320-6F (FAA, 2018).

Asphalt mixtures for runways and major-use areas typically have a NMAS of ¾ inches (19 mm) or 1 inch (25 mm). The heavier wheel loads, tire pressures often exceeding 200 psi (1,380 kPa), and number of wheel applications all require special consideration in the pavement and mixture design. The key areas in airports are main taxiways, aprons, and the ends of runways. These areas carry the slow-moving, channelized aircraft loads (Acott, 1986).

There are several other "off road" areas that require special consideration. These include facilities at ports, railway yards, container terminals, warehouses, mining and log-hauling routes, industrial material handling areas, and military facilities. Pavements in these areas are subject to a wide variety of vehicles and service conditions, ranging from high-punching shear effects of static loading imposed by the small dolly wheels of a trailer to massive body-dump haul vehicles whose gross weight may exceed 180,000 lbs. (81,700 kg) (Acott et al., 1988).

Modern transportation infrastructure, such as intermodal freight transport facilities, consist of pavements designed to handle extremely heavy traffic loads in order to reduce cargo handling and freight transportation times. Examples of intermodal facilities built with heavy-duty asphalt pavements include the BNSF Railway Co. intermodal facility in Memphis, Tennessee, which was designed to handle 1 million freight containers per year, and the Port of Huntsville Global Logistics Park facility in Alabama, which was designed to handle more than 200 million pounds of air-to-rail cargo transit.

Most of the facilities requiring heavy-duty asphalt mixtures and pavements can be classified into four categories, defined in Table 1-1 along with the primary design factor for each. The more difficult design condition is when multiple categories exist for a specific facility and/or use. Port facility pavements, for example, are designed for very heavy wheel loads, high contact stress concentrations, and slow-moving vehicles, while truck lanes for tollways and Critical Commerce Corridors are designed for heavy wheel loads, high truck volumes, and high speeds.

Objective of This Document

The objective of this publication is to provide a state-of-the-practice for the material selection, mixture design, structural design, and construction of asphalt mixtures and pavements used under heavy truck traffic or specialized loading conditions.

The publication also consolidates and updates various documents, standards, and specifications related to heavy-duty pavements in a concise format. Some of these publications specifically address large-stone mixtures and aggregate sizing, the use of polymers, and other additives commonly used to provide higher strengths for heavy-duty asphalt mixtures.

The document also provides information about mixture design, binder selection, and construction challenges associated with large-stone mixtures and other asphalt mixtures for heavy-duty pavements.

It contains information regarding structural design to ensure sufficient layer thickness to prevent load-related fatigue cracks and to protect all unbound layers, including the subgrade, from distortion caused by heavier tire loads and greater truck volumes.

Table 1-1. Category of Facilities for Heavy-Duty Mixtures and Pavements

Facility Category	Defined	Primary Factor to Consider
High Speeds	Greater than 75 mph (121 km/h)	Surface smoothness
High Truck Volumes	Greater than 50 million trucks	Total asphalt layer thickness
High Stress Concentrations	Greater than 140 psi (965 kPa)	Asphalt mixture strength
High Wheel Loads	Greater than 7,000 lbs. wheel load (3,175 kg)	Supporting layer stiffness

2 A Brief History of Heavy-Duty Mixtures

The use of asphalt as a binder and a construction material dates back to the 18th Century (Davis, 1988). The use in the form of what today is referred to as hot-mix asphalt (HMA) dates to a series of patents filed by Frederick J. Warren in 1901 for a material he termed "Bitulithic," which included a combination of asphalt, sand, and stone. Patent No. 727,505, issued to Warren in 1903, showed an excellent understanding of the principles of asphalt pavement design.

The patent specified a top aggregate size of 3 inches (75 mm) that was graded for maximum density and stability or strength. The high density and the large stone reduced the optimum asphalt content of the mixture, which reduced its cost. The high stability made it possible to compact the pavement to less than 2 percent air voids without causing deformation of the pavement under the heaviest loads (Davis, 1988).

Today, this material is referred to simply as an asphalt pavement mixture, which encompasses several types of bituminous materials, including warm-mix asphalt (WMA), polymer-modified asphalt (PMA), and recycled tire rubber (RTR) asphalt.

By 1910, the increasing number of cars in the United States was having an impact on road building. Water-bound macadam pavements had given good service under horse-drawn vehicles, but the faster-moving automobile traffic stripped the fine aggregate. Not only were the clouds of dust objectionable, but the loss of fine aggregate resulted in the loosening of the larger stones and the subsequent disintegration of the pavement. The use of asphalt binder, particularly in HMA, overcame these types of problems.

In the 1960s, Heukelom & Klomp (1964) showed that as the volume concentration of coarse aggregate in a mixture increased, so did the mixture stiffness. Stiffer asphalt mixtures were being required or specified because of higher truck volumes and loads. Davis (1988) advocated the use of large stones in heavy-duty mixtures to overcome the stresses imposed by heavy loads.

As an asphalt technologist with Koppers Co.,

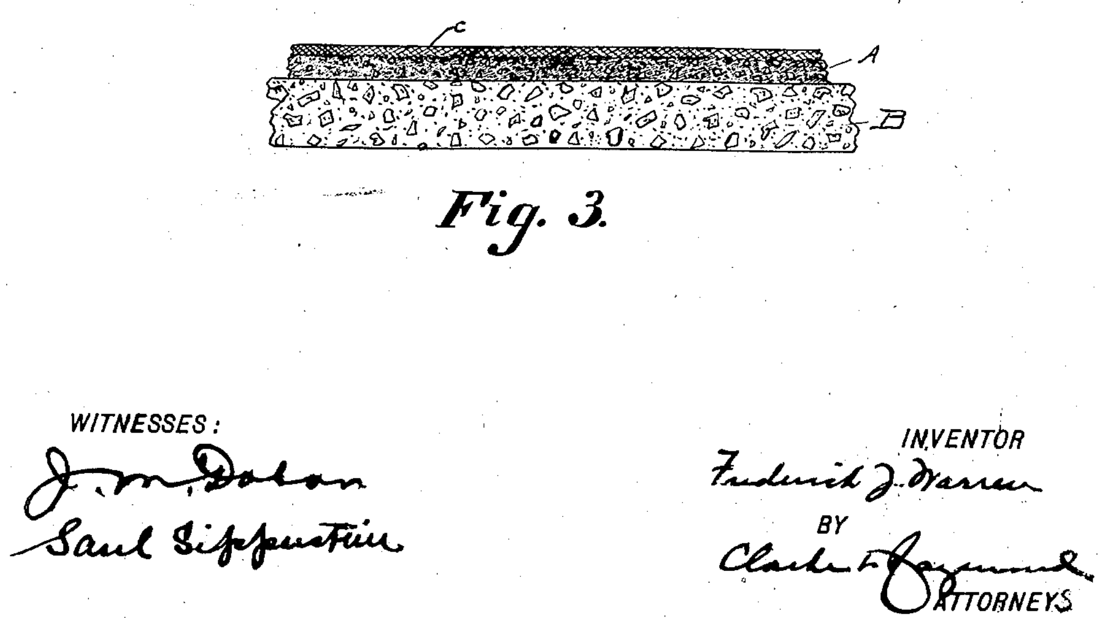


Illustration from U.S. Patent No. 727,505 issued to Frederick J. Warren in 1903 showing the pavement cross section and the interplay between aggregates and binder in creating a strong pavement structure.

Davis found that "…if one wanted to support heavy loads, the volume of hard stone should be maximized while the asphalt should be used to fill the interstices and waterproof and bind the stones together. It was apparent that the gradation of the stone was the key to increasing the volume concentration of the stone" (Davis, 1988). Davis found that to increase the volume concentration, one should start with the largest pieces of stone and introduce increasingly smaller sizes.

In the 1970s and 1980s, some agencies reported an increase in rutting and distress along interstate roadways. The National Cooperative Highway Research Program (NCHRP) and the Federal Highway Administration (FHWA) sponsored research to address this concern. In particular, NCHRP Project 09-06(1), the "Asphalt–Aggregate Mixture Analysis System (AAMAS)," focused on the interaction between mixture and structural design to address the increase in distress (Von Quintus et al., 1991). Later, NCHRP Project 04-18, "Design and Evaluation of Large-Stone Mixes and Guidelines for Construction of HMA Incorporating Large-Stone Mixes," focused on reducing rut depths (Button et al., 1997).

While the use of large-stone mixtures was not new, there was a concern that aggregate size had become more important than aggregate sizing. Research from the Strategic Highway Research Program (SHRP) from the late 1980s to the early 1990s proved that the stiffness of the binder was also an important factor in resisting deformation and cracking from heavy loads. Specific mixtures — generally PMA and stone-matrix asphalt (SMA), which includes polymer-modified asphalt, mineral filler, and fibers — increase the toughness of the mixture and are commonly used today in facilities with heavy wheel loads of slow-moving vehicles.

Individual agencies, like the Utah Department of Transportation (DOT), have investigated the use of polymers and other materials to reduce cracking and rutting in extreme climates with severe loading stress conditions caused by slow-moving trucks through mountainous terrain. For these high-stress loading conditions, Utah DOT decided to use PMA in all layers, rather than just in the wearing surface (Peterson & Anderson, 1998).

Similarly, SMA has been found to be a very tough wearing surface mixture. DOTs in Georgia, Maryland, Michigan, Texas, and other states are using SMA mixtures for high volume and high wheel load roadways because of their excellent performance. SMA has also demonstrated success as an ungrooved runway surface at high-volume airports.

In summary, the design strategy of using heavy-duty asphalt mixtures and pavements has been around for a long time. The design criteria, specifications, and performance tests, however, have changed to increase the reliability and/or reduce the risk of premature distress developing under high-stress loading conditions. The following chapters of this document summarize the criteria, recommendations, and "lessons learned" from the successes and research projects to design and build heavy-duty asphalt mixtures and pavements to retain their structural integrity and smoothness under high-stress loading conditions over the design period.

3 Structural Design Considerations

An asphalt pavement's ability to carry heavy loads is governed by selection of materials to design a well-performing mixture, as well as the selection and design of an adequate pavement structure. Table 1-1 identifies the load-related design parameters or performance measures considered most critical to the long-term performance of heavy-duty pavements and high-stress mixtures. The structural layers play a vital role in handling the stresses and strains that a pavement experiences under repetitive traffic loads, multiple wheel load configurations, high tire pressures, and thermal cycles.

A brief overview of various pavement structural design methods is included in the sections that follow, along with the primary design parameters for each of the heavy-duty pavement categories. A detailed description of these procedures is beyond the scope of this publication.

Layer Thickness Design Procedures

Pavement thickness design procedures are generally grouped into two categories:

1. Empirical-based procedures, like the 1993 American Association of State and Highway Transportation Officials (AASHTO) Guide for the Design of Pavement Structures (AASHTO, 1993).
2. Mechanistic-empirical (ME) based procedures, like the AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) and its associated AASHTOWare® Pavement™ ME Design software (AASHTO, 2015).

A third category is a fully mechanistic procedure. Fully mechanistic procedures have not been adopted by any agency to date and are not covered within this publication.

Table 3-1 lists some of the thickness design procedures in terms of whether they are applicable to the different heavy-duty pavement categories outlined in Tables 1-1 and 3-1. The following provides a brief discussion on the applicability and use of existing thickness design procedures relative to the different heavy-duty pavement categories.

Empirical-Based Design — 1993 AASHTO

The initial AASHTO design procedure was developed from a series of road experiments conducted by the American Association of State Highway Officials

Table 3-1. Category of Facilities for Heavy-Duty Mixtures and Pavements

Design Procedure	Facility Category			
	High Speeds	High Truck Volumes	High Stress Concentrations	High Wheel Loads
1993 AASHTO[1]	✓ < 50 mph (80 km/h)	✓ < 2 million ESALs		
Shell	✓	✓		
MS-23	✓	✓	✓	✓
PerRoad	✓	✓	✓	✓
FPS21	✓	✓		
CalME	✓	✓	✓	✓
AASHTOWare Pavement ME Design	✓	✓	✓	✓

[1] The 1993 AASHTO Guide for Design of Pavement Structures is listed above to provide a relative comparison to the other ME-based design procedures. The total number of trucks in developing that procedure do not meet the definition of heavy-duty asphalt mixtures included in Chapter 1.

(AASHO) from the late 1950s to early 1960s in Ottawa, Illinois. The design process takes into account several factors affecting pavement design, such as the surface type (flexible asphalt or rigid portland cement concrete), material properties, subgrade soils, traffic loads and load equivalencies, thickness design, and pavement performance.

The AASHO Road Test results led to a thickness design procedure that involves determining the required thickness of various pavement layers from empirical equations or charts (also referred to as nomographs). The asphalt layer thickness is obtained from a regression equation developed from the AASHO Road Test as a function of the pavement's structural number, reliability, allowable drop in pavement serviceability, and resilient modulus of the subgrade. From the time the original design reports were issued, the AASHO design procedure evolved through a series of projects in the 1970s, 1980s and 1990s into the 1993 AASHTO Design Guide for Pavement Structures (i.e., 1993 AASHTO Design).

The design procedure is based on the concept of selecting a layer structure and design parameters to achieve a structural number such that the predicted load carrying capacity of the pavement (in terms of equivalent single axle loads or ESALs) equals or exceeds the estimated traffic (Timm et al., 2014). The load equivalency concept, however, does not accurately account for high tire pressures, super single tires, and multi-axle configurations. Heavy-duty pavements are often designed to account for atypical axle and wheel configurations using PMA or SMA mixes and other design aspects not covered by the 1993 AASHTO Design method. More importantly, the total truck traffic applied at the AASHO Road Test was about 2 million ESALs, which is significantly less than the truck volume for heavy-duty pavements (refer to Table 1-1 and Table 3-1). As such, empirical design methods, like the 1993 AASHTO Design procedure, are not recommended for heavy-duty mixtures and pavements.

ME-Based Thickness Design

The Asphalt Institute MS-23 (AI, 2007) and Shell (1978) methods are some of the earliest analytical or ME-based procedures developed to calculate the required thickness of pavement structural layers. For a given design traffic, the thickness of the

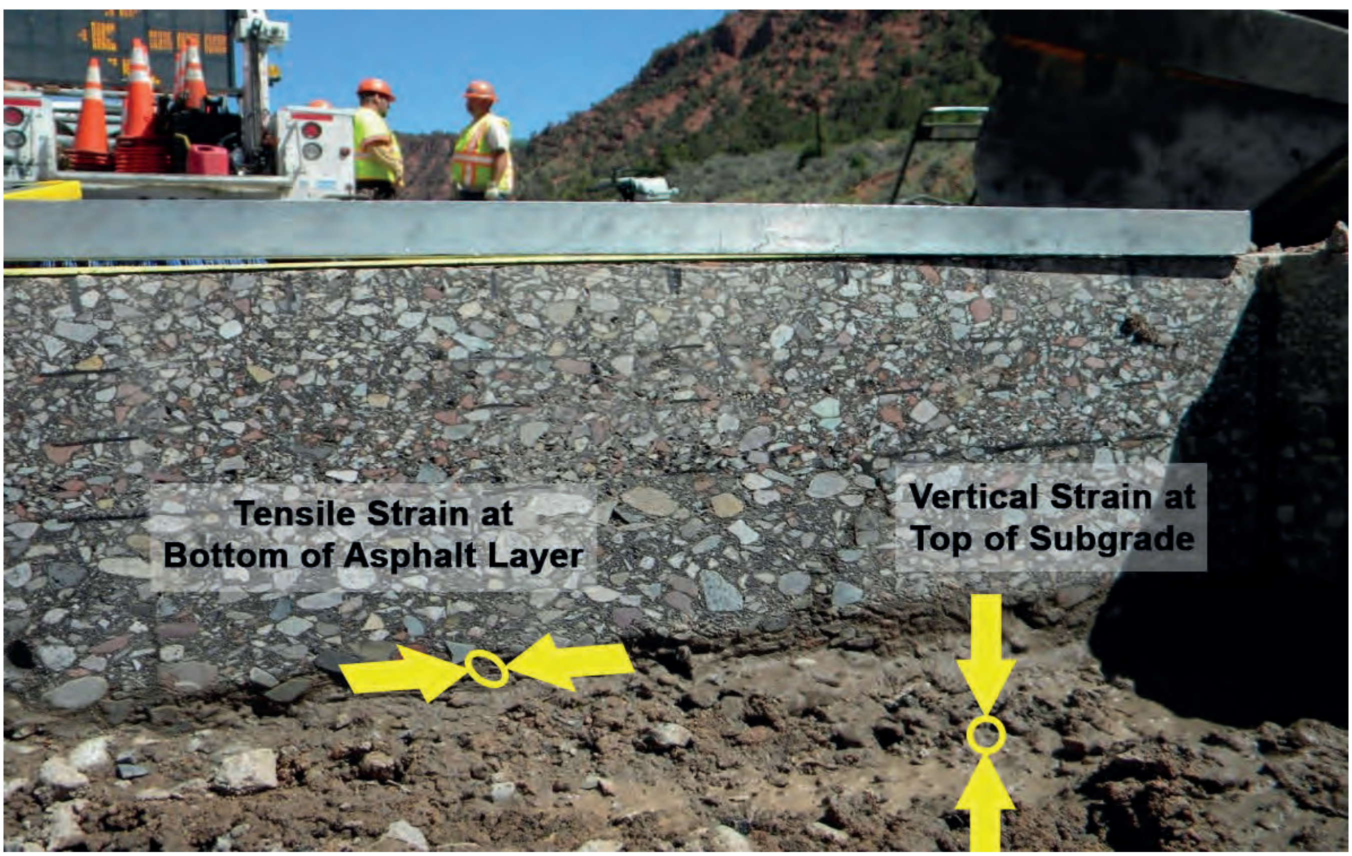


Figure 3-1. Location of Critical Strains in a Full-Depth Asphalt Pavement

asphalt layer is selected such that two critical pavement responses — tensile strain at the bottom of the lower asphalt layer and vertical strain at the top of subgrade — are controlled within acceptable limits to limit the amount of cracking and deformation in the embankment and subgrade layers.

For a given mixture type and number of load applications, the horizontal tensile strain is used to control fatigue cracking (cracking starting at the bottom of asphalt layer); whereas, excess deformation in the subgrade is controlled by the vertical compressive strain at the top of the subgrade soils. The location of the critical horizontal and vertical strains is shown in Figure 3-1. For heavy-duty pavements, the values of these strains can be calculated with a reasonable degree of accuracy, assuming the mixture property of stiffness is accurately estimated.

The initial ME-based procedures focused more on determining the layer thickness using standard dense-graded asphalt mixtures. Most of those procedures simply assumed that the difference in the asphalt elasticity or dynamic moduli could explain any difference in resistance to cracking and rutting. This assumption is reasonable but inappropriate for the non-conventional or specialized asphalt mixtures specified for heavy-duty asphalt pavements.

There have been significant changes in highway, air, and freight traffic composition over the past few decades in terms of traffic volume, gross vehicle weights, and axle and tire configurations. Vehicles having much higher gross weights and wheel loads, as well as different wheel spacing characteristics, do not permit the use of standard thickness design methods and/or the use of design catalogs.

Some of the pavement design methods have been updated to address changes in truck traffic composition. The AI MS-23 ME-based design method contains a procedure for calculating design thickness of asphalt pavements for heavy wheel loads (AI, 2007), while the more advanced design methods, such as the NCHRP Project 01-37A MEPDG (ERES, 2004) procedure and the Perpetual Pavement design procedure (Newcomb et al., 2010), include the capability to consider varying truck weights, axle configurations, and other truck parameters.

Table 3-2 lists some of the ME-based procedures available for the design of heavy-duty pavements, including the Flexible Pavement Design System 21 (FPS 21) and Texas Mechanistic-Empirical Thickness Design System (TxME) developed at the Texas A&M Transportation Institute for Texas DOT; CalME developed by California DOT and the University of California Pavement Research Center; PerRoad Perpetual Pavement design software developed at Auburn University; and FAA Rigid and Flexible Iterative Elastic Layered Design (FAARFIELD).

As shown, all the ME-based design procedures in Table 3-2 consider bottom-up alligator fatigue cracking, while only a few consider smoothness degradation and top-down fatigue cracking. All ME-based design methods use a “transfer function” to predict the distress magnitude measured on the pavement surface from critical pavement responses. In other words, the transfer function ties the calculated

Table 3-2. Pavement ME-Based Design Procedures for Predicting Load-Related Distresses Considered for Heavy Duty Pavement Facilities

Design Procedure	Rut Depth	Bottom-Up Fatigue Cracking	Top-Down Fatigue Cracking	Smoothness, IRI
Shell	✓	✓		
MS-23	✓	✓		
PerRoad		✓		
FPS 21	✓	✓		
TxME	✓	✓		
CalME	✓	✓	✓	✓
AASHTOWare Pavement ME Design	✓	✓	✓	✓
FAARFIELD	✓	✓		

mechanistic response to the amount of cracking and rutting measured at the pavement surface.

As noted above, most of the ME-based thickness design methods use a constant set of fatigue cracking and rutting constants for all asphalt mixtures and only the modulus of the asphalt mixture is used to explain the difference in fatigue cracking and rutting. The AASHTO (2015) MEPDG Design Guide is one of a few procedures where the fatigue cracking and rutting coefficients of the distress transfer functions can be measured in the laboratory and used in the AASHTOWare Pavement ME Design software, integrating mixture design with structural design. A practitioner's guide is available for preparing test specimens, testing the specimens, and interpreting the test results to determine the laboratory-derived coefficients of the distress transfer functions for fatigue cracking and rutting (Bonaquist, 2019; Von Quintus & Bonaquist, 2019). This guide is useful for measuring the distortion and fracture properties for mixtures selected for use in heavy-duty pavements and mixtures (refer to "Integration of Structural & Mixture Design" in this chapter).

ME-based thickness design procedures can be further grouped into two categories:

- Fatigue cracking failure-based methods, which include Shell, MS-23, CalME, FPS 21, and AASHTOWare Pavement ME Design.
- Perpetual or long-life based methods, which include PerRoad, CalME, and AASHTOWare Pavement ME Design.

The difference between these two groups is that the fatigue cracking failure-based methods determine the asphalt layer thickness for which the area of alligator fatigue cracks will be less than some threshold value or percent area of cracking at the end of the design period. The Perpetual Pavement methods, referred to as long-life designs, determine the minimum asphalt layer thickness so that alligator fatigue cracks do not occur within or after the design period. The Perpetual-based methods determine the layer thickness so that the calculated tensile strain at the bottom of the lowest asphalt layer is less than the endurance limit.

The fatigue endurance limit (FEL) is defined as the tensile strain below which no fatigue cracking damage accumulates with continued truck loadings. However, recent research conducted at the National Center for Asphalt Technology at Auburn University (NCAT) has shown increased strains in the field can be larger than the FEL, so long as the adjusted cumulative strain distribution falls below the limit (Tran et al., 2016).

Perpetual Pavement Thickness Design

The Asphalt Pavement Alliance (APA) defines Perpetual Pavement as an asphalt pavement designed and built to last longer than 50 years that requires only periodic surface renewal without the need for major structural rehabilitation or reconstruction (Newcomb et al., 2010). Failure-based methods, such as FPS 21, the MEPDG, and other ME-based pavement design procedures, require a pavement thickness to handle heavy truck loads and number of loading applications, but require a structural layer or overlay to be added at the end of the design period. Perpetual Pavement design involves determining a pavement thickness that can sustain the heaviest traffic loads over an extended design life without additional structure.

The objective of the Perpetual Pavement design procedure is to ensure distresses such as cracking and rutting occur only at the surface. Thus, only minimal corrective measures through surface rehabilitation are needed at the end of the pavement life cycle. Perpetual Pavements have lower life-cycle costs, lower environmental impact, and reduced user-delay costs than flexible pavements designed using empirical and ME failure-based design methods.

Perpetual Pavements can be designed as high modulus pavements, where the base and intermediate layers consist of a very stiff asphalt mixture with high binder content and low air voids (Leiva-Villacorta et al., 2017). The high stiffness of the base layer leads to lower total thickness of the pavement and reduced material costs, resulting in a more sustainable design (Rodezno et al., 2018). Full-depth pavements that consist of asphalt layers on compacted or treated subgrade, as well as deep-strength pavements that consist of asphalt layers on a granular base, can also meet the requirements for Perpetual Pavement design.

For Perpetual Pavements, there are limiting strains, the FEL, below which structural damage does not accumulate in the pavement layers (Prowell et al., 2010; Bateman, 2012; Witczak et al., 2013; Tran et al., 2016). Facilities that require heavy-duty pavements are subjected to wheel loads that cause much higher strains, and therefore significantly greater damage than standard trucks transporting goods on the interstate system within the legal load limit. Perpetual

Pavements are an excellent choice for structural design of pavements at such facilities, where the heaviest loads can be estimated with a high degree of certainty.

Most of the early studies used a single value for the FEL, but few reported reasonable correlations between the laboratory-derived FEL and field-measured strains or observed cracking. Tran et al. (2016), however, observed a large difference in the cumulative tensile strain distribution at the NCAT Test Track between sections that exhibited fatigue cracking and those sections that did not exhibit cracking. A cumulative strain distribution was derived based on the percent of measured strains less than or equal to a specific strain level. As such, Tran et al. (2016) suggested the use of the strain distribution concept and criteria based on field-measured strains for which no fatigue cracking occurred.

All types of asphalt pavements, however, need to be designed to resist the detrimental impact of frost-susceptible soils and soils with high volume change potential. Most of the ME-based methods do not include predictions or estimates of frost heave and volume change of the underlying soils. The subgrade site condition factors are considered separately and discussed in Chapter 4.

Pavement layer thicknesses should be selected such that strains from the heaviest anticipated loads are below the threshold but do not result in an overdesigned pavement structure. Thicker pavements designed using this methodology are also effective at limiting structural rutting in the pavement, which is the permanent deformation of underlying granular base and subgrade layers. Remediation of structural rutting is a very expensive process, typically requiring major rehabilitation or reconstruction of the pavement.

The Perpetual Pavement design procedure developed by Von Quintus for the state of Michigan (Von Quintus, 2001) used limits on predicted distresses as the design criteria instead of limiting strains. Other design methods, such as PerRoad, CalME, and FPS 21, were also developed for designing Perpetual Pavements. The AASHTOWare Pavement ME Design software includes the endurance limit as an input value. The MEPDG Manual of Practice (AASHTO, 2015), however, recommends that the endurance limit not be used, because calibration of the fatigue

Because of heavy industrial truck traffic in the corridor, Glendale Avenue in Washoe County, Nevada, was reconstructed in 2018 with nearly 49,000 tons of a 19 mm NMAS mix. *(Photo courtesy Granite Construction Co.)*

cracking transfer function excluded use of the endurance limit. The reason AASHTOWare Pavement ME Design software was included in the above list is that the design threshold value or criterion for alligator cracking can be set to 1 percent over the design life, meeting the definition of a long-life pavement.

Critical Pavement Responses for Design

The following section summarizes the critical pavement responses used for predicting pavement performance measures and/or designing the asphalt pavement structure. For more detailed information on how the specific design procedures were developed and their mathematical functions, consult the specific references for each method.

Bottom-Up Alligator Fatigue Cracking

All the ME-based thickness design procedures included in Table 3-2 use the calculated tensile strain at the bottom of the lower asphalt layer to limit the area of bottom-up fatigue cracks. Some procedures (like the Shell method) use an annual temperature and asphalt layer modulus to calculate the critical tensile strain, while others (CalME and AASHTOWare Pavement ME Design) use the monthly temperatures and asphalt layer modulus values to calculate the tensile strain at the bottom of the asphalt layer on a periodic or monthly basis.

Top-Down Fatigue Cracking

Top-down cracking is a major concern today, but it has been exhibited on asphalt pavements for many decades. Top-down cracks start at or near the surface of the wearing surface and propagate downward. Such cracking may only propagate a few inches or less below the surface, where they can be easily mitigated by a mill-and-overlay project; however, if left unaddressed such cracking may grow. Many projects where cores have been drilled at the crack, however, show the surface-initiated crack can propagate deeper, as seen in Figure 3-2. There is general consensus within industry that top-down cracks are caused by high-stress conditions (high tire pressures, excessive tire loads) in combination with selected asphalt mixture properties (stiff or brittle mixtures, accelerated aging or hardening of the asphalt at the surface, greater air void gradients, low adhesion between the larger stone particles and asphalt, low tensile strength, etc.).

The AASHTOWare Pavement ME Design is the only design method to consider and predict the area and length of top-down fatigue cracks. The procedure developed under NCHRP Project 01-52 uses fracture mechanics to predict the timing and length of top-down longitudinal cracks (Lytton et al., 2018). The procedure calculates the time at which the top-down cracking starts, the growth of these cracks along the pavement surface, and the time needed to propagate the surface-initiated cracks through the asphalt layer. The tensile stress or opening mode and shear stress at the crack tip determine how fast and to what depth the crack propagates.

Figure 3-2. Location of Critical Strains in a Full-Depth Asphalt Pavement

Rut Depth

All the ME-based thickness design procedures included in Table 3-2 use the calculated vertical or compressive strain in the asphalt layers to limit the rut depth and/or protect the subgrade soil from overstresses. The vertical strain is calculated at the mid-depth of the asphalt layer for some procedures

(Shell), while others (AASHTOWare Pavement ME Design and CalME) calculate the vertical strain at different depth intervals throughout the asphalt and unbound layers. AASHTOWare Pavement ME Design and CalME calculate the vertical strains incrementally within all the pavement layers and subgrade at specific depth increments to limit plastic deformation or rutting in the individual layers.

Other ME-based procedures simply assume the unbound aggregate base layers will be properly constructed so that no significant rutting will occur in the underlying layers. Some of the procedures (Shell) only use the vertical compressive strain at the top of the subgrade as a limiting value to ensure structural rutting does not occur in the subgrade. This limiting subgrade vertical strain criterion is dependent on the resilient modulus of the subgrade soil.

IRI or Smoothness Degradation

The more recently developed ME-based design procedures (for example, the AASHTO MEPDG Design Guide) consider the increase in roughness with time, as measured by the International Roughness Index (IRI). AASHTOWare Pavement ME Design predicts IRI over time based on site factors in combination with the occurrence of other distresses (rut depth, fatigue cracking, and transverse cracking). Some methods calculate IRI using an empirical regression equation based on properties of the pavement structure and subgrade, as well as site condition features, such as climate. The ME-based Michigan and FHWA procedures used the calculated mechanistic response of deflection to predict IRI over time (Baladi, 1989; Kenis, 1977).

Integration of Structural & Mixture Design

Implicit in structural design procedures is the assumption that the asphalt and other pavement layers will be designed and constructed to ensure the pavement will not deform excessively. This is controlled through proper materials selection, good mixture design, and proper construction techniques. In addition, there may be other functional requirements such as resistance to indentations from container stacking, resistance to tracked vehicles, or resistance to turning operations and abrasive forces (Acott, 1986).

Taken in isolation, a mixture may be designed properly and perform well under ordinary conditions but may require adjustment to perform well under heavy or unique loading conditions (refer to Table 1-1).

The traditional approach to mixture design has been to select a mixture with characteristics that strike a balance among factors, such as:

- Stability and stiffness or the ability to resist deformation.
- Fatigue resistance or the ability of the mixture to bend frequently without cracking.
- High strength or the resistance of the mixture to tensile fracture or cracking.
- Compliant mixtures or the ability of the mixture to recover from thermal stresses; good relaxation properties.
- Durability or the ability of the mixture to retain good properties over time and resist aging and stripping in the presence of water.
- Low permeability or the ability of the mixture to resist accelerated aging.
- Skid resistance or the resistance to polishing.

The structural design for conventional and heavy-duty asphalt pavements is usually completed prior to, and in some cases years before, the mixture design process, except on design–build projects. As such, the layer properties used in structural design must be assumed or extracted from a library of asphalt mixtures and other layers.

For heavy-duty asphalt mixtures and pavements, it is important that the properties assumed and used in the structural design be confirmed, at a minimum. This confirmation process for unique loading conditions is determined through integration of the structural and mixture design processes (Von Quintus & Hall, 2016).

Selecting proper materials and designing a mixture that will be resistant to high-stress conditions is covered in the next two chapters of this document. The approach for most design procedures is a compromise in which only some properties are optimized. Thus, for heavy wheel loads, this approach may not provide an adequate margin of safety.

By recognizing that certain distress levels can be reduced by good structural design, emphasis can be focused on controlling the most critical parameters in the mixture design process. It is therefore essential to integrate mixture and structural design and to translate the integration into the selection and proportioning of raw materials. There is also a need to define how parameters from the structural design process are confirmed in designing mixtures for heavy-duty pavements (Acott, 1986; Von Quintus & Hall, 2016).

4 Layer Stiffness Properties & Factors for High-Stress Loading

Two pavement distresses used in designing asphalt pavements are rutting and cracking. Rutting refers to plastic deformation of the pavement layers and subgrade due to repeated application of wheel loads. Rut depths are depressions in the wheel path with varying depth and can become worse in the presence of a weaker underlying layer (e.g., a subgrade with low modulus).

Pavement cracking can be either load induced or non-load related. Load-induced cracking includes bottom-up fatigue cracking, also referred to as alligator cracks, and top-down cracking, typically referred to as longitudinal cracks. Non-load related cracking or transverse cracks occur from high thermal stresses in the asphalt surface layer caused by cooling cycles that exceed the mixture's tensile strength.

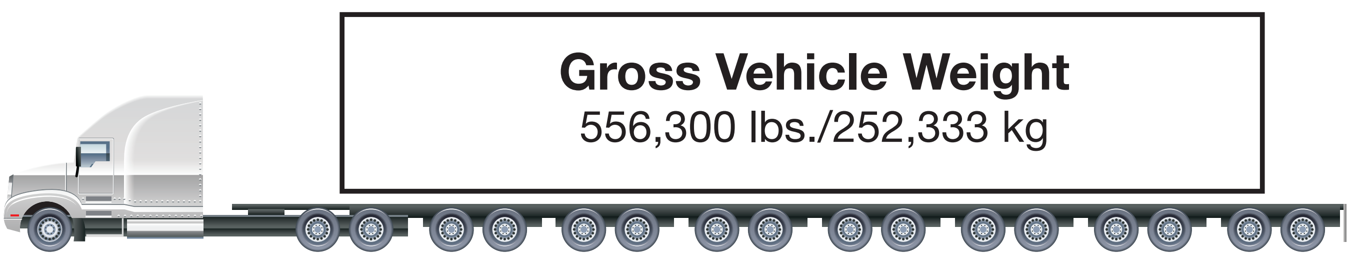
Chapter 3 listed the critical pavement responses used in many of the ME-based pavement design procedures, and they are listed below for reference:

- Tensile strain at the bottom of the lower asphalt layer for bottom-up fatigue cracks.
- Tensile stress at the surface adjacent to the edge of the tires for top-down fatigue cracks.
- Tensile stress at the surface for thermal or transverse cracks.
- Vertical compressive strain at various depths in the asphalt and unbound layers for rutting.
- Vertical compressive strain at the surface of the subgrade for rutting in the subgrade and fatigue cracking in the asphalt layer.

The use of stiffer or higher moduli for all pavement layers reduces the tensile strain and vertical compressive strain in any layer. The use of materials/layers with higher moduli is preferred for heavy-duty pavements, except for when addressing top-down fatigue and transverse thermal cracks. For these distresses, the wearing surface should be more compliant or have good relaxation properties with higher tensile strengths.

In summary, the pavement layers should have:

- Adequate stiffness (high modulus) to resist rutting.
- Sufficient thickness to handle bending forces from heavy wheel loads.
- Sufficient asphalt binder and high density in the asphalt mixture to prevent early occurrence of both rutting and fatigue cracking and to reduce permeability.
- High fatigue strength and low air voids/high density of the asphalt base layer to resist fatigue cracks.
- Adequate tensile strength and compliance or relaxation properties of the wearing surface to prevent the early occurrence of thermal or transverse cracks.
- Sufficient support from the pavement substructure to minimize fatigue cracking and deformation.



Trailer Weight per Tire = 7,720 lbs./3,502 kg
Tractor Steer Axle Weight per Tire = 8,050 lbs./3,651 kg
Tractor Drive Axle Weight per Tire = 5,738 lbs./2,603 kg
Dual Tire Spacing = 30 inches/0.76 m
Tandem Axle Spacing = 59 inches/1.5 m
Vehicle Speed = 5 mph/8 km/h
Tire Pressure = 125 psi/862 kPa

Figure 4-1. Megaload Truck

It should be noted that the mixture-related properties listed above are the same mixture characteristics listed in Chapter 3, emphasizing the need to tie mixture to structural design for heavy-duty pavements.

Due to the viscoelastic nature of asphalt binder, it exhibits lower stiffness at high temperature and low rate of loading (slow movement of traffic). The critical loading condition for any viscoelastic material is heavy wheel loads that are moving slowly down the roadway or facility. Megaload trucks and vehicles for handling containers within a port facility are examples of this loading condition, as shown in Figure 4-1 and Figure 4-2. These types of vehicles and loads impose high stresses on the surface, throughout the asphalt layers, high bending stresses and strains at the bottom of the lower asphalt layer, and high compressive stresses and strains in the unbound aggregate base and subgrade layers.

Under these conditions, it is important that the aggregate skeleton structure have a suitable gradation with good quality aggregate held together by a sufficient quantity of binder. In addition to gradation and quality, shape of the aggregate also plays a major role in providing sufficient interlock to the aggregate skeleton. Angular aggregates are required over rounded or semi-round aggregates as they have a larger number of fractured surfaces, providing a better interlock and thus higher strength to the mixture. In addition, the unbound layer needs to have a high resilient modulus and compressive strength.

The following sections discuss some of the material requirements for the unbound and asphalt layers under heavy loading or high-stress conditions.

Subsurface Layers — Aggregate Base & Subgrade

The parameters needed for structural design of heavy-duty pavements are no different than for conventional pavement design projects. The foundation is characterized to provide support to the pavement structure as part of the design process. Layered resilient modulus (specifically, resilient modulus or approximations of the modulus of elasticity or Young's modulus) is the property needed for pavement design and analysis. Support characterization, as used in this context, refers to the process of determining the properties of the existing soil and other unbound layers that make up the pavement structure. These include the surface layers, base and subbase layers, and other special pavement features.

The only difference in terms of design for heavy-duty pavements is that the wheel loads can be much higher, so they have a larger impact on the underlying unbound layers, including the subgrade. The basic difference or added requirement for the design of heavy-duty asphalt pavements is that a minimum support resilient modulus should be specified. Minimum support conditions are needed to ensure the pavement structure has sufficient thickness to reduce the stresses to an acceptable level, as well as to provide sufficient support to the upper layers to limit the deflections of the pavement. The minimum design resilient moduli for the different unbound layers are:

- 15,000 psi (103,421 kPa) for embankment soil layers
- 25,000 psi (172,369 kPa) for crushed stone or aggregate base layers

Relative compaction of subgrade soils should be at least 95 percent of standard Proctor test for cohesive or higher plasticity soils and 95 percent of modified Proctor test for cohesionless or non-cohesive soils. Higher densities result in higher resilient

Figure 4-2. A Straddle Carrier-Style Container Handling Vehicle
(Photo courtesy Port of Tacoma)

moduli and compressive strengths, making the layer more resistant to deformations. When compacting the subgrade to a lower percentage of compaction, a thicker aggregate base and embankment layer are needed to lower the vertical compressive strains in the subgrade. Figure 4-3 shows the recommended depth of subgrade corresponding to percent compaction for both cohesionless and cohesive soils as a function of an equivalent single wheel load. It is better practice to increase the resilient modulus of the layers and subgrade supporting the asphalt layers, rather than increase the thickness of the crushed aggregate base and/or embankment layers to account for lower resilient moduli for heavy-duty pavements.

Similarly, crushed stone or aggregate base layers should be compacted to 100 percent of modified Proctor to support heavy wheel loads and trucks. Higher densities of an aggregate base increase the resilient modulus and compressive strength, providing adequate support for placing and compacting the asphalt layers.

The horizontal and vertical variations in subsurface soil types, moisture contents, densities, and water table depths must be considered during the pavement design process. The AASHTO MEPDG Manual of Practice provides information on the subsurface exploration and to identify problem soils that need to be treated prior to placing the pavement structure (AASHTO, 2015). Proper treatment and preparation of the subgrade soil (or foundation) is extremely important for a long-lasting pavement structure, especially for heavy-duty asphalt pavement structures.

The following provides a summary of the problem soils that need to be treated for heavy-duty pavements.

It is important to identify any saturated soil strata, the depth to ground water, and subsurface water flow between soil strata. Subsurface water is especially important to recognize and identify in the transition areas between cut and fill segments. If allowed to saturate unbound base/subbase materials and subgrade soils, subsurface water can decrease the strength and modulus of these materials and soils significantly. Significant reductions in strength can result in premature surface depressions, rutting, or cracking. Seasonal moisture flow through selected soil strata can also significantly magnify the effects of differential volume change in expansive soils. Cut areas are particularly critical for subsurface water.

Collapsible or highly compressible (very weak) soils are susceptible to large settlements and deformations with time that can have a detrimental effect on pavement performance. If these compressible soils are not treated properly, large surface depressions with random cracking can develop. The surface depressions can allow water to pond on the pavement's surface and more readily infiltrate the pavement structure, compounding an already severe problem.

Swelling or expansive soils are susceptible to volume change (shrink and swell) with seasonal fluctuations in moisture content. The magnitude of this volume change is dependent on the type of soil (its shrink–swell potential) and its change in moisture content. A loss of moisture will cause the soil to shrink, while an increase in moisture will cause it to expand or swell. This volume change of clay-type soils can result in longitudinal cracks near the pavement's edge and significant surface roughness (varying swells and depressions) along the pavement's length.

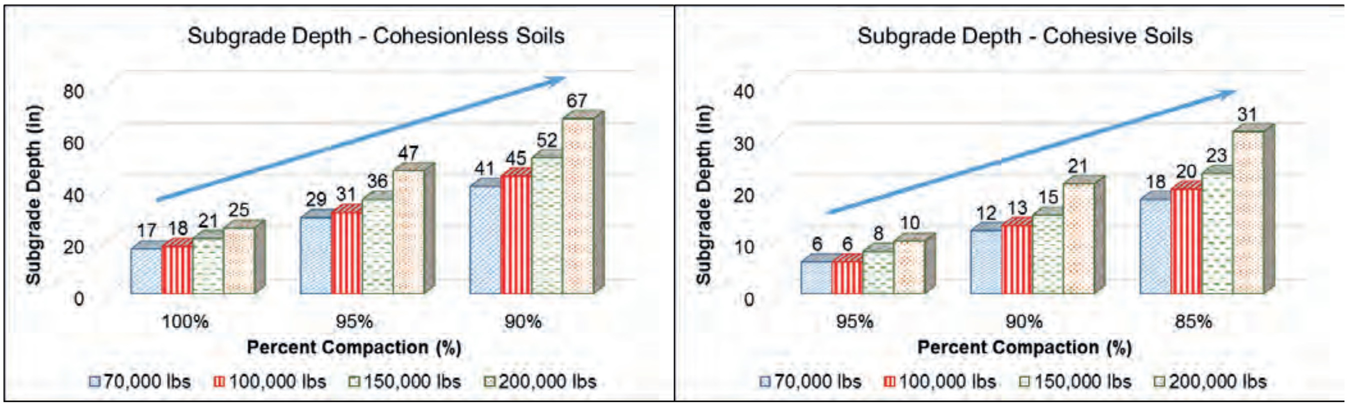


Figure 4-3. Recommended Subgrade or Embankment Depth for Cohesionless Soils (left) and Cohesive Soils (right)

Frost action can cause differential heaving, surface roughness and cracking, blocked drainage, and a reduction in bearing capacity during thaw periods. These effects range from slight to severe, depending on types and uniformity of subsoil and the availability of water. One effect of frost action on pavements is frost heaving caused by crystallization of ice lenses in voids of soils containing fine particles.

Types of Asphalt Mixtures/Layers

For heavy-duty pavements, the asphalt mixture should have medium to high stiffness because a mixture with higher stiffness resists rutting better than a mix with low stiffness. Stiffness of the mixture is controlled by the quality, volume and gradation of aggregate in the mixture, asphalt binder properties (binder grade), binder quantity by volume of the mixture, and mixture density.

Mixture density is an important parameter for all asphalt layers because the higher the density and the lower the air voids of the mixture, the stiffer and more resistant the mixture is to the occurrence of distress (distortion or fracture-type distresses). The more important asphalt layer properties required for heavy-duty mixtures are dependent on the depth or location of the asphalt layer in the pavement structure, which are summarized below:

- **Wearing surface** — high density, low air voids (less than 6 percent), low permeability, compliant mixture with good relaxation, high tensile strength, and high stability. Asphalt mixtures with these properties include SMA and PMA.
- **Intermediate asphalt layers** — high density and medium to high stiffness.
- **Base layer** — high density, high stiffness, low air voids (less than 4 percent), low permeability, and high fatigue strength. Asphalt mixtures with these properties include coarse-graded, high fatigue strength, and PMA mixtures.

Modified Binders/Mixtures

Modifiers are added to the asphalt binder to improve material properties for the desired application, for example to increase stiffness at higher temperatures. These are chemical compounds that affect the molecular structure of asphalt and its constituents, improving its handling and pumping at the mixing facility as well as its placement and performance in the pavement. Various types of modifiers can be added to the asphalt binder to achieve the desired properties (AI, 2001a).

Polymer modifiers are compounds added to reduce rutting and improve fatigue and thermal cracking resistance of the mix. The most commonly used polymers are styrene-butadiene rubber (SBR) and styrene-butadiene-styrene (SBS). Utah DOT conducted a field study in 1998 and made a decision to use polymer modifiers in all asphalt mixtures placed in high-stress areas (Petersen & Anderson, 1998). The Asphalt Institute sponsored a study to compare the performance (fatigue cracking, rutting, and transverse cracking) of neat asphalt and PMA mixtures. The study reported PMA mixtures were significantly more resistant to all forms of distress (Von Quintus et al., 2003). Colorado DOT sponsored a similar study, which came to the same conclusion (Von Quintus & Mallela, 2005).

Plastomers like low-density polyethylene (LDPE) and ethylene-vinyl acetate (EVA) may also improve rutting resistance of the mixture.

Chemical modifiers like polyphosphoric acid (PPA) can be used in combination with polymers to increase stiffness of the mix at high temperatures. The Asphalt Institute sponsored a study to evaluate and compare the performance of asphalt mixtures with and without PPA. The study found no significant difference in performance when small amounts of PPA were used to increase the stiffness of the mixture (Von Quintus, 2014). Too much PPA, however, can result in very stiff binders susceptible to moisture damage and cracking. Some state agencies specify a maximum amount of PPA and others restrict the use of PPA in asphalt mixtures, because of the reported increase in moisture damage and cracking at some locations. Users of heavy-duty mixes should refer to the local state agency regarding use of PPA in asphalt mixtures.

RTR is an elastomer obtained from ground tires. RTR is primarily used to address rutting. Two processes can be used to produce RTR mixtures: binder modification or mixture modification. For mixture-modified RTR mixes, the crumb rubber is added to the asphalt mix; for binder-modified RTR mixes, the crumb rubber is blended with the asphalt binder. Binder-modified RTR is most commonly used in today's market. Mixture-modified RTR is more difficult to use and control in dense-graded mixtures and its properties are dependent on the size of the rubber particles.

Along with modifiers that improve rutting and cracking resistance, anti-strip agents can also be added to a mixture to make it less susceptible to moisture damage and to increase durability. The two most widely used anti-strip agents are liquid additives and hydrated lime. Many agencies require the use of hydrated lime in high-stress areas. The use of an anti-strip agent is warranted by high moisture susceptibility of the mixture as identified through performance testing, such as the indirect tensile strength ratio (AASHTO T 283) or may be prescribed in an agency's mixture design specifications.

Recycled/Reclaimed Asphalt Materials

Asphalt pavements are the most recycled product in the United States and increasing amounts of recycled material have been used in the construction of new pavements over the past decade. Use of reclaimed asphalt pavement (RAP) reduces construction costs by replacing virgin aggregates and lowering the required amount of virgin asphalt binder. It also has a positive environmental impact by diverting materials from landfills and putting waste and byproducts to productive use.

Asphalt binder is reclaimed from two sources — RAP collected from old asphalt pavements through maintenance and repair operations and recycled asphalt roofing shingles (RAS). The National Asphalt Pavement Association (NAPA) surveys asphalt mixture producers annually regarding the use of recycled materials. During the 2017 construction season, more than 76 million tons of RAP and nearly 1 million tons of RAS were used in new asphalt pavement mixtures (Williams et al., 2018). Other waste materials and byproducts, such as recycled tire rubber, blast furnace slag, steel slag, cellulose fibers, fly ash, and foundry sand, are also regularly used in pavements.

Use of higher percentages of RAP and RAS can be cost-effective and environmentally friendly, as well as have engineering benefits, such as improving rutting resistance. As such, the use of RAP/RAS can be advantageous in heavy-duty asphalt mixes. Recycled asphalt binder, however, is stiffer than virgin or new binders because of its prolonged prior exposure to the environment. The percentage of recycled material in a mixture depends on several variables, such as properties of the recycled material (RAP, RAS, or a combination of both), properties of virgin binder

The heavy-duty lots at the Amazon Distribution Facility in Chesterfield Township, Michigan, made use of up to 40 percent RAP in the binder and surface layers. *(Photo courtesy Cadillac Asphalt, a CRH Co.)*

and aggregates, mixture design specifications, and mixture production technology (i.e., traditional hot-mix asphalt versus warm-mix asphalt technologies).

Some state specifications allow asphalt mixtures to contain up to 70 percent RAP under certain conditions. In practice, however, a maximum of 25–50 percent RAP is more common for several reasons, including supply limitations and maintaining an efficient quality control system. Some state agencies have set limits on the amount of RAP and/or RAS that can be included in different asphalt layers due to concerns that increasing RAP/RAS may reduce the fracture resistance and durability of the mixture.

To reduce the potential detrimental impact of severely aged binder from RAP and RAS, softening or recycling agents are increasingly used. Recycling agents are chemicals added to the recycled material to lower the viscosity of the aged binder to improve its workability and blending with virgin binder. Even with the use of these agents, some agencies restrict the percentage of RAP/RAS in the wearing surface because higher percentages of the recycled material may make the mixture less compliant and more susceptible to transverse cracks and top-down cracking.

The practice of using RAP in mixtures incorporating larger size aggregate is similar to the design of conventional mixtures. As with any use of RAP, the gradation and asphalt content of the material must be known and controlled within strict limits (Brown et al., 2009). RAP in Superpave mixture design was evaluated in NCHRP Project 09-12, "Incorporation of Reclaimed Asphalt Pavement in the Superpave System" (McDaniel & Anderson, 2001), to understand how the recycled material interacts with virgin binder and aggregates when blended in different percentages.

McDaniel & Anderson (2001) reported RAP does not act like a black rock; instead, regardless of the stiffness of the binder, RAP contributes to the overall mixture. West et al. (2013) continued research into the use of RAP in asphalt mixtures relative to mixture design practices. Results from these studies suggest low contents of RAP (25 percent or lower) do not significantly change the asphalt binder and mixture properties and that RAP can be used directly as an aggregate replacement without characterizing the recovered binder.

When a higher percentage of RAP (greater than 25 percent) is used, however, the asphalt binder from RAP stockpiles needs to be recovered and tested to develop blending charts to determine the required PG grade of virgin asphalt binder. This step is important for heavy-duty mixes as an exceptionally stiff mixture with a high RAP content and poor virgin binder selection can result in premature fatigue and/or transverse cracking.

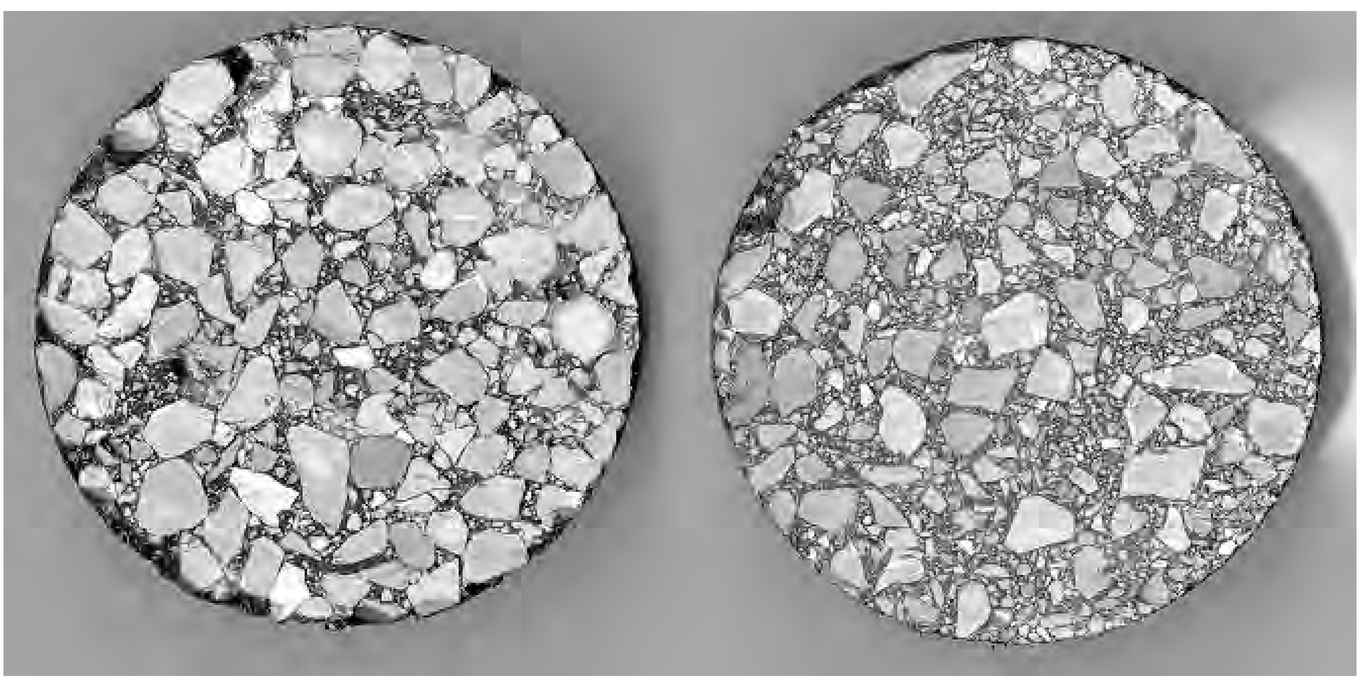


Figure 4-4. Aggregate Gradations With and Without Stone-on-Stone Contact

Warm Mix Asphalt

WMA refers to a range of technologies and processes of producing and placing asphalt mixture at temperatures lower than conventional production temperatures. Additives such as asphalt viscosity modifiers (e.g., paraffin wax), chemical additives, or foaming the asphalt binder with water are used to achieve the temperature reduction. Similar to RAP and RAS, the quantity of asphalt mixture produced using WMA technologies has also increased considerably over the past decade. Many contractors use WMA technologies with and without temperature reduction as a compaction-aide to increase the density of the asphalt mat (Williams et al., 2018).

WMA is associated with higher initial costs related to the materials (in case of additives) and equipment (asphalt foaming device), but the costs are offset by economic and environmental benefits. Lower production and lay-down temperatures lead to several benefits such as:

- Reduced fuel costs for heating aggregates
- Reduced emissions
- Extended construction season
- Allow materials to be hauled over longer distances
- Allow higher percentage of recycled or reclaimed asphalt materials (RAP and RAS)

Approximately 150 million tons of asphalt mixtures were produced using WMA technology in the year 2017, making up about 39 percent of the total estimated asphalt market (Williams et al., 2018). Plant-produced foamed asphalt accounted for nearly 65 percent of all WMA mixtures, while chemical additive technologies accounted for 32 percent of the mixtures. Although there has been an increase in the use of the WMA technology over the past decade, many producers still use the production temperatures associated with HMA. As noted above, WMA is used as a compaction aide in these conditions.

WMA technologies like foaming and certain chemical additives that induce water into the asphalt mix can cause the mixture to undergo less aging than conventional HMA. This can result in a mixture with lower stiffness that may be susceptible to rutting. No studies have reported increases in moisture damage or stripping of WMA even when the foaming method was used. Heavy-duty pavements require an asphalt mixture with higher stiffness to prevent excessive rutting. Therefore, use of an anti-strip additive is recommended when using WMA for heavy-duty mixtures to improve the asphalt–aggregate bond when higher percentages of RAP are used to increase mixture stiffness.

NMAS & Minimum Asphalt Layer/Lift Thickness

The NMAS relative to layer thickness plays an important role in mitigating strains caused by heavy loads and high tire pressures (Brown & Bassett, 1990; Mahboub & Allen 1990). Multiple references support the use of large-sized aggregate to ensure the load is carried by the stone. However, aggregate sizing or the gradation of the aggregate blend plays a more important role.

Figure 4-4 shows two 19 mm NMAS mixtures. The mixture on the left exhibits stone-on-stone contact, while the mixture on the right does not. In other words, the larger aggregate particles in the mixture on the right are floating in a "sea of fines." These aggregate blends (right) are susceptible to rutting or do not exhibit the benefit from the larger aggregate particles in comparison to the gradation shown by the gap-graded aggregate blend on the left.

Another factor considered for heavy-duty and conventional mixtures is to maintain a minimum lift thickness to NMAS ratio of 4:1. As the NMAS increases, the lift thickness increases. Brown et al. (2004) researched the impact of lift thickness and NMAS on in-place air voids and mix permeability. They found that as the lift thickness to NMAS ratio increased, there was a corresponding decrease in the in-place air voids and permeability of the mix. Thus, the higher the ratio, the lower the air voids and permeability, which will increase pavement performance. The lift thickness to NMAS ratio, however, should not exceed 6:1, especially when using larger-sized aggregate.

Using thicker lift thicknesses provides a secondary benefit in that the mat retains higher temperatures for longer periods of time, extending the time available for compaction and helping to achieve higher and more uniform mat densities. The benefit of compacting the mat to higher density levels cannot be overstated, because higher densities increase the mixture's tensile strength, stiffness, fatigue strength, and rutting resistance.

5 Material Selection & Requirements

Materials used in the asphalt surface and underlying layers of heavy-duty pavements should provide adequate support for heavy wheel loads. Heavy-duty mixtures should be designed to handle not only the high stresses exerted by wheel loads on the pavement, but to also withstand thermal stresses due to extreme weather conditions. Mixture design is therefore dependent on three primary factors:

1. Location where the mixture is to be placed (mitigating effect of climate);
2. Weight and speed of the wheel loads; and
3. Number of heavy wheel load applications.

It is common practice to select materials for use in heavy-duty mixtures in accordance with an agency's standard specifications and then to adjust them for traffic and climatic conditions.

Asphalt binder and aggregate tests and specifications are used to determine the material's ability to handle heavy traffic and limit pavement distresses. These material component tests play an important role in determining the requirements for heavy-duty mixtures as part of the mixture design process, discussed in Chapter 6. This chapter provides guidance for selecting the asphalt binder, aggregates, and sizing. Inclusion of recycled materials in the asphalt mixture and use of additives and modifiers to improve the mixture properties for resisting distortions and cracking were discussed in Chapter 4.

Aggregate Properties

Aggregates used in heavy-duty mixtures should satisfy rigorous quality requirements, as the aggregate skeleton is responsible for carrying the traffic load. Superpave and FAA specifications both require coarse and fine aggregate particles to satisfy quality characteristics related to shape, texture, durability, and absorption. For Superpave aggregates, SHRP researchers identified rutting as the major distress

Table 5-1. Coarse Aggregate Properties

Coarse Aggregate Property	Superpave Specification	FAA Specification
Maximum to minimum dimension ratio, percentage of particles with ratio (ASTM D4791)	< 10% with ratio 5:1	< 8% with ratio 5:1 < 20% with ratio 3:1
Crushed faces, min. percentage of particles with 2 or more fractured faces[1] (AASHTO T 326)	> 30M ESALs: 100% 10–30M ESALs: 90% > 4 in. (100 mm): 80%	< 60,000 lbs. (27,200 kg): 50% > 60,000 lbs. (27,200 kg): 75%
Crushed faces, min. percentage of particles with at least one fractured face[1] (AASHTO T 326)	> 30M ESALs: 100% 10–30M ESALs: 90% > 4 in. (100 mm): 80%	< 60,000 lbs. (27,200 kg): 65% > 60,000 lbs. (27,200 kg): 85%
Durability — L.A. abrasion test, percentage loss of weight for heavy-duty mixes (AASHTO T 96)	< 30%	< 40%
Soundness — Percentage loss of weight after 5 cycles of sulfate immersion (AASHTO T 104)	Sodium sulfate: < 15% Magnesium sulfate: < 20%	Sodium sulfate: < 12% Magnesium sulfate: < 18%

[1] Specification for percentage particles with crushed faces is provided for traffic level (Million ESALs) or asphalt layer thickness by Superpave and for aircraft gross weight by FAA

affected by aggregate quality, while fatigue cracking and low-temperature cracking were less affected. The Superpave aggregate properties were divided into two categories: (1) consensus properties that include criteria determined during the SHRP program through wide agreement between pavement experts, and (2) source properties that are specific to the aggregates used in a mixture.

Coarse Aggregate Properties

Coarse aggregate is defined as particles larger than 3⁄16 inch (4.75 mm). For heavy-duty pavements, it is desirable that the coarse aggregate be obtained from crushed stone, crushed slag, or crushed gravel. It should be free of deleterious material, weathered and disintegrated particles, and should be uniform in quality. Table 5-1 shows a summary of coarse aggregate properties according to Superpave and FAA specifications for use in heavy-duty pavements.

Shape

Aggregate particles that have a cubical shape and rough surface texture impart better strength to the mixture. Flat and elongated particles are not desirable as they have a tendency to break during construction and under traffic. Coarse aggregate shape also affects skid resistance of the asphalt surface. Particles with cubical shape provide better skid resistance compared to flat and elongated particles.

According to the Superpave mixture design consensus specifications, coarse aggregate for all traffic levels should not have more than 10 percent of particles with a maximum to minimum dimension ratio of 5:1. The FAA specifications state that no more than 8 percent of coarse aggregate particles should have a ratio greater than 5:1, and no more than 20 percent should be greater than 3:1.

Crushed Faces

Aggregates in a heavy-duty mixture are required to have several fractured faces, as a greater degree of coarse aggregate angularity (CAA) provides better interlock and stability. According to ASTM D5821, 100 percent of coarse aggregates used in an asphalt mix for traffic volumes greater than 30 million ESALs should have at least two fractured faces (AI, 2015).

Some states that rely heavily on crushed gravel have reduced this requirement to greater than 95 percent with two or more fractured faces to avoid rejecting good sources of coarse aggregates. For an estimated traffic level of 10 million to 30 million ESALs, asphalt layers 4 inches (100 mm) within the surface should have coarse aggregates that are 95 percent one fractured face and 90 percent two or more fractured faces. For asphalt layers deeper than 4 inches (100 mm) from the surface, the requirements are 85 percent one fractured face and 80 percent two or more fractured faces.

CAA specifications by the FAA are based on aircraft gross weight. For pavements designed to carry aircraft with gross weight 60,000 lbs. (27,200 kg) or more, coarse aggregates should have 85 percent one fractured face and 75 percent two or more fractured faces. For lighter aircraft, the requirement is reduced to 65 percent one fractured face and 50 percent two or more fractured faces.

Durability

Coarse aggregates for heavy-duty mixtures should be durable enough to resist abrasion and mechanical degradation during handling, construction, and service, as well as resist damage due to climatic factors. Toughness is evaluated using two test criteria — abrasion loss and soundness. Abrasion loss is measured as a percentage loss of material by weight due to abrasion by steel spheres during the Los Angeles (L.A.) Abrasion test (AASHTO T 96 or ASTM C131). Soundness is the percent loss of material from an aggregate sample during a sodium or magnesium sulfate soundness test (AASHTO T 104 or ASTM C88). In this test, the loss of material by weight is measured by immersing an aggregate sample into a sulfate solution and drying it, repeating the process for several cycles.

Superpave specifies that coarse aggregates should not lose more than 30 percent of weight from the L.A. Abrasion test. The requirement for heavy-duty mixes is lower than the range of typical maximum loss values of 35–45 percent, which indicates the significance of high durability. FAA requires that the percentage of wear should not be greater than 40 percent.

The soundness test is performed to estimate the resistance of both coarse and fine aggregates to in-service weathering. Maximum loss of coarse aggregate particles by weight should not be more than 15 percent after five cycles of sodium sulfate conditioning, and no more than 20 percent after five cycles of magnesium sulfate conditioning (AASHTO T 104). Under similar testing conditions, FAA specifies that the sodium sulfate soundness loss should not exceed 12 percent and the magnesium sulfate soundness loss should not exceed 18 percent.

Fine Aggregate Properties

Fine aggregate for heavy-duty pavements can be produced by crushing stone, slag, or gravel. The fine aggregates should have good durability and soundness and should be clean and free from organic matter and clay. Table 5-2 shows a summary of fine aggregate properties according to Superpave and FAA specifications for use in heavy-duty pavements.

Fine Aggregate Angularity

Highly angular fine aggregate ensure good internal friction and rutting resistance. Angularity of fine aggregates is defined in terms of percent air voids in loosely compacted aggregate particles smaller than 2.36 mm, according to AASHTO T 304. A high air void content indicates highly angular aggregates. The Fine Aggregate Angularity test (AASHTO T 304) has been demonstrated to be a measure of the angularity and is preferred over the descriptive terms of "natural" or "crushed" sands. A minimum value of 45 percent should be used to assure adequate angularity of the fine aggregate.

Natural sand can be used under certain conditions in limited quantities to obtain the required gradation of the aggregate blend. Natural sands normally increase workability and compactability of the mixture, but an excessive amount of sands tends to decrease stability and stiffness of the mixture.

For heavy-duty mixtures, natural sand content has often been limited to 15 percent by mass of the aggregate blend to minimize the potential for rounded sands to act like "ball bearings" in the mixture, making it weak and susceptible to distortion and lateral flow.

Soundness

Soundness loss of fine aggregates should not exceed 15 percent using sodium sulfate conditioning and 20 percent using magnesium sulfate conditioning after five cycles. The corresponding soundness loss criteria specified by the FAA for airfield pavement mixes are 10 and 15 percent, respectively.

Table 5-2. Fine Aggregate Properties

Fine Aggregate Property	Superpave Specification	FAA Specification
Fine aggregate angularity (AASHTO T 304 Method A)	Min. 45%	No specification
Natural sand, percentage by mass of aggregate blend	Max. 15%	No specification
Soundness — Percentage loss of weight after five cycles of sulfate immersion (AASHTO T 104)	Sodium sulfate: < 15% Magnesium sulfate: < 20%	Sodium sulfate: < 10% Magnesium sulfate: < 15%
Clay content, percentage by weight of fine aggregates (AASHTO T 112)	0.2 to 10%	Max. 1%
Sand equivalent (AASHTO T 176)	Min. 50%	No specification
Filler and baghouse fines, percentage by weight of blend	0.8 to 1.6%	No specification

Clay Content and Deleterious Material

Aggregates commonly contain clay and other foreign particles that are deleterious to the asphalt mixture. These particles have lower strength than aggregates and deteriorate quickly due to traffic and climatic conditions. The criteria for allowable percentage of deleterious materials in Superpave mixes varies widely from as little as 0.2 to 10 percent, depending on the contaminant. For airfield mixes, the permissible amount of clay and friable particles specified by the FAA is 1 percent by weight of aggregates.

Sand Equivalent

The sand equivalent test is used to determine the relative portions of sand and clay-like particles and dust in accordance with AASHTO T 176. The sand equivalent test is also used to estimate the stripping potential caused by clay and dust that can coat the coarse aggregate, reducing the tensile strength and adhesion between the asphalt and stone particles. The minimum sand equivalent value for high truck volumes (more than 30 million ESALs) is 50 percent.

Filler and Baghouse Fines

Filler refers to very fine material added to the mix to fill the voids in the aggregate matrix to reduce the quantity of the binder required. In addition to acting as a void-filling material, added filler also increases the viscosity of asphalt binder and filler system thereby increasing the stiffness of the total mixture.

Depending on the shape and size, with the reintroduction of more fines from the production facility baghouse, the potential for fines that can act like a binder extender has increased. To produce a medium- to high-stiffness mix, it is beneficial to increase the filler content up to an allowable limit. Care should be taken not to produce an overly rich mix by void filling or binder extension. To assure that a brittle, dry mix is not designed, a limit of from 0.8–1.6 percent (by weight) is sometimes placed on the filler to effective binder content ratio. Additional information on evaluation of baghouse fines is available in NAPA Information Series 127, *Evaluation of Baghouse Fines for Hot Mix Asphalt* (Kandhal, 1999).

Asphalt Binder Selection

Asphalt binder selection for mixture design consists of two steps: (1) selection of asphalt binder grade and (2) selection of asphalt binder content in the mixture. The binder grade determination is covered within this section, while the determination of the asphalt binder content is covered in Chapter 6 on mixture design.

The emphasis of Superpave was to develop tests that ensure mixture performance under different traffic levels and climatic conditions (AI, 2003). The Superpave binder specification and test methods

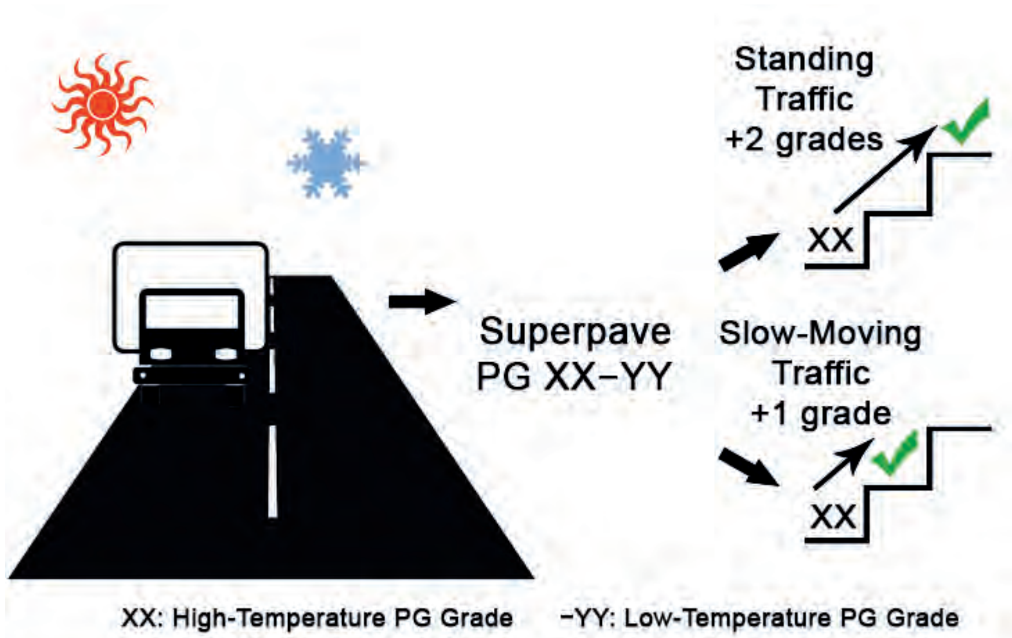


Figure 5-1. Superpave PG Binder Grade Adjustment for Standing and Slow-Moving Traffic

can be used to characterize both neat (unmodified) and modified asphalt binders, and are contained in AASHTO M 320, *Standard Specification for Performance-Graded Asphalt Binder*. These measured properties are related to the behavior of the asphalt mixture during mixing, construction, and service.

Although it is common knowledge today, asphalt is graded as a performance grade (PG) with two numbers representing high and low temperatures in accordance with the Superpave specification. For example, a Superpave binder with grade PG 64–28 satisfies all test criteria or binder properties for performance under climatic conditions with an average 7-day maximum pavement temperature of 64°C and a minimum pavement temperature of –28°C. In order to perform well under heavy loading conditions, the asphalt binder should have sufficient stiffness at high temperatures, which may require increasing the high-temperature PG grade without increasing the low-temperature grade.

The selection of high and low PG grade of the asphalt binder depends primarily on the project location. Asphalt pavements constructed in warmer climates are more prone to rutting compared to other distresses, whereas pavements in colder climates are more susceptible to cracking as a result of loss of flexibility at low temperatures. It should be understood, however, that excessive rutting can occur in cold climates and excessive cracking in warmer climates when proper mixture design and material selection procedures are not followed.

Depending on climatic conditions as well as traffic levels, agencies specify PG binder grade for use in different asphalt layers. Sometimes a softer grade asphalt is used in the lower asphalt layers, because the vertical and horizontal stresses decrease with depth in the asphalt layer. For heavy-duty mixtures higher stiffness is a benefit, so long as the mixture does not become brittle.

Adjustment to the PG high temperature grade for handling heavy loads depends on both the volume and speed of traffic. Superpave requires the selected high temperature PG grade to be increased for slow and standing load applications. The high PG grade for standing traffic (where average traffic speed is 12 mph (20 km/h) or lower) should be two grades higher than the selected grade. The process of increasing the PG for specific truck loading conditions has been referred to as grade "bumping." Also, the high PG grade for slow-moving traffic (average traffic speed between 12 and 45 mph (20 and 70 km/h)) or high traffic volume exceeding 30 million ESALs should be one grade higher than the selected grade (AI, 2001b). The adjustment for standing and slow traffic loads is illustrated in Figure 5-1.

As much as a stiffer binder imparts better rutting resistance to the mixture, Superpave specifications state that binders stiffer than PG 82–YY should be

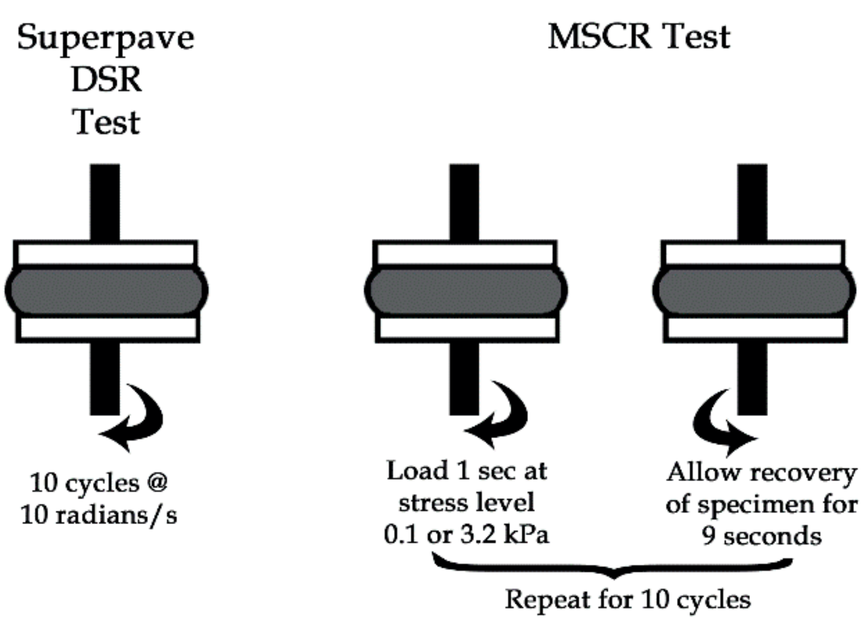


Figure 5-2. Superpave DSR and MSCR Test Procedure

avoided for two basic reasons: production/constructability issues and less flexibility. These hard binders can be difficult to pump during production and difficult to compact without increasing the production temperatures, which can result in more hardening of the binder. If these stiff binders are used, mixture performance tests should be used to estimate the tensile strength, compliance, and fatigue strength. These performance tests are explained in Chapter 6.

The Multiple Stress and Creep Recovery (MSCR) test, AASHTO M 332, was developed as an improvement to the Superpave PG binder grading system. The MSCR test uses the creep and recovery properties of asphalt to determine the binder grade. Multiple stress levels allow for better characterization of polymer-modified binders. Figure 5-2 shows a comparison of the test procedure for Superpave binder test and MSCR test using the dynamic shear rheometer.

Rutting criteria in the MSCR test are evaluated in terms of a parameter called the non-recoverable creep compliance, J_{nr}, which is the ratio of unrecoverable or plastic strain to applied stress. The lower the value of J_{nr}, the stiffer the asphalt binder. The MSCR grading system also eliminates the need for increasing or "bumping" the PG binder grade to account for heavy loads and slow-moving or standing traffic. Based on the MSCR procedure, the Superpave PG grade remains unchanged but is assigned an additional grade (noted with a letter S, H, V, or E) for traffic level or volume based on the J_{nr} value. The difference between Superpave and MSCR grading systems in selecting binder grades for various traffic

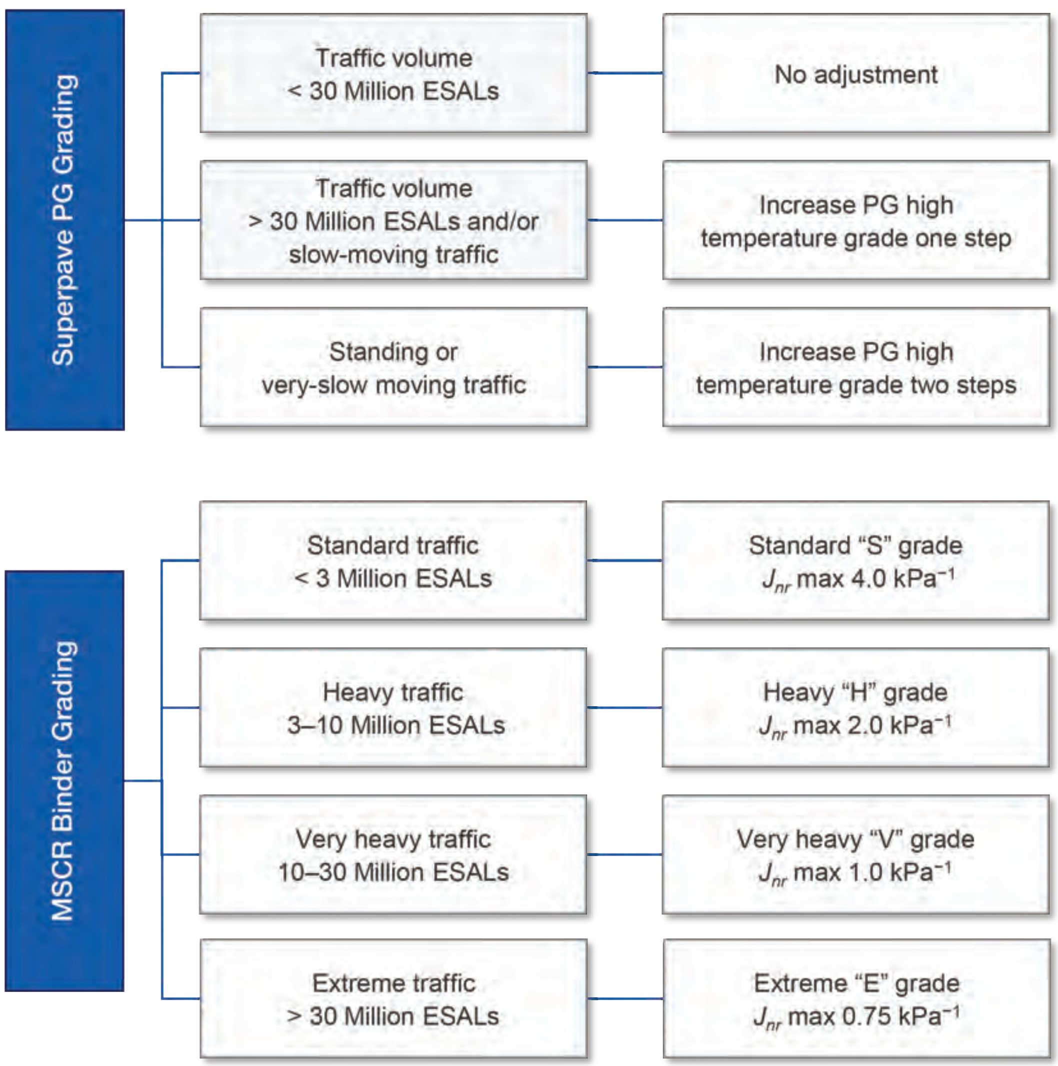


Figure 5-3. Superpave PG and MSCR Binder Grade Adjustments for Heavy Traffic

levels is shown using an example in Figure 5-3.

The truck traffic parameter not directly considered in the MSCR procedure is the speed of slow-moving vehicles, such as megaload trucks (see Figure 4-1), container handling vehicles (see Figure 4-2), and other trucks moving large, heavy loads. No guidance is provided in AASHTO M 332 for selecting the binder grade for slow-moving vehicles under high-stress conditions. For heavy-duty mixtures, the following are recommended for use depending on the heavy-duty facility (see Table 1-1):

- Slow speed and high-stress concentrations — use very heavy grade (V).
- Slow speed and high wheel loads — use very heavy grade (V).
- Slow speed and high wheel loads with high-stress concentrations — Use extreme grade (E).

For design of heavy-duty pavements, the performance graded binder should be compatible with the temperature regime and traffic loading contained in the Superpave design process. Guidance on electing PG binder grades is available in the Asphalt Institute publication SP-2, *Superpave Mix Design* (AI, 2003). Many heavy-duty mixtures use high PMA whose behavior is different from neat asphalt binders. Additives and modifiers used to change rheological properties of the binder are also considered in the asphalt binder-selection process.

For heavy-duty mixtures, a modified binder should increase mixture stiffness at high temperatures to resist permanent deformation, and to maintain the resistance to cracking at low temperatures. An engineering and life-cycle cost analysis should be used to determine which layers, if any, should include a modified asphalt binder to maximize performance for the minimal cost.

Binder grade can also be selected using LTPPBind Online (*https://infopave.fhwa.dot.gov/Tools/LTPPBindOnline*). Part of the LTPP InfoPave suite of tools developed by FHWA, LTPPBind Online helps agencies select the most suitable PG binder for project-specific climatic and traffic conditions. The tool selects the high temperature PG based on a rutting damage model and low temperature PG grade from climatic data at a specified level of reliability. The output from the tool consists of a Superpave PG binder adjusted for traffic and climatic conditions according to the AASHTO M 323-13 procedure, as well as the MSCR PG according to the AASHTO M 332-14 procedure.

Logging trucks are a common heavily laden, multiaxle truck that can increase pavement loading dramatically. *(Photo courtesy Mussi Katz)*

6 Mixture Design for Heavy-Duty Pavements

An asphalt mixture may be designed properly and perform well under ordinary conditions, but given the requirements of a heavy-duty mixture, the same mixture may not perform at all under heavy loads. The traditional approach to mixture design has been to select a mix with characteristics that strike a balance among the multiple factors identified in the discussion of structural and mixture design in Chapter 3.

Asphalt Mixture Design Methods & Specifications

The most commonly used procedure for designing asphalt mixtures is the Superpave method, which was developed as part of the SHRP project in the 1990s. Prior to Superpave, the Marshall method was used by about 76 percent of agencies and about 20 percent used the Hveem procedure (Acott, 1986). Since 2000, however, most agencies have transitioned to the Superpave mixture design procedure. The Superpave design procedure for heavy-duty mixes does not differ in concept from the design of traditional asphalt pavement mixtures.

FAA requires the asphalt mixture in airfield pavements to meet criteria for specific material classes (FAA, 2016). The FAA specifications include criteria for two major categories of asphalt mixes: P-401 for surface courses designed to handle aircraft heavier than 12,500 lbs. (5,670 kg), and P-403 for base or leveling courses and surface courses for aircraft weighing less than 12,500 lbs. (5,670 kg). FAA also specifies material P-601, which is a fuel-resistant surface mixture for use in areas subject to fuel and hydraulic oil spills.

The main steps involved in mix design are: (1) selection of aggregate and asphalt binder (discussed in Chapter 5), (2) determining the blended aggregate gradation, (3) defining the target binder content, (4) deciding whether an anti-stripping additive is needed, and (5) confirming the final mixture will perform as designed. Both the FAA and Superpave methods contain specifications for volumetric properties related to various aspects of production, placement, compaction, and in-service performance. The following sections provide a brief overview of the Marshall, Superpave, and FAA mixture design methods for heavy-duty mixtures.

Modified Marshall Mixture Design Method for Heavy-Duty Large-Stone Mixes

Design of asphalt mixes using the Marshall method involves selecting an aggregate gradation and asphalt binder that yields 4 percent air voids in specimens compacted to a specific number of blows using a hammer. For critical areas that are subjected to heavy traffic, such as intersections, interstate highways, bus stops, tollbooths, etc., an increased compaction effort is required to achieve a higher mixture density. Heavy-duty mixes are compacted to 75 blows, corresponding to a traffic level of greater than 10 million ESALs over a 20-year design life (AI, 2015). This mixture will be more resistant to rutting and shoving due to increased density but may require more rollers during construction. Mix design criteria for heavy-duty mixes also require the mix to have a stability value greater than 1,500 lbf (6672 N) and a flow value between 8 and 16 (measured in units of 0.01 inch or 0.25 mm).

The traditional Marshall method uses a 4-inch (100 mm) diameter mold in which the asphalt mixture is compacted to prepare test specimens. When heavy-duty mixtures designed with aggregates larger than 1 inch (25 mm) are compacted in a Marshall mold, it unduly restricts compaction. The smaller mold size limits the ability to understand the behavior of the larger aggregates that are primarily responsible for providing strength to the mixture.

In the 1980s, Pennsylvania DOT developed a mix design procedure based on the Marshall method that would allow compaction of mixtures containing large maximum size aggregates. This work was the basis for ASTM D5581, adopted in 1994, which was developed for use with a 6-inch (150 mm) diameter mold in the Marshall method (Kandhal, 1990). According to ASTM D5581, the minimum Marshall stability requirement for 6-inch (150 mm) diameter specimens should be 2.25 times the requirement for 4-inch (100 mm) diameter specimens. The allowable range of flow values for 6-inch (150 mm) diameter specimens are adjusted to 1.5 times the values required for 4-inch (100 mm) specimens.

The significant differences in the compaction process from the older procedure are the use of:

- A mold assembly and breaking head to accommodate specimens 6 inches (150 mm) in diameter by 3¾ inches (95 mm) in height.
- A mechanical compaction hammer with a 5⅞-inch (149.4 mm) diameter tamping face, 22.5 lb. (10.2 kg) sliding weight with a free fall of 18 inches (457 mm).
- About 4,500 grams of mix required to prepare one 6-inch (150 mm) Marshall specimen.
- Mixture placed in the mold in approximately four equal increments.
- A compactive effort of 75 or 112 blows per face, which is comparable to 50 or 75 blows of a typical Marshall 4-inch (100 mm) specimen using ASTM D1559 (Brown et al., 2009).

Superpave Mixture Design Method

The Superpave method is a volumetric mixture design process where aggregate and binder are compacted to achieve 4 percent design air void content under a specified level of compaction (N_{des}). A range of 3–5 percent design air void is specified by some agencies, depending upon the climate and pavement layer. For example, Arizona DOT specifies a design air void of 5 percent to include less asphalt in mixtures placed in its hot climates, while Texas DOT recommends a design air void level of 3 percent to include more asphalt for asphalt base layers in its long-life pavements.

Asphalt mixtures designed using the Superpave procedure are required to satisfy volumetric criteria such as air voids at initial and maximum design gyrations, minimum voids in mineral aggregate (VMA), maximum voids filled with asphalt (VFA), and dust-to-binder ratio. The number of gyrations to which the mixture is compacted in a Superpave gyratory compactor depends on the estimated traffic level. A higher number of gyrations is required for higher traffic volumes. Some agencies, however, have reduced the design number of gyrations (N_{des}) originally specified because of premature cracking and durability issues.

Currently, a few agencies use one value of N_{des} for all traffic levels. As such, the mixture should be designed according to specifications set by the local agency, if available, when the Superpave mixture design procedure is used or those contained in the Asphalt Institute publication SP-2, *Superpave Mix Design* (AI, 2001b).

Two more levels of compaction are included in the original Superpave method: (1) initial gyrations (N_{ini}) used to estimate the compactability of the mixture and (2) maximum gyrations (N_{max}) used as a check to safeguard against plastic failure caused by traffic in excess of the design level (AI, 2001b). Table 6-1 shows the recommended compaction levels (N_{ini}, N_{des}, and N_{max} values) for Superpave mixtures at different traffic levels as stated in AASHTO R 35, *Standard Practice for Superpave Volumetric Design of Asphalt Mixtures*. Many state agencies use N_{ini} and N_{des} but exclude N_{max} from their mixture design specifications.

Research has shown that mixtures designed in accordance with the original Superpave method were very resistant to rutting (Brown & Powell, 2007) but susceptible to cracking and durability issues. Some agencies questioned the high number of gyrations, which were believed to be the cause of producing "dry" or low asphalt content mixtures susceptible to cracking.

Another finding from Brown & Powell (2007) was the ultimate in-place density of several Superpave mixtures was higher than the laboratory-compacted density at N_{des} by only about 1.5 percent. The researchers suggested eliminating the N_{max} requirement for the final or ultimate density of the mix because it was not indicative of the mixture's rutting potential. As such, many agencies have eliminated the N_{max} requirement. The compaction levels recommended by Brown & Powell (2007) are included in Table 6-2.

The N_{des} value was further reduced for asphalt with a high temperature grade exceeding 76°C and for mixtures placed 4 inches (100 mm) below the surface. Table 6-2 includes the reduced N_{des} values for those conditions. Superpave mixtures compacted to lower N_{des} gyrations require a higher asphalt content to achieve 4 percent air voids, everything else being equal. The additional asphalt leads to better flexibility, and therefore better fatigue cracking resistance of the mixture.

Further studies using data measured at the NCAT Test Track showed mixtures containing modified asphalt (PG 76–22) exhibited less densification and lower rutting than mixtures containing neat asphalt (PG 67–22). Von Quintus et al. (2012) used the rut-depth data measured on neat and modified asphalt test sections for improving on the rut-depth transfer function included in the AASHTOWare Pavement ME Design software.

In a much earlier study, Von Quintus et al. (1991) used compatibility curves (compaction effort versus air voids) to demonstrate the effect of compaction effort on air voids, as well as density versus asphalt content using multiple compaction devices (Marshall hammer, kneading compactor, gyratory, and vibratory hammer). A lower compaction effort requires more asphalt for the same target air void level using the same aggregate blend. It should be understood, however, the asphalt content selected at the target air void level can be increased or decreased by varying the aggregate blend for a constant compaction effort.

In summary, the N_{des} gyrations included in Table 6-1 were considered too high; the values in Table

Table 6-1. Superpave Gyratory Compactor Levels (AASHTO R 35)

Design Traffic Level (Million ESALs)	Gyration Levels			Percent G_{mm} at N_{ini}	Percent G_{mm} at N_{max}
	N_{ini}	N_{des}	N_{max}		
< 0.1	6	50	75	< 91.5	< 98.0
0.1 to < 1.0	7	75	115	< 90.5	
1.0 to < 30.0	8	100	160	< 89.0	
> 30.0	9	125	205	< 89.0	

Table 6-2. Superpave Gyratory Compactor Levels (Brown & Powell, 2007)

Design Traffic Level (Million ESALs @ 20 yrs.)	N_{des} Number of Gyrations	
	PG < 76	PG ≥ 76 <u>*or*</u> Mixes Placed > 4 in. (100 mm) from Surface
< 0.3	50	N/A
0.3 to < 3.0	65	50
3.0 to < 30.0	80	65
> 30.0	100	80

Table 6-3. Superpave Gyratory Compactor Levels for Heavy-Duty Pavements

Design Traffic Level (Million ESALs @ 20 yrs.)	Gyration Levels						Percent G_{mm} at N_{ini}	Percent G_{mm} at N_{max}
	N_{ini}		N_{des}		N_{max}			
	PG < 76	PG ≥ 76*	PG < 76	PG ≥ 76*	PG < 76	PG ≥ 76*		
< 0.1	6	N/A	50	N/A	75	N/A	< 91.5	< 98.0
0.1 to < 0.3	6	N/A	50	N/A	75	N/A	< 90.5	
0.3 to < 1.0	7	6	65	50	100	75		
1.0 to < 3.0	7	6	65	50	100	75	< 89.0	
3.0 to < 30.0	7	7	80	65	125	100		
> 30.0	8	7	100	80	160	125		

* PG high temperature ≥ 76°C <u>*or*</u> mixes placed > 4 inches (100 mm) from the surface

6-2 are recommended for use, even for heavy-duty mixtures. For heavy-duty wearing surface and intermediate layer mixtures supporting high tire pressures with heavy wheel loads, the N_{max} should be included in the mixture design specifications.

Table 6-3 provides Superpave gyratory compactor levels for heavy-duty pavements based upon the Table 6-2 N_{des} values and recalculated N_{ini} and N_{max} values per Brown et al. (2009).

FAA Mix Design Specifications

The FAA material specifications for airfield pavements were prepared for three asphalt mixtures, designated P-401, P-403, and P-601. Each mixture represents an application to airfield pavements based on aircraft gross weight and location, as summarized below.

Item P-401 is an asphalt mixture intended for use in the surface course of flexible pavements designed to carry gross weights greater than 12,500 lbs. (5,670 kg) (FAA, 2014). The asphalt grade used in this mixture is selected according to the applicable agency specifications for interstate paving, which is further adjusted for aircraft gross weight. The high temperature grade of the binder is increased by one grade for aircraft gross weight greater than 12,500 lbs. but less than 100,000 lbs. (45,360 kg), and by two grades for gross weight greater than 100,000 lbs.

Item P-403 is an asphalt mixture used in the surface course of pavements designed for gross weights less than 12,500 lbs. (5,670 kg), stabilized base course, binder course and leveling courses. It is also used in pavements that are not subjected to full aircraft loading, such as service roads, shoulders, and blast pads.

Item P-601 is a fuel-resistant asphalt mixture intended for use only as a surface course in areas subjected to fuel spills. Specifications for this mixture allow a layer thickness between 1 inch (25 mm) and 2 inches (50 mm), with a Superpave asphalt grade of PG 82–22 and design air voids of 2.5 percent. FAA specifications do not allow RAP and/or millings in this mixture.

The FAA Advisory Circular 150/5370-10H specifications (FAA, 2018) allow asphalt mixtures for use in airfield pavements to be designed using the Marshall or Superpave methods in accordance with the Asphalt Institute MS-2 mixture design manual (AI, 2015). Specimens for the Marshall method are prepared using the manually operated hammer as specified

Table 6-4. Superpave Gyratory Compactor Levels (Brown & Powell, 2007)

Test Property		Aircraft Gross Weight ≥ 60,000 lbs. (27,216 kg) *or* Tire Pressure ≥ 100 psi	Aircraft Gross Weight < 60,000 lbs. (27,216 kg) *or* Tire Pressure < 100 psi
Marshall	Number of blows	75	50
	Stability, minimum Pound-force (Newtons)	2,150 (9,560)	1,350 (6,000)
	Flow, 0.01 in. (0.25 mm)	10 – 16	10 – 18
	Target air voids (percent)	3.5	3.5
	Percent VMA, minimum*	14 – 16	14 – 16
Superpave	Number of compactor gyrations, N_{des}	75	50
	Target air voids (percent)	3.5	3.5
	Percent VMA, minimum*	14 – 16	14 – 16

* Minimum percent voids in mineral aggregate (VMA) requirement varies from 14–16 percent and depends on the NMAS and aggregate gradation.

in ASTM D6926, and these specimens are tested for Marshall stability and flow according to ASTM D6727. Superpave mixture design specimens are compacted using the gyratory compactor according to ASTM D6925. Resistance to moisture damage is required for both methods using the indirect tensile strength ratio (TSR) test, which requires specimens to have a minimum TSR between 70 and 80 percent, depending on exposure of the mixture to freeze and stripping. Anti-strip agent is required for mixtures that do not satisfy the minimum TSR requirement.

Table 6-4 shows the Marshall and Superpave criteria for surface mixes (P-401) designed for different aircraft gross weights and/or tire pressure. Asphalt base mixtures (P-403) have less restrictive limits for Marshall stability and flow values, but similar criteria for the Superpave method. The flow requirement for Marshall is not applicable to mixtures containing PMA.

An alternative compaction device and procedure, ASTM D3387, *Standard Test Method for Compaction and Shear Properties of Bituminous Mixtures by Means of the U.S. Corps of Engineers Gyratory Testing Machine*, predates the Superpave gyratory compactor. This procedure was developed as a laboratory compaction method that can produce the densities that develop under channelized aircraft wheel loading with high tire pressures and has been used successfully by the U.S. Corps of Engineers.

Figure 6-1. Flow Chart of Asphalt Mixture Design

Mixture Design Steps

The two most important aspects in design of asphalt mixtures are selection of materials (aggregate and asphalt binder) and determination of the target asphalt content. Figure 6-1 shows the six steps for designing asphalt mixtures. The process for designing heavy-duty asphalt mixtures is the same as for

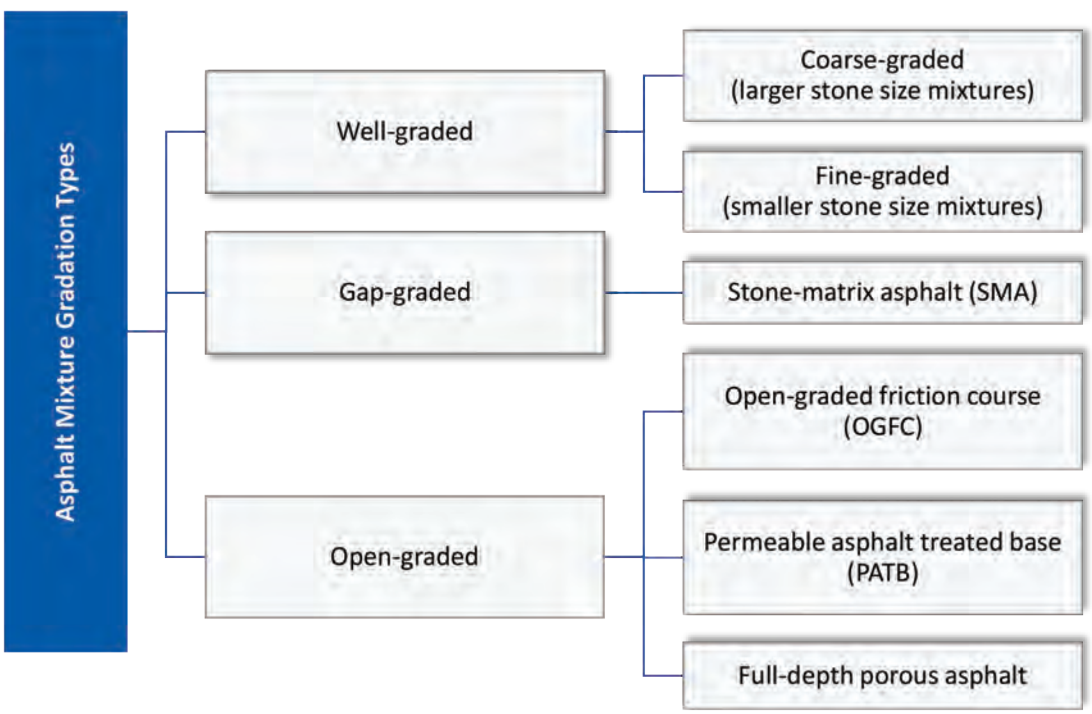


Figure 6-2. Types of Aggregate Gradations

conventional mixtures, except that some of the criteria are different. As noted in Chapter 3, integration of the structural and mixture design is important for heavy-duty pavements because of the more severe loading conditions. The following sections of this chapter discuss the mixture design steps, except for the aggregate and binder selection steps already discussed in Chapter 5.

1. Select proper aggregate materials (refer to Chapter 5).
2. Determine an aggregate gradation yielding good aggregate interlock.
3. Determine binder grade and additives/modifiers necessary to provide necessary mixture stiffness (refer to Chapters 4 and 5).
4. Select the target binder content that provides the desired air voids.
5. Ensure the asphalt mixture meets or exceeds the minimum VMA requirement.
6. Evaluate rutting, fatigue, and moisture susceptibility of the mixture based on agency requirements.

Aggregate Sizing or Gradation

Because aggregates provide the load-supporting capacity of an asphalt pavement, care must be taken to ensure the mix design uses an appropriate selection of aggregate.

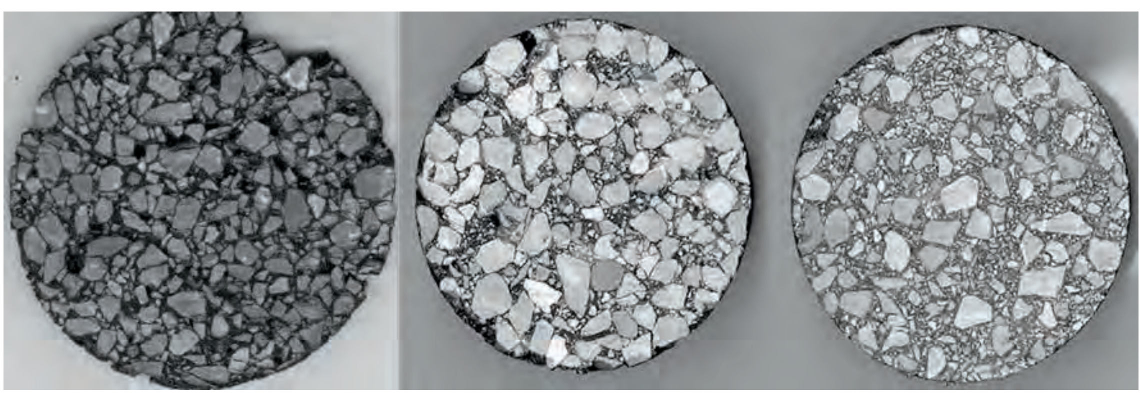
Types of Aggregate Gradation

Just about all asphalt mixtures can be grouped into one of three aggregate gradation categories, as shown in Figure 6-2: well-graded, gap-graded, and open-graded. Figure 6-3 shows samples of the different aggregate blends discussed below.

Dense, well-graded mixes have a relatively uniform distribution of different particle sizes. They have very low permeability when properly compacted and are suitable for all types of structural layers, including pavement surface layers, and for all traffic conditions. These dense-graded mixtures can be further classified as coarse- or fine-graded. Coarse-graded aggregate blends can require a lower asphalt content compared to fine-graded blends because the finer aggregates have larger surface areas to be coated. However, the aggregate gradation or sizing and the amount of finer aggregate in the coarser aggregate blends defines the amount of asphalt needed, which is discussed in the next section of this chapter.

Gap-graded mixes contain higher percentages of both large and small aggregate particles with some intermediate particle sizes missing in the gradation. The goal of designing gap-graded mixes is to create stone-on-stone contact using the larger aggregate particles, with the smaller particles supporting the skeleton. They require more durable aggregates, higher asphalt content, and contain modifiers and fibers to prevent draindown of the asphalt during storage or transport. SMA is the most commonly used gap-graded mixture and has been reported to exhibit excellent performance as a durable wearing surface resistant to the abrasive forces of horizontal loads and heavy wheel loads.

Open-graded mixtures are highly permeable and designed to allow quick drainage of water from the pavement. They contain a large percentage of highly



Open-Graded Aggregate Blend (air voids ≈18%); dark areas in core are air voids

Dense Gap-Graded Blend (SMA) (air voids ≈6%)

Dense Well-Graded Blend (air voids ≈6%)

Figure 6-3. Asphalt Mixtures With Different Types of Aggregate Blends angular coarse aggregate, a small percentage of manufactured sands and/or fines. Open-graded mixtures are typically used as open-graded friction course (OGFC) in the pavement surface or as permeable asphalt-treated base (PATB) below less-permeable layers, as well as in full-depth porous asphalt pavements.

The well- and gap-graded gradations are dense-graded asphalt mixtures and designed with air voids around 4 percent, while the open-graded mixtures are designed to have air voids exceeding 15 percent. The dense-graded aggregate blends (well- and gap-graded) are used in any layer of the pavement structure, but gap-graded are more often used in the wearing surface. Open-graded aggregate blends are used as a wearing course to decrease noise from the truck tires and/or to reduce "splash effect" and hydroplaning during rainfall. PATB open-graded mixtures are also included as a part of the drainage system design to prevent water from penetrating the lower unbound layers and subgrade.

Dense-graded asphalt mixes are defined further based on the aggregate size or NMAS and gradation. Figure 6-4 shows different size asphalt mixtures going from fine- to coarse-graded aggregate blends. The finer aggregate blends (4.75 to 12.5 mm) are normally used in the wearing surface for achieving a smoother surface or lower IRI value after placement, while the larger-sized mixtures are used in the lower asphalt layers either as an intermediate or base layer. As noted in Chapter 4, the larger-sized mixtures require thicker lifts during placement but can be more susceptible to aggregate segregation. Aggregate segregation is discussed in detail in Chapter 7.

Any of these aggregate blends can be designed to be resistant to rutting and fatigue cracking. However, the larger aggregate mixtures can have greater bearing or compressive strengths for heavy loads because of the larger diameters, assuming there is stone-on-stone contact for the larger aggregate sizes and the aggregates have crushed faces (see Chapter 5). Figure 6-5 shows different types of dense-graded asphalt mixtures in a thick asphalt pavement. As shown, some of the layers have the same designated NMAS but the gradations are different. More importantly, none of these layers exhibit stone-on-stone contact for the larger-sized aggregate particles and consist of more rounded aggregates. The mixtures illustrated in Figure 6-3 and Figure 6-4 meet the requirement of crushed surfaces for heavy-duty mixtures.

A vast majority of asphalt pavements built in the United States use dense-graded mixtures. Asphalt mixtures designed using the Superpave method have a strong aggregate skeleton to carry the traffic loads and perform better than mixtures designed using older methods. SMA is a gap-graded mix where the larger aggregates form a strong stone-on-stone aggregate skeleton to carry the heavy loads. The space or voids between these larger particles is filled with a passive matrix that consists of asphalt binder and very fine particles (filler) known as mastic. SMA has a higher asphalt binder content that makes it more resistant to aging, which is described as the process of asphalt binder hardening over time and becoming more susceptible to brittle failure.

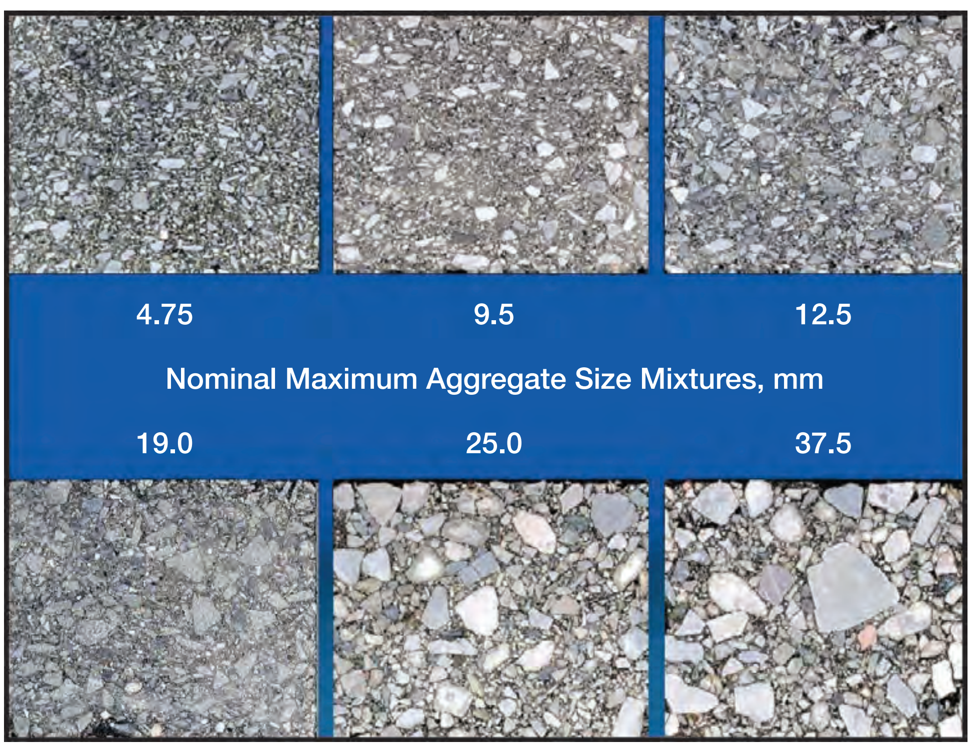


Figure 6-4. Different NMAS Asphalt Mixtures

Despite a higher initial cost, SMA is strong and durable and should be considered for pavements where benefits outweigh the additional initial cost, especially for heavy-duty mixtures.

Dense, continuously graded aggregates are normally preferred for heavy-duty mixtures. Provided the aggregate has good shape and surface texture characteristics and is held together with sufficient binder content, continuously graded asphalt resists deformation primarily through the development of particle-to-particle interlock. For thick asphalt layers, continuous grading can result in stiff, relatively low air void content mixtures that have good fatigue properties. A key requirement is to ensure that the gradation produces an aggregate skeleton with stone-on-stone contact.

For both base and wearing course mixtures, the selection of the maximum aggregate size raises some interesting possibilities. As the nominal maximum aggregate size is normally limited to one-third to one-quarter of the layer thickness, for thick-lift construction there are opportunities for using large size aggregate. For pavements subjected to very heavy loads, high tire pressures, or combinations of punching and standing loads, stiff mixtures with an increased resistance to indentation, abrasion, and deformation can be achieved by including 1½-inch (37.5 mm) crushed stone in the mix (Holt, 1984; Davis, 1988). In addition, the use of larger size stone reduces the aggregate surface area and increases the volume concentration of aggregate. Both factors contribute to a reduction in the design binder content and improve the economic features of the mixture (Acott, 1986).

In addition to mat thickness, the selection of the maximum stone size is related to the degree of aggregate segregation. As heavy-duty mixtures using large stone have a tendency to segregate, special attention should be paid to materials handling, to the proper loading of haul trucks, and the paving procedures (Brock, 1986). Techniques for avoiding

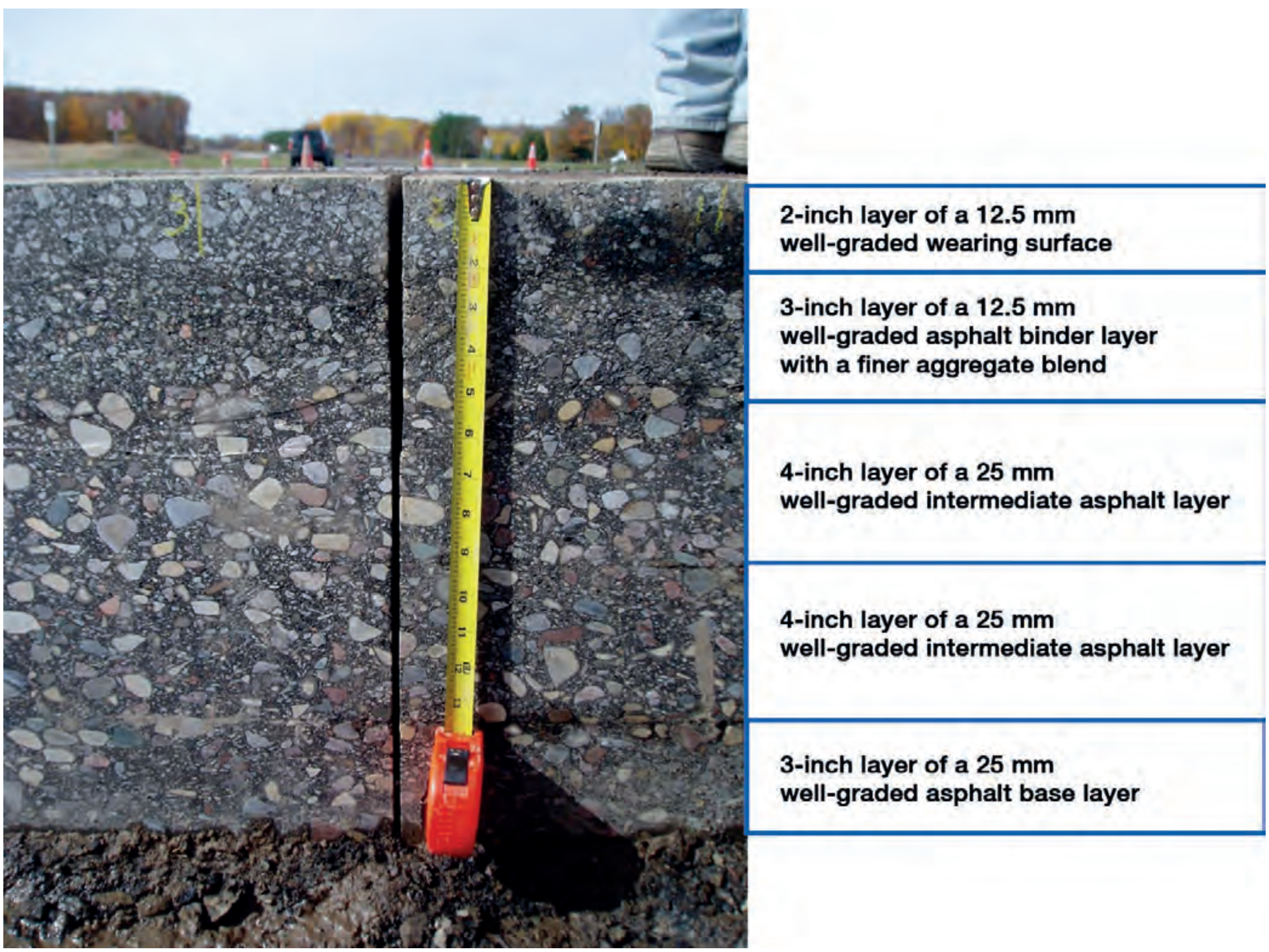


Figure 6-5. Different Asphalt Mixtures in the Pavement Structure

segregation are provided in Chapter 7. Agency experiences with mixtures that have proven to perform well in comparable pavement structures and under similar traffic and environmental conditions should be used in the material selection process.

In view of the stringent requirements for surface smoothness for airport runways and taxiways, the use of heavy-duty mixtures using large stone in the surface course is not suggested for these pavements. Consideration should, however, be given to the use of large stone sizes for base courses on the above facilities, as well as for off-road facilities and on highways where there are combinations of slow-moving traffic, channelized traffic, and high ambient temperatures.

Providing Aggregate Skeleton: Stone-on-Stone Contact

Resistance of an asphalt mixture to rutting and shoving in critical loading areas can be improved by adjusting the aggregate sizing or blend. These adjustments include:

- **Choose aggregate gradation to optimize stability and stiffness** — The stability and stiffness of an asphalt mixture depends on the strength of the aggregate skeleton in the mixture. An aggregate gradation that maximizes stone-on-stone contact between the crushed particles for the type of aggregate used provides increased strength and greater resistance to rutting (e.g., SMA mixtures).
- **Use a high percentage of crushed aggregate** — Asphalt mixtures that contain a high percentage of crushed, angular aggregate provide better interlock and resistance to deformation.

The assurance of an adequate aggregate skeleton through stone-on-stone contact is vital because the skeleton is what must carry the load. Having the coarse aggregate "floating" in a matrix of fines will not provide the strength necessary to carry heavy loads. The concept used here is similar to that used in designing SMA mixtures.

Providing stone-on-stone contact is accomplished by establishing the voids in coarse aggregate (VCA) of the coarse aggregate fraction and testing the VCA of the compacted asphalt mixture to assure that this latter value is equal to or less than the VCA of the coarse aggregate fraction (Brown & Haddock, 1997). The coarse aggregate fraction is that portion of the total aggregate blend retained on the 4.75 mm (No. 4) sieve.

The procedure for determining VCA is described in NCAT Report No. 97-2, *A Method to Ensure Stone-on-Stone Contact in Stone Matrix Asphalt Paving Mixtures* (Brown & Haddock, 1997).

Selecting a Target Asphalt Content

Asphalt mixtures designed using the Superpave and FAA procedures are required to meet volumetric criteria, such as air voids at initial and maximum design gyrations, minimum VMA, maximum VFA, and dust-to-binder ratio. This section summarizes the volumetric criteria and compaction of the test specimens for heavy-duty mixtures.

Mixture Volumetric Criteria

Once the aggregate structure or gradation has been determined, the design or target asphalt content is derived by its relationship with air voids and VMA.

Laboratory Compaction of Test Specimens

In the preparation of laboratory specimens, it is vital to select a compaction technique and effort that will produce air void levels in the specimen as close as possible to the levels anticipated in the pavement after construction and some period of usage, usually 2–5 years. Mixture design specimens are compacted to an air void content between 3 and 5 percent in the laboratory, as noted above. This range corresponds to the density that an asphalt mixture will attain in the field after being subjected to typical truck traffic. If the design air voids of the wearing surface are much lower than 3 percent, the mixture can be more susceptible to bleeding and flushing reducing the skid resistance of the surface. If the air voids are greater than 5 percent, the mixture may undergo early cracking or raveling. Air voids have a significant impact on the aging or durability and fracture resistance of the mixture. The higher the air voids, the lower the tensile and fatigue strength.

The level of effort to which the asphalt mixture is compacted is the number of gyrations with a Superpave gyratory compactor in accordance with the Superpave method or the number of drops per face of the Marshall hammer in accordance with the FAA method. The compaction level of effort depends on the estimated traffic level for both methods, as summarized in the first section of this chapter. The degree of additional densification is determined by many factors, including initial compaction, mix type, rate of asphalt hardening, layer thickness, temperature, traffic conditions, and traffic wander. Research has shown that under heavy interstate traffic, the constructed air voids of properly designed mixtures tend to decrease for about 2 years and then level off (Hughes, 1990). The laboratory compaction effort should attempt to produce an air void level that corresponds to traffic densification but be as low as possible without resulting in bleeding or a reduction in shear strength or loss of stability.

Heavy-duty mixes have been compacted during the mixture design process to a higher number of design gyrations to handle a large number of load repetitions (greater than 50 million trucks) compared to mixtures designed for normal traffic levels (Brown & Prowell, 2007). Due to increased compaction effort, less asphalt is required for the mixture to reach 4 percent air voids at the design number of gyrations (N_{des}). The lower asphalt binder content results in more aggregates by volume in the mixture and therefore greater resistance to rutting, but it also reduces flexibility of the mixture, leading to more fatigue cracking.

Therefore, mixtures for heavy-duty pavements should be designed such that their performance with both rutting and cracking is optimized. This can be achieved by modifying the Superpave specification criteria or by lowering the design gyrations and verifying mixture performance with additional tests for rutting and fatigue cracking or torture tests to confirm the mixture (Brown & Prowell, 2007).

Design Air Void Level

Most mixture design methods used today are volumetric-based methods where the aggregates and binder are blended to achieve a design air void content of 4 percent with a specific level of compaction. The asphalt content in a mixture is selected so that the design air voids and VMA are achieved at the specified level of compaction. The design asphalt content should satisfy both the air void and VMA requirements, as well as other volumetric criteria related to performance.

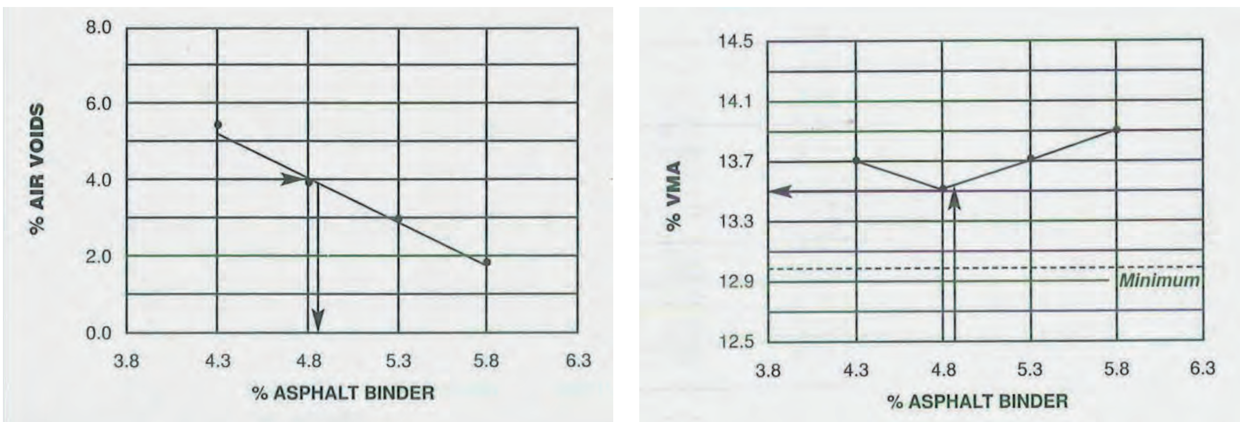


Figure 6-6. Percent Air Voids (left) and percent VMA (right), as a Function of Asphalt Content (AI, 2001b)

For air void contents in the range of 3–5 percent, both air and water permeability of the mixture are usually low for both coarse and fine-graded aggregate blends. This ensures good mixture durability and a reduction in the possibility of moisture damage. A minimum void content of 3 percent is specified

Table 6-5. Asphalt Mixture VMA Requirements (AI, 2001b)

Nominal Maximum Aggregate Size	VMA, percent (minimum)
9.5 mm (3/8 in)	15
12.5 mm (1/2 in)	14
19.0 mm (3/4 in)	13
25.0 mm (1 in)	12
37.5 mm (1.5 in)	11

because air voids below this level can result in poor mix stability and flushing/bleeding. Conversely, a maximum air void content of 5 percent is specified because the tensile strength, durability, and fatigue strength are significantly reduced. To ensure the low and high air void limits are not violated, the design asphalt content is most often chosen at an air void content of 4 percent, as shown in Figure 6-6.

Voids in Mineral Aggregate

Limits on VMA are used as a requirement to ensure sufficient void space for the asphalt in the aggregate gradation to ensure good durability regardless of the loading condition. Table 6-5 lists the minimum VMA values for different NMAS based on 4 percent air voids to ensure sufficient void space.

A plot of VMA against asphalt content provides a useful measure of changes in the packing characteristics of the aggregate versus increases in asphalt content. The convex downward-shaped curve shown in Figure 6-6 (right) is typical for many mixtures. As the amount of asphalt is increased from a low value, the aggregate particles are lubricated, increasing the density of the mixture for a specified level of compaction until a minimum VMA is reached. This is the asphalt content of maximum aggregate density. When more asphalt is added to the mixture, the additional asphalt starts displacing the aggregate particles, causing an increase in VMA (Acott, 1986). This point is also called the "saturation asphalt content." The portion of the relationship where VMA decreases with adding asphalt is called the "dry side," while the portion where VMA increases with more asphalt is called the "wet side."

Care should be taken in using mixtures that exhibit sharp VMA versus asphalt curves. Although they may have satisfactory laboratory characteristics, they are often very sensitive to small changes in mixture proportions, aggregate gradations, aggregate characteristics, and/or asphalt content. It is more advisable to select an aggregate gradation where the VMA is not significantly affected by changes in the asphalt content. In the selection of the job mix formula (JMF), the design asphalt content should be on the "dry side" of the asphalt content at minimum VMA. Mixtures on the rich side of the minimum VMA tend to have a low resistance to deformation due to reduced aggregate interparticle friction.

Confirmation of Volumetric Properties

Mixture specimens are prepared and compacted using the JMF's target gradation and asphalt content) to confirm the volumetric properties and evaluate the mixture's moisture damage susceptibility. The mixture's moisture susceptibility is discussed in the next section, while Table 6-6 summarizes the volumetric properties that are applicable to heavy-duty mixtures.

The VMA should be less than 2 percent above the required minimum value. A very high VMA indicates that insufficient matrix is available to provide necessary rutting resistance, especially in mixtures whose

Table 6-6. Volumetric Property Evaluation Parameters

Traffic Level, million ESALs	VMA, percent (minimum)	VMA, percent (maximum)	VFA, percent	Dust-to-Binder Ratio
< 0.3	See Table 6-5	< 2 percent above values in Table 6-5	70 to 80	0.6 to 1.2
0.3 to 3.0			65 to 78	
> 3.0			65 to 75	

Table 6-7. Criterion for Moisture Damage Assessment

High Temperature Binder Grade	Indirect Tensile Strength Ratio (AASHTO T 283)	Hamburg Wheel-Tracking Test, Min. Passes (AASHTO T 324)	Max. Rut Depth @ 50°C*
PG 64–YY	0.80	10,000	0.5 inches (12.5 mm)
PG 70–YY		15,000	
PG 76–YY		20,000	

*This is a typical value; consult state or local agency specifications for maximum rut depth and/or stripping inflection point criteria gradation is on the coarse side of the maximum density line. Thus, once the asphalt content is selected at an air void content of 4 percent, the VMA is checked to ensure the minimum VMA requirements (refer to Figure 6-6), which are related to the NMAS as shown in Table 6-5, are met.

Evaluate Mixture Moisture Susceptibility

Moisture damage occurs when water infiltrates the asphalt mixture and weakens the bond between asphalt and aggregates, resulting in loss of mixture strength. The moisture susceptibility of a mixture should be tested in the laboratory prior to construction, and anti-strip additives should be used if the mixture is found to be susceptible to moisture damage, as stated in Chapter 4.

Two tests are commonly used to assess the moisture damage or stripping susceptibility of a mixture: AASHTO T 283 using the indirect tensile test and AASHTO T 324 for the Hamburg wheel-tracking test (Stuart & Mogawer, 2000). The criterion for deciding whether the asphalt mixture is susceptible to moisture damage is agency dependent. Table 6-7 provides a summary of the commonly used values that are also applicable to heavy-duty mixtures.

Performance Testing to Confirm Mixture Design

Asphalt mixture design is based on specification criteria that relate volumetric properties to mixture performance. However, the design process does not directly include performance tests as part of the specifications. Therefore, additional mixture tests are conducted after selecting a target asphalt content. These tests evaluate resistance of the mixture to rutting, moisture damage, and other pavement distresses.

Most agencies require at least one additional performance test be conducted as part of specifications for acceptance of the mixture design. Agencies specify acceptance criteria for performance tests based on their experience or through correlation between test results and field performance. Rutting resistance of mixtures is evaluated using accelerated wheel-tracking tests or "torture tests" that subject an asphalt mixture specimen to repeated load applications under controlled conditions. Performance testing is also done to assess a mixture's resistance to fatigue cracking, moisture damage and thermal cracking.

Details of supplemental tests on asphalt mixtures are provided in this section.

Performance Testing of Asphalt Binders

The selection of the asphalt was included in Chapter 5. This section of Chapter 6 provides additional information on the asphalt of heavy-duty pavements to ensure adequate performance under severe loading conditions.

Asphalt binder testing to evaluate in-service performance has two primary objectives — (1) ensure the asphalt has sufficient stiffness at high temperatures to resist deformation, and (2) ensure it has sufficient flexibility at low and intermediate temperatures to resist cracking. Asphalt binder in the mixture also goes through different aging mechanisms during mixing, hauling, placement, and compaction. It is therefore necessary to measure asphalt binder properties that correlate to mix performance at these different stages of the construction process.

The Superpave tests from the SHRP program were developed to evaluate high-, intermediate-, and low-temperature properties of asphalt binders. Several state highway agencies (SHA) also specify additional empirical, non-performance-based tests — also known as SHRP+ specifications — to characterize and differentiate between polymer-modified and conventional asphalt binders. Specification criteria for various binder tests for heavy-duty mixes are presented in this section.

Very heavy or slow-moving traffic causes rutting in an asphalt pavement at high temperatures due to lower stiffness of the mixture. Asphalt is also subjected to higher temperatures that typically vary from 325°F (162°C) during mixing to 300°F (150°C) during placement and compaction, in addition to daily temperature variation for several years after placement. The binder selected for heavy-duty mix design should have sufficient fluidity to ensure a workable mix during mixing and compaction, while having sufficient stiffness at high temperatures experienced by the in-service pavement.

Fatigue cracking occurs at intermediate temperatures due to repeated heavy loads and is affected by a number of factors like pavement thickness, strength of underlying layers, drainage characteristics, construction quality, and air voids in the asphalt mixture. For the pavement to withstand repeated traffic loads without cracking, the asphalt mixture should have enough tensile strength to handle tensile strains at the bottom of the asphalt layer. Because softer binders have better fatigue cracking resistance than harder asphalts, binder stiffness should not exceed an upper limit to ensure selection of a soft, flexible binder.

Low-temperature cracking or thermal cracking is caused by tensile stresses induced in the asphalt layer at low temperatures due to thermal contraction. Because this is not a load-related distress, no additional considerations are necessary for heavy-duty mixes. The procedure for selecting low-temperature binder grade is therefore identical to that for standard asphalt mixes specified by the SHA.

Modifiers are chemical additives added to the asphalt binder or mixture to change their properties, as discussed in Chapter 4. The most common type of modifiers are those used to increase stiffness of the asphalt at high temperatures to improve the mixture's resistance to rutting.

Tests to Evaluate Rutting Resistance

Rutting is the most important distress to be considered when selecting the high temperature grade of an asphalt binder. Superpave specifies the ratio of the shear modulus (G^*) to the sine of phase angle ($\sin \delta$) to be greater than 1.0 kPa when the binder is tested at the estimated 7-day pavement high temperature. close to the estimated pavement high temperature, but may lose stiffness rapidly when tested at higher temperatures that are not experienced by the pavement. Therefore, binder grade adjustment using the MSCR test is done by measuring the non-recoverable strain at different stress levels after 10 creep and relaxation cycles. For very heavy traffic, the binder should have a non-recoverable creep compliance J_{nr} of less than 1.0 kPa^{-1} for traffic of 10 million to 30 million ESALs, and should not exceed 0.75 kPa^{-1} for traffic greater than 30 million ESALs.

Tests to Evaluate Fatigue Cracking Resistance

Asphalt binders are also tested at intermediate temperatures using the DSR to evaluate the fatigue cracking resistance of the binder. To perform better under repeated loading, the asphalt binder should be flexible with lower stiffness at intermediate temperatures. Superpave specifies a maximum value of 2.20 kPa for binders that have been subjected to short-term aging in a rolling thin-film oven (RTFO), which simulates in-service pavement aging.

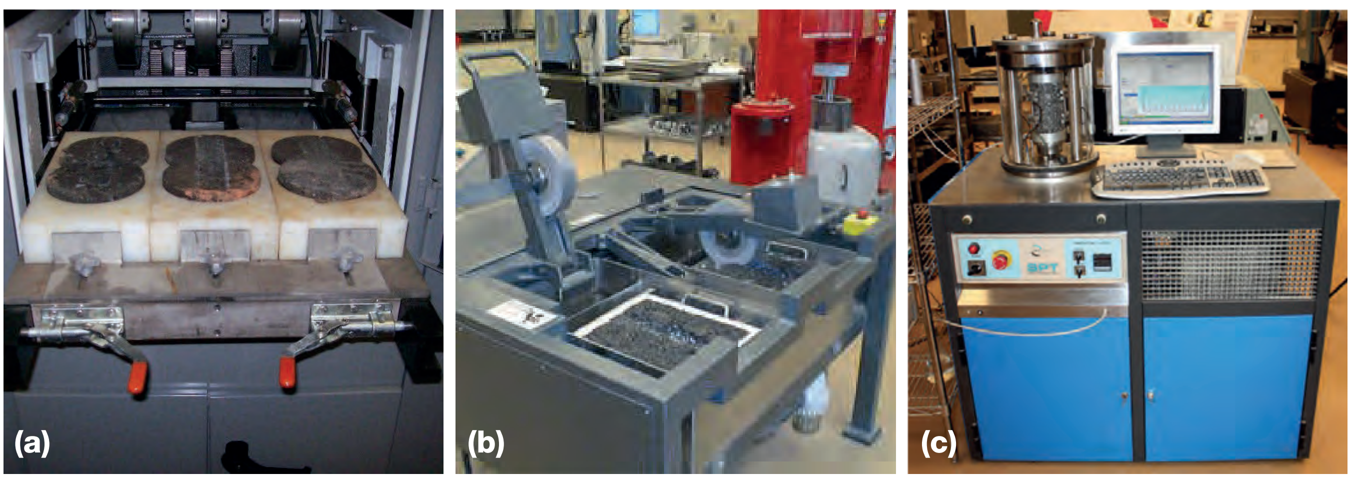


Figure 6-7. Testing Devices to Measure Rutting Potential of Asphalt Mixtures, Left to Right: (a) Asphalt Pavement Analyzer (APA), (b) Hamburg Wheel-Tracking Device, and (c) Asphalt Mixture Performance Tester (AMPT) Device

This high temperature PG grade is further increased or "bumped" by one grade when the traffic volume exceeds 30 million ESALs or when there is slow-moving traffic on the pavement. The high PG grade is bumped by two grades when the pavement is designed for very slow or standing traffic (Figure 5-1).

The MSCR grading system does not recommend increasing the PG high temperature grade because it does not properly characterize PMAs. Some PMAs provide additional stiffness at service temperatures

SHAs also use additional empirical tests in the SHRP+ specifications, like the Elastic Recovery (ER) test to measure the binder's elastic properties at intermediate temperatures (10°C or 25°C). Asphalt binders that have a higher percentage of recovery should be selected for heavy-duty mix design. PMAs generally have higher ER percentages than conventional or unmodified asphalts.

A force ductility test can also be conducted to estimate the binder's resistance to fatigue cracking, as well as thermal cracking and raveling. The test measures the ratio of force applied at initial and second peaks on a load-deformation curve for an asphalt binder that is pulled at a constant deformation rate. A minimum force ratio is specified to ensure that the binder can still handle heavy-load applications under deformation.

Performance Testing of Asphalt Mixtures

Agencies use various performance tests to assess cracking, rutting, and moisture susceptibility of the mix in addition to Superpave volumetric criteria. Additional testing of mixes may also be used to evaluate fatigue resistance and susceptibility to moisture damage.

Commonly used tests to assess rutting susceptibility of the mix are Hamburg wheel-tracking device (shown in Figure 16(b) from Stuart & Mogawer, 2000) and asphalt pavement analyzer (APA) test (shown in Figure 16(a), courtesy Pavement Technology). Rutting resistance can also be evaluated using the asphalt mixture performance tester (AMPT) device (shown in Figure 16(c) from FHWA, 2013), which measures flow number of the asphalt mix.

Flow number (F_n) is defined as the number of cyclic load repetitions at which the mix exhibits tertiary flow, i.e., shear deformation similar to the mechanism that produces rutting in the actual pavement. The flow number obtained from AMPT testing should not be confused with the Marshall flow, which measures deformation of specimen loaded diametrically at a constant loading rate.

Flow number criteria were developed for HMA mixes in NCHRP Project 09-33, "A Mix Design Manual for Hot Mix Asphalt" (Advanced Asphalt Technologies LLC, 2011) and for WMA mixes in NCHRP Project 09-43 (Advanced Asphalt Technologies LLC, 2012). The criteria are different for HMA and WMA due to different short-term conditioning requirements for the two mixes prior to compaction. HMA mixes are subjected to 4 hours of short-term aging at 135°C (275°F), whereas WMA mixes are subjected to 2 hours of short-term oven aging at the compaction temperature.

Table 6-8 shows the flow number test criteria for both HMA and WMA (FHWA, 2013). Heavy-duty mixes should have a higher flow number, indicating that the mix has greater resistance to rutting.

Another mix test to evaluate and confirm resistance to rutting is the repeated load plastic deformation test. The test specimen preparation, test set up, and execution are similar to the flow number test, except that confinement is used (Von Quintus et al., 2012; Von Quintus & Bonaquist, 2019). The data analyses are also different in that the intercept and exponents of the rut-depth transfer function included in the AASHTOWare Pavement ME Design are determined so they can be entered directly into the software.

There are no global standard specifications for rutting acceptance criteria measured from wheel-tracking tests on laboratory-compacted specimens. These criteria are typically specified by individual agencies based on the agency's experience and findings from state-specific research studies. West et al. (2018) summarized the requirements or criteria used by different agencies for designing and accepting asphalt mixtures using the APA and Hamburg loaded-wheel testers for NCHRP Project 20-07/Task 406.

Table 6-8. Flow Number Criteria for HMA and WMA Mixtures

Design Traffic, Million ESALs	HMA F_n	WMA F_n
< 3	Not specified	Not specified
3 to 10	50	30
10 to 30	190	105
> 30	740	415

More importantly, West et al. (2018) proposed a standard specification for balanced mix design (BMD) to serve as the next generation of asphalt mix design, which considers rutting, fracture, and durability. BMD, defined as an asphalt mixture "designed to achieve an optimal balance between rutting resistance and cracking resistance using appropriately selected mixture performance tests rather than relying solely on volumetric guidelines" (West et al., 2018), is especially important for heavy-duty asphalt mixtures where the wheel loads, tire pressures, frequency of loadings, and speed of loadings can all have a significant effect on the mixture and its performance.

7 Production & Placement of Heavy-Duty Mixtures

This section covers mixture production, placement, compaction, and quality control. Many aspects of production and placement of mixes for heavy-duty asphalt mixtures are similar to those of typical asphalt mixtures, so only areas of difference or potential problems unique to heavy-duty mixes are covered in detail.

Challenges & Considerations in Constructing Heavy-Duty Mixes

Three principal challenges may arise when using large maximum size aggregate for heavy-duty pavements: segregation, aggregate fracture, and equipment wear (Button et al., 1997). A fourth challenge relates to rolling large-stone mixtures to obtain adequate density. These challenges can all be overcome, however. For example, following the best practices outlined in this section can eliminate segregation. Breakdown of the aggregate can be minimized by following good quality control procedures and making adjustments to the mix produced in the field to meet volumetric requirements. Increased inspection of wear parts at the plant and paver can eliminate any negative impacts on the mixture from increased equipment wear. These challenges and solutions are discussed below.

Segregation

Segregation is defined as the separation of the coarsest aggregate particles from the rest of the asphalt pavement mixture. It is the single most common problem with mixes incorporating large aggregate, and it can affect production, placement, and compaction. Segregation of the large aggregate particles can occur at several points during the manufacture, storage, hauling, and placement of mixes with large aggregate sizes, and these mixes are more prone to segregation than finer mixes because the aggregate sizes vary greatly in the mix (Button et al., 1997).

Segregation in large-stone mixes has probably been one of the greatest deterrents to more widespread use of this mix type. Segregated areas appear on the surface and at the bottom of the asphalt mat. The surface texture of the segregated area is more open than that of the surrounding pavement surface. Segregated pavement areas lack the load-spreading capabilities of more uniform areas and tend to ravel under traffic. Segregation also reduces the service life of the mix as the segregated areas have high air void contents and age more rapidly than more uniform areas.

Therefore, preventing segregation of the coarse aggregate is one of most important factors in the production and construction of mixes incorporating large aggregate sizes. Thus, considerable discussion of the causes and prevention of segregation is presented before operational components are covered.

To prevent segregation, it first must be identified. Identifying segregated areas is difficult at best, especially for large-stone, heavy-duty mixtures, because of the macro-texture at the surface of the lift. One method used to effectively identify segregated areas is paver-mounted thermal profiling (PMTP), as specified under AASHTO PP 80. The thermal scanner measures temperature differentials across and along the mat during placement in real time. Segregated areas that exhibit much higher air voids cool more quickly and are illustrated by temperature differentials in localized areas.

Aggregate Fracture

The fracture of the larger aggregate in the mix during the production process can become a problem. Depending on the quality and hardness of the coarse aggregate particles, the corners of the large aggregate may break off inside the plant dryer or mixer during heating, drying, and mixing. In addition, larger stones impacting the smaller particles may cause this fracture.

This fracture changes the gradation and the VMA of the mix, possibly reducing the effectiveness of the larger particles. This breakage of particles creates additional dust that increases the aggregate surface area to be coated with asphalt and increases the dust-to-binder ratio. This may also negatively affect the interlock desired between the various aggregate particles and, ultimately, the strength and performance of the pavement.

During compaction, aggregate fracture can occur under the rollers. More fracture typically occurs when the mixture contains many larger aggregate particles or relatively soft coarse particles. Normally, more fracture occurs when a vibratory roller is used in the breakdown position, directly behind the paver, than when a pneumatic-tired or static roller is used to initially compact the mix (Button et al., 1997).

Equipment Wear

The use of large maximum size aggregate may increase the wear of various components in the asphalt plant and the paver.

In a batch plant production operation, the larger-sized coarse aggregate may create additional wear on the flights inside the dryer and the dryer shell, on the screen cloth at the top of the tower, and on the liner plate and paddle tips in the pugmill.

In a drum mix plant operation, incorporation of larger-sized coarse aggregate may increase the wear on the flights inside the drum, as well as on the drum shell. Some increased wear can be expected on the flights and liner plates of the slat conveyor, on the liner inside the silo, and on the liner of the discharge cone on the silo. This increased wear results, in part, from the smaller proportion of fine aggregate in the mix and the lack of sand-sized particles to cushion the coarsest aggregate particles as the aggregate moves through the plant (Button et al., 1997).

At the paver, increased wear can be expected on the flights of the drag slat conveyor, which carries the mix from the hopper to the rear of the paver. Slight additional wear may be found on the augers that distribute the mix across the width of the screed.

Compaction

Compacting heavy-duty mixes does not differ from other asphalt mixes. The same equipment or rollers are used to densify the heavy-duty mix. A critical item, just like for other mixes, is to use a control strip to define the rolling pattern to ensure the compaction train can densify the mix to the specified air void level of percent compaction. A benefit to using larger stone mixtures, however, is the larger size aggregates require the use of thicker lifts, and thicker lifts increase the time available for compaction (TAC). A latter part of this section provides more discussion on rolling operations and the type of rollers more amenable to heavy-duty mixes.

Segregation

Because heavy-duty pavements often use coarse-graded mixes with large maximum size aggregate, it is important to take proper steps to minimize the risk of segregation.

Types & Causes

Three principal types of segregation are found in asphalt pavement layers: random or rock pocket, longitudinal or side-to-side, and truckload-to-truckload. Each type has a different pattern on the roadway and a different cause. More importantly, because the source of each type of segregation is different, their solution must be directed at specific causes. As stated previously, segregation is defined as the separation of the coarse aggregate particles from the remainder of the mix; typically, the asphalt content also varies in inverse proportion to the coarse aggregate content within the segregated area. Segregation, except random, can be significantly reduced or prevented by limiting the distance the coarse aggregate particles can roll during various phases of the construction process (Button et al., 1997).

Random Segregation

Random segregation, sometimes called “rock-pocket segregation,” can occur in any lift of asphalt at variable locations, both transversely and longitudinally, along a roadway. The segregated areas may occur fairly regularly or only intermittently in the pavement mat. Rock pockets are generally caused by improper handling of the coarse aggregates at the asphalt plant — both at the aggregate stockpiles and at the cold-feed bins.

Pockets of coarse aggregates can occur in the aggregate stockpiles if those piles are improperly constructed. The coarsest aggregate particles tend to roll down the side of the pile and collect at the bottom. If this occurs, the front-end loader operator must re-blend the aggregate together before the material is picked up for transfer to the cold-feed bins. If the segregated aggregate is not re-blended, the loader operation will eventually place a bucketful of the coarser aggregate into a particular cold-feed bin, followed by a bucketful or two of finer coarse aggregate material. This can result in significant variation in the gradation of the paving mix produced, depending on the type of plant used.

Random segregation, even for large-stone mixes, is generally not a problem in a batch plant. In a batch plant operation, a variation in the gradation of the coarsest aggregates in the cold-feed bins will result in a change in the amount of material in the hot bins. So long as the plant operator does not run any individual hot bin empty or charge additional coarse aggregate into the mixture if a hot bin is overflowing, any segregation that occurs at the stockpile and cold-feed bins will be eliminated at the hot bins. Furthermore, the pugmill on the batch plant is very efficient in re-blending any segregated aggregate during the mixing process.

In a drum mix plant operation (either parallel flow or counter flow), however, segregation that occurs in the coarsest aggregate at the stockpile and/or at the cold-feed bins will typically show up on the roadway behind the paver. A drum plant operates on a first-in, first-out principle. Because these plants operate on a continuous basis, any material delivered from the cold-feed bins to the plant will pass through the plant relatively unchanged in gradation. Coarser-than-expected aggregate discharged from the cold-feed bins will be discharged from the drum mixer with only minimal changes in aggregate size and gradation.

Random segregation also may occur during the truck-loading operation. If a batch of mix is delivered from the pugmill, random segregation is rarely a problem because the mix is discharged in a mass from the pugmill into the truck bed. If the mix is delivered from a silo into the haul truck, random segregation may occur, depending on how the truck is loaded. Rock pockets or random segregation may readily occur if the plant operator continually opens and closes the discharge gate in the silo to deliver small quantities of mix into the truck to top off the load (Button et al., 1997).

Longitudinal Segregation

Segregation that occurs intermittently on one side of the paver is usually caused by improper loading of the haul trucks from the pugmill or silo. If the mix is not delivered into the center of the width of the truck bed, the coarsest aggregate particles in the mix can roll to one side of the truck bed and collect there. When the mix is delivered into the paver hopper, the segregated mix will be placed on the roadway along the same side, and the segregation will appear as an area of coarser texture in the longitudinal direction on one side of the paver only. This type of longitudinal segregation will generally be intermittent because most haul trucks tend to load into the middle of the width of the truck bed. If caused by improper truck loading, side-to-side segregation will also change sides at the paver depending on whether the truck was off center to the left or the right under the silo.

Longitudinal segregation that is continuous normally originates at the top of the silo. It is caused by the method used to deliver mix into the silo from the conveying device — drag slat conveyor, bucket elevator, or conveyor belt. The mix should be introduced into the center of the silo, either into the batcher or directly into the silo itself. If the mix leaving the slat or belt conveyor or bucket elevator is thrown to the far side of the silo, it will travel down that side of the silo and eventually be discharged into the same side of the haul truck. If the mix is deflected to the same side of the silo as the conveying device, the coarsest aggregate particles will roll and collect on that side of the silo, travel down that side of the silo, and be delivered into the same side of the haul truck.

Longitudinal segregation, if caused by the way the mix is charged into the silo, will always be on the same side of the paver. In addition, this type of segregation will be continuous. Therefore, if the haul trucks are brought under the silo from the opposite direction and loaded, the segregation should switch sides at the paver. This test can help isolate the cause of segregation (Button et al., 1997).

Longitudinal segregation can also be a result of the paver operations. The more common locations for longitudinal segregation on one or both sides of the paver are along the edges of the slat conveyors or along the outside edges of the augers. Longitudinal segregation along the edges of the slat conveyor was a common issue with some pavers and an anti-segregation kit was developed and deployed by manufacturers to eliminate this type of segregation.

Centerline longitudinal segregation is another type of segregation that occurs under the paver's gear box. This type can be a result of excessive wear on the kick-back flights that tuck the mix under the gear box.

Truckload-to-Truckload Segregation

Truckload-to-truckload segregation may occur at every location where a truck transfers mix to the paver, or it may occur only intermittently at transfer points down the roadway. The frequency of this type of segregation depends on the method used to load the haul trucks at a batch plant pugmill or silo. Furthermore, truckload-to-truckload segregation depends on the specific method used to transfer the mix from the truck bed to the paver hopper and the condition of the hopper between truckloads of mix.

In general, the truck-loading process from the silo at a batch or drum mix plant is the point at which this type of segregation occurs. To prevent truckload-to-truckload segregation, it is necessary to place some of the mix against the front bulkhead of the truck bed. It is also necessary to deposit some mix against its tailgate. Thus, the plant operator needs to pay particular attention to how and where the mix is discharged from the silo and placed in the haul truck bed.

Truckload-to-truckload segregation has been incorrectly described as "end of load" segregation. This type of segregation is really a combination of the last coarse aggregate particles from one truck bed and the first from the next truck bed. If a haul truck is loaded with mix in one or two drops in the center of the length of the truck bed, the coarsest aggregate particles will tend to roll down the mound of mix toward the front and the rear of the bed.

Another form of truckload-to-truckload segregation occurs when the paver operator completely empties the hopper of the paver between truckloads of mix. The coarse aggregate particles that have collected at the tailgate of the truck bed will be delivered directly into the bottom of the paver hopper and onto its drag slat conveyors. Those coarse, segregated particles will pass through the paver to the augers and then onto the pavement surface under the screed. As the haul truck is emptied, any coarse aggregate particles that have rolled to the front of the bed during loading will be delivered last into the paver hopper. If the hopper is nearly empty when this occurs, the segregated material will quickly appear on the surface of the roadway behind the paver. Thus, the process of delivering the mix to the paver and the condition of the paver hopper between truckloads of mix can either increase or decrease the magnitude of segregation (Button et al., 1997).

Eliminating Segregation

Because segregation is the major challenge for mixtures incorporating large-stone aggregate, some ways to overcome or minimize this problem are addressed throughout this chapter. The remaining sections focus on different aspects of mixture production and placement in terms of minimizing the occurrence of segregation and producing a high-quality heavy-duty mixture that is resistant to distress and maximizes the overall performance of the mixture. For a more detailed discussion of segregation, refer to the AASHTO–NAPA publication *Segregation: Causes and Cures for Hot Mix Asphalt* (AASHTO–NAPA, 1997).

Building Aggregate Stockpiles

Random rock-pocket problems can be reduced by building the stockpile, particularly one containing coarse aggregate, in layers and use the lowest stockpile height that space will allow. If stockpiles are not built up in layers, the coarsest particles tend to roll down the pile and collect around the perimeter. Stockpiles that are built by conveyor in a conical shape are the most susceptible to this type of segregation. In addition, as the size of the largest aggregate particle increases, segregation tends to increase.

If coarse aggregate particles do accumulate around the bottom of the stockpile, the front-end loader operator must re-blend the material before it is placed in the appropriate cold-feed bin. This may require significant manipulation of the pile to eliminate segregation. Stockpile management, both in terms of adding aggregate to the stockpile and its subsequent removal, is key to eliminating the rock-pocket problem on the roadway behind the paver.

Other precautions that may minimize segregation are to split the coarse aggregate into more size fractions for stockpiling and feed each individual coarse aggregate stockpile into more than one cold feeder. This latter step will allow the high volume of coarse aggregate to be divided into two bins, allowing each bin to be fed at a reduced rate, which will allow for better gradation control (AASHTO, 1997).

Asphalt Mixture Production

The following sections summarize potential detrimental impacts on the large-stone asphalt mixtures that can be a result of mix production. Most, but not all, are focused on aggregate segregation.

Batch Plant Operations

The operation of a batch plant is not normally a contributing factor to the occurrence of random segregation, longitudinal segregation, or truckload-to-truckload segregation. Differences in the texture of the finished mat may result, however, if proper stockpile management techniques are not used.

If the coarsest aggregate particles are segregated in the cold-feed bins, the aggregate will pass through the dryer without any significant blending with the other aggregate because the heating and drying process is a continuous-flow operation. After the aggregate is discharged from the dryer and travels up the hot elevator and across the screen deck, it is divided into sizes and deposited in the appropriate hot bin. So long as the operator regulates the plant consistently, does not empty a hot bin of aggregate or overflow a hot bin with too much aggregate, and maintains constant bin pulls from each hot bin, the gradation of the mix will be consistent. No random segregation problems will occur on the roadway because of the condition of the aggregate stockpiles.

A plant will become "out of balance" if the front-end loader operator feeds a few buckets full of coarser aggregates and then a full bucket or two of less coarse aggregate into a particular cold-feed bin. The coarse aggregate hot bins in the plant (bins Nos. 3 and 4 at the top of the tower beneath the screen deck) may run out of material or may overflow depending on the rate of delivery of the aggregate into the cold-feed bins and through the dryer.

If this occurs, the plant operator should shut the plant down, work with the loader operator to eliminate the cold feed delivery problem, and then restart the plant.

Drum Mix Plant Operations

For drum mix operations, care must be taken in how the coarsest aggregates are delivered into and removed from the stockpile, as well as how the coarsest aggregate particles are placed in the cold-feed bins, as discussed above. There is generally nothing in the operation of either a parallel-flow or a counter-flow drum mix plant (in the mixing drum itself) that contributes to either longitudinal or truckload-to-truckload segregation.

If segregated aggregates are deposited into the cold-feed bins, then the segregated material will pass through the drum mix plant without any significant blending with the other aggregates because of the continuous-flow process employed in drum mix plant operation. Indeed, the segregated mix will be discharged from the drum, travel up the slat conveyor and through the silo, be transported to the paver in the haul truck, and pass through the paver to the surface of the pavement layer being constructed. Random segregation can and does occur in drum mix plant operations. Proper stockpile management can solve random segregation.

Aggregate Drying Considerations

Drying and heating large-stone mixes may be more difficult than mixtures with smaller aggregates for two reasons:

1. It takes longer for heat to penetrate to the center of larger aggregates and to heat the stone thoroughly.
2. The veil of aggregate through which the hot air in the dryer passes is typically less dense, decreasing the efficiency of the dryer.

Theoretically, a change in the flight design or dryer slope to increase retention time of the aggregate in the dryer can be made, but because this disrupts production it may not be practical. Monitoring the difference between exhaust gas and mixture temperature may provide a check on the drying efficiency. The difference in temperatures should be small (NAPA, 1998).

When drying large aggregate size mixes, the dryer should be run at or near full capacity to keep the aggregate veil as heavy as possible. Material dams, or rings welded around the interior circumference of the dryer, may also be used to increase dwell time and veiling density. Some caution is advised in using dams as they increase exhaust gas velocities and may trap larger aggregates that may later end up in a finer mix.

Because of possible retained moisture and non-uniform heating, large aggregate size mixes may tend to exhibit two problems not often encountered in conventional mixtures. First, mixtures with large aggregates may cool more quickly than conventional mixtures, resulting in less time to adequately compact the mixture for the same lift thickness. As noted earlier, however, thicker lifts retain heat longer than thinner lifts everything else being equal. Second, if the large aggregate is not thoroughly dried, the retained moisture and the binder content may combine to produce a mixture with higher than desirable fluids content, creating a tender mix problem. This can become a critical issue when the aggregate has high absorption values and there is significant moisture in the stockpiles (Scherocman, 2000).

The hot bins in batch plants are designed so that the fine (No. 1) bin contains approximately 50 percent of the total hot-bin volume. The remaining hot bins (Nos. 2–4) contain the remaining approximately 50 percent of the total bin volume. The bins were designed in this manner because most mixtures have a high percentage of fine aggregate. With large-stone mixes, it may be difficult to keep the hot bins balanced and to prevent overflow of one of the bins. As a result, the cold-feed settings must be closely controlled (NAPA, 1998).

Silo Operations

It is important for the mix to be directed into the center of the batcher at the top of the silo (if a batcher is used) or into the center of the silo. Baffle plates or other deflection devices may be needed at the top of the silo to help solve the problem, particularly if the silo is not equipped with a batcher. Longitudinal segregation can readily occur when the mix is improperly delivered into the silo. The cause for this type of longitudinal segregation can be identified on the mat surface as summarized below:

- If side-to-side or longitudinal segregation occurs continuously on one side of the paver, then mix is being thrown to one side of the silo or batcher as it leaves the conveyor or elevator. In most cases, the coarsest aggregate particles in the mix will be flung to the far side of the silo and travel down that side.
- Side-to-side segregation that occurs intermittently and on both sides of the paver at different times is typically related to the position of the haul truck under the silo or under the pugmill of a batch plant. If the truck is off-center while being loaded, the coarsest aggregate particles in the mix, particularly in large-stone mixtures, may roll to one side of the truck bed. These coarse aggregate particles will be delivered into one side of the paver hopper and come out directly behind the screed on the same side of the paver.

The roadway should be inspected to determine if longitudinal segregation is continuous or intermittent and if it always occurs on one side of the laydown machine or on both sides. If the longitudinal segregation is intermittent and changes from side to side, the loading of the haul trucks at the plant should be investigated. Each truck should be loaded in the center of its bed from the center of the width of the batch plant pugmill or from the center of the silo discharge gate or gates.

If the longitudinal segregation always occurs only on one side of the paver, the direction the haul trucks are facing when being loaded under the silo should be reversed. For example, if the trucks normally load while facing north, some trucks should be loaded while facing south. When the latter trucks arrive at the paver, the segregation typically found on one side of the laydown machine should switch to the opposite side of the paver. If this occurs, it is confirmation that the longitudinal segregation is occurring at the top of the silo.

Prevention of longitudinal (side-to-side) segregation on the roadway begins at the top of the silo. Mix delivered to the top of the silo by slat conveyor, belt conveyor, or bucket elevator will be discharged to the far side of the silo by the natural centrifugal force of the conveying device, unless some means is used to redirect the flow to the center of the silo.

On some silos, a series of baffles are used to control the direction of the material. Other silos are equipped with a splitter system that divides the mix as it is delivered, causing a portion to be placed in each part of the silo. Use of baffle and splitter systems can reduce the tendency for longitudinal segregation on the roadway but does not always eliminate it. Use of a batcher system at the top of the silo is a better means to reduce this type of segregation.

Storage Considerations

There are two additional concerns for heavy-duty mixtures during production: excessive storage time and draindown in the silo.

Asphalt mix production plants are equipped with various types and sizes of storage silos. Storage silos are very useful for maintaining a continuous flow of trucks to the project site. The higher temperature required for some mixes, however, can result in excessive hardening of the binder if the mixes are stored in the silo too long (NAPA, 1998). Excessive hardening reduces the ability of the mixture to resist transverse and fatigue cracking.

Draindown of the binder in the silo is another potential concern and is the reason why evaluation of draindown susceptibility of a mixture is part of the mixture design procedure. For SMA, which typically has higher asphalt content, draindown is usually not a concern because the binder typically is a PMA and the mixture includes fibers to control draindown.

Loading & Delivery of Mix

Loading and unloading of the heavy-duty mixture is no different than for conventional asphalt mixtures, assuming best practices are followed. Heavy-duty mixtures are usually coarse- or gap-graded and can be susceptible to segregation. Thus, extensive discussion is included in this section of eliminating truckload-to-truckload segregation because it is so detrimental to long-term pavement performance for any mixture.

Loading of Mix at the Plant

The objective of the truck-loading operation is to fill the haul truck with mix and transport it to the paver as quickly as possible. This objective must be balanced, however, with the need to minimize any segregation of the mix that occurs during loading. The primary cause of truckload-to-truckload segregation is improper loading of the haul truck with mix from the silo.

Proper loading procedures dictate multiple drops of mix into the truck instead of only one or two drops. This is necessary to minimize the distance the coarse aggregate particles can roll and to keep the mix consistent in gradation throughout the entire load. Using multiple drops of mix under the surge silo means that the truck should not be loaded by discharging the mix in only one or two drops into the center of the length of the truck bed and the truck cannot be loaded while moving slowly forward under the silo during loading. If multiple drops are not used, the coarsest aggregate particles in the mix will tend to roll back to the tailgate of the truck bed or to its bulkhead.

It is important to deposit the mix in a mass into the haul truck. The gates on the bottom of the cone should be opened and closed quickly. The gates should also open completely so that the flow of mix is unrestricted. There is only one reason to cut off the flow of mix into the vehicle once delivery has started — in order to divide the delivery of the mix among different segments of the truck bed.

End Dump Trucks

If a tandem axle or a triaxle end dump truck (Figure 7-1) is used to haul the mix, one drop of the material must be placed as close to the bulkhead of the bed of the haul truck as possible. In addition, another drop should be placed as close to the tailgate of the haul truck bed as possible. Both drops will minimize the distance the coarse aggregate particles can roll to the front and rear of the truck bed. For either of these two types of trucks, a third drop of mix should be placed into the truck bed between the first two drops. Further, to ensure that the proper amount of mix is placed against the tailgate of the truck, it is good practice to place the first drop of mixture at the rear of the truck bed, the second drop at the front of the truck bed, and the third drop between the first two drops of mix.

Semi- and Live-Bottom Trucks

If a semi-truck and trailer-type haul unit (Figure 7-2), including live-bottom trailers, are used by the contractor, the loading sequence should be as follows: the first drop should be made into the rear of the truck bed as close to the tailgate as possible. The truck should then back up and the second drop should be made into the truck bed as close to the front of the truck bed as possible. A series of additional drops should be placed between the first and second drops.

Using multiple drops from the silo to load a haul truck can help to avoid truckload-to-truckload segregation.

The number of additional drops depends on the length of the semi-trailer truck bed. In general, at least three additional drops should be made, for a total of five drops. In no case should the bed of a semi-trailer be loaded while the truck is moving slowly forward under the silo. This action causes a preponderance of the coarse aggregate particles to roll toward the tailgate area of the truck bed. Truckload-to-truckload segregation is a combination of both the end of one load of mix (at the front of the truck bed of the first truck) and the beginning of the next truckload of mix (at the tailgate of the truck bed of the second truck). Thus, segregation can be eliminated by depositing the mixture into the truck bed as close as possible to the bulkhead and tailgate (refer to Figure 7-2).

For live-bottom trucks, after the first drop of mix has been made at the rear of the truck bed, it may be acceptable to move the truck backward and then load the truck from front to rear with the truck moving slowly forward for some dense-graded mixes; however, this should *never* be done with large aggregate size mix. When mix delivery reaches the rear of the truck bed, it will contact the mix already placed during the first drop. Normally, any coarse aggregate particles that have rolled toward the rear of the bed will be mixed in with the remainder of the mix as the conveyor in the bottom of the truck pushes the mix out the back of the truck. *However, because they tend to segregate more, this loading procedure is not recommended for large aggregate size mix. Distinct, multiple drops of mix into the live-bottom truck bed should be used for large aggregate size mixes.*

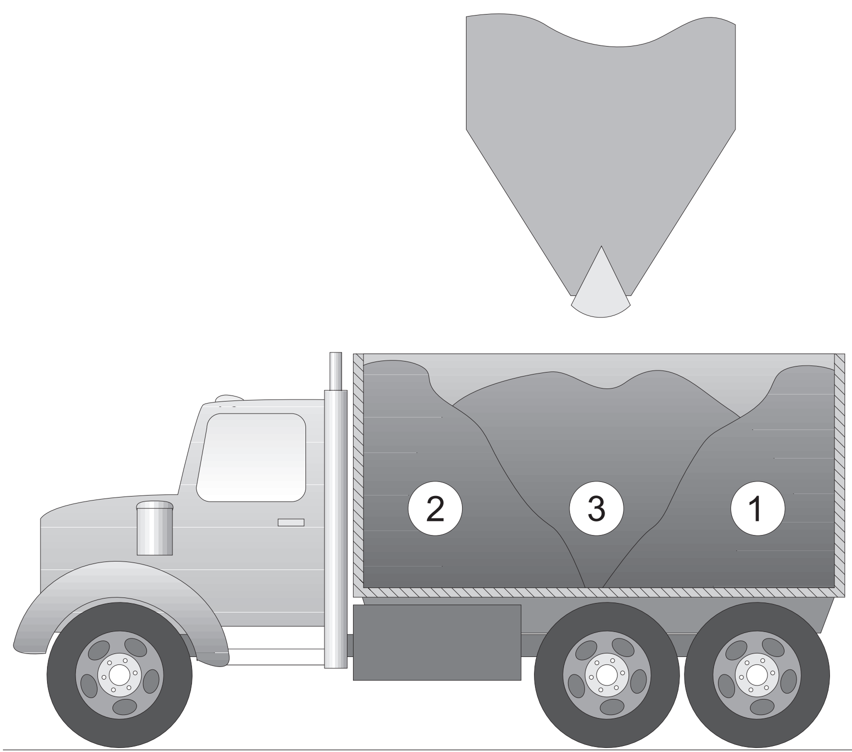


Figure 7-1. Proper Loading Sequence to Reduce Truckload-to-Truckload Segregation

Weight Limits

In many states, weight distribution laws do not permit a contractor to place the same amount of mix into the truck bed at each drop of mix from the silo. In most cases, it is necessary to deposit less mix into the rear of the truck bed than in the rest of the truck bed. Local laws must be checked to determine how much mix can be placed over the rear and front axles of the truck. For example, if a tandem axle or triaxle dump truck is used, about 20 percent of the total weight of mix to be hauled should be loaded into the middle of the rear half of the truck bed.

The truck should then be backed up so that the next 40 percent or so of the total load can be deposited into the middle of the front half of the bed, near the front wall. The vehicle should then be moved forward again so that the remaining 40 percent of the mix can be dropped into the center of the bed, between the first two drops. The actual amount of mix deposited into the truck on each drop will depend on the length of the truck; the number, configuration, and spacing of the axles; and the weight distribution requirements.

One practice that should not be permitted, especially for large aggregate size mixes, is topping off a truckload of mix to attain the maximum legal weight for the haul truck. In many cases, the haul truck is sitting on a scale under the silo as it is loaded. The plant operator wants to maximize the amount of mix the truck hauls to the paver. If the total weight of the truck is not at its maximum, the plant operator might open the silo gates briefly to add a little extra mix to the load. If the small drop is not enough, the silo gates might be opened additional times to fill the truck to the legal weight limit.

The primary problem with this sort of loading operation is that the small drops of mix fall on top of the mounds of mix already in the bed. The large aggregate particles in the mix roll down the slope to the front of the haul truck bed and to the tailgate. This can significantly increase the amount of segregation that occurs with each truckload of mix.

Belly-Dump Trucks

For many dense-graded mixtures, bottom- or belly-dump trucks (Figure 7-3) can be loaded directly over the discharge gates at the bottom of the bed, and segregation will not normally be a problem because the discharge gate is the lowest point in the truck bed. With large aggregate size mix, however, the coarsest aggregate particles tend to roll to the front and rear of the bed from the top of the load as the mix is delivered from a silo into the center of a belly-dump truck. The coarsest aggregate particles, in the top four corners of the load, are discharged last from the belly dump truck. In this case, segregation occurs at the end, rather than the beginning, of each truck load delivery.

Therefore, for large aggregate size mix, a bottom- or belly-dump truck should also be loaded in multiple drops. If the truck bed has only one discharge gate, the first drop of mix should be in the center of the truck bed, directly over the gate. Depending on the size of the truck bed, up to 70 percent of the total weight of the load should be delivered on the first drop. Before the truck is fully loaded, however, the truck should be moved backward and part of the load placed at the front of the bed. Then the truck should be pulled forward and the remainder of the load should be placed on the rear.

If the belly-dump truck has two discharge gates, the first drop of mix should be placed directly over the front gate. The truck should then be moved forward and the second drop of mix should be deposited directly over the rear gate. Drops three and four should be made on the front of the bed and on the rear of the bed. This procedure will greatly reduce the distance the coarsest aggregate particles can roll and will significantly decrease the probability of segregation.

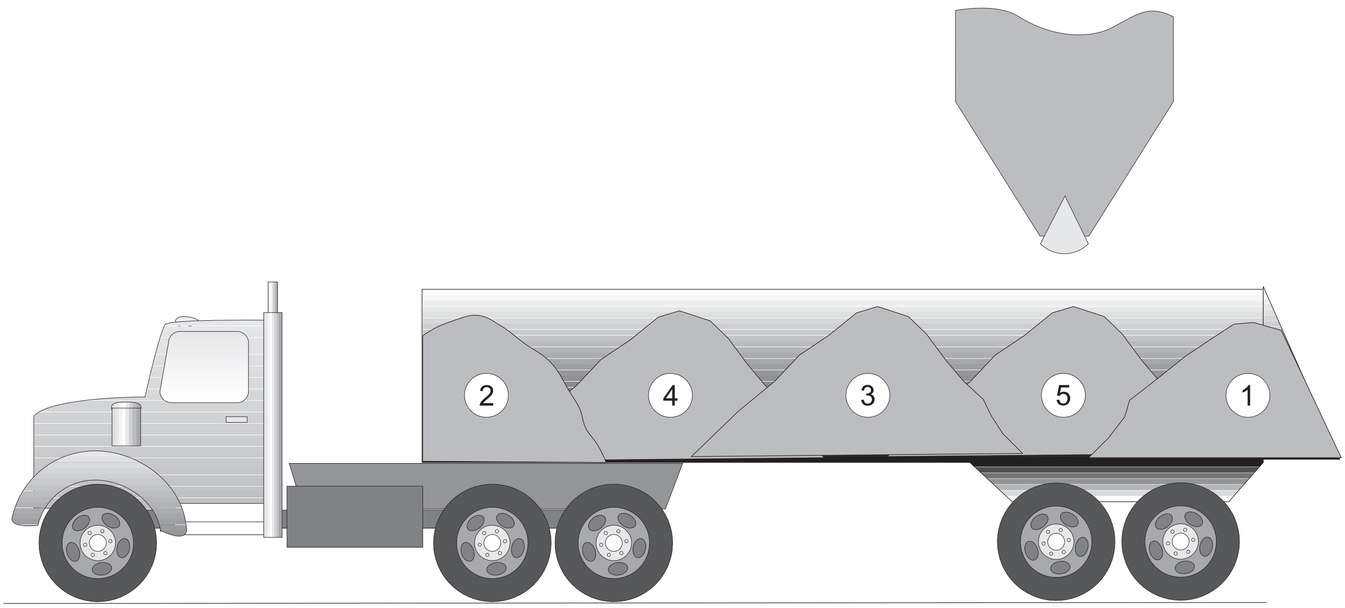


Figure 7-2. Proper Loading Sequence for Semi- and Live-Bottom Truck Loading

Time Needed for Loading

The truck loading procedures recommended here, using multiple drops of mix into the truck bed regardless of the type of truck, will increase the time needed to fully load the truck. However, this will not typically increase the cost of mix delivery because plant production capacity normally controls the overall rate of the construction process. For example, assume that the plant capacity is 400 tons per hour and the triaxle haul trucks can legally carry 20 tons of mix per load. Twenty trucks per hour will then be needed to deliver the mix produced to the paver. Therefore, approximately 3 minutes are available to load each truck. Because only about 20 seconds are needed to place a drop of mix into the truck bed, plenty of time is available to load the trucks with three drops of material per truck and move the truck between drops.

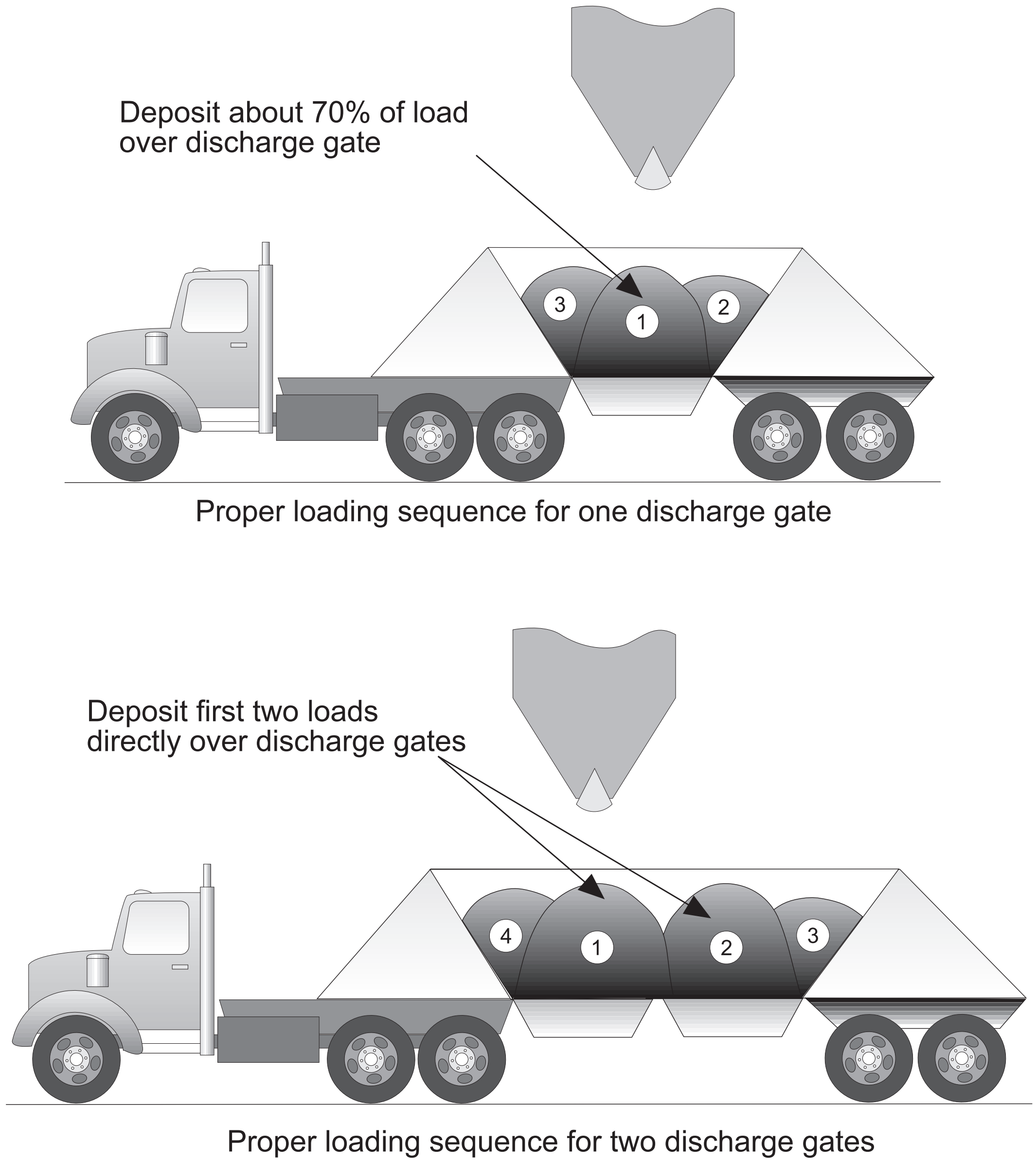


Figure 7-3. Proper Loading Sequence for Belly-Dump Truck Loading

Truckload-to-truckload segregation is minimized by loading the haul truck correctly at the asphalt plant. The contractor's cost to correct severe segregation or the agency's cost of reduced pavement life resulting from segregated mix on the surface of the roadway will typically outweigh the extra cost, if any, associated with properly loading the truck.

Unloading Mix at the Paving Site

Just as how a truck is loaded can influence the potential for mix segregation, the unloading of mix at a paving site can also influence the chance for segregation. In general, mix is unloaded directly into the paver hopper, into windrows, or into a material transfer vehicle.

Dumping Directly into the Paver Hopper

Unloading procedures used to deposit the mix into the paver hopper from the haul trucks are also important to minimize segregation. If an end-dump truck is used and if the mix being delivered to the paver tends to segregate, the truck driver should raise the truck bed, with the tailgate closed, to the point where the mix shifts toward the tailgate of the truck (Figure 7-4). The bed should remain partly raised while the truck driver is waiting to deliver mix to the paver (while another truck is in front of the paver) and also while the truck is backed into position at the paving machine.

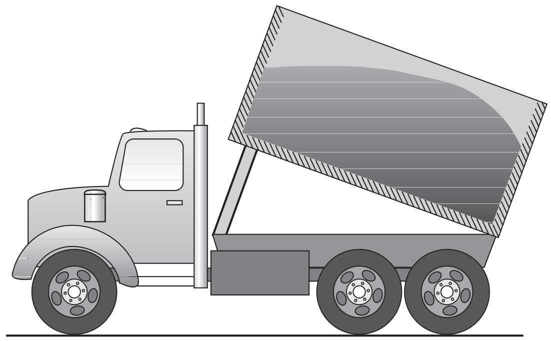
Once the truck and the paver are in contact, the tailgate should be opened and the mix discharged into the paver hopper. This procedure will deliver the mix from the truck in a mass and "flood" the hopper of the paver, reducing the probability of segregation behind the paver screed. When the mix is moved as a mass, the coarsest aggregate particles will not have a tendency to separate or roll away from the remainder of the mix.

For end-dump truck operation, the driver normally waits until the truck bed is empty before raising the bed to its highest position. This action causes all the coarsest aggregate particles collected in the front corners of the bed to tumble into the paver hopper as individual particles, instead of moving into the hopper as part of the mass of mix. It is much better to raise the truck bed to its highest position when 20–30 percent of the load is still in the bed. This permits incorporation of the coarse aggregate particles in the front corners of the bed into the remaining mass of mix and will, in turn, significantly reduce the segregation that occurs at the end of each truckload.

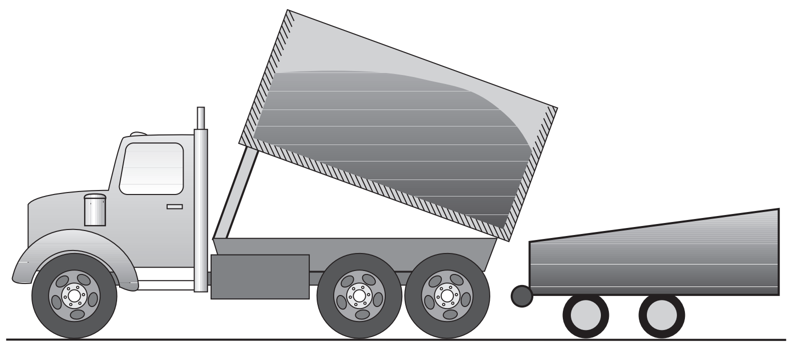
When a live-bottom truck is used to transport the mix, the belt or slat conveyor should be started for a few seconds before the end gate on the truck is opened. This will create a mass of material that can be delivered to the hopper, instead of allowing any coarse aggregate particles that have rolled to the rear of the truck bed or end gate to be discharged into the hopper first.

Dumping into Windrows

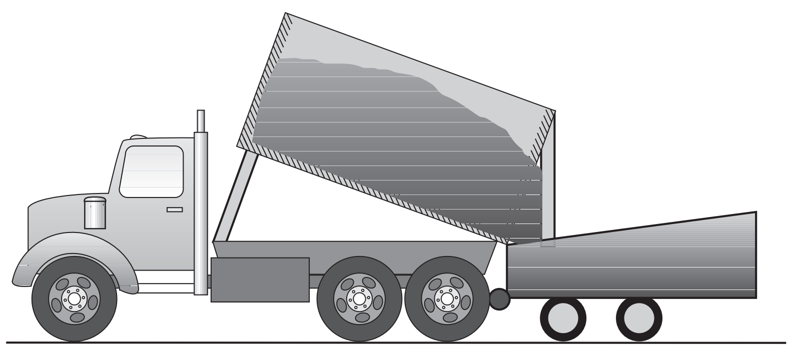
A bottom- or belly-dump truck can be used to deposit mix in an elongated pile, called a windrow, ahead of the paver. A windrow elevator then carries the mix from the ground to the paver hopper. A windrow-sizing box should be used to control the dimensions of the windrow. With the box in place, the gates on the bottom of the truck bed can be opened wide to discharge a mass of mix rather than a trickle. If truck discharge is controlled manually, the gates should still be opened wide so that the mix is deposited in a mass onto the roadway. Windrow size should be controlled by the forward speed of the haul truck and should match the cross-section of the mat being paved to ensure the paver hopper does not run out of mix or become



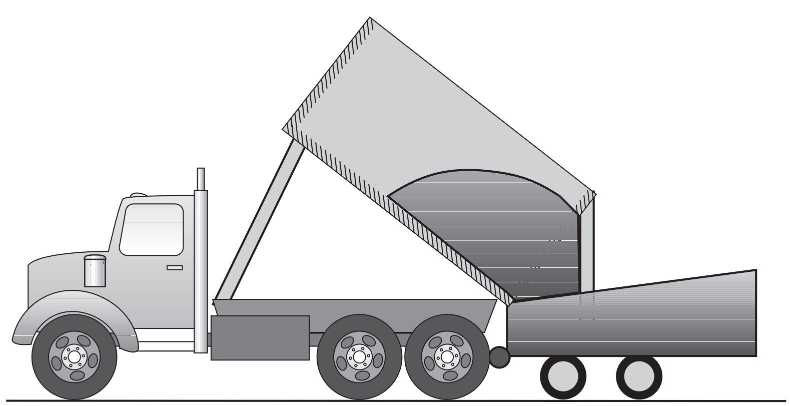
Break load before backing up to paver.



Back up to paver, stopping just short of paver.



Paver pulls forward, picking up truck. Release gate and break.



Raise bed completely when 20–30% of load remains in truck.

Figure 7-4. Proper Dump Operations

overloaded (NAPA, 2002).

If coarse aggregate particles are visible on the top of the windrow at the end of the discharge of the mix from the belly dump truck, this material should be distributed down the roadway and not left in a pile at the end of the load. This can be done by almost completely closing the discharge gates on the truck just before the bed is empty and keeping the truck moving forward until the bed is empty. This procedure is unnecessary, however, if the truck is loaded properly at the plant.

Dumping into a Material Transfer Vehicle

Another method used to deliver mix to the paver is with a material transfer vehicle (MTV). The MTV allows almost continuous paver operation (without stopping between truckloads of mix) if a continuous supply of mix is available from the asphalt plant. This provides for a smoother mat behind the paver screed because the paver operator can keep the head of material in front of the screed constant by supplying a continuous flow of mix back to the screed. The equipment also prevents the haul trucks from bumping the paver and truck drivers from applying their brakes when the truck is being pushed by the paver.

MTVs windrow elevators are capable of remixing materials to varying degrees. Some devices include mixing augers and/or paddles to blend materials before they are transferred to the paver hopper. Some devices use paver hopper inserts with mixing paddles to help remix materials. Whether or not an MTV is used, loading the haul trucks properly at the asphalt batch or drum mix plant and proper dumping of the mixture will help in preventing segregation.

PMTP quantified the benefit of using an MTV in placing asphalt mixtures through mat surface temperatures during the field demonstration projects. Table 7-1 summarizes the number of severe temperature differentials with and without the use of an MTV. As shown, the percentage of severe temperature differentials with an MTV was less than 10 percent for many projects, while that percentage increased to over 40 percent when an MTV was not included.

Asphalt Mixture Placement

Additional considerations must be made during placement of heavy-duty mixes to ensure a successful paving project.

Table 7-1. Summary of Overall Results from Demonstration Projects, including Paver Stops (Reiter et al., in press)

Demonstration Project	Delivery Truck Type	MTV Included	Percent Severe Temp. Differentials	Thermal Streaking
Alaska	Bottom Dump	Windrows	17	None
Alabama	End Dump	Yes	4	None
Maine	End Dump	Yes	5	None
Illinois	End Dump	Yes	7	None
Virginia	End Dump	Yes	5	None
North Carolina	End Dump	Yes	18	None
New Jersey	End Dump	Yes	21	None
Missouri	End Dump & Live Bottom	Yes	25	None
West Virginia	End Dump	Yes	5	None
West Virginia	End Dump	No	41	None
Illinois	End Dump	No	40	None
Eastern Federal Lands	End Dump	No	83	None

General Paving Considerations

It is important that mixtures be placed in thick enough lifts to allow for adequate compaction and avoid excessive aggregate breakage. It is suggested for large aggregate size mixes that the layer thickness be equal to or greater than four times the nominal maximum aggregate size in order to reduce the tearing of the mat under the paver screed and obtain a more uniform surface texture (NAPA, 1998).

Yield is often difficult to check when placing heavy-duty mixtures using large aggregate sizes. Many paver screed operators use a probe to periodically check the mat thickness of conventional mixes being placed by a paver. The angle of attack of the screed is then adjusted to increase or decrease the mat thickness as needed. A better procedure is to periodically check the yield by comparing the amount of mix actually placed over a particular length and width of pavement to the quantity of material planned for placement over that area. If the values are significantly different, a small adjustment should be made in the angle of attack of the screed.

In a properly designed large aggregate size mixture, it is difficult to push any type of rod or probe through the layer being constructed because of the amount of coarse aggregate in the mix and the thickness of the mat. Thus, using a probe stuck into the mat behind the screed can convey misleading measurements, which could result in an improper adjustment to the angle of attack of the screed (Button et al., 1997). A large aggregate size mixture can also have less roll down under the screed because of the larger size aggregate even if a vibratory screed is used.

Surface Preparation & Tack Coats

Bonding asphalt lifts together is a critical factor in the long-term performance of all asphalt pavements. However, it is more critical relative to heavy-duty mixes because of the higher stresses and potentially larger horizontal stresses at the interface between lifts or layers caused by slow-moving vehicles and/or turning movements of concentrated wheel loads.

Tack coats should be used between all lifts of heavy-duty pavements at the proper application rate uniformly applied over the entire surface. AASHTO TP 114-17, *Provisional Standard Method of Test for Determining the Interlayer Shear Strength (ISS) of Asphalt Pavement Layers*, is available to help ensure adequate bond exists between the different asphalt lifts and layers. The Louisiana Transportation Research Center developed and prepared this test method under NCHRP Project 09-40 (Mohammed et al., 2012). NCAT developed another test method to measure the bond strength between two asphalt layers for the Alabama DOT (West et al., 2005).

Mixture Placement

The paver operator should keep the paver hopper at least half-full between truckloads of mix to minimize segregation. The coarse aggregate particles delivered into the hopper from the end of one truckload and the beginning of the next will be deposited into the mass of mix already in the hopper. Thus, the amount of segregation that occurs on the road surface will be significantly reduced. If the paver operator empties the hopper between truckloads, the degree of segregation that occurs on the pavement surface may be increased. If the paver operator dumps the wings on the sides of the paver hopper between truckloads of mix, the amount of segregation will be further increased.

After the haul truck has deposited all its mix into the paver hopper, the truck driver should be directed to quickly lower the truck bed and drive away. Mixture delivery should be scheduled to allow for continuous paving operations whenever possible, but if the paver hopper reaches the half-full point, the operator should quickly and smoothly stop the paver until the next truck is backed up to the paver. The paver operator then picks up the truck and the operator smoothly and quickly accelerates to the desired paving speed and maintains the paver hopper at least half-full.

The wings at the sides of the paver hopper should not be emptied between truckloads of mix. Coarse aggregate that accumulates in the front of the truck bed typically slides down the sides of the bed last-and into the wings on the paver. The problem is that when the wings are dumped into an empty hopper, all the coarsest aggregate particles that have collected in the wings are deposited in the bottom of the hopper on top of the slat conveyors. When the conveyors are started, all that segregated material is carried back through the paver and delivered to the augers. This results in a segregated pavement surface.

One possible solution is to allow mix to accumulate in the corners of the paver hopper over the course of the day. At the completion of paving, the cold material in the hopper wings is wasted or returned to the plant for recycling. Another solution is to slightly reduce the capacity of the hopper by placing a fillet or cutoff plate for each back corner of hopper. This will prevent mix from collecting in the corners, making dumping of the wings unnecessary. Segregation of large aggregate size mixes can be greatly reduced by not dumping the wings.

During paving, the flow gates at the rear of the paver hopper must be set so that the slat conveyors at the bottom of the hopper operate as close to 100 percent of the time as possible. This will supply a relatively constant head of material to the augers in front of the paver screed and allow the paver screed to ski at a constant angle of attack. If the paver operator empties the hopper between truckloads, the head of material in front of the screed will decrease as the augers are emptied of mix, and the thickness of the mat being placed will decrease.

The combination of emptying the hopper, folding the wings and depositing segregated material from the end and beginning of truckloads can result in severe truckload-to-truckload segregation.

Longitudinal Joint Construction

Longitudinal joint construction should follow best practices. The paver and rollers used to place and compact longitudinal joints for heavy-duty or large-stone mixtures are no different than for conventional asphalt mixtures.

The only difference is the thicker lifts required for larger stone mixtures. The thicker lift thickness creates a safety hazard for higher speed traffic or motorcycles when placed as an overlay on existing roadways, such as the interstate system, due to the dropoff from the new overlay to the existing pavement in a neighboring lane. The larger stone mixtures should not be used under traffic, except when the roadway is closed to traffic until after all lower layers with the larger stone mixtures have been placed.

It is recommended that echelon paving be used whenever possible to reduce the number of longitudinal joints with a hot and cold side. Echelon paving creates a better joint with higher densities because both sides of the longitudinal joint include a hot side.

Handwork

For most asphalt paving projects, some handwork is necessary around catch basins, manholes, curbs, and driveways and in the comers of the pavement at intersections. In these cases, the paver operator usually feeds extra mix back through the paver and the laborers on the paving crew manually shovel the mix to the proper location. Once the mixture has been moved into its approximate final position, it is further spread with a rake or lute to provide a uniform pavement surface ready for compaction.

Handwork is difficult, at best, with mixtures containing large aggregate sizes and should be avoided wherever possible. Because of the size of the aggregate in the mix and because of the relatively thicker lift typically being constructed, it is not realistic to expect laborers to move the mix by hand. For large aggregate size mix, the paver operator must use the machine to place the mix as close to its final position as possible. This means more maneuvering of the paver and perhaps a slightly slower paving operation, depending on the layout of the project.

In some locations, particularly areas which do not receive much direct traffic action, consideration should be given to using a conventional dense-graded base course mix in place of a large aggregate size mix in areas where handwork is required.

It is difficult to properly level large aggregate size mixes with a rake or lute. In addition, large aggregate size mixes will not be as dense as a conventional mix when moved by hand. This means raking must leave large aggregate size mixes higher than the elevation of the surrounding mix in order to achieve the proper density after final compaction. *For good construction, large aggregate size mixes should be placed by the paver, instead of by hand, wherever possible.*

For the same reasons, broadcasting of large aggregate size mixes back over a mat already placed by the paver should never be done. In most cases, the added mix will sit on top of the previously placed mat and will not blend well with the original mix. After compaction, the broadcasted mixture will cause the "repaired" area to have a different surface texture and a different density than the mat adjacent to that area.

If it is necessary to place additional large aggregate size mix in a location that lacks mixture for some reason, care must be taken to place the new mix only in the area that needs to be filled or repaired and not to spread mix over the surrounding pavement surface. This means, once again, that any handwork with large aggregate size mix is more difficult and time consuming than handwork with a conventional, dense graded mix.

The paver operator should overlap the top of the mat in the adjacent lane by 1.5 inches (63 mm) or less. Then, no raking of the longitudinal joint will be necessary because the paver will place the correct amount of mix in the proper location. Because of the difficulty of moving the mix by hand (shovel or rake or lute), the mix should be placed in the correct position by the paver instead of by the rake.

Attempting to rake a longitudinal joint constructed of large-stone mix is difficult and tiring. In addition, large aggregate particles that are pushed back across the new mat will not roll into the mat properly and will create variations in density and mat texture. Thus, the best longitudinal joint that can be constructed with large aggregate size mix is one placed by the paver screed and not raked at all.

Compaction or Rolling Operations

Compaction is the single most important factor in the ultimate performance of a properly designed and mixed asphalt pavement. As a result of compaction, the asphalt-coated aggregates in the mix are forced together, which increases aggregate interlock and interparticle friction and reduces the air voids content of the mix. Adequate compaction of the mix increases the fatigue life, decreases permanent deformation (rutting), reduces oxidation or age hardening, decreases moisture sensitivity, increases strength and stability, and decreases low-temperature cracking.

A paving mix that has all the desirable mix design characteristics will perform poorly under traffic if it is not compacted to the proper density (Button et al., 1997). Mixes with large-sized aggregate may require levels of compactive effort and rolling patterns or procedures that are considerably different from those used on conventional mixes. The rollers, however, used for these mixes are no different than those used on conventional mixes.

Test or Control Strips

The actual rolling pattern used to compact the mix on a paving project should be determined at the inception of the project through the construction of a roller test strip. It is important that this strip be located at a convenient point where the test layer will remain in place as part of the final pavement structure. The condition of the underlying layers at the test strip location should be representative of those on the remainder of the project. The mix should also be representative of the material to be produced for the project, and the thickness and width of the layer placed should be the same as that shown on the plans for the large-stone mix course.

The test strip should be placed and compacted at the same temperature using the same construction techniques as are planned for the construction process. This will allow an evaluation of how the mixture will act under specific rollers. It is important at this point to develop a correlation between the densities measured from the nuclear gauge readings and cores cut from the pavement. If necessary, more than one test strip should be placed to assure that adequate densities are obtained (NAPA, 1998).

Rolling Procedures

To compact large-stone mixtures properly, a different rolling pattern may be necessary than when compacting a conventional mixture with smaller aggregate for several reasons. In general, the larger aggregate sizes can require more compactive effort to increase the density of the mix, but placing thicker lifts will allow for more time to complete compaction.

Breakdown Rollers

When a vibratory roller is used in the breakdown position to compact a large-stone mix, the roller should be operated at the highest possible frequency setting and with an amplitude setting that is related to the thickness of the layer being compacted. For large-stone mixes more than 4 inches (100 mm) in compacted thickness, the amplitude setting on the vibratory roller should be high. For large-stone mix courses between 2 and 4 inches (50 mm and 100 mm) in compacted thickness, the amplitude setting should be set on medium (if the roller has a medium-amplitude setting). If the roller does not have a medium-amplitude setting, the roller test pattern should be conducted twice, once with the amplitude setting on low and again with the amplitude setting on high, to determine the most efficient setting to obtain the required density level (Button et al., 1997).

One of the primary problems with using a vibratory roller in the high-amplitude setting in the breakdown rolling position is fracture of the larger aggregate in a large-stone mix. The amount of fracture depends on several factors, including gradation of the mix, hardness of the coarse aggregate, thickness of the layer being compacted, and speed of the roller. If the amount of fracture experienced becomes excessive, the compactive force of the vibratory roller should be reduced from the high-amplitude setting to a medium or low setting. This change in compactive effort, however, may significantly reduce the effectiveness of the vibratory roller, and more roller passes may be needed to achieve the same air voids content as at the higher amplitude setting.

When pneumatic-tire rollers are used, the tire pressure should be approximately 80 to 90 psi (550 to 620 kPa) or greater, and the weight per wheel should be a minimum 2,800 to 4,500 pounds (1,270 to 2,040 kg). If the pneumatic-tire roller is used in the breakdown position, the tires on the roller must be heated to the same temperature as the mix to prevent pickup on the tires. This means that early in the morning, before paving begins, the pneumatic-tire roller should be operated on the old pavement for 5 to 15 minutes (depending on environmental conditions) to build up heat in the tires before the roller is placed on the mat.

It may be necessary for the pneumatic-tire roller to operate on the mat behind the vibratory roller for 5 to 10 minutes until the temperature of the surface of the tires approaches the temperature of the mat and pickup of the mix ceases. In this regard, using the pneumatic tire roller in the breakdown position on large-stone mixes is no different than using the same roller in the breakdown position on a conventional, dense-graded mix. Because of the size of the aggregate and the thickness of the large aggregate size mix layer, however, consideration should be given to using the largest pneumatic tire roller available (Button et al., 1997).

When a nuclear density gauge is used to measure the density during compaction, the surface texture created by the coarse mix or by the roller type, particularly when a pneumatic roller is used, may be irregular, creating an erroneous reading. However, this same problem occurs when the pneumatic roller is used for initial compaction of a conventional, dense-graded mix. Nuclear gauge density measurements need to be made after the vibratory roller in the intermediate position has made at least two passes over the mix. Cores cut from the compacted pavement in the test section should be used to determine the actual level of density achieved for each roller pattern tested.

Intermediate Rollers

If a vibratory roller is used in the intermediate position behind a pneumatic-tire roller, it should be operated in the low-amplitude mode. When operated at a high-amplitude setting in the second rolling position, the vibratory roller will often cause a significant amount of fracture of the coarse aggregate in the mix. Finish rolling should be completed using a static steel-wheel roller in the conventional fashion.

As with any mix, desired density levels are easier to obtain when the mix is hot. Because the internal stability of a large-stone mix is generally greater than that of a conventional mix due to the increased degree of aggregate interlock in the mix, all rollers can typically operate closer to the paver. Instead of using the traditional roller train concept with one breakdown, intermediate, and finish roller, consideration should be given to using two intermediate vibratory rollers in tandem (side by side) following the pneumatic-tire breakdown roller. This compaction procedure should ensure that the desired level of density is obtained in the mix with a minimum of roller passes.

Temperature-Sensitive or Tender Zone

On some large-stone mixes, especially those designed by the Superpave method, a tender zone may exist for the mix in the temperature range of 240–190°F (116–88°C). In such cases, the mixture can be satisfactorily compacted above and below this range, but the mixture is tender within the temperature range and cannot be adequately compacted. The mixture may be satisfactorily rolled with pneumatic rollers within this tender range, however (NAPA, 1998).

When a mixture is produced that is tender in the mid-temperature range, the preferred compaction method is to obtain the necessary density prior to cooling to the tender zone. This may require an additional breakdown roller or other changes in the rolling technique. In some cases, the mixture temperature may be increased slightly to provide more compaction time before the tender zone is reached. However, excessive temperatures may magnify the problem.

The use of two double-drum vibrating rollers in tandem has proven effective in obtaining an adequate level of compaction prior to the temperature reaching the tender zone (Scherocman, 2000). Another alternative is to use a vibratory breakdown roller above the tender zone, followed by a pneumatic roller in the tender zone. The finish roller should be used after the mixture has cooled below the tender zone (NAPA, 1998).

If the tenderness problem produces a pavement with poor in-place density, or if the paving train length is excessively long due to the time required for the mixture to cool, adjustments in the mixture design must be made to eliminate or reduce the temperature tenderness zone. To correct this problem, it is important for the paving crew working at the laydown site to communicate with plant personnel (NAPA, 1998).

8 Quality Control for Production & Construction

Quality control for large aggregate size mixtures is the same as for conventional asphalt mixtures, but there are some challenges that are discussed below.

Mixtures containing large aggregate sizes will have a different appearance than a conventional mix, particularly fine-graded mixtures. Mixtures with large aggregate size may tend to look rich, primarily due to the low surface area of the aggregate, and may exhibit macro-texture that might be incorrectly classified as segregation. Care must be taken to not make changes in the mixture based on appearance alone. Volumetric properties must be measured to provide the information needed to determine if changes are necessary (NAPA, 1998).

Sample and core size for larger stone heavy-duty mixtures are generally larger in comparison to conventional smaller aggregate size mixes. Sampling the heavy-duty mix from the paver hopper or roadway can also be difficult due to the larger aggregate and stiffer binders. In general, sampling at the plant using mechanized sampling techniques reduces biases from the sampling operation. For conventional asphalt mixtures with smaller aggregate sizes, 4-inch diameter cores recovered from the asphalt lift are typically required. For large-stone, heavy-duty mixes, 6-inch diameter cores are generally required to obtain more accurate measurement of the specified volumetric properties.

Generally, the aggregate properties specified are for the blended material and not for each individual aggregate. Thus, testing should be performed on the blended aggregates. Care must be taken when selecting the sample location so that it provides a realistic representation of the gradation being produced. Also, because it is the blended aggregate that is important, RAP, when used, should be included in the analysis.

When aggregate samples are obtained from stockpiles prior to introduction to the plant, the properties may be different than after mixing. The aggregate may tend to become more rounded as it tumbles through the dryer. Fine aggregate angularity may be reduced by this action, and more fines may be generated as the aggregate passes through the plant.

As discussed above, there is a tendency for the coarse aggregate to break down more than conventional asphalt mixtures. So, there may be some changes in the volumetric properties for large

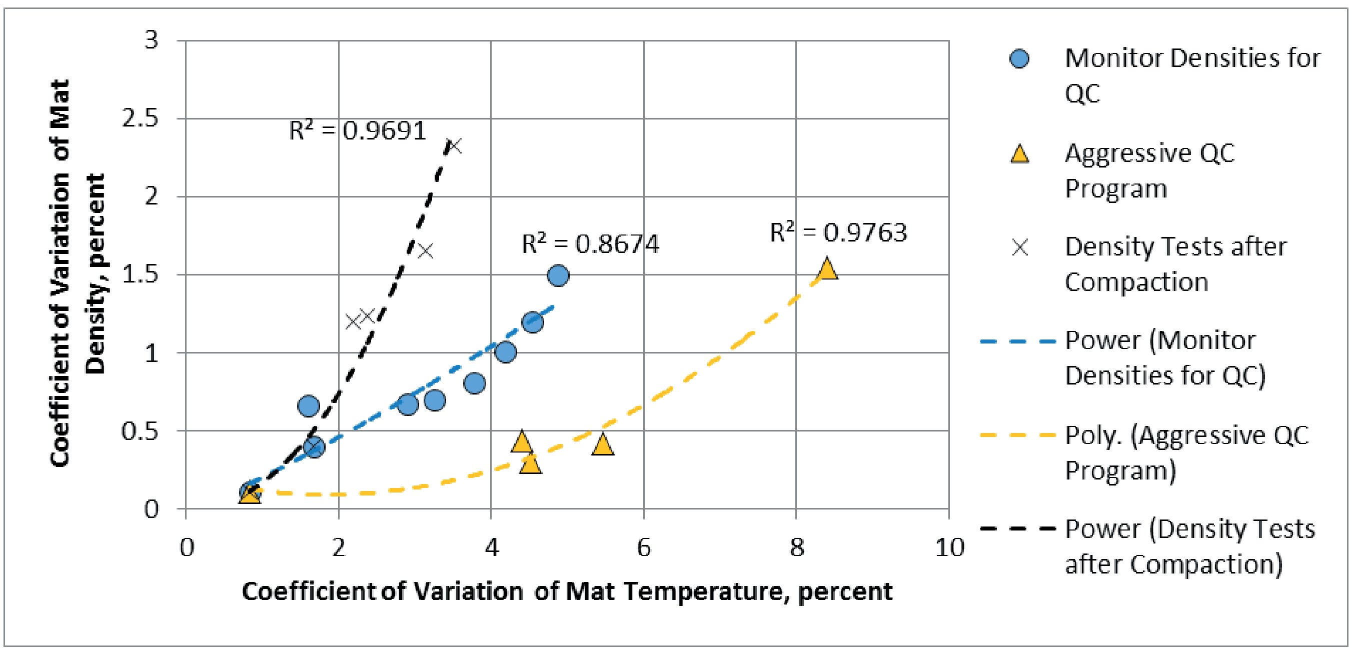


Figure 8-1. Mat Density Coefficient of Variation as Related to the Mat Temperature Coefficient of Variation

aggregate size mixes after production. Knowing the extent of these changes is helpful when conducting the mixture design so that an estimate of the aggregate breakdown can be considered in the mixture design process.

Aggregate testing for mixtures incorporating large aggregate sizes should be performed similarly to that for conventional mixtures. However, there is some possibility that the sensitivity of the mixture to gradation changes may be greater for mixtures with large size stone. Therefore, the uniformity of the aggregate and of the aggregate feed is important. Calculating the yield frequently to assure the thickness placed is consistent with the specifications is important because the thickness determined from the pavement design procedure must be met in order to provide the desired load-carrying capability.

Quality control of density by a nuclear gauge and acceptance by cores has proven to be an effective way of adequately assessing the density.

As noted earlier, PMTP can be a good tool for distinguishing in real time between a macro-texture surface versus a surface that is segregated in localized areas. Results from the PMTP field demonstration projects illustrated the temperature–density relationship. The relationship tied the temperature differentials or variability to variability in mat density and not the magnitude of density (Reiter et al., in press). Figure 8-1 shows the relationship between the coefficient of variation of surface temperature and coefficient of variation of mat density. As the temperature coefficient of variation increased, the coefficient of variation of mat density increased for different quality control programs.

Contractor acceptance testing with owner verification is becoming more common. When done, proper equipment calibration and qualified technicians assure that the test results from the two entities are compatible. These are two aspects that need to be addressed.

Both contractor and owner technicians must be capable of troubleshooting problems or defects to identify likely causes. Table 8-1 contains some troubleshooting items that are particular to mixtures containing large maximum size aggregates (NAPA, 1998).

Table 8-1. Troubleshooting Table Specific to Large-Stone Mixes

Problem	Possible Cause	Possible Solution
Draindown	1. Mix temperature too high 2. Binder content too high	1. Lower temperature 2. Use stiffer binder 3. Increase filler and/or reduce binder
In-place permeability	Low density	1. Increase compactive effort 2. Avoid rolling in the tender zone 3. Lift thickness to nominal maximum size, minimum ratio 4:1 and maximum ratio 6:1
Lateral and/or longitudinal movement under rollers	Tender mixture	1. Avoid rolling in the tender zone 2. Use pneumatic roller 3. Change rollers and/or roller pattern 4. Finish compaction above 250°F (121°C)
Poor workability	1. Coarse mixture 2. Modified binder 3. Low temperature	1. Minimize handwork 2. Increase temperature

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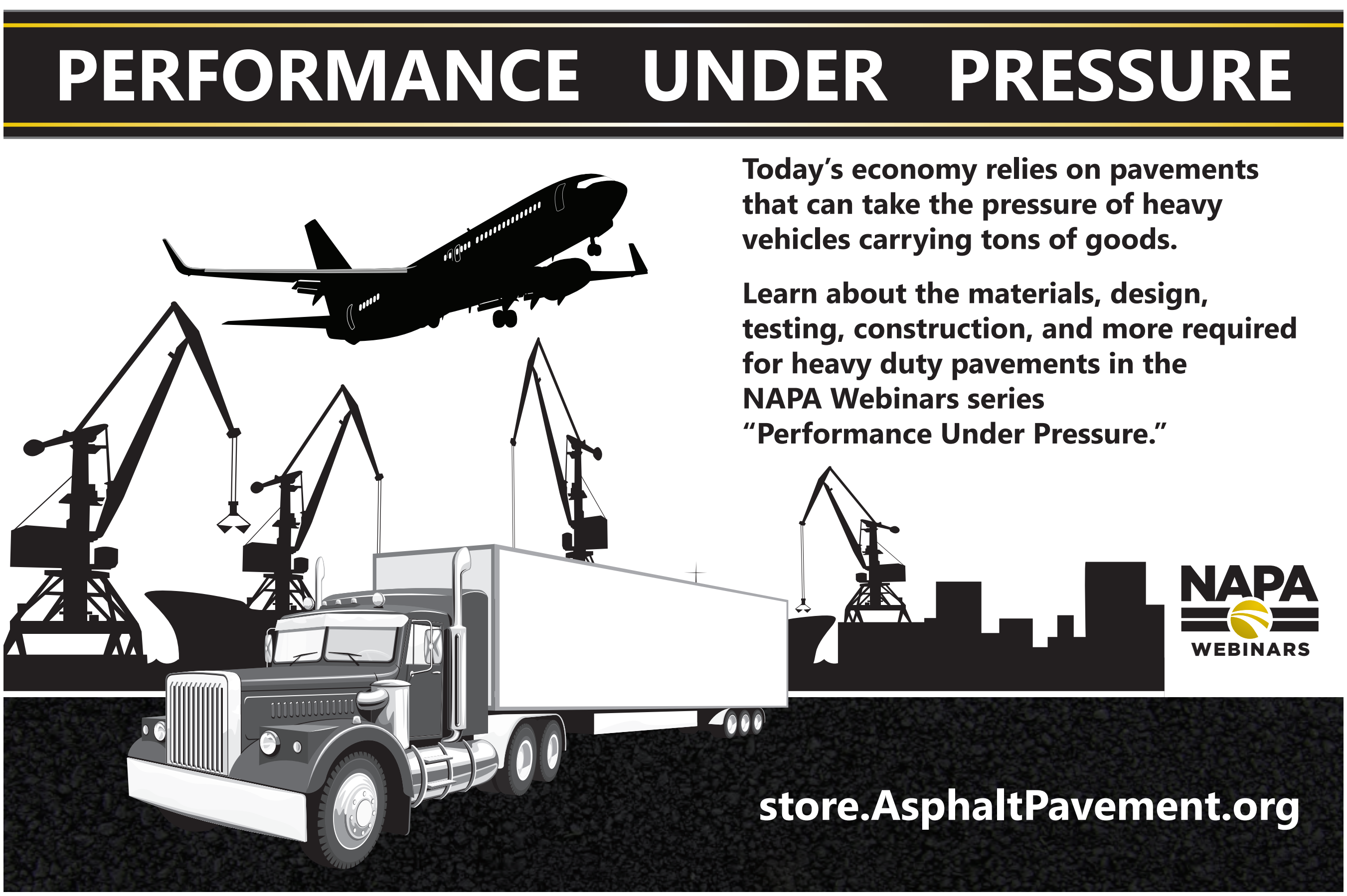
Performance Under Pressure

During 2018 and 2019, the National Asphalt Pavement Association presented a series of webinars on the design, construction, and performance of heavy-duty pavements for high-stress applications that compliments this publication. Presenters include William R. Vavrik, Ph.D., P.E.; Brian E. Prowell, Ph.D., P.E.; David H. Timm, Ph.D., P.E.; Navneet Garg, Ph.D.; Imad L. Al-Qadi, Ph.D.; Graham C. Hurley, P.E.; Brett Stanton, P.E.; R. Buzz Powell, Ph.D., P.E.; and Harold L. Von Quintus, P.E.

Webinars in the series include:

- Heavy-Duty Pavements: Design Features
- Heavy-Duty Pavements: Materials Selection
- Heavy-Duty Pavements: Perpetual Pavements
- Heavy-Duty Pavements: Structural Design Tools
- Heavy-Duty Pavements: Performance Testing
- Heavy-Duty Pavements: Production & Placement Best Practices
- Heavy-Duty Pavements: Preservation & Preventive Maintenance
- Introducing QIP-123: *Design & Construction of Heavy-Duty Pavements*

Archived versions of all these webinars can be accessed via the NAPA online store at http://store.asphaltpavement.org



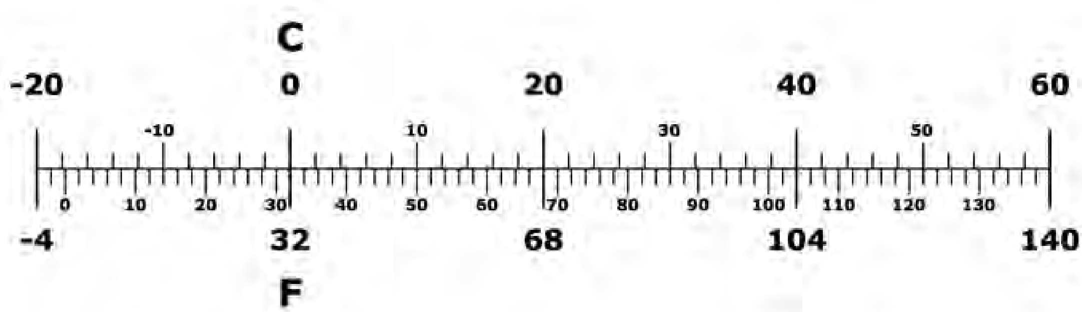
SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSION TO SI UNITS

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	645.2	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 L should be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lbs	pounds	0.454	kilograms	kg
T	short tons	0.907	megagrams	Mg
T	short tons	0.907	metric tonnes	t
NOTE: A short ton is equal to 2,000 lbs				
TEMPERATURE (exact)				
°F	Fahrenheit	$\frac{5\times(F-32)}{9}$	Celsius	°C

APPROXIMATE CONVERSION FROM SI UNITS

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.315	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lbs
Mg	megagrams	1.102	short tons	T
t	metric tonnes	1.102	short tons	T
NOTE: A short ton is equal to 2,000 lbs				
TEMPERATURE (exact)				
°C	Celsius	(1.8×C)+32	Fahrenheit	°F



*SI is the symbol for the International System of Units

NAPA: THE SOURCE

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National Asphalt Pavement Association
NAPA Building
5100 Forbes Blvd.
Lanham, Maryland 20706-4407
www.AsphaltPavement.org
NAPA@AsphaltPavement.org
Tel: 301-731-4748
Fax: 301-731-4621
Toll Free: 1-888-468-6499

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