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DEVELOPMENT OF PRELIMINARY BALANCED MIX DESIGN METHOD FOR STONE MATRIX ASPHALT

Final Report

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DISCLAIMER

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EXECUTIVE SUMMARY

There has been a national consensus to incorporate performance tests in mix design methods. As a result, balanced mix design (BMD) approaches for hot mix asphalt (HMA) have been developed and applied in many states. However, there has not been sufficient research efforts in the development of BMD methods for stone matrix asphalt (SMA) mixtures. SMA is a gap-graded mixture with rich binder content and usually considered with superior field performance. Recently, as a variety of locally available components has been used in SMA mix designs, it is necessary to develop BMD approaches for SMA mixes.

In this study, a BMD approach for SMA mixes was proposed. The approach was tailored to accommodate SMA design considerations, such as the stone-on-stone contact and its constructability. The design approach was demonstrated with the mix designs for two SMA mixtures using traprock or steel slag as coarse aggregates, respectively. The design procedure flow in this study began with the volumetric design to establish the initial aggregate structure, binder grade, and volumetric optimum binder content. This approach ensured valid volumetric properties, such as sufficient Voids in Mineral Aggregate (*VMA*), to provide adequate space within the mixture for the proper coating and binding of asphalt binder to the aggregate particles. Furthermore, the voids in the coarse aggregate of the mix (VCA_{mix}) lower than the dry-rodded condition (VCA_{DRC}) indicated effective contact among coarse aggregates and the formation of an aggregate skeleton in the SMA mixtures. As the gradation was adjusted to meet the *VMA* criteria, a strong correlation between *VMA* and the percentage of aggregate retained on or passing the #8 sieve was observed and later applied to tune the design in this study. Based on the results of performance evaluation for initial volumetric designed mixture with a single volumetric optimum binder content, the subsequent adjustments on binder content were employed in identifying a balanced binder content range where the mixture met performance requirements. The volumetric design for SMA mixture with traprock passed the performance criteria. However, the performance evaluation results showed that although the initial volumetric design for SMA mixture with steel slag met all volumetric criteria, it exhibited insufficient cracking resistance. Given that the gradation provides sufficient *VMA* and stone-on-stone contact, the binder content was adjusted firstly to improve the mixture performance. After conducting performance tests on multiple binder levels, the performance optimum binder content was determined given the

satisfied performance. Then the cracking resistance, rutting resistance, durability and the constructability of the newly designed mixture was verified since a different binder content was used. Thus, the design for SMA mixture steel slag was finalized with the volumetric optimum gradation and the performance optimum binder content.

CHAPTER 1 INTRODUCTION

1.1 Background

Every year, around 360 million tons of asphalt mixtures with a cost of more than $20 billion are placed on the roads in the United States. However, the performance and rideability have been constantly evaluated as 'poor' for the past decades (ASCE 2021). Improving the performance and the durability of the designed mixtures has been important research topics for pavement engineers. The Superpave mix design method, as the major product of the Strategic Highway Research Program (SHRP), was adopted by most state highway agencies (SHAs) in the late 1990s and the early 2000s. However, the design method was developed based on the empirical volumetric relationships and did not require performance and durability tests during design. As a result, early pavement failure due to severe distresses have been reported by highway agencies. Many roads suffered from cracked surfaces due to insufficient asphalt binder in the mix design, and the mixtures with too much binder prone to exhibit permanent deformation under the wheel path (Zhou et al 2007, Newcomb 2018, Wang et al. 2021, Liu et al. 2022).

In recent years, there has been a sweeping trend to develop and use balanced mix design (BMD) methods for hot mix asphalt (HMA) in the U.S. According to the recent studies, over 30 states have been developing their BMD specifications and mixtures (Yin and West 2021, Wang et al. 2023). The BMD methods were initially proposed to balance the cracking and rutting resistance of the designed mixture because of the limitations of the volumetric-based mix design methods, such as the lack of performance verification and their insufficiency in evaluating the quality of mix components (Zhou et al. 2007, Zhou et al. 2014, Newcomb 2018, West et al. 2018, Diefenderfer and Bowers 2019). Four BMD approaches with cracking and rutting performance tests have been documented in the provisional AASHTO standards MP 46 and PP 105, including Volumetric Design with Performance Verification, Volumetric Design with Performance Optimization, Performance-Modified Volumetric Mix Design, and Performance Design, namely Approaches 1 – 4. From Approaches 1 to 4, the procedures provide more flexibilities to the designers as the designs are based on more performance and less volumetric limits. To fully encompass the predicted mix performance in mix design, a method currently known as the Federal Highway Administration's BMD+ method has been developed. The BMD+ approach applies fundamental mechanistic models to predict the fatigue, rutting, and thermal cracking performance of all the reasonable combinations of the given mix components (Wang et al. 2021, Kim et al. 2022).

However, the associated mixture tests may require longer turnaround time than the rapid pass/fail tests, such as the commonly used IDEAL-CT cracking and Humburg rutting tests. While performance is considered and more volumetric constrains are lifted in mix design, the BMD methods have become inclusive to unconventional asphalt mixtures, such as mixes including polymer modified binder and recycled sustainable materials. However, most of the discussion and development of BMD are revolved around the dense-graded HMA, and the gap-graded mixture, Stone Matrix Asphalt (SMA), has not been fully considered with the BMD implementation thus far (Buttlar et al. 2020).

SMA is a bituminous mixture with gap-graded aggregate and high asphalt binder content, relying on stone-to-stone contact of aggregates for improved structural capacity and stability. The structural and ingredient difference in SMA was designed to maximize deformation resistance and durability. It was originally developed in the Europe and has been adopted by many U.S. SHAs as a high-quality mix used on primary roads. The mixture is generally more expensive than a typical dense-graded HMA as it requires more durable aggregates, higher asphalt content, and typically, a modified asphalt binder and fibers. In some state construction specifications, only high-quality coarse aggregates, such as traprock, are allowed in SMA design (Cross 1999, Celaya and Haddock 2006). In recent years, since such aggregates are costly and not always locally available, SHAs have been seeking alternatives. Commonly used aggregates, such as gravel and limestone, have been considered in SMA production. As the BMD methods becomes prevalent in HMA design, some researchers have been arguing that the additional mechanical tests may not be necessary for SMAs due to their superior aggregate structure, material selection, and performance history. However, as a variety of materials are being incorporated in SMA design, it is necessary to develop and implement BMD methods to ensure the performance of the newly designed SMA mixtures.

In this study, a BMD approach with SMA specific design parameters, such as the dry-rodded condition (VCA_{DRC}) and voids in the coarse aggregate of the mix (VCA_{mix}), was developed, and the approach was demonstrated with the mix designs for two SMA mixtures using traprock or steel slag as coarse aggregates, respectively. Traprock is required for SMA mixtures in Missouri Department of Transportation (MoDOT)'s specification, while steel slag is a type of affordable and sustainable coarse aggregate recycled from the steel production. The IDEAL-CT and Humburg Wheel Track Test (HWTT), which are currently used by MoDOT as BMD performance tests for job mix approval (BMD Performance Testing for Job Mix Approval NJSP-21-08b), were used in this study as the cracking and rutting performance tests, respectively. Testing results and the determination of the gradation and binder contents are presented in this report.

1.2 Objective

The objective of this project is to develop a preliminary BMD method for SMA mixtures.

1.3 Report Layout

The report consists of five chapters. Chapter 1 introduces the study's background and objective. Chapter 2 presents the literature review about the development of BMD and SMA mixture designs. Chapter 3 details the proposed mix design and experimental procedures for SMA mixtures. Chapter 4 presents a case study applying the proposed BMD mix design for SMA mixtures. Finally, Chapter 5 summarizes the conclusions and recommendations.

CHAPTER 2 LITERATURE REVIEW

This literature review organized and presented the latest information related to the great efforts in incorporating performance in mix mixture design. The efforts on SMA mixture design including gradation, compaction, and design procedure were also summarized.

2.1 Development of Performance Mix Design Methods

2.1.1 Performance Mix Design Approaches

In the 2000s, several years after the Superpave mix design was widely implemented in the U.S., multiple simple performance tests were developed and incorporated into mix design methods, including the prevalent BMD. The performance mix design methods are introduced as index-based performance mix design (IPMD) and predictive performance design. The existing BMD methods are IPMDs as the incorporated performance testing methods are index or tolerance tests.

2.1.1.1 Index-Based Performance Mix Design/Balanced Mix Design

The concept of BMD was first proposed in 2007, as a ‘balanced binder content’ was expected to be identified for given mix components through index-based performance tests so that the designed mix was neither too ‘lean’ to form pavement fatigue cracking or too ‘wet’ to yield deep rut depth (Zhou et al. 2007). In September 2015, the FHWA Expert Task Group (ETD) on Mixtures and Construction founded a BMD task force. The BMD task force defined BMD as “asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distress taking into consideration mix aging, traffic climate and location within the pavement structure” (West et al. 2018). Three pathways were originally developed by the task force, and later, they were expanded to four approaches when the corresponding provisional AASHTO standards PP105-20 and MP 46-20 were submitted, as presented in Figure 2.1(Yin and West 2021). The details and the highlights in each approach are demonstrated in Table 2.1. Under the BMD framework, several implementation plans have been developed among SHAs (Paye 2014, Cross and Li 2019, ALDOT 2020, Bennert 2020, Coleri et al. 2020).

Like the index-based performance specifications, the advantages of IPMD or BMD include the relatively short turnaround time of the simple performance tests and the intuitive design philosophy. Using both the volumetric and performance criteria provides the pavement engineers confidence of the mixture quality. However, the index threshold limits can only be determined based on empirical relationships between field performance and performance test results. Besides, the indices cannot take the project-specific information (i.e., structural, environment, and traffic conditions) into account, and neither can the formation of pavement distress as a function of service time be predicted using the index-based approaches, as envisioned in the original SHRP project.

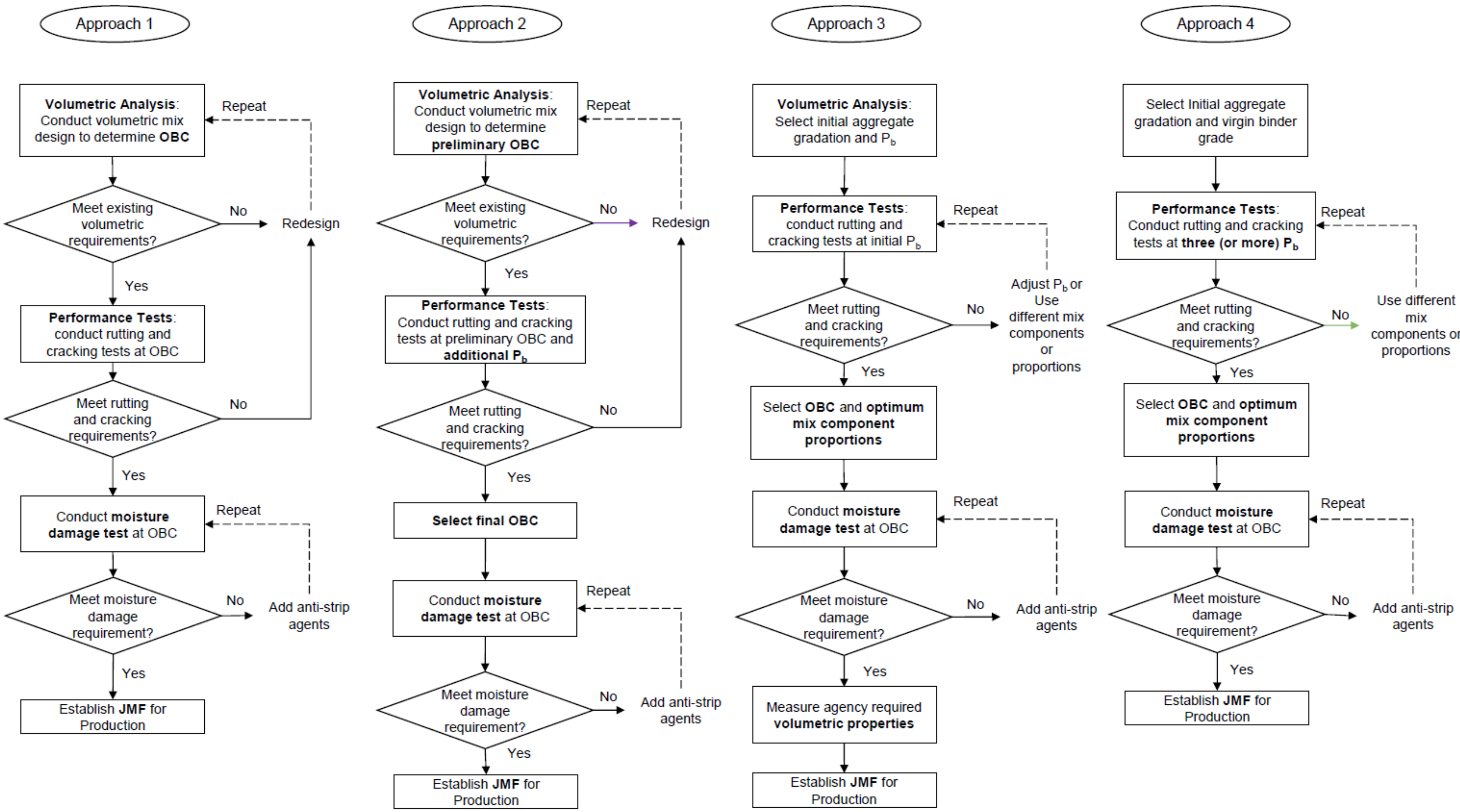


Figure 2.1 Flowcharts demonstrating BMD approaches (Yin and West 2021)

Table 2.1 Highlights of Different BMD Approaches

Approach	Description	Highlights
BMD Approach 1	Volumetric Design with Performance Verification Approach	• This approach makes sure that all the mix designs are products of volumetric design methods with performance requirements satisfied. • This approach applies additional constraints for performance requirements onto the original volumetric designs. This combination provides the engineers the most confidence but least design flexibility for the contractors.
BMD Approach 2	Volumetric Design with Performance Optimization Approach	• This approach is an expanded version of Approach 1, and it was not included in the original three approaches proposed by the former FHWA BMD Task Force. • This approach allows a potential offset in optimum binder content determined based on the performance test results from volumetric optimum binder content while the mixture gradation and other mix components will remain the same as designed by the volumetric-based method. • When this approach is adopted, the binder contents for performance testing will usually be preliminary OBC - 0.5%, preliminary OBC, preliminary OBC + 0.5%, and preliminary OBC + 1.0%.
BMD Approach 3	Performance-Modified Volumetric Design Approach	• This approach and Approach 1 both start with volumetric design. • Unlike Approach 1, this approach allows adjustments for both the gradation and binder content based on the performance test results. The final combination of the gradation and binder content is not directly obtained from volumetric design, and only some volumetric criteria are required to be met.
BMD Approach 4	Performance Design Approach	• This approach is similar to the third approach proposed by the former FHWA BMD Task Force, but more details and instructions were provided than the descriptions when it was first introduced by the task force. • This approach is a combination of Approach 2 and Approach 3, and it may not necessarily start with a volumetric design. • After the initial selection of an initial selection of aggregate gradation, recycled asphalt materials, content, and virgin binder grade is determined, the binder contents for performance testing will usually be initial binder content - 0.5%, initial binder content, initial binder content + 0.5%, and initial binder content + 1.0%.

2.1.1.2 Predictive Performance Mix Design

Predictive mix design utilizes the mixture/pavement performance predicted from the mechanistic models to determine the optimum mixture design. One predictive design approach has been proposed by NCSU. The method is also known as the Performance-Engineered Mix Design (PEMD) (Wang 2019, Kim et al. 2022, Wang et al. 2021). One feature of the method is that instead of using the trial-and-error approach (creating one trial design and using volumetric or performance criteria to determine pass or fail), the PEMD identifies the performance-optimum design directly from the infinite numbers of combinations of the given material components. The identification of the optimum design can be achieved by using the performance-volumetric relationship (PVR). PVR characterizes a given mix design with two variables, the in-place Voids in Mineral Aggregate (VMA_{IP}) and in-place voids filled with asphalt (VFA_{IP}), and forms a two-dimensional volumetric space. Each point in the space is corresponding to one combination of gradation, binder content, and compaction level, as presented in Figure 2.2 (a). Previous research (Wang et al. 2019) found that when the climate, traffic, and structural conditions are known, the predicted pavement performance (% fatigue damage and permanent deformation) is a bilinear function of VMA_{IP} and VFA_{IP}. The PVR function, therefore, provides a spectrum of performance as a function of the change of gradation, binder content, and compaction level, as presented in Figure 2.2 (b). The performance optimum design can be acquired by combining the predicted pavement life determined by fatigue life and rutting failure (Wang 2019, Wang et al. 2021). It will be the SHA's discretion to require all or some of the volumetric limits to be met, and the moisture susceptibility of the design mixture can be tested afterward. The design procedure requires four sets of performance tests to calibrate the PVR function coefficients. The performance tests used in PEMD are the cyclic fatigue test and the Stress Sweep Rutting (SSR) test. If the design candidate fails the volumetric or the moisture tests, the designer can select another combination from the volumetric spectrum without conducting additional performance tests. Therefore, unlike the unknown numbers of iterations that the IPMD methods may require, with the fixed number of performance tests and testing time, the design timeline can be planned by the SHAs and contractors. 12 days are expected to complete the design including the specimen preparation and testing time (Wang et al. 2021a).

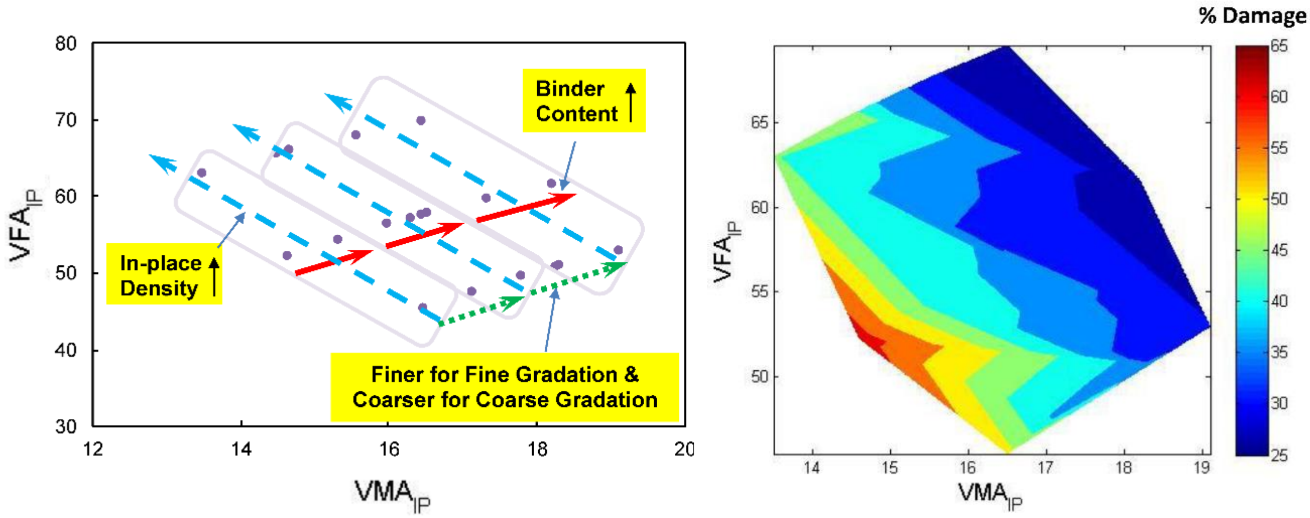


Figure 2.2 (a) Volumetric space formed by *VMA*IP and VFAIP and effects of mix design parameters on *VMA*IP and VFAIP and (b) %Damage contour in a pavement structure in the volumetric space (Wang et al. 2019)

2.1.2 Comparison of Performance Mix Design Approaches

Error! Reference source not found. summarized several important criteria to evaluate the performance design approach. Among the four BMD approaches, the involvement of the performance increases from Approaches 1 to 4 as the volumetric restrictions for binder contents and gradations are gradually released. As a result, Approach 1 provides the agency highest confidence and lowest risks when BMD is first implemented. However, Approach 1 meanwhile grants the contractor the least design flexibility. As for the predicative performance mix design methods, the performance involvements and design flexibility would be the highest among all the methods. However, the agency may have the least confidence since the design will primarily be based on the predicted performance instead of the conventional volumetric parameters. In terms of the design effort needed in each approach, the predictive performance mix design method may consume the longest time because of complexity of the required performance tests.

However, the BMD approaches may take longer time if multiple iterations are needed for redesign or adjustments. In contrast, the number of performance tests is fixed for the predictive performance design method. As for the development of performance specification, in each approach, the same performance requirements can be consistently applied in mix design and in quality assurance (QA) as long as the specifications are well engineered.

Table 2.2 Factors to Consider for Comparing Performance Design Approaches

Evaluation	Description
Performance Involvement	The extent of performance involved in the design procedure. If the performance tests are only used for pass/fail decision after volumetric design, the approach will be evaluated with low performance involvement. High involvements are granted to the methods where gradation, binder content, and other design parameters are determined based on the mix performance.
Confidence and Risk	The confidence level that SHA has when they first switch from volumetric mix design to this approach. For example, if volumetric limits are not required in a new mix design, the SHA would have less confidence and take higher risk on the mix than on the mixtures that meet the volumetric requirements.
Design Flexibility	The flexibility that the contractor has while conducting the mix design. For example, if the volumetric requirements are inherited, the additional constraints added for performance will further limit the design flexibilities for contractors. Higher design flexibility can provide contractors incentives to apply innovative materials and technologies.
Design Effort	The design effort indicates the time and resources that the performance design approach costs. This criterion should be evaluated based on the number of gyratory specimens required to be fabricated, the number of performance tests, the testing turnaround time, and the estimated design time in days.
Performance Prediction Capacity	The performance prediction capacity indicates how well the mixture performance is incorporated in the mix design approach. Does the mix design rigorously consider the target pavement structure, climate, traffic volume, and other factors? Can the mix design approach predict the pavement distress deterioration with time as initially expected in the Superpave Level III design? Are the performance threshold limits determined by empirical or mechanistic method?
Compatibility with QA	The compatibility with QA index indicates the difficulty level to develop a QA method and a performance construction specification with pay adjustments using the same testing methods and/or performance threshold limits.

2.2 SMA Mixture Design

The goal of the mix design is to develop a high-quality SMA mixture using a simple, straightforward, and repeatable method. The parameters that should be considered in the mix design procedure included aggregate toughness, flat and elongated particle ratio, mixture aggregate gradation, percent passing 0.02 mm sieve, stone-on-stone contact, voids in the total mixture (VTM), *VMA*, asphalt binder content, compactive effort, and asphalt binder draindown (Brown et al. 1997). In SMA mixture design, the effect of gradation, asphalt-aggregate ratio, and fiber content on overall performance was ranked from most to least influential: gradation, asphalt-aggregate ratio, and fiber contents (Ai et al. 2016).

2.2.1 Gradation

The mix design should keep the gradation consistent, ensure an adequate coarse aggregate skeleton and satisfactory mixture volume, while changing the percentages of different types of aggregates and meeting the desired aggregate content (McDaniel et al 2012). SMA is a gap-graded HMA that is designed to maximize deformation resistance and durability by using a structural basis of stone-on-stone contacts. It was originally developed in the Europe and adopted in the U.S. the 1990s. Figures 2.3 and 2.4 present the differences in gradation and appearance between the aggregates structure of the SMA and conventional HMA mixtures. The mixture is generally more expensive than a typical dense-graded HMA as it requires more durable aggregates, higher asphalt content, and typically, a modified asphalt binder and fibers.

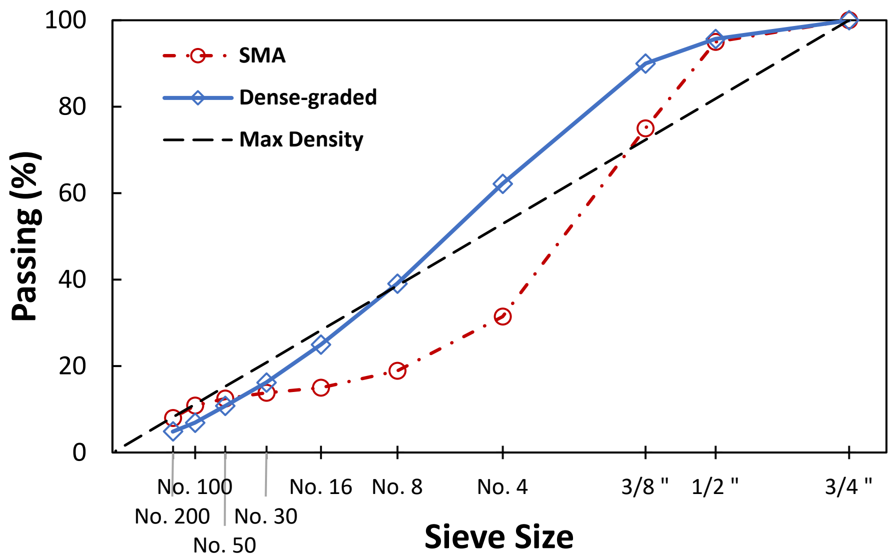
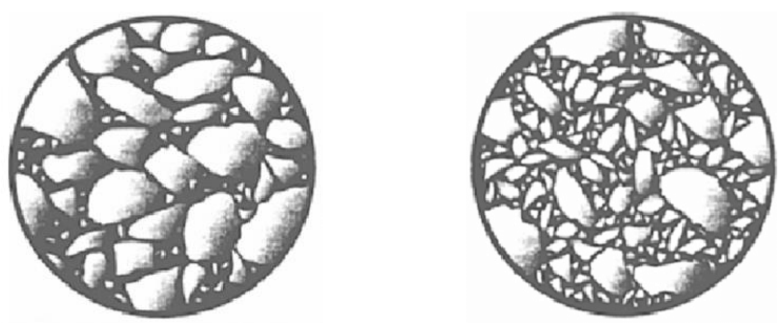


Figure 2.3 Gradations of typical 12.5 mm SMA and dense-graded HMA.



(a) (b)

Figure 2.4 Cross sections of SMA and conventional dense-graded HMA: (a) SMA and (b) dense-graded HMA.

The design of aggregate gradation varies across institutions, influenced by factors such as location, climatic conditions, availability, and cost of the aggregates. The performance of SMA and Superpave mixtures in the laboratory is significantly affected by the aggregate gradation, suggesting that very tight control of the aggregate gradation is required during construction (Brown 1992). Roque et al. (1997) compared the shear strength of 18 different mixtures with different gradations and concluded that the coarse aggregate gradation controlled the shear performance of SMA mixtures.

Proper aggregate gradation allows easier stone-on-stone contact in the mixtures. SMA mixtures with a low percentage (no more than 30%) of particles passing the 4.75 mm sieve (the critical sieve size for the mixes) more easily formed a good stone-on-stone contact structure and were less sensitive to low air void content (Brown et al. 1993,1997). The contact energy index, representing the ability of asphalt mixtures to develop aggregate contact and resist shear deformation, can be calculated by shear force and deformation during compaction (Dessouky et al. 2003, 2004).

Verification of stone-on-stone contact with *VCA* is essential because it has a direct impact on the aggregates contact in SMA (Gatchalian et al. 2006). Brown et al. (1997) proposed a method to check stone-on-stone contact in SMA mixtures by controlling the *VCA* for both the coarse aggregates alone and the entire SMA mixture. The values for *VCA* are determined by using the equation in the AASHTO T 19 as shown in Equations 2.1 and 2.2.

$$VCA_{DRC} = \left[\frac{G_{CA}\gamma_W - \gamma_s}{G_{CA}\gamma_W}\right] * 100 \tag{2.1}$$

Where:

G_{CA} = bulk specific gravity of the coarse aggregate

γ_W = unit weight of water (998 kg/m^3)

γ_s = unit weight of the coarse aggregate fraction of the aggregate blend

$$VCA_{MIX} = 100 - \left[\frac{G_{MB}}{G_{CA}} P_{CA}\right] \tag{2.2}$$

Where:

G_{MB}= bulk specific gravity of mix

G_{CA}= bulk specific gravity of coarse aggregate

P_{CA} = percent of coarse aggregate (retained on breakpoint sieve) by weight of total mix

The size of aggregates also has a significant effect on the performance of SMA mixtures and Superpave mixtures. A higher percentage of SMA-9.5 mixtures passing through the No. 4 sieve can be observed in poor field performance (Apeagyei et al. 2013). The use of larger size aggregates in SMA mixtures improved rutting resistance and stiffness but reduced fatigue life (Hafeez et al. 2015). Kowalski et al. (2010) claimed that larger nominal maximum aggregate size (NMAS) had better overall friction properties than smaller-sized mixtures. Two aggregate gradations with NMAS of 16 mm and 13 mm were compared and concluded that the mixture with the larger coarse aggregate size performed better (Sarang et al. 2014). Qiu et al. (2006) adopted the Bailey method in the mix design to quantify contact between aggregates, which improved the rutting resistance of SMA mixtures.

2.2.2 Mixture Compaction

The compaction method has a significant impact on the aggregate quality and structure created by the SMA non-continuous gradation. Different compaction methods can lead to differences in air voids, different levels of aggregate breakdown, and different performance of the designed SMA mixture in the laboratory and in the field. Several compaction methods have been considered for SMA mixture compaction by researchers and agencies, such as Texas gyratory, rolling wheel, kneading, SHRP gyratory, Marshall hammer compactor, Superpave gyratory compactor (SGC), and California Kneading compactor (Sousa et al. 1995).

Some U.S. highway agencies now use the SGC method for lab compaction for SMA. Maryland, which has been at the forefront of SMA use in the U.S., has been using 100 gyrations for its SMA mixtures for several years (Michael et al. 2003). The resultant density of SMA samples fabricated by 100 revolutions of the SGC method is close to that of a Marshall hammer method at 50 blows, and the SGC method could cause less aggregate breakdown than the Marshall hammer method (Brown et al. 1997). A similar conclusion was made by West et al. (2005). They found that compaction with the SGC method caused less aggregate breakdown than with the Marshall hammer method by comparing changes in percent passing the 4.75 mm sieve and the 0.075 mm sieve before and after the compaction. Smit et al. (2011) suggested designing SMA mixtures with local aggregates and utilizing the SGC method with the capability of measuring the shear stress of the mix during compaction. Hainin et al. (2013) found that the SGC method could reduce degradation and represent a field roller well. Miranda (2019) evaluated the effect of different aggregate skeleton matrices performed by different compaction methods on permanent deformation. The results demonstrated that proctor and steel roller compaction could optimize higher content of coarse aggregates and binder, which meant better cracking resistance and durability. Miranda (2019) also proposed new parameters, such as the ratio between binder film thickness and porosity and the ratio between Marshall stability and flow, which were related to permanent deformation. Qiu (2007) found a positive correlation between the different degrees of internal aggregate packing in SMA and rutting resistance.

As shown in the Table 2.3, the SMA mixture requirements for the specimens compacted by the SGC method at 100 gyrations are specified in AASHTO M 325.

Table 2.3 SMA Mixture Requirements for SGC

Property	Requirement
Asphalt Binder Content, %	6 minimum
Air Voids, %	4
***VMA*, %**	17 minimum
***VCA* of Compacted SMA (VCA_{mix}), %**	Less than *VCA* in dry-rodded condition (VCA_{DRC})
TSR, %	80 minimum
Draindown at Production Temperature, %	0.3 maximum

2.2.3 Additives in the Mixtures

Traditionally, stabilizing additives are used to maintain the binder in the mixture at high temperatures, preventing draindown during production, transportation, and construction. The additives include cellulose fiber, rock wool fiber, or polymer, which can also reduce the age hardening of the binder (Stuart et al. 1994). In addition, the fibers can reduce the draindown of asphalt so that the permanent deformation would be reduced as well (Woodside et al. 1997).

Coconut fiber is a suitable replacement for cellulose fiber used in SMA mixtures (Vale et al. 2014). Raghuram et al. (2013) claimed that low-cost fibers can also be used as stabilizers to improve the performance of SMA mixtures by retarding the draindown of asphalt from the SMA mixtures to a greater extent. 0.3% of cellulose fiber is a suitable content to stabilize the mixture even without conducting draindown tests (Devulapalli et al. 2022).

2.2.4 SMA Mixture Design Procedure

For SMA mix design, five basic steps are required to obtain a satisfactory SMA mixture: 1) select materials; 2) determine optimum aggregate gradation yielding stone-on-stone contact; 3) determine optimum asphalt binder content that provides the desired air void level; 4) evaluate asphalt draindown potential; and 5) evaluate moisture susceptibility using AASHTO T 283 (Brown et al.1997). The SMA mixtures that met the criterion of $VCA_{mix} < VCA_{DRC}$ indicate good stone-on-stone contact and a denser coarse aggregate fraction (Liu et al. 2019).

West et al. (2005) examined Lock Point in the SMA mix design. Lock point was defined by Alabama Department of Transportation (ALDOT) as the second of two consecutive gyrations, which have the same recorded sample height. This is the limit of gyrations where the aggregate has locked together to reduce aggregate breakdown, indicating that good stone-on-stone contact has been achieved and that further gyrations may only degrade the aggregate. Comparing the results from the lab and field, 70 gyrations with the SGC method are recommended to replace the 50 blow Marshall hammer method for SMA mix designs in Alabama.

Miranda et al. (2019) developed a new analytical approach for SMA mix design for the optimization of the stone-on-stone effect. In addition to volumetric characteristic of SMA test sample, they evaluated the characteristic of coarse aggregates prepared using different aggregate compaction method, such as VCA, VCA_{mix}, air void content, void filler with bituminous binder (VFB) and workability of SMA. Compared to pre-established grading, the SMA mixture with aggregates compacted using Proctor compaction resulted in an air void and particle breakage more like field results. Qiu and Lum (2006) proposed a mix design procedure based on and adapted from the Bailey method, which can quantify aggregate stone-on-stone contact in SMA.

While some volumetric criteria are necessary in the SMA design, still, measuring volumetrics only cannot guarantee reliable performance, and the owner of the pavements, i.e., the highway agencies, have been taking the risk of performance failure. Therefore, it is necessary to implement the balanced mix design methods incorporated with performance tests on SMA design and quality assurance. However, there has not been sufficient research efforts in the development of the BMD methods for SMA mixtures (West et al. 2018, Buttlar et al. 2020, Wang et al. 2023).

2.3 Summary

The literature review provides an overview of efforts in development of BMD and SMA mixture design. The summary is stated as follows.

- Four approaches in balanced mix design/index-based performance mix design and one predictive performance mix design method are demonstrated. The five approaches are compared based on six evaluation criteria proposed in this chapter.
- SMA mix design should focus on optimizing stone-on-stone contact, considering volumetric characteristics, compaction methods, and workability for enhanced performance.

- Mixture design steps include material selection, determining optimal gradation and binder content based on the volumetric parameters such *VMA* and VCA, evaluating draindown, and assessing moisture susceptibility.
- The gradation of the SMA mixture can directly impact stone-on-stone contact, shear strength, and overall performance.
- Methods such as the dilation concept, lock-up concept, and Bailey method were used for optimizing the gradation of SMA mixtures used for aggregate gradation.
- After comparing different compaction methods, the SGC method was determined to be preferred method due to its consistency and minimal aggregate breakdown.
- Stabilizing additives like cellulose fiber or polymers maintain binder integrity and improve performance of SMA.
- While some volumetric criteria are necessary in the SMA design, still, measuring volumetrics only cannot guarantee reliable performance. There has not been sufficient research efforts in the development of the BMD methods for SMA mixtures.

CHAPTER 3 DESIGN PROCEDURE AND EXPERIMENTAL DETAILS

3.1 A BMD Approach for SMA

Because of the structural and ingredient differences between SMA and conventional HMA, the design process of an SMA mixture is also different (Celaya et al. 2006). In addition to the typical volumetric parameters, such as the *VMA* and VFA, the parameters to ensure the stone-on-stone contact in the coarse aggregate structure, such as the VCA_{DRC} and VCA_{mix}, also need be determined. A well-designed SMA should have a VCA_{mix} lower than the VCA_{DRC} of the aggregates without the fine aggregates and asphalt binder. Also, according to AASHTO R 46, the draindown test evaluating sensitivity of the SMA mixture to the plant temperature fluctuations needs to be performed as part of the design. While volumetric parameters are still necessary for SMA design, especially for ensuring the stone-on-stone contact, the performance tests in the BMD methods appear to be important as different components including alternative coarse aggregates are considered in mix design.

As the development of the BMD approaches thus far in the asphalt industry, four approaches with different levels of performance test involves have been proposed. Among the four pathways, Approach A is established based on the volumetric design with performance verification. Though adding more constrains and reducing some levels of flexibility, since this method preserves the volumetric limits, it offers the least risks to SHAs when transitioning to performance-based designs. Thus, it has been adopted by the most states that have experienced BMD (Wang et al. 2023). In terms of SMA mix design, because the strength of the material greatly relies on its skeleton aggregate structure, the BMD method for SMA is developed using volumetric parameters. In the meantime, multiple binder contents will be tested if the initial volumetric optimum design does not pass the performance criteria. Therefore, the proposed procedure has the advantages of Approaches A and B from the AASTHO PP 105. The flow of the design procedure is presented in Figure 3.1. The method uses the volumetric parameters including the VCA_{DRC} and VCA_{mix} to determine the initial gradation and binder content. The volumetric criteria are applied to ensure a stable skeleton structure and sufficient fine materials for a gap-graded mixture, and the draindown test is used to assure its constructability. The performance tests (highlighted in red in Figure 3.1) are included to ensure the mixture performance as a variety of components are used in the SMA design.

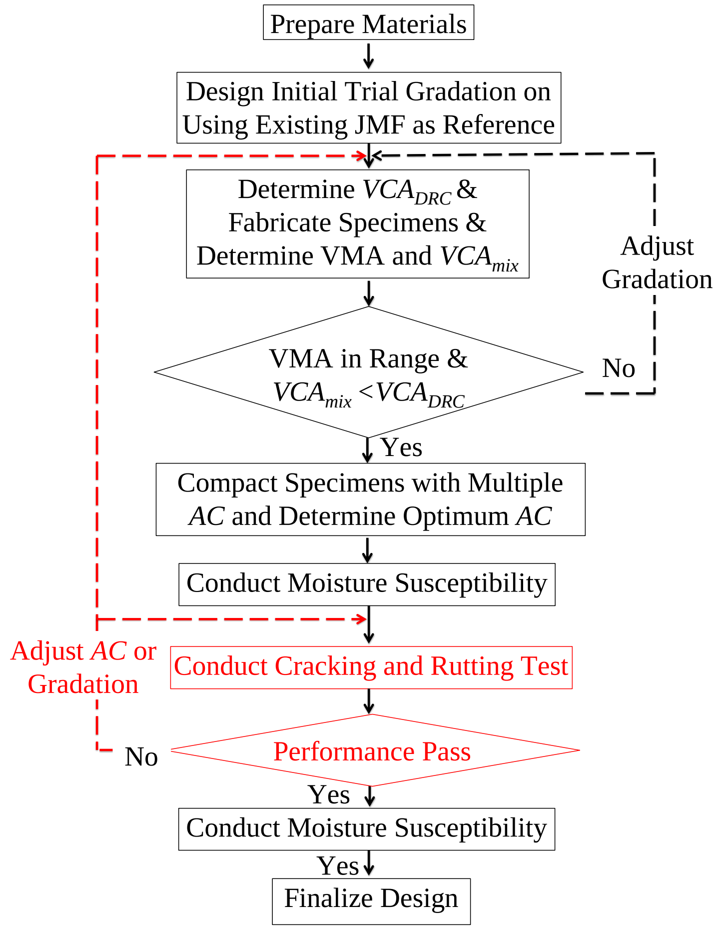


Figure 3.1 Preliminary BMD design procedure for SMA.

3.2 Testing Materials

3.2.1 Aggregates

The BMD approach for SMA is demonstrated with the mix designs for two SMA mixtures using traprock or steel slag as coarse aggregates, respectively. The sampled aggregates are shown in Figure 3.2. Steel slag is a by-product of steel production, obtained during the separation of the molten steel from furnace impurities. The major components of steel slag are calcium oxide, silicon dioxide, and iron (II) oxide. In this study, a furnace slag produced in Missouri is used in the SMA design as an alternative coarse aggregate to the commonly used traprock. The physical and mechanical properties of the main coarse aggregates traprock and steel slag are presented in Table 3.1.

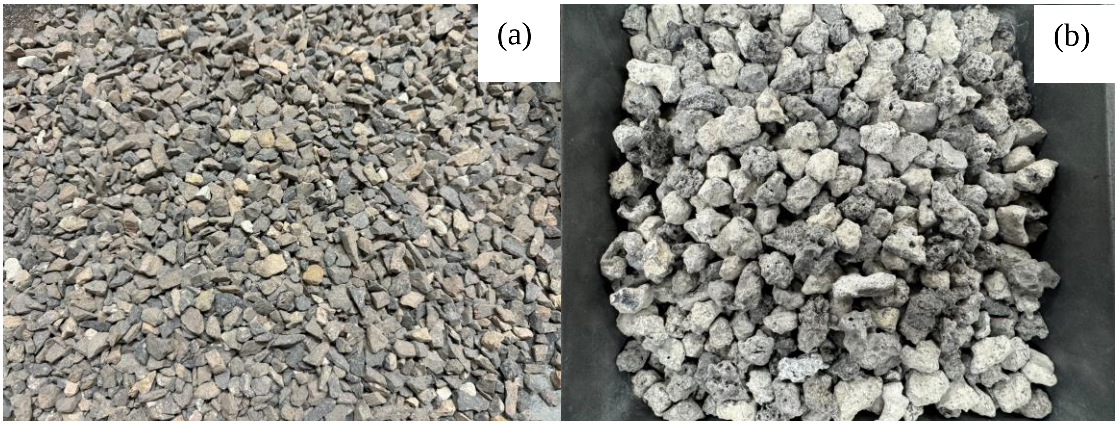


Figure 3.2 Sampled candidate aggregates: (a) traprock, and (b) steel slag.

Table 3.1 Physical and Mechanical Properties of Coarse Aggregates

Property	Value for Traprock	Value for Steel Slag	Testing Method	Limit*
LA Abrasion	21%	19.5%	AASHTO T 96	< 40%
Micro-Deval Abrasion	2.4%	7.1%	AASHTO T 85	< 18%
Flat and Elongated Aggregates (3:1)	18%	5%	ASTM D4791	< 20%
Flat and Elongated Aggregates (5:1)	0%	0%	ASTM D4791	< 5%
Angularity (One Face)	100%	100%	ASTM D5821	100%
Angularity (Two Faces)	100%	100%	ASTM D5821	100%
Sand Equivalent	56%	55%	AASHTO T 176	> 50%
Bulk Specific Gravity (Coarse)	2.591	3.25	AASHTO T 85	None
Bulk Specific Gravity (Fine)	2.583	2.90	AASHTO T 84	None
Absorption	0.7%	2.3%	AASHTO T 85	< 3.5%
Soundness	0.2%	0.2%	AASHTO T 104	< 12%

* limits in MoDOT Construction Specification except for the Micro-Deval abrasion

3.2.2 Binder

In this study, the binder used in the SMA is a PG 64V-22, produced in St. Louis, MO. Figure 3.3 presents the test results from the rotational viscometer (RV). The mixing and compaction temperatures were determined to be 166-172°C and 157-161°C, resulting in viscosity values of 0.15-0.20 Pa·s and 0.25-0.30 Pa·s, respectively.

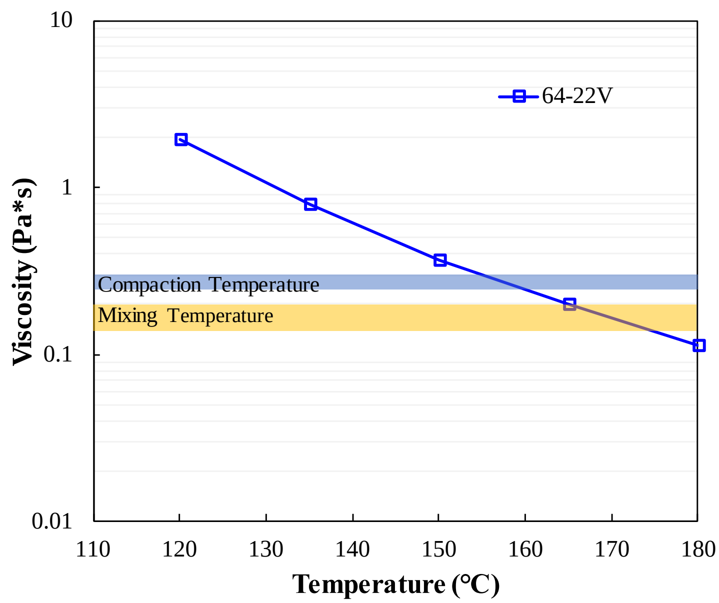


Figure 3.3 Viscosity test results of binder.

3.2.3 Mixtures

The Job Mix Formula (JMF) for SMA mixtures were provided by MoDOT as references, which used the traprock as the main coarse aggregates. The mixture to be designed is a 12.5 mm gap-graded mix. The SMA mix design using traprock started from the same gradation and binder content with JMF. The design with steel slag started from replacing the traprock with steel slag while keeping the remaining components consistent. Then the mix designs were adjusted to meet all the requirements specified in AASHTO M 325**.** The information of designed SMA mixtures is summarized in Table 3.2.

Table 3.2 SMA Mixtures with Different Coarse Aggregates

Type of Mixture	Main Coarse Aggregates	Binder	Abbreviation for Mixtures
SMA	Traprock	PG 64-22V	ST
	Steel Slag		SS

3.3 Testing Methods

3.3.1 IDEAL-CT

The IDEAL-CT test is a rapid cracking test that is convenient to use in mix design and quality assurance (Liu et al. 2022). The testing procedures followed ASTM D 8225 and were conducted at 25 ℃ with cylindrical specimens at a constant loading rate of 50mm/min, as shown in Figure 3.4. The test specimens had a diameter of 150 mm and a height of 62 mm, with air voids of 6±0.5% for SMA mixture. The CT_{Index} was calculated using Equation 3.1 (Zhou 2019). In accordance with MoDOT's specification (BMD Performance Testing for Job Mix Approval NJSP-21-08b), for SMA mixture, CT_{Index} should be no less than 135.

$$CT_{Index} = \frac{t}{62} * \frac{G_f}{|m_{75}|} * \left(\frac{l_{75}}{D}\right) \tag{3.1}$$

where:

t = the thickness of testing sample.

G_f = the fracture energy.

$|m_{75}|$ = the post-peak slope of the load–displacement curve at 75% of the peak load.

D = the diameter of the testing sample.

l_{75} = the displacement at 75% of the peak load.

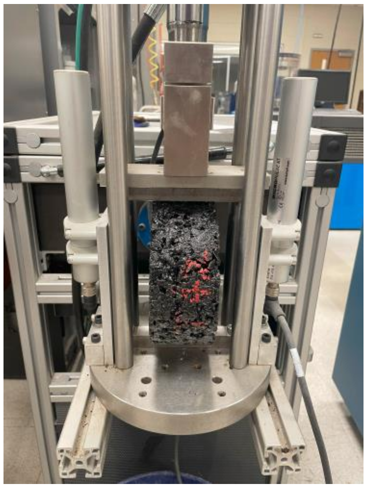


Figure 3.4 IDEAL-CT equipment.

The analysis method developed by Yin et al. (2023) was further used to understand the IDEAL-CT testing result. The analysis decomposed the CT_{Index} into two parameters: the average G_f, which indicated the mixture's toughness, and the average l_{75}/m_{75} ratio, which reflected its ductile-brittle behavior. This approach helped distinguish mixtures with similar CT_{Index} values but different load vs. displacement curve shapes from the IDEAL-CT tests. By plotting these parameters on a two-dimensional diagram, each asphalt mix's position revealed its relative toughness and brittleness.

3.3.2 HWTT

The HWTT can evaluate the mixture moisture susceptibility and rutting resistance simultaneously. The testing device is shown in Figure 3.5. The test specimens had a diameter of 150 mm and a height of 62 mm, with air voids of 6±0.5% for SMA mixture. The testing procedures followed AASHTO T 324. In accordance with MoDOT’s specification NJSP-21-08, for SMA mixture, the rut depth should not exceed 12.5 mm under 20,000 passes. Additionally, the rutting resistance index (RRI), calculated using Equation 3.2 (Liu 2022), provides a comparative measure for tests completed at different loading cycles. The RRI parameter accounts for both the combined effect of the number of passes and the rut depth, addressing the nonlinear impact of loading passes on pavement rutting. The minimum requirement of RRI can be calculated as 9.9 for a 12.5mm rut depth at 20,000 loading cycles.

$$RRI = N^{0.3}\left(1 - \frac{RD}{25.4}\right) \tag{3.2}$$

Where:

RRI = rutting resistance index.

N = 20,000 or number of passes reaching 12.5-mm rut depth.

RD = rut depth at 20,000 passes or 12.5 mm for those reaching 12.5 mm rut depth before 20,000 passes.

Figure 3.5 HWTT equipment.

CHAPTER 4 DEMONSTRATION OF BMD APPROACH FOR SMA MIXTURES

4.1 Initial Volumetric Design

Like HMA, using volumetric indices to initiate an SMA mix design is a low-risk solution; besides, volumetric parameters, such as VCA_{DRC} and VCA_{mix}, have been used as effective indicators to the stone-on-stone contact. The MoDOT construction specification requires at least 17% *VMA* in the SMA mixture. The researchers in this study discovered that, while designs using the original coarse aggregate, i.e., traprock, can easily meet the requirement, as alternative coarse aggregate candidates, such as gravel, limestone and dolomite, are considered, meeting the *VMA* limit can be challenging, and the gradation should be carefully engineered to achieve such volumetric values.

As the gradation is adjusted to meet the *VMA* criteria, a strong correlation between *VMA* and the percentage of aggregate retained on or passing the #8 sieve has been observed and later applied to tune the design in this study, as presented in Figure 4.1. The relationship was obtained from compacted specimens under the same compaction levels while adjusting the proportions in the aggregate combination. Such relationships were also observed in SMA mixtures with other types of alternative coarse aggregates, such as limestone, dolomite, gravel, and chat. It indicates that when designing a new mixture, engineers can develop the linear relationship using two or three datapoints and apply the trend to achieve the target volumetric properties.

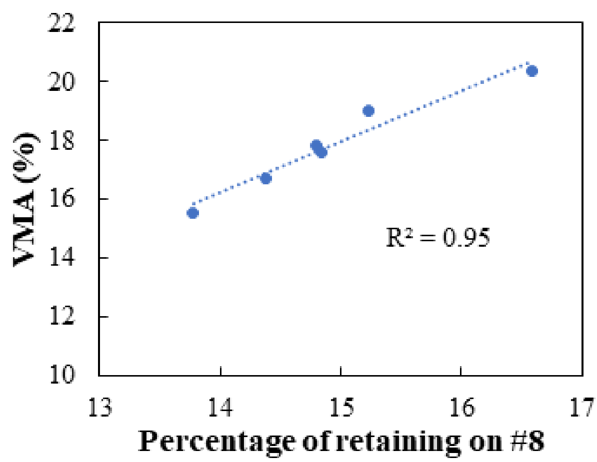


Figure 4.1 The percent of retaining on the #8 sieve vs. *VMA*.

4.1.1 Volumetric Mix Design for ST

The SMA mix design with traprock began with verifying the JMF, using identical aggregates, specific proportions, combined gradation, and binder content as outlined in the JMF. However, verification results revealed a notable deviation on the volumetric parameters from the data in the JMF, as illustrated in Table 4.1. The mixture design for ST followed by JMF failed to meet the *VMA* requirement of 17%. Therefore, the ST was redesigned to meet the volumetric requirements of AASHTO M 325.

Table 4.1 Volumetric Parameters Comparison Between Testing Results and JMF

Volumetric Parameters	JMF	Test Data
G_{mb}	2.299	2.276
G_{sb}	2.606	2.557
P_s, %	93.5	93.5
G_{ca}, %	N/A	2.552
P_b, %	6.2	6.2
P_{CA}, %	68.1	67.2
G_{mm}	2.394	2.423
VMA, ≥17%	17.3	16.8
VCA_{mix}, %	39.8	40.1
P_a, %	4.0	6.1

N/A: Data is not provided in the JMF

To meet the volumetric design criteria, the coarse aggregate proportion was increased from the original JMF portion given the low measured *VMA* during mix design verification. An asphalt content of 6.5% for the trial mixtures was determined based on the bulk specific gravity of coarse aggregate (G_{ca}) following AASHTO R 46.

Figure 4.2 and Table 4.2 display the gradations and volumetric parameters of ST mixtures from the three trial designs, all exceeding the required 17% *VMA* in AASHTO M 325. Considering potential *VMA* reduction for other candidate aggregates, Design 3, with *VMA* close to 17%, was deemed less favorable than the other two trial designs. Design 1, with a lower proportion of coarse aggregate, was preferred over Design 2, despite comparable *VMA*. Design 1, with VCA_{DRC} of 41.54% exceeding VCA_{mix} of 37.3%, was chosen as the desired gradation. Finally, Design 1 with 7.5% binder content was selected as the optimal design for ST after measuring the volumetric parameters for the optimum Design 1 with varying binder contents.

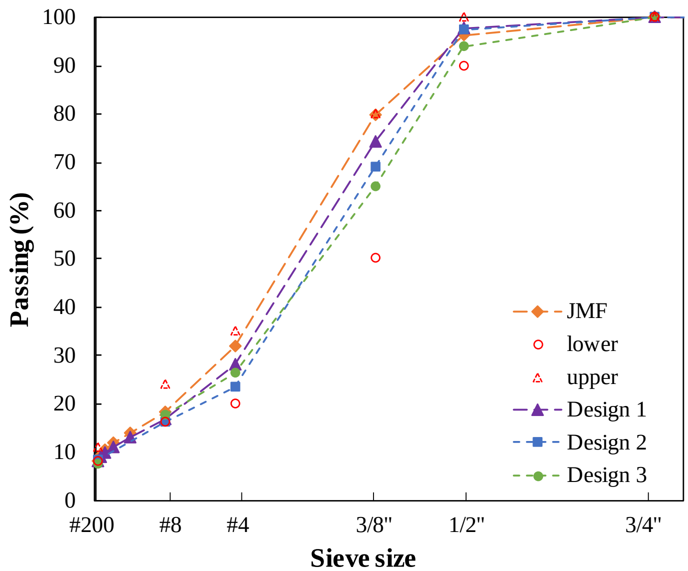


Figure 4.2 Trial gradations for ST.

Table 4.2 Volumetric Parameters of Trial Mixtures for ST

Volumetric Parameters	Design 1	Design 2	Design 3
G_{mb}	2.236	2.223	2.270
G_{sb}	2.579	2.571	2.557
P_s, %	93.2	93.2	93.2
P_b, %	6.5	6.5	6.5
G_{ca}, %	2.566	2.558	2.556
P_{CA}, %	71.9	76.6	79.1
G_{mm}	2.404	2.387	2.400
VMA, ≥17%	19.2	19.4	17.2
VCA_{mix}, %	37.3	33.4	29.7
P_a, %	7.0	6.9	5.4

4.1.2 Volumetric Mix Design for SS

As illustrated in Figure 4.3, the gradation of the SMA mixture containing 65% steel slag initially matched that of ST. Additionally another gradation with a lower proportion of steel slag (31%) was also evaluated. This analysis helped to understand the correlation between steel slag content and relative volumetric parameters. The binder content for SS was determined to be 6.0% based on the G_{ca} of the blended aggregates.

Table 4.3 presents the volumetric parameters of SS mixtures from the two trial designs, both surpassing the required 17% *VMA* in accordance with AASHTO M 325. Design 1, exhibiting a higher *VMA*, was preferred over Design 2. The VCA_{DRC} of 45.8% exceeding VCA_{mix} of 34.5% indicated sufficient contact among coarse aggregates. Design 1, with 6.5% binder content, was selected as the optimal mix design for SS after comparing the volumetric parameters for the optimal gradation with varying binder contents.

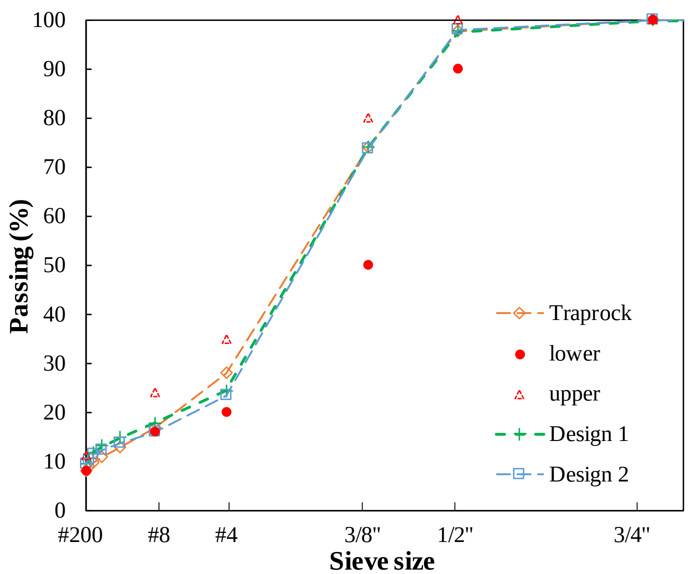


Figure 4.3 Trial gradations for SS.

Table 4.3 Volumetric Parameters of Trial Mixtures for SS

Volumetric Parameters	Design 1	Design 2
G_{mb}	2.641	2.448
G_{sb}	3.027	2.768
P_s, %	93.7	93.7
P_b, %	6.0	6.0
G_{ca}, %	3.048	2.769
P_{CA}, %	75.6	76.7
G_{mm}	2.801	2.558
VMA, ≥17%	18.2	17.1
VCA_{mix}, %	34.5	32.2
P_a, %	5.7	4.3

4.1.3 SMA Final Volumetric Mix Design

The final gradations and volumetric parameters required in the standards for the SMA mixtures with traprock or steel slag are presented in Figure 4.4 and Table 4.4. Ultimately, both mixtures met the 17% limit of *VMA* and 4% air voids under design gyrations (100). Furthermore, the VCA_{mix} of all SMA mixtures was lower than VCA_{DRC}, indicating effective contact among coarse aggregates and the formation of an aggregate skeleton in the SMA mixtures.

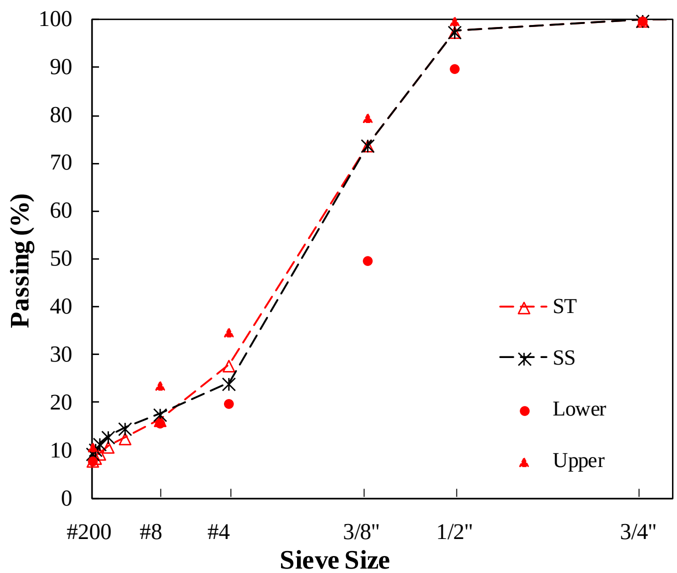


Figure 4.4 Final gradation of SMA mixtures.

Table 4.4 Volumetric Parameters of SMA Mixtures

Volumetric Parameters	ST	SS
G_{mb}	2.261	2.656
G_{sb}	2.579	3.027
P_s, %	92.2	93.2
G_{ca}, %	2.566	3.048
P_b, %	7.5	6.5
P_{CA}, %	71.9	75.6
G_{mm}	2.362	2.764
VMA, ≥17%	19.1	18.2
VCA_{mix}, %	37.3	34.5
VCA_{DRC}, %	41.5	45.8

As depicted in Figure 4.5(a), the draindown percentage was determined as 0.18% and 0.21% for ST and SS, respectively, well within the limit of 0.3%. Figure 4.5(b) indicates that the TSR values tested as 0.91 for ST and 0.96 for SS, both exceeding the minimum requirement of 0.8. The composition of the final volumetric mix design for SMA mixtures is presented in Table 4.5.

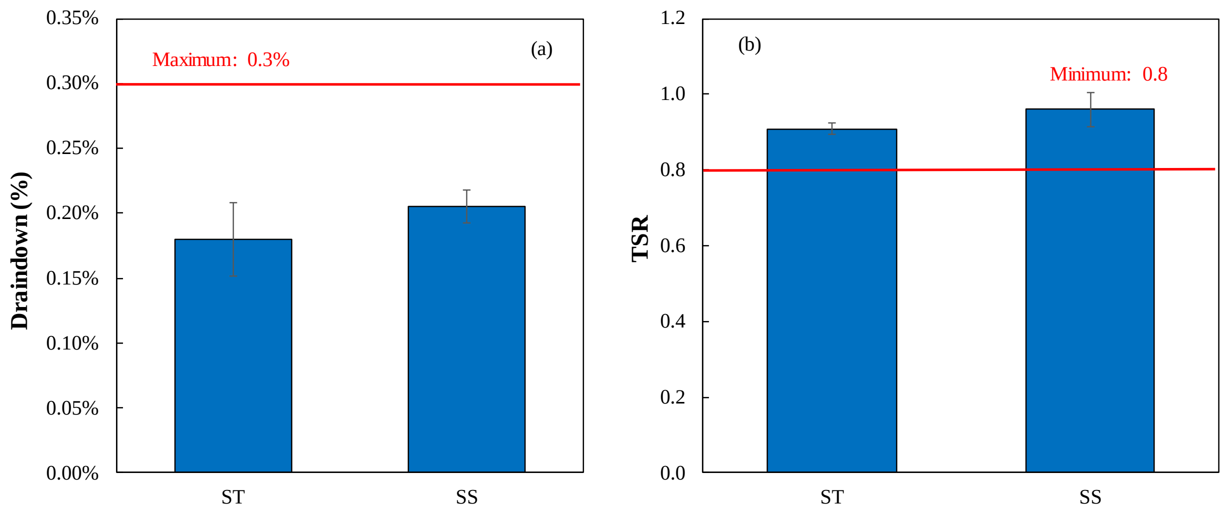


Figure 4.5 Performance test results of SMA mixtures: (a) draindown, and (b) moisture susceptibility.

Table 4.5 Composition of Final Volumetric Designs for SMA Mixtures

Main Coarse Aggregates in Mixtures		**Remaining Parts in Mixtures**				
		Other Aggregates		**Binder Content**	**Fly Ash**	**Fiber**
		Dolomite _1/2"C	Dolomite _3/8"M	PG 64-22V	Class C	Cellulose Fibers
Traprock	65%	22%	6%	7.50%	7%	0.30%
Steel Slag	65%	22%	6%	6.50%	7%	0.30%

4.2 Mix Performance Evaluation

After the volumetric optimum gradation and binder content were determined following the design specification, a series performance tests were conducted to evaluate the mix performance for the preliminary design. In this study, the IDEAL-CT and the HWTT, which are currently used by MoDOT as BMD performance tests for job mix approval (BMD Performance Testing for Job Mix Approval NJSP-21-08b), were selected to assess the cracking and rutting resistance, respectively. According to the testing criteria, a well-designed SMA mixture should have a

CT_{Index} above 135 and an RRI value obtained from the HWTT greater than 9.9, as illustrated in the green zone (top-right corner) in Figure 4.6.

The testing results are also plotted in the BMD design diagram in Figure 4.6. For mixture ST, the results fell within the green zoon, indicating sufficient cracking and rutting resistance. Thus, the ST mix design was finalized with the volumetric design. For mixture SS, while the rutting index, RRI, passed its requirement, the cracking resistance index, CT_{Index}, was lower than the limit of 135. The testing results indicated that even though the SS satisfied all volumetric criteria and durability requirements for SMA mixtures, the design still needed to be adjusted to improve its cracking resistance.

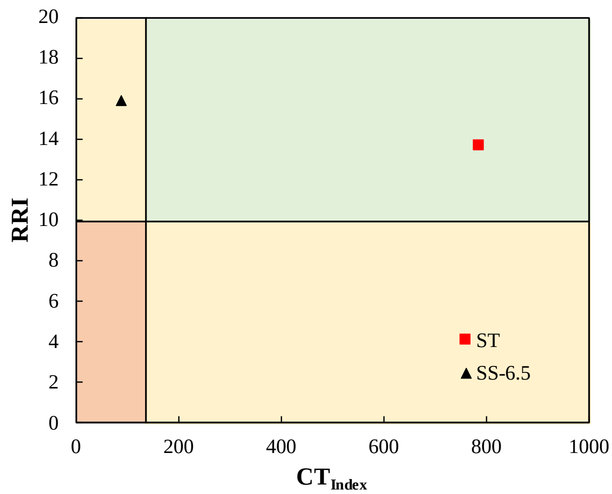


Figure 4.6 BMD diagram with cracking and rutting resistance of the initial volumetric designs for SMA mixtures.

4.3 Binder Content Adjustment for SS

Since the gradation of the mixture SS had been confirmed to yield sufficient *VMA* and stone-on-stone contact, adjusting the binder content was first used as a simple strategy to improve the mix performance. The volumetric optimum binder content for the given components was 6.5%. To increase its cracking resistance, two higher levels of binder contents, i.e., 7.0% and 7.5%, were used to fabricate specimens while the gradation remained the same. The specimens were compacted to the same air void level for the cracking and rutting tests, and the testing results are presented in Figures 4.7 to 4.9.

As shown in Figure 4.7(a), as the binder content increased, while the maximum load in the IDEAL-CT cracking tests decreased, the slope of the post-peak slope of the load vs. displacement curves decreased as well. As a result, as the binder content increased, the CT_{Index} increased, and the index value passed the threshold of 135 for SS mixture at the binder content of 7.5%. Figure 4.8 further illustrates the trends of the fracture indices changes as a function of binder contents. As the binder content increased, the fracture energy, G_f, or the area under the load-displacement curve increased, and the value of l_{75}/m_{75} or the ductility of the mixtures increased as well. The cracking resistance of the designed mixtures, hereby, increased.

The rutting resistance of the SS mixtures with different binder contents was tested using the HWTT, and the testing results are presented in Figure 4.9. As the binder content increased, the obtained rut depth under the testing wheel increased. As a result, the corresponding RRI values of the SS mixtures decreased with the increase of binder content. However, RRI values from mixtures with different levels of binder contents all passed the minimum requirement of 9.9. Given the obtained cracking and rutting resistance of the SS mixtures with different binder content levels, the binder content of the original volumetric can be adjusted to ensure sufficient mix performance.

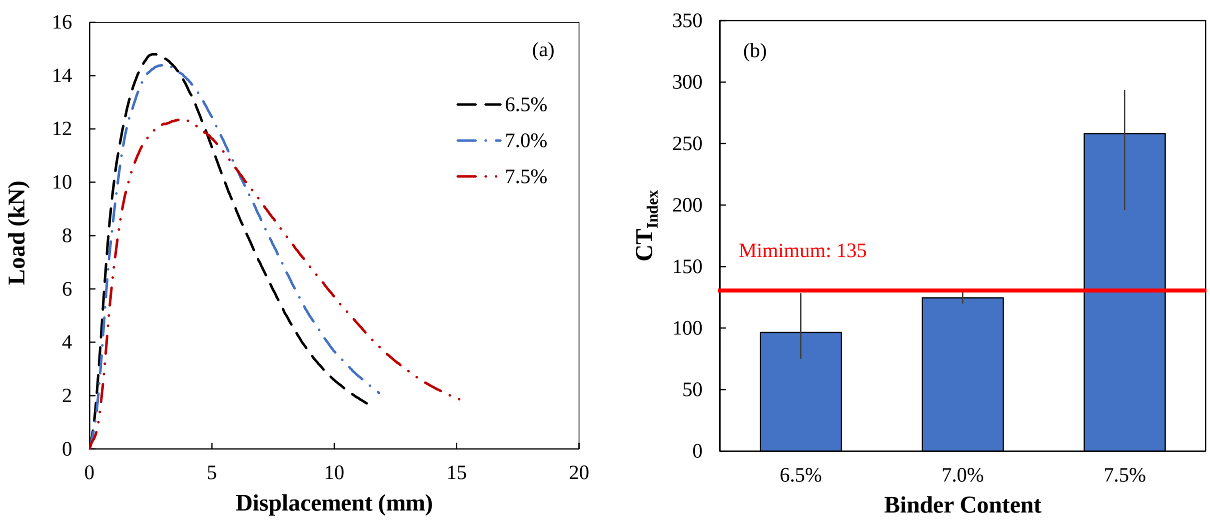


Figure 4.7 IDEAL-CT testing results for SS mixtures with different binder contents: (a) averaged load vs. displacement curves, and (b) CT_{Index} values.

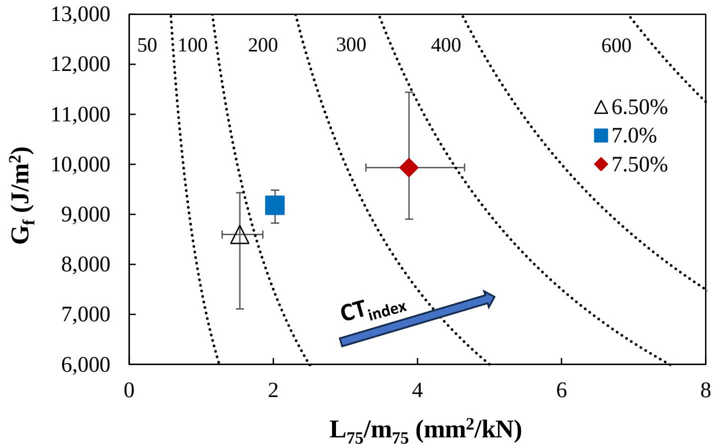


Figure 4.8 G_f vs. l_{75}/m_{75} interaction diagrams of SS mixtures with different binder contents.

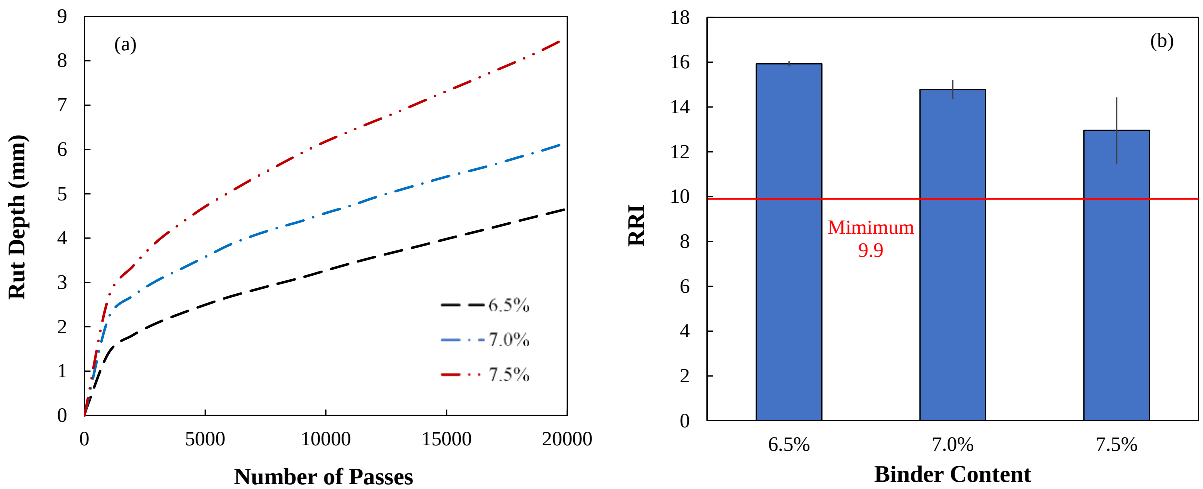


Figure 4.9 HWTT Testing results of SS mixtures with different binder contents: (a) averaged rut depth vs. passing number curves, and (b) RRI values.

4.4 Determine Optimum Performance Binder Content for SS

The mix performance of the SS mixtures with different design conditions was plotted in the BMD diagram, as presented in Figure 4.10. The figure indicates that as the binder content increased, the position of the mix performance moved from the top-left yellow section with sufficient rutting resistance but lack of cracking resistance to the green zone with satisfying rutting and cracking resistance. It can be also observed that while the mixture with 7.5% binder fell in the middle the green zone, the mixture with 7.0% binder was barely on the edge. It indicated a binder content of 7.5% may be more than sufficient. For the economic propose, the binder content of the mixture can be further optimized.

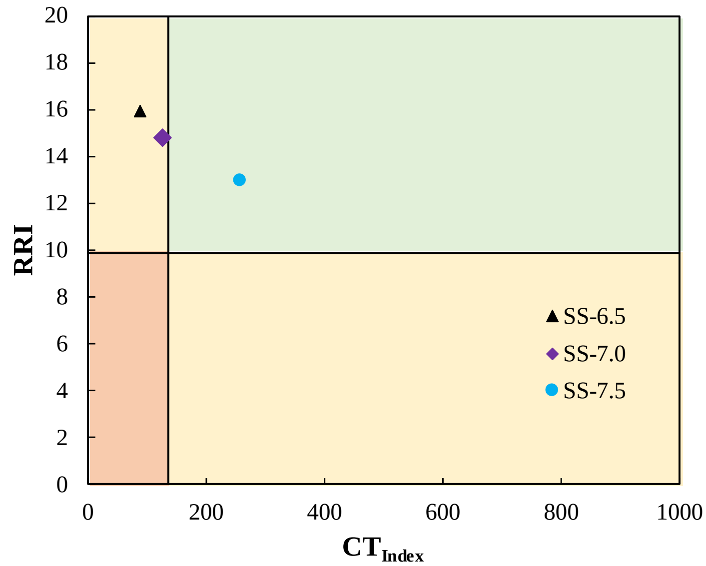


Figure 4.10 BMD diagram with cracking and rutting resistance of designs with different binder contents.

The trends of the cracking and rutting resistance changes as a function of binder content are presented in Figure 4.11. The range of the design binder content should be determined based on the acceptable performance limits. In this case, as shown in Figure 4.11, the cracking resistance requirement restrained the lower limit of binder content, and the upper limit was estimated through the projection of the rutting resistance testing result. The highlighted area in the figure represented the range of binder content that allowed the mix to meet performance requirements. The suitable binder content was approximately 7.1% to 7.9%; whereas the optimum volumetric binder content was 6.5%. Considering the variability, uncertainty, and cost in construction, based on the testing results, the performance optimum binder content was determined as 7.3% in this design. There is a certain possibility that, in some design cases, the lower limit determined by the cracking test is higher than upper limit restricted by the rutting test. In this scenario, as indicated in Figure 3.1, the design iteration may return further to the gradation adjustment. While ensuring a well-structured gap gradation, the proportions in the aggregate combination can be revised.

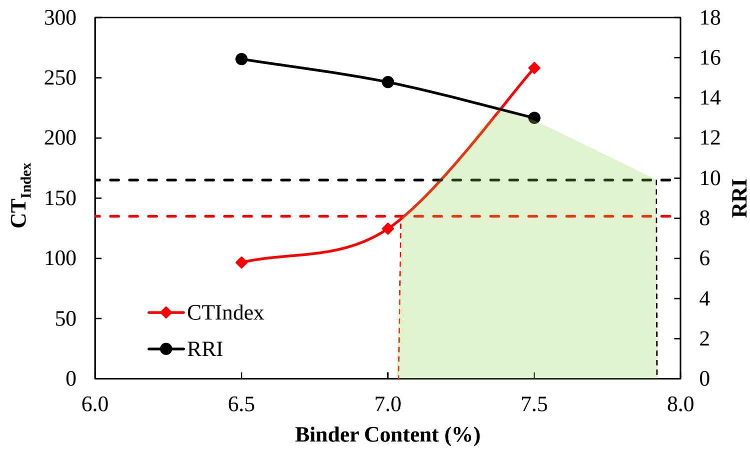


Figure 4.11 Balanced range of binder content for performance requirements.

4.5 Performance Verification for SS

After the preliminary determination of performance optimum binder content, the cracking resistance, rutting resistance, durability and the constructability of the newly designed mix needed to be verified since a different binder content was used. The IDEAL-CT, HWTT, moisture susceptibility and the draindown tests were performed again under the new design. It can be observed with an increased binder content, the draindown percentages slightly increased from testing results with 6.5% binder. Figure 4.12 shows the comparison of performance test results for SS at the volumetric optimum binder content of 6.5% and the performance optimum binder content of 7.3%. Increasing the binder content led to an obvious increase in CT_{Index} value from 84.9 to 194.8 and a decrease in RRI value from 15.9 to 13.7. Both the CT_{Index} and RRI passed the performance requirements of 135 and 9.9, respectively.

The workability and moisture susceptibility of the newly designed SS were further validated through draindown and TSR tests (Figure 4.13). The increased binder content resulted in a slight increase in draindown percentages from 0.17% to 0.21% and a decrease in TSR value from 0.96 to 0.85. However, both draindown percentages and TSR values still met the requirements of 0.3% and 0.8, respectively. Thus, the design for SS was finalized with the volumetric optimum gradation and the performance optimum binder content 7.3%.

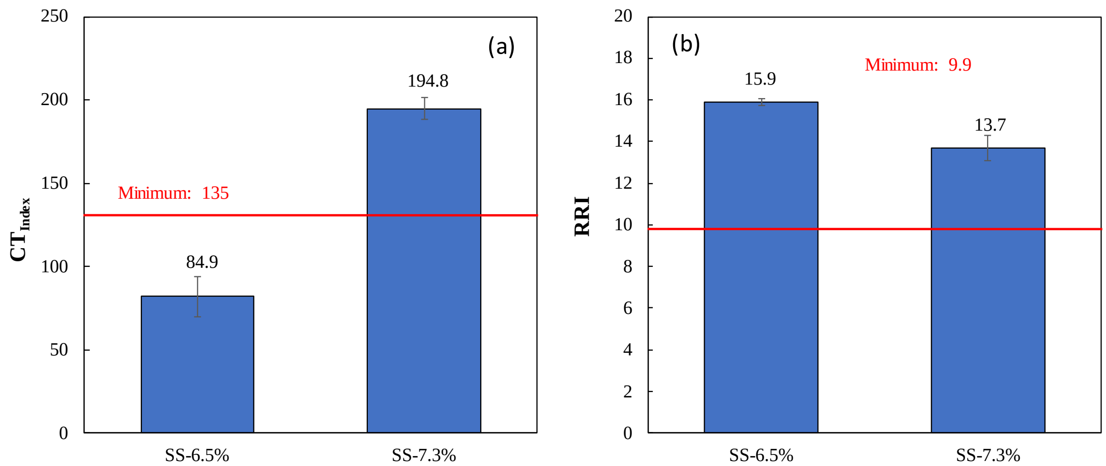


Figure 4.12 Performance validation results of new SS design.

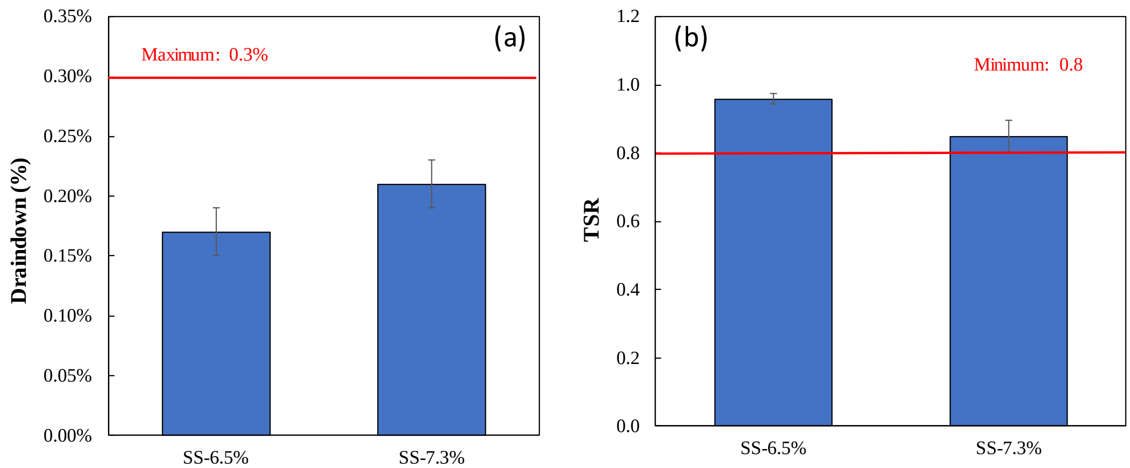


Figure 4.13 Draindown and moisture susceptibility validation results of new SS design.

4.6 Final SMA Mix Designs

The composition of the final mix designs for mixtures ST and SS is presented in Table 4.6. The mix design for ST was finalized based on the volumetric design, meeting all the performance requirements. For SS, the optimum performance binder content was 7.3%, compared to 6.5% as determined by the volumetric mix design, while the gradation and other components in the mixture remained consistent with the volumetric design.

Table 4.6 Composition of Initial Volumetric Design for SMA Mixtures

Main Coarse Aggregates in Mixtures		**Remaining Parts in Mixtures**				
		Other Aggregates		**Binder Content**	**Fly Ash**	**Fiber**
		Dolomite _1/2"C	Dolomite _3/8"M	PG 64-22V	Class C	Cellulose Fibers
Traprock	65%	22%	6%	7.50%	7%	0.30%
Steel Slag	65%	22%	6%	7.3%	7%	0.30%

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

The objective of this project is to develop a preliminary BMD method for SMA mixtures. In this study, a BMD approach for SMA was developed. The design approach has also been demonstrated with the mix designs for two SMA mixtures using traprock or steel slag as coarse aggregates, respectively. The following conclusions can be summarized from the study.

- The BMD method considered the specific structural and constructability requirements for SMA mixtures. The stone-on-stone contact was ensured by the volumetric parameters, and the performance of design candidates was verified through cracking and rutting laboratory tests.
- The BMD method was demonstrated using the mix designs for two SMA mixtures using traprock or steel slag as coarse aggregates, respectively. The volumetric design for SMA with traprock passed the performance requirements and was finalized. The initial volumetric design for SMA mixture with steel slag yielded insufficient cracking resistance. After conducting performance tests on multiple binder levels, the performance optimum binder content was determined given the performance requirements, durability, construction variability, and cost-effectiveness.
- As the gradation was adjusted to meet the *VMA* criteria, a strong correlation between *VMA* and the percentage of aggregate retained on or passing the #8 sieve was observed and later applied to tune the design in this study.
- This method can be practical when locally available coarse aggregates are considered in the gap-graded mixtures.
- For future studies, as more laboratory performance testing data are available for SMA mixtures, the BMD approaches with more performance-based strategies can be developed. Such future approaches may apply fewer volumetric constrains and rely the gradation and binder content selection more on performance verification and prediction; therefore, provide more flexibility for designs with unconventional innovative and sustainable components.

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