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Quarry By-product Fines for Otta Seal Surfacing of Local Roads

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16. Abstract
This report evaluates through comprehensive laboratory testing the potential of utilizing quarry by-products (QBs) in Otta seal applications as a sustainable and economical alternative to conventional aggregates. An asphalt surface treatment used on low-volume roads, Otta seal consists of a relatively thick application of asphalt binder, covered with a graded aggregate layer that allows the use of locally available and marginal-quality materials. Commonly used chip seal design methods were modified to develop a rational design approach for Otta seal, as the conventional Otta seal design procedure is largely empirical. Material characterization was conducted to determine aggregate gradation, physical properties, and emulsion characteristics required for Otta seal design. A double-layer Otta seal configuration was selected based on laboratory optimization involving testing of various configurations and incorporating QBs. The effect of curing temperature and duration on performance was also investigated through weight-loss monitoring and post-curing sweep testing. The performance of laboratory-optimized, QB-based Otta seals was then evaluated and compared with typical Otta seal aggregate through multiple laboratory tests. Performance assessment included sweep testing to evaluate aggregate retention, a modified Hamburg wheel-tracking (HWT) test to evaluate aggregate retention under simulated braking conditions, and close-range photogrammetry to quantify surface texture. The QB-based Otta seal specimens showed performance trends comparable to those constructed with typical Otta seal aggregate. The best-performing design method was selected, and QB-based specimens were further evaluated for susceptibility to bleeding under repeated wheel passes using modified HWT, friction characteristics using a dynamic friction tester, and changes in composite modulus using a box-test setup with lightweight deflectometer testing. Results indicated that QB-based Otta seal provides adequate resistance to bleeding and sufficient friction for safe traffic movement, demonstrating strong potential as a sustainable and cost-effective pavement-preservation alternative for low-volume roads.

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- John Senger, TRP Chair, Illinois Department of Transportation
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EXECUTIVE SUMMARY

This report presents a detailed laboratory evaluation of the performance trends of Otta seal specimens incorporating quarry by-products (QBs) as aggregate. The primary objective of the laboratory investigation was to assess the feasibility of using locally available QB materials as a sustainable alternative to conventional aggregates for Otta seal coat construction, while ensuring satisfactory performance in aggregate retention, resistance to bleeding, surface durability, and overall stability under varying traffic-loading conditions. The study developed a rational design approach capable of providing adequate binder- and aggregate-application rates for QB-based Otta seal applications, rather than relying on conventional design approaches.

For material selection, eight QB materials obtained from various Illinois quarries were initially evaluated, and two representative materials were selected based on Overby-gradation characteristics. The first selected QB, designated as QB-5, consisted of a relatively coarser limestone-based material, while the second QB, designated as QB-2, consisted of finer dolomitic aggregates. These QB designations were based on the previous ICT R27-248 project materials. The variation in gradation and mineral composition between these two materials provided a basis for evaluating the influence of aggregate characteristics on the performance trends of QB-based Otta seal coats. To satisfy Overby-gradation requirements, the finer QB was blended with coarser aggregates. For comparison, a control aggregate gradation was prepared using a dense-graded CA-6 aggregate material. Two high-float, rapid-set (HFRS) asphalt emulsions were selected for the study—an unmodified emulsion, HFRS-2, and a polymer-modified emulsion, HFRS-2P—to investigate the effect of binder type on coating behavior, aggregate retention, and overall performance.

Considering the high fine content in QB materials, a laboratory-optimized, double-layer Otta seal configuration was developed to improve binder distribution and surface-texture characteristics by evaluating loose aggregates on top of the specimen. This configuration was developed in the laboratory by preparing a sequence of single- and double-layer Otta seal samples. In the configuration developed, two layers of emulsion and two aggregate layers were applied. The aggregates were separated using a No. 8 sieve (2.36 mm). The first emulsion layer was followed with finer QB particles, and the second emulsion layer was followed with coarser particles. This double-layer configuration allowed the distribution of emulsion between fine and coarse particles, and the coarser particles in the top layer contributed to improved surface texture. Laboratory observations indicated that this optimized double-layer configuration achieved complete binder coverage and minimized the presence of loose or uncoated particles.

A rational design method was adapted based on evaluating three chip seal design approaches—the McLeod method, the modified Kearby method, and the Austroads method—for their applicability in Otta seal design. The objective was to develop a design procedure capable of providing adequate binder content to achieve sufficient coating and durable aggregate–binder interaction for QB-based Otta seal systems.

A curing study was also conducted to evaluate the influence of curing temperature and curing duration on aggregate–binder bonding strength. Because Otta seal performance is strongly dependent on the development of adequate adhesion between binder and aggregate particles, the curing process plays an important role in determining early-life and long-term performance. Laboratory results indicated that a higher curing temperature improved aggregate retention by accelerating the breaking and setting process of the asphalt emulsion. Specimens subjected to extended curing periods exhibited consistently lower aggregate-loss values, as compared to specimens subjected to shorter curing periods. These findings highlight the importance of adequate curing temperature and duration for achieving optimal performance of QB-based Otta seal in the field.

Laboratory performance evaluation comprised three tests conducted on 18 specimens—representing combinations of three aggregate types, two emulsion types, and three design methods. The tests included a sweep test to evaluate aggregate–binder adhesion and traffic-induced abrasion, a modified Hamburg wheel-tracking (HWT) test with a locked tire to assess abrasion from simulated braking, and close-range photogrammetry (CRP) to measure surface texture. The sweep-test and modified-HWT test results indicated that QB-based Otta seals achieved aggregate retention values comparable to, or better than, those observed for typical Otta seal aggregate. Among the design methods, the modified Kearby method consistently demonstrated the lowest aggregate-loss values. This improved performance is attributed to the relatively higher emulsion-to-aggregate ratio recommended by this design procedure. The higher binder content improved aggregate coating and enhanced the development of strong adhesive bonds between the binder and the aggregate particles. In contrast, the Austroads method resulted in the lowest binder contents, which produced the highest aggregate-loss values. After identifying the best-performing design method, additional testing was conducted using the modified Kearby method to evaluate the bleeding susceptibility, bearing capacity, and friction performance of QB-based Otta seal designs.

The bleeding test was conducted using a modified-HWT device with a rotating pneumatic tire to evaluate the bleeding susceptibility of QB-based Otta seal specimens. Photos of the specimen were captured after every few thousand passes to monitor surface changes and binder migration. The results indicated that QB-based Otta seal specimens exhibited no evidence of bleeding, which can be attributed to the well-graded nature and complex void structure of QBs. For evaluating improvement in bearing capacity due to adding an Otta seal, lightweight deflectometer (LWD) testing was conducted on an Otta seal layer applied over a small-scale laboratory box setup. The results indicated an increase in the measured composite modulus following application of the Otta seal layer. The observed increase in modulus was primarily attributed to surface-confinement effects and improved stress distribution provided by the Otta seal layer.

Friction characteristics of QB-based Otta seal were measured using a dynamic friction tester (DFT), following the ASTM E1911 (2024) method. The test measures the friction coefficient of a specimen surface as a function of speed by rotating a disk with rubber sliders on the wetted specimen surface. The results indicated that the QB-based Otta seal exhibited friction levels exceeding minimum safety requirements and were comparable to those measured at the Illinois Center for Transportation (ICT) parking-lot asphalt surface, demonstrating adequate skid resistance for safe traffic movement.

Overall, the laboratory performance evaluations demonstrated that quarry by-products can serve as a viable and sustainable aggregate material for Otta seal applications on low-volume roads. The results indicated that QB-based Otta seals can achieve satisfactory aggregate retention, excellent resistance to bleeding, and good surface characteristics when appropriate mixture design and curing conditions are applied. The modified Kearby design method is recommended as the preferred design approach for QB-based Otta seal mixtures due to its ability to provide sufficient binder content for effective aggregate coating and improved resistance to aggregate loss. The findings of this study support the potential use of quarry by-products as an economical and environmentally beneficial material for Otta seal coat construction in Illinois, which has abundant QB resources.

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CHAPTER 1: INTRODUCTION

BACKGROUND AND MOTIVATION

Surface sealing of unpaved roads is commonly done to improve ride quality, control dust, and reduce maintenance requirements. Unsealed granular roads are highly susceptible to moisture infiltration, surface erosion, and rutting under traffic loading and environmental exposure. Bituminous surface treatments provide a protective layer that improves surface durability, reduces moisture penetration into the base layer, and enhances functional performance (Overby, 1999). Conventional surface treatments such as chip seals and sand seals are widely used; however, these methods require uniformly graded, high-quality aggregates with controlled particle-size distribution. In many cases, availability of such aggregates is limited due to local material constraints or high hauling and processing costs. Therefore, alternative surface-treatment methods capable of utilizing locally available materials are needed.

The Otta seal was originally developed in the Otta Valley in Norway to provide an economical method for improving gravel roads using locally available materials. Since then, Otta seal has been applied in several countries—including Scandinavian regions, Iceland, eastern and southern Africa, Bangladesh—as well as selected states in the United States, such as South Dakota, Minnesota, and Iowa (Gushgari et al., 2019; Jibon, Yang, et al., 2023; Overby, 1999). These applications demonstrate the suitability of Otta seal for a wide range of environmental and traffic conditions. In addition, field studies of Otta seal have reported improvements in surface durability, reduction in dust generation, improved ride quality, waterproofing, and improved freeze–thaw durability (Jibon, Mahedi, et al., 2023). These outcomes indicate that Otta seal provides a reliable functional performance and presents a viable alternative to conventional surface treatments for low- to medium-volume roads. Otta seal was initially developed as an economical maintenance treatment for unpaved gravel roads; but over time, its application has expanded to include asphalt surface treatment with no traffic limitations other than those applied for conventional asphalt surface treatments (Gushgari et al., 2019; Overby, 1999).

Construction of an Otta seal coat involves the application of a relatively thick layer of low-viscosity asphalt binder, followed by placement of well-graded aggregates. The use of well-graded aggregates improves particle packing and aggregate interlock within the surface layer. Under compaction and traffic loading, the aggregates become embedded into the binder, while the binder gradually redistributes and coats the aggregate particles, forming a stable wearing surface. Depending on traffic conditions and design requirements, Otta seals can be constructed as single- or double-layer systems, with total thickness typically ranging from approximately 0.63 in. to 1.26 in. (16 mm to 32 mm) (Overby & Pinard, 2013). A single-layer Otta seal configuration is suitable for average daily traffic (ADT) of up to 500 vehicles, and double-layer Otta seals can be used for ADT up to 2,000 vehicles (Overby, 1999; Overby & Pinard, 2013). However, chip seals can be applied for higher traffic conditions and have been reported to perform effectively on roads carrying ADT of more than 5,000 vehicles, as documented by a National Cooperative Highway Research Program (NCHRP) report in 2005 (Gransberg & James, 2005). For low-volume roads, Otta seals offer several advantages over chip seals. One of the key advantages of Otta seals is the ability to utilize a wide range of locally available and marginal-quality aggregates. Unlike chip seals, which require uniformly graded and high-quality aggregates, Otta seal can incorporate well-graded materials with a broad particle-size distribution. This capability allows the use of quarry by-product, natural gravels, and other lower-quality aggregates that may not meet strict specifications for traditional surface treatments. This flexibility in material selection makes Otta seal particularly suitable for regions where high-quality aggregates are scarce or expensive to obtain or transport. A second advantage is cost-effectiveness achieved by utilizing locally available and marginal aggregates, which reduces the need for processing, transportation, and procurement of high-quality aggregates. In addition, Otta seal requires relatively simple construction techniques and equipment, further minimizing implementation costs. One study found that Otta seal construction may reduce project cost by approximately 30%, as compared to chip seal, due to the use of locally available aggregates and reduced material-processing requirements (Gushgari et al., 2019). In addition to economic advantages, Otta seals also demonstrate favorable long-term performance. Previous studies indicate that single-layer Otta seals generally provide service lives of approximately 8 to 12 years, while double Otta seals may last 12 to 16 years, both of which are longer than the typical 4- to 6-year service lives reported for conventional chip seals (Overby & Pinard, 2013).

From a sustainability perspective, Otta seals can be particularly beneficial, as they can utilize marginal aggregates and reduce reliance on high-quality virgin aggregates, thereby lowering material-extraction life cycle costs, reducing the need for transportation of aggregates, and providing an overall beneficial environmental impact. At the end of its service life, the Otta seal layer can be reclaimed and reused as unbound or stabilized material, which supports material circularity and reduces construction waste (Gushgari et al., 2019). The use of recycled materials or industrial by-products in Otta seal mixtures can further improve sustainability by reducing environmental impacts associated with aggregate production and transportation. Identification of alternative aggregate materials that meet performance requirements while improving resource efficiency has become an important consideration in pavement engineering.

Quarry by-products (QBs) are residual materials generated during quarrying operations such as blasting, crushing, washing, and screening of aggregates. Production of QBs is unavoidable during crushed-stone manufacturing, resulting in significant quantities of material that are often stockpiled due to limited established applications. Previous studies have reported that at least 175 million tons (159 million metric tons) of QBs are produced annually in the United States from more than 3,000 quarries (Stroup-Gardiner & Wattenberg-Komas, 2013). As part of Illinois Center for Transportation (ICT) project R27-125, a survey of aggregate producers in Illinois showed that the quantity of QBs generated annually is considerable, with estimates reaching approximately 950,000 tons (862,000 metric tons) per year (Tutumluer et al., 2015). The quantity of QBs is expected to increase with continued growth in construction activities and aggregate demand, creating challenges related to stockpiling, disposal, and environmental management. QBs are generally sand-sized, well-graded aggregates containing fines (particles passing the No. 200 standard sieve) at contents ranging from 10% to 20% (Hou et al., 2019; Tutumluer et al., 2015). Because QBs are generated during aggregate production, they are readily available from many local production sites. This local availability, combined with their well-graded characteristics, makes them a potential aggregate source for Otta seal applications.

Although Otta seals offer several advantages, their current design approach remains primarily empirical and relies on generalized design charts that do not explicitly account for the aggregate and binder physical and chemical properties that govern aggregate–binder interaction. The limited availability of documented information on Otta seal material properties, design procedures, construction practices, and field performance, combined with industry's reluctance to adopt nonconventional technologies, has further restricted wider implementation of this surface treatment (Overby, 1999). In addition, limited research has investigated the use of QBs or similar marginal materials in Otta seal applications. These limitations highlight the need for systematic evaluation of QB materials and the development of rational design procedures that incorporate material properties and performance-related parameters, resulting in improved and more effective Otta seal design and construction practices.

Based on these limitations, this project aimed to evaluate the feasibility of utilizing QBs as an alternative aggregate source in Otta seal applications. This study focuses on assessing whether QBs can meet the functional requirements of Otta seals, while providing a cost-effective and sustainable alternative to conventional aggregates. In addition, the study aims to develop a rational design methodology for Otta seals by adapting established chip seal design approaches that account for aggregate and binder properties, including the McLeod, modified Kearby, and Austroads methods. The findings are presented in this report to provide recommendations for optimizing the use of QBs in Otta seal applications and promoting a sustainable design framework that effectively incorporates these materials.

OBJECTIVE AND SCOPE

The primary objective of this study is to evaluate the feasibility of utilizing QBs as aggregate in Otta seal applications. QBs have the potential to serve as suitable aggregate materials because they exhibit well-graded characteristics and are locally available, although they are often considered marginal-quality materials. This study aims to assess whether the gradation characteristics and performance behavior of QBs can meet the functional requirements of Otta seals, thereby providing a cost-effective and sustainable alternative to conventional aggregates. Furthermore, the study aims to develop a rational design methodology for Otta seals by adapting established chip seal design approaches and reducing reliance on conventional empirical design practices.

The scope of this study includes a comprehensive literature review of Otta seal design parameters, including aggregate- and binder-selection criteria, as well as relevant laboratory-testing methods. Otta seal specimens incorporating QBs were optimized at the laboratory scale and subsequently subjected to a comprehensive laboratory-performance evaluation to assess their suitability as alternative aggregate materials for Otta seal applications. The experimental program included the sweep test and a modified Hamburg wheel-tracking (HWT) test with a locked-wheel configuration to evaluate susceptibility to aggregate loss under simulated traffic abrasion and braking conditions, respectively. Surface-texture characteristics were quantified using close-range photogrammetry (CRP). The performance of QB-based Otta seal specimens was compared with that of control specimens prepared using typical Otta seal aggregate produced by blending different sizes of CA-6 material, a standard Illinois Department of Transportation (IDOT) dense-graded aggregate. For the

QB-based Otta seal specimens, friction properties were assessed using the dynamic friction tester (DFT), bleeding susceptibility was evaluated using the modified HWT with a rotating-wheel configuration, and changes in bearing capacity were measured using the lightweight deflectometer (LWD). Overall, these evaluations provide a comprehensive assessment of the functional performance of QB-based Otta seals, supporting their potential applicability as a sustainable alternative to conventional aggregate in Otta seal.

RESEARCH METHODOLOGY

To fulfill the above research objectives, the following tasks and methodologies were considered in this study:

- *Material characterization of QBs and emulsions:* Physical and engineering properties of QBs, including gradation, specific gravity, and absorption, were evaluated to better understand their suitability for Otta seal applications. Properties of emulsions were also measured to ensure compatibility with the selected QB materials.

- *Development of laboratory-optimized, QB-based Otta seal design:* Because QBs predominantly consist of sand-sized aggregate with high fine contents and large surface areas, they tend to absorb a significant amount of emulsion, which may adversely affect surface texture and reduce friction when applied directly as a single surface. Therefore, the design configuration incorporating QBs was optimized to establish an appropriate methodology for QB-based Otta seals, using a double-layer configuration and separated aggregate fractions to achieve adequate binder distribution and improved texture.

- *Evaluation under different curing conditions:* Otta seal specimens were prepared and subjected to different curing conditions with varying temperatures and durations to evaluate the influence of curing parameters on performance, particularly aggregate loss measured using the sweep test. This evaluation facilitated identification of appropriate curing conditions required to achieve adequate binder–aggregate interaction and improved performance of QB-based Otta seals.

- *Performance evaluation of QB-based Otta seals:* Laboratory-performance tests were conducted to evaluate aggregate retention, resistance to traffic abrasion, surface-texture characteristics, friction performance, effects on bearing-capacity improvement, and susceptibility to bleeding. These results were used to assess the feasibility and performance characteristics of QB-based Otta seals.

- *Development of guidelines for field implementation and final reporting:* Based on the results of this study, a framework was developed with recommendations for field implementation, including guidance for field evaluation and performance monitoring. Finally, all research findings were compiled and presented in a comprehensive final report summarizing the research methodology, laboratory results, design recommendations, and implementation guidance.

REPORT ORGANIZATION

This report consists of seven chapters, including this introductory chapter.

Chapter 2, Literature Review, presents a comprehensive review of the development and application of Otta seals. This chapter summarizes the traditional Otta seal design methodology, commonly referred to as the Overby design method. In addition, rational design approaches commonly used for chip seals are reviewed and evaluated for their potential adaptation to Otta seal applications. The chapter also provides background information on the production process and typical characteristics of quarry by-products (QBs) from previous studies, as well as construction and performance of Otta seals in various regions around the world.

Chapter 3, Material Characterization and Test Matrix, describes the sources and selection process of the QBs used in this study. This chapter includes detailed laboratory characterization of QB materials, including evaluation of gradation and other relevant physical properties required to assess their suitability for Otta seal applications and to determine application rates using rational design methods. The selection of the emulsified asphalt binder is also discussed, as well as laboratory testing performed to determine key binder properties influencing adhesion and overall Otta seal performance. Furthermore, this chapter presents the modification of relevant parameters required to adapt established rational chip seal design methodologies for application to Otta seals. The experimental design framework and test matrix adopted for the preparation and laboratory-performance evaluation of Otta seal specimens are also presented in this chapter.

Chapter 4, Laboratory Optimization of QB-based Otta Seals, focuses on the development of an optimized QB-based Otta seal layer, considering the high fine content of QB materials. This chapter presents the methodology used to establish an appropriate layer configuration, including aggregate separation and double-layer placement to improve binder distribution and surface texture. It also describes the detailed laboratory specimen-preparation procedures for both QB-based and conventional Otta seal samples.

Chapter 5, Effect of Curing Conditions on Otta Seal Performance, examines how variations in curing conditions influence binder–aggregate interaction and the resulting performance of QB-based Otta seals in terms of aggregate retention. The findings are used to determine appropriate curing conditions required to achieve adequate cohesion and satisfactory performance of QB-based Otta seal specimens.

Chapter 6, Performance Evaluation of Otta Seal Designs, discusses the laboratory testing conducted to evaluate the performance characteristics of QB-based Otta seal specimens and compares the results with those of control Otta seal specimens prepared using typical Otta seal aggregate.

Chapter 7, Conclusions and Recommendations, summarizes the key research findings and presents the conclusions of this study. This chapter also provides guidelines for field implementation of QB-based Otta seal application and discusses recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

DEVELOPMENT AND APPLICATIONS OF OTTA SEAL

In the early 1960s, nearly half of Norway's public road network consisted of unpaved gravel roads with low bearing capacity and annual average daily traffic (AADT) ranging from 50 to 500 vehicles (Overby, 1999). During the spring thaw period, many of these roads experienced significant strength loss due to moisture-induced weakening of the base layers and often became impassable. At that time, conventional practice required complete road reconstruction before applying bituminous surfacing; but this process was slow due to limited funding and construction resources. To address this issue, the Norwegian Road Authorities initiated research in 1963 to develop a cost-effective surface treatment that could improve the performance of gravel roads without full reconstruction. The treatment was required to be economical, simple to construct, capable of utilizing locally available aggregates, and able to provide adequate waterproofing, flexibility, and durability. The Norwegian Road Research Laboratory conducted experimental trials between 1963 and 1965 in the Otta Valley, from which the treatment derives its name (Overby, 1999). Although initially developed as a temporary bituminous maintenance treatment for gravel roads, Otta seal demonstrated satisfactory field performance and was later applied to both newly constructed and existing bituminous roads under low- and medium-traffic conditions. Over time, its application expanded from a maintenance treatment to a conventional bituminous-surfacing option (Overby, 1999).

Between 1965 and 1985, approximately 30% of Norway's previously unpaved roads were surfaced using the Otta seal treatment (Overby, 1999). Following successful implementation in Norway, Otta seals were gradually adopted in several countries over subsequent decades due to their cost-effectiveness and ability to utilize locally available materials. The method has been successfully applied under a wide range of climatic conditions, including cold, hot, wet, and dry environments, with reported applications in countries such as Norway, Sweden, Iceland, Lithuania, Bangladesh, Australia, Botswana, Kenya, Zimbabwe, and other parts of Africa (Overby, 1999; Overby & Pinard, 2013; Vaitkus et al., 2018). In the United States, Otta seal has been successfully applied in states such as South Dakota, Minnesota, and Iowa (Ceylan et al., 2018; Gushgari et al., 2019; Jibon et al., 2025; Jibon, Mahedi, et al., 2023; Jibon, Yang, et al., 2023; Johnson, 2003; Nahvi et al., 2019).

Overby Design Method

The first guidelines providing practical recommendations for Otta seal design were provided by Charles Overby in 1999 and are commonly known as the Overby design method. These guidelines also summarize experience gained from Otta seal applications over the previous three decades in various regions worldwide. According to the guidelines, aggregates can be used in Otta seal application if their gradation falls within the gradation band presented in Figure 1 (Overby, 1999).

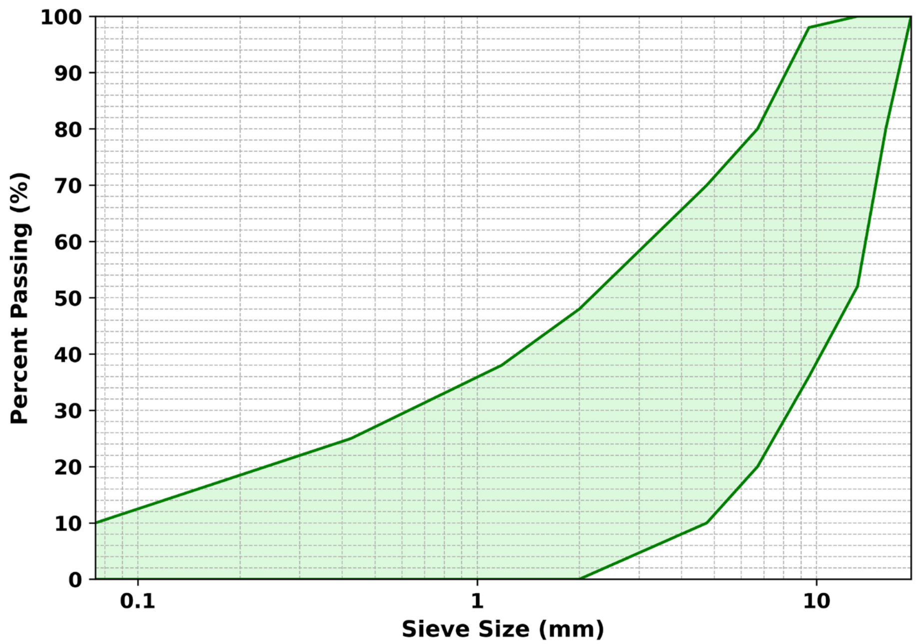


Figure 1. Graph. General aggregate-gradation band for Otta seal recommended by Overby method.

Source: Overby (1999)

A flowchart of the design procedure based on the Overby design method is presented in Figure 2. In this design method, the first step involves the selection of the appropriate Otta seal configuration based on the traffic level. For low-volume traffic with AADT less than 500, a single-layer Otta seal is generally recommended, whereas an AADT greater than or equal to 500 typically demands a double-layer Otta seal to provide more durability and load resistance. After selection of Otta seal type, the second step is determining an appropriate aggregate gradation based on traffic demand, as summarised in Table 1. Open gradation is recommended for low-volume traffic (AADT < 100), a medium gradation is suggested for moderate traffic levels (100–1,000 AADT), and dense gradation is utilized for higher traffic conditions (AADT > 1,000). The particle-size distributions corresponding to open, medium, and dense gradations should conform to the gradation bands presented in Figure 3. The third step involves selection of binder type, as outlined in Table 2, considering both traffic level and aggregate gradation. In general, softer binders are preferred for dense-graded aggregates to ensure adequate coating and penetration within the dense aggregate matrix. Note that the original guidelines for binder selection were developed based on the use of medium-curing (MC) cutback asphalt. However, the use of cutback asphalt is often restricted in the United States due to environmental and safety concerns. Therefore, emulsified asphalt binders, such as high-float emulsions, can be utilized as suitable alternative binders for Otta seal applications (Gushgari et al., 2019). Finally, Table 3 is used to determine the appropriate binder-application rate based on the selected aggregate gradation and the number of Otta seal layers, while Table 4 is used to select the corresponding aggregate-application rate, considering the same gradation and layer configuration. Dense-graded aggregates typically require higher binder-application rates due to their greater surface area. The application rates provided in this method are derived from field-performance experience, indicating that this approach is primarily empirical in nature (Overby, 1999).

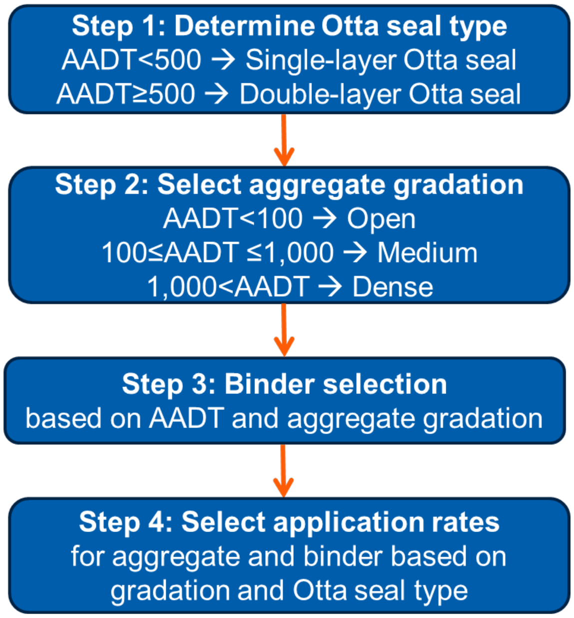


Figure 2. Flowchart. Stepwise procedure for Otta seal design, using the Overby method.

Table 1. Preferred Aggregate Grading for Different Traffic Volumes

AADT	Best-suited Grading
Less than 100	Open
100–1,000	Medium
More than 1,000	Dense

Source: Overby (1999)

Table 2. Binder Selection, Based on Traffic and Aggregate Gradation

AADT at the Time of Construction	Open Gradation	Medium Gradation	Dense Gradation
More than 1,000	Not applicable	150/200 pen.* grade	MC# 3000; MC 800 in cold weather
100–1,000	150/200 pen. grade	150/200 pen. grade in cold weather	MC 3000; MC 800 in cold weather
Less than 100	150/200 pen. grade	MC 3000	MC 800

*Pen. = penetration grade bitumen; #MC = medium-curing cutback asphalt.

Source: Overby (1999)

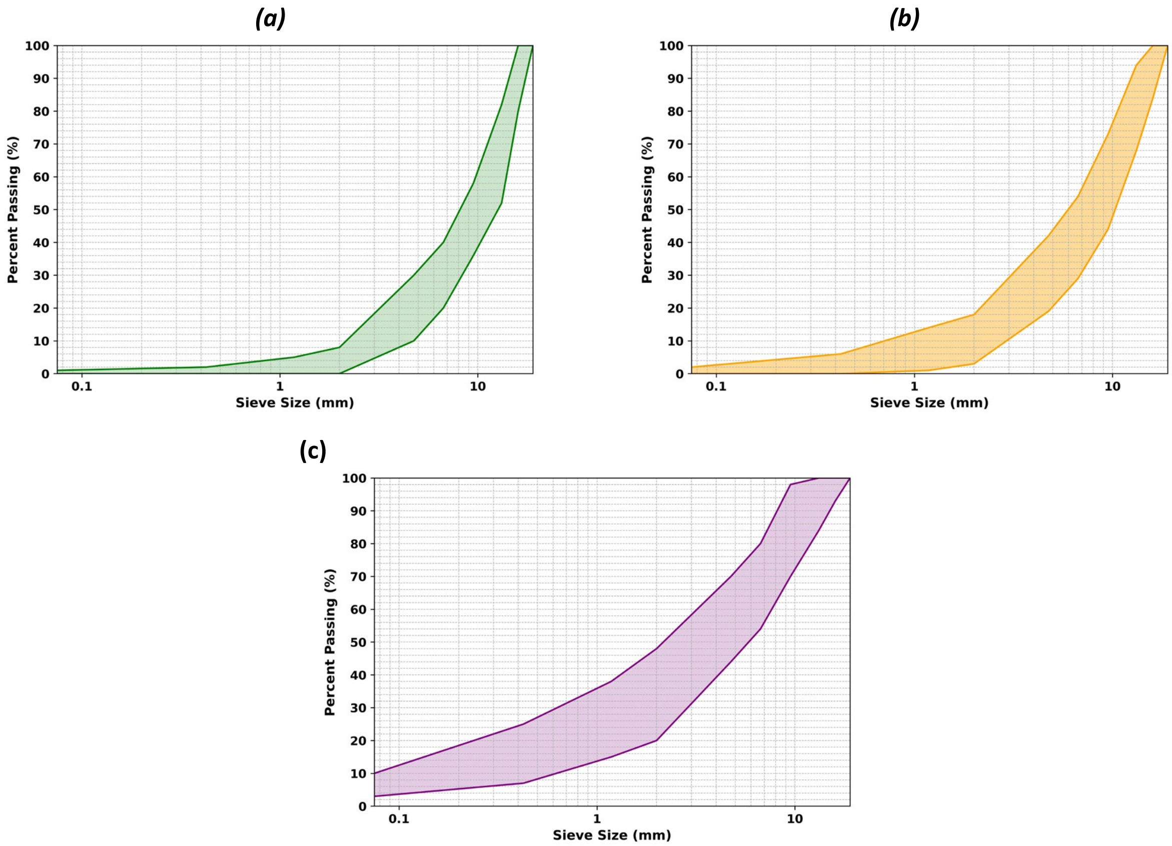


Figure 3. Graph. Particle-size distributions recommended by Overby method for (a) open, (b) medium, and (c) dense gradations. The shaded regions represent the allowable gradation ranges for each gradation type.

Source: Overby (1999)

Table 3. Binder-Application Rate Recommended by the Overby Method

Bitumen spray rates for unprimed base course (L/m^2)					
Type of Otta Seal	**Grading**	**Open**	**Medium**	**Dense**	
				AADT <100	**AADT ⩾100#**
Double	First layer	1.6	1.7	1.8	1.7
	Second layer*	1.5	1.6	2.0	1.9
Single, with a sand cover seal	Fine sand	0.7	0.7	—	0.6
	Crushed dust or coarse sand	0.9	0.8	—	0.7
	First layer*	1.6	1.7	2.0	1.9
Single*		1.7	1.8	2.0	1.9
Maintenance reseal (single)		1.5	1.6	1.8	1.7

*On a primed base course, the spray rate shall be reduced by 0.2 L/m2 in the first layer.

#The original guidelines specify AADT>100; for completeness AADT≥100 is used herein.

Source: Overby (1999)

Table 4. Aggregate-Application Rates Recommended by the Overby Method

Type of Seal	Aggregate spread rates (m^3/m^2)		
	Open	Medium	Dense
Otta seals	0.013–0.016	0.013–0.016	0.016–0.020
Sand cover seals	0.010–0.012	0.010–0.012	0.010–0.012

Source: Overby (1999)

RATIONAL DESIGN METHODS FOR SURFACE TREATMENTS

The Overby design method is a commonly used approach for Otta seal design and is primarily based on empirical guidelines. As noted previously, this method relies on recommended tables and charts to select aggregate gradation and binder-application rates, rather than material-specific properties. Although the Overby method has been widely used in many countries, it does not explicitly account for the physical and chemical properties of the aggregate and binder, which influence aggregate–binder interaction and overall performance of the surface treatment. As a result, the design may not fully capture variations in material properties that affect field performance, especially when novel materials are utilized.

In contrast, rational design methods explicitly incorporate the physical and chemical properties of both aggregate and binder as inputs for determining material selection and application rates. For Otta seals, no rational design methodology currently exists; however, several rational approaches have been developed for chip seal design. Among these, the McLeod, modified Kearby, and Austroads methods are the most widely used worldwide. According to National Cooperative Highway Research Program (NCHRP) Synthesis 342, the McLeod method and the modified Kearby method are among the most widely adopted rational design approaches for surface-treatment design in the United States and Canada (Gransberg & James, 2005). The McLeod method, developed in the 1970s and later adopted by the Asphalt Institute, determines application rates based on aggregate properties and traffic conditions (TxDOT, 2024). The Kearby method, originally developed in the 1950s and later refined by Epps and associates in the 1980s (Epps et al., 1980) estimates application rate by considering aggregate embedment in binder on a volumetric basis (Gransberg & James, 2005; TxDOT, 2024). The Austroads method, widely implemented in Australia and New Zealand, builds upon foundational concepts introduced by Hanson in the 1930s and has been further refined to account for traffic loading, aggregate gradation, and binder properties (Patrick, 2019). Table 5 presents a comparative summary of the key design elements of these three methodologies. These rational design methods offer a systematic basis for estimating material-application rate and assessing material suitability, representing a significant advancement over purely empirical procedures. In this study, these established methodologies were adapted and extended to develop a rational design framework specifically for Otta seal applications.

Table 5. Comparison of Key Design Elements for the Three Rational Design Methods

Design Element	McLeod	Kearby	Austroads
Design basis	Aggregate layer one-stone thick and voids in aggregate layer 70% filled with asphalt	One-stone-thick aggregate layer embedded in asphalt binder	Based on field-calibrated adjustment
Embedment assumptions	Considers role of traffic in embedment of aggregate into binder via traffic factor	Average mat thickness based on percentage aggregate embedment	Accounts for traffic-induced embedment and loss of voids
Binder-application rate	Volumetric, considering 70% voids to be filled by asphalt	Volumetric, based on average mat thickness for embedment of aggregate, and seasonal correction	Volumetric, with adjustments for traffic, aggregate shape, and absorption
Aggregate-application rate	Volumetric, based on voids in loose aggregates, average least dimension, and traffic whip-off factor	Board test	Volumetric, based on average least dimension using field-calibrated equation

AGGREGATE QUARRY BY-PRODUCTS

During quarrying operations—including blasting, crushing and washing, and screening of rocks for aggregate production—substantial quantities of fine residual materials are generated. These materials have commonly been referred to as quarry by-products (QBs), quarry dust, and quarry screenings; more recently, they have also been described as underutilized quarry materials. The properties of QBs can vary among quarries due to differences in parent-rock mineralogy, crushing methods, and processing conditions (Stroup-Gardiner & Wattenberg-Komas, 2013). In general, however, QBs are sand-sized materials with relatively well-graded particle-size distributions and fine contents (passing the No. 200 sieve), typically ranging from approximately 10% to 20% (Kong et al., 2025a; Tutumluer et al., 2015).

Over the past decade, considerable attention has been directed toward the use of QBs in pavement applications (Kong et al., 2025a; Qamhia et al., 2018; Qamhia, Tutumluer, Ozer, & Boler, 2019; Tutumluer et al., 2015). Studies conducted at Illinois Center for Transportation (ICT) have investigated the engineering properties of QBs and their potential use in pavement infrastructure, particularly in pavement-foundation applications. These studies have demonstrated that QBs can serve as viable alternative construction materials in pavement-foundation applications, offering advantages such as local availability, cost-efficiency, and improved environmental sustainability.

One of the earlier ICT studies (Tutumluer et al., 2015) evaluated QB production, utilization, and stockpiling across multiple quarries in Illinois. The study reported that QBs are produced in large quantities, with annual QB production in Illinois estimated at 950,000 tons (862,000 metric tons). However, their utilization remained limited, resulting in approximately 3,475,000 tons (3,150,000 metric tons) of QBs accumulated in stockpiles. These quantities are expected to have increased due to growth in construction activities and the associated demand for construction aggregates. Because QBs are generally considered marginal aggregate materials, the incorporation of small amounts of stabilizers, such as cement and Class C fly ash, is often necessary to improve performance (Mwumvaneza et al., 2015). Stabilization has been shown to significantly enhance strength, making QBs suitable for base and subbase applications. Full-scale test sections constructed with QBs at ICT and evaluated through accelerated pavement testing (APT) demonstrated that stabilized QB sections provided sufficient rutting resistance, adequate layer modulus, and strong wet–dry durability, indicating the promising potential of QBs as alternative aggregate sources in base layers (Qamhia, Tutumluer, Ozer, Shoup, et al., 2019; Qamhia et al., 2020).

More recently, ICT project R27-248 focused on characterizing the mineralogical and physical properties of carbonate QBs and examining the influence of these material characteristics on strength and freeze–thaw durability (Kong et al., 2025a). The study emphasized the importance of both physical and mineralogical composition in governing strength development and resistance to freeze–thaw damage. Key findings highlighted the role of optimum aggregate packing based on particle gradation, as well as the superior performance of dolomitic QBs, which promoted hydrotalcite formation and refined void structure during long-term cementation, in contrast to limestone-based QBs (Kong et al., 2024; Kong et al., 2025b). Follow-up studies have examined the incorporation of supplementary cementitious materials, such as metakaolin and ladle furnace slag, to further advance sustainable practices by reducing cement content while maintaining adequate strength performance (Kong et al., 2026; Kong & Tutumluer, 2026).

These findings demonstrate that QBs can serve as promising alternative aggregate sources for pavement construction, particularly when their physical and mineralogical characteristics are appropriately considered and suitable stabilization methods are employed. Their local availability, potential cost savings, and ability to reduce stockpiled quarry waste further support their use in sustainable pavement-infrastructure applications. Nevertheless, although substantial research has focused on the use of QBs in pavement-foundation layers, limited studies have investigated their application in asphalt surface treatments. Therefore, additional research is needed to evaluate the constructability and performance of asphalt surface treatments for low-volume roads, such as Otta seals, incorporating QBs.

CHAPTER 3: MATERIAL CHARACTERIZATION AND TEST MATRIX

AGGREGATES

For this study, two quarry by-products (QBs) were selected to evaluate the behavior of different types of QBs in Otta seal applications. In addition, one control aggregate, referred to as “typical Otta seal aggregate,” was included to provide a baseline for performance comparison. The following section presents the selection criteria and properties of the selected QBs and typical Otta seal aggregate.

Selection of Quarry By-Products

A total of eight QBs previously collected under ICT R27-248, which investigated the long-term cementation of dolomitic and limestone QBs (Kong et al., 2025a), were initially evaluated to identify suitable candidates for the present study. The aggregate gradations of all eight QBs, determined in accordance with ASTM C136 (2015), were compared with the gradation band recommended by Overby, as presented in Figure 4 (Overby, 1999). This comparison was used as the primary screening criterion to identify suitable candidate materials for further analysis. Based on the comparison with the Overby gradation band two QBs—QB-5 and QB-2—were selected for detailed evaluation. The gradation curves for both QBs are presented in Figure 5, and their quarry locations relative to ICT’s laboratory in Rantoul, Illinois, are depicted in Figure 6. QB-5 was selected because its gradation falls within the particle-size gradation range recommended by Overby, indicating its suitability for Otta seal applications. QB-2 was selected despite not meeting the Overby gradation requirements, to evalute the feasibility of using finer QBs in Otta seal applications when blended with coarser aggregates. QB-2 was of particular interest because it demonstrated favorable engineering properties in the previous ICT R27-248 project, where its particle-size distribution closely followed optimum packing, resulting in the highest density and improved performance (Kong et al., 2025a). To address its deviation from the recommended Overby gradation band, QB-2 was blended with coarser aggregates to improve its particle-size distribution. Hence, a blend consisting of 50% QB-2 and 50% coarse aggregate was also developed to maximize QB utilization while achieving a well-graded aggregate suitable for Otta seal applications. The coarse fraction included three aggregate sizes (0.37 in. [9.5 mm], 0.25 in. [6.3 mm], and 0.19 in. [4.75 mm]). The resulting blended material satisfies the Overby gradation requirements, as presented in Figure 7, and was therefore used in subsequent performance evaluation. The blended QB-2 aggregate is referred to as QB-2B in this study.

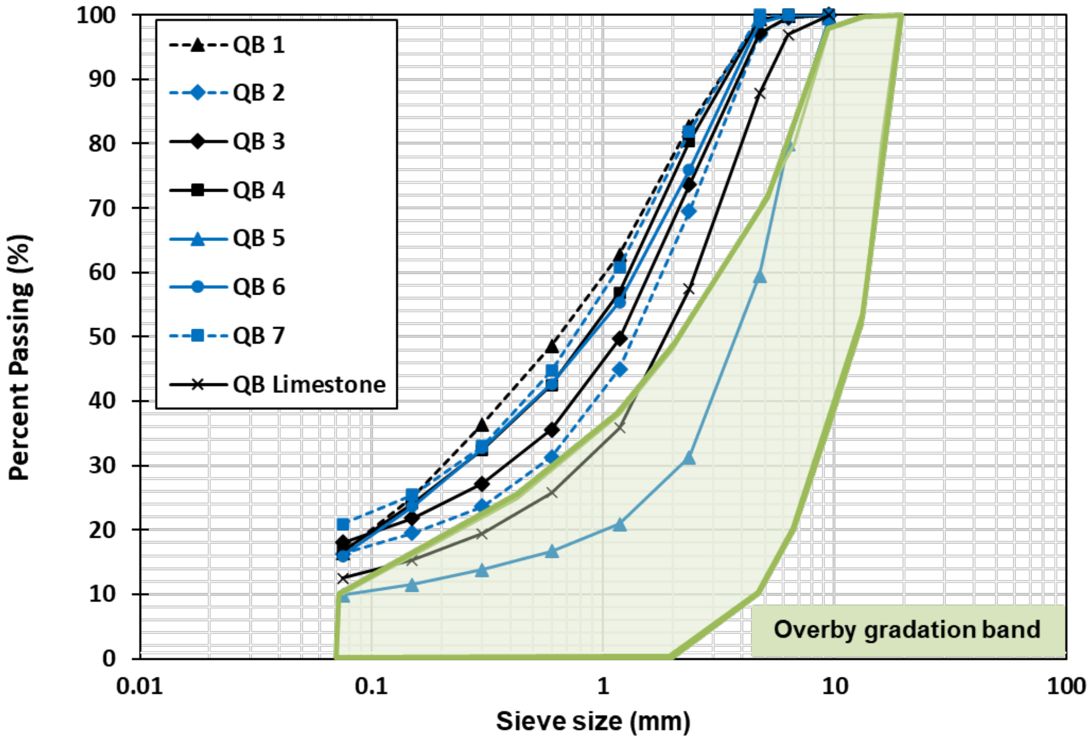


Figure 4. Graph. Gradations of QBs from eight sources, with the Overby gradation band.

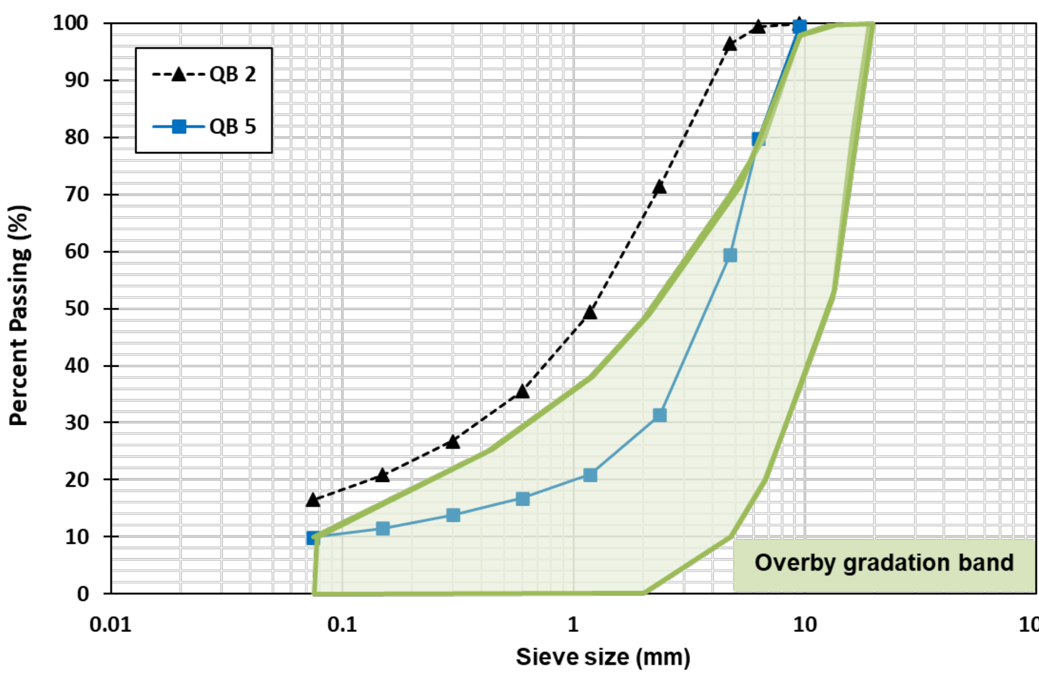


Figure 5. Graph. Gradations of selected QBs, with the Overby gradation band.

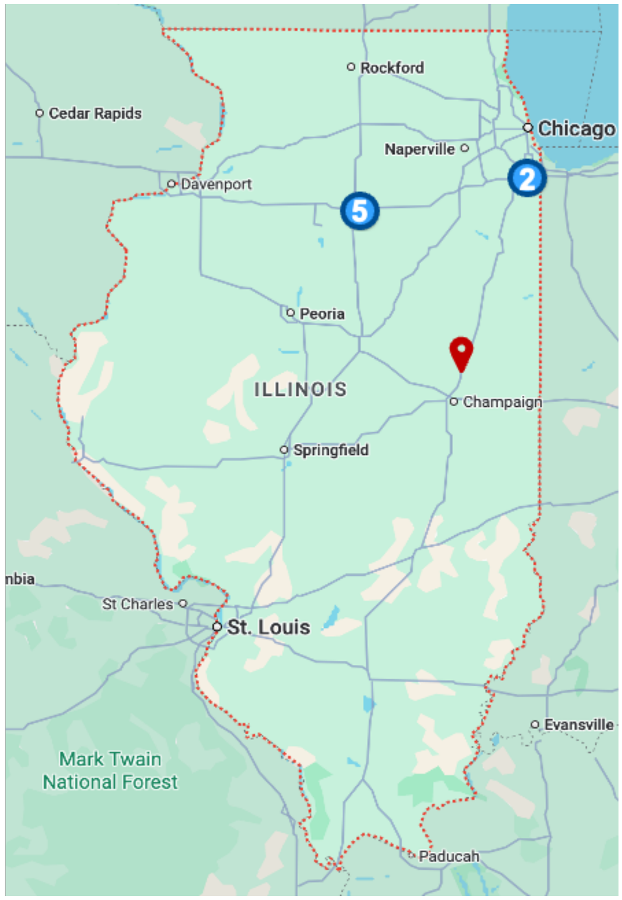


Figure 6. Map. Geographical locations of source quarries for QB2 and QB5 and the location of Illinois Center for Transportation's laboratory (marked with a red pin).

For performance comparison, a control aggregate, herein referred to as typical Otta seal aggregate, was prepared using CA-6, an Illinois-based, dense-graded crushed stone commonly used as a base course material. The gradation curves of QB-5, QB-2B, and the typical Otta seal aggregate are presented in Figure 7. Photographic views of both QBs and the typical Otta seal aggregate are provided in Appendix A. These selected aggregates exhibit different gradation characteristics, which may influence packing, binder demand, and overall performance characteristics of the Otta seal designs. QB materials generally contain a higher percentage of fines, resulting in greater surface area and higher binder absorption. In contrast, the typical Otta seal aggregate has a relatively coarser gradation with limited fines content and lies near the lower boundary of the Overby gradation band. A previous study reported that Otta seals prepared with aggregate containing lower fine-aggregate content exhibited reduced aggregate loss during performance testing (Jibon, Mahedi, et al., 2023). Therefore, the typical Otta seal aggregate gradation that demonstrated the best performance of various gradations compared in this study was selected as the control for comparison with the QB-based Otta seal.

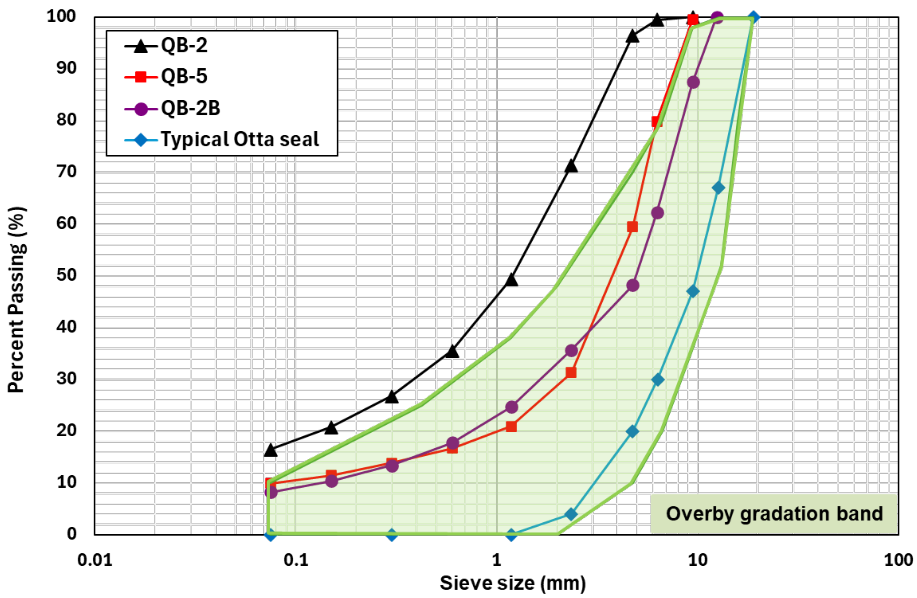


Figure 7. Graph. Gradations of selected aggregates, with the Overby gradation band.

Aggregate Physical Properties

The physical properties of aggregates play a critical role in evaluating their suitability for Otta seal applications and in determining aggregate- and binder-application rates across all three selected rational design methods. The physical properties determined in this study included bulk specific gravity, flakiness index, voids in loose aggregate, absorption, dry loose unit weight, and median particle size, as presented in Table 6.

Bulk specific gravity and absorption were determined in accordance with ASTM C127 (2024) and ASTM C128 (2022) for coarse and fine aggregates, respectively. All aggregates exhibited comparable bulk specific gravity values, indicating similar material density. However, notable differences were observed in absorption values. QB-5 exhibited a relatively high absorption value of 4.3%, whereas QB-2 had an absorption value of 2.5%. Higher absorption indicates increased binder demand, as more emulsion is required to adequately coat and embed the aggregate particles. Dry loose unit weight and voids in loose aggregate were determined following ASTM C29 (2017) using particles retained on the No. 4 sieve (4.75 mm). This approach was adopted to represent the void structure of the coarse-aggregate fraction that governs binder quantity and aggregate embedment in the Otta seal, consistent with a previous study (Jibon, Mahedi, et al., 2023), which used this approach to modify the McLeod method for Otta seal mix design. The results showed similar dry loose unit weight and void content in all three aggregate types, with void content of 48.7% for QB-2, 45.5% for QB-5, and 45.3% for typical Otta seal aggregate.

Median particle size, defined as the sieve size corresponding to 50% passing on the gradation curve, was calculated based on the sieve analysis described above. QB-2 exhibited a median particle size of 0.05 in. (1.3 mm), indicating a finer gradation than QB-5, which had a median particle size of 0.16 in. (4 mm). After blending QB-2 with coarser materials, the median particle size of QB-2B increased to

0.20 in. (5 mm), reflecting a shift toward coarse distribution. In comparison, typical Otta seal aggregates exhibited a median particle size of 0.37 in. (9.5 mm), indicating coarser characteristics. Overall, these results indicate that QB materials are finer and more absorptive than typical Otta seal aggregate, which should be considered during the design process and binder selection.

Flakiness index values of aggregates were determined for particles retained on the No. 4 sieve using the University of Illinois aggregate image analyser (UIAIA), which provides more accurate quantifiable index measurements than the conventional ASTM D4791 (2023) method (Tutumluer et al., 2000). QB-2 exhibited a higher flakiness index, as compared to QB-5, indicating a greater proportion of flat and elongated particles. Visual observations further supported these findings, with QB-2 showing more angular and elongated shapes, while QB-5 particles appeared more rounded and cubical. All properties determined were considered for calculating aggregate- and binder-application rates.

Table 6. Summary of Physical Properties of QBs and the Typical Otta Seal Aggregate

Property	QB-5	QB-2	QB-2B	Typical Otta seal
Bulk specific gravity	2.603	2.700	2.702	2.704
Flakiness index (%)	19	36	29	22
Voids in loose aggregate (%) (for particles retained on the No. 4 sieve)	45.5	48.7	48.7	45.3
Absorption (%)	4.6	2.7	2.1	1.5
Dry loose unit weight of aggregate, pcf (kg/m^3)	88 (1,416)	86 (1,385)	89 (1,429)	92 (1,473)
Median particle size, in. (mm)	0.16 (4)	0.05 (1.3)	0.20 (5)	0.37 (9.5)

EMULSION

Asphalt emulsion is a dispersion of asphalt binder stabilized in water by an emulsifying agent. The emulsifying agent reduces surface tension and prevents separation, allowing the asphalt to remain uniformly in water until the emulsion is “broken.” This property enables the binder to be applied at lower temperatures than conventional hot-applied asphalt binder, improving workability and energy efficiency. After application of the emulsion, the water evaporates and the emulsion breaks, allowing the asphalt to coat and bind the aggregate particles.

Selection Criteria

The selection of emulsified asphalt was based on compatibility with aggregate mineralogy and regional practice. The selected QB materials, QB-2 and QB-5, are primarily dolomitic and limestone aggregates, which are cationic in nature. Therefore, anionic emulsions were selected in this study to promote favorable interaction and adhesion between the aggregate surface and asphalt droplets. Although cutback asphalt is recommended in Otta seal design based on the Overby method, an emulsion-based binder was selected due to environmental and health concerns associated with volatile organic compounds in cutback binders. Two high-float, rapid-set (HFRS) asphalt emulsions were selected: an unmodified emulsion, HFRS-2; and a polymer-modified emulsion, HFRS-2P. HFRS emulsions were selected instead of high-float, medium-set (HFMS) emulsion, another binder recommended by the previous studies (Gushgari et al., 2019), because HFRS emulsions are commonly used in Illinois for surface-treatment applications.

Properties of Emulsion

The performance of emulsions in Otta seals is governed by their residual asphalt content and the mechanical properties of their residue, which directly influence binder–aggregate interaction, coating efficiency, and long-term durability of Otta seal. For both emulsions, the residual asphalt content, along with poker chip ductility and tensile strength of the residual asphalt, was measured. The residual asphalt content was also used in determination of binder application rates for all three rational design methods. These properties of both emulsion types are summarized in Table 7. Residual asphalt represents the amount of effective binder available after emulsion breaking and complete curing and therefore plays a key role in binder-film development and aggregate coating. Residual asphalt was measured in accordance with ASTM D7497 (2009). The polymer-modified emulsion, HFRS-2P, exhibited a higher residual asphalt content than the unmodified HFRS-2, indicating that, for a given emulsion application rate, HFRS-2P may provide improved aggregate coating and bonding. The tensile strength and ductility of the recovered binder were determined using the poker chip test performed at a loading rate of 2 N/sec at room temperature (Vyas et al., 2023). The results of the poker chip test for both emulsions are presented in Figure 8. The higher ductility and tensile strength values observed for HFRS-2P are attributed to the presence of polymer, suggesting enhanced potential to resist cracking and deformation.

Table 7. Physical Properties of Selected Asphalt-Emulsion Types

Property	HFRS-2P	HFRS-2
Residual asphalt (%)	75	68
Ductility (%)	635	166
Tensile strength (kPa)	157.5	120.7

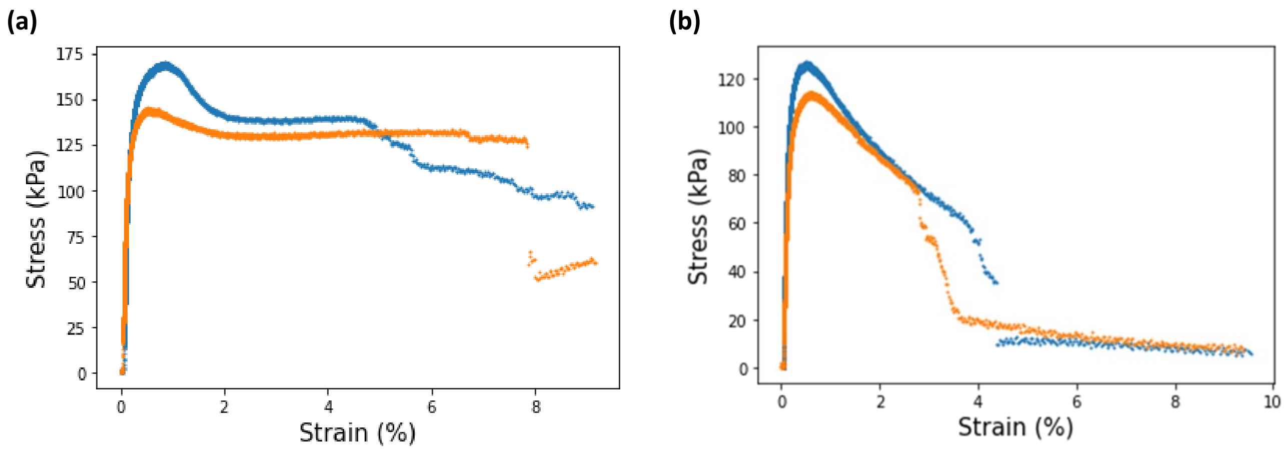


Figure 8. Graphs. Poker chip test results for both emulsion types—(a) HFRS-2P and (b) HFRS-2—with two replicates for each.

For a more comprehensive characterization, Fourier transform infrared (FTIR) spectroscopy and frequency sweep tests were performed. To evaluate the rheological properties of emulsion residues, frequency sweep tests were conducted using a dynamic shear rheometer (DSR) over a temperature range of 10°C to 64°C (50°F to 147°F). An 8 mm parallel plate geometry with a 2,000 µm gap was used at 10°C, 20°C, and 30°C (50°F, 68°F, and 86°F), while a 25 mm parallel plate with 1,000 µm gap was used at 52°C, 58°C, and 64°C (126°F, 136°F, and 147°F). The frequency sweep ranged from 0.1 to 100 rad/s, with a strain level of 1% for all temperatures except 10°C (50°F), where 0.1% strain was applied to ensure testing within the linear viscoelastic (LVE) range. Based on these results, master curves were constructed at a reference temperature of 20°C (68°F), as presented in Figure 9. The polymer-modified residual binder exhibited a higher complex shear modulus than the unmodified binder, particularly at lower frequencies, which represent high-temperature conditions, suggesting enhanced rutting and bleeding resistance. In contrast, at higher frequencies, corresponding to low to intermediate temperatures, both residual binders exhibited similar behavior, indicating comparable behavior at intermediate temperatures.

Chemical characterization was performed using FTIR spectroscopy on both the emulsions and their corresponding residues, as presented in Figure 10. The results confirmed the removal of water-associated O-H bonds after residue recovery. Distinct peaks corresponding to polybutadiene and polystyrene at 966 cm^{-1} and 699 cm^{-1}, respectively, were clearly observed in the modified emulsion residue, confirming the presence of styrene-butadiene-styrene (SBS) modification (Canto et al., 2006). This study evaluated only an SBS type polymer modified emulsion, and therefore the findings of this study are specific to SBS-modified emulsions and should be validated before being applied to emulsions containing other polymer types.

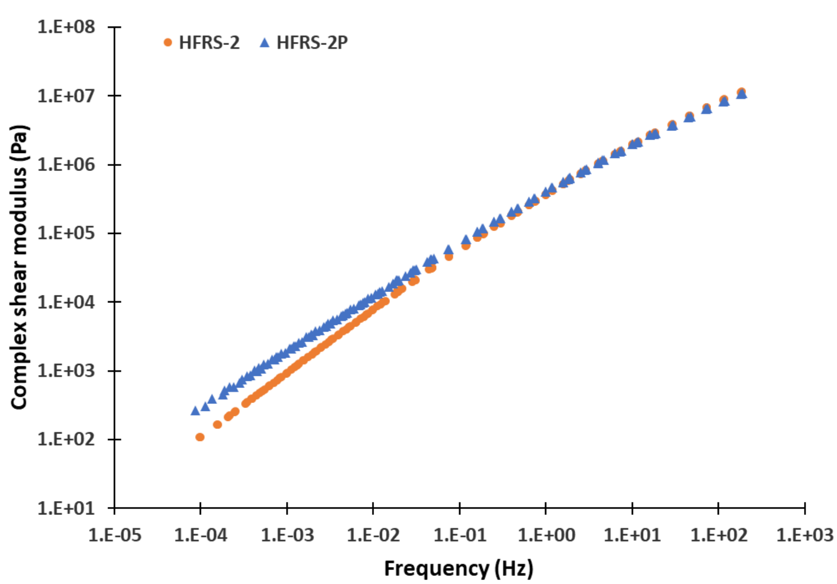


Figure 9. Graph. Frequency sweep-test results show the master curves for both emulsion types.

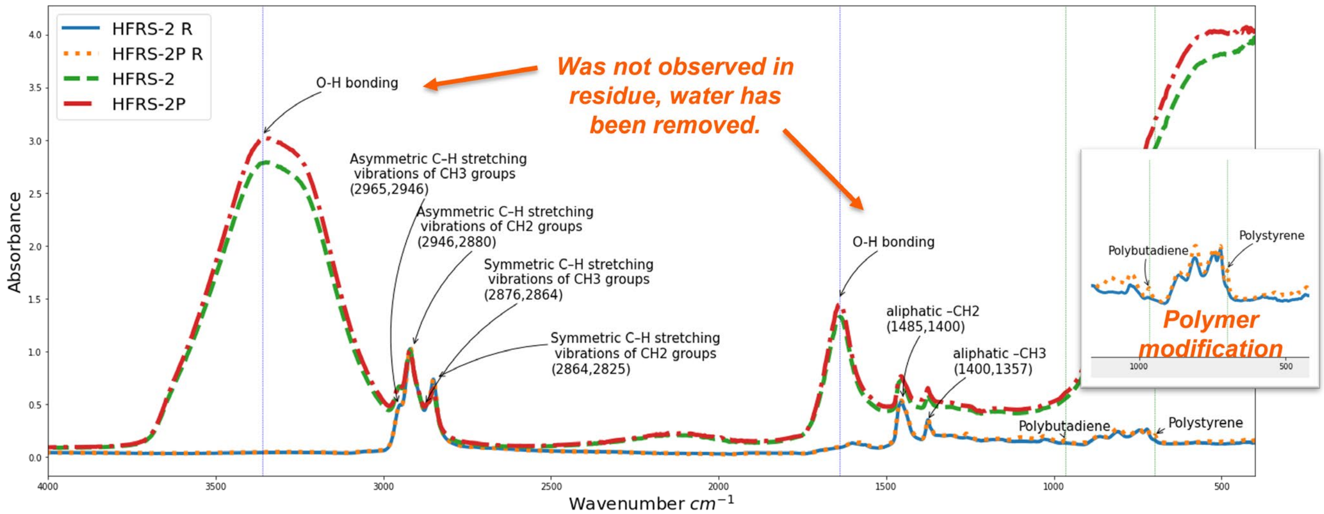


Figure 10. Graph. FTIR analyses of both emulsion types and their residues to evaluate the presence of polymer modification.

RATIONAL DESIGN METHODS MODIFIED FOR OTTA SEAL APPLICATION

Otta seals are predominantly utilized in African and European countries, where the Overby method is widely applied. However, the Overby method heavily relies on empirical approaches and does not adequately account for the specific properties of aggregates and binders. To address these limitations, only the recommended aggregate gradation from the Overby method was adopted, while alternative design methods were evaluated for computing aggregate- and binder-application rates. These include the McLeod, modified Kearby, and Austroads methods. Although these design methods were originally developed for chip seal applications, the design equations were modified to account for Otta seals and the specific properties of QB materials for Otta seal applications, as described below.

Modified McLeod Method

A previous study modified the original McLeod method by incorporating measurements of voids in loose aggregate and the average least dimension for particles larger than 0.5 in. (12.7 mm) (Jibon, Mahedi, et al., 2023). In the present study, the method was further adapted to incorporate QB-specific properties, particularly higher absorption and fine contents. Voids in loose aggregate and flakiness index were measured for aggregates retained on the No. 4 sieve (4.75 mm), representing the largest particle-size fraction of QB materials. The average least dimension, *H* (mm) was calculated using the relationship provided in the original method, as presented in Figure 11, where *M* is median particle size and *FI* is flakiness index. This approach was considered more practical and efficient than directly measuring individual particles using calipers. The aggregate-application rate was calculated using the equation presented in Figure 12, where *C* is cover-aggregate rate (kg/m^2), *V* is voids in loose aggregate (%), *G* is bulk specific gravity, *E* is wastage factor (1.05), *H* is average least dimension in mm, *M* is median particle size in mm, and *FI* is flakiness index. The binder-application rate was determined using the equation in Figure 13, where *T* is traffic factor (0.75), *A* is aggregate absorption factor (L/m^2) (considered 0.6 for QBs and 0.1 for typical Otta-seal), and *R* is residual asphalt content in the emulsion.

$$H = \frac{M}{1.139285} + 0.011506 \times FI$$

Figure 11. Equation. Formula for calculating average least dimension (ALD).

$$C = (1 - 0.4 \times V) H \times G \times E$$

Figure 12. Equation. Cover-aggregate application-rate calculation for modified McLeod method.

$$B = \frac{0.4 \times H \times T \times V + A}{R}$$

Figure 13. Equation. Binder-application rate calculation for modified McLeod method.

Modified Kearby Method

The modified Kerby method estimates the aggregate application rate using a "board test," in which the quantity of aggregate required to form a single, uniform layer is determined within a container of known dimensions, as presented in Figure 14. The binder-application rate was calculated using the equation presented in Figure 15, where $A = 5.61 \times E \times V \times T + V_c$. In this equation, *E* is embedment depth, defined as $E = e \times d$; *e* is percentage embedment; and *d* is average mat depth in inches, calculated as $d = 39.4 \times Q/W$. Here, *Q* is aggregate quantity determined from the board test in kg/m^2; and *W* is dry loose unit weight of aggregate (kg/m^3). The term *V* is voids in loose aggregates, *T* is traffic-correction factor, V_c represents a correction factor for surface condition, *K* is seasonal correction factor (taken as 0.8), and *R* is residual asphalt content in the emulsion. This method was modified by measuring voids in loose aggregates for aggregates retained on the No. 4 sieve (4.75 mm).

Figure 14. Photo. Board test for calculating aggregate-application rate for modified Kearby method.

$$B = 4.527[A + K\times\left(\frac{A}{R} - A\right)]$$

Figure 15. Equation. Binder-application rate calculation for modified Kearby method.

Austroads Method

The Austroads method calculates the aggregate-application rate using the equation presented in Figure 16, where *G* is the specific gravity and *H* is the average least dimension in mm. The binder-application rate was determined using the equation presented in Figure 17. The basic binder rate (B_b) is calculated as $B_b = V_F \times H$, where V_F is design voids factor, defined as $V_F = V_f + V_a + V_t$. In this expression, V_f is the basic voids factor; V_a is an adjustment for aggregate shape; V_t is an adjustment for traffic effects; *H* is the average least dimension of aggregate; and *F* is a binder factor, which accounts for binder properties. This method was modified by calculating *H* using median particle size of aggregate and considering an allowance for aggregate absorption as 0.6 for QBs and 0.1 for typical Otta seal aggregate.

$$C = G\times 1000\times H/950$$

Figure 16. Equation. Cover-aggregate application-rate calculation for Austroads method.

$$B = B_b\times F + allowances$$

Figure 17. Equation. Binder-application rate calculation for Austroads method.

TEST MATRIX: AGGREGATE- AND BINDER-APPLICATION RATES

A comprehensive experimental matrix was developed to evaluate the combined effects of aggregate type, binder type, and design methodology on the performance of Otta seals. The study included three aggregate types—QB-5, QB-2B, and typical Otta seal aggregate; two emulsion types—HFRS-2P and HFRS-2; and three design approaches—modified McLeod, modified Kearby, and Austroads. The combination of these variables resulted in a total of 18 distinct test combinations, as illustrated in Figure 18. The corresponding aggregate- and binder-application rates for all combinations, calculated using the previously described design methods, are presented in Table 8. These application rates were initially determined assuming a single-layer Otta seal configuration. However, for performance testing, a double-layer configuration was adopted to improve binder distribution and surface texture, particularly for QB-based mixtures with high fines content, as discussed in greater detail in Chapter 4. As presented in Table 8, the modified Kearby method produced the highest binder-application rate, while the Austroads method calculated the lowest. Further, the Austroads method computed equal binder-application rate for both emulsion types, as it does not account for individual differences in residual asphalt content.

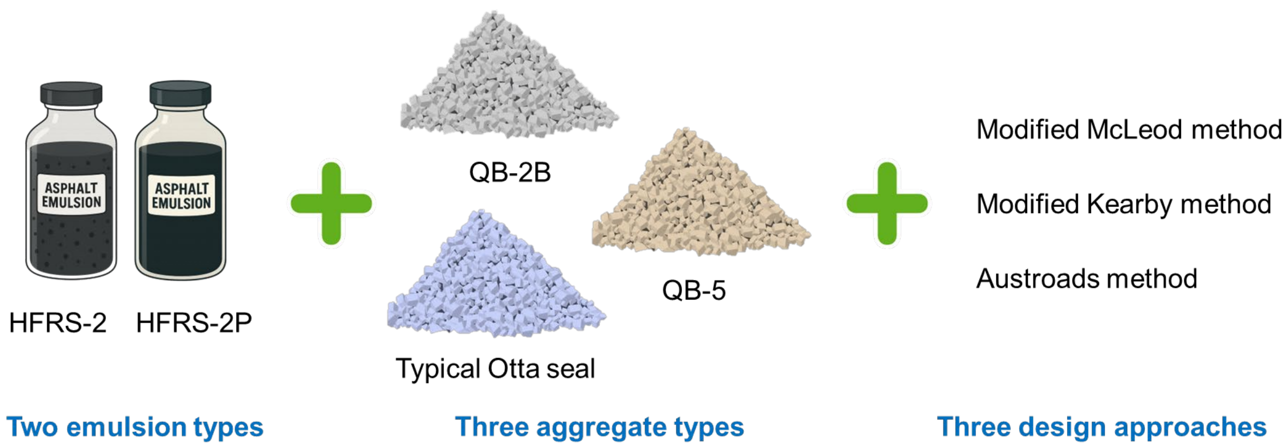


Figure 18. Illustration. Test matrix of 18 combinations for laboratory-performance testing, comprising two emulsion types, three aggregate types, and three modified design methods.

Table 8. Aggregate- and Binder-Application Rates for the Three Modified Design Methods

Design Method	Rate of application	QB-5 (HFRS-2P)	QB-2B (HFRS-2P)	Typical Otta seal (HFRS-2P)	QB-5 (HFRS-2)	QB-2B (HFRS-2)	Typical Otta seal (HFRS-2)
Modified McLeod method	Aggregate rate (lb/yd^2) [kg/m^2]	15.37 [8.34]	19.91 [10.80]	36.76 [19.94]	15.37 [8.34]	19.91 [10.80]	36.76 [19.94]
Modified McLeod method	Binder rate (gal/yd^2) [L/m^2]	0.33 [1.48]	0.38 [1.72]	0.37 [1.69]	0.37 [1.66]	0.43 [1.93]	0.48 [2.19]
Modified Kearby method	Aggregate rate (lb/yd^2) [kg/m^2]	22.47 [12.19]	18.98 [10.30]	30.39 [16.49]	22.47 [12.19]	18.98 [10.30]	30.39 [16.49]
Modified Kearby method	Binder rate (gal/yd^2) [L/m^2]	0.53 [2.40]	0.47 [2.11]	0.67 [3.03]	0.58 [2.64]	0.51 [2.33]	0.74 [3.34]
Austroads method	Aggregate rate (lb/yd^2) [kg/m^2]	18.84 [10.22]	24.77 [13.44]	45.01 [24.42]	18.84 [10.22]	24.77 [13.44]	45.01 [24.42]
Austroads method	Binder rate (gal/yd^2) [L/m^2]	0.32 [1.46]	0.36 [1.64]	0.46 [2.08]	0.32 [1.46]	0.36 [1.64]	0.46 [2.08]

Note: For all three design methods, the aggregate- and binder-application rates were calculated based on a single-layer configuration. However, for laboratory-specimen preparation, the materials were placed in two layers.

CHAPTER 4: LABORATORY OPTIMIZATION OF QB-BASED OTTA SEALS

OPTIMIZATION APPROACH FOR QB-BASED OTTA SEALS

The selected quarry by-product (QB) materials contain a relatively high amount of fine particles and exhibit high absorption values. These characteristics increase binder demand and influence aggregate–binder interaction during construction. Initial specimens prepared using a single-layer Otta seal configuration showed a significant amount of loose aggregates on the surface, indicating insufficient binder content and inadequate bonding of the aggregate. This behavior suggested that the standard single-layer approach may not be suitable for QB materials without modifications to the design or preparation process.

To address this issue, the Otta seal design procedure was refined at the laboratory scale. A series of specimens was prepared using the same type and quantity of materials, with QB-5 used as the aggregate and HFRS-2 as the emulsion for all specimens. The modified McLeod method was used for all specimens to maintain consistency in the design approach. During specimen preparation, the aggregate-separation method and layering sequence were systematically varied to evaluate their effects on loose aggregate retention at the surface and aggregate–binder bonding. This approach enabled the identification of an appropriate design and construction method for QB-based Otta seals. The details of specimen preparation and selection of the optimal design method are presented in the following sections of this chapter.

OTTA SEAL CONFIGURATIONS

Otta seals can be constructed in either single- or double-layer configurations, depending on traffic level and other performance requirements. In a single-layer Otta seal, one application of asphalt emulsion is followed by one layer of aggregate, forming a relatively thin surface treatment. However, a double-layer Otta seal consists of two successive applications of emulsion, each followed by an aggregate layer.

Single-layer Otta Seal

For laboratory-scale optimization of the Otta seal design, the initial specimen was prepared using a single-layer configuration. As presented in Figure 19-a, a circular felt disk with a diameter of 11.8 in. (30 cm) was first cut and used as the base. Emulsion was then applied uniformly over the felt sheet, followed by placement of the aggregate on the emulsion layer, as presented in Figure 19-b and Figure 19-c. The specimen was compacted using a curved steel compactor compliant with ASTM D7000 (2019), as presented in Figure 19-d, by applying seven passes in one horizontal direction and seven passes in the perpendicular direction. The prepared specimen was subsequently cured in an oven at 35°C (95°F) for one hour, followed by curing at 25°C (77°F) for 48 hours, consistent with the curing method reported by previous research (Jibon, Mahedi, et al., 2023). After curing, nearly half of the applied aggregate remained loose on the surface, as presented in Figure 19-e. This behavior was attributed to the high fine-aggregate content and high absorption capacity of QB materials, where finer particles rapidly absorbed a substantial portion of the emulsion. As a result, sufficient binder was not available to coat the coarser aggregate particles effectively. To address this issue, the specimen-preparation approach was revised to a double-layer Otta seal configuration, while maintaining the same total emulsion and aggregate quantities across both layers. This modification was implemented to achieve a more uniform binder distribution between the fine and coarse fractions and to enhance overall aggregate–binder adhesion.

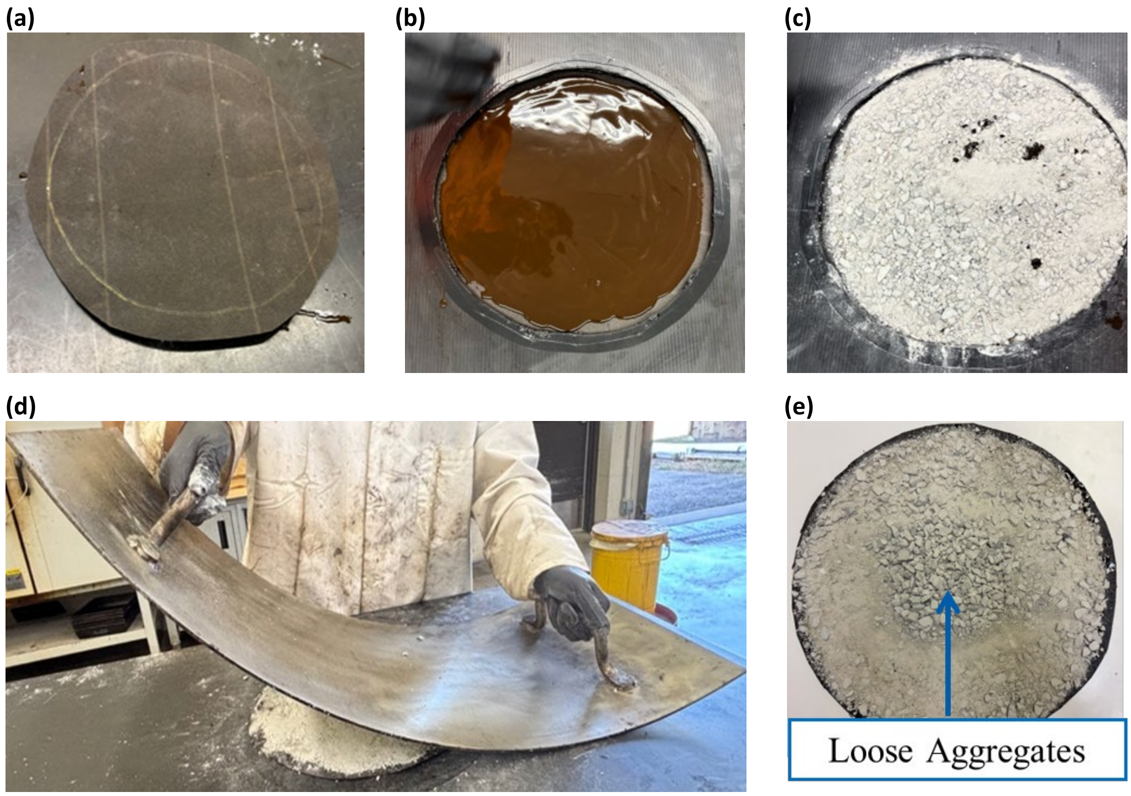


Figure 19. Photos. Preparation of single-layer Otta seal specimen: (a) cutting a 30 cm diameter felt disk, (b) uniform application of emulsion, (c) aggregates spread over the emulsion, (d) manual compaction using a steel compactor, and (e) final prepared specimen showing loose aggregates concentrated at the center.

Double-layer Otta Seal

All double-layer Otta seal specimens were prepared using QB-5 aggregate and HFRS-2 emulsion following the modified McLeod design method. The first double-layer specimen was prepared without separating the aggregate into coarse and fine fractions. In this configuration, the total quantities of emulsion and aggregate were divided equally between the two layers, with half of the emulsion and aggregates applied in the first layer and the remaining half applied in the second layer. Both emulsion layers were applied using a spray gun to ensure uniform coverage, and a weighing scale was used to accurately control the applied emulsion quantity, as presented in Figure 20. Each layer was compacted using the compactor conforming to ASTM D7000 (2019), presented in Figure 19-d, with seven passes in the horizontal direction, followed by seven passes in the perpendicular direction. The prepared specimen was cured in an oven at 65°C (149°F) for 24 hours, followed by curing at 25°C (77°F) for 24 hours. This curing approach was adopted based on observations from single-layer Otta seal specimens, where curing at lower temperature resulted in incomplete emulsion breaking and a soft binder after curing. Therefore, a higher curing temperature was applied for double-layer Otta seal specimens to ensure complete emulsion breaking.

This configuration reduced the amount of loose aggregate to 15%, as presented in Figure 21-a. To further reduce loose aggregates on the surface, additional specimens were prepared by fractionating the QB materials using the No. 4 (4.75 mm) and No. 8 (2.36 mm) sieves. The coarse-aggregate fraction was placed in the bottom layer, and the fine-aggregate fraction was placed in the top layer, as presented in Figure 21-b and Figure 21-c. This arrangement was intended to minimize loose aggregates and enhance densification of layers; however, it resulted in approximately 20% loose aggregate, on average. Moreover, the resulting surface exhibited a relatively smooth surface texture, which may result in safety concerns due to reduced surface texture and therefore potential skid-resistance issues.

For the next configuration, the layering sequence was reversed by placing fine aggregate in the bottom layer and coarse aggregate in the top layer, with material separation performed using the No. 4 sieve, as presented in Figure 21-d. Although this arrangement improved surface texture and eliminated loose aggregates, the quantity of coarse aggregate was insufficient to provide complete coverage of the emulsion layer. As a result, portions of the emulsion film remained exposed at the surface. This condition raises concerns regarding potential bleeding under field traffic loading and indicates that the emulsion was not utilized efficiently.

Finally, the specimen prepared with aggregate separated using the No. 8 sieve, with fine aggregate placed in the bottom layer and coarse aggregate placed in the top layer, demonstrated the most favorable performance among all configurations, as presented in Figure 21-e. This configuration achieved complete emulsion coverage and showed no observable loose aggregate after curing. Additionally, the presence of coarse aggregate at the surface provided improved surface texture and enhanced surface roughness.

The aggregate-separation-based Otta seal preparation approach facilitated more uniform binder distribution and improved texture in the double-layer configuration. Based on a comparative evaluation of surface texture, loose aggregate on the surface, and binder coverage, the configuration using sieve No. 8 for separation, with fines in the bottom layer and coarse aggregate in the top layer, was identified as the optimal laboratory-scale, double-layer Otta seal design incorporating QB materials. This configuration was therefore selected for all subsequent QB-based specimen preparation and performance testing.

Figure 20. Photo. Use of a spray gun for uniform application of emulsion and a weighing scale to ensure accurate measurement of applied emulsion mass.

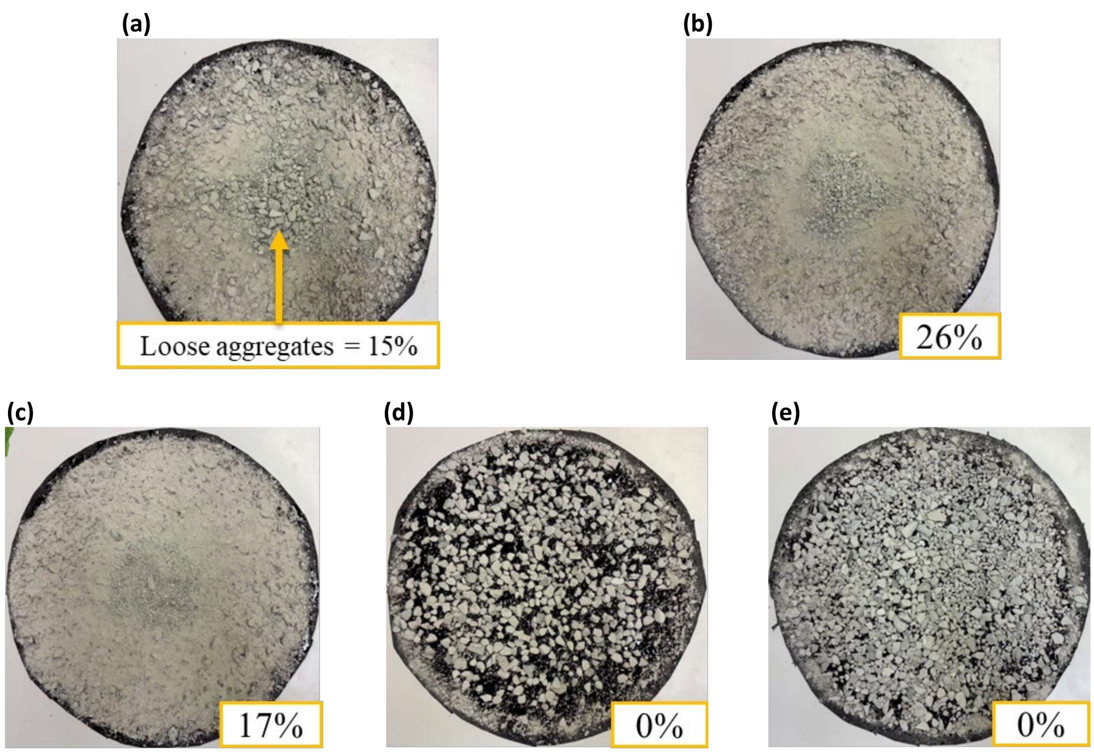


Figure 21. Photos. Double-layer Otta seal specimens prepared using several configurations, with loose aggregate piled at the center: (a) specimen without separation of aggregates, (b) specimen with aggregates separated using No. 4 sieve with fines on the top layer, (c) specimen with aggregates separated using No. 8 sieve with fines on the top layer, (d) specimen with aggregates separated using No. 4 sieve with coarse particles on the top layer, and (e) specimen with aggregates separated using No. 8 sieve with coarse particles on the top layer.

SAMPLE-PREPARATION PROCEDURES FOR PERFORMANCE TESTING

QB-based Otta Seal Specimens

Specimens for all performance tests were prepared using the laboratory-optimized, double-layer Otta seal configuration, as detailed earlier in this chapter. The specimen-preparation process began by cutting a felt sheet into a circular specimen of 30 cm diameter, as presented in Figure 22-a. The total emulsion quantity, calculated using the three design methods described in Chapter 3, were equally divided between both layers. The aggregate quantity was divided as per gradation curve, where the quantity finer than No. 8 was applied in the first layer and the remaining in the second layer. For each layer, the emulsion was applied using a spray gun to achieve uniform distribution representative of field practice, and the application rate was verified using a weighing scale.

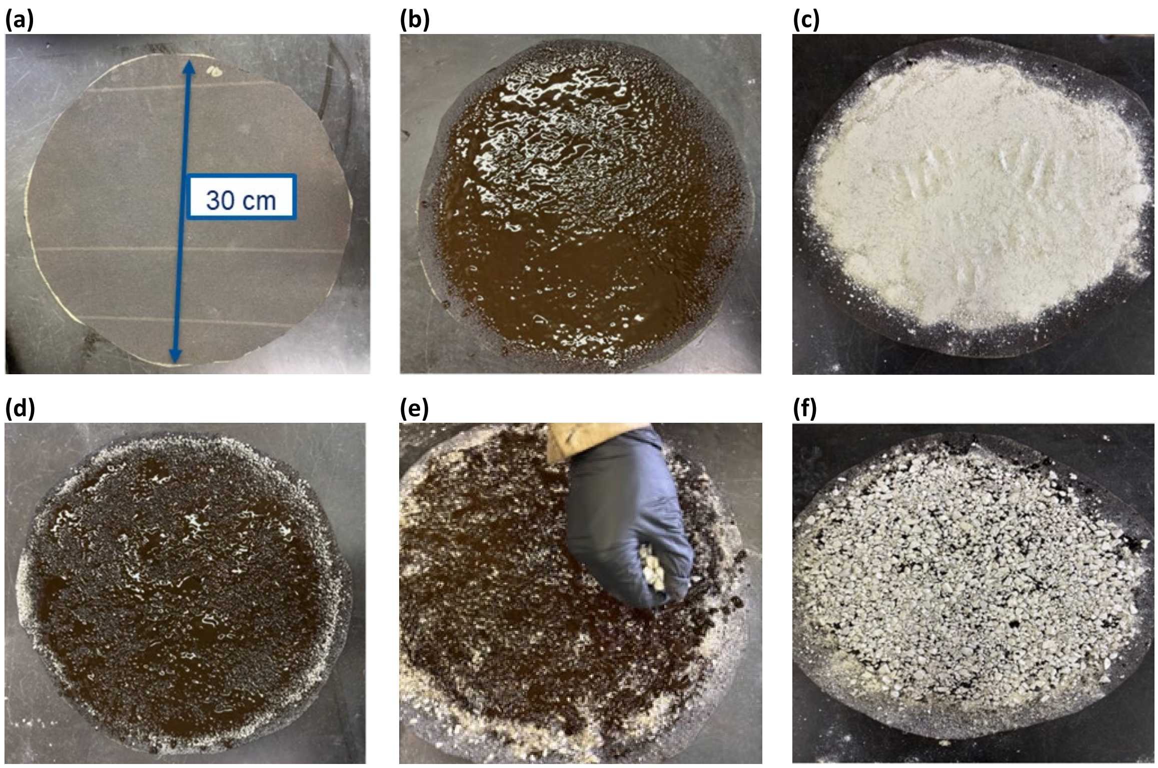


Figure 22. Photos. Preparation of double-layer Otta seal specimen: (a) cutting felt sheet into a circular shape of 30 cm diameter, (b) application of the first layer of emulsion, (c) placement of the first aggregate layer (fines), (d) application of the second layer of emulsion, (e) spreading the second layer of aggregates (coarse), and (f) the final prepared specimen.

The first emulsion layer was applied (Figure 22-b), followed by the first aggregate layer, which consisted of fine aggregate passing the No. 8 sieve (Figure 22-c). After compaction of the first layer with the manual steel compactor, the second emulsion layer was applied (Figure 22-d), followed by the placement of the coarse aggregate retained on the No. 8 sieve as the top layer (Figure 22-e). The same compaction effort was then applied to the second layer. The compacted specimen is presented in Figure 22-f. The specimens were then cured in an oven at 65°C (149°F) for 24 hours, followed by curing at 25°C (77°F) under room-temperature conditions for 24 hours. The rationale of selecting this curing temperature and duration is discussed in Chapter 5. The cured specimens were subsequently subjected to various performance tests.

Typical Otta Seal Aggregate Specimens

For control specimens prepared using typical Otta seal aggregates, a double-layer configuration was adopted to ensure direct comparability with the double-layer, QB-based specimens. The total emulsion quantity was divided into two equal portions and applied sequentially in two layers. For emulsion application, a spray gun and a weighing scale were used, consistent with the QB-based specimens. However, aggregate separation into fine and coarse fractions was not performed because only approximately 4% of the materials passed the No. 8 sieve, indicating a predominantly coarse gradation. Therefore, the total aggregate mass was divided into two equal portions, with one portion applied in each layer. Each aggregate layer was compacted in the same manner as the QB-based specimens, using seven passes in the horizontal direction followed by seven passes in the perpendicular direction. After the compaction, the specimens were cured following the same procedure used for QB-based specimens. All prepared specimens were subsequently used for various performance tests, as discussed in greater detail in Chapter 6.

CHAPTER 5: EFFECT OF CURING CONDITIONS ON OTTA SEAL PERFORMANCE

IMPORTANCE OF CURING FOR OTTA SEALS

Otta seal performance is strongly influenced by the behavior of the asphalt emulsion after application, particularly during the breaking and curing stages. While Chapter 3 discussed the material properties of emulsions, this chapter focuses on the curing process and its role in governing Otta seal performance. After application, interaction between the emulsion and aggregate surface initiates the breaking process, during which water separates from the asphalt binder and the asphalt droplets coalesce to form a continuous film that uniformly coats the aggregate particles (McHattie, 2001). This phase is followed by curing, which involves the gradual evaporation of water from the emulsion and the subsequent development of adhesive bonds between the binder and aggregates. Therefore, the curing process is critical for achieving adequate aggregate–binder bonding and ensuring the stability of the Otta seal layer.

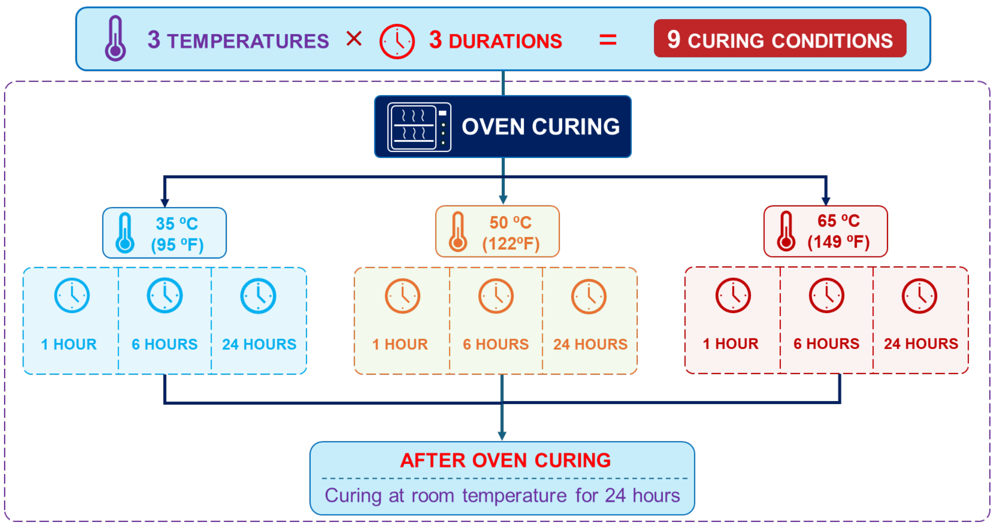
Curing behavior is influenced by several factors, including ambient temperature, humidity, wind, initial emulsion water content, and aggregate–binder compatibility (Moraes & Bahia, 2013). These factors collectively control the rate of water loss, binder redistribution, and film formation. Adequate curing promotes the development of strong adhesive bonds between binder and aggregate, resulting in a structurally stable and durable surface layer. However, insufficient curing can lead to delayed strength gain; increased susceptibility to aggregate loss; and premature surface deterioration, such as raveling. Limited research has been conducted on optimal curing conditions for Otta seal applications, and the number of layers, such as the double-layer configuration used for QB-based Otta seals, which is expected to influence curing behavior.

Given the importance of curing in emulsion-based surface treatments and the limited established practice for choosing appropriate laboratory-curing conditions of Otta seal specimens, this chapter evaluates the curing behavior of the double-layer Otta seal system, with particular emphasis on specimens incorporating QB materials. A systematic experimental program was conducted to investigate the effect of curing temperature and duration on performance. The performance of specimens subjected to different curing conditions was evaluated by quantifying aggregate loss via sweep testing per ASTM D7000 (2019).

EXPERIMENTAL PROCEDURE: MATERIAL AND SPECIMEN PREPARATION

This study was performed using QB-5 aggregate and HFRS-2 emulsion, with the mixture design based on the modified Kearby method. This design method was selected because it yielded the highest binder-application rate, enabling clearer evaluation of the curing behavior. Using the modified Kearby method, all specimens were prepared with the same aggregate and binder contents, minimizing variability associated with material quantities. Each specimen was constructed as a double-layer Otta seal following the optimized laboratory configuration described in Chapter 4. After preparation, all specimens were subjected to controlled curing conditions to evaluate systematically the effects of curing temperature and time on performance.

The experimental curing matrix, presented in Figure 23, consisted of nine distinct curing conditions formed by combining three temperatures, 35°C, 50°C, and 65°C (95°F, 122°F, and 149°F), with three curing durations, 1, 6, and 24 hours. Curing at 50°C (122°F) and 65°C (149°F) was performed using a laboratory oven, whereas curing at 35°C (95°F) was carried out in a temperature-controlled chamber, due to limitations in maintaining stable low temperatures in the oven. Following the elevated-temperature curing phase, all specimens were subjected to an additional 24 hours of curing at room temperature to ensure consistent post-curing conditions prior to performance testing.



Note: Mass of the specimens was measured hourly to monitor the emulsion curing behavior for 24 hours.

Figure 23. Flowchart. Experimental workflow for evaluating emulsion curing behavior for nine curing conditions.

MASS-LOSS MONITORING

During curing, the mass of specimens subjected to different elevated curing temperatures was continuously monitored over a 24 hour period to quantify the curing rate and extent of moisture loss from the emulsion. As curing progresses, water evaporation from the emulsion results in a corresponding reduction in specimen mass. Monitoring this mass change over time provides an indirect measure of curing progression and enables identification of conditions approaching a stable or fully cured state. Figure 24 presents the normalized mass loss of the Otta seal specimens, defined as the percentage reduction in specimen mass relative to its initial mass, allowing consistent comparison across specimens with slightly different initial mass. The results show a rapid initial decrease in mass during the early stages of curing, followed by a more gradual reduction, reflecting progressive curing and continued moisture evaporation from the emulsion. Specimens cured at higher temperatures exhibited greater overall mass loss, demonstrating that elevated temperatures accelerate evaporation and increase curing rates. The theoretical maximal line represents the expected mass loss corresponding to complete evaporation of all water initially present in the emulsion and serves as a benchmark for evaluating curing completeness. As presented in Figure 24, none of the specimens reached this theoretical limit within 24 hours, indicating that complete moisture removal was not achieved under the investigated conditions.

The mass-loss trends obtained during the initial 24 hour curing period were extrapolated to estimate the time required for specimens to reach a fully cured state. Figure 25 presents the projected total curing duration required for complete water evaporation under constant temperature conditions, based on this extrapolation. The results demonstrate a strong dependence of curing time on temperature. At 65°C (149°F), full curing was projected to occur in approximately 3 days (80 hours). In comparison, curing at 50°C (122°F) was considerably slower, with an estimated duration of approximately 19 days (459 hours) to achieve complete curing. The slowest rate was observed at 35°C (95°F), where full curing was projected to require approximately 33 days (789 hours). These findings indicate that lower curing temperatures significantly reduce the rate of moisture evaporation, thereby prolonging the time required for the emulsion to reach a fully cured condition.

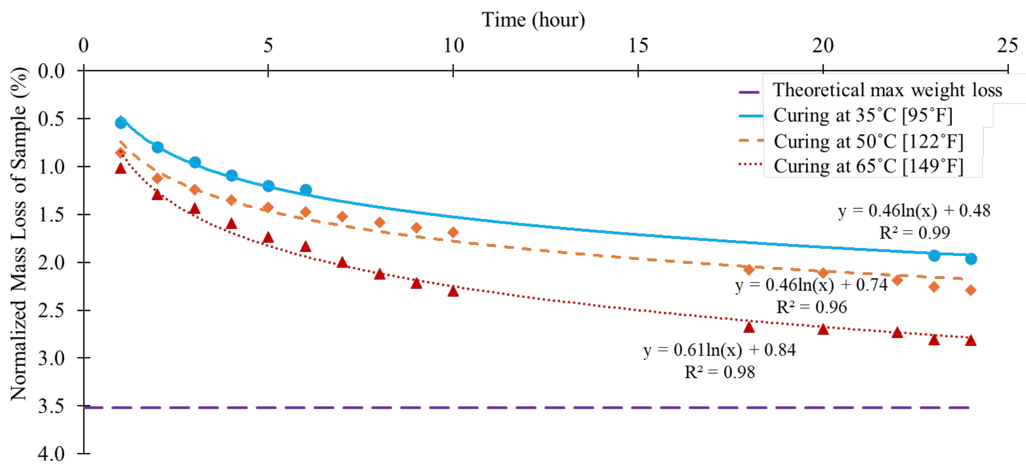


Figure 24. Graph. Normalized mass loss of specimens cured at different temperatures overtime.

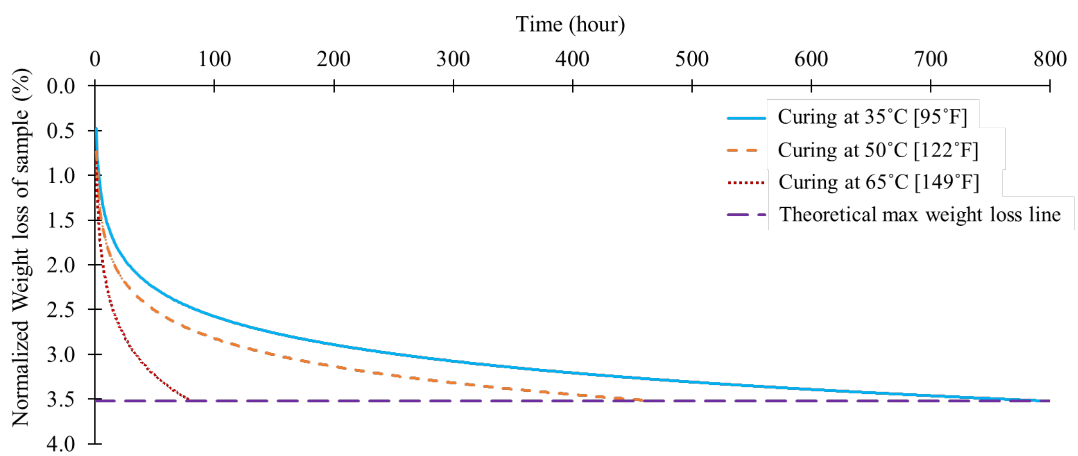


Figure 25. Graph. Normalized mass loss of specimens cured for different durations, extrapolated to determine the time needed to achieve maximal theoretical mass loss.

SWEEP-TEST RESULTS FOR CURED SPECIMENS

Specimen performance, in terms of aggregate–binder adhesion development during curing, was assessed by measuring aggregate loss using the sweep test in accordance with ASTM D7000 (2019). This test evaluates curing effectiveness by subjecting the specimen surface to mechanical brooming action that simulates traffic abrasion. The results, presented in Figure 26, indicate that curing temperature significantly influenced aggregate–binder bonding. Specimens cured at lower temperature, 35°C (95°F), exhibited the highest aggregate loss, suggesting incomplete emulsion breaking and insufficient moisture evaporation, which limited proper binder-film formation and resulted in a weak adhesion between the binder and aggregate particles. In contrast, specimens cured at 50°C (122°F) and 65°C (149°F) demonstrated progressively lower aggregate loss, indicating more efficient curing and improved aggregate retention with increasing temperature. Curing duration also had a notable influence on specimen performance. Longer curing periods consistently resulted in lower aggregate loss, indicating continued curing and progressive strengthening of adhesive bonds. Based on these findings, a curing condition of 65°C (149°F) for 24 hours was adopted for subsequent laboratory testing, which is discussed in Chapter 6.

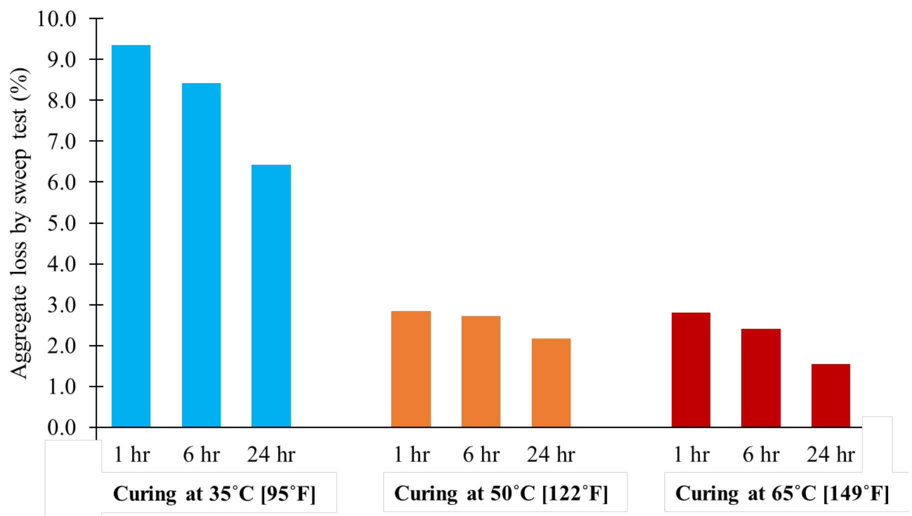


Figure 26. Chart. Aggregate losses from sweep test for specimens cured under different curing conditions.

These findings demonstrate that both curing temperature and curing duration are critical for adequate bond development and improved resistance to aggregate loss in Otta seal specimens. From a field perspective, achieving proper curing is essential for ensuring the durability and long-term performance of Otta seals. Inadequate curing can result in weak bonding, leading to raveling and reduced service life. Therefore, sufficient curing time must be provided before opening the road surface to traffic. However, controlling curing conditions in the field is often challenging due to variability in weather conditions, including temperature fluctuations and rainfall, and construction-scheduling constraints. As a result, careful planning of construction timing and consideration of environmental conditions are necessary to facilitate adequate curing.

CHAPTER 6: PERFORMANCE EVALUATIONS OF OTTA SEAL DESIGNS

OVERVIEW OF TEST METHODS

This chapter presents a comprehensive laboratory-testing program for evaluation of QB-based Otta seal specimens. A total of eighteen specimens were prepared, including combinations of three aggregate types, two emulsion types, and three design methods, following the test matrix outlined in Chapter 3. The performance trends of QB-based Otta seal specimens were compared with control specimens prepared using typical Otta seal aggregates. The testing program included three tests: the sweep test as per ASTM D7000 (2019) to assess traffic-induced abrasion, a modified Hamburg wheel-tracking (HWT) test with a locked pneumatic wheel to assess aggregate loss by braking-induced abrasion, and close-range photogrammetry (CRP) to quantify surface texture. Based on the outcome of these tests, the most effective design method was identified as the modified Kearby method. Following the selection of the best-performing design method, additional laboratory testing was conducted to further evaluate the characteristics of QB-based Otta seal specimens. These tests focused on bleeding susceptibility, bearing-capacity improvement, and friction characteristics.

AGGREGATE LOSS USING SWEEP TESTER

Methodology

The preparation procedure used for all specimens is described in Chapter 4. All specimens were prepared using a double-layer configuration. Three replicates were prepared for each combination of design method, aggregate type, and emulsion type to ensure repeatability and account for inherent variability in laboratory testing. After preparation and curing, the specimens were subjected to performance evaluation, using the sweep test to assess their resistance to traffic-induced abrasion. The test was conducted in accordance with ASTM D7000 (2019). Before testing, each specimen was held vertically to remove any loose aggregates; and the initial specimen weight was recorded. The specimen was then placed in the bottom pan of the sweep tester, presented in Figure 27; and the brush was lowered until it contacted the surface. Sweeping was performed at a rate of 0.83 gyrations per second for a duration of 60 seconds. Following the test, the specimen was removed and again held vertically to dislodge any remaining loose particles. The final weight of the specimen was then measured. Aggregate loss was calculated using the equation presented in Figure 28, where *A* represents the initial specimen weight, *B* represents the final specimen weight, and *C* represents the weight of the felt disk. This procedure provides a quantitative measure of aggregate loss and was used to evaluate the extent of aggregate–binder bonding in the Otta seal specimens.

Figure 27. Photo. Sweep-test equipment.

$$Aggregate\ loss\ (\%) = \frac{A - B}{A - C} \times 1.33 \times 100$$

Figure 28. Equation. Calculation of aggregate loss from sweep test.

Results and Discussion

Representative specimen photographs for each aggregate type, captured before and after sweep testing, are provided in Appendix A. The sweep test results for all aggregate types, emulsion types, and design methods are presented in Figure 29. The error bars represent two standard deviations, showing one standard deviation above and one below the mean.

Aggregate loss was used as an indicator of aggregate–binder adhesion, where higher loss reflects weaker bonding and lower loss indicates better aggregate embedment within the binder. As presented in Figure 29, the QB-based Otta seal specimens—including QB-5 and QB-2B—exhibited aggregate retention comparable to, and in some cases better than, the typical Otta seal aggregate. The variation in aggregate loss for typical Otta seal specimens was greater than that observed for QB-based specimens across all design methods. The higher variability can be attributed to the presence of larger aggregate particles, which weigh more and tend to have limited embedment, making them more susceptible to displacement during mechanical sweeping.

Among the design methods, the modified Kearby method consistently resulted in the lowest aggregate loss for all aggregate and emulsion types. This improved performance is attributed to its higher emulsion-to-aggregate ratio, which provides sufficient binder for effective aggregate coating and embedment. In contrast, the Austroads method resulted in the highest aggregate loss, indicating that the binder content may be insufficient to adequately coat and retain aggregates, particularly for finer QB materials.

The influence of emulsion type varied depending on the aggregate type and design method. HFRS-2P performed better for typical Otta seal aggregate and for the Austroads design method. This behavior is attributed to the higher residual asphalt content and polymer modification of HFRS-2P, which provides strong adhesion bond strength for larger particles of typical Otta seal aggregate. Under the Austroads method, which applies a constant binder rate regardless of emulsion properties, HFRS-2P consistently outperformed HFRS-2 across all aggregate types. However, for QB-based specimens prepared using the modified McLeod and modified Kearby methods, HFRS-2 exhibited slightly better performance than HFRS-2P. These design methods account for binder demand and compensate for the lower residual asphalt content of HFRS-2 by recommending higher application rates. The increased emulsion content during specimen preparation improved the coating of fine QB particles and enhanced aggregate–binder adhesion. As a result, aggregates are less likely to be dislodged, leading to improved aggregate embedment and reduced aggregate loss.

Overall, the results demonstrate that both aggregate characteristics and binder properties significantly influence Otta seal performance. Appropriate selection of design method and binder-application rate can enable unmodified emulsions to achieve performance comparable to polymer-modified emulsions, particularly for finer QB materials. However, when emulsion content is held constant, polymer-modified emulsions performed better. Further, these findings confirm that QB-based Otta seals can achieve adequate aggregate retention when proper gradation control, layering configuration, and design methods are implemented.

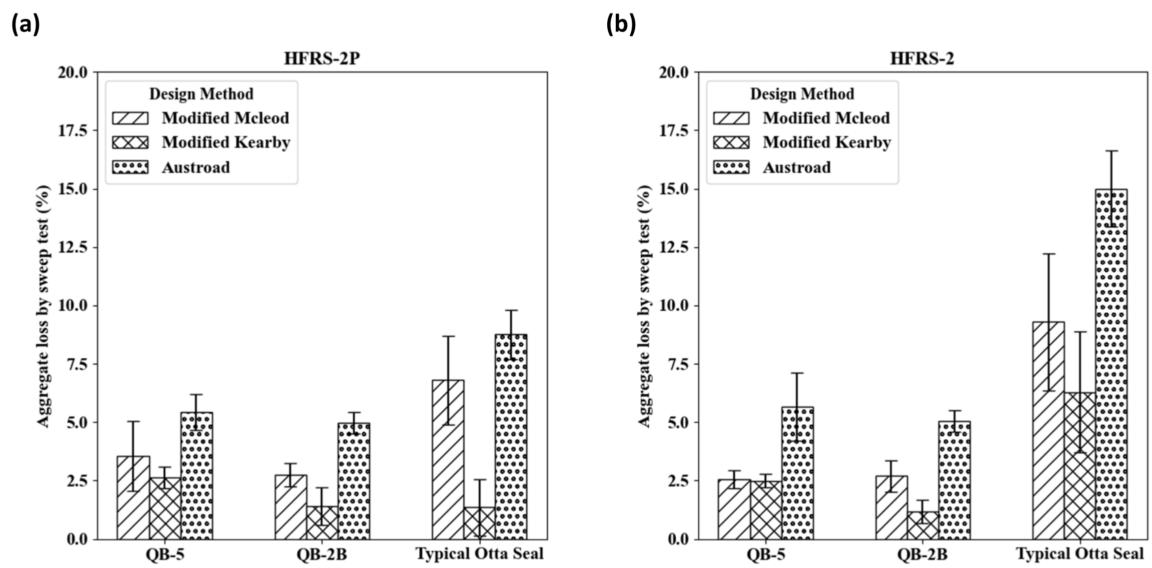


Figure 29. Charts. Aggregate losses from sweep test for selected aggregate types using (a) HFRS-2P and (b) HFRS-2 emulsions.

AGGREGATE LOSS USING MODIFIED HAMBURG WHEEL-TRACKING TEST

Methodology

The modified Hamburg wheel-tracking (HWT) test was conducted to evaluate aggregate loss under simulated braking conditions, following an approach similar to that used by Kim et al. (2023). Unlike conventional HWT testing, which primarily evaluates rutting and moisture damage under rolling wheel loads, this modified approach was designed to replicate shear stresses induced during vehicle braking. The modification involved replacing the standard steel wheel with a pneumatic tire that was locked to restrict rotation. This modification forced the tire to slide, rather than roll, thereby simulating braking-induced shear stresses. The test setup is presented in Figure 30.

For specimen preparation, the optimized double-layer Otta seal configuration was constructed on dummy asphalt disks used as bases, as presented in Figure 31-a. These disks were cut to a specified depth to accommodate the thickness of the double-layer Otta seal. The first emulsion layer and first aggregate layer were placed on the asphalt disk (Figure 31-b and Figure 31-c), followed by the second emulsion layer and second aggregate layer (Figure 31-d). For each combination of design method, aggregate type, and emulsion type, two replicates were prepared to ensure repeatability and account for variability in laboratory measurements. After specimen preparation and curing, the modified HWT test was conducted by applying 10 passes with a load of 39.3 lbf (175 N) to each specimen (Kim et al., 2023). Water and temperature control were not utilized during testing, as the objective was to evaluate aggregate loss under braking conditions, rather than high-temperature moisture damage. Aggregate loss was calculated using the relationship presented in Figure 32, where *A* represents the initial sample weight, *B* represents the specimen weight after testing, and *C* represents the weight of the asphalt dummy disk.

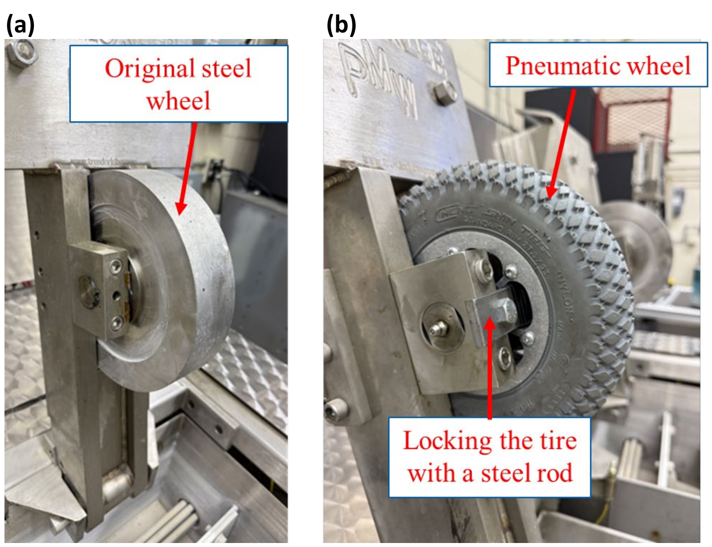


Figure 30. Photos. HWT device with (a) original steel wheel and (b) modified setup with pneumatic wheel in locked configuration.

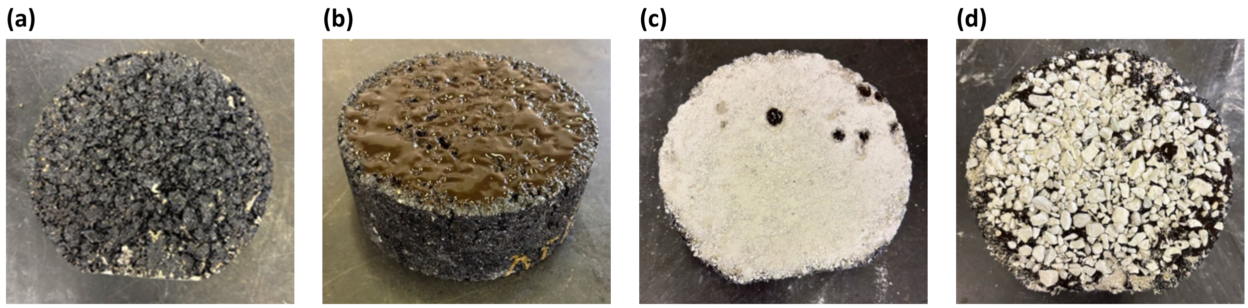


Figure 31. Photos. Preparation of modified-HWT specimen: (a) asphalt concrete disk, (b) application of first emulsion layer on the disk, (c) application of first aggregate layer (fines), (d) prepared specimen after application of second emulsion layer followed by a second aggregate layer (coarse).

$$Aggregate\ loss\ (\%) = \frac{A - B}{A - C} \times 100$$

Figure 32. Equation. Aggregate-loss calculation for modified-HWT testing.

Results and Discussion

The results of the modified HWT test for all aggregate types, emulsion types, and design methods are presented in Figure 33. Representative photographs of specimens for each aggregate type before and after testing are included in Appendix A. Aggregate loss was used as the primary performance indicator to evaluate the effect of repeated shear loading under simulated braking conditions. Similar to the sweep test, lower aggregate loss indicates better aggregate embedment and stronger aggregate–binder interaction, whereas higher loss indicates inadequate bonding and increased susceptibility to particle dislodgement.

Overall, the trends observed from the modified HWT test were consistent with those obtained from the sweep test. However, the magnitude of aggregate loss was generally higher. This increase is attributed to the more severe loading conditions imposed by the locked pneumatic tire, which induces significant shear stresses through scraping action rather than rolling contact. Across all aggregate and emulsion types, specimens designed using the modified Kearby method consistently exhibited the lowest aggregate loss, generally less than 6%. This superior performance is attributed to the higher emulsion-to-aggregate ratio provided by this method. The increased binder content allows the aggregate particles to be properly coated and provides greater resistance to the shear forces generated by the locked wheel during testing. In contrast, specimens prepared using the Austroads method exhibited significantly higher aggregate loss, suggesting that this method may underestimate the binder requirement for QB materials, resulting in insufficient coating and reduced embedment.

QB-based specimens demonstrated performance comparable to the typical Otta seal aggregate. This finding indicates that, despite their finer gradation and higher fine-aggregate content, QB materials can perform effectively when appropriate design methods and binder application rates are employed.

The influence of emulsion type was particularly evident under the Austroads design method. Specimens prepared with HFRS-2P exhibited lower aggregate loss, as compared to those prepared with HFRS-2. Because the Austroads method applies the same binder rate regardless of emulsion properties, this difference in performance can be attributed to the higher residual asphalt content and polymer modification of HFRS-2P. The overall results demonstrate that QB-based Otta seals can achieve satisfactory performance under severe shear loading when appropriate binder content, aggregate gradation, and optimized configurations are utilized.

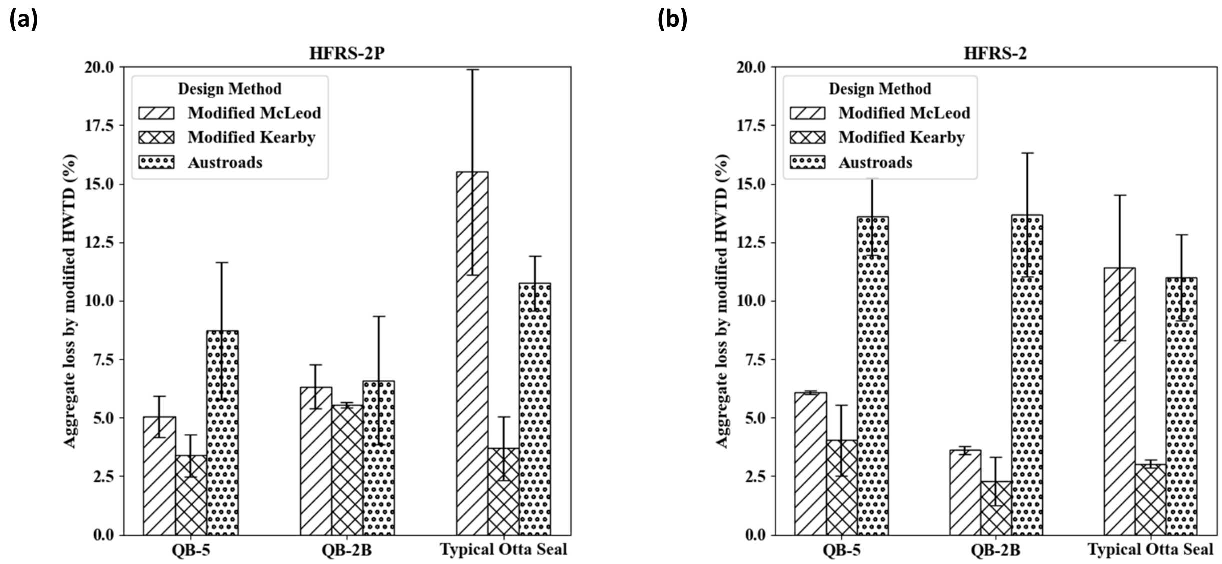


Figure 33. Chart. Aggregate losses from modified-HWT results for the three aggregate types, using (a) HFRS-2P and (b) HFRS-2 emulsions.

SURFACE TEXTURE USING CLOSE-RANGE PHOTOGRAMMETRY

Procedure of CRP Technique

The surface texture of Otta seal specimens was evaluated using a nondestructive close-range photogrammetry (CRP) technique, following the methodology reported by a previous study (Maia et al., 2024). The analysis was performed on specimens prepared for sweep testing prior to testing to quantify surface characteristics relevant to functional performance. The procedure involved capturing approximately 30 images around each specimen using a smartphone camera. These images were processed in Autodesk ReCap Photo to generate high-resolution 3D point clouds or meshes. The generated meshes were then exported as .xyz files using MeshLab and further analyzed in Gwyddion software to quantify surface-texture parameters. To ensure accuracy in texture characterization, several data-processing steps were applied, including rasterization, polynomial leveling, zero-shift adjustment, and background correction. A representative 3D point cloud and corresponding processed texture map are presented in Figure 34. From the processed surface data, statistical texture parameters, including mean surface roughness (S_a) and root-mean-square roughness (S_q), were calculated and compared across all specimens. These parameters provide a quantitative assessment of surface-texture variability and roughness characteristics.

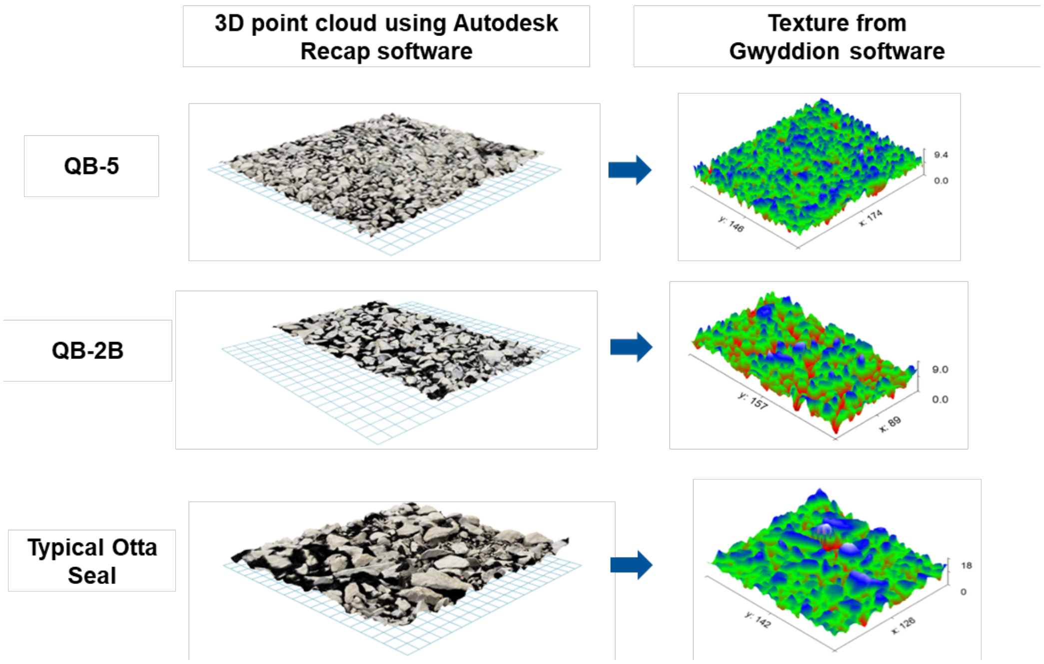


Figure 34. Illustrations. 3D point cloud and surface texture characteristics for QB-5, QB-2B, and typical Otta seal aggregate.

Results and Discussion

Surface texture was quantified using standard parameters defined in ISO 25178-2 (2021). The arithmetic-mean height (S_a) represents the average absolute deviation of surface heights from the mean plane and provides a general measure of surface roughness. The root-mean-square height (S_q) represents the root-mean-square of surface-height deviations and is more sensitive to larger peaks and valleys. The S_a values for specimens prepared with HFRS-2P and HFRS-2 are presented in Figure 35-a and Figure 35-b, respectively, while the corresponding S_q values are presented in Figure 36-a and Figure 36-b. The results indicate that surface texture was strongly influenced by aggregate gradation. QB-based specimens exhibited relatively lower S_a and S_q values than the typical Otta seal aggregate, reflecting a smoother and more uniform surface due to the finer gradation of QB materials. Among the QB specimens, QB-2B showed higher texture values than QB-5, which can be attributed to the inclusion of coarser aggregates in the blend to meet Overby-gradation requirements. In contrast, the typical Otta seal aggregate exhibited the highest S_a and S_q values, due to the presence of larger coarse-aggregate particles.

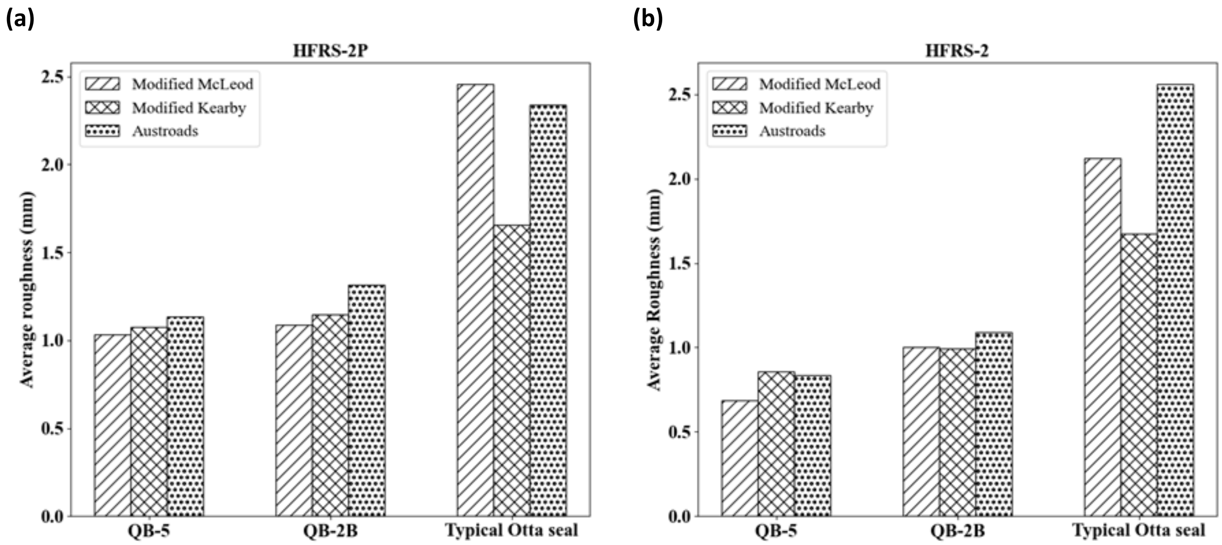


Figure 35. Charts. Average roughness values for the three aggregate types, using (a) HFRS-2P and (b) HFRS-2 emulsions.

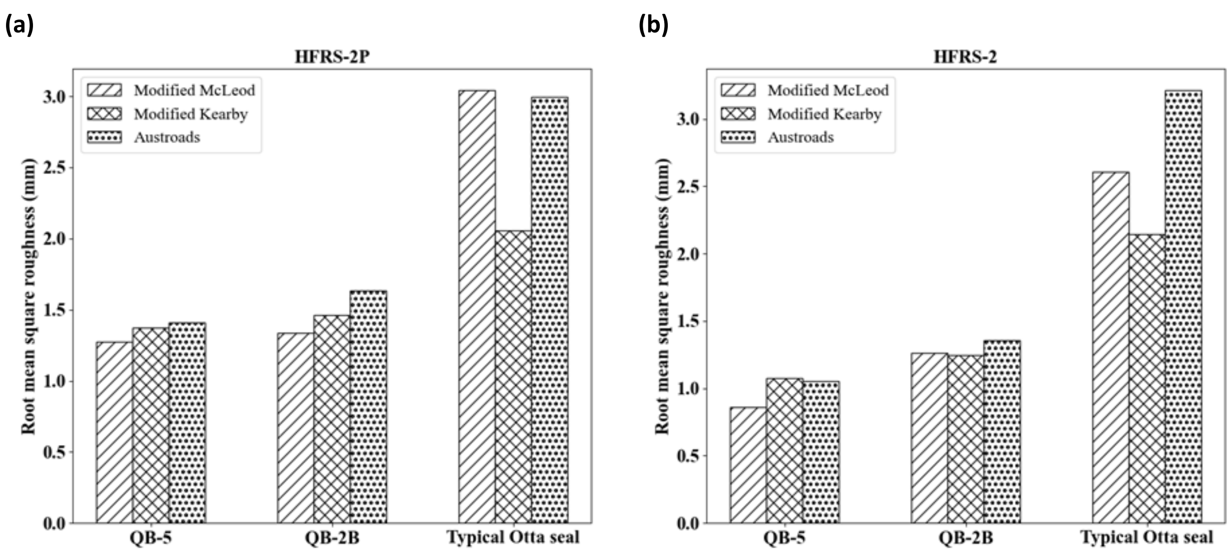


Figure 36. Charts. Root-mean-square roughness values for the three aggregate types, using (a) HFRS-2P and (b) HFRS-2 emulsions.

Although higher surface-texture values indicate increased surface roughness, they may also reflect reduced aggregate embedment. This trend is consistent with the performance results, in which specimens with higher texture, particularly those prepared with typical Otta seal aggregate, exhibited greater aggregate loss in both sweep and modified HWT tests. Conversely, QB-based specimens, especially those with finer gradation, showed improved aggregate retention despite having lower surface roughness. The effect of emulsion type was also evident. Specimens prepared with HFRS-2P generally exhibited slightly higher texture values than those prepared with HFRS-2, likely due to reduced embedment associated with the higher stiffness of the polymer-modified binder. In contrast, HFRS-2 promoted greater aggregate embedment, resulting in a smoother surface and improved aggregate retention. Among the design methods, the Austroads method produced the highest surface-texture values, which is consistent with its lower binder-application rates and reduced aggregate embedment observed in the sweep and modified-HWT results. Overall, this pattern indicates that there is a trade-off between reduction of raveling and improving the service life versus improving the surface texture of Otta seals. As both raveling and friction loss due to texture loss present safety issues, this trade-off should be managed carefully.

BLEEDING SUSCEPTIBILITY OF QB-BASED OTTA SEAL SPECIMENS USING MODIFIED HAMBURG WHEEL-TRACKING TEST

Bleeding is an important performance indicator for surface treatments. It refers to the upward migration of excess binder to the pavement surface under the combined influence of traffic loading and elevated temperature. In surface treatments such as Otta seals, bleeding can significantly reduce skid resistance, particularly under wet conditions. Therefore, evaluating bleeding is important for ensuring an appropriate balance between adequate aggregate retention and safe surface friction.

Methodology

Bleeding performance of a QB-based Otta seal was evaluated using the modified-HWT device. The test setup consisted of a rotating pneumatic tire, rather than the locked wheel used in the performance test to simulate braking effects, repeatedly passing over the Otta seal surface to simulate traffic movement, following an approach similar to that reported by Kim et al. (2023). The objective of this test was to examine the potential for binder migration to the pavement surface under repeated loading conditions.

The test specimen was prepared using QB-5 aggregate and HFRS-2P emulsion. The binder-application rate was determined using the modified Kearby design method because it produced the highest binder content among the methods evaluated, thereby increasing bleeding susceptibility. Specimens were prepared in the laboratory following the same procedure, presented in Figure 31. After preparation and curing, the specimens were subjected to repeated wheel passes using the modified-HWT device. Initially, the test was conducted at room temperature, approximately 16°C (61°F), in the month of January. However, no bleeding was observed even after 4,000 wheel passes with a load of 39.3 lbf (175 N). Therefore, to further evaluate bleeding potential, the surface temperature of the Otta seal specimen was increased to 50°C (122°F), as bleeding is more likely to occur during summer when pavement temperatures are elevated. The specimen was first heated in an oven, and the target temperature was maintained during testing using a heat gun and monitored with a laser thermometer, as in Figure 37. The specimen was subjected to 2,000 wheel passes with the same load at this elevated temperature. During testing, specimen images were captured after every thousand wheel passes, using the camera setup in Figure 37. The captured images were used to monitor potential binder migration to the surface and changes in surface texture with increasing wheel passes.

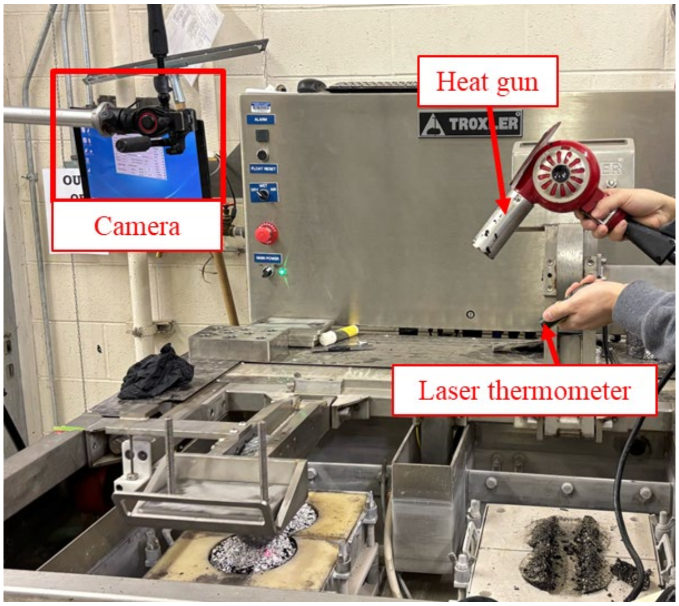


Figure 37. Photo. Modified-HWT setup for bleeding test.

Results and Discussion

During the testing process, the specimen was subjected to 4,000 passes at 16°C (61°F), followed by 2,000 passes at 50°C (122°F). Images of the specimen captured during the testing are presented in Figure 38. These images show no evidence of bleeding in the QB-based Otta seal specimen. No visible binder migration was observed on the surface throughout the testing period, even at the elevated temperature of 50°C (122°F). Some aggregate loss was observed at the higher temperature, as in Figure 38-d and Figure 38-e, likely due to binder softening; however, bleeding was not observed. The absence of bleeding can be attributed to the well-graded aggregate structure of Otta seals, particularly with QB material, which forms a dense aggregate matrix with relatively few interconnected voids. This dense matrix effectively retains the binder within the aggregate skeleton and reduces the potential for binder migration toward the surface under repeated loading.

However, a gradual change in surface texture was observed with an increasing number of wheel passes, as in Figure 39. The specimen texture after 4,000 passes at 16°C (61°F) is presented in Figure 39-a and that after an additional 2,000 passes at 50°C (122°F) in Figure 39-b. This change was mainly associated with progressive aggregate embedment into the binder layer rather than binder migration to the surface. The observed embedment behavior may be attributed to limitations of laboratory manual compaction using the steel compactor in Figure 19-d, which may not fully replicate the level of densification achieved in the field using heavy rollers and subsequent traffic. As a result, additional densification of the Otta seal layer occurred under repeated wheel loading during the HWT test, similar to the effect expected from traffic. The test results overall indicate that QB-based Otta seals prepared with QB-5 aggregate demonstrated low susceptibility to bleeding, even with the relatively highest binder-application rate and elevated temperature; however, some loss of texture may occur over time.

(a) (b) (c) (d) (e)

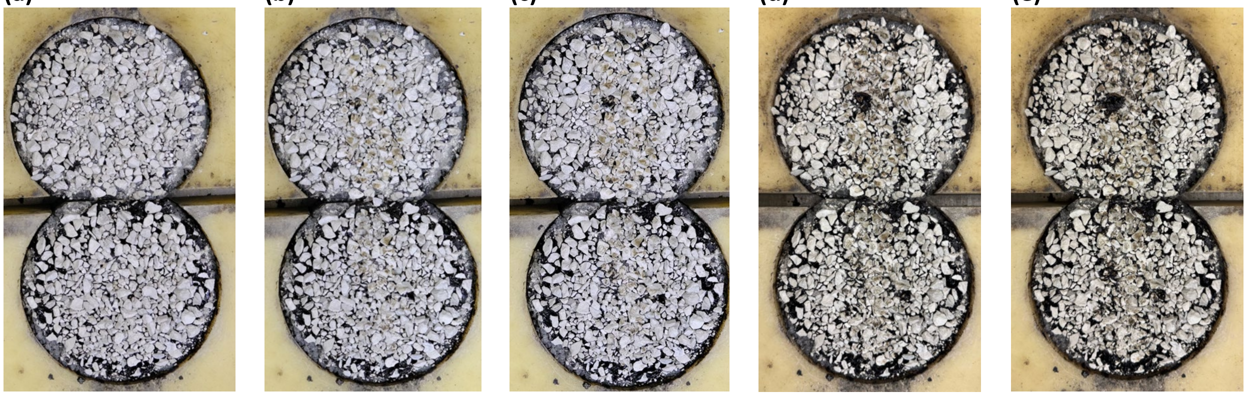


Figure 38. Photos. Specimen images: (a) initial condition, (b) after 2,000 passes at 16°C (61°F), (c) after 4,000 passes at 16°C (61°F), (d) after an additional 1,000 passes at 50°C (122°F), and (e) after 2,000 passes at 50°C (122°F).

(a) (b)

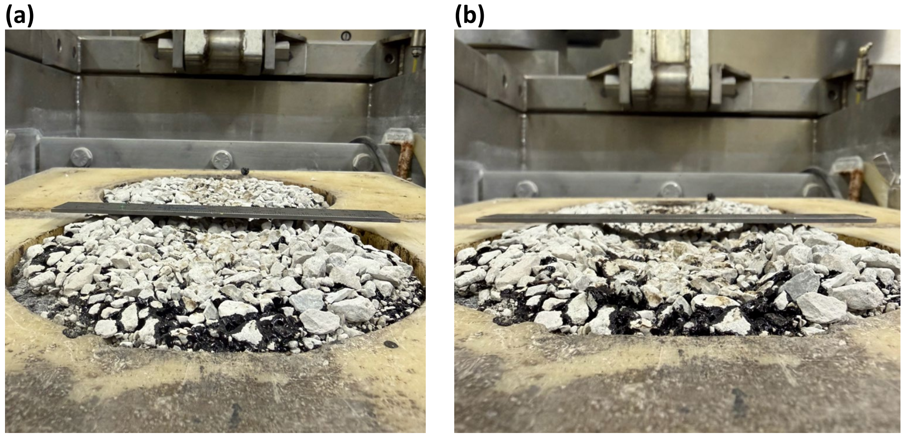


Figure 39. Photos. Specimen texture after applying (a) 4,000 passes at 16°C (61°F) and (b) after an additional 2,000 passes at 50°C (122°F).

STRUCTURAL PERFORMANCE OF QB-BASED OTTA SEAL EVALUATED USING LIGHTWEIGHT DEFLECTOMETER TESTING

The structural performance of QB-based Otta seal surfacing was evaluated by determining its composite modulus using a controlled small-scale laboratory box setup and lightweight deflectometer (LWD) testing.

Box Setup and LWD Testing

A small-scale steel box with dimensions of 24 in. × 24 in. (61 cm × 61 cm) and a depth of 21 in. (53 cm), as presented in Figure 40, was used to simulate pavement layers under controlled laboratory conditions. To represent subgrade conditions, a 6 in. (15 cm) thick geofoam layer with a California bearing ratio (CBR) of approximately five was placed at the base of the box. A 15 in. (38 cm) thick, dense-graded CA-6 aggregate layer was constructed above the geofoam to simulate the base course, as presented in Figure 41. The CA-6 material was placed in dry condition and compacted in two equal lifts using a vibratory-plate compactor. Compaction was continued until no further reduction in layer thickness was observed, indicating that a stable and well-compacted condition had been achieved. The final compacted density was estimated based on the total mass of material and compacted height, resulting in a density of 132 pcf (2114 kg/m³). Following the base preparation, QB-based Otta seal surfacing was applied using the modified Kearby method, which was selected based on its superior performance and lower aggregate loss observed in the previous sweep and modified HWT tests. QB-5 aggregate and HFRS-2 emulsion were used for specimen preparation.

The laboratory-optimized Otta seal configuration described in Chapter 4 was constructed on top of the base. The Otta seal layer consisted of an initial emulsion application followed by fine fraction, and a second emulsion application followed by coarse fraction. Each aggregate layer was compacted using the manual compactor presented in Figure 19-d, with seven passes in a horizontal direction and seven passes in the perpendicular direction. The specimen preparation procedure is illustrated in Figure 42. After construction of the Otta seal layer, the specimen was cured at room temperature of 21°C (70°F) for three days to allow emulsion breaking and setting before applying the second layer. The second Otta seal configuration was applied and cured similarly for three days. Due to the large size of the box, oven curing was not feasible; therefore, extended ambient curing was used to ensure adequate binder setting.

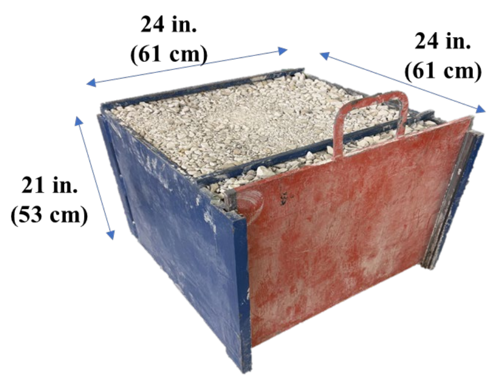


Figure 40. Photo. 3D view of box setup showing dimensions.

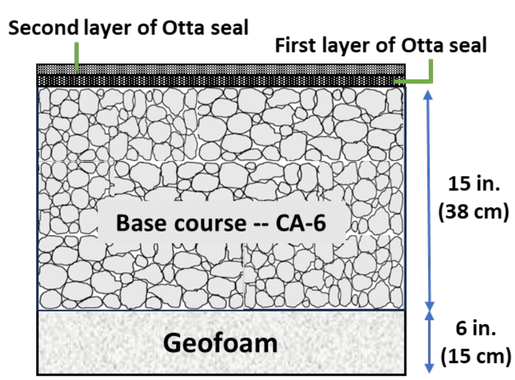


Figure 41. Illustration. Cross-sectional view of the box setup showing layer configuration.

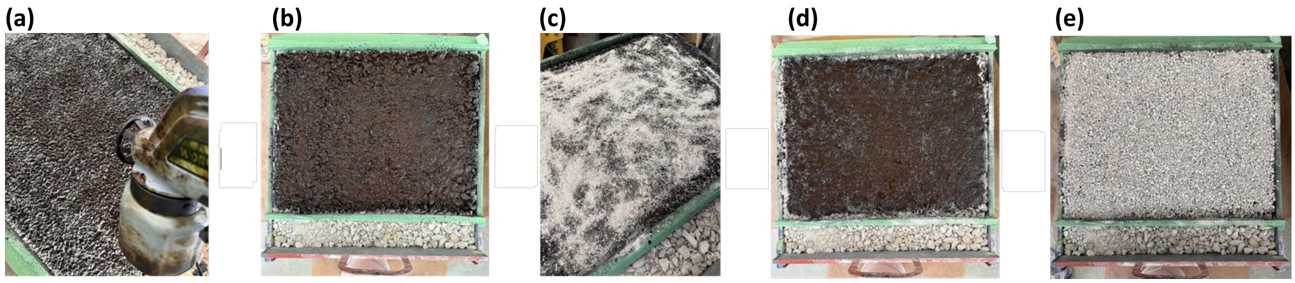


Figure 42. Photos. Preparation of Otta seal specimen on box setup: (a) application of emulsion using spray gun, (b) application of first emulsion layer, (c) first aggregate layer consisting of fine aggregate, (d) application of second emulsion layer, and (e) second aggregate layer consisting of coarse aggregate, completing the specimen.

Composite Modulus Assessment

The structural response of the system was evaluated using the LWD. The LWD is a nondestructive testing device that estimates in situ stiffness, typically of soils and granular pavement layers, by measuring surface deflection under an impact load. The test involves dropping a known weight from a specified height onto a circular loading plate and recording the resulting peak surface deflection. The measured deflection is interpreted based on Boussinesq's elastic half-space theory, which assumes the material behaves as a homogeneous, isotropic, and semi-infinite medium subjected to uniform loading. The elastic modulus was calculated using the equation presented in Figure 43, where v is Poisson's ratio, q is the applied stress, r is the plate radius, and w is the measured central deflection. In practice, the results are reported as the dynamic deformation modulus (E_{vd}), assuming a Poisson's ratio of close to 0.5 to represent an incompressible condition. The LWD used in this study consisted of a 22 lb (10 kg) falling weight dropped from a height of 28.5 in. (72.4 cm) onto an 11.8 in. (300 mm) diameter plate, presented in Figure 44. Testing was conducted at three locations, as presented in Figure 45, on the base layer and after each Otta seal application stage to ensure repeatability. For Otta seal layers, measurements were performed after a three-day curing period to allow sufficient binder setting.

$$E = \frac{2\left(1-\nu^2\right)\cdot q\cdot r}{w}$$

Figure 43. Equation. Elastic modulus calculation for LWD.

The LWD-influence depth extends to approximately 1.5 times the diameter of the loading plate; therefore, the measured modulus represents the composite stiffness of the entire system, including the Otta seal layer, base course, and subgrade. The results showed a clear increase in the modulus following the application of the Otta seal layers, as presented in Figure 46. This increase indicates an improvement in the overall stiffness of the system after surfacing. An additional increase in modulus was observed 10 days after the placement of the second Otta seal layer, indicating continued curing and strengthening of the binder–aggregate matrix over time.

Figure 44. Photo. LWD device.

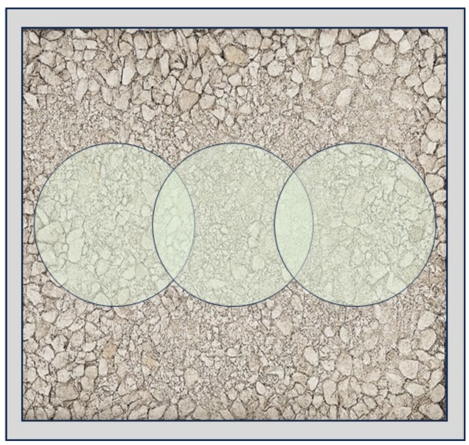


Figure 45. Illustration. Plan view of box setup showing three test locations for LWD measurements.

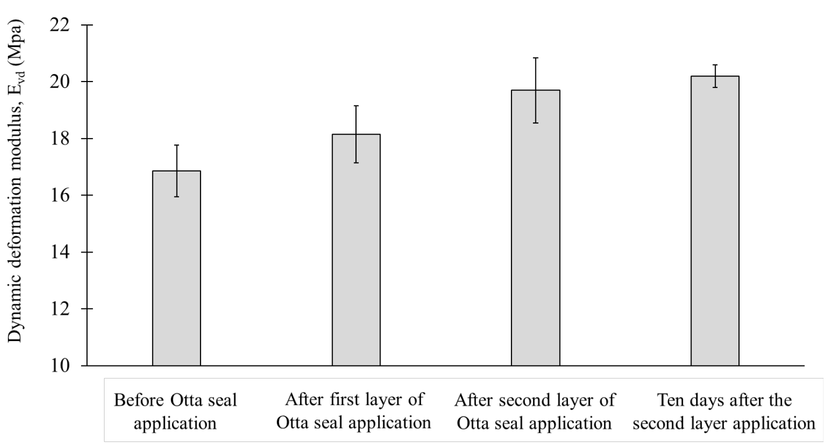


Figure 46. Chart. Dynamic deformation modulus measured using the LWD test before and after applying Otta seal layer.

Although Otta seal is primarily intended as a surface treatment for waterproofing, dust control, ride-quality improvement, and friction improvement rather than structural enhancement, the LWD results indicate an apparent increase in bearing capacity. Previous field studies have reported similar improvement in composite modulus, but the increases in stiffness were attributed to additional compaction of the base and subgrade during Otta seal construction (Jibon, Mahedi, et al., 2023; Yang et al., 2021). However, in the present controlled laboratory setup, the observed increase is not likely to be solely attributed to further densification of the base layer, as it had already been compacted to a stable condition prior to Otta seal placement. This finding suggests that the improvement in measured stiffness is primarily associated with the contribution of the Otta seal layer itself rather than changes in base compaction. The binder enhances particle interlock and reduces aggregate mobility, thereby minimizing localized deformation under loading. Additionally, the Otta seal acts as a thin, semi-bound layer that improves stress distribution by dispersing applied loads over a broader area of the base. The continued increase in stiffness over time further confirms progressive curing and strengthening of the Otta seal layer, resulting in enhanced surface confinement, improved stability, and higher composite modulus values.

Surface-Texture Characteristics Using CRP on Box Setup

Before and after Otta seal application, the surface-texture characteristics of the specimens were evaluated using the CRP technique discussed in the previous section. The results presented in Figure 47 indicate a reduction in macrotexture depth following the application of the Otta seal layer. Both the arithmetic-mean roughness (S_a) and the root-mean-square roughness (S_q) decreased following Otta seal application. This reduction is attributed to the penetration of asphalt emulsion into surface voids and the rearrangement of aggregate particles during application and compaction. The binder fills gaps between coarse particles, with finer QB particles occupy void spaces, resulting in a smoother and more compact surface profile.

Despite the reduction in overall roughness, this decrease does not necessarily indicate reduced friction. The well-graded nature of QB aggregate produces a more uniform and consistent surface texture, unlike the base course, which exhibits pronounced peaks and valleys at the surface due to aggregates of larger size. The uniform texture in the QB specimen reduces localized stress concentrations and may enhance durability under repeated loading. As a result, the QB-based Otta seal provides a balance between reduced macrotexture and improved surface uniformity. This characteristic will also result in a much smoother ride quality.

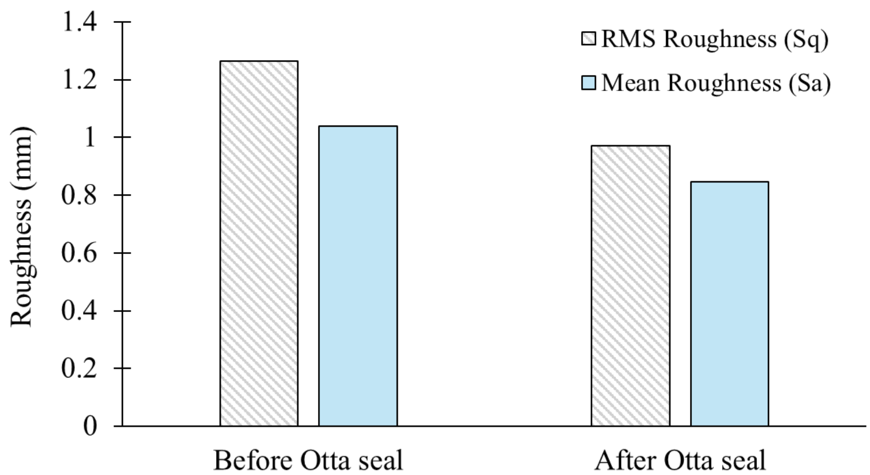


Figure 47. Chart. Mean-roughness and root-mean-square roughness values derived from the CRP technique, before and after Otta seal application.

FRICTION PROPERTIES OF QB-BASED OTTA SEAL SPECIMENS USING DYNAMIC FRICTION TESTER

Methodology of DFT

Friction performance of the QB-based Otta seal was evaluated using a dynamic friction tester (DFT), following the ASTM E1911 (2024) standard. The DFT device consists of a horizontal rotating disk equipped with three standardized rubber sliders positioned at equal spacing. The DFT equipment and rotating disk, along with sliders, are presented in Figure 48. During testing, the DFT unit is placed on the test surface; and a controlled flow of water is applied to simulate wet pavement conditions. The disk is initially rotated without contact with the surface, and rotational speed is gradually increased to the target speed of 50 mph (80 km/h). Once the desired speed is reached, the rubber sliders come into contact with the wet surface. Friction between the rubber sliders and the surface cause the rotating disk to decelerate. The torque required to reduce the rotational speed of the disk is continuously measured and used to calculate the friction coefficient at the specified speed.

(a) **(b)**

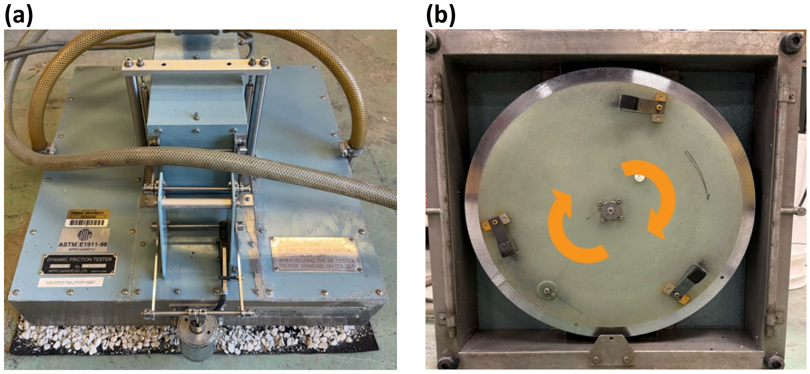


Figure 48. Photos. (a) DFT equipment and (b) plan view of the equipment showing DFT rotating disk with sliders.

DFT testing was performed on the QB-based Otta seal layer applied on the laboratory box setup (Figure 49), which was also used for LWD testing, as discussed above. However, the DFT testing on the Otta seal constructed over the box setup was not successful, as the rotating DFT sliders removed a significant portion of the top-layer aggregates. Photos of the specimen before and after testing are presented in Figure 49-b and Figure 49-c, respectively. This behavior is attributed to the compaction method used. The Otta seal layer in the box setup was compacted using the manual steel compactor presented in Figure 19-d, which did not provide sufficient embedment of aggregates into the binder layer. As a result, the aggregate particles were easily dislodged by the rubber sliders rotating at a high speed of 50 mph (80km/h) during testing. The resulting aggregate loss disrupted the surface contact required for accurate friction measurement, therefore, reliable friction values could not be obtained.

To address this issue, new specimens were prepared on asphalt felt sheets cut into 20 in. × 20 in. (50.8 cm × 50.8 cm) squares. This size was selected to accomodate proper placement and operation of the DFT during testing. The specimens were prepared and cured following the optimized double-layer Otta seal configuration as described in Chapter 4. For comparison purposes, specimens were prepared using all three aggregate types—QB-5, QB-2B, and typical Otta seal aggregates—using HFRS-2P emulsion. The modified Kearby method was used for computing aggregate- and binder-application rate, as it showed the best performance in the sweep and modified HWT tests. After preparation of the Otta seal specimen on the asphalt sheets, compaction was performed using a truck tire moving repeatedly over the surface in both forward and backward directions, as presented in Figure 50-a and Figure 50-b. A sorbent pad was placed between the specimen and the truck tire during compaction to prevent breakage of QB aggregates, which are relatively marginal in quality.

(a) **(b)** **(c)**

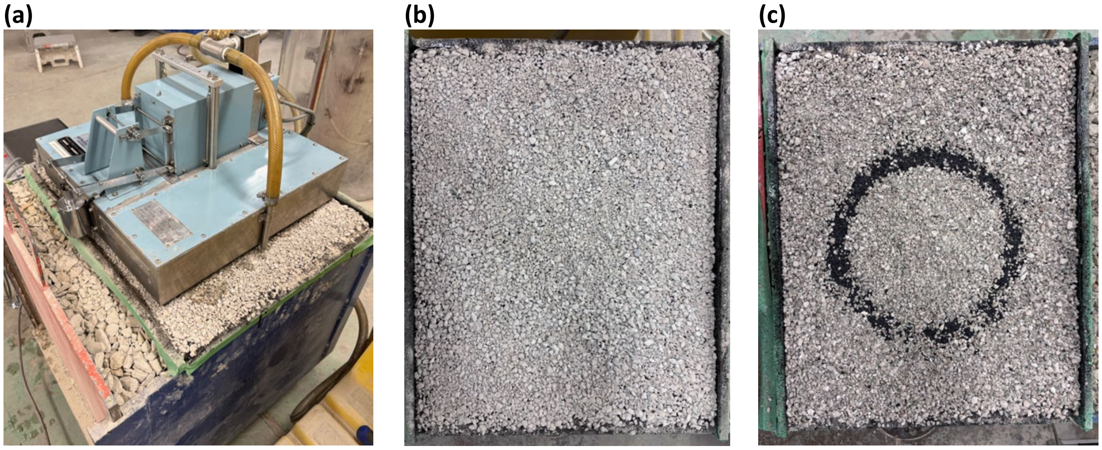


Figure 49. Photos. (a) DFT testing of Otta seal applied over the box setup, (b) specimen photo before testing, and (c) specimen photo after DFT testing.

Compaction using the truck tire better simulated field compaction conditions with pneumatic rollers and ensured proper aggregate embedment into the binder layer. After curing, friction testing was conducted using the DFT. No aggregate dislodgement was observed during testing, indicating adequate aggregate embedment and good surface stability. A representative specimen after testing is presented in Figure 50-c. The QB-based specimen images before and after DFT testing are presented in Appendix A. To provide a reference representative of field-pavement conditions, friction measurements were also conducted on a recently paved asphalt surface at the ICT parking lot (Figure 51) utilized an IDOT-approved mix design. Three replicate measurements were obtained at the same location for each specimen to ensure repeatability and consistency. The average of these measurements was used to compare the frictional performance of all surfaces.

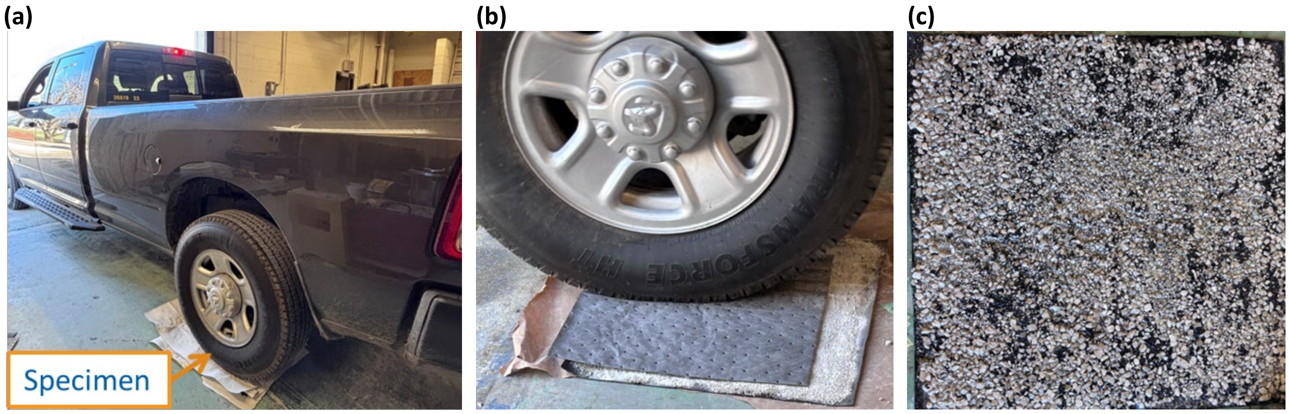


Figure 50. Photos. Preparation of QB-specimen for DFT testing: (a) compaction of specimen using a truck tire, (b) close view of specimen compaction, and (c) specimen after DFT testing.

Figure 51. Photo. DFT measurement of asphalt surface at the ICT parking lot.

Friction Characteristics

The complete DFT curves, showing the relationship between friction value and speed for all measured surfaces, are provided in Appendix B. The DFT measurements obtained at a speed of 12.4 mph (20 km/h) are presented in Figure 52. The DFT values at this speed were used for comparison because this speed is used for calculating the International Friction Index in accordance with ASTM E1960 (2015) and has been shown to exhibit strong corelation with pavement microtexture (Shah & Youngblood, 2024). According to ASTM E1960 (2015), the recommended range for DFT at 12.4 mph (20 km/h) is 0.3 to 0.9. The measured DFT values were 0.77 for QB-5 and 0.66 for QB-2B, both falling within this recommended range. Further, for safe traffic operation on wet pavement surfaces, a friction value greater than 0.4 is generally considered acceptable and is presented as a threshold in Figure 52 (White & Thompson, 1958). Because the DFT values for QB-based specimens exceed this threshold, the results indicate that QB-based Otta seal surfaces provided adequate skid resistance and satisfactory friction performance.

DFT testing could not be performed on the specimen prepared with typical Otta seal aggregate because the relatively large aggregate particles obstructed the rubber sliders and prevented proper rotation of the DFT disk. For comparison, DFT testing on the recently paved ICT parking-lot surface yielded a friction value of 0.65, which was similar to the values obtained for the QB-based Otta seal specimens. This similarity indicates that the QB-based Otta seal specimens provide friction performance comparable to a relatively new in-service pavement surface, further supporting the suitability of QB materials for Otta seal applications.

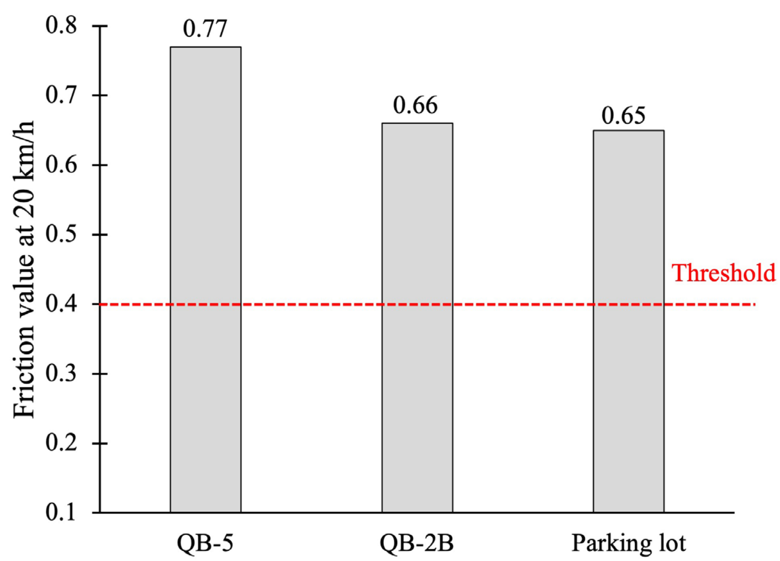


Figure 52. Chart. DFT friction results for QB-based Otta seal specimens and ICT parking-lot surface, with a threshold line indicating the minimum friction requirement (0.4) for safe traffic movement.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

This research study evaluated the feasibility of using quarry by-products (QBs) as alternative aggregate materials in Otta seal surface-treatment applications. An asphalt surface treatment for low-volume roads, Otta seal consists of spraying an emulsion layer, followed by the application of well-graded aggregates, and offers an advantage of utilizing locally available and/or marginal-quality materials. The primary objective of this research was to determine whether QBs can satisfy the functional and performance requirements of Otta seal while reducing reliance on high-quality virgin aggregates. Additionally, this study aimed to develop a rational design approach for Otta seal by adapting established chip seal design methods, including the McLeod, modified Kearby, and Austroads methods, which account for material properties rather than relying solely on empirical guidelines.

For material selection, two QBs—QB-5 and QB-2 from the previous ICT R27-248 project—were selected from an initial pool of eight QBs, based on gradation requirements provided by the Overby method and their prior performance in other admixture-stabilized base/subbase applications. QB-5 falls within the Overby gradation band; however, QB-2 did not meet gradation requirements and therefore was blended with coarser aggregates to produce QB-2B. For comparison, a control aggregate, referred to as typical Otta seal aggregate, was prepared from CA-6 aggregates. Material property tests were conducted for all three aggregates to evaluate aggregate gradation, specific gravity, absorption, flakiness index, and void content. The results indicated that QB materials were generally finer and more absorptive, as compared to conventional aggregates, which influenced binder demand and aggregate–binder interaction. As the selected aggregates are from limestone and dolomitic sources and exhibit cationic characteristics, two anionic emulsions—unmodified high-float, rapid-setting (HFRS-2) and polymer-modified, high-float, rapid-setting HFRS-2P—were chosen. The HFRS-2P emulsion modified with styrene-butadiene-styrene (SBS) polymer was used in this study. Binder characterization included evaluations of residual asphalt content, tensile strength, ductility, rheological behavior, and chemical composition. The polymer-modified binder exhibited improved tensile strength, ductility, and stiffness, indicating enhanced resistance to deformation and improved durability. Since this study investigated only an SBS-modified polymer emulsion, the findings presented in this report should be validated before applying to emulsions containing other polymer types.

Following material selection and characterization, laboratory optimization of QB-based Otta seal was performed to address challenges associated with high fine contents and high absorption values of QBs. Initial single-layer configurations resulted in significant loose aggregates due to insufficient binder availability for coating coarse particles. This behavior was attributed to the high surface area and absorption capacity of QB materials, which led to rapid binder absorption by fine particles, leaving insufficient binder to coat the coarse particles effectively. To address this issue, a double-layer configuration was developed with separation of fine and coarse aggregates. The optimal configuration involved placing fine aggregate in the bottom layer and coarse aggregate in the top layer, using the No. 8 sieve for separation. This approach improved binder distribution between coarse and fine aggregates, enhanced aggregate interlock, and produced a well-textured surface, while minimizing the presence of loose aggregates.

In addition to laboratory optimization of QB-based Otta seal specimens, the effect of curing conditions on double-layer Otta seal performance was evaluated to understand their influence on binder–aggregate interaction and strength development. Curing behavior was assessed through weight-loss monitoring of specimens cured under different temperatures. The impact of curing on performance was assessed by measuring aggregate loss with sweep testing for specimens cured under different conditions. The results showed that higher curing temperatures and longer curing durations significantly accelerated water evaporation from the emulsion, leading to faster binder breaking and improved binder–aggregate adhesion. In contrast, inadequate curing resulted in weak adhesion and increased susceptibility to aggregate loss. These findings emphasized that curing is a critical factor governing early-age performance and long-term durability of Otta seals.

Subsequently, a comprehensive performance evaluation of QB-based Otta seals was conducted using multiple laboratory tests. Sweep and modified Hamburg wheel-tracking (HWT) tests were conducted to assess aggregate loss under simulated traffic abrasion and braking conditions, respectively. The results indicated that QB-based Otta seal specimens demonstrated adequate resistance to aggregate loss comparable to or better than those fabricated with typical Otta seal aggregates. Surface-texture characteristics were quantified using the close-range photogrammetry (CRP) technique. This technique provided 3D surface profiles and roughness parameters. The QB-based specimens showed lower surface texture than typical Otta seal specimens, due to the finer aggregate particles in QB, which reduce extreme peaks and valleys in the texture and may provide more consistent tire–surface contact. From these tests, the modified Kearby method showed the least aggregate loss of the three design methods and therefore was established as the best-performing design method. Additional evaluations were performed on Otta seals with QBs designed using the modified Kearby design method. These included bleeding susceptibility, improvement in bearing capacity, and frictional characteristics of Otta seals. Bleeding susceptibility of the QB-based Otta seal was evaluated using a modified HWT test, with repeated wheel passes on the specimen. Structural performance was assessed using lightweight deflectometer (LWD) testing, which indicated an increase in composite modulus after application of the Otta seal layer. Friction performance was evaluated using a dynamic friction tester (DFT), showing that QB-based Otta seal can provide adequate friction for safe traffic movement and exhibit performance comparable to an in-service hot-mix asphalt pavement surface.

CONCLUSIONS

This study examined the use of QBs as a viable and sustainable alternative to conventional aggregates in Otta seal applications. A key outcome of this research is the development of an optimized double-layer Otta seal configuration developed for QB materials. The separation of fine and coarse aggregates using the No. 8 sieve significantly improved binder distribution and aggregate embedment, addressing challenges associated with the high amount of fine particles in QBs. This approach ensures better coating of aggregates and enhances the durability and performance of the surface treatment.

The study also highlights the importance of curing conditions, demonstrating that adequate temperature and curing durations are essential for achieving proper binder breaking and strong aggregate–binder adhesion.

The performance-evaluation results indicated that QB-based Otta seal outperformed typical Otta seal aggregate in terms of resistance to aggregate loss under simulated traffic abrasion and vehicle-braking conditions. Further, QB-based specimens exhibited strong resistance to bleeding, even at elevated temperatures, which can be attributed to the dense QB matrix that provides better interlock and fewer voids to hold the binder in place. Although the surface texture was lower due to the fine particle size of QBs, the friction performance remained above the threshold required for safe traffic movement, ensuring reliable pavement performance.

Further, structural evaluation using LWD indicated an increase in composite modulus after Otta seal application, suggesting improved stiffness and load distribution for the surface treatment. Although Otta seal is not intended to function as a structural layer, its contribution to surface confinement and aggregate–binder interaction contributes to an increase in overall composite stiffness of the pavement. These findings suggest that QB-based Otta seal can provide both functional and structural benefits. Overall, this study establishes that with proper design, compaction, and curing practices, QB-based Otta seal can serve as a cost-effective, durable, and sustainable surfacing solution for low-volume roads. The ability to utilize locally available underutilized and marginal-quality materials not only reduces material costs, but also promotes sustainable construction practices by minimizing the use of high-quality virgin aggregates.

RECOMMENDATIONS FOR FIELD IMPLEMENTATION

Preliminary guidelines for field implementation of Otta seal were developed to provide a systematic framework covering preconstruction, construction, and postconstruction phases. These guidelines aim to ensure proper material utilization, construction quality, and long-term performance of QB-based Otta seals under field conditions.

Preconstruction Phase

A preconstruction phase will include proper site evaluation and surface preparation to ensure a uniform, stable, and structurally sound foundation for Otta seal application. Surface-preparation activities include providing grading of the roadway to achieve the desired cross slope for proper drainage. Adequate drainage is essential to prevent water accumulation within the pavement structure, which can weaken the base and lead to premature failures. Site preparation also involves removal of loose materials, dust, debris, and vegetation to ensure proper bonding between the binder and the base surface. In addition, the subgrade should possess sufficient strength and stiffness to support traffic loading without excessive deformation. Weak or nonuniform support conditions may lead to rutting, differential settlement, or early surface distress. Mechanical compaction may be applied to improve density or stability of the base layer. In a case where the load-bearing capacity of the base layer is inadequate, stabilization methods such as addition of granular material, chemical stabilization using cement or lime, or geosynthetic stabilization may be considered. Establishing a stable and uniform foundation during the preconstruction phase is critical to improve durability and ensure satisfactory long-term functional and structural performance of the pilot QB-based Otta seal.

Construction Phase

The construction phase focuses on proper application of binder and aggregates, along with adequate compaction to ensure sufficient aggregate embedment for long-term durability. Construction should be carried out under favorable environmental conditions, typically avoiding low temperatures, high humidity, or rainfall, as these conditions may adversely affect emulsion breaking and curing. Binder- and aggregate-application rates determined using any rational design method should be adjusted for field conditions to account for variability in surface and environmental factors. The binder should be applied uniformly using calibrated spray equipment to ensure consistent coverage across the surface. Nonuniform binder distribution may result in localized bleeding or insufficient coating of aggregates. Immediately after binder application, fine aggregate passing a No. 8 sieve should be uniformly spread to form the first layer. Compaction is a critical step in Otta seal construction. Adequate compaction should be achieved using pneumatic-tire rollers to ensure proper embedment of aggregates into the binder layer. Insufficient compaction may lead to aggregate dislodgement. Based on laboratory observations and previous field implementation of Otta seal, approximately 30 passes of a pneumatic-tire roller are recommended to achieve sufficient embedment for each layer. After compaction of the first layer, a second layer of binder should be applied, followed by placement of coarse aggregate to form the second layer of Otta seal. This layer should also be compacted with 30 passes of a penumatic-tire roller. Traffic control during construction is also important. In some cases, controlled traffic can be allowed to aid in further compaction and aggregate embedment; however, traffic speed should be regulated to prevent displacement of aggregates. If necessary, additional rolling may be performed after the initial curing to improve surface stability.

Postconstruction Phase

The postconstruction phase involves monitoring and evaluation of the Otta seal performance at regular intervals (e.g., every few months) to evaluate surface and structural performance. Surface roughness can be measured using a laser profiler to assess ride quality. Friction characteristics can be evaluated using a locked-wheel skid tester (LWST) to ensure adequate skid resistance for safe traffic movement. Aggregate retention can be assessed by measuring aggregate loss within a defined area to evaluate surface durability. Structural capacity of the Otta seal system can be monitored using a lightweight deflectometer (LWD), which provides an indication of stiffness and load-bearing ability. In addition, dust generation can be evaluated using a dust-measurement device, such as a Dustometer, to assess environmental and user-comfort aspects. Visual inspection should also be conducted regularly to identify surface distresses such as bleeding, rutting, potholes, raveling, and cracking. These observations provide important insights into performance trends and help in planning maintenance activities. Based on the monitoring results, maintenance strategies such as additional rolling, application of sand or aggregate, or localized repairs can be implemented to extend the service life. Continuous evaluation during the postconstruction phase is essential to validate the performance of QB-based Otta seal and to support its wider implementation in practice.

RECOMMENDATIONS FOR FUTURE RESEARCH

This study comprehensively evaluated the laboratory performance of Otta seal designs incorporating QBs, highlighting the feasibility of utilizing marginal and locally available materials in surface-treatment applications for local roads. The findings indicate that QBs can be effectively used as aggregate in Otta seal application, contributing to resource conservation, reduced material waste, and potential cost savings. The use of QBs represents an environmentally sustainable practice by promoting the beneficial utilization of quarry-produced materials that would otherwise require disposal, and reducing the demand for high-quality virgin aggregates typically required in conventional surface treatments. The following topics are recommended for future research:

- QBs are typically characterized as marginal, low-quality materials with relatively lower strength and higher susceptibility to degradation, as compared to conventional aggregates. Therefore, further investigation is needed to evaluate the potential for particle breakage during compaction and under repeated traffic loading. Understanding the extent of aggregate degradation is critical for assessing changes in gradation, surface texture, and structural stability of the Otta seal layer over time. An aggregate-breakage study can provide critical insights into changes in gradation before and after gyratory compaction, enabling evaluation of the susceptibility of QB aggregates to degradation during compaction and in service.

- The scope of the present study was limited to controlled laboratory testing. Therefore, field pilot studies are necessary to verify the constructability, durability, and long-term performance of QB-based Otta seals under real traffic and environmental conditions. In addition, the curing conditions adopted in the laboratory should be correlated with field-curing conditions by accounting for variations in temperature, moisture, and temperature cycles that may influence binder setting, aggregate adhesion, and early-age performance, thereby providing guidance on appropriate timing for traffic opening. Furthermore, laboratory-compaction procedures should be calibrated with field-compaction practices to ensure that the achieved density, aggregate orientation, and embedment depth in laboratory specimens are representative of field conditions. Establishing this correlation will improve the reliability of laboratory-based performance prediction and support the development of practical field-construction guidelines for QB-based Otta seal applications.

- Comprehensive sustainability evaluations are recommended to quantify the environmental and economical benefits associated with the use of QB materials in Otta seal applications. A life cycle assessment should be conducted to evaluate the environmental impacts associated with material production, transportation, construction, maintenance, and end-of-life considerations. This analysis will help determine the overall environmental footprint of QB-based Otta seals relative to conventional surface treatments. Furthermore, a life cycle cost analysis can be performed to assess the economic feasibility of utilizing QBs in Otta seals by comparing initial construction costs, maintenance requirements, and long-term performance benefits with those of other surface treatments and typical Otta seals. These analyses would provide transportation agencies with quantitative evidence of potential cost savings and sustainability advantages, supporting the broader implementation of QB-based Otta seal, particularly in regions where budget constraints limit the use of high-quality aggregates.

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APPENDIX A: MATERIALS AND SPECIMENS

Figure 53. Photos. Selected aggregates: (a) QB-2, (b) QB-5, and (c) typical Otta seal.

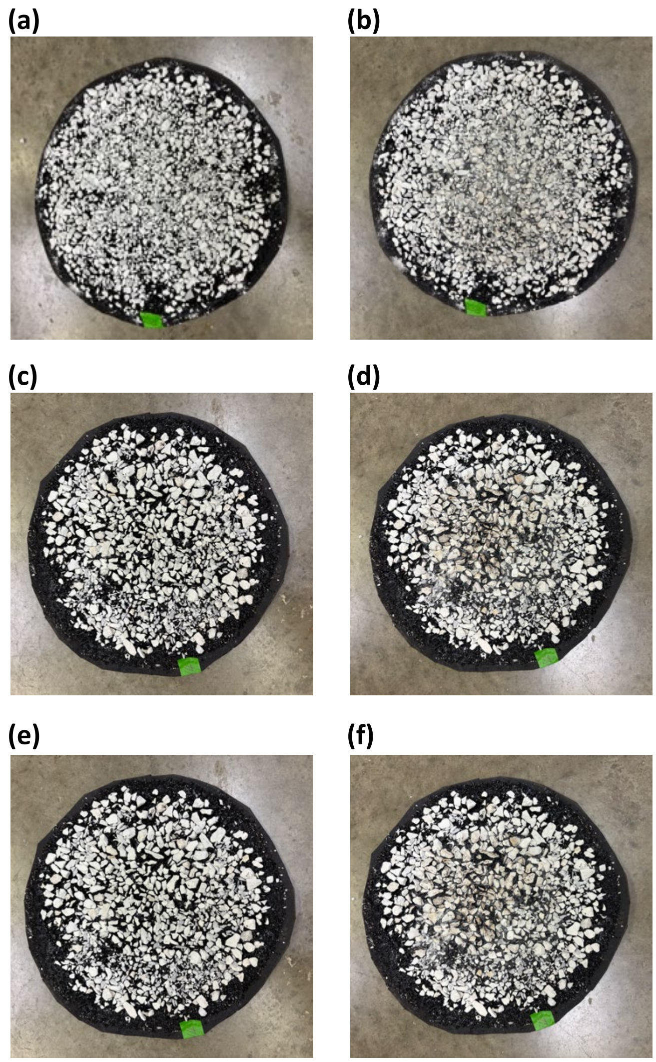

Figure 54. Photos. Double-layer Otta seal specimens: QB-5 (a) before and (b) after sweep testing, QB-2B (c) before and (d) after sweep testing, and typical Otta seal aggregate (e) before and (f) after sweep testing.

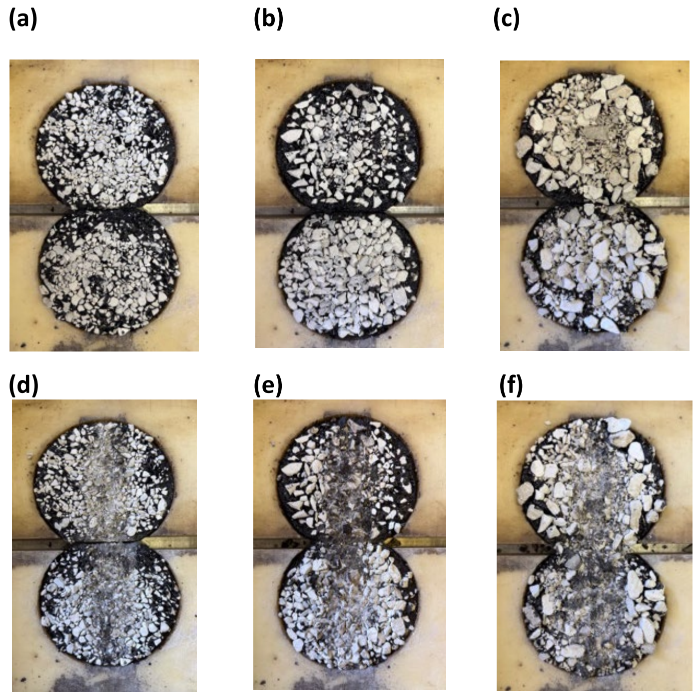

Figure 55. Photos. Specimens before and after HWT testing with locked wheel: before testing for (a) QB-5, (b) QB-2B, and (c) typical Otta seal aggregate and after testing for (d) QB-5, (e) QB-2B, and (f) typical Otta seal aggregate.

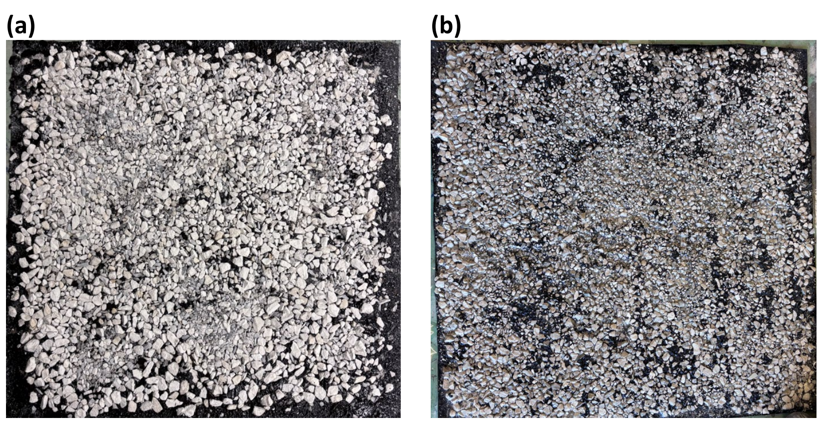

Figure 56. Photos. Specimen image (a) before and (b) after DFT testing

APPENDIX B: DYNAMIC FRICTION TESTER (DFT) RESULTS

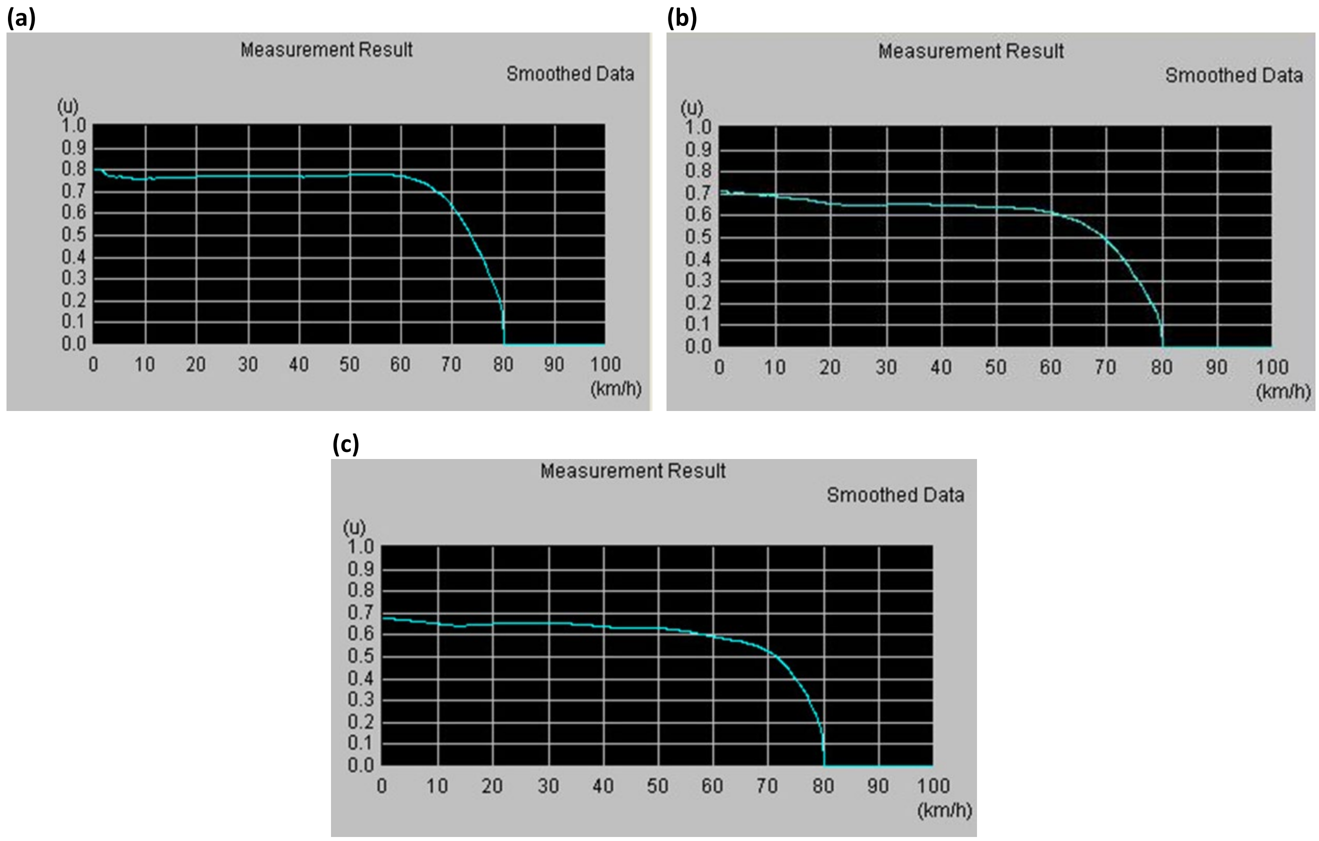

Figure 57. Graph. DFT results for (a) QB-5, (b) QB-2B, and (c) parking-lot surface.