MASTER OF ENGINEERING IN CIVIL ENGINEERING

Evaluation of Moisture Sensitivity of Hot Mix Asphalt Using Different Types of Materials and Additives.

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Munshi Ruhul Amin

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Declaration

This is to declare that the project work has been submitted here with in partial fulfillment of the degree of Master of Engineering in Civil Engineering. I hereby declare that the project work submitted has been performed by me and this work has never before been submitted for a degree elsewhere.

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Abstract

The damage due to moisture to asphalt concrete is a major concern, particularly in regions with high annual precipitation like Bangladesh. Stripping, or the loss of bitumen's adherence to aggregate particles is a frequent deterioration of bituminous pavement that is made worse by factors affecting like aggregate type, traffic loads, bitumen characteristics. It has been common practice to reduce moisture-related damage in hot mix asphalt (HMA) by adding liquid antistripping agents or mineral antistripping additives.

This study evaluates the moisture sensitivity of HMA using two commonly used aggregates in Bangladesh’s road construction are Source-A Stone Aggregate and Source-B Stone Aggregate and investigates the effect of two liquid antistripping additives, Type-A (Aminosilane) and Type-B (fatty polyamine condensate) and a mineral filler (cement) on the Moisture susceptibility of HMA. The research focuses on improvement of moisture susceptibility of HMA using those aggregate and Mixes were prepared with 0.06% Type-A, 0.1% Type-B and 1% cement as mineral filler and their performance was assessed using the indirect tensile strength (ITS) and Tensile strength (TSR) tests.

The results demonstrated improved moisture resistance for all additive-modified mixes compared to control samples, with TSR values increasing by 27%, 16% and 13% for cement, Type-A and Type-B additives, respectively. Cement filler exhibits the highest efficacy in enhancing moisture resistance, suggesting its significant potential for mitigating moisture damage in asphalt pavements. The findings highlight the importance of selecting appropriate additive systems to enhance the durability and performance of HMA in moisture-prone regions. The findings also provide valuable insights into interaction between commonly used materials and additives, offering practical solution for designing durable asphalt pavements in Bangladesh.

<u>Keywords:</u> Hot Mix Asphalt (HMA), moisture-induced damage, cement, mineral filler, liquid anti-stripping additives, Source-A Stone Aggregate, Source-B Stone Aggregate, Asphalt durability, moisture resistance, moisture susceptibility, indirect tensile strength (ITS), and tensile strength ratio (TSR).

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List of Abbreviations

HMA – Hot mix asphalt

IDT – Indirect Tensile test

ITS – Indirect tensile strength

TSR – Tensile strength ratio

DSR – Dynamic shear rheometer

OPC – Ordinary Portland cement

SCB – Semi-circular bending test

WMX – Warm mix additives

LAS – Liquid anti-stripping additives

F-T – freeze thaw cycle

RHD – Roads and highway department of Bangladesh

AASHTO – American association of state highway and transportation officials

ASTM – American Society for testing and materials

ACV – Aggregate crushing value

TFV – Ten percent finer value

LAA – Los Angeles abrasion

OBC – Optimum bitumen content

VMA – Void in mineral aggregate

VFA – Void filled with asphalt

PMB – Polymer modified bitumen

BRT – Bus rapid transit

BOGCL – Bashundhara oil and gas company limited

Chapter 1: Introduction

1.1 General

Moisture induced damage as one of the major concerns for asphalt pavements (Huang et al., 2010). Moisture damaged pavement can result to a failed pavement as the weakened pavement structure suffers from other types of damages such as rutting, potholes, and different types of cracking (Hamedi, 2017). Moisture damage occurs in asphalt pavements due to the separation of asphalt binder from the surface of the aggregate in the presence of moisture-commonly known as stripping thereby reducing the cohesion and integrity of the asphalt mixture (Hesami & Mehdizadeh, 2017).

In order to prevent moisture induced damage to asphalt pavements, several precautions are implemented. Hot mix asphalt is modified with liquid and mineral antistripping additives.

By interacting with aggregate surfaces and their polar ends, certain liquid antistripping agents, which are often a family of amine based chemicals, can increase the adhesion and affinity between asphalt binder and aggregate particles (Huang et al., 2010). As mineral or powdered antistripping additives, cement and hydrated lime are the most widely used antistripping additive in asphalt pavements. Due to its chemically active nature, hydrated lime is very effective in controlling water sensitivity (Little & Petersen, 2005). To evaluate moisture susceptibility of an asphalt mix, modified Lottman test (AASHTO T-283) are generally performed on mixes. Researchers observed that moisture susceptibility is dependent on the combination of types of aggregate, bitumen and additives used (Nazirizad et al., 2015).

Under this study, laboratory experiments have been conducted to investigate the effects of different cementitious fillers and liquid antistripping additives on moisture susceptibility of HMA mixtures through TSR test (AASHTO T-283). Knowledge gathered through this study will help Bangladeshi pavement engineers and contractors to select appropriate materials and additives for producing moisture resistant asphalt pavement.

1.2 Research Gaps and Justification

There are still a number of unanswered questions about moisture susceptibility in Hot Mix Asphalt (HMA), especially when it comes to the use of locally sourced ingredients and the interactions between various additives. Research on standardized materials has dominated since material properties show different patterns in Bangladesh while disregarding regional aggregate and binder specifications. Scientific research should evaluate local materials under different moisture conditions to demonstrate their specific requirements. Studies about multiple additive effects remain scarce while independent assessments of cement and hydrated lime show extensive research results. The development of local solutions for moisture-resistant asphalt formulations depends on researching the available spaces for improvement.

Engineers working in Bangladesh must rely on this research because moisture degradation substantially affects the longevity of asphalt pavement. The research investigates the water resistance characteristics of Bangladeshi paving materials and their response to various additive treatments in order to advance construction and design methods. Bangladeshi engineers must address existing research gaps to create distinctive asphalt mixtures which will achieve longer-lasting pavements and cheaper maintenance expenses and promote better roadway safety. This research investigation will lead to practical solutions which enhance both sustainability and performance quality of pavements.

Research into moisture resistance of HMA needs complete laboratory testing of Bangladesh local aggregates and binders to identify their specific moisture resistance characteristics. Additional scientific exploration into combined additive systems should establish combined effects among various fillers and modifiers to enhance moisture-resistant formula development. To evaluate how well asphalt mixtures with various additives function in harsh weather, long-term field research is also required. Additionally, new approaches to enhancing moisture resistance may be provided via creative additive development, such as nanomaterials or bio-based solutions. Particularly in areas that are prone to moisture, filling in these research gaps can greatly improve the performance and longevity of asphalt pavements.

1.3 Project Aims and Objectives

- Identify effect of aggregate type and gradation for moisture resistant pavement construction in the context of Bangladesh.
- Compare appropriate types of additives for HMA against moisture induced damaged of asphalt pavements.

1.4 Scope of the Project

This study has provided a suggestion to improving the moisture sensitivity of Asphalt pavements using different type's fillers (mineral antistripping additives) and liquid antistripping additives through TSR Test. It can be a guideline for practicing engineers on usage of antistrip additives and selection of aggregates for protection of pavement against moisture damage.

1.5 Project Outline

This project is comprised with six chapters with reference provided at the end. The chapters are as follows

1. Introduction
2. Literature review
3. Experimental procedure
4. Results and discussion
5. Conclusion

In the first chapter, Chapter 1, includes general short background related to improvement of moisture sensitivity of HMA using various types of cementitious filler, antistripping additives as liquid form. To evaluation of moisture sensitivity generally used modified lottman test. Additionally, it also describes aims, objectives and scope of the study. Chapter 2 contains different types of antistripping additives, cementitious filler, comprehensive description on previous related studies on effect of antistripping additives on HMA, improvement of moisture induced damaged of pavement, effect of cement filler on HMA, stripping of aggregate in presence of moisture and moisture sensitivity analyzing techniques over the years. Chapter 3 outlines the details experimental procedure to determine Asphalt concrete mixture strength through indirect tensile strength test (TSR) as modified lottman test, examining effect of different types of additives and cement with asphalt when contact in moisture. Different types of locally available aggregate gradation, job mix design, Marshall mix design to find out optimum Asphalt content. In Chapter 4, results with different graphs of TSR and tensile strength of HMA conditioning and un-conditioning state for various types of modification. Chapter 5 gives the conclusion and findings of this study work including avenues for future study.

Chapter 2: Literature Review

2.1 Introduction

Moisture sensitivity in hot mix asphalt (HMA) is a critical concern that significantly impacts the durability and performance of pavement structure. The sustainability of flexible pavement is significantly impacted by moisture degradation. Moisture induced damage is very common and crucial cause of loss of bonding between binder and aggregate, stripping and resulting failures of flexible pavement (Hamzah et al., 2015). Moisture damages also occurs when moisture allows to seepage through Asphalt concrete layer and repeated traffic load make it more susceptible to moisture damages (Little et al., 2003). The deterioration of HMA pavements includes alligator cracking although bleeding and rutting and raveling equally contribute to this condition through moisture sensitivity problems. Constructions having both low asphalt content and aged asphalt binder will tend to show surface aggregate loss known as raveling or water sensitivity. The main objective of this literature review explore mechanism of moisture damages, identify the factors influencing the moisture sensitivity, examine the role of materials and additives to enhancing moisture resistance and review the various testing method and case studies related to this topic. The findings from this experiment could be local guide to evaluating the efficiency of anti-stripping additives and cement filler to improving moisture resistance of HMA pavement in context of Bangladesh.

2.2 Process of Asphalt failure

High temperature and excessive moisture create major conditions which adversely impact the service life of HMA Pavements. Pavement failure will occur early if critical environmental conditions team up with inadequate materials combined with excess traffic volume. Failure typically happens because the asphalt binder washes off from aggregate particles. Three main mechanisms enable moisture to harm the HMA material structure:

1. Loss of Cohesion: The strength reduction of asphalt film depends on several different factors.
2. Failure of Adhesion: weakened the bond between binder and aggregate.

3. Separation of Aggregate particles: The weakening or fracturing of individuals aggregate particles when exposed to freezing conditions.

Figure 2.1: Raveling and pot hole of Pavement due to Moisture induced damage (Brown et al., 2001).

Aggregates with a strong tendency to absorb water often exacerbate stripping, as water replaces the asphalt binder on the aggregate surface. This stripping process reduces the quality of the mixture. Leading to pavement failures such as raveling, pothole (Fig 2.1) rutting or cracking. Asphalt mixture damage caused by moisture exists only when water successfully breaks through the asphalt mix composition. Full comprehension of moisture-induced damage processes helps identify and reproduce them within asphalt mixtures. Rainwater infiltration enables water to move freely through macro-pores in the asphalt wearing surface as depicted in figure 2.2(a). Open-graded mixes exhibit this effect because they are engineered for high permeability. Freezing moisture may become trapped inside the open spaces found within asphalt mixture composition. The substance exists either as liquid or vapor as illustrated in figure 2.2(b). Three factors contribute to moisture accumulation in asphalt-wearing surfaces: remaining water from rain precipitation as well as sponge-like subgrade saturation beneath the surface and exposure to high humidity. The aggregate preparation can contain preexisting moisture according to the illustration in figure 2.2(c).

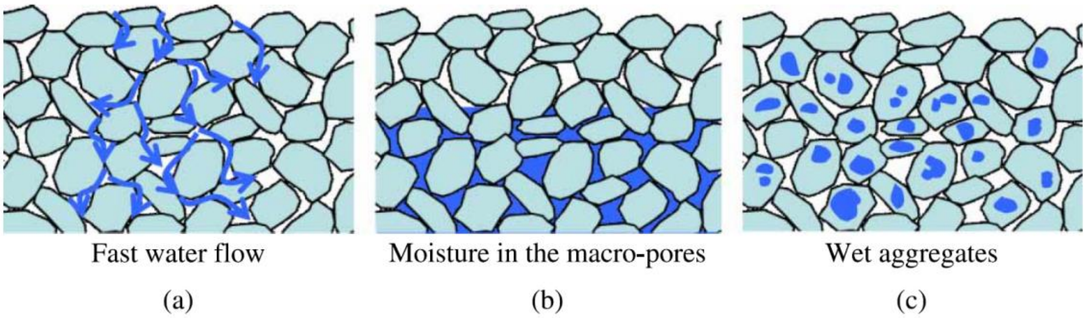

Figure 2.2: Moisture penetration into the asphalt mix *(Kringos et al., 2008)*.

Moisture–induced damage processes are divided into physical and mechanical processes: The physical processes considered significant contributors to moisture-induced damage include the molecular diffusion of moisture, which weakens both the asphalt and bond between the aggregate and asphalt. Additionally, high water pressures or rapid water flow can result in the erosion or washing of the asphalt, as illustrated in Figure 2.3(a).

Mechanical damage contributing to moisture-induced deterioration includes intense water pressure within the mix caused by traffic loads, leading to additional plastic deformation, a phenomenon known as "pumping action." These physical and mechanical processes interact and are incorporated into a constitutive model for overall moisture-mechanical damages, as shown in Figure 2.3(b).

Ultimately, moisture-induced damage results from the combined effect of physical and mechanical processes that weaken both asphalt and the bond between the aggregate and asphalt, as shown in Figure 2.3(c).

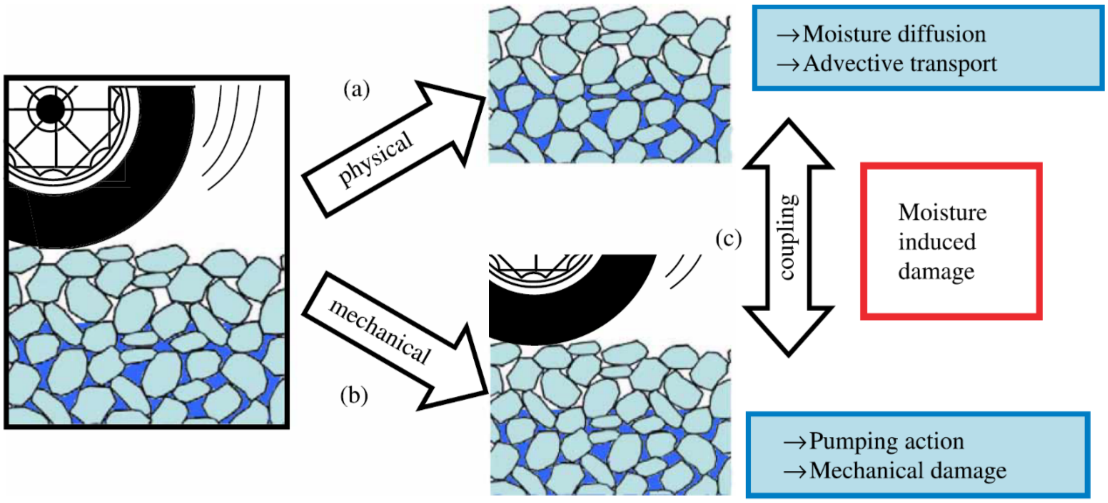

Figure 2.3: Combined action failure process of Asphalt *(Kringos et al., 2008).*

2.3 Factors Influencing Moisture Sensitivity

Moisture susceptibility represents a multifaceted phenomenon influenced by various mechanisms previously discussed. The intricate nature of these mechanisms and their interactions complicates the ability to accurately predict which specific characteristics will predominantly influence moisture susceptibility. Generally, any factor that elevates the moisture content within HMA, diminishes the adhesion between the asphalt binder and the aggregate surface, or physically erodes the asphalt binder tends to increase moisture susceptibility. While the factors outlined below each contribute to moisture susceptibility to varying extents, none can serve as definitive standard for reliable forecasting moisture susceptibility.

Moisture damage in asphalt pavements is influenced by several factors that can grouped into four main categories. These include:

1) Asphalt concrete characteristic, including aggregate, asphalt cement and type of mixture.
2) Weather during construction of pavement
3) Environmental effects after construction of pavements
4) Pavement surface drainage

2.3.1 Asphalt Concrete Characteristics

The characteristics of asphalt concrete that significantly influence moisture damage mechanisms include the properties of both the aggregate and the asphalt binder, as well as the type of mixture used. Aggregate characteristics play a crucial role in stripping resistance and include factors such as surface texture, porosity, mineralogy. Surface moisture, coatings and chemical composition, these properties determine the aggregate's ability to bond effectively with the asphalt binder and resist water infiltration. For asphalt binder, viscosity is an important factor to consider, as it affects he binder's ability to coat and adhere to the aggregate. However, the aggregate's properties are generally regarded as more critical in determining resistance to moisture damage, as they directly influence the adhesion between the binder and the aggregate surface.

Usually consider dense-graded asphalt mixtures to be more vulnerable to moisture-related damage than their open-graded counterparts. The close aggregate structure of dense-graded composites allows them to trap water within the matrix thus increasing the likelihood of stripping and other moisture-related failures. Open-graded mixtures offer better water drainage capabilities through their high permeability and thus minimize water-related damage. The excellent drainage capabilities of open-graded mixtures need designers to maintain strict attention to detail because poor maintenance could allow oxidation and durability problems to negatively affect the materials (Hicks. R.G., 1991).

The nature of asphalt chemicals determines how easily water will break down the material. Specific sulfoxides along with carboxylic acids exhibit high sensitivity towards water damage due to their chemical interactions with moisture (Kandhal et al., 1989).

2.3.2 Construction of Weather

Asphalt pavements become more prone to moisture degradation after construction when weather conditions present unfavorable environments. Moisture-related issues in pavements become more likely because autumns often bring cool and damp conditions to the construction site. A high air void mix content that occurs from poor compaction makes pavements more susceptible to damage because water can readily penetrate through the weak structure. The prevention of moisture-related damage to pavements depends on both proper compaction methods during specific weather conditions (Hicks. R.G., 1991).

2.3.3 Environments effects of Pavements construction

Stripping in asphalt pavements experiences major effects due to environmental elements which include traffic volume and climate patterns after construction. The asphalt-aggregate connection weakens because of temperature changes and freezes then thaws and wet-dry cycles resulting in moisture damage. The degradation processes occur mainly through water effects as they accelerate through hydraulic scouring from traffic cycles and pore pressure formation in addition to high traffic intensity that worsens moisture-induced stripping. Pavement lifespan extension alongside decreased effects of moisture damage strongly depends on thorough drainage system planning and design.

2.3.4 Surface drainage of pavements

The presence of water within pavements accelerates asphalt mixture deterioration because insufficient drainage systems allow water to remain trapped in the pavement structure. The Pennsylvania Department of Transportation has proved that stored moisture speeds up pavement damage so an efficient drainage system is essential to prevent such deterioration (Kandhal et al., 1989).

2.4 Steps to Prevent Moisture damage

The existence of moisture really damages how asphalt pavements function and their possibility of surviving. Several approaches can be used to resolve this issue. The strategies focus on both material modifications and design methods to address this problem. The following section details the evaluation of these performance approaches.

2.4.1 Methods based on design

Design-based techniques include strengthening asphalt pavements' structural integrity to increase their resilience to moisture damage. The foundation requires selection of proper aggregate sizes along with effective drainage components and waterproofing design elements. Accelerated interlocking between particles occurs when well-graded aggregates are chosen because this reduces voids and prevents moisture penetration (Arepalli et al., 2019). Constructing pavements with adequate drainage elements coupled with sufficient cross-slope will help minimize moisture-related problems (Hamedi et al., 2018). As a vital aspect of design-based techniques technicians spread tack coatings between asphalt layers to enhance their performance. The application of tack coat creates a stronger bond between layers at reduced risk for moisture intrusion which leads to better pavement condition (Ismael & Ismael, 2019). The durability of moisture-induced damage in materials increases due to flexible structural features which manage thermal expansion and contraction (Hamedi et al., 2018).

2.4.2 Moisture resistance improving agents

The introduction of additives becomes essential for asphalt mixtures to achieve moisture resistance. The additives enhance aggregate-asphalt binder bond strength which lowers the opportunity for moisture damage. Hot mix asphalt (HMA) shows the best performance improvement when using powdered additives which include cement and hydrated lime.

2.4.2.1 Liquid anti-stripping Additives based on amines

These hydrocarbon chains in amines function as the basis for their compatibility with asphalt products. Water introduces ionization that leads to positively charged amine ions named RNH3. Fatty amines allow modification of their physical characteristics by adjusting their structures. The hydrocarbon chain structure can be modified to adjust physical properties whereas chemical properties function according to the placement of amine groups in the molecule. The placement of amine groups in the molecule alongside the number of these groups allows adjustment of chemical properties. The structural adjustments to amines allow scientists to choose optimal chemical configurations for asphalt applications. The bond between fatty amines and aggregate surfaces improves through their reaction with exposed surfaces. The aggregate bonds to the amines while the hydrophobic chains from the molecule insert themselves inside the asphalt.

The chemical properties of fatty amines create a tough durable connection with asphalt as they embed into its structure (Little et al., 2003).

Amine-based additives perform as standard additives for enhancing asphalt binder adhesion capabilities. The compounds enhance surface energy at the binder-aggregate interface which leads to both stronger bond strength and reduced chance of moisture-based failures. Scientists have verified the effectiveness of amine-based additives that promote polar connections with aggregates particularly hydrophilic ones to combat moisture damage (Ji et al., 2012).

2.4.2.2 Cement's Function as an Additive and Filler

The addition of cement as both fillers and additives improves asphalt mixture moisture resistance. The mineral properties of cement function to both enhance the mixture stability and improve moisture resistance (Ali & Ismael, 2020). When cement fills empty spaces of aggregate structure it produces materials that become dense and tighter as well as cohesive. Because of its denser structure cement reduces the risk of stripping between binder and aggregate while limiting water from entering the area.

The cement's chemical elements which include calcium silicates contribute to improved binding strength of the mixture. The moisture resistance of Rigid Paving depends on the combined effects of cement along with bitumen and aggregates. When bitumen reacts chemically with cement through linkages both the adhesion strength increases and moisture-induced peeling reduces (Ahmed Ebrahim Abu El-Maaty Behiry, 2013).

2.4.2.3 Hydrated Lime

Hydrated lime stands as a widely used modification ingredient to protect asphalt mixtures from moisture damage. Processing hydrated lime effectively reduces moisture susceptibility because we need to understand the fundamental properties along with its chemical reactions with bitumen. When hydrated lime raises the interfacial surface energy it improves the bonding strength of bitumen. Asphalt mixture durability improves along with a reduced risk of moisture-related damage when hydration to lime improves bonding between asphalt components (Rahman, 2012). The chemical binding between asphalt binder and hydrated lime produces new stable connections which enhance moisture protection levels. Laboratory results show that asphalt mixes gain better protection against moisture damage when hydrated lime is added into their composition particularly during wetting-drying conditions.

2.5 Testing Methods for Moisture Sensitivity

Hot Mix Asphalt (HMA) displays a critical weakness that affects pavement deterioration during its early stages because of moisture susceptibility. Long-lasting durability of asphalt pavements depends on how effectively moisture susceptibility is analyzed. Several testing methods have been created to examine moisture susceptibility where each approach contains specific evaluation criteria and test steps. The section outlines extensive research on several testing methods.

The Moisture Sensitivity tests for Hot Mix Asphalt consist of two main categories namely the testing of loose mixtures for stripping and the testing of compacted mixes for stripping. Testing of compacted mixtures measures hardened specimen responses under conditions that mimic traffic activities and environmental elements but loose mixture testing measures binder-aggregate interface reactions with moisture presence. Table 2.1 provides the detailed description of methods to test compacted HMA mixtures' moisture sensitivity.

2.5.1 Techniques for evaluating stripping on loose mixtures

The test procedures conduct examinations at a quicker pace while being simpler to execute along with being cost-effective compared to tests on compacted specimens. These methods are accessible to execute since they need simpler equipment along with workflow procedures. A fundamental problem emerges from the researchers' insufficient consideration of key performance assessment elements which include mixture mechanical characteristics together with pore pressure and traffic action (Solaimanian et al., 2003). Techniques for evaluating stripping on loose mixtures samples are mainly,

1) Static immersion test (ASTM D1664/ AASHTO T182)
2) Boiling water test (ASTM D3625)

2.5.2 Techniques for evaluating stripping on compacted mixes

Modified Lottman test (AASHTO T 283) is widely used regarded as an effective method for investigating moisture damage and evaluating pavement materials due to its high predictive success rates (Hicks. R.G., 1991). However, Airey & Choi (2002) highlight that the immersion wheel tracker and the Hamburg wheel-tracking device are also popular choices for moisture damage assessment. A general review of these tests is provided, with compacted mixture test methods summarized in Table 2.1

Table 2.1: Popular Test methods to assess stripping on compacted HMA *(Omar et al., 2020)*.

Test Method	Measures	Short Description	Test Image	Reference
Immersion-Compression Test	The ratio of Compressive strength (wet/dry)	Determined compressive strength of the compacted asphalt mixtures kept water bath in 60°C for 24 h, 23°C for 4 h in wet and dry conditions.		AASHTO T165/ ASTM D1075

Marshall Stability Test	Marshall stability ratio (wet/dry)	Determined the ratio of Marshall stability for the compacted mixtures which are kept in water at 60^{o}C for 48 h.		AASHTO T245
Modified Lottman Test	Indirect tensile strength ratio (TSR), (wet/dry)	Sample conditioning: vacuum saturation should be 55% to 80%, wrapping with plastic film, kept sample -18^{o}C to -12^{o}C for 15 h, 60^{o}C for 24 h, 25^{o}C for 2 h.		AASHTO T283
Tunnicliff and Root test	Indirect tensile strength ratio (TSR), (wet/dry)	Similar to modified Lottman test.	Similar to modified Lottman test.	ASTM D4867

Humburg wheel-tracking test	Number of passes at the junction of the stripping slope and creep slope	Simulating traffic conditions on compacted mixes submerged in water at 25°C to 70°C using wheel tracking.		AASHTO T324
Immersion wheel-tracking Test	Measures failure time to determine for asphalt mixtures immersed in water	Simulating traffic conditions on compacted mixes submerged in water at 60°C for at least four hours using wheel tracking device.		MAT 62

2.6 Case Studies and Experimental Evaluations

Understanding moisture susceptibility in Hot Mix Asphalt (HMA) involves examining both international and regional studies to assess the effectiveness of materials and additives under varying climatic and environmental conditions. These studies provide valuable insights into strategies for enhancing moisture resistance. This section reviews significant global research findings alongside regional challenges, emphasizing the roles of cement mineral filler and liquid anti-stripping additives in mitigating moisture-related damage.

2.6.1 Case studies related to cement as mineral filler

A study conducted by Hossain (2022) explored the use of cement to improve the properties of Hot Mix Asphalt (HMA). The experts selected Source-B Stone Aggregate as an aggregate and determined asphalt mix design would need a 5.6% bitumen percentage. The addition of cement reached 0.50 percent at this stage. An improvement in Tensile Strength Ratio (TSR) allowed a measurement of moisture resistance to reach 85.03% indicating better durability and resistance to moisture susceptibility.

Huang et al. (2010) analyzed how three types of hydrated lime when combined with fly ash and cement kiln dust alongside five cementitious fillers would affect moisture sensitivity in hot mix asphalt (HMA). The use of finer hydrated lime particles produced outstanding moisture resistance based on testing methods that included dynamic modulus and Superpave IDT and TSR and DSR which each yielded TSR values above 80%. The study showed cementitious fillers strengthen the bond between asphalt binder and aggregates which creates a more resistant material structure against water damage.

Wang et al. (2018) showed that asphalt-to-aggregate ratio at 5.0 gave the best cement filler performance in asphalt mixtures. Evaluation of the mixture performance required four different testing methods including permeability tests together with dynamic stability tests alongside immersion Marshall stability tests and freeze-thaw splitting tests. The results showed excellent resistance to moisture attacks through TSR reaching 74.4% and achieving stability at 78.9%. Results from testing show that asphalt mixtures with cement fillers achieve superior standards or exceed them which leads to better performance and longevity as high-performance pavement solutions.

Guha & Assaf (2020) showed that Ordinary Portland Cement (OPC) functions as an effective filler material within hot-mix asphalt (HMA) to enhance its performance characteristics in hot temperatures. Researchers tested B60/70 bitumen mixed with low-quality aggregates along with 0%, 2%, 4% and 6% OPC levels to verify better mix stability and reduced flow and severe rutting reduction. Asphalt mixes that included 6% Ordinary Portland Cement showed improved rutting resistance together with stability and moisture resistance and presented an economical means to boost asphalt performance under hot dry conditions.

2.6.2 Case studies pertaining to anti-stripping liquids

Hesami & Mehdizadeh (2017) conducted research on liquid amine-based anti-stripping agents in hot mix asphalt (HMA) by employing TSR and SCB tests during production simulation in a plant facility. The findings demonstrate that after extended heating during manufacture, these compounds' efficacy dramatically declines. While these agents perform well in laboratory conditions (AASHTO T283), their effectiveness diminishes under actual plant conditions, with anti-stripping effects nearly eliminated after one day of production and storage at high temperatures. Polyamine additives proved more effective than amidoamine agents, with 0.4% being the optimal dosage for polyamine agents. The study recommends reevaluating manufacturer-suggested dosages for practical application.

Watson et al. (2013) assessed three anti-stripping agents—liquid additive (LAS), hydrated lime, and warm-mix additive (WMX)—in asphalt mixtures under severe conditions. Field and lab samples were tested using freeze-thaw cycles, Hamburg wheel tracking, dynamic modulus, and flow number tests. Hydrated lime demonstrated the highest tensile strength and TSR, consistently meeting the 80% TSR threshold, while WMX failed after five or more freeze-thaw cycles but improved in strength over time. LAS had the lowest performance across tests. The study concluded that hydrated lime is the most effective for moisture resistance under extreme conditions.

Nazirizad et al. (2015) study evaluated the effects of hydrated lime and a liquid anti-stripping agent (Iterlene In/400-S) on the moisture susceptibility of hot mix asphalt (HMA). Using the boiling water test (ASTM D3625) and Modified Lottman test (AASHTO T283), samples were tested with varying dosages: 0.2%, 0.3%, and 0.4% for the liquid additive, and 1%, 1.5%, and 2% for hydrated lime. Results showed that both additives improved moisture resistance, increasing TSR by 13% and 16%, respectively. However, mixtures with the liquid anti-stripping additive exhibited better correlation and resistance to water damage compared to control mixes and those with hydrated lime.

Hamedi et al. (2019) examined that the impact of two liquid anti-stripping additives on the performance of asphalt mixtures using limestone and granite aggregates with varying moisture sensitivity. Testing included AASHTO T283 under 1, 3, and 5 freeze-thaw cycles, as well as performance evaluations for fatigue and rutting. Results showed that liquid anti-stripping additives significantly reduced moisture damage, with their positive effects increasing under more freeze-thaw cycles. The additives also improved fatigue life without negatively impacting rutting or cracking resistance. The mixture with 0.2% Additive B produced the highest indirect tensile strength ratio primarily when used with granite aggregates.

Park et al. (2017) demonstrated that liquid antistripping additives based on aliphatic amines at 0.5% binder weight enhanced moisture resistance together with rutting performance compared to alternative agents. The effectiveness of these solutions was verified through boiling water tests as well as TSR and Hamburg wheel tracking assessments with additional improvements coming from 2% mineral powder additions.

Hamedi (2017) determined the effectiveness of Wetfix N422 and Wetfix 312 liquid anti-stripping additives for HMA moisture protection. Researchers examined samples subjected to 1, 3 and 5 freeze-thaw processes through using quartzite and granite and limestone aggregate combinations. The experimental outcomes showed that the additives enhanced indirect tensile strength (ITS) and tensile strength ratio (TSR) in wet and dry conditions and established better resistance to moisture. Specimens with limestone aggregate coupled with Wetfix 312 achieved superior performance through highest TSR values compared to Wetfix N422 under elevated freeze-thaw testing. The effectiveness of these additives depends on the binder type together with aggregate material and operational dosage levels.

Rashid (2022) provided evidence regarding how Zycotherm (0.12%) and Wetbond-S (0.08%) demonstrated effectiveness towards reducing stripping in HMA. Laboratory tests, including boil and stripping value tests, showed that Zycotherm increased retained coating by 12.95% and Wetbond-S by 14.12%. Retained Marshall Stability improved by 10% with Zycotherm and 9% with Wetbond-S. Both agents enhanced durability, with Zycotherm proving more effective overall. These dosages were recommended for optimal stripping resistance.

Singh et al. (2017) evaluated that the impact of 0.1% Zycotherm additive on bitumen and bituminous concrete mixtures. The results showed minimal effects on Marshall Stability and Indirect Tensile Strength (ITS), but slight improvements in conventional properties, such as increased softening point and reduced penetration. Rheological tests revealed a decrease in bitumen viscosity at higher temperatures, which could lower mixing temperatures and energy consumption. Zycotherm helped lower the mixing temperature, perhaps saving energy during production, but it had minimal effect on rutting and fatigue resistance.

Chapter 3: Experimental Procedure

3.1 Materials

To run this experiment, require two types of available stone aggregates are Source-A Stone Aggregate (appearance light gray, basalt) and Source-B Stone Aggregate (appearance black, basalt). All of stone has different in sizes and gradation. Also needs two types of anti-stripping liquid additives name Type-A and Type-B has been mixed with bitumen modification and subsequently with HMA. Another additive is Portland cement has been used as filler with HMA. Total works summary has been showed at a glance in Fig 3.1.

Experiment flow chart Diagram

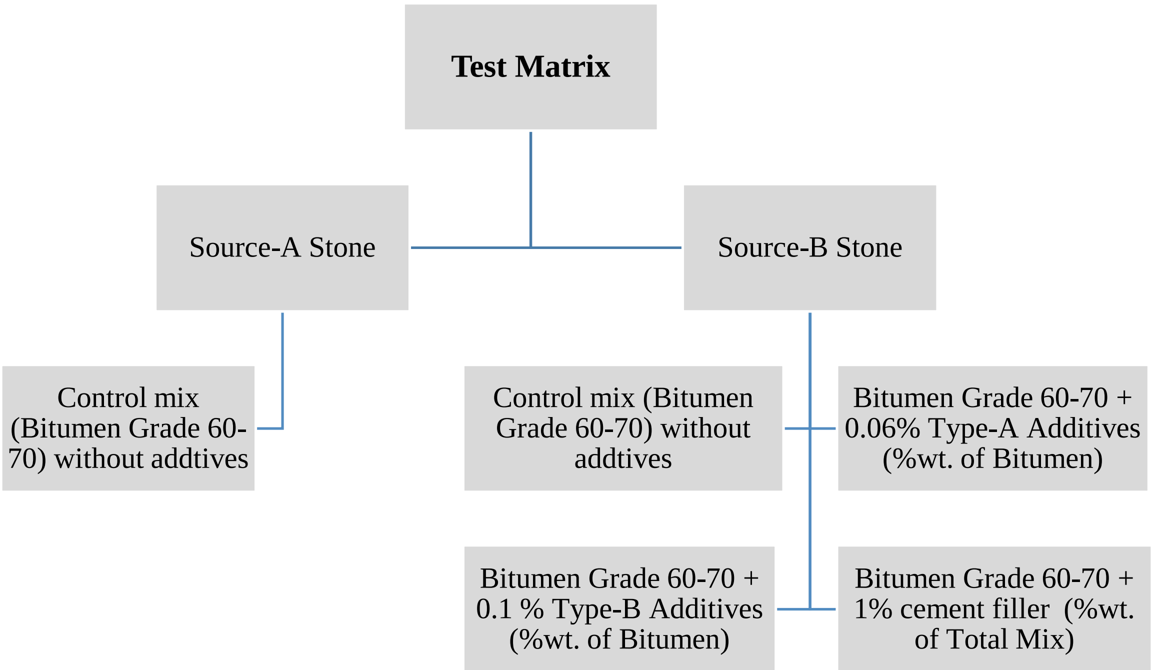

Figure 3.1: Experiment flow chart Diagram

3.2 Aggregates

Two different source of aggregates has been collected in this study which are different in size, color and texture. All these types of aggregate are commonly used in Bangladesh for construction of pavement. First completed all types and sizes of aggregate individual gradation for combined aggregate gradation. Source-A Stone Aggregate are 4 sizes (Fig 3.2) and Source-B Stone Aggregate are also 4 sizes (Fig 3.5) available in this experiment. 10X Magnifying Microscope Image (Fig 3.3 and Fig 3.4) for Source-A Stone Aggregate and (Fig

3.6 and Fig 3.7) for Source-B Stone Aggregate found from Carl Zeiss Axioscope5.0 to visual observation of surface texture. It has been observed that Source-B Stone Aggregate contain high feldspar & pyroxenes and has a fine grain black more homogenous with smoother surface. Source-A aggregate contain mineral such as plagioclase and pyroxene which exhibited variety of crystalline with gray to dark gray rough surface. Aggregate characteristics are summarized in Table 3.1 and Table 3.2 for Source-A Stone Aggregate and Source-B Stone Aggregate respectively.

Figure 3. 2 Source-A Stone Aggregate

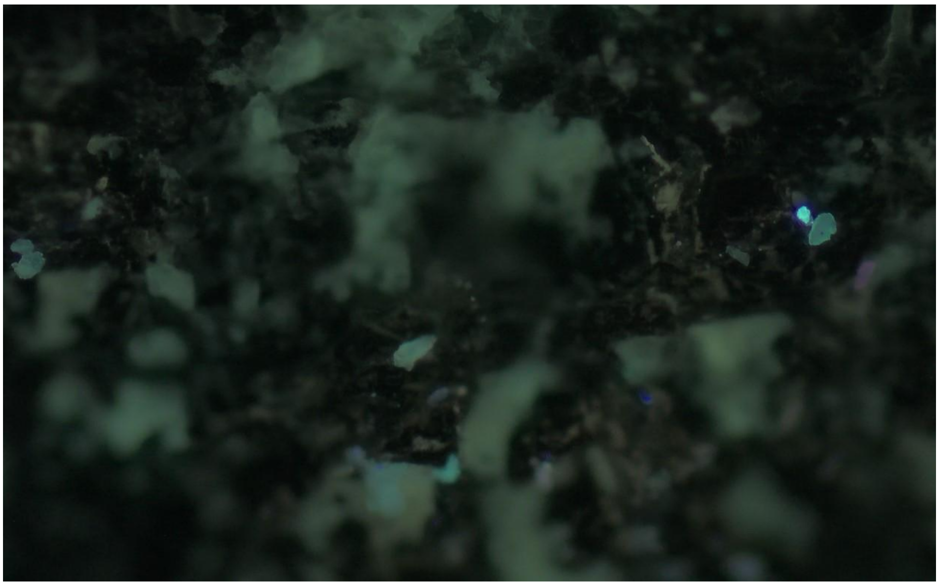

Figure 3. 3 10X Magnifier Microscopic Image Source-A Stone Aggregate

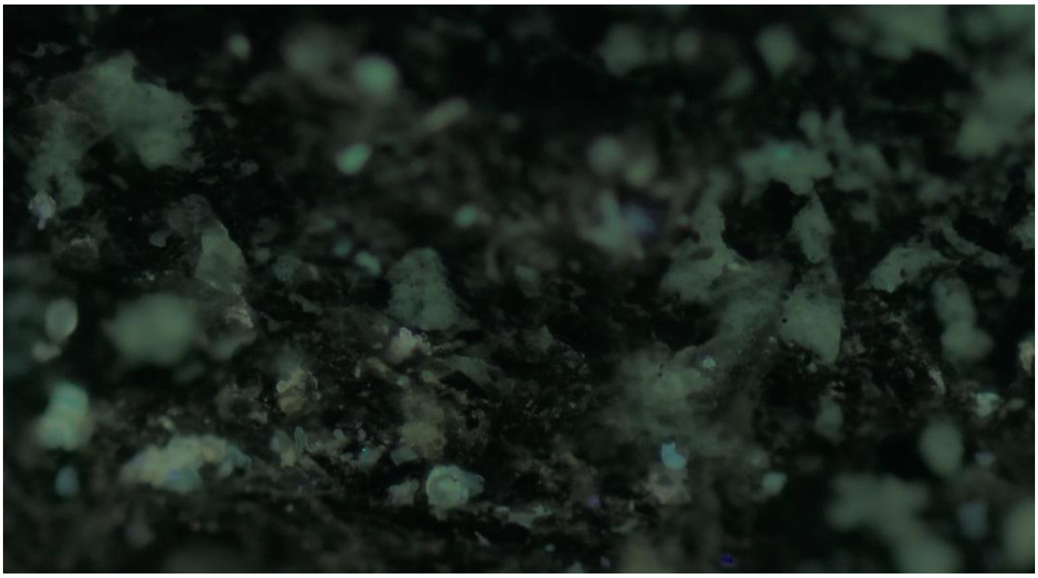

Figure 3. 4 10X Magnifier Microscopic Image Source-A Stone Aggregate

Figure 3. 5 Source-B Stone Aggregate

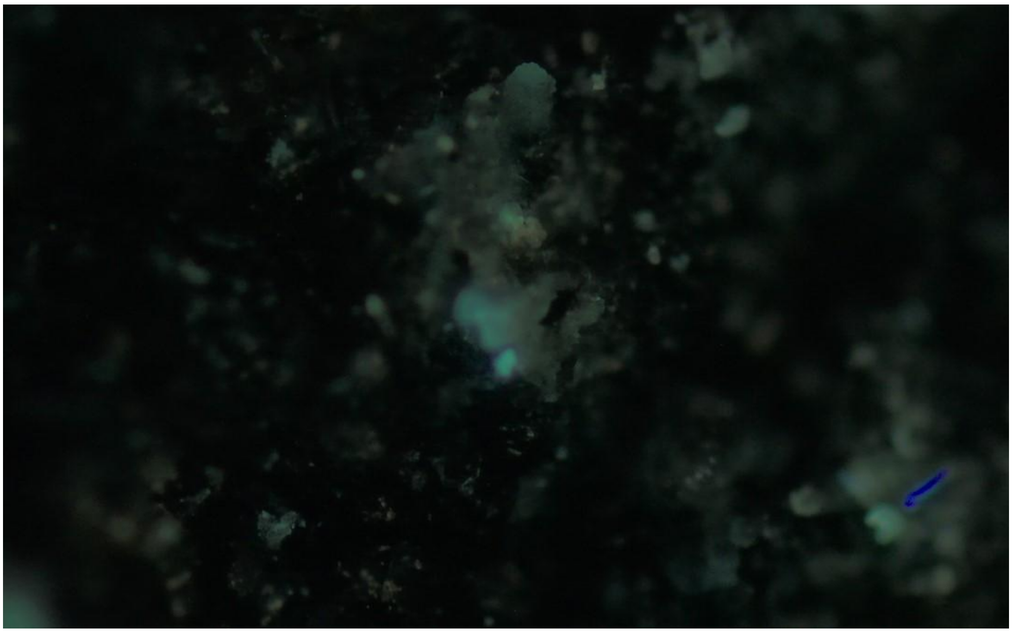

Figure 3. 6 10X Magnifier Microscopic Images of Source-B Stone Aggregate

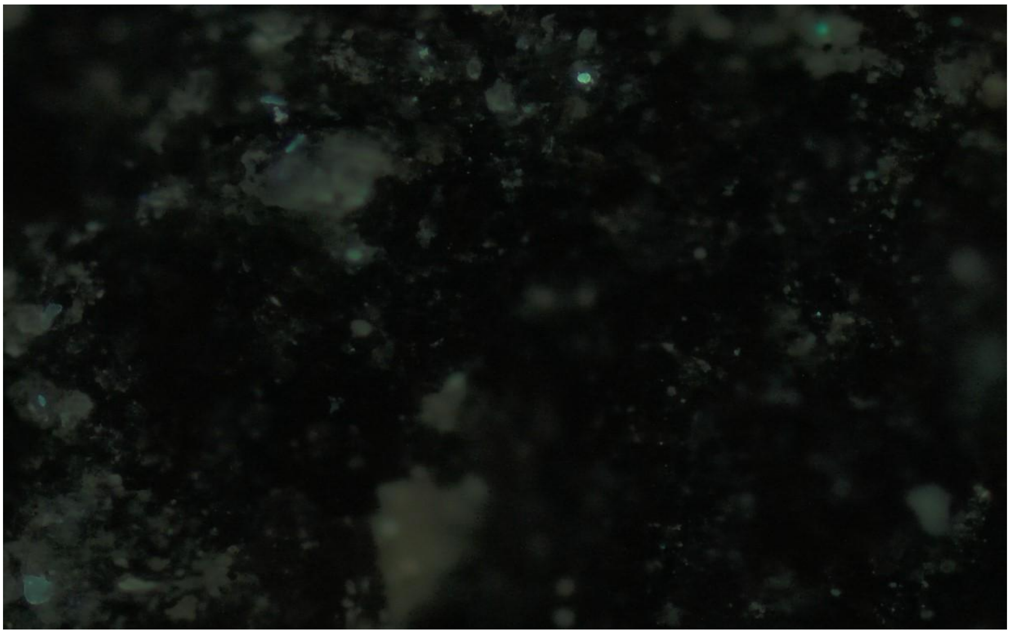

Figure 3. 7 10X Magnifier Microscopic images of Source-B Stone Aggregate

Table 3.1: Quality Test of Source-A Stone Aggregate

Sl. No.	Name of Tests	Results	Unit
01	Aggregate Crushing Value (ACV)	14	%
02	Ten percent fines value (TFV)	277	kN
03	Flakiness Index	16	%
04	Broken face	100	%
05	Average Water Absorption	1.11	%

(Sourced: Greater Dhaka Sustainable Urban Transport Project (BRT, Gazipur-Airport), Client: RHD, Consultant: SMEC Int. Pvt. Ltd, Contracor: China Gezhouba Group Co., Ltd)

Table 3.2: Quality Test of Source-B Stone Aggregate

Sl. No.	Name of Tests	Results	Unit
01	Aggregate Crushing Value (ACV)	17	%
02	Ten percent fines value (TFV)	296	kN
03	Flakiness Index	17	%
04	Broken face	100	%
05	Loss Angeles abrasion (LAA)	16.0	%
06	Average Water Absorption	1.28	%

(Sourced: Road Construction of Kuril Flyover to Kanchon Bridge Intersection, Client: 24 ECB, Bangladesh army, Contractor: BBL-BTC-MLB JV)

3.3 Antistripping additives

To improve moisture sensitivity different types of antistripping additives can be used. Some of available liquid form whereas others are found powder form in market. Additives react with binder organic acid and create strong coating with aggregate which can resist moisture induced damaged of pavement.

3.3.1 Additives (Type-A)

This additives (Fig 3.8 Type-A) improve bitumen adherence and create a long-lasting chemical link with the aggregate. There are notable improvements in the pavements resistance to moisture, longevity and total life cycle costs because of the permanent nature of the chemical connection that is created. Properties of the additives are in table 3.3

Table 3.3: Physical and chemical properties of Additives (Type-A)

Commercial name	Chemical name	Appearance	Dynamic viscosity @30^0C	Specific gravity	odor	PH
Type-A	Aminosilane	Golden yellow transparent	100 to 500 CP	1.110	Slightly sweet	Slightly acidic

(Sourced: product data sheet).

3.3.2 Additives (Type-B)

Additives Type-B (Fig 3.8 Type-B) is a next-generation, silicon-based anti-stripping additive for asphalt, developed using advanced nanotechnology. This innovative product leverages silicon molecular chemistry to form non-reversible covalent bonds between bitumen and the silica present in road aggregates. The molecular-level bonding achieved by one of the strongest known in modern chemistry, offering exceptional resistance to high temperatures and water, making it highly effective in enhancing the durability of asphalt pavement. Physical and chemical properties of this additives are in table 3.4

Table 3.4: Physical and chemical properties of Additives Type-B.

Commercial name	Chemical name	Appearance	Dynamic viscosity @30⁰C	Specific gravity	Odor	PH
Type-B	Fatty polyamine condensate	Dark Brown Liquid	NA	0.95	Ammonical	Slightly acidic

(Sourced: Product data sheet).

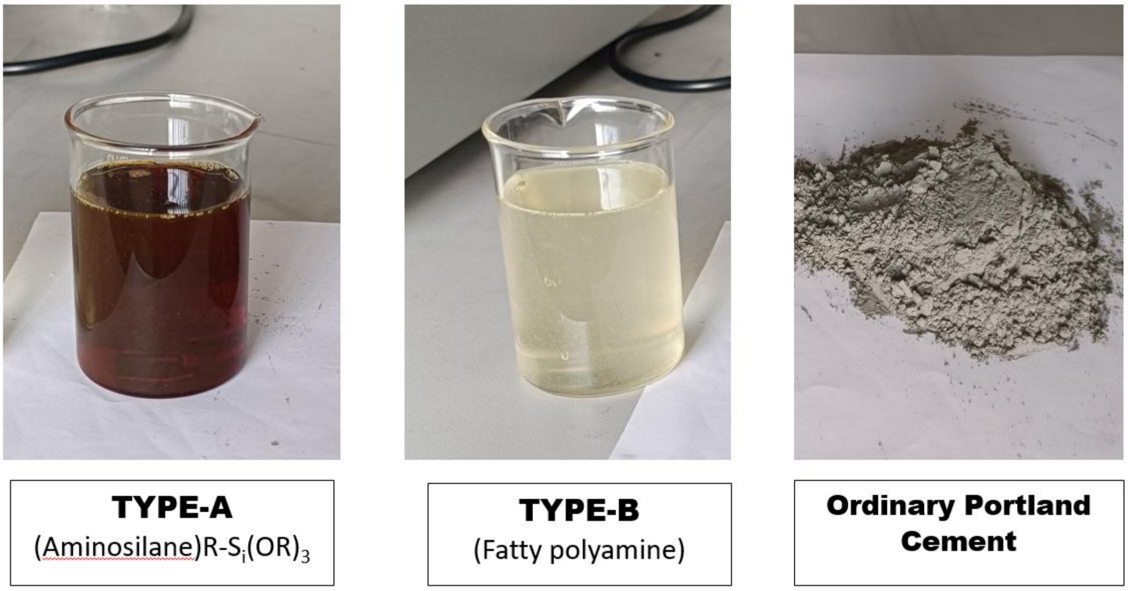

Figure 3. 8 Different types of Additives and filler

3.3.3 Additives (Cement filler)

The properties of cement filler (Fig 3.8 Portland cement) are used in this experiment are tabulated below Table 3.5, Cement used as a substitute portion of mineral filler in asphalt concrete mixing. Cement imparts high moisture resistance in HMA when contact in moisture and gives strength while cement hydrated in contact with moisture.

Table 3.5: The basic properties of cement filler

Properties	**Values**
Specific Gravity	3.12
Normal Consistency	29%
Initial Setting time	65min
Final Setting time	275 min
Fineness	330 kg/m^2
Soundness	2.5mm
Bulk Density	830-1650 kg/m^3

3.4 Bitumen

The following property of binder table 3.6 has been used in this experiment. Bitumen Grade 60/70 were collected from BOGCL laboratory.

Table 3.6: Properties of bitumen

SL No.	Name of the Test	Test Condition	Results
01	Penetration	25^0C, 100g, 5 sec	64.8
02	Softening Point	Ring & ball	49.1 ^{0}C
03	Ductility	25^0C, 5 cm/min	100+ cm
04	Flash Point & Fire Point	Cleveland open cup	300^0C & 360^0C
05	Specific Gravity	25^0C	1.028
06	Loss on Heating (TFOT)	5 Hours, 163^0C	0.03%
07	Solubility	Trichloroethylene	99.5 %

3.5 Bitumen Modified with liquid anti-stripping additives

To improve moisture sensitivity of HMA needs to modify the base bitumen with suitable anti-stripping additives. In this study two liquid anti-stripping additives used to improve TSR value. Before mixing with aggregate bitumen mixing with additives with proper described process provided by manufacturer. Depends on different types of aggregate and moisture content dosages of anti-stripping additives should be selected.

3.5.1 Mixing process of Type-A additives with bitumen

The aggregate and bitumen create a permanent chemical link, which improves adherence to bitumen, in contrast to traditional antistrips that only create a weak physical bond. The chemical bond that is created is permanent, which results in notable improvements in the pavement's resistance to moisture, longevity, and total life cycle costs. As an environmentally benign, non-corrosive, and odorless addition, Type-A is compatible with all types of aggregate and operates at far lower dosages than traditional antistrips.

The dosages of this additives selected 0.1% w/w of bitumen stirred for 30 minutes after dosing at a temperature 140-145 ^{0}C. Stored it to use in HMA mixing.

3.5.2 Mixing process of Type-B additives with bitumen

This is a very heat-resistant, low-dosage additive that can be used in both warm-mix and hot-mix road construction. Aggregates with extremely high and difficult-to-control stripping profiles are particularly well suited for this product.

Type-B additive can be conveniently mixed with hot bitumen by following methods. First heat the raw bitumen at temperature 135-140 ^{0}C, then add 0.06% w/w of bitumen. Mixing with stirred for 30 minutes. This modified bitumen can be used directly with HMA mixing as per job mix design.

3.5.3 Cement as a filler

Ordinary Portland cement(OPC) has been used as mineral filler materials additionally with stone dust. Mixing 1% of cement with stone dust in HMA.

3.6 Evaluation of TSR improvement using different additives and fillers

This section explores method to enhance the tensile strength ratio (TSR) of hot mix asphalt (HMA) pavements. The study evaluated various combinations of aggregate, bitumen, anti-stripping additives and cement filler to improve the moisture sensitivity of the HMA layer. A series of trials were conducted under this experiment using two different types of anti-stripping additives and one cement filler are tabulated in Table 3.7. All possible combinations were tested to identify effective measures for reducing stripping potential and increasing moisture resistance.

Table 3.7: Trial Matrix for TSR of Both Type of Aggregates.

Trail No.	Aggregate Type	Aggregate-additive condition	Bitumen and Additives	Required No. of Specimen (wet/dry)
Trial 01	Source-A Stone Aggregate	Same aggregate	Bitumen Grade 60-70 (Control Mix) without additive	6
Trial 02	Source-B Stone Aggregate	Same aggregate with varied additive	Bitumen Grade 60-70 (Control Mix) without additive	6
Trial 03	Source-B Stone Aggregate		Bitumen Grade 60-70 + 0.06% Type-A	6
Trial 04	Source-B Stone Aggregate		Bitumen 60-70 + 0.1 % Type-B	6
Trial 05	Source-B Stone Aggregate		Bitumen Grade 60-70 + 1% Cement filler	6
			Total No. of specimen for TSR Test (wet/dry)=	30

Each combination was tested to determine its impact on improving the TSR, with a focus on understanding the effectiveness of the anti-stripping additives and filler. The results provided insights into the most effective materials and combinations for enhancing the moisture resistance and durability oh HMA pavements.

3.7 Aggregate Gradation

Aggregate gradation is a critical step in the design of hot mix asphalt, ensuring the aggregates fit within specified size distributions to provide durability, stability, and proper compaction. The stone aggregate has been collected from different source and sizes. Firstly, all the aggregates have been sieved according to AASHTO T27 individually to find the gradation following the guideline RHD Specification. Sieve sizes for fine and coarser aggregate are 25.0 mm, 20.0 mm, 14 mm, 10 mm, 5 mm, 2.4 mm, 1.2 mm, 600 µm, 300 µm. 150 µm, 75 µm. all of the sieve analysis reports are included in the Appendix-I.

3.8 Combined Aggregate Gradation

Combined aggregate gradation involves blending different aggregates to meet the target graduation requirements of the specified HMA mix. This ensures optimal packing, stability, and durability of HMA.

Use the weighted average formula to calculate the percentage passing for each sieve in the combined blend:

$P=\sum(P_i \times W_i)$

Where:

P =Percentage passing of the combined blend on a specific sieve.

P_i =Percentage passing for individual aggregate on that sieve.

W_i =Proportion of each aggregate in the blend (in decimal form).

Table 3.8: RHD Sieve sizes and weight passing for Base Course of HMA.

Mix Classification	1	2	3
Course	**Base**	**Base/Wearing course**	**Wearing Course**
Thickness (mm)	**60-75**	**40-60**	**40-50**
Sieve Size (mm)	**Total % by weight Passing (including filter)**		
25	100	- - -	- - -
20	90-100	100	100
14	-	85-100	85-100
10	55-82	65-90	70-90
5	35-57	45-65	52-72
2.4	20-40	25-45	40-58
1.2	15-33	15-35	30-48
0.600	10-26	12-30	20-38
0.300	6-20	9-20	14-28
0.150	5-13	5-15	8-20
0.075	3-7	3-7	6-10
	Bitumen Content by total weight of mixture. Percentage by weight found by analysis		
	4.0-6.0	4.5-6.5	5.0-7.0

Source: General specification, RHD, July 2011.

All the three types of aggregate blend separately with their own available sizes by trial and error procedure until they have not meet the required base binder asphalt concrete gradation of RHD Table 3.8. All data and graphs of Combined and individual gradation of Source-A Stone Aggregate and Source-B Stone Aggregate are separately included in Appendix-I.

3.9 Job Mix Design

The job mix design process establishes the optimal combination of aggregates, asphalt binder, and additives to achieve the required performance criteria for a specific pavement application.

The mix design process involves three basic steps:

1. Selecting the aggregate
2. Selecting the asphalt binder
3. Determining the optimum asphalt binder content

Job Mix design basically named Marshall Mix design by which determined optimal bitumen content considering various types of parameters has been meet specified limits. In this experiment, considered RHD marshal mix design specification tabulated below Table 3.9 Desired properties of Marshal mix.

Table 3.9: Desired properties of Marshall mix

Test Parameters	**RHD Specifications**	**Units**
Marshall Stability @ 60^0C	Not less than, 550	kg
Marshall Flow	2 – 4	mm
Air Void %	3 - 5	%
Void Filled with Bitumen	65 - 80	%

3.10 Determination of Optimum Bitumen Content(OBC)

The process of determining the job mix formula for an asphaltic concrete surface course involves establishing the optimum bitumen content for the mix. This bitumen content must comply with the specified limits outlined in the mixture composition requirements. To determine the optimum bitumen content, laboratory procedures involve preparing trial mixtures using the selected aggregates combined with varying percentages of bitumen, staying within the specified limits. Each trial mixture is prepared to achieve maximum density, representing the highest practically attainable densities in both laboratory and field conditions. The density, stability, and other properties of each trial mixture are then measured and recorded for analysis.

3.11 The Marshall Method of Asphalt Concrete Design

The Marshall test procedure have been standardized by the ASTM D1559. Only hot mixtures with bitumen penetration grade and aggregate no larger than 25 mm can use this procedure. The Marshall method uses standard test specimen 63.5 mm high and 101.6 mm in diameter. They are made by heating, mixing, and compacting the asphalt aggregate mixture according to a defined process. Preparation of Marshall specimen and required calculation to mix design for Base course are described step by step below.

3.12 Preparation of test specimen

In Marshall method, it is very essential that the gradation of the aggregate and the quantity of bitumen be very carefully controlled. In this experiment bitumen content fixed with trial basis varying range with 4.5 % to 6.0 % of total mixture. Bitumen content 0.5% increments of different trial mix to find out the optimum bitumen content regarding maximum density, maximum stability and 4% air void. Each Marshall specimen weight 1200 gm required and minimum 3 sample required for each bitumen content for testing purpose.

First all sizes of Source-A Stone Aggregate and Source-B Stone Aggregate heated oven 110^{0}C for 2 to 3 hours or until reached constant mass. Cool at room temperature and then weighted 1200 gm aggregate including bitumen weight according to previously fixed up combined aggregate blending. Then heated the aggregate up to 165^{0}C and bitumen heated separately (Fig 3.9).

Figure 3. 9 Aggregate and bitumen heated in oven 165^{0}C

Figure 3. 10 Asphalt concrete Mixture machine

Then mixed with laboratory asphalt concrete mixture machine (Fig 3.10). The mixing and compaction temperature of asphalt mixture has been set by calculating temperature against viscosities 170±20 and 280±30 centistokes kinematic respectively. During mixing of asphalt applied rotation 180 nos. in 3 minutes. After complete mixing of aggregate with bitumen (Fig 3.11), mixture has been placed in preheated specified mold with 1200 gm. Then specimen has been compacted with standard mechanical hammer which weighs 4.5 kg and designed to drop a height of 457 mm (Fig 3.13). A compactive effort of 50 blows is applied considering medium traffic category for both side of specimen. After compaction of specimen cured for at least 24 hours before test (Fig 3.12).

Figure 3. 11 Asphalt loose mixture

Figure 3. 12 Marshall Specimen

Figure 3. 13 Marshall Compactor

3.12.1 Compute the aggregate's bulk specific gravity

When the aggregate is composed of distinct fractions of mineral filler, fine aggregate, and coarse aggregate, each with a distinct specific gravity, the bulk specific gravity of the aggregate G_{sb} is determined using the following formula Eq. 3.1:

$$G_{sb} = \frac{P_1 + P_2 + P_3}{\frac{P_1}{g_1} + \frac{P_2}{g_2} + \frac{P_3}{g_3}} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.1)$$

The proportion weight of coarse aggregate, fine aggregate, and mineral filler is denoted by P_1, P_2, and P_3, correspondingly.

g_1 is the bulk specific gravity of coarse aggregate, as determined by AASHTO T85 or ASTM C127.

g_2 is the fine aggregate's bulk specific gravity as determined by ASTM C128 or AASHTO T84.

g_3 is the mineral filler's apparent specific gravity as determined by ASTM D854 or AASHTO T100.

3.12.2 Compute the aggregate's effective specific gravity.

With the exception of those that absorb asphalt, all of the vacant spaces in the aggregate particles are included in the aggregate's effective specific gravity (G_{se}). It is computed by this formula Eq. 3.2:

$$G_{se} = \frac{P_{mm} - P_b}{\frac{P_{mm}}{G_{mm}} + \frac{P_b}{G_b}} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.2)$$

In Which,

P_{mm}, is the total loose mixture expressed as a percentage of the mixture's total weight.
P_b, Bitumen (percentage of mixed weight)
G_{mm}, is the paving mixture's highest specific gravity (air void excluded). ASTM D2041

G_b is the Bitumen specific gravity; AASHTO T228 or ASTM70

3.12.3 Compute the Asphalt absorption of the Aggregate

Absorption is given as a percentage of aggregate weight. This Eq. 3.3 is used to determine the absorption Pba:

$$P_{ba} = 100 \frac{G_{se} - G_{sb}}{G_{sb}\, G_{se}}\, G_b \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

Where, $\mathbf{P_{ba}}$ is the percentage of aggregate weight that is absorbed by asphalt.

3.12.4 Compute the paving mixture's effective asphalt content

After some asphalt is lost by absorption into aggregate particles, the amount of the total asphalt content that is left as a coating on the outside of the aggregate particles is known as the effective asphalt content, or Pbe. It is computed using the following formula Eq. 3.4:

$$P_{be} = P_b - \frac{P_{ba}}{100}\, P_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

Where, $\mathbf{P_{be}}$ is the effective asphalt content expressed as a percentage of the mixture's total weight.

$\mathbf{P_s}$ is % of aggregate (% by total mixture)

3.12.5 Compute the percentage of void in the mineral aggregate (VMA)

The inter-granular empty area between aggregate particles in a compacted paving mixture, including air voids and the effective asphalt content, is known as the void in the mineral aggregate. It is stated as a percentage of the whole volume. The VMA is a percentage of the bulk volume of the compacted paving mixture and is determined by the aggregate's bulk specific gravity. The following formula can be used to determine VMA:

$$VMA = 100 - \frac{G_{mb}}{G_{sb}}\, P_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.5)$$

3.12.6 Compute the percentage of Air void in the compacted mixture

The tiny air gap between the coated aggregate particles makes up the air void in a compacted pavement mixture. The following formula Eq. 3.6 is used to calculate the proportion of air void in a compacted mixture:

$$P_a = 100 \frac{G_{mm} - G_{mb}}{G_{mm}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

3.12.7 Compute the percentage of void filled with asphalt(VFA)

The following formula Eq. 3.7 can be used to calculate the percentage of the total voids in the mineral aggregate that are filled with asphalt, VFA

$$VFA = \frac{100(VMA - V_a)}{VMA} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.7)$$

3.13 Marshall stability and flow test

The Marshall stability-flow test determines a standard test specimen's maximum load resistance and associated deformation (or flow) at 60^0C when subjected to a load by a standardized test procedure (Fig 3.14). It is intended to simulate pavement failure under the worst conditions expected in the field conditions. Loading is done with the specimen lying on its side in a split loading head at a constant rate of deformation 51 mm/min until failure occurs. The Marshall stability value is the total amount of pounds, or kN, needed to cause failure. At maximum load, the deformation is noted.

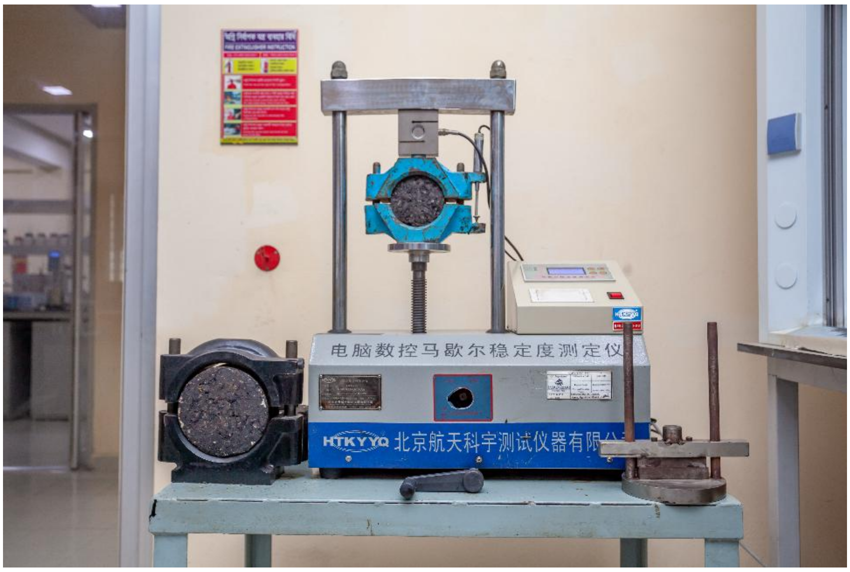

Figure 3. 14 Marshall Stability testing machine

3.14 Indirect Tensile (IDT) Strength Test (ASTM D6931-17)

This test method outlines procedures for preparing and testing laboratory fabricated or field recovered asphalt mixture cores to determine their Indirect Tensile (IDT) Strength. The IDT strength is measured by loading a cylindrical specimen across its vertical diameter plane at a specified deformation rate and test temperature (Fig 3.15).

The specimen's IDT strength is determined by recording the peak load at failure. These strength values are useful for evaluating the relative quality of asphalt mixtures, particularly in conjunction with laboratory mix design testing. Additionally, they can help estimate the mixture's potential resistance to rutting or cracking. When findings are gathered from both conditioned and unconditioned specimens, this technique can also reveal information on the possibility of moisture damage to field pavement.

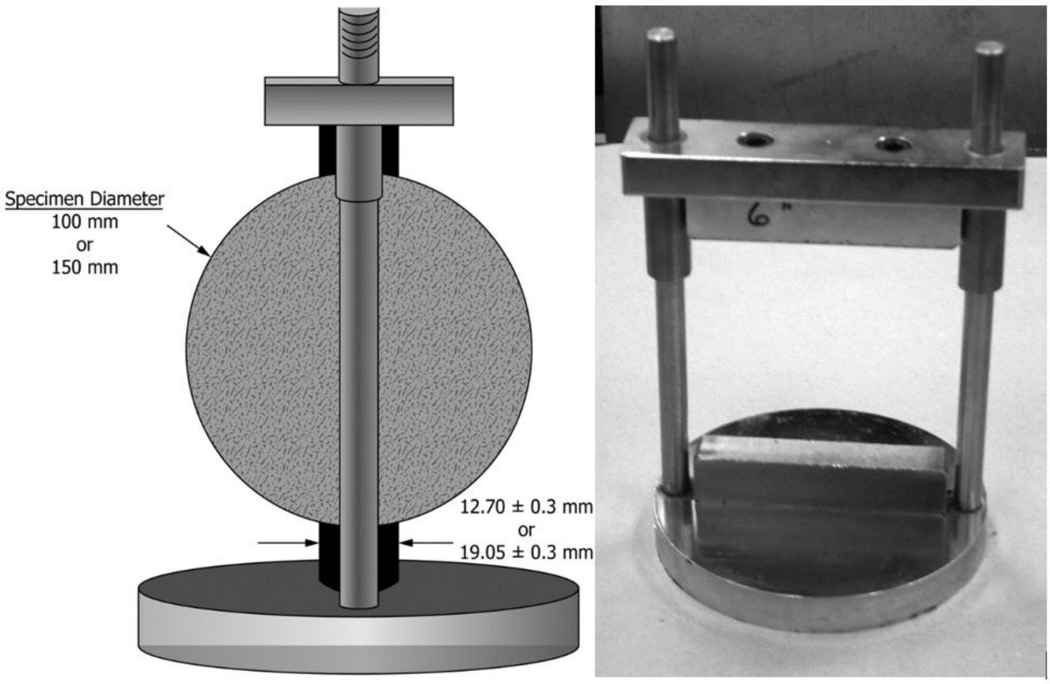

Figure 3. 15 Fixture for IDT Strength Loading (ASTM D6931-17)

Calculation of IDT strength as follows Eq. 3.8,

$$S_t = \frac{2000P}{\pi t D} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(3.8)}$$

Where:

S_t = IDT Strength, kPa

P = Maximum load, N

t = Specimen height immediately before test, mm

D = Specimen diameter, mm

3.15 Moisture Induced Damage Test

Certain materials used to make HMA may be sensitive to the presence of water in the final pavement. Water will prevent the binder from sticking to the aggregate. Since the binder serves as the "glue" holding the pavement together, if it is unable to stick to the aggregate, the pavement will likely disintegrate quickly. This is commonly known as stripping. Additives such hydrated lime or liquid anti-stripping chemicals may be needed to aid stop stripping. AASHTO T 283 is a test procedure that can be used to assess the efficacy of additives and identify materials that might be susceptible to stripping. Compaction of specimens to an air void level of 6 to 8 percent is how the test is carried out. Three specimens are chosen to be conditioned by soaking in water that has undergone a freeze cycle and then a warm-water soaking cycle, while three other specimens are chosen to serve as a control and be examined without moisture conditioning. After that, the specimens are loaded steadily and the force needed to break them is measured in order to test their indirect tensile strength. To calculate the tensile strength ratio (TSR), the conditioned specimens' tensile strength is contrasted with that of the control specimens. Additionally, cores extracted from the completed pavement may be used for this test.

3.16 The Modified Lottman Test (AASHTO T 283)

The Lottman, Tunnicliff, and Root tests combined. The split tensile strength (Fig. 3.16) of unconditioned samples and those that have been slightly saturated with water are compared. The test includes an optional freeze-thaw cycle and partial vacuum saturation for the conditioned group. While a decreased tensile strength is to be expected from the water-conditioned samples, extremely low values suggest the possibility of moisture damage.

The following formula Eq. 3.9 and Eq. 3.10 is used to determine the tensile strength:

English units:

$$S_t = \frac{2P}{\pi t D} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots (3.9)$$

Where,

S_t = Tensile strength, psi

P = Maximum load, pounds

t = Specimen thickness, in.

D = Specimen diameter, in.

SI units:

$$S_t = \frac{2000P}{\pi t D} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots (3.10)$$

where:

S_t = tensile strength, kPa

P = maximum load, Newtons

t = specimen thickness, mm

D = specimen diameter, mm

The tensile strength ratio(TSR) is calculated as follows Eq. 3.11:

$$\%\ TSR = \frac{S_2}{S_1}\ x\ 100 \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots (3.11)$$

where:

S_1 = average tensile strength of the dry subset, psi (kPa)

S_2 = average tensile strength of the conditioned subset, psi (kPa)

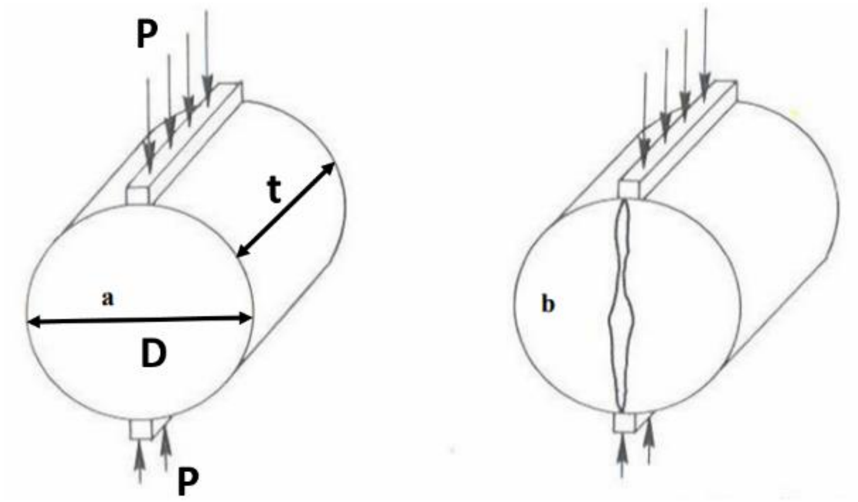

Figure 3. 16 Indirect Tensile Strength Test (Gupta, L., Suresh, G. (2018).

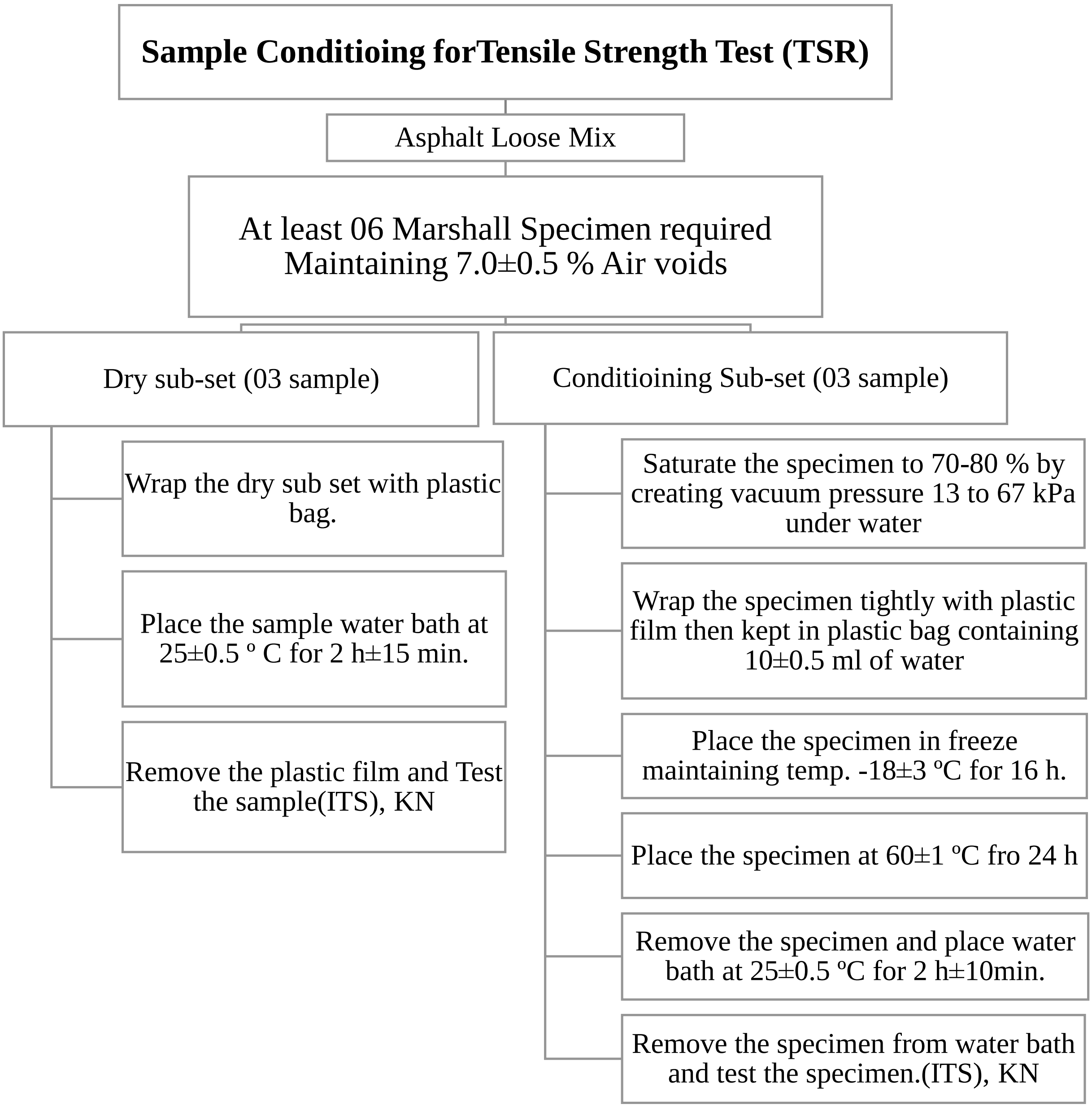

Figure 3. 17 Sample Conditioning Flow chart

3.17 Specimen Conditioning for Indirect tensile strength (ITS) Test

After finalized the job mix design of two different types of aggregate, then started the Test to determine Resistance of compacted asphalt mixtures to moisture induced damage as per Standard AASHTO T283. Sample conditioning process are shown in Fig 3.17.

Prepared 8 Nos. specimen for Source-B Stone Aggregate using 5.3% raw bitumen content. Among the specimen classified them in two subset containing 3 samples for each dry and condition F-T cycle subset. Additional 2 specimen required for established compaction procedure for specimen void maintaining 7±0.5 %. And find out the vacuum saturation techniques maintain degree of saturation 70% to 80%.

Prepared asphalt mixture large quantity as per job mix formula and cooled the mixture for 2 hours in room temperature (Fig 3.18). Then kept the cooled mixture in oven for 16±1 h maintained oven temperature 60±3 ^{0}C.

Figure 3. 18 Asphalt Mixture cooled in room temperature

Placed the asphalt mixture in an oven for 2 h ± 10 min at the compaction temperature 135^{0}C. After reaching compaction temperature compacted the specimen 63.5 mm height and 101.6 mm diameter with 1200 gm of asphalt mixture. To created void 7±0.5% in specimen adjusted the Marshall compactor blow to 38 Nos. both face of specimen. Removed Compacted specimen and cooled it room temperature for 24 h. (Fig 3.19).

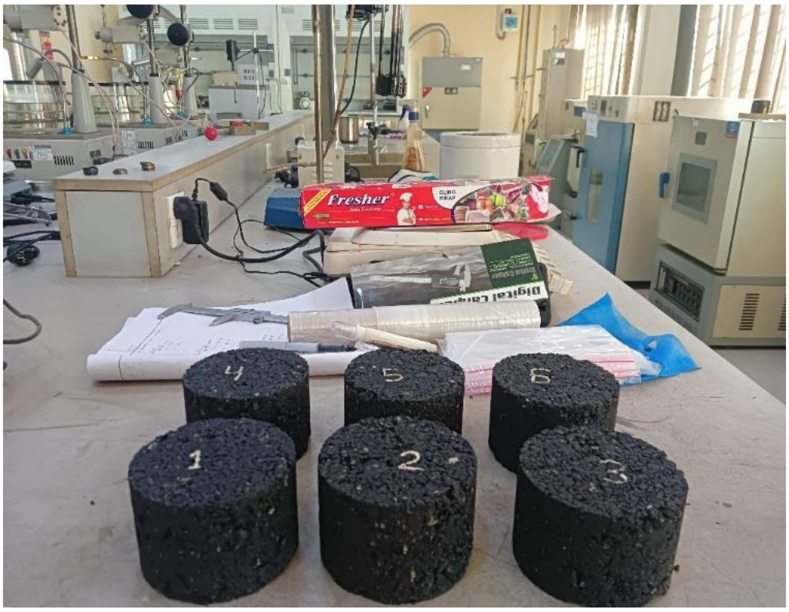

Figure 3. 19 Specimen cooled at room temperature

3.18 Preconditioning of test specimens

Separated the specimens into two subsets, three specimens each maintained average air voids of the two subsets are approximately equal.

Dry subset

Figure 3. 20 Plastic wrapped specimen

Recorded the measurements of specimen. Wrapped the dry subset with plastic film and heavy duty leak-proof plastic bag (Fig 3.20). Placed the wrapped specimen into water bath maintained 25±0.5 ^{0}C for 2 hours (Fig 3.21). Remove the specimen from water bath and takeoff the plastic bag. Immediately test the specimen of indirect tensile strength test.

Figure 3. 21 Specimen at 25^{0}C water bath

Wet Subset

Recorded the measurements of wet subset. Then placed the specimen in the vacuum container (Fig 3.22) filled with potable water maintaining vacuum pressure 13 to 67 kPa for 15 minutes to achieved 70 to 80 percent degree of saturation. Removed the specimen from vacuum and leave the specimen submerged in water for 10 minutes. Then damp dry the specimen with towel and determined the saturated surface dry (B') weight of the specimen.

Calculated the volume of absorbed water (J') in cm^3 by following Eq. 3.12:

$$J' = B' - A \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.12)$$

Where, J' = volume of absorbed water, cm^3

B' = mass of the SSD specimen, gm

A = mass of the dry specimen in air, gm

Determined the degree of saturation (S') by comparing the volume of absorbed water (J') with the volume of air void (Va) using the following Eq. 3.13:

$$S' = \frac{100\,J'}{Va} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3.13)$$

Where S' = degree of saturation, percent.

Figure 3. 22 vacuum saturation of specimen

When desired degree of saturation 70 to 80 percent achieved then immediately wrapping the specimen with plastic film (Fig 3.23). Then placed the wrapped specimen in a plastic bag containing 10±0.5 ml of water and seal the bag. (Fig. 3.24).

Figure 3. 23 Specimen wrapped with plastic film

Figure 3. 24 Specimen in plastic bag

Placed the plastic bag containing specimen in freezer at a temperature of -18 ± 3^{0}C for a minimum of 16 h (Fig 3.25). Remove the specimen from freezer and placed the specimen in a bath containing potable water at 60 ± 1^{0}C for 24 h (Fig 3.26). Removed the plastic and thin plastic film from specimen as soon as possible after placed the warm water bath.

Figure 3. 25 Specimen at -18^{0}C freezer

Figure 3. 26 specimen at 60^{0}C water bath

After 24 h in 60±1^{0}C water bath, removed the specimen and placed them in a water bath at 25±0.5^{0}C for 2 h (Fig 3.27). Removed the specimen from water bath and test ITS as described in section 3.14. (Fig 3.28)

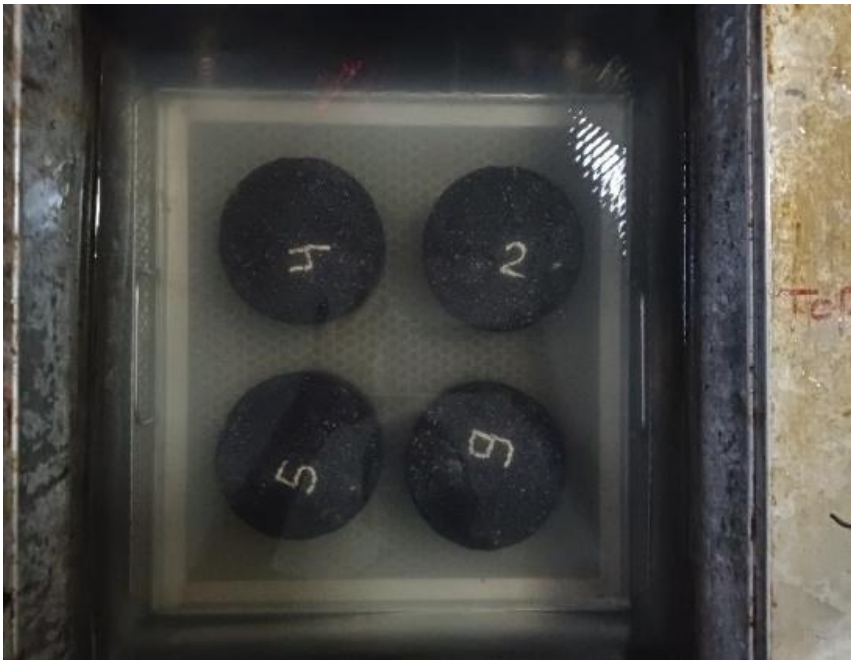

Figure 3. 27 Specimen in 25^{0}C water bath

Figure 3. 28 Indirect Tensile Strength Test

Chapter 4: Results and Discussion

This Chapter presents the results and analysis of the Marshall Mix Design, Optimum Bitumen Content (OBC), and Moisture Sensitivity Evaluation of Hot Mix Asphalt (HMA) using different aggregates and additives. The chapter begins with the Marshall Mix Design and OBC determination for Source-A Stone Aggregate, followed by an evaluation of its Indirect Tensile Strength (ITS) and Tensile Strength Ratio (TSR). The results indicate that Source-A Stone Aggregate exhibits excellent moisture resistance, as reflected in its high TSR value. Due to this inherent resistance, no anti-stripping additives were tested with this aggregate. Next, the Marshall Mix Design and OBC of Source-B Stone Aggregate are presented, along with its ITS and TSR results without additives. The findings reveal a lower TSR value, indicating higher moisture susceptibility compared to Source-A Stone Aggregate. To address this, various anti-stripping additives (Type-A and Type-B) and cement filler were incorporated to enhance moisture resistance. The final section of the chapter discusses the impact of these additives and filler on ITS and TSR improvement in Source-B Stone Aggregate. The results demonstrate that Type-A additive provided the highest TSR improvement among the liquid additives, while cement filler showed the most significant enhancement in moisture resistance, achieving the highest TSR value.

4.1 Marshall Mix Design and Optimum Bitumen Content of Source-A Stone Aggregate

To conduct moisture sensitivity test of HMA mixture and different trials to improving moisture induced damaged a Marshall mix design has been finalized for two different types of aggregate. Table 4.1 shows Marshall mix design for Source-A aggregate with different trials of bitumen content. Bitumen content trial from 4.0 % to 5.5 % with 0.5 % incremental rate of total asphalt mix. Maximum density found 2.445 gm/cc at bitumen content 5.0% from Fig 4.1 and Fig 4.2 shows the marshal flow rate Vs bitumen content and found flow 2.5 mm for OBC 4.8 %. Fig 4.3 shows that the maximum stability of marshal mix design found 13.9 kN at 4.8 % bitumen content. Fig 4.4 shows that the void in mineral aggregate found 16.8 % at OBC 4.8 % which should be more than 13 % as per guideline of RHD asphalt mix design. Fig 4.5 shows the bitumen filled with aggregate found 77.58 % of air void at OBC 4.8 % which also comply the range 65%-80% of RHD specification. Fig 4.6 shows the bitumen content 4.7 % for 4 % air void which satisfying the air void beyond 3 %-

5 %. Table 4.2 shows Optimum bitumen content 4.8 % of this aggregate gradation based on maximum stability, maximum density and 4 % air void.

Table 4.1: Marshall Mix design for Source-A Stone Aggregate

Marshall Mix Design Results (Source-A Stone Aggregate-BRT Project)								
SL NO.	**Bitumen Content (%)**	**G_{mm}**	**G_{mb}**	**%VMA**	**%V_a**	**%VFA**	**Stability (kN)**	**Flow (mm)**
1	4.0	2.544	2.36	18.73	7.23	61.4	10.9	1.98
2	4.5	2.533	2.423	17.00	4.34	74.45	14.1	2.34
3	5.0	2.53	2.445	16.68	3.36	79.86	13.1	2.61
4	5.5	2.512	2.432	17.56	3.18	81.87	11.4	2.68

Table 4.2: Determined optimum Bitumen content for Source-A Stone Aggregate.

Description	**Bitumen Content**
Maximum Density	5.0%
Maximum Stability	4.8%
4% Air void	4.7%
Optimum Bitumen Content %	4.8%

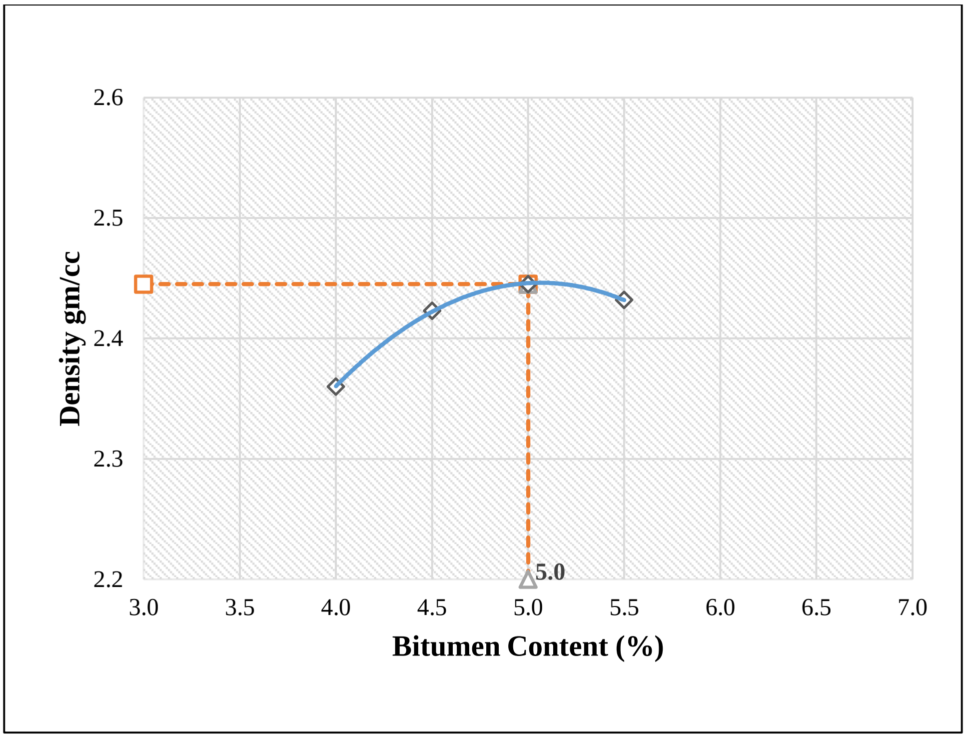

Figure 4. 1 Density Vs Bitumen Content of Source-A aggregate

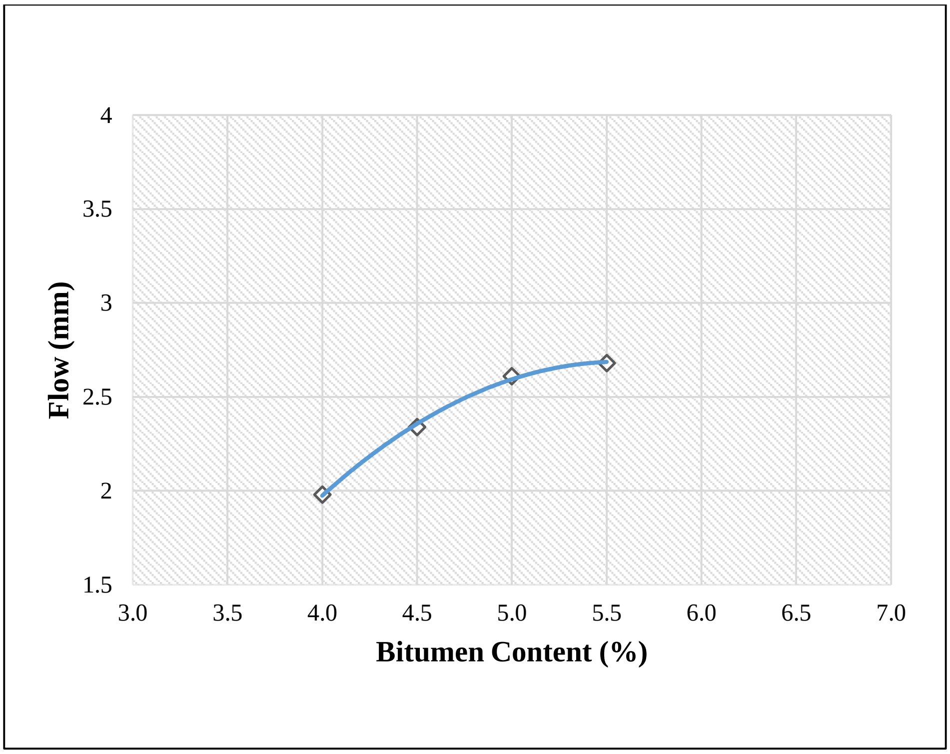

Figure 4. 2 Flow Vs Bitumen Content of Source-A aggregate

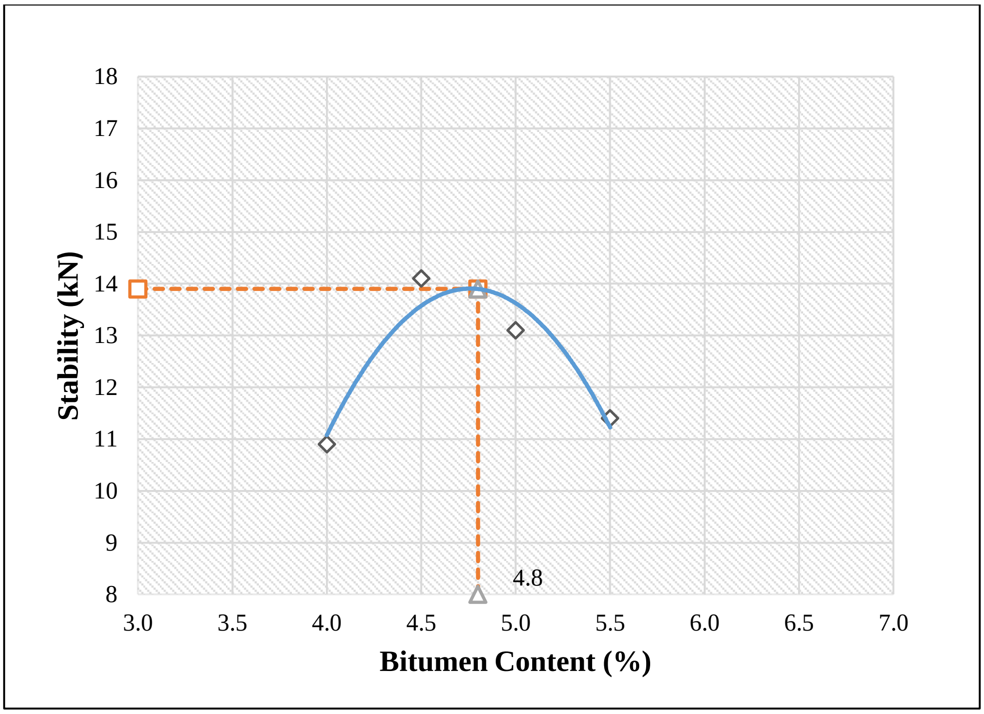

Figure 4. 3 Stability Vs Bitumen Content of Source- A aggregate

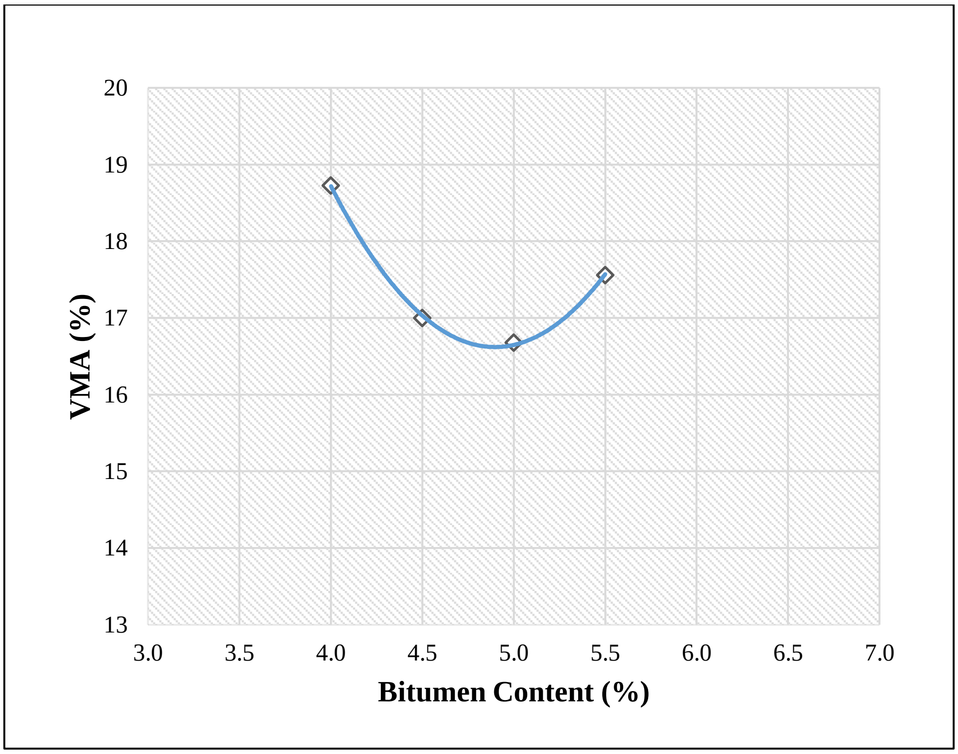

Figure 4. 4 VMA Vs Bitumen Content of Source-A aggregate

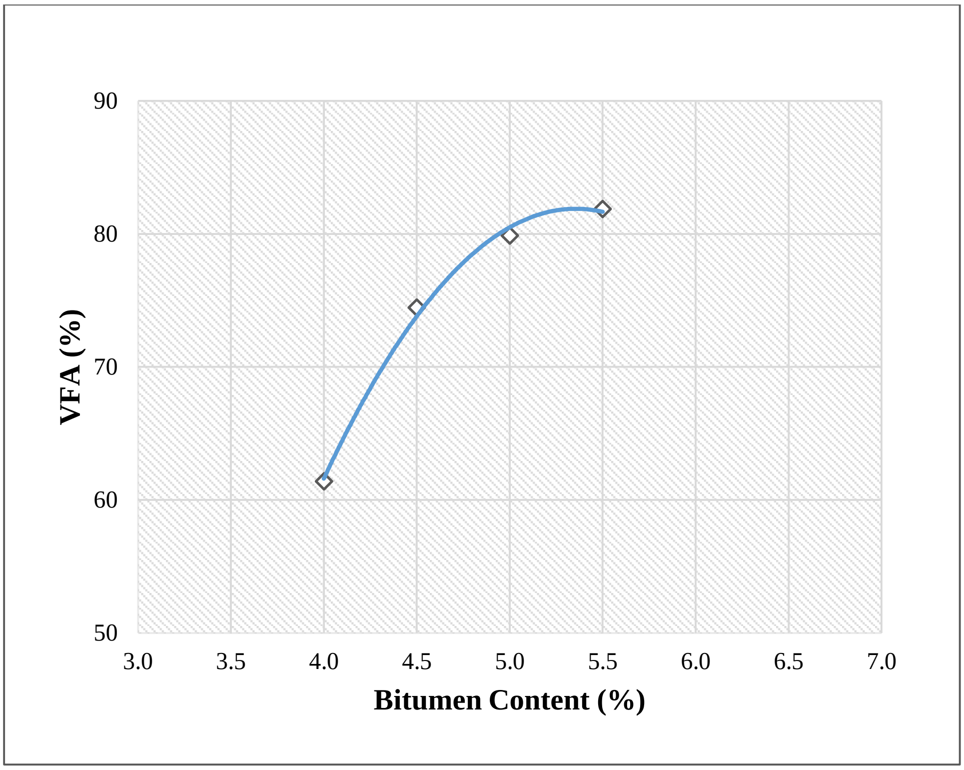

Figure 4. 5 VFA Vs Bitumen Content of Source-A aggregate

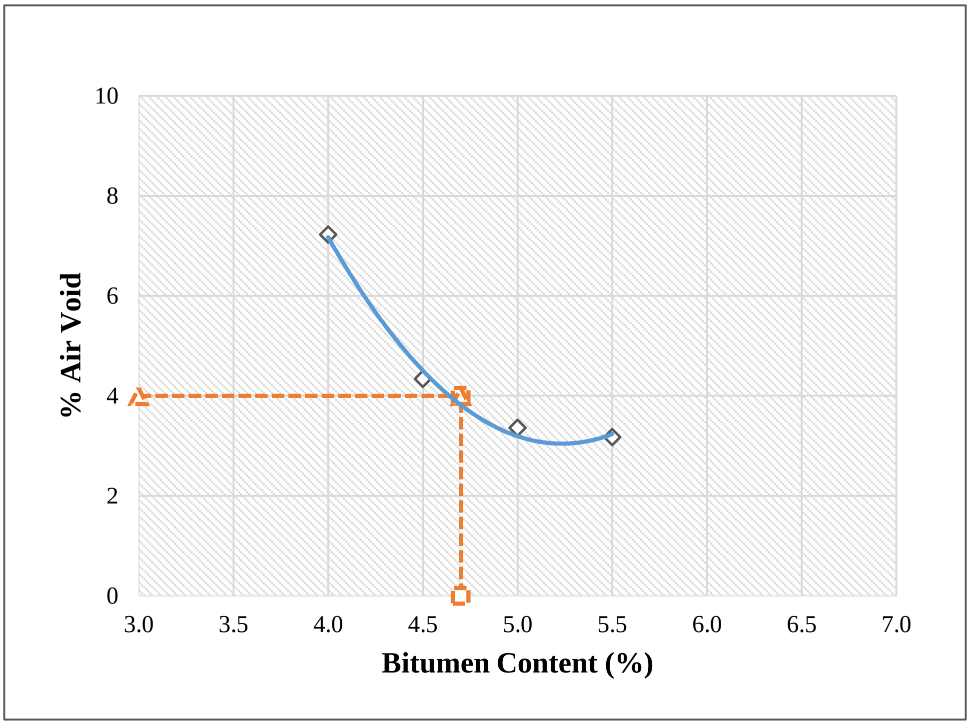

Figure 4. 6 Air Void Vs Bitumen Content of Source-A aggregate

Table 4. 3: Determination of TSR of Source-A Stone Aggregate with Bitumen Grade 60-70 (without Additives)

Binder Types	**Specimen Mark**	**Specimen Type**	**Air void% (a)**	**Degree of Saturation, S'= 100*(B-A)/ V_a**	**Tensile Load, KN**	**Tensile Strength, S_t=2000P/πDt**	**Average Tensile Strength, kPa**	**Tensile strength Ration (TSR) , % TSR= S_2/S_1x100**
(Bitumen Grade 60/70) without additive	F-01	Dry Sub-set (S_1)			10.52	1039.13	1032.4	94
	F-02				10.44	1029.60		
	F-03				10.38	1028.54		
	F-04	Condition Sub-Set (S_2)	7.4	72.26	9.90	974.82	970.5	
	F-05			75.42	9.72	961.62		
	F-06			70.88	9.81	973.60		

4.2 Indirect tensile strength (ITS) Test of Source-A Stone Aggregate

The evaluation of Source-A Stone Aggregate as an aggregate in Hot Mix Asphalt (HMA) formulations yielded promising results, particularly regarding its moisture resistance. In Table 4.3, The aggregate exhibited a TSR value of 94%, indicating good performance against moisture-induced damage. The Bitumen grade 60-70 (without additive) combined with Source-A Stone Aggregate demonstrated an ITS of 1032.4 kPa for the dry subset and an impressive increase to 970.5 kPa for the F-T conditioned subset. This increase suggests that the Source-A Stone Aggregate enhances the binder's performance under moisture exposure, likely due to favorable bonding characteristics. Notably, no trials were conducted with anti-stripping additives, as the high TSR value indicates that the inherent properties of Source-A Stone Aggregate provide sufficient moisture resistance.

The aggregate's gradation aligns well with high-performance asphalt requirements, further contributing to its effectiveness. Overall, these findings suggest that Source-A Stone Aggregate is a viable option for HMA formulations, particularly in moisture-prone environments.

4.3 Marshall Mix Design and OBC content of Source-B Stone Aggregate

Marshal mix design necessary to fix up the optimum bitumen content which has been used to asphalt mixture for moisture sensitivity test. Table 4.4 shows Marshall mix design for Source-B aggregate with different trials of bitumen content. Bitumen content trial from 4.5 % to 6.0 % with 0.5 % incremental rate of total asphalt mix. Maximum density found 2.448gm/cc at bitumen content 5.5% from Fig 4.7 and Fig 4.8 shows the marshal flow rate Vs bitumen content and found flow 2.58 mm for OBC 5.4 %. Fig 4.9 shows that the maximum stability of marshal mix design found 11.4 kN at 5.2 % bitumen content. Fig 4.10 shows that the void in mineral aggregate found 15.4 % at OBC 5.4 % which should be more than 13 % as per guideline of RHD asphalt mix design. Fig 4.11 shows the bitumen filled with aggregate found 72.34 % of air void at OBC 5.4 % which also comply the range 65%-80 % of RHD specification. Fig 4.12 shows the bitumen content 5.4 % for 4 % air void which satisfying the air void beyond 3%-5 %. Table 4.2 shows Optimum bitumen content 5.4 % of this aggregate gradation based on maximum stability, maximum density and 4 % air void.

Table 4.4: Marshall Mix design for Source-B Stone Aggregate

Marshall Mix Design Results (Source-B Stone Aggregate)								
SL NO.	**Bitumen Content (%)**	**G_{mm}**	**G_{mb}**	**%VMA**	**%V_a**	**%VFA**	**Stability (kN)**	**Flow (mm)**
1	4.5	2.568	2.376	16.9	7.47	55.75	9.38	1.95
2	5	2.550	2.424	15.6	4.94	68.32	11.87	2.42
3	5.5	2.552	2.448	15.3	4.07	73.36	10.31	2.68
4	6	2.517	2.438	16.1	3.13	80.51	8.98	2.84

Table 4.5: Determined optimum Bitumen content for Source-B Stone Aggregate.

Description	Bitumen Content
Maximum Density	5.5 %
Maximum Stability	5.2 %
4% Air void	5.4 %
Optimum Bitumen Content %	**5.4 %**

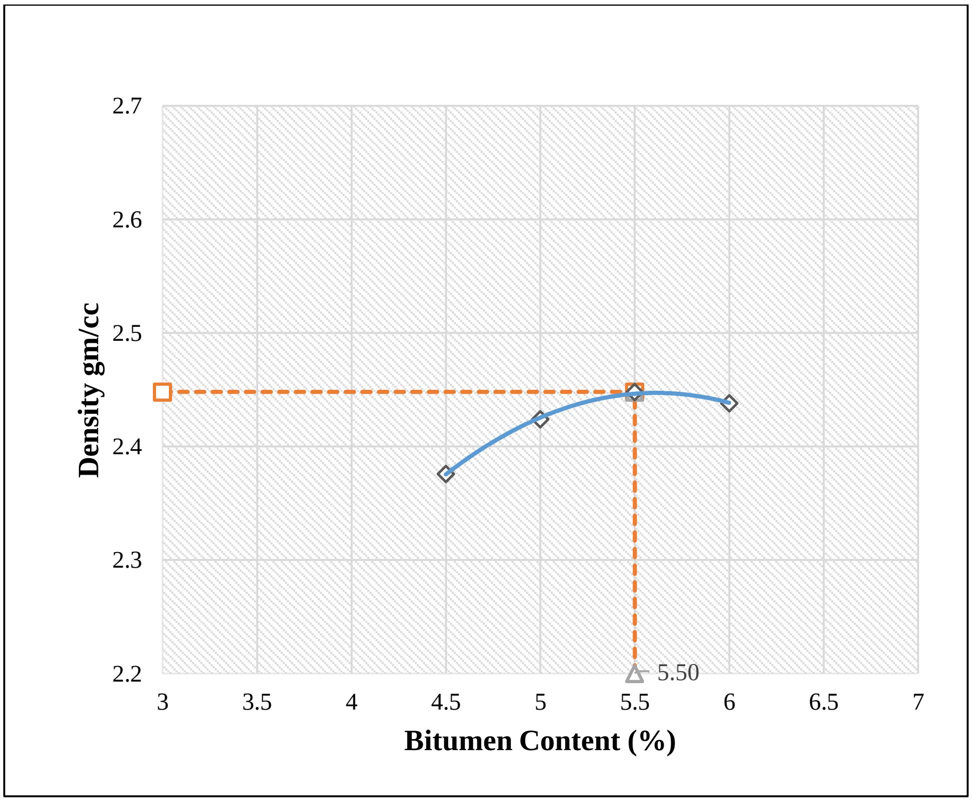

Figure 4. 7 Density Vs Bitumen Content of Source -B aggregate

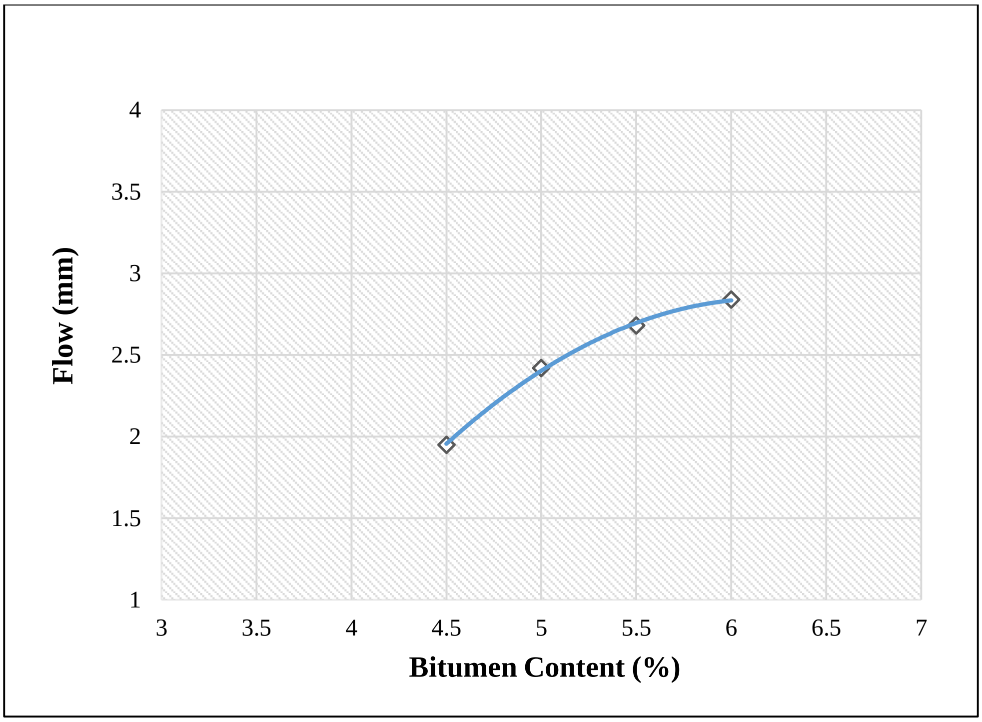

Figure 4. 8 Flow Vs Bitumen Content of Source -B aggregate

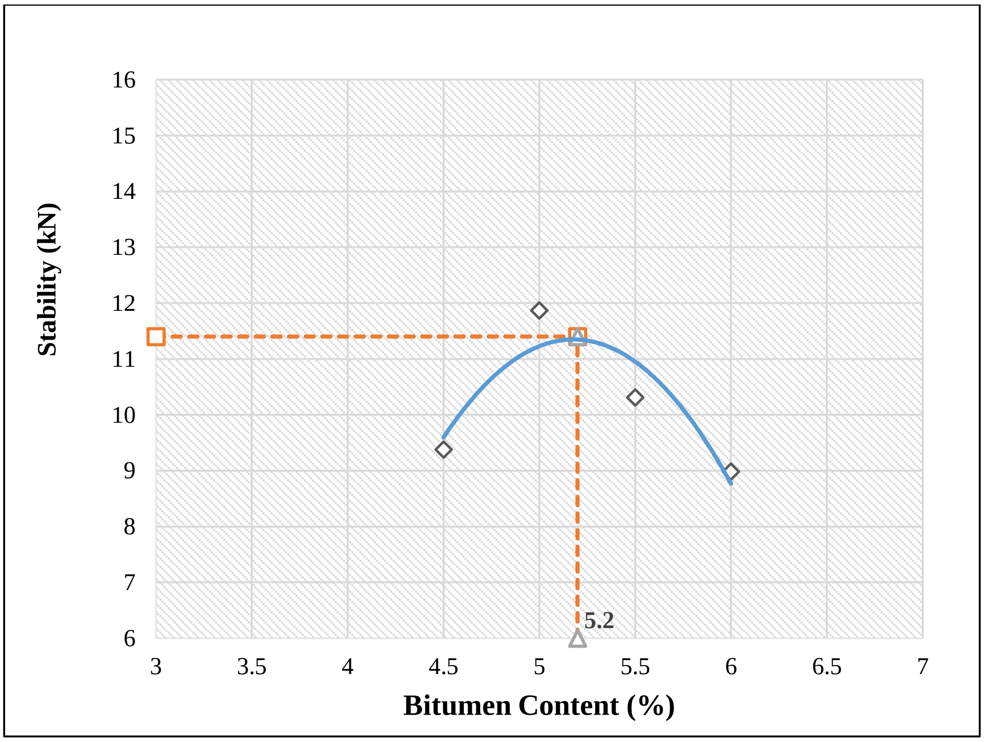

Figure 4. 9 Stability Vs Bitumen Content of Source -B aggregate

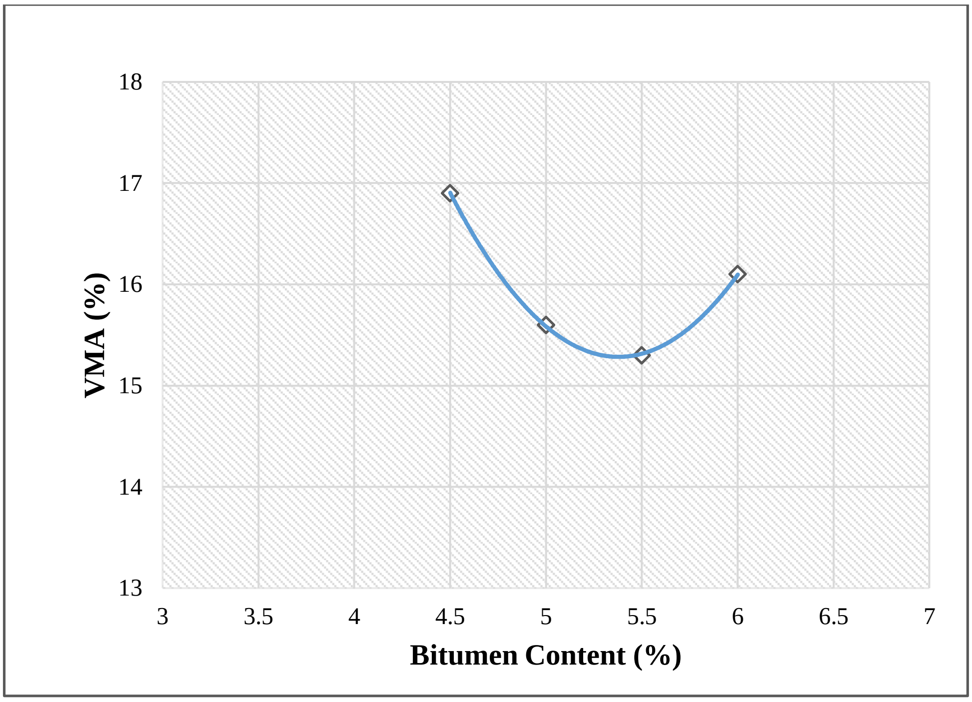

Figure 4. 10 VMA Vs Bitumen Content of Source -B aggregate

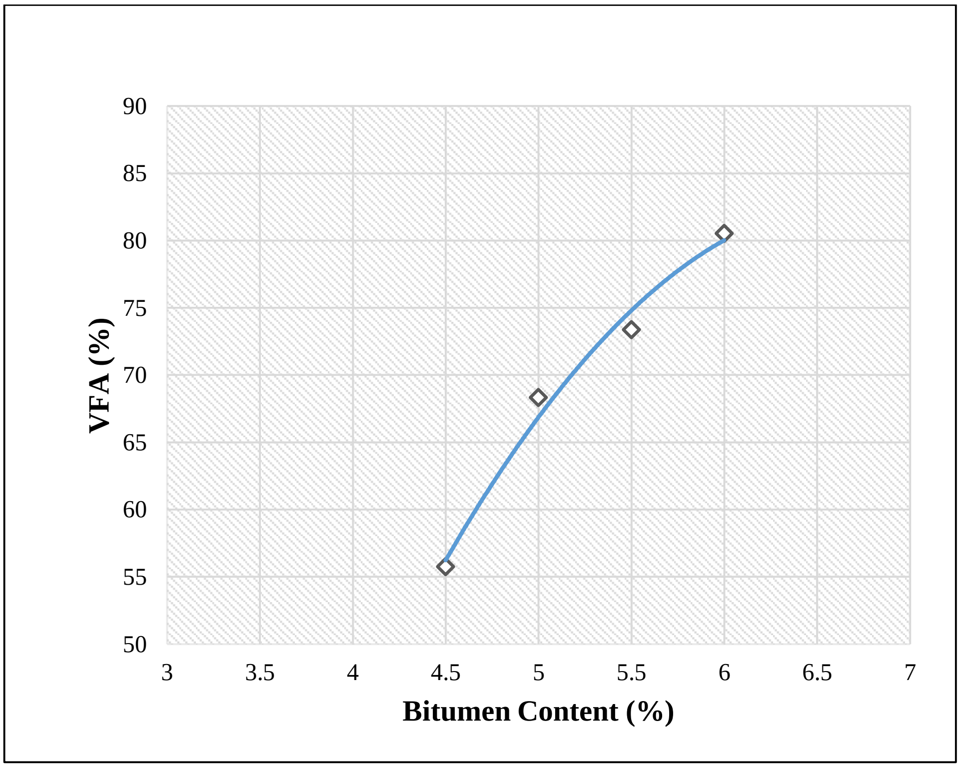

Figure 4. 11 VFA Vs Bitumen Content of Source -B aggregate

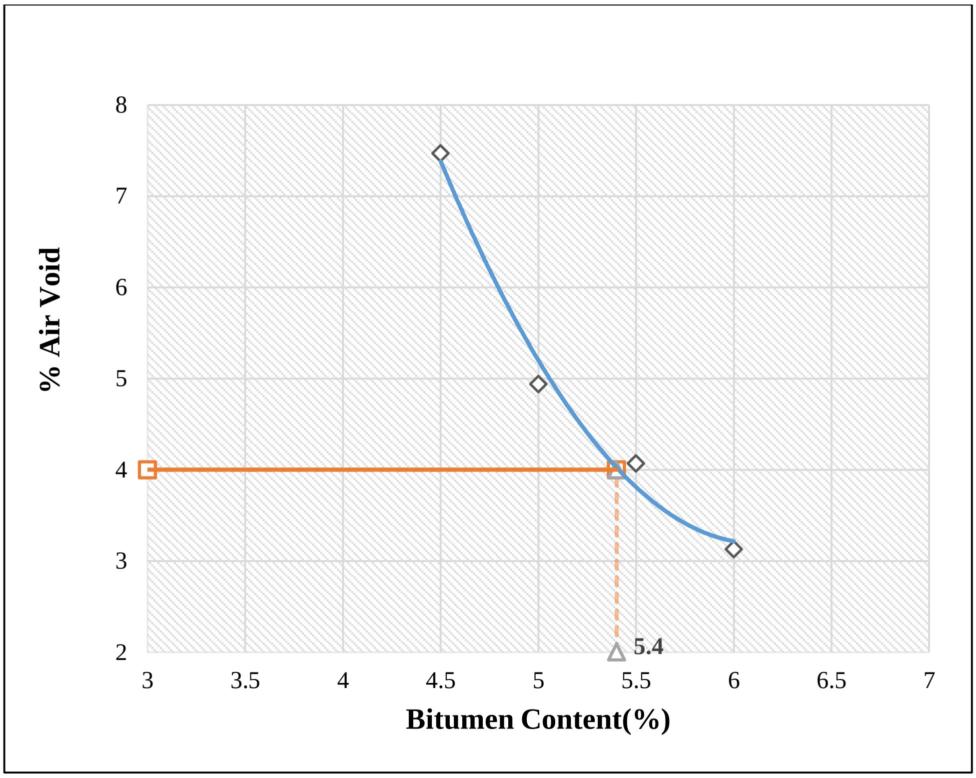

Figure 4. 12 Air Void Vs Bitumen Content of Source -B aggregate

4.4 Indirect tensile strength (ITS) Test of Source-B Stone Aggregate

The results of the tensile strength tests and indirect tensile strength (ITS) assessments for various binder modifications with Source-B Stone Aggregate under both dry and freeze-thaw (F-T) conditioned conditions provide significant insights into the moisture susceptibility of Hot Mix Asphalt (HMA). The findings are summarized in Figures 4.13 and 4.14, which present the tensile strength and tensile strength ratio, respectively, and in Table 4.6 provides the corresponding experimental data used to assess moisture sensitivity.

For the Bitumen Grade 60-70 (without additive), the tensile strength of the dry subset was recorded at 1045.86 kPa, while the F-T conditioned subset exhibited a reduced tensile strength of 848.42 kPa, resulting in a Tensile Strength Ratio (TSR) of 81%. The performance of the fresh binder greatly declines when exposed to moisture conditions, as indicated by its TSR value, which shows a substantial susceptibility to moisture damage. The lower TSR value indicates how moisture adversely affects the binder's mechanical integrity.

However, the modified binder made of Bitumen 60-70 and 0.06% Type-A liquid additive showed a slightly lower F-T conditioned tensile strength of 882.38 kPa and a dry tensile strength of 914.35 kPa, resulting in a TSR of 97%. Although there is a minor decrease in ITS, the addition of Type-A appears to improve the binder's resistance to moisture-induced degradation, as evidenced by the higher TSR value as compared to the fresh binder.

Bitumen 60/70 and 0.1% Type-B liquid additive were added to the modified binder, which produced a TSR of 94% with a dry ITS of 968.75 kPa and a conditioned ITS of 906.39 kPa. The Type-B formulation showed better moisture resistance than Bitumen Grade 60-70, much like the Type-A modified binder did. However, a minor drop in ITS was noted after additive application.

It's interesting to note that the formulation with Bitumen Grade 60-70 and 1% cement filler demonstrated a dry ITS of 852.43 kPa. Following F-T conditioning, this value rose to 917.50 kPa, yielding a TSR of 108%. This outcome is particularly noteworthy as it indicates that the presence of cement filler contributes positively to moisture resistance, with the hydration process enhancing the strength of the binder upon moisture exposure.

Table 4.6: Determination of TSR using different types additives and filler with Source-B Stone Aggregate

SL.	**Binder Types**	**Specimen Mark**	**Specimen Type**	**Air void% (a)**	**Degree of Saturation, S'= 100*(B-A)/ V_a**	**Tensile Load, KN**	**Tensile Strength, S_t=2000P/πDt**	**Average Tensile Strength, kPa**	**Tensile strength Ration (TSR) , % TSR= S_2/S1x100**
1	Fresh Binder (Bitumen 60/70)	F-01	Dry Sub-set (S_1)			10.61	1048.60	1045.86	81
		F-02				10.48	1040.68		
		F-03				10.59	1048.28		
		F-04	Condition Sub-Set (S_2)	7.3	74.27	8.62	847.92	848.42	
		F-05			77.53	8.68	860.57		
		F-06			71.84	8.48	836.77		
2	Modified Binder (Bitumen 60/70 + 0.06% Type-A)	W-01	Dry Sub-set (S_1)			9.17	902.02	914.35	97
		W-02				9.24	919.00		
		W-03				9.3	922.04		
		W-04	Condition Sub-Set (S_2)	7.1	76.85	8.98	888.91	882.38	
		W-05			71.13	8.87	875.26		
		W-06			74.10	8.92	882.97		
3	Modified Binder (Bitumen 60/70 + 0.1% Type-B)	Z-01	Dry Sub-set (S_1)			9.85	973.49	968.75	94
		Z-02				9.83	976.13		
		Z-03				9.71	956.64		
		Z-04	Condition Sub-Set (S_2)	7.1	73.52	8.99	882.93	906.39	
		Z-05			73.98	9.23	912.22		
		Z-06			74.22	9.32	924.03		
4	Bitumen 60/70 + 1% Cement filler	C-01	Dry Sub-set (S_1)			8.43	826.63	852.43	108
		C-02				8.78	867.74		
		C-03				8.69	862.93		
		C-04	Condition Sub-Set (S_2)	6.9	76.13	9.3	919.13	917.50	
		C-05			73.19	9.17	904.86		
		C-06			79.07	9.38	928.51		

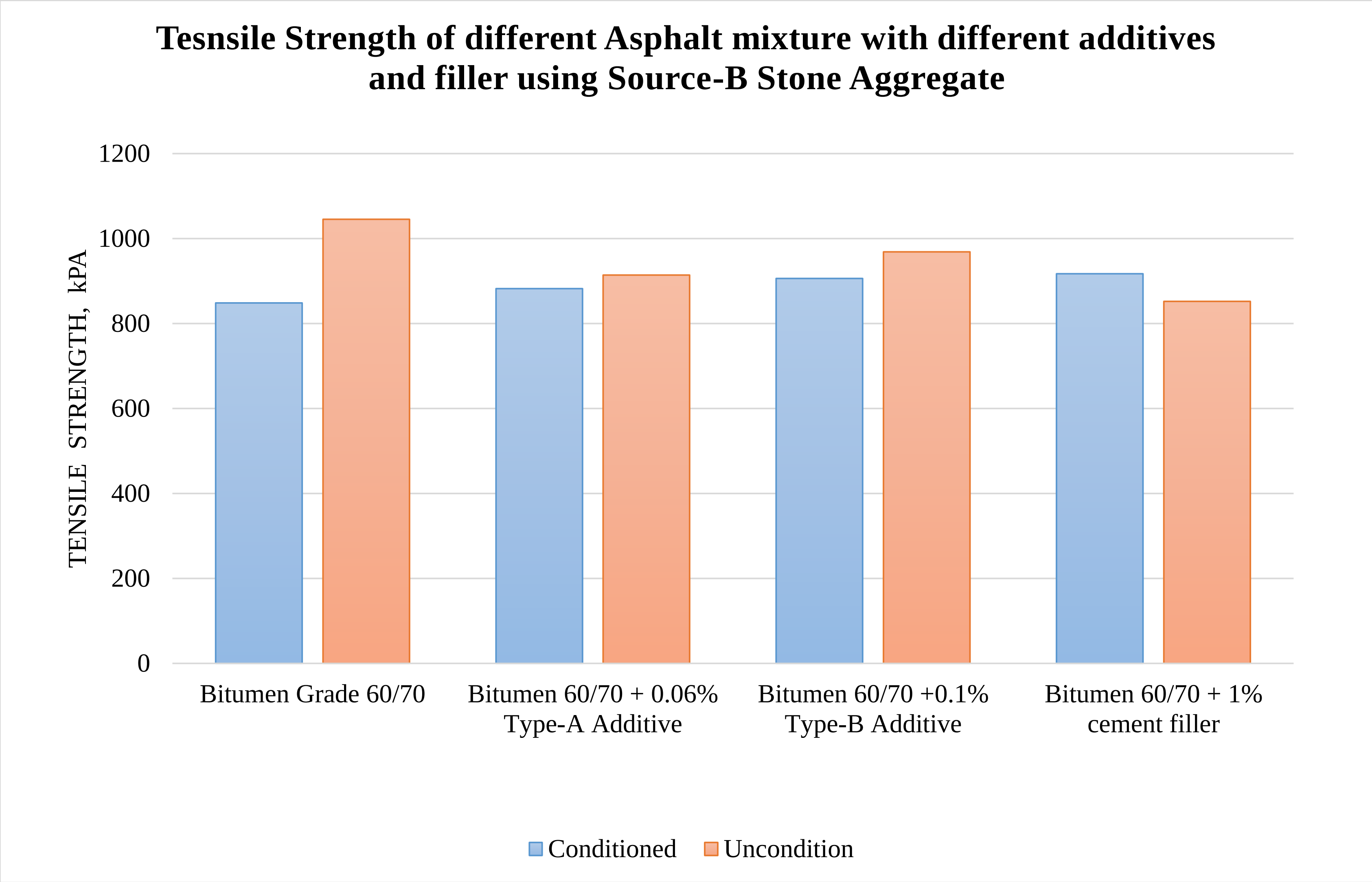

Figure 4.13 Tensile strength Vs different binders with conditioned and unconditioned sample

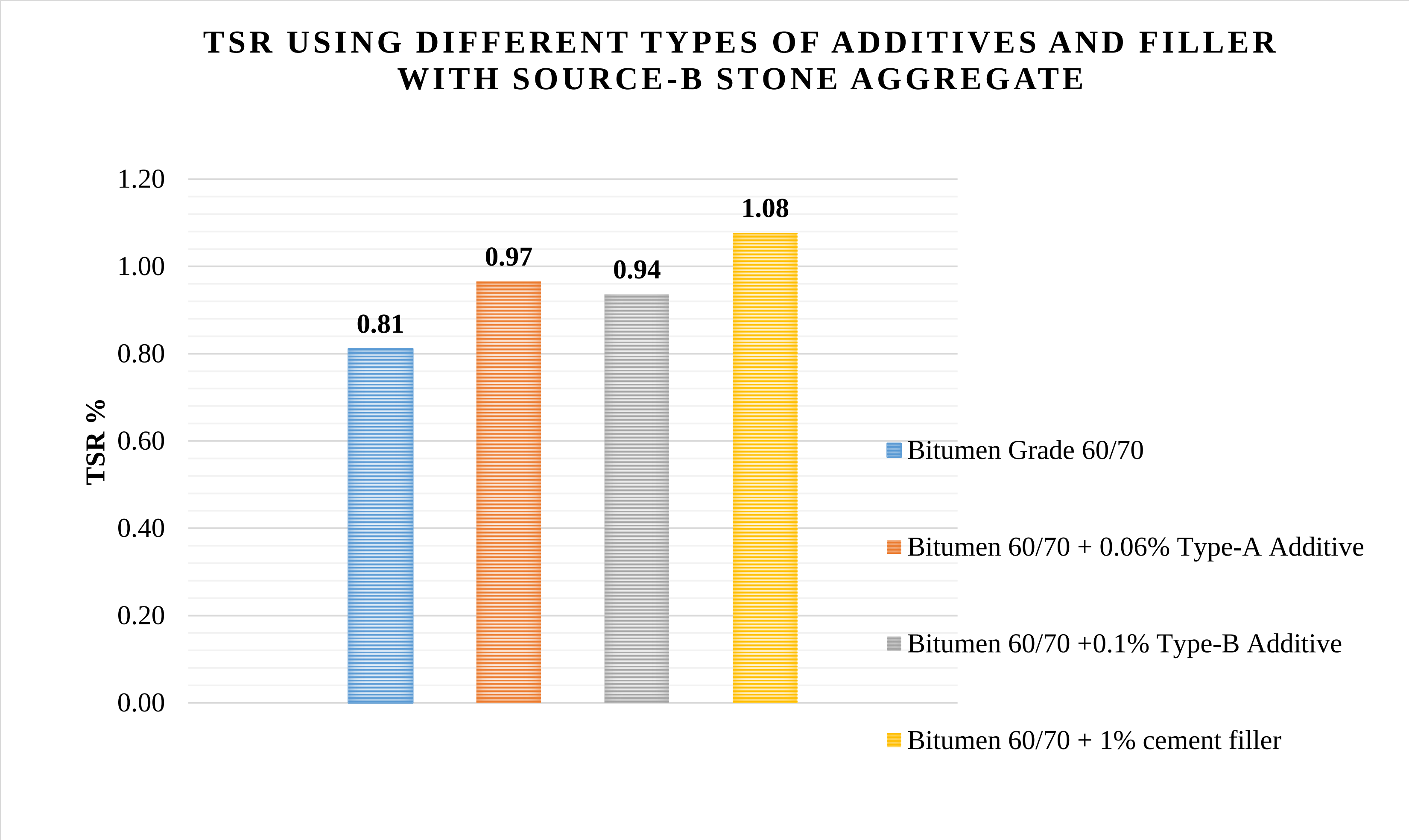

Figure 4.14 Tensile Strength Ratio (TSR) Vs Different types of Binder

Chapter 5: Conclusion and Recommendations

5.1 Conclusion

The study introducing two difference source of aggregate naming Source-A and Source-B which are very common and frequently used in our asphalt pavement construction industry in context of Bangladesh. In presence of moisture, Early deterioration of asphalt pavement is occurring and this issue is very crucial for asphalt industry. To prevent such type of moisture related damage of pavement this study also introducing two liquid anti-stripping additives and mineral filler with hot mix asphalt. Different trail has been made to evaluated moisture sensitivity of HMA and develop moisture resistant asphalt. To evaluated the moisture sensitivity this study has been used AASHTO T283. Results obtained from this study showing that both liquid additives and mineral filler improving TSR among them cement performing best. This study conclude that asphalt pavement can be preventing such type of moisture related damages and durable using a combination of additives and materials.

The study evaluated the effect of aggregates type, use of liquid anti-stripping additives and cement filler on the moisture sensitivity of HMA and yielded the following conclusion:

- Source-A Stone Aggregate mixing with Bitumen grade 60-70 (without additive) demonstrated excellent resistance to moisture-induced damages as evidence by high TSR value (94%).
- Source-B Stone Aggregate mixing with Bitumen grade 60-70 (without additive) exhibited lower TSR value (81%), indicating a reduced ability to resist moisture damage of HMA. However, the use of liquid anti-stripping additives significantly improved its TSR values 97% and 94% for Type-A and Type-B additives respectively, enhancing its moisture resistance.
- Source-A Stone Aggregate demonstrated excellent moisture resistance compared to Source-B Stone Aggregate when used with Bitumen grade 60-70 and a specific aggregate gradation.

- Among the anti-stripping additives, Type-A exhibited greater improvement in the Tensile Strength ration (TSR) for Source-B Stone Aggregate compared to Type-B.
- The identification of Source-A Stone Aggregate as a naturally moisture-resistant aggregate offers valuable guidance for selecting materials in road construction, particularly in regions susceptible to moisture damage.
- Cement filler stood out as the most effective material in this study, offering the highest TSR values 108% when used with Source-B Stone Aggregate. Its performance is attributed to the hydration process that occurs upon moisture contact, which significantly increased TSR and provided superior durability and moisture resistance to the asphalt mixture.
- The outstanding performance of cement filler demonstrates its potential as a useful pavement design addition, particularly in high moisture conditions.

5.2 Limitations of the Study

- The study was limited to only two types of aggregates (Source-A and Source-B), which may not represent the full range of materials used in asphalt pavement construction in Bangladesh.
- Fixed dosages of liquid anti-stripping additives were used (Type-A: 0.1%, Type-B: 0.06%), and the effects of varying dosages or other types of additives were not explored.
- Only one mineral filler (cement) was used, and its interaction with different aggregates or at varying percentages was not studied.
- The research was conducted entirely under laboratory conditions without any field validation or long-term performance assessment under real traffic and environmental conditions.
- This study does not provide conclusive guidelines for implementation by any person, agency, or department. Consultants, contractors, and implementing agencies should rely on their own specifications and conduct comprehensive trials with their materials before applying any additives. The conclusions are intended to support future research, not direct application.

Further Study

- The Modified Lottman test served to explore the materials sensitivity to water content during this investigation. The Hamburg Wheel-Tracking test and the Immersion Wheel-Tracking test should be used alongside standard evaluation methods for comprehensive moisture damage analysis in asphalt mixtures. Various testing methods provide detailed insights regarding moisture effects on hot mix asphalt (HMA) strength and operational characteristics.
- The use of accessible local aggregates including Modhyapara Granite stone should be considered for evaluation based on their performance in HMA and their resistance to moisture. The use of local stone from Modhyapara Granite for performance assessment in HMA construction should be evaluated for moisture sensitivity.
- The pavement performance can be enhanced through modification of wearing course aggregate gradation and investigation of new job mix formulas.
- The study requires evaluation of bitumen samples from different sources or polymer modified bitumen (PMB).
- The performance enhancement requires adjusting both Type-A and Type-B anti-stripping additives amounts and examining substitute additives to verify compatibility with local aggregates.
- The performance of lime as a mineral filler to improve moisture resistance needs evaluation for comparison with cement.
- The investigation needs to examine how changes in both cement and lime dosages influence asphalt mixture durability.
- HMA moisture sensitivity assessment requires conducting freeze-thaw cycle experiments multiple times to determine its prolonged durability characteristics.

Future research implementations according to these guidelines will grow our understanding of HMA moisture sensitivity while developing field-effective pavement enhancement strategies for Bangladesh.

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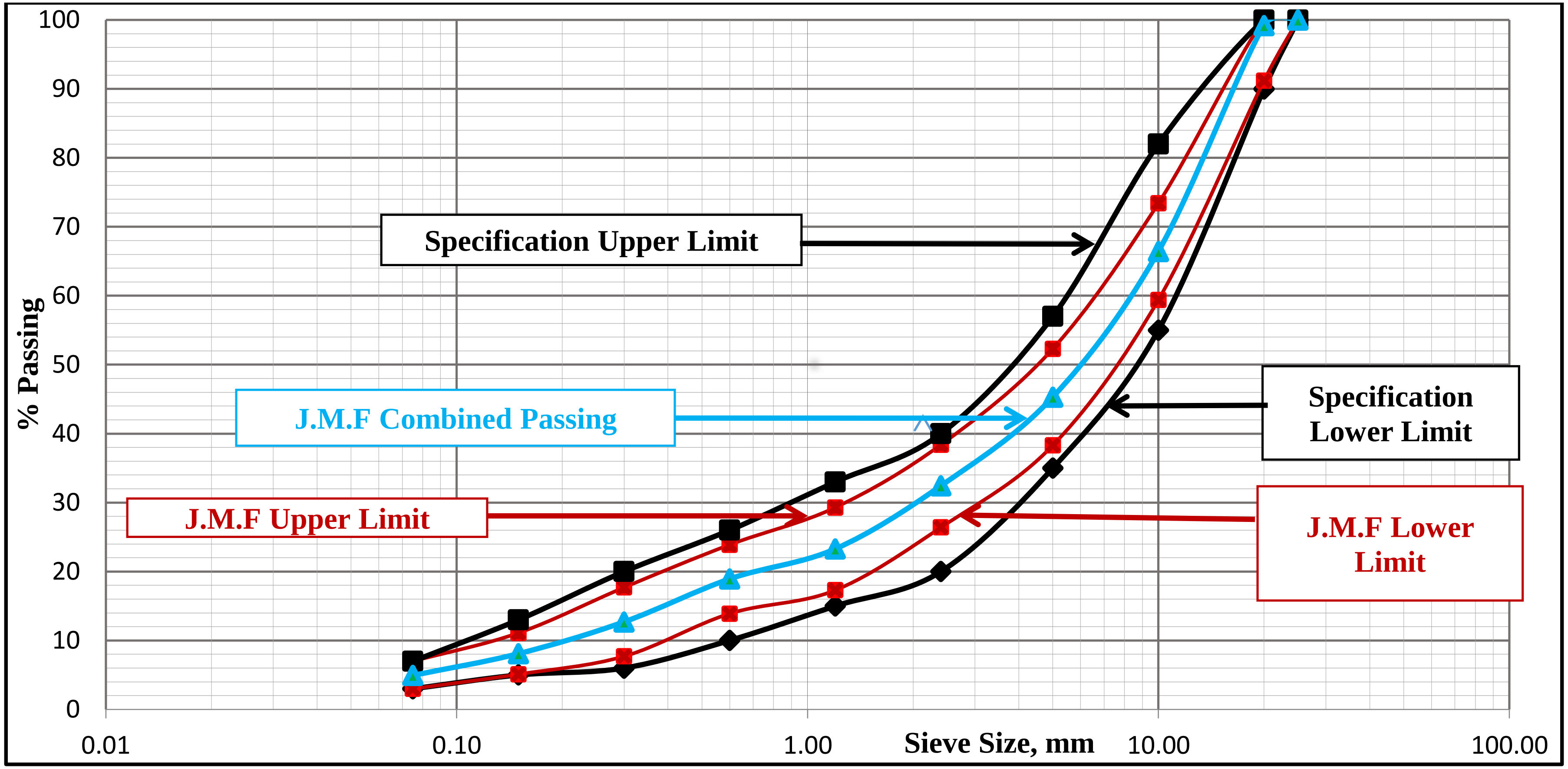
Appendix-I

Source-A Stone Aggregate Combined Gradation (Source: BRT Project, Dhaka)

Description of Materials :				
Aggregate Size No.1 0 mm- 5 mm	20.0%	Aggregate Size No.4 - 200 µm(Stone dust)	24.0%	100.0%
Aggregate Size No.2 5 mm -10 mm	14.0%			
Aggregate Size No.3 10 mm-20 mm	42.0%			

Sieve size in mm	Aggregate Size No.1 0 mm-5 mm	20.0%	Aggregate Size No.2 5 mm -10 mm	14.0%	Aggregate Size No.3 10 mm-20	42.0%	Aggregate Size No.4 - 200 µm(Stone	24.0%	Cement	0.0%	Combined % Passing	J.M.F Mid Line	Job Mix Lower Limit	Job Mix Upper Limit	RHD Specification Limits for Base Course		Jo Mix Tolerances ASTM D3515
	Av. % Passing	% Passing	Av. % Passing	% Passing	Av. % Passing	% Passing	Av. % Passing	% Passing	Av. % Passing	% Passing							
25.00	100.0	20.0	100.0	14.0	100.0	42.0	100.0	24.0	0.0	0.0	100.0	100.0	100.0	100.0	100	100	±8
20.00	100.0	20.0	100.0	14.0	98.1	41.2	100.0	24.0	0.0	0.0	99.2	99.2	91.2	100.0	90	100	±8
10.00	100.0	20.0	94.6	13.2	21.8	9.2	100.0	24.0	0.0	0.0	66.4	66.4	59.4	73.4	55	82	±7
5.00	99.1	19.8	12.6	1.8	1.5	0.6	96.2	23.1	0.0	0.0	45.3	45.3	38.3	52.3	35	57	±7
2.40	47.6	9.5	1.4	0.2	0.6	0.3	93.6	22.5	0.0	0.0	32.4	32.4	26.4	38.4	20	40	±6
1.20	12.7	2.5	0.7	0.1	0.6	0.2	84.9	20.4	0.0	0.0	23.3	23.3	17.3	29.3	15	33	±6
0.600	8.2	1.6	0.0	0.0	0.0	0.0	72.0	17.3	0.0	0.0	18.9	18.9	13.9	23.9	10	26	±5
0.300	6.5	1.3	0.0	0.0	0.0	0.0	47.5	11.4	0.0	0.0	12.7	12.7	7.7	17.7	6	20	±5
0.150	1.3	0.3	0.0	0.0	0.0	0.0	32.5	7.8	0.0	0.0	8.1	8.1	5.1	11.1	5	13	±3
0.075	0.5	0.1	0.0	0.0	0.0	0.0	20.1	4.8	0.0	0.0	4.9	4.9	3.0	7.0	3	7	±3

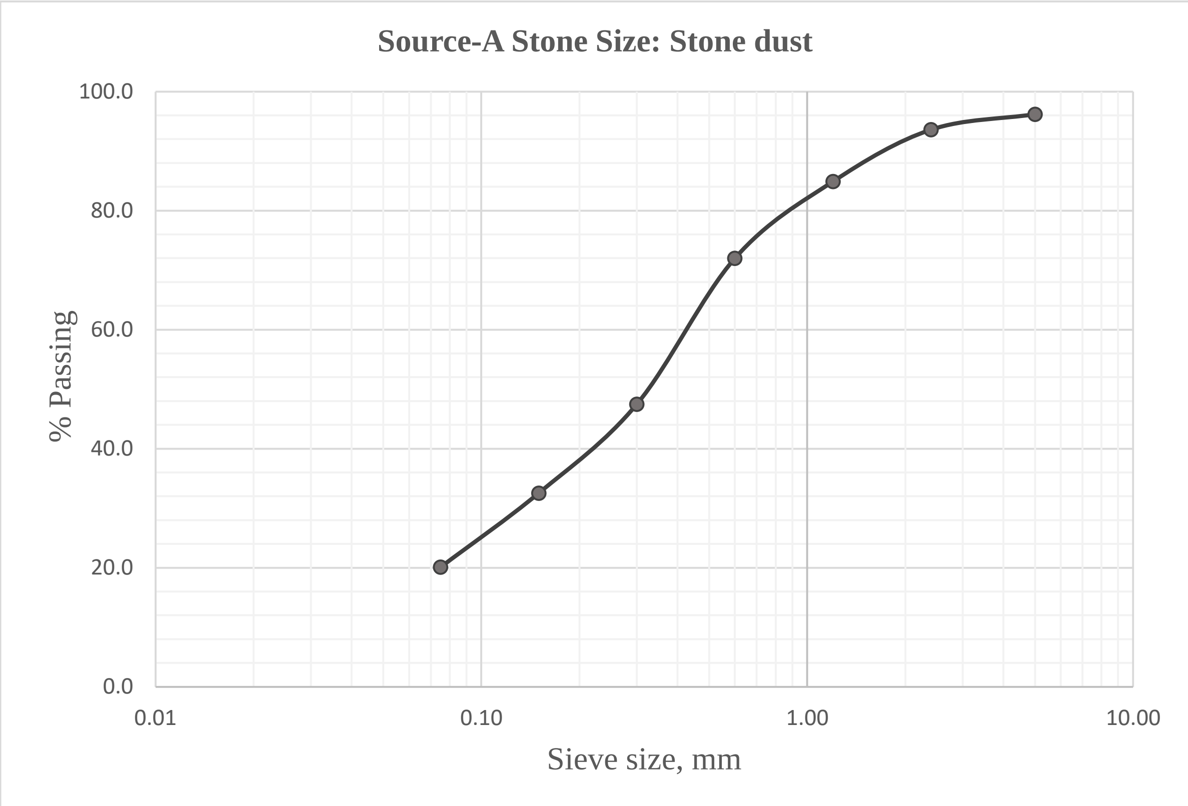


100
90
80
70
60
50
40
30
20
10
0
% Passing
0.01
0.10
1.00
10.00
100.00
Sieve Size, mm
Specification Upper Limit
J.M.F Combined Passing
J.M.F Upper Limit
Specification Lower Limit
J.M.F Lower Limit

Fine Aggregate Sieve Analysis

Aggregate: BRT Project Aggregate (Source-A Stone Aggregate). size: Stone dust

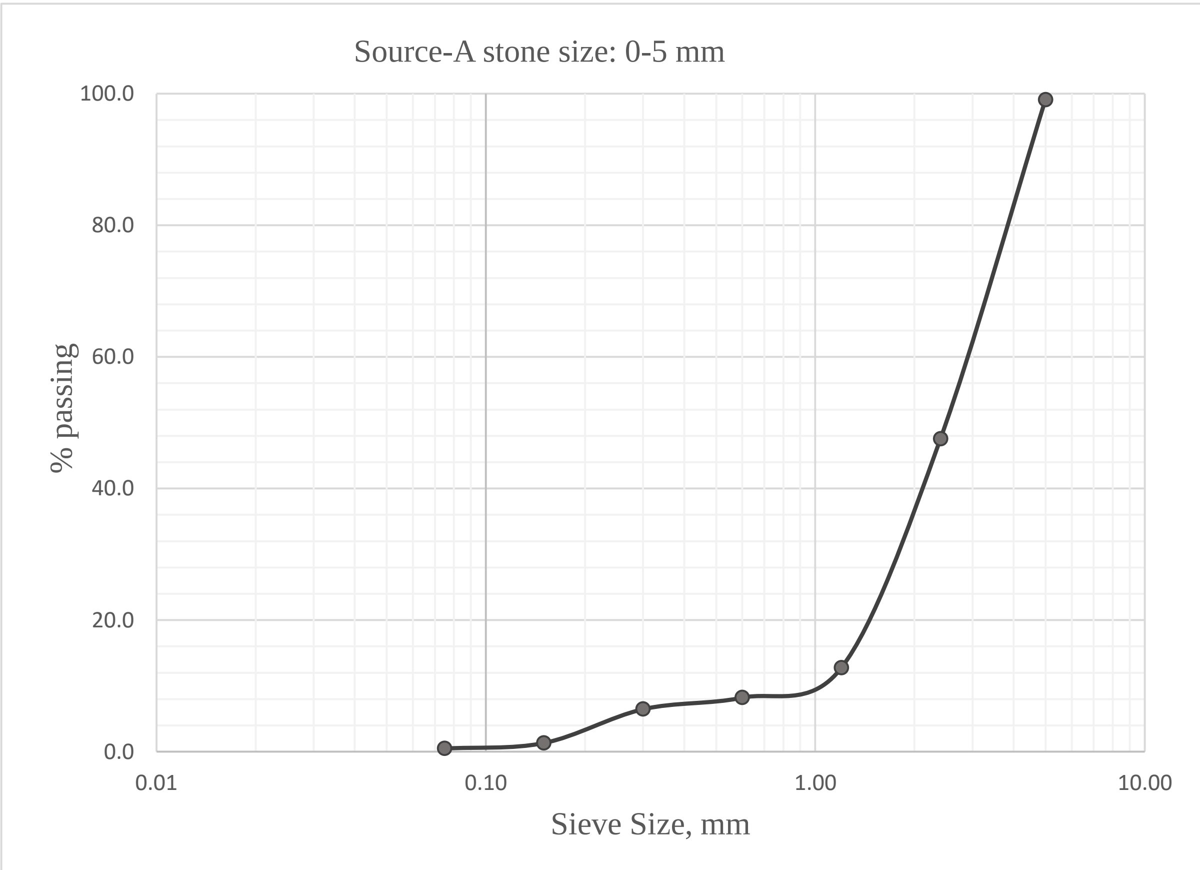
Sieve Size (mm)	Retained wt.(gm)	% wt. of Retained	% cumulative wt. of retained	% passing
5.00	30.3	3.8	3.8	96.2
2.40	20.5	2.6	6.4	93.6
1.20	68.9	8.7	15.1	84.9
0.60	102	12.9	28.0	72.0
0.300	194	24.5	52.5	47.5
0.150	118.2	14.9	67.5	32.5
0.075	98.4	12.4	79.9	20.1
Pan	158.9	20.1	100.0	0.0



Fine Aggregate Sieve Analysis

Aggregate: BRT Project Aggregate (Source-A). size: 0-5 mm

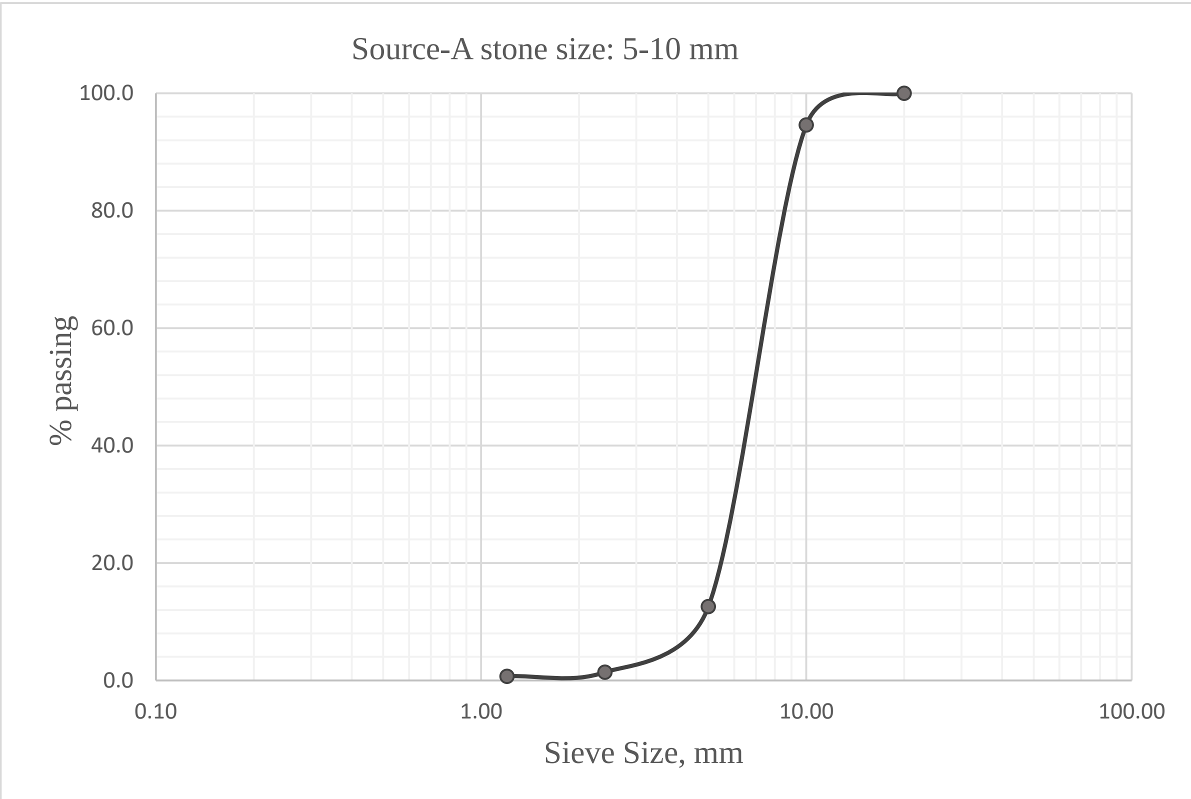
Sieve Size (mm)	Retained wt.(gm)	% wt. of Retained	% cumulative wt. of retained	% passing
5.00	9.9	0.9	0.9	99.1
2.40	568.9	51.5	52.4	47.6
1.20	384.1	34.8	87.3	12.7
0.60	50	4.5	91.8	8.2
0.300	19.4	1.8	93.5	6.5
0.150	56.6	5.1	98.7	1.3
0.075	9.3	0.8	99.5	0.5
Pan	5.4	0.5	100.0	0.0



Coarse Aggregate Sieve Analysis

Aggregate: BRT Project Aggregate (Source-A). size: 5-10 mm

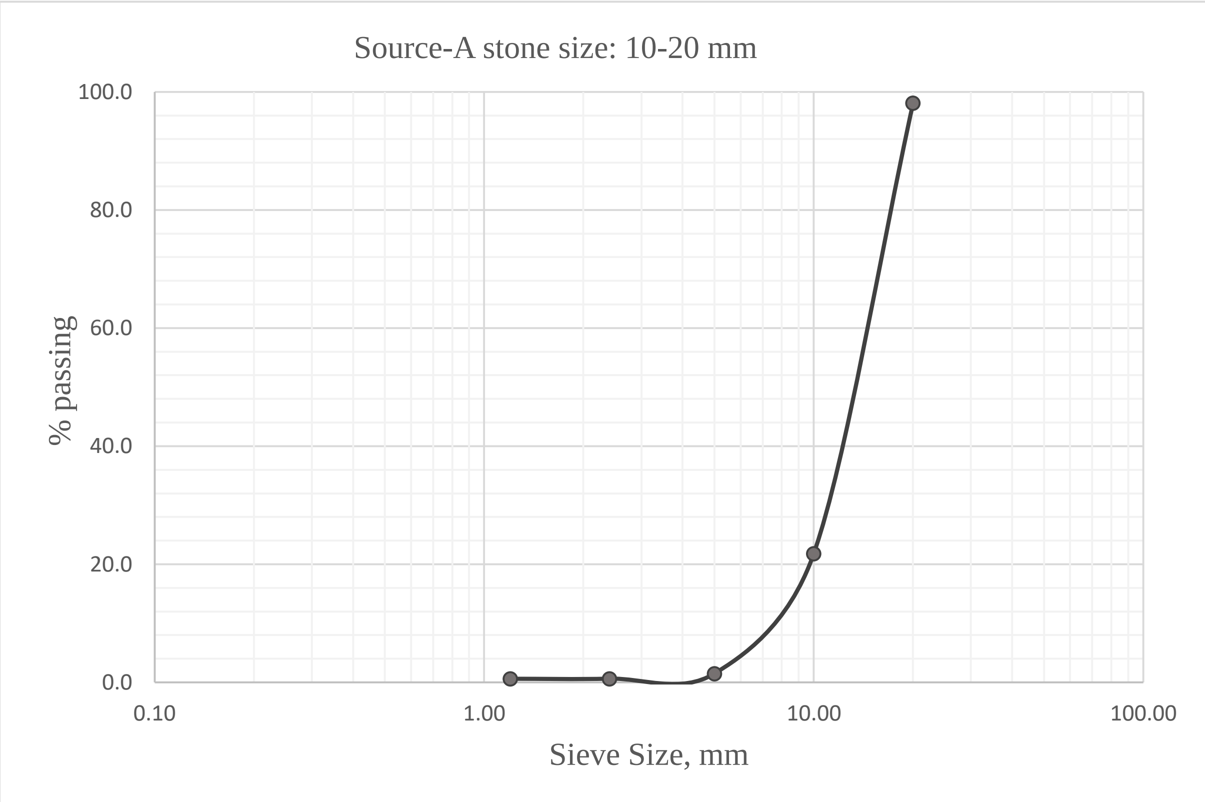
Sieve Size (mm)	Retained wt.(gm)	% wt. of Retained	% cumulative wt. of retained	% passing
20.00	0	0.0	0.0	100.0
10.00	72.2	5.4	5.4	94.6
5.00	1092.6	82.0	87.4	12.6
2.40	149.2	11.2	98.6	1.4
1.20	9.2	0.7	99.3	0.7
Pan	9.5	0.7	100.0	0.0



Coarse Aggregate Sieve Analysis

Aggregate: BRT Project Aggregate (Source-A). size: 10-20 mm

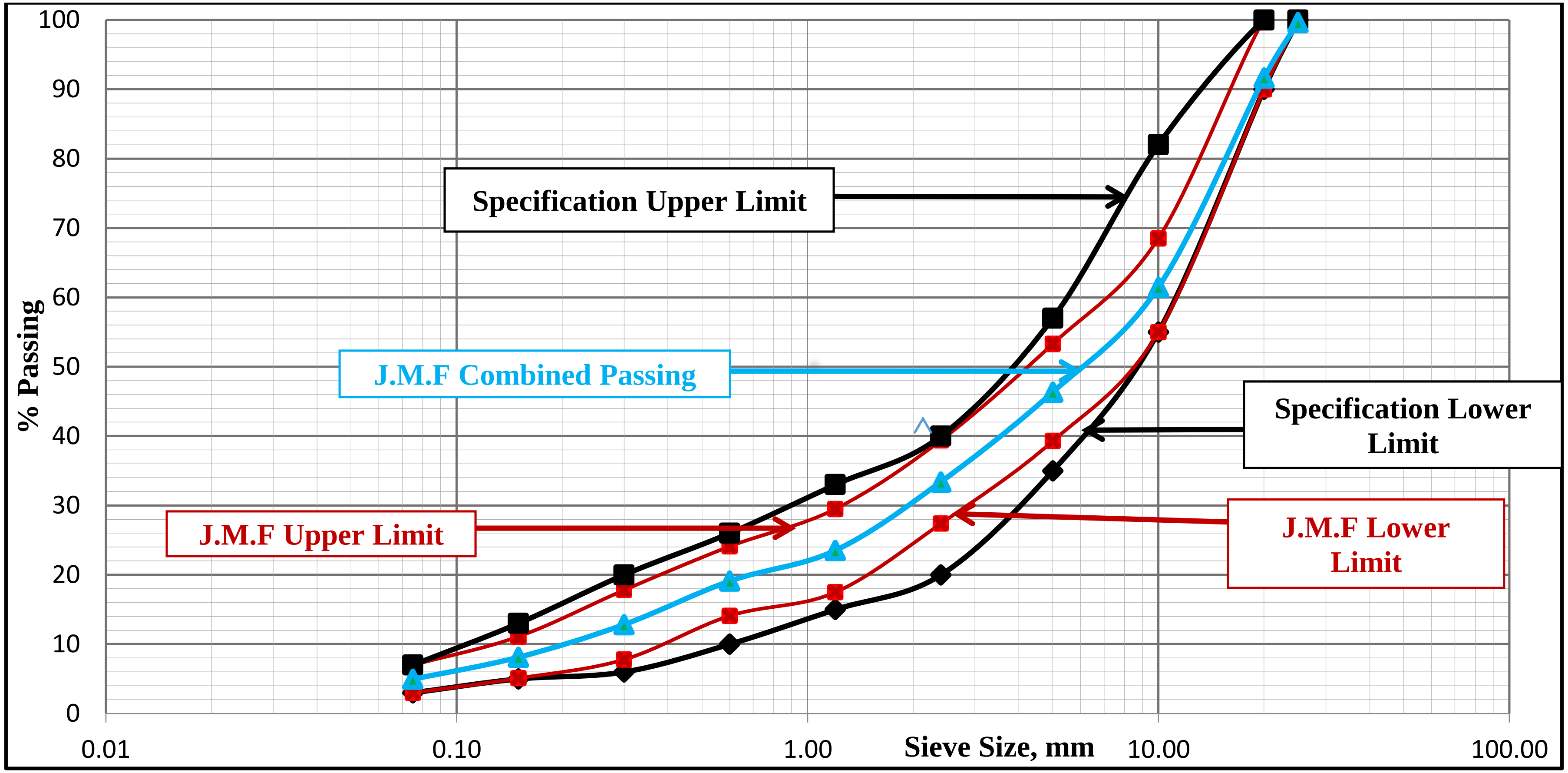
Sieve Size (mm)	Retained wt.(gm)	% wt. of Retained	% cumulative wt. of retained	% passing
20.00	97.3	1.9	1.9	98.1
10.00	3856	76.3	78.2	21.8
5.00	1027.5	20.3	98.5	1.5
2.40	44.2	0.9	99.4	0.6
1.20	0.8	0.0	99.4	0.6
Pan	30	0.6	100.0	0.0



Source-B Stone Aggregate Combined Gradation

Description of Materials :				
Aggregate Size No.1 0 mm. - 5 mm.	22.0%	Aggregate Size No.4 - 200 µm(Stone dust)	24.0%	100.0%
Aggregate Size No.2 5 mm - 10 mm.	16.0%			
Aggregate Size No.3 10 mm - 20 mm.	38.0%			

Sieve size in mm	Aggregate Size No.1 0 mm. - 5 mm. Av. % Passing	22.0% % Passing	Aggregate Size No.2 5 mm - 10 mm. Av. % Passing	16.0% % Passing	Aggregate Size No.3 10 mm - 20 mm. Av. % Passing	38.0% % Passing	Aggregate Size No.4 - 200 µm(Stone Av. % Passing	24.0% % Passing	Cement Av. % Passing	0.0% % Passing	Combined % Passing	J.M.F Mid Line	Job Mix Lower Limit	Job Mix Upper Limit	RHD Specification Limits for Base Course		Jo Mix Tolerances ASTM D3515
25.00	100.0	22.0	100.0	16.0	99.0	37.6	100.0	24.0	0.0	0.0	99.6	99.6	100.0	100.0	100	100	±8
20.00	100.0	22.0	100.0	16.0	78.0	29.6	100.0	24.0	0.0	0.0	91.6	91.6	90.0	100.0	90	100	±8
10.00	100.0	22.0	77.9	12.5	7.9	3.0	100.0	24.0	0.0	0.0	61.5	61.5	55.0	68.5	55	82	±7
5.00	99.1	21.8	7.7	1.2	0.6	0.2	96.2	23.1	0.0	0.0	46.3	46.3	39.3	53.3	35	57	±7
2.40	47.6	10.5	1.9	0.3	0.4	0.2	93.6	22.5	0.0	0.0	33.4	33.4	27.4	39.4	20	40	±6
1.20	12.7	2.8	1.2	0.2	0.4	0.1	84.9	20.4	0.0	0.0	23.5	23.5	17.5	29.5	15	33	±6
0.600	8.2	1.8	0.0	0.0	0.0	0.0	72.0	17.3	0.0	0.0	19.1	19.1	14.1	24.1	10	26	±5
0.300	6.5	1.4	0.0	0.0	0.0	0.0	47.5	11.4	0.0	0.0	12.8	12.8	7.8	17.8	6	20	±5
0.150	1.3	0.3	0.0	0.0	0.0	0.0	32.5	7.8	0.0	0.0	8.1	8.1	5.1	11.1	5	13	±3
0.075	0.5	0.1	0.0	0.0	0.0	0.0	20.1	4.8	0.0	0.0	4.9	4.9	3.0	7.0	3	7	±3



100
90
80
70
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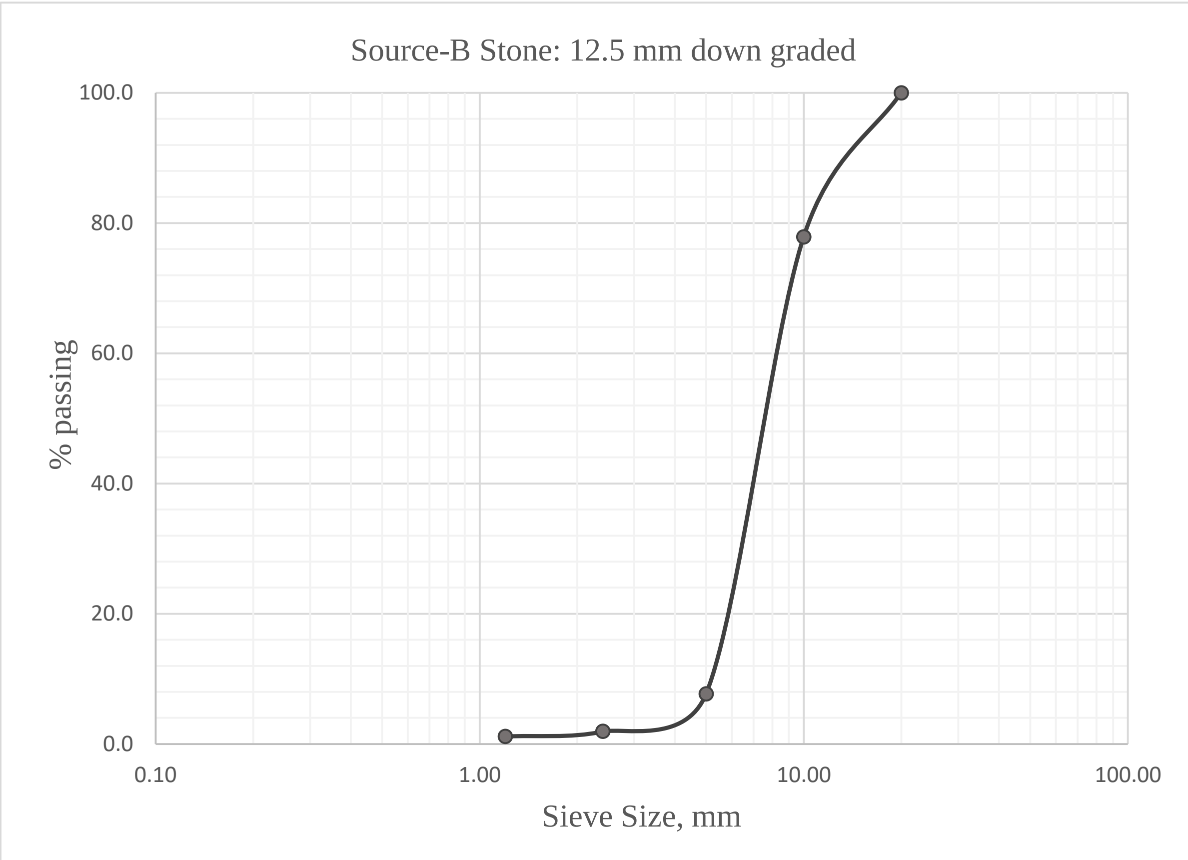
10
0
% Passing
Specification Upper Limit
J.M.F Combined Passing
Specification Lower Limit
J.M.F Upper Limit
J.M.F Lower Limit
0.01
0.10
1.00
Sieve Size, mm
10.00
100.00

Coarse Aggregate Sieve Analysis

Aggregate: Source-B Stone Aggregate size 12.5mm down graded

Sieve Size (mm)	Retained wt.(gm)	% wt. of Retained	% Cumulative Retained	% Passing
20.00	0	0.0	0.0	100.0
10.00	675.6	22.1	22.1	77.9
5.00	2139.8	70.1	92.3	7.7
2.40	176.3	5.8	98.1	1.9
1.20	23.2	0.8	98.8	1.2
Pan	35.7	1.2	100.0	0.0



Coarse Aggregate Sieve Analysis

Aggregate: Source-B Stone Aggregate size 20mm down graded

Sieve Size (mm)	Retained wt. (gm)	% wt. of Retained	% Cumulative Retained	% Passing
25.00	57.1	1.0	1.0	99.0
20.00	1259	21.0	22.0	78.0
10.00	4197.1	70.1	92.1	7.9
5.00	437.3	7.3	99.4	0.6
2.40	9.2	0.2	99.6	0.4
1.20	3.3	0.1	99.6	0.4
Pan	22.3	0.4	100.0	0.0