DEVELOPMENT OF MARBLE DUST BASED SUSTAINABLE CEMENTITIOUS GROUT FOR SEMI FLEXIBLE PAVEMENT APPLICATION

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A thesis submitted in partial

fulfillment of the requirement for

Master of Science

in

Transportation Engineering

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CERTIFICATE OF THESIS ACCEPTANCE

It is to certify that the undersigned reviewed the final version of the master's thesis (MS thesis) written by Engr. Muhammad Nouman Khan, Reg. No. 00000318023 of the Military College of Engineering (MCE) NUST, Risalpur Campus, and found it to be partially satisfactory for the award of an MS degree in transportation engineering. The thesis was completed in accordance with NUST statutes and regulations and was free of plagiarism and errors. It is also confirmed that the revisions recommended by the scholar's GEC members have been included in the aforementioned thesis.

Signature: ______________________________

Name of Supervisor: Dr. Muhammad Imran Khan__

Date: ___________17/08/2023_________________

Signature (**H.O.D**): __________________________

Date: ___________17/08/2023_________________

DEDICATION

This research achievement is dedicated to my wife, parents, family, research supervisor and GEC members.

ACKNOWLEDGEMENT

I'm grateful to Allah Ta'ala for granting me the stamina to complete this task. Without his grace and favors, I might not have been able to do my assignment while he granted me the patience and wisdom to get out of challenging circumstances and granted my requests.

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(Engr. Muhammad Nouman Khan)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AASHTO	-American Association of State Highway and Transportation Officials
ASTM	-American Society for Testing Materials
NCAT	-National Centre for Asphalt Technology
NCHRP	-National Cooperative Highway Research Program
TRB	-Transportation Research Program
DOT	-Department of Transportation
NHA	-National Highway Authority
BS	-British Standards
HMA	-Hot Mix Asphalt
MD	-Marble Dust
SP	-Superplasticizer
OPC	-Ordinary Portland Cement
ARL	-Attock Refinery Limited
DGA	-Dense Graded Asphalt
OGAS	-Open Graded Asphalt Skeleton
DM	-Dynamic Modulus
ESAL	-Equivalent Single Axle Load
G_{mb}	-Bulk Specific Gravity
G_{mm}	-Maximum Theoretical Specific Gravity
V_A	-Air Voids
VFA	-Voids Filled with Asphalt
VMA	-Voids in Mineral Aggregate
HWTT	-Hamburg Wheel Tracking Test
ITS	-Indirect Tensile Strength
ITSM	-Indirect Tensile Strength Modulus
MR	-Resilient Modulus
NMAS	-Nominal Maximum Aggregate Size
RMR	-Resilient Modulus Ratio
TSR	-Tensile Strength Ratio
SEM	-Scanning Electronic Microscopy
EDS	-Energy Dispersive X- Spectroscopy

ABSTRACT

The topmost layer of grouted macadam comprised of a semi flexible material that has numerous advantages over concrete and conventional bitumen. It is resistant to rutting and has a certain amount of flexibility. It is made up of a cementitious slurry that is grouted into a framework of open-graded asphalt that has voids between 25% and 35% in volume. Because of its impermeable covering, it also prevents water from seeping into the base of the structure. This investigation focuses on Marble Dust (MD)-based cementitious grouting for semi flexible pavement applications. The experimental design includes preparation of Marble Dust (MD) based sustainable cementitious grout with 6 different percentages of marble dust ranging from 0% to 25% substitution in cement. Water to cement ratio (w/c) for preparation of grout ranges from 0.35 to 0.5 at an increment of 0.5 based on previous research studies and a constant superplasticizer of 0.5% to achieve the flowability. Mortar was prepared using Hobart Mortar mixer and flowability at each replacement level were recorded. Compressive strength tests of grouts (7-days & 28-days) were performed at each replacement level in triplicate. Response Surface Methodology (RSM) was also used to optimize the independent variable known as factor (MD, w/c) and to achieve desired outcome that is response (Flow, Compressive strength) Based on experiment results and RSM optimization with predicted model R^2 of greater than 0.9 it was concluded that up to 15% of cement replacement by MD with w/c of 0.4 reveals identical results to the control mix and within specification limits of grout for semi-flexible pavement application. Microstructure analysis SEM and EDS were performed on optimum and control grouts to analyze the behavior of marble dust in grout. From analysis it was confirmed that MD being inert filler improved density by reducing pores, cracks, and lower Ca/Si ratio. Open graded specimens were prepared at OBC of 3.0% and cement grout (with optimum combination) was poured on surface with infiltration ranged from 94% to 97%. The final composite that is Semi-flexible pavement prepared with MD based sustainable cementitious grout were subjected to different physical and performance tests as per standards. Marshall stability increased up to 70%, Tensile strength ratio of SFM-MD is 30% enhanced as compared to HMA, stiffness modulus enhanced at high and low temperature, dynamic modulus performed double the HMA at high temperature and low frequency and fuel resistance of semi-flexible mix increased more the 600% as compared to conventional HMA. The new hybrid semi-flexible and joint-free topping is superior for durability and wear resistance, according to findings.

CHAPTER 1

INTRODUCTION

1.1 Study Background

Any nation's socioeconomic progress depends on transport and communication. Economic growth is increasingly connected to transport efficiency. Pakistan's economy is heavily impacted by transport and road infrastructure. In today's world, road infrastructure determines a nation's development. Pakistan's 260,000 km road network connects towns and villages, with 156,000 km (60%) paved and 104,000 km (40%) unpaved. All roads under NHA, FWO, C&W, and other government agencies motorways, highways, major or national roads, minor or regional roads make up the road network.

Pakistan uses flexible and rigid pavements for the construction of roads and repair. Flexible pavements have multiple layers with various properties and purposes. Due to traffic loading, climate, and construction quality, flexible pavements develop distresses including rutting, cracking, roughness, longitudinal and transverse cracking. Rigid pavements have a single layer of concrete reinforced with steel bars. Rigid Pavement is expensive and lasts longer to lower life cycle cost, resulting in a smooth and slippery surface. Opening to traffic requires a 28-day curing time. Cracks in bound layers enable water to infiltrate the granular layers and subgrade, degrading pavement prematurely.

Semi-flexible surface courses have been utilized to combines the finest properties of conventional flexible and rigid pavements, such as jointless, prolonged service life, and high load bearing capacity, while protecting the foundation from water. Semi-flexible mix comprised of open-graded asphalt structure having 25-35% voids space filled with cementitious grout. That hybrid mixture is fuel- and oil-resistant and rut-resistant for heavy-duty pavements in industrial areas, airports, and harbors with slow traffic. Grouting macadams is a two-day process. Flexible pavement construction machinery applies open-graded asphalt first. The day after the asphalt gets cooled, rubber scrapers distribute the grout over the top surface, penetrating the asphalt's voids to the base of the layer. The advantageous qualities of this mix are dependent on the connection of the voids so that grout may properly infiltrate through them and the flowability of the grout to saturate the voids. Empty voids leads to pavement failure.

Cement production is a significant source of carbon emissions, and replacing cement in mortar with byproducts or industrial refuse can help reduce the carbon footprint of the production process. Pakistan's marble industry produces marble dust. Pakistan produces marble dust based on marble extraction and processing. Pakistan has around 1,800 marble processing plants and produces 3 million tons of marble goods annually, according to PASDEC. Pakistan produces marble dust through cutting, grinding, and polishing machinery. Marble dust can substitute cement in mortar and concrete.

However, marble dust disposal in Pakistan is a big issue due to its environmental and health risks. Dust contaminates air and soil, causing respiratory concerns for employees and adjacent populations. Marble dust disposal can pollute groundwater and soil.

Pakistan's marble dust disposal rules address these challenges. PASDEC also promotes marble waste utilization in infrastructure construction and tile and brick manufacturing. These projects support sustainable growth and minimize Pakistan's marble industry's environmental effect. These considerations support the importance of the work being done on this project, the results of which will advance the design of a sustainable cementitious grout based on MD for use in semi-flexible pavements.

1.2 Problem Statement

Pakistan's transportation network relies largely on conventional flexible and rigid pavements, which have performance and maintenance limitations. These pavements are susceptible to a variety of distresses, which reduces their service life, raises maintenance expenses, and compromises road user safety. Common pavement distresses in Pakistan include rutting, fatigue cracking, and reflective cracking, which are caused by large axle loads, high traffic volume, and temperature variations. In contrast, subgrade settlement, temperature variations, and traffic pressures can cause joint spalling, faulting, and cracking in rigid pavements.

Semi-flexible pavement, which incorporates the benefits of flexible and rigid pavements, has the potential to help with these problems by providing a more durable, structurally sound, and cost-effective pavement type.

One promising solution to these challenges is the use of environmentally friendly cement grout for semi-rigid pavements, which incorporates partial cement replacement with marble dust. Marble dust, a byproduct of marble cutting and polishing, may reduce waste and pollution when used in construction. Additionally, the incorporation of marble dust can enhance mechanical qualities of the cementitious grout, resulting in a more durable and sustainable pavement.

Marble dust-based cementitious grout will be compared to standard pavement materials for strength, durability, and environmental effect. The study will also evaluate the cost of raw materials, transportation, and construction for semi-flexible pavement construction in Pakistan. This study will reveal the benefits as well as the limitations of marble dust-based sustainable cement grout for semi-flexible surface in Pakistan. This research seeks to improve Pakistan's quality of life by delivering an ecologically friendly and cost-effective pavement alternative.

1.3 Research Objectives

The primary objective of this investigation is to evaluate the suitability of a sustainable cementitious grout made from marble dust for semi-flexible pavement in Pakistan as an alternative to conventional flexible and rigid pavements. The particular goals of the research study are stated below:

- To investigate the viability of substituting Marble Dust (MD) in cementitious grouts for the application of semi-flexible pavements.
- To evaluate the mechanical, performance and microstructure characteristics of the cementitious grouts that contains Marble Dust (MD) and to optimize their constituents using the RSM tool.
- To examine the performance properties of the semi-flexible mix containing Marble Dust (MD) based cement grouts.

1.4 Scope of this Study

This study objectives were established, and a methodology and list of activities were developed to achieve them. In this investigation, we will make cementitious grout by substituting some of the cement with MD (at concentrations between 5%, 10%, 15%, 20%, 25%). In addition, the water-to-cement ratio ranges from 0.35, 0.40, 0.45 to 0.5 and amount of superplasticizer (SP) (0.5%) will be maintained Compressive strength, as well as flowability, will be tested on the grouts. We will employ statistical analysis to find the best mix of w/c and MD. The optimized and final chosen and highly flowable cement grout will be put over the pre-design and prepared open-graded asphaltic mix (25-35% voids) and allowed to penetrate under gravity and minimal vibration so that the grout fills the gaps. After curing, semi-flexible specimens will be tested for grout saturation, volumetric characteristics, Marshall stability, moisture & fuel resistance, indirect tensile strength, compressive strength, dynamic and resilient modulus.

The semi-flexible pavement created by partially replacing cement with Marble Dust (MD) will reduce land filling costs and the negative health effects of MD disposal.

1.5 Study Limitations

The utilization of semi-flexible pavement surfacing is constrained to particular and specialized road segments. These pavements are typically constructed in road sections that experience significant vehicular load, either in the form of heavy traffic or slow-moving and static loads. Additionally, they are suitable for areas where the pavement surface is exposed to fuel spillage. Some examples of infrastructure elements include bus terminals/stops, loading/unloading bays, industrial parking areas, signalized road intersections, toll plazas, oil refineries, gas stations, and airport aprons and taxiways, among others.

1.6 Significance

The study's findings will help stakeholders and road construction agencies find environmentally and economically viable ways to reuse leftover marble dust in the production of semi-flexible pavement surfacings. It'll also be a great solution for reusing marble dust that would otherwise be dumped in landfills or flushed down the drain. When employed in road construction that is subjected to severe loadings and exposed to gasoline, this sort of semi-flexible pavement surface would give strong resistance against rutting, fatigue, and fuel spills. Road interchanges, bus terminals, loading zones, petrol stations, oil refineries, airport runways, and refueling areas are just some of the potential locations for the semi-flexible pavement covering made from discarded marble dust.

A novel approach was employed to incorporate waste marble dust as a partial substitute for cement in cementitious grouts for semi-flexible pavement application. Currently there is rare research on the substitution of cement with waste marble dust and its utilization in cementitious grouts for semi-flexible pavement surfacings. Furthermore, a significant gap exists in the literature regarding the utilization of an experimental design and analysis tool to effectively design, analyze, and optimize the compositions of cement grout. Consequently, the formulation of cementitious grout was additionally devised, examined, modeled, and enhanced through the utilization of an experimental design technique referred to as "Response Surface Methodology". Furthermore, the optimized formulations of grouts were subsequently employed in the fabrication of semi-flexible specimens, which were then assessed for their performance characteristics and resistance to fuel spillage. The construction industry also focusing on using various byproducts. Hence, this study can be a benchmark for designer, and contractor to utilize waste marble dust for pavement construction.

1.7 Thesis Structure and Organization

This study's findings are presented in the five major chapters.

Chapter-1 Provides a brief introduction about the investigation, including the historical context that led to the formation of the problem statement. In addition, the objectives to achieve, also the scope of the intended research were discussed.

Chapter 2 We will take a quick look at the many pavements that have been utilized in the past to build roads. In addition to the primary research topic of semi-flexible pavement surface, a thorough literature evaluation is conducted. Semi-flexible pavement surfacings of varying gradations utilized in the lab and on the road are discussed in this chapter as well. In this chapter, we also examine the properties of cementitious grout and its various formulations.

Chapter 3 In this section, we detail the approach used in order to complete the stated goals of this study. It describes the components and features of the materials that were tested. In this chapter, we'll go through the procedures and protocols for making and testing cementitious grouts. As part of the process of designing, analyzing, and optimizing the grout's composition, the "Response Surface Methodology" experimental design and analysis tool is taken into account. This chapter also details the experimental methodologies and processes used to assess the efficiency of semi-flexible mixes. The process also covers designing a semi-flexible pavement and ensuring that grout is compatible with asphalt.

Chapter 4 The findings and analysis of the cementitious grouts designed for the semi-flexible surface are presented in this chapter. The microstructure and performance characteristics of cement grouts containing varied amounts of waste marble dust are also evaluated. This chapter also includes the ANOVA findings and the RSM analysis-derived prediction equation. Discussion follows the findings about microstructural analysis of cement grouts. Further the performance characteristics of semi-flexible mixes are also discussed and the findings are presented. The Marshall stability, tensile strength ration, moisture resistance, and comparability of semi-flexible mixes to traditional HMA combinations were also covered. The findings of the stiffness and dynamic modulus of semi-flexible and HMA mixes are described in detail. In terms of their fuel resistance, a comparison between semi-flexible and HMA is also provided.

Chapter 5 In the last chapter a summary about key findings from this research is provided that were covered in the preceding chapter. The suggestion for potential future work is also made here.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The chapter discuss varieties of the road pavement. The materials utilized in the different structures type are also specified. The main pavement design methods are provided to help the project. Traffic is maintained by road pavements. Structure is required to sustain vehicles loads providing a surface with sufficient smoothness with slip resistance for vehicles and user comfort and safety because the route selection procedure does not account for the bearing capacity of the bottom layer. Due to vehicle loads and bad weather, the subgrade would permanently distort or collapse without this protection structure.

2.2 Types of Pavements

The surface layer, also referred to as the wearing course, is responsible for preventing water from permeating the subgrade through the pavement construction while also providing adequate riding attributes (skid resistance, noise, spray, etc.). Therefore, the surface course should prevent water from penetrating into the gaps or fractures and altering the layers underneath, lowering the pavement's weight-bearing capacity. Based on the top layer materials and how they perform, pavements are classified as flexible, rigid, rigid composite & semi-flexible.

Granular materials, mechanically stabilized, make lower layers of each of the four categories of pavements trafficable during construction and increase their bearing capacity without increasing costs. Semi-flexible surface can combine the finest characteristics of both flexible pavement and rigid pavements, such as joint-free nature of asphalt, the strength and load-bearing capacity of rigid pavement. The impermeable surface of pavement combined with grout to provides excellent protection against water intrusion for the foundation. This paving material necessitates a two-step setup process. However, the time required before traffic can be opened is significantly shorter than when concrete is used.

Table 2.1 Different Type Roads Surface & Their Main Features [1]

Type of Pavements	Merits	Demerits
Flexible Pavement	Flexible, good riding quality, jointless, quickly serviceable	Limitations on static bearing capacity and service life
Concrete Pavement	High carrying capacity and strength	Slow setting, fractures, joints, and thick layers
Semi Rigid Pavement	Excellent riding quality and high bearing capacity	Cracked foundation, reflecting cracking, and surface rutting
Semi-flexible Pavement	high strength, lack of joints, increased durability, flexibility, and ease of maintenance	Building of the surface course in two stages

2.2.1 Flexible Pavement

The topmost layers of a flexible pavement are composed of bituminous materials. A number of asphaltic mixtures may be utilized in these layers depends on their function. To prevent water from penetrating to the layers below (unless in the case of porous asphalt), the surface course must be generally impermeable and offer sufficient skid resistance for the vehicles. Figure 2.1 depicts an example of a flexible pavement structure. The foundation, which comprises the subbase and any sealing (used), is often granular materials. The surface layers are typically bituminous, the base could be bituminous or granular in nature. The more costly layers are positioned on top of the base as a platform. Its goal is to spread out the stresses brought on by heavy traffic so that they may be transferred to the subgrade without causing discomfort. Additionally, it may be utilized to prevent subgrade disruption in areas where frost protection is crucial. The pavement's foundation is a crucial component both during construction and throughout its useful life, when the forces imposed by continuous traffic may be much greater than those produced during operation.

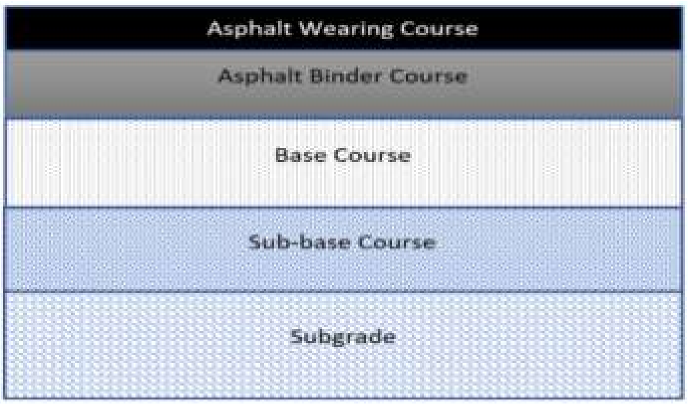


Figure 2.1 Components of flexible pavements

2.2.2 Rigid Pavement

Rigid pavements, often known as concrete road, typically have structural components of sub-base and the concrete surface slab. In concrete pavement, the top and bottom layers may each include a different kind of aggregate. It is also possible to utilize a capping layer, higher and lower layers of the subbase [2]. Poor subgrades may be protected and improved using the capping approach, which involves sandwiching an economical material above the subgrade. Depending on the concrete slab type used, the pavement structure may vary, but its general composition remains the same (Figure 2.2). The concrete slab may or may not be strengthened, and it may or may not contain joints.

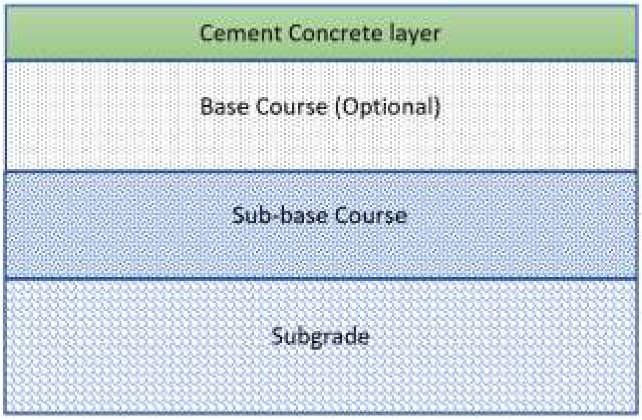


Figure 2.2 Components of concrete pavements

Transverse joints are often created by cutting the concrete block across at least a third of its thickness. Expansion joints are very sometimes used in the winter and only in specialized circumstances, such as on bridges or other structures that are coming closer together. If the surface width is greater than 4.50 meters, a longitudinal joint is often constructed across the traffic lanes to prevent longitudinal fractures from occurring across the axis of the pavement. With the exception of small highways, joints are frequently filled with a bituminous filler after a suitable-sized groove is made on the top surface of the junction. [3].

Rigid pavements are normally anticipated to maintain their structural integrity for a design life of ranging from 30 to 40 years (however some roads are built for an unlimited service life). Nevertheless, during the course of their existence, these pavements undergo frequent surface treatments in an effort to regain their riding qualities, particularly their skid resistance. A slab's collapse is often determined by the appearance of large fractures along the whole width of the slab. However, since a thorough depth repair is often necessary, rehabilitating concrete pavements with localized distress (such as shallow spalling and joint sealant loss) is sometimes more expensive and difficult than rehabilitating flexible pavements. The enormous overabundance of heavy reinforcement in the concrete slab makes this issue worse in continuously reinforced pavements.

2.2.3 Concrete Composite Pavement

Concrete composite pavement is a form of pavement that consists of an asphaltic surface and a cement concrete foundation. It is a composite type of pavement. Figure 2.3 depicts the usual layers that are used in the construction of rigid composite pavement.

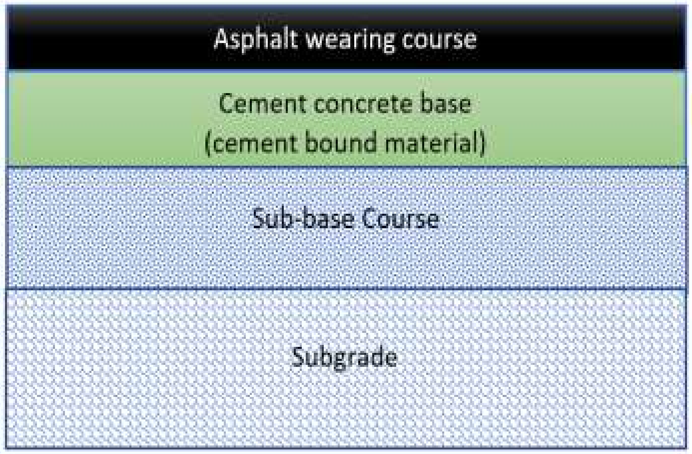


Figure 2.3 The typical layers found in a stiff composite pavement

Cracking that runs transverse to the direction of the pavement is the kind of damage that shows up most often in stiff composite pavement. These fractures appear in the top layer as a mirror of the fissures that first appeared in the cement-bound components (the concrete foundation). The generated stresses in the concrete slab (due to external load or internal stress owing to shrinkage and hydration of cement) are greater than the tensile strength, which results in fractures. This may be caused by either external load or internal stress.

2.2.4 Semi Flexible Pavement

When flexible layers are present at the top, roads or paved areas exposed to heavy and low frequency, majority of the traffic is canalized, like a buses lane, parking lots, taxiways, distribution facilities, are more susceptible to continuous deformation of the pavement structure. These locations are usually constructed with rigid pavements consequently. When opposed to flexible pavements, concrete pavements' principal drawbacks include construction delays and the need for seams to allow for thermal movement of the concrete, which prevents the development of distributed fractures in the pavement since such movements are restricted.

In order to offer a semi flexible surface layer that is joint-free, resistant to rutting and fractures, a third kind of material has been designed as shown in figure 2.4.

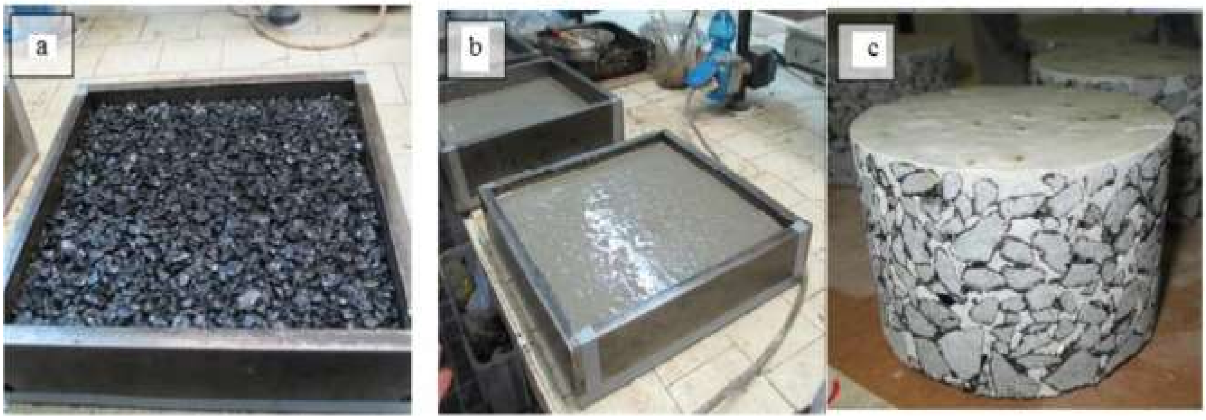


Figure 2.4 Steps of semi-flexible Mix construction (a) Open-graded asphalt mixture (b) Introducing grout into the asphalt mixture (c) Specimen after curing process (Corradini et al. 2017)

In France the procedure of semi flexible pavement originated in 1950s to safegaurd asphalt surface courses against the adverse effects of discarded oils and fuels [4]. This method, known as Salviacim, was improved upon as a more affordable substitute for Portland cement concrete by the French construction Jean Lefebvre Enterprises [1]. Following the success of the Salviacim, its use extended to nations such as the U.K, South Africa, Australia, Japan, and Saudi Arabia [5]. Since then, comparable items have been utilized with various labels based on locale. As a result, it is named as Resin Modified Pavement (RMP) in the United States [6]. Hardicrete Heavy Duty Surfacing is a product available throughout Europe [7]. Worthycim Heavy Duty Paving (BBA, 1996), Densiphalt® [8] to mention some of the brand names.

These pavements have excellent bearing capacity and rut resistance, therefore which are typically referred to as semi-flexible pavements, such as industrial, warehouses, distribution centers, workshops, harbors, road intersections, buses stations, parking lots with a lot of vehicles, airport roadways, retaining bays, cargo places, also places expecting loaded traffic, are the most common application fields [9]. For instance, the Copenhagen Airport's 165000 m2 of grouted macadams were built between 1988 and 2000 [10].

2.3 Components of Semi Flexible Pavement

SFP construction typically has two phases. In the beginning, machinery lighter than or equivalent to that used in AC is utilized to prepare and pave the OGA mattress. The HCM may be applied to the surface once the asphalt has cooled. Because OGA's voids are well connected, HCM may penetrate the whole layer using rubber scrapers and light vibratory rollers to produce an extremely low residential void rate for SFP. Through a variety of days of curing, the SFP gradually acquires the strength needed for traffic. Due to current difficulties, mechanical analysis, and damage avoidance, such as cracks, have become more difficult. The advantageous qualities of this model depend on careful construction process management [11].

2.3.1 Aggregates

The size, type, and aggregate properties used to produce SFM vary based on the patent or the authors' or suppliers' recommendations. It primarily maintains traffic loads' compressive pressures and produces OGA inter-air voids. As a result, the proper gradation may provide a high compressive strength as well as a consistent and linked void [11]. The performance and characteristics of the finished mix are greatly influenced upon selection of the gradation. The aggregate of single-sized for open-graded asphalt gradation is commonly used to make porous asphalt mixes. In order to create mixes for semi flexible pavement applications, typically 90 to 95 percent of coarse particles, 4 to 5 percent fine aggregate, and 2 to 4 percent filler material are used in the formulation [12] (Saboo et al. 2019). For grouted macadam to fully permeate the layer, the recommended gradation should offer 25 to 35% air voids in the open-graded asphalt mixture. Only a modest bitumen quantity (2% to 4% by weight) is utilized since the open-graded gradation has high quantity of coarse aggregate and extremely low quantity of particles and additives [13]. Densiphalt type 12 was found to be the appropriate porous asphalt mix that may be applied to pavement surfaces that are semi-flexible, hence this mixture was selected [13]. As shown in Figure 2.7, numerous gradation techniques have been used in the past by various researchers for the mixture producing of the porous bitumen skeleton.

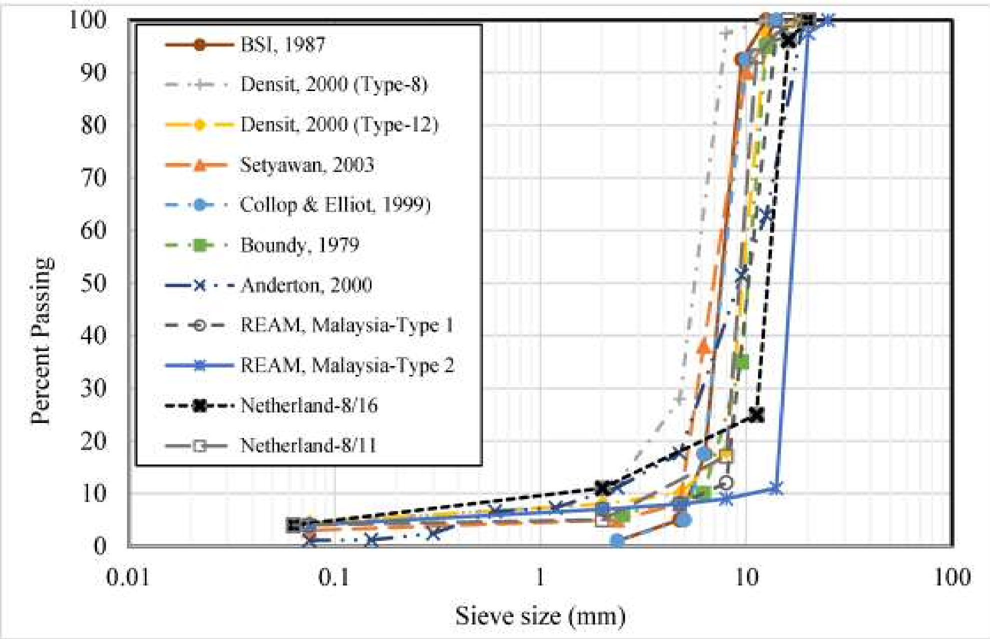


Figure 2.5 Porous aggregate gradation used in past studies (M. I. Khan et al. 2022)

2.3.2 Cementitious Grout

Typically, the necessity to create a substance that can be easily percolate into the cracks of the asphaltic skeleton determines the composition of grout. Additionally, the grout has to be strong enough to resist applying pressures and strains without crumbling. Water to cement ratio is the most crucial element in influencing the workability and strength of cement mortar [11]. Cement paste without sand and cement mortar with the proper formulas may both be utilized as a grouting material; however cement grout was advised owing to its higher performance [14]. The most common ingredients in grouting are a combination of sand, cement, water, mineral additives, and chemical additives. The basic components are cement, mineral admixture, sand, and water. The bulk of which are industrial wastes, react similarly to Portland cement, to improve specific performance chemical additives are utilized without pozzolanic reaction [15]. For semi-flexible macadam surface applications, several commercial grouts are also offered in the UK, Canada, and other countries. Information on a number of commercially available cement grouts is included in the summary that follows.

2.3.3 Water to Cement Ratio

The grouts should be flowable in order to saturate the porous bitumen structure of semi-flexible paving surfaces. Compressive strength and flowability of cementitious grouts are dependent on water-to-cement ratio. Using compression strength data from the 7-day and 28-day curing periods, a variety of water-to-cement ratios (0.35, 0.40, 0.45, and 0.5) were presented to identify the optimal w/c ratio.

After 7 days of curing at a water to cement ratio of 0.40, the desired strength of 15–35 MPa was attained [16]. Water-to-cement ratio and the amount of superplasticizer in grout formulations for usage on grouted macadam surfaces were optimized by [17] using a response surface technique. The effects of cemented paste and cement mortar formulation and composition as a grout for semi flexible pavement were examined by [14]. For cement grout and cement mortar, water-to-cement ratio had great influence on fluidity, strength, and dry shrinkage.

[18] looked at how the composition of grouting materials affected their effectiveness. They concluded from range study that w/c contributed most to the dry shrinkage and 7 days strength and that it had a little impact on fluidity. The results of both experiments showed that water to cement ratio was the most critical element. Then, but not least, enough water ensures that fresh grouts remain fluid while maintaining enough strength. W/c should be between 0.3 and 0.6, and w/b should be between 0.25-0.55 [15].

2.3.4 Superplasticizer

The main purpose of superplasticizers, a frequent addition for grouting materials, is to guarantee enough fluidity [17], [19], [20], [21]. Specifically, one of the most important factors affecting how easily grout flows is the adsorption of superplasticizers. In a study [22] has put up a model to describe the relevance of the influence it has on the flow time. Their investigation showed that the superplasticizer had a capacity for particle dispersion, avoiding the agglomeration of cement particles, as depicted in Figure. 2.6.

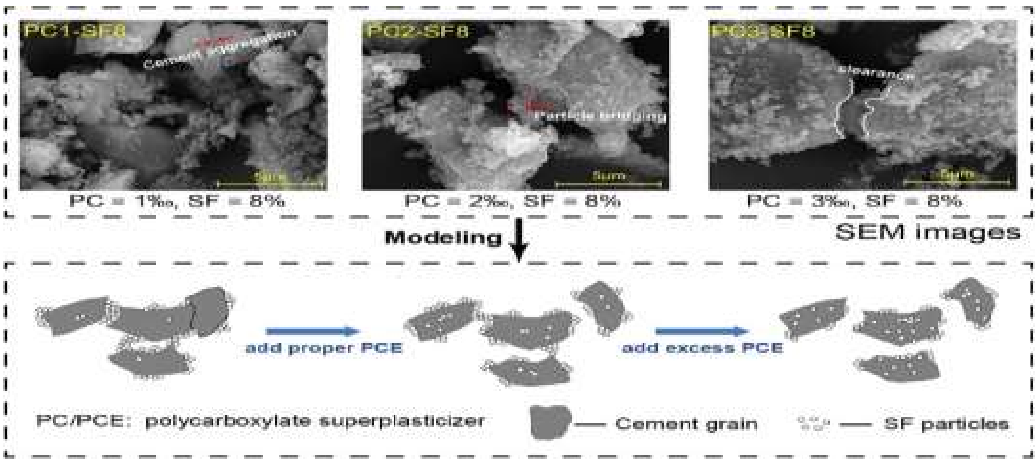


Figure 2.6 Superplasticizer influences on cement slurry particle aggregation [22]

Additionally, there are a lot of different superplasticizers, such as superplasticizers based on polycarboxylate, naphthalene, and the air-entraining superplasticizer (AS). PS has the best fluidity out of all these materials, according to B. Fang et al. [23]. Different researchers have also used PS to create grouts [17], [19], [20],[22]. Note that excessive superplasticizer can result in segregation and bleeding [17]. The recommended dosage range for superplasticizers is between 1% and 2% of binders [15]. The most recommended polycarboxylate-based superplasticizer from previous research was used in this study.

2.3.5 Waste Marble Dust

Marble cutting and polishing produces 30% marble waste powder. However, the cement and concrete industry is using more supplementary materials (SM) to save natural resources. Cement production releases 0.8–0.9 tons of CO_2 [24]. To reduce energy consumption and environmental effect, mortar and concrete manufacturers must use byproduct trash.

There have been several research done on adding marble dust (MD) to cement mortar and concrete formulations, but none have looked at how marble dust (MD)-based cement grout performs when used to build semi-flexible pavement. [25] 5%, 7.5%, 10%, and 15% by weight of substitution ratios of marble powder for cement or grit were examined for their effects. The experiment found that utilizing waste marble powder in place of fine aggregate or cement to improves the characteristics of concrete and mortar due to the filler effect. [26] Various compositions based on binder or fine aggregate substitution were assessed and concluded that up to 10% sand replacement with waste marble powder produced the maximum compressive strength while preserving a comparable workability. [27] The study's findings suggest that without degrading the mixture's technical qualities, marble flour may replace cement up to 10% of the time. In fact, using waste marble powder in place of up to 10% of the cement enhances the mixture's workability without reducing its compressive strength. [28] Contrasted with the control mix, marble slurry-incorporated concrete at w/c of 0.35 & 0.40 demonstrates superior mechanical qualities. However, the compressive strength at w/c of 0.45 increased by 10%. Marble dust's particle size has no appreciable impact on concrete's compressive strength, but the full raw material that went through a 300-mesh sieve achieved great results. Therefore, the main objective of this study is to determine whether or not discarded marble powder may be used in grout to substitute for of cement.

2.4 Bitumen

According to the authors, binder employed for creation of open-graded bitumen, varies depending on the aggregate. The bitumen must possess a penetrating number within 40 and 100 at 25 degrees Celsius, according to Anderton's (in 2000) proposal. The bitumen employed in the aforementioned experiment had a penetration value of 89. The different writers seem to be more in accord when it comes to the binder concentration of open-graded asphalt, with figures fluctuating between 3.5% to 4.6% by mixed mass [29], [8], [1]. According to [29], Based on the previously discovered aggregate qualities by (Roffee 1989b), equation 2.1 was used to get to the ideal bitumen content.

$$OAC = 3.25\,(\alpha)\,\Sigma^{0.2} \tag{2.1}$$

That is:

α = 2.65/Gsb
Gsb = The aggregates' combined specific gravity (apparent)
Σ = The formula for specific surface area is 0.21G+5.4S+7.2s+1.35f
G = The proportion that was retained on a 4.75 mm sieve
S = Proportion that retained on a 600 µm sieve after passing a 4.75-mm sieve
f = Passing percentage on 75 µm sieve.

However, other varieties of binder have been utilized in the past, such as the 60/70 pen bitumen utilized by Boundy (1979). In this investigation, laboratory mix design samples were created using the predicted optimal asphalt content of 3.0%, There are two asphalt contents higher this number and two more under it. These five bitumen contents—2.6%, 2.8%, 3.0%, 3.2%, and 3.4% were assessed in increments of 0.2 percent.

2.5 RSM-Response Surface Methodology

RSM is an efficient technique for designing experiments requiring a limited number of trials. It may be used to choose the best set of elements (variables) in order to get the intended results (responses). RSM also can build a prediction model and identify the link between variables and outcomes. In one study of [30], which investigated the viability of partial substitution of cement by waste marble dust, the percentage of marble dust (MD) and water-to-cement (w/c) were chosen as a variable, the responses included flowability and compressive strength (7 days and 28 days). In another study [17], Superplasticizer dose and water-to-cement ratio (w/c) were chosen as factors, with flowability and compressive strength as a response.

2.6 Summary

Although semi-flexible pavement surfacings have been used since the 1950s, however, not much has been published about this type of pavement surfacing. The research-based development of semi flexible surfacing had been started from the last few decades and hence very limited literature is available on this topic. The literature gap from various studies has been identified and is outlined here:

As mentioned in the introduction, massive garbage disposal and poor recycling rates pose a severe environmental threat. Few studies have used discarded marble dust (MD) to substitute sand or aggregates in cement-mortar and concrete. Waste marble dust as a grout substitute has not been studied. SFM laboratory specimen materials are described in this chapter. Also provided are mix design methods for determining optimal blending formulae. Finally, the chapter describes how test specimens are physically produced and cured.

The dynamic modulus predicts the asphalt aggregate's performance and can help design the pavement's structure. Laboratory testing thoroughly explains the HMA, which has a temperature tier of -10 to 60C and loading frequencies of 0.1 to 25Hz, according toAASHTO-TP-62-07. 4.4 and 21.1 °C at 5 Hz indicate fracture resistance, whereas 37.8 and 54.4 indicate rutting.

CHAPTER 3

RESEARCH METHODOLGY

3.1 Introduction

In this chapter methodology for laboratory specimens to conduct further testing is discussed. A description is given of the mix design processes that are used to identify the most effective blending formula. For the sake of completeness, the steps that were taken to physically to produce specimens and final finished samples for testing is described at the end of this chapter.

3.2 Research Methodology

This study's experimental portion is divided into four phases. The First Phase outlines the gathering of materials and evaluation of their fundamental properties. In this phase, the accumulation of waste marble dust is also described. The second phase is concerned with the preparation of cementitious grouts, their performance evaluation, morphological characterization, and determining the optimal grout composition combination. RSM is a technique for designing and analyzing experiments, has been used for experimental design, analysis, and optimization of cementitious grout compositions. In Phase Three, an open-graded asphalt skeleton (OGAS) was chosen based on a literature review. In order to finalize the mix design for semi-flexible pavement surfacings, the optimal bitumen content (OBC) and the selected OGAS were evaluated for fundamental properties including voids analysis and grouting ability. The performance evaluation of semi-flexible specimens like Marshall stability, stiffness modulus, tensile strength ratio, dynamic modulus, moisture sensitivity, compressive strength properties, and fuel resistance comprise the fourth phase. These four phases are described in detail in the sections that follow also a methodology flow chart for this research study is shown in Figure 3.1.

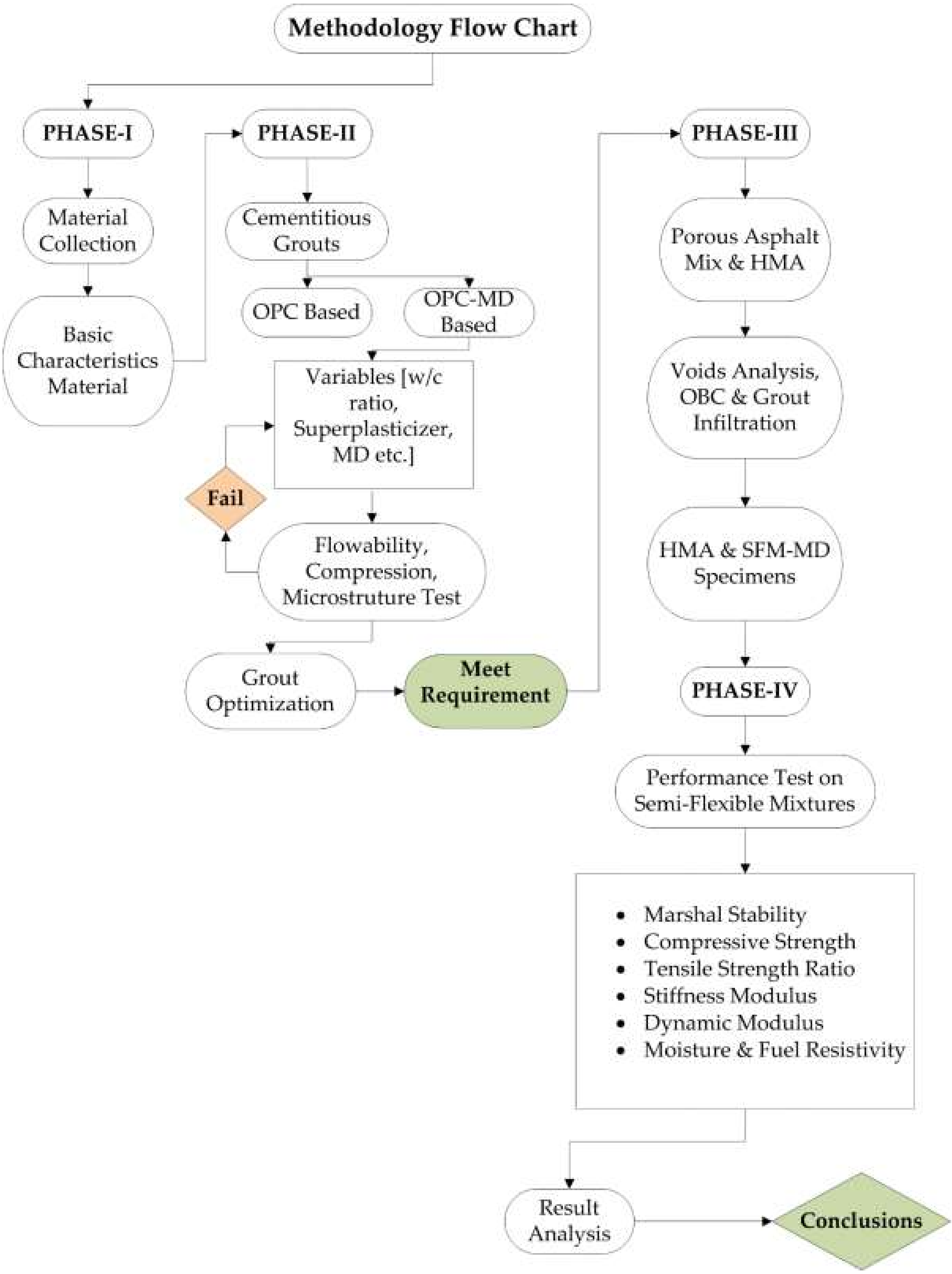


Figure 3.1 Research methodology

3.3 PHASE-I Material Selection and Characterization.

3.3.1 Cementing Materials

OPC utilized in the investigation was acquired from local supplier and conformed to ASTM C150 specifications [31]. Waste marble dust (WMD) obtained from the local marble industry was also used as partial replacement of cement in grout. Table 3.1 listed the chemical composition of OPC [32] & WMD. The findings in Table 3.1 indicates that the composition of CaO in WMD is greater than 10% and the summation of Si02, A103 and Fe2O3 is less than 70% which fulfills the requirement of high calcium (type C) as per ASTM 618-10.

Table 3.1 Chemical Composition of OPC and WMD [32]

Material	SiO_2	Al_2O_3	Fe_20_3	CaO	MgO	Na_2O	K_2O	$S0_3$	FL	IR	LOI
Cement	21.24	5.56	3.24	63.53	0.93	0.13	0.2	2.55	0.55	0.64	1.24
WMD			0.678	55.45							

3.3.2 Superplasticizer

The third generation polycarboxylate-based superplasticizer for concrete, Sika® ViscoCrete®-3110, was used in this investigation as a superplasticizer (SP) to manufacture excellent fluidity cementitious grouts needed for semi-flexible pavement application. It produces steric hindrance and electrostatic repulsion between cement particles through surface absorption, resulting in increased dispersion, flow, and retention. SP was supplied by local vendor.

3.3.3 Waste Marble Dust

This study's primary objective was to use waste marble dust (WMD) as a partial substitution of cement in cementitious grout. The local marble industry in Economic zone Rashakai, Nowshera, supplied the refuse WMD in powder form. During the cutting and refining process, enough marble stone is reduced to powder and carelessly discarded into the surrounding environment, negatively impacting the local ecosystem and water bodies. Slurry particles, which are very tiny, block the pores of agricultural soil, preventing water from penetrating and decreasing the fertility of the soil. The factory's waste marble dust was obtained for purpose of this investigation. The grain size of WMD derived from the factory ranged from 35 microns to

1 millimeter. The obtained weapons of mass destruction were then sieved to produce a fine powder. Lastly, waste WMD powder with a grain size of less than 200 microns was used to partially substitute for OPC in cementitious grouts. As shown in Figure 3.2 the WMP used in this study was fine white powder. In Table 3.2 the properties are also tabulated.

Figure 3.2 WMD utilized in the current research

Table 3.2 Physical Properties of WMD [33]

Description	Testing standards	Results
Specific gravity	ASTM-C-128	2.41
Water Absorption (%)	ASTM-C-127	0.34
Bulk density/unit weight(lbs/ft3)	ASTM-C-29	84.75
Fineness modulus	ASTM-C-136	0.99

3.3.4 Aggregates

For this research, aggregate was obtained from a quarry site in Babuzai, Katlang, KPK, with nominal maximum aggregate size of 12mm. Mixture design begins with selecting aggregates that fulfill all the necessary characteristics. Designing a blend for mixes necessitates attention to the stone-on-stone contact characteristics of the aggregates. Toughness and form of aggregates are significantly more crucial than in ordinary DGA mixes. The aggregates used in the test portion were sourced from the Babuzai quarry and subjected to a variety of laboratory testing to ensure they met minimum quality standards. Figure 3.3 shows different working condition of mechanical sieves at Babuzai quarry site.

Figure 3.3 Babuzai quarry site

Mixture design begins with selecting aggregates that fulfill all the necessary characteristics. Designing a blend for SFP mixes necessitates attention to the stone-on-stone contact characteristics of the aggregates. Toughness and form of aggregates are significantly more crucial than ordinary dense graded asphalt mixes. The aggregated used for preparation of mix were subjected to a variety of laboratory testing to ensure they met minimum quality standards. Table 3.3 is a summary of the aggregates' quality tests:

Table 3.3 Properties of Aggregates

Test Name	**Standard**
Impact Value Test	BS-812
Flakiness and Elongation Test	ASTM-D-4791
Crushing Value Test	BS-812
Los Angeles Abrasion	ASTM-C-131
Specific Gravity Test	ASTM-C-128
Water Absorption	ASTM-C-127

3.3.5 Aggregate Impact value

Aggregates' capacity to endure traffic impact loads is determined by their impact value. Impact load and hammering motion may lead to fractures in the road surface Aggregate impact value is tested in accordance with BS 812-112, 1990 and IS 383, which provide detailed instructions. To measure impact value, a 75mm diameter and 50mm depth cylindrical mould was required, as was a 230mm length tamping rod with a circular section of 10mm, and 1/2, 3/8", and #8 sieves (2.36mm). Three (3) layers of 350g of aggregate were tamped 25 times for the Impact

Testing Machine show in Figure 3.4. The sample was put in the larger mold of the machine, and 15 blows were delivered from a height of 38cm using a hammer weighing 13.5-14.5kg. The retrieved aggregate was processed using sieve #8. The impact value was calculated by taking the percentage of aggregate that made it through a 2.36mm sieve. An interpretation of the results may be found in Table 3.4.

The calculations were done using the formulae.

Impact value = (B / A) x 100

In above equation B is the weight of material passed through sieve #8 while A is the weight used for test passing through the 14 mm and retained on the 10 mm.

Figure 3.4 Aggregate impact value apparatus

3.3.6 Aggregate Crushing Testing

To generate a higher quality and stronger pavement, the aggregates must be able to bear traffic loads. Test is conducted in accordance with established protocols (BS812-112, 1990). Compressive testing equipment, cylindrical measuring device, balance, tamping rod, and plunger with 150mm piston diameter were the instruments used in this test to measure the compression of aggregate as shown in Figure 3.5. Those aggregates that passed through a 1/2" sieve and retained 3/8" were selected. Each layer received 25 tamping after being laid on top of the cylindrical measure, is then dried in an oven and weighed (W1). This was proceeded by inserting a steel plunger into the cylinder that had been positioned on top of it. Afterwards, it was put through a compression process of analysis. Weight was added at a pace of 4 tons per minute until a total of 40 tons was attained. Crushed material was recovered from the steel cylinder and separated from the material before it was sieved at 2.36mm. Everything that have already gone must be collected and weighed, crushing value of aggregate was calculated using W2/W1 x 100. The results are tabulated in Table 3.4.

Figure 3.5 Aggregate crushing value apparatus

3.3.7 Los Angeles Abrasion Test

It is essential that aggregates resist decomposition, degradation, and breakage under traffic stresses. This test is used to find aggregate durability and strength. The test is conducted as per standard practice by (AASHTO T96-92, n.d.) and apparatus shown in Figure 3.6. As a result of heavy traffic, aggregate's hardness and abrasion qualities are tested by the LA test. The quality of abrasion resistance must be checked since the aggregate in the mix is exposed to high levels of recurrent load that cause fragmentation, degradation, and crushing. In this experiment, we used the LA Abrasion machine, a weight balance, a set of sieves, and steel balls we call charge. Testing technique or grade B was employed in this procedure. In addition to the 2500 g of material held on 1/2" and 3/8" sieves, the Los Angeles abrasion instrument was loaded with 11 steel balls or charges totaling 5000 g (W1). After that, it was spun for 500 revolutions at 30–33 revolutions per minute. The particles were separated using a 1.7mm sieve. The abrasion value was calculated from the sample weight (W2), which was recorded using the formula = W2/W1 100. The abrasion value of coarse aggregates must be less than 30% for wearing course according to NHA guidelines. Table 3.4 shows the results.

Figure 3.6 LA abrasion apparatus

3.3.8 Flakiness and Elongation Index of Aggregates

The flakiness and elongation test is used to measure the dimensional ratios of aggregate passing through various sieves. Using this definition, deteriorated aggregate may be identified by using apparatus shown in Figure 3.7 in laboratory, as having a tendency to hinder compaction or having difficulty meeting VMA standards. Elongated or flat particles tend to lock up (rather than orient) more rapidly during compression, making it more difficult to compact them. They may also develop weak and narrow compression fractures that reduce aggregate sizes and reduce VMA values below expectations.

If the average sieve size is less than 0.6 times its actual size, it is considered a flaky particle. If the particle's length exceeds 1.8 sieve sizes, it is considered elongated. There are two separate ways to go about it. The standard process for identifying flat and elongated particles is still employed for all non-Superpave applications. A second method is utilized for Superpave requirements, which mainly entails comparing the maximum and minimum particle sizes. Because they lock up more quickly throughout the process, flat and long particles are more difficult to compact. Aggregate particles are also reoriented during compaction, and this tendency to shatter leads to a finer aggregate grade, which reduces Voids in Mineral Aggregates (VMA). There should be no more than 15% elongated or flat particles, as specified by ASTM. A few aggregates' lab tests are within the acceptable range. Table 3.4 shows the results.

Figure 3.7 Flakiness and elongation test apparatus

3.3.9 Water Absorption and Specific Gravity Test

An object's specific gravity is determined by comparing its air weight to that of its distilled water to determine how much it weighs in air. AASHTO T 85-91 lays forth the procedures for performing the specific gravity & water absorption tests (ASTM-C-127, 2001). The aggregates' permeability allows water to permeate into the pores of each particle, changing the density.

Particle density is critical for creating asphalt paving mixtures. In the planning of pavement and building projects, it is commonly employed by engineers. Bulk-specific gravity is used to calculate the absorbed binder and the VMA. Weight-volume characteristics of aggregate material are expressed as specific gravity, which is frequently referred to as relative density. Mass to volume ratio of a substance at a certain temperature. Crushed rock that has passed through filter No. 4 but not sieve No. 4 is referred to as "fine aggregate". Course and fine aggregate specific gravities were calculated separately.

3.3.9.1 Coarse Aggregate specific Gravity

Water absorption and specific gravity may be conducted using the (ASTM C127, 2001). To remove the remaining aggregates from sieve number four, the aggregates were roasted and submerged for 24 hours in water. The saturated aggregates weight was then determined by rolling them in cotton. Then, the weight of aggregates submerged in water, as well as their specific gravity and water absorption, were calculated. Unlike the oven-dried sample, the aggregate voids are filled with water in the saturated surface dry state.

3.3.9.2 Fine Aggregate Specific Gravity

Like coarse aggregates, fine aggregates are water-permeable and may be utilized to create porous surfaces. AASHTO T 84-93 and similar procedures were utilized for this test (ASTM C128, 2008). After passing sieve #4, the aggregates were soaked in water for around 24 hours before being sprayed on a tray and allowed to dry until they were saturated on the surface. This process was repeated three times. Filling the cone with fine aggregate, compacting it twenty-five times, and then placing it on a level surface, the process was completed as shown in Figure 3.8. When the cone was removed, the aggregates could be seen. They were not SSD if they resembled the mold. After the aggregate was dried a second time, the same procedure was followed until the aggregate slumped a little after the cone was removed. A pycnometer was loaded with water and weighed once the correct level was reached. Sand was poured in the flask and weighed once again after it had dried to a saturated surface. Specific gravity and absorption were obtained after drying sand at 110 °C in an oven. The obtained results are tabulated in Table 3.4. Calculation is for the mentioned values is done using following equations:

$$\text{Specific Gravity Apparent} = \{A\ /\ (A - C)\} \text{ x } 100$$

$$\text{Specific Gravity Bulk} = \{A\ /\ (B - C)\} \text{ x } 100$$

$$\text{Percentage Water Absorption} = \{(B - C)/A\} \text{ x } 100$$

A = Aggregate dried weight

B = SSD weight and C = submerged aggregate weight

Figure 3.8 Coarse aggregate specific gravity apparatus

Table 3.4 Aggregate Testing Results

Type of Test		Results %	Specification
Los Angeles Abrasion		21.00	45% (Max)
Flakiness Index		10.80	15% (Max)
Elongation Index of Aggregate		3.20	15% (Max)
Aggregate Impact Value		15.5	30% (Max)
Crushing Value of Aggregate		19.6	30% (Max)
Water Absorption	Fine Aggregate	2.22	3% (Max)
	Coarse Aggregate	0.56	3% (Max)
Specific Gravities	Fine Aggregate	2.55	-
	Coarse Aggregate	2.64	-

3.4 Binder Testing

Pakistan's Attock Refinery Limited - ARL was the source of the 60 by 70 grade bitumen utilized in this study. According to the AI MS 4 manual, a binder must possess three essential characteristics: consistency, safety, and hygiene. As the temperature changes, so does the density of the asphalt binder. As a consequence, asphalt binder consistency must be evaluated at a constant temperature. Bitumen binder consistency is typically evaluated with a penetration test (Asphalt Institute MS-4, 1988). In addition, the material's softening point and ductility can be used to determine its consistency. Table 3.5 listed the properties of bitumen.

Table 3.5 Bitumen Grade 60/70 Properties

Tests	Standard
Flash and Fire Point	ASTM-D-92
Penetration Grade	ASTM-D-5
Softening Point	ASTM-D-36
Ductility	ASTM-D-113
Specific Gravity	ASTM-D-70

3.4.1 Flash and Fire Point Test

The stated range of flash and fire points is crucial for ensuring the safety standards for the worksite are satisfied. The test is run as per the guidelines in the ASTM D92, 2005 using apparatus shown in Figure 3.9. The binder's flashpoint is the temperature at which the vapors of a bitumen sample in the Cleveland Open Cup suddenly ignite when an open flame is present. This is the moment at which the binder's surface catches fire and continues to create flames for at least five seconds. In a metal cup, the bitumen was poured until it reached a certain volume. After that, it was slowly warmed up while a test flare was passed over it on a regular basis. A measurement was made of the temperature at which the flash and fire broke out after the necessary conditions had been satisfied. The temperatures for each binder were determined after three different testing. In line with the regulations, the flashpoint should always be over 232 °C for penetration grade 60/70.

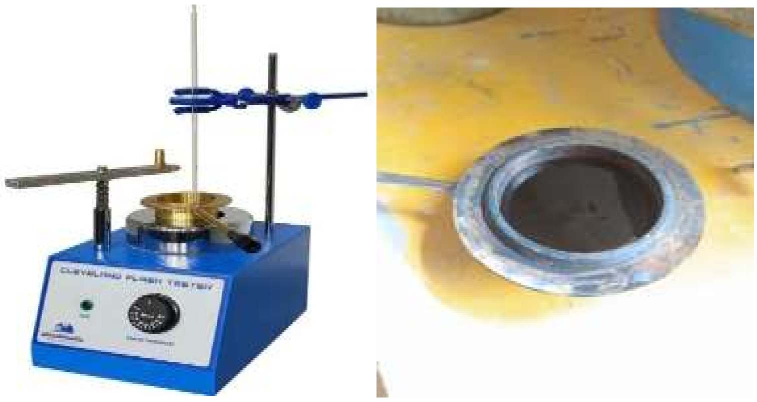


Figure 3.9 Cleveland open cup apparatus and heated bitumen sample

3.4.2 Bitumen Penetration Test

The test of penetration is a typical first stage in determining the quality and consistency of an asphalt compound. The procedure for the testing was completed in compliance with (ASTM D5, 2008) and (AASHTO T 49-93, 2019) using apparatus as shown in Figure 3.10. It's one of the first methods of figuring out whether asphalt binders have enough consistency. Binders are classified according to their softness or hardness, with the results used to create a standardized classification system. The penetration value of a soft and thin binder is greater. Regarding hot regions, a lower penetration value is preferable, whereas a higher penetration value is favored in colder climates. To begin, the binder is heated to a temperature that allows it to flow without trapping any air, but not so hot that it damages the binder's properties. Finally, a temperature-controlled bath is employed to maintain the binder at 25 °C. A 100g load is passed through a needle in a penetrometer for 5 seconds once the container has reached the proper temperature. There were five sites on each bitumen sample where penetration values were recorded on two samples of each bitumen.

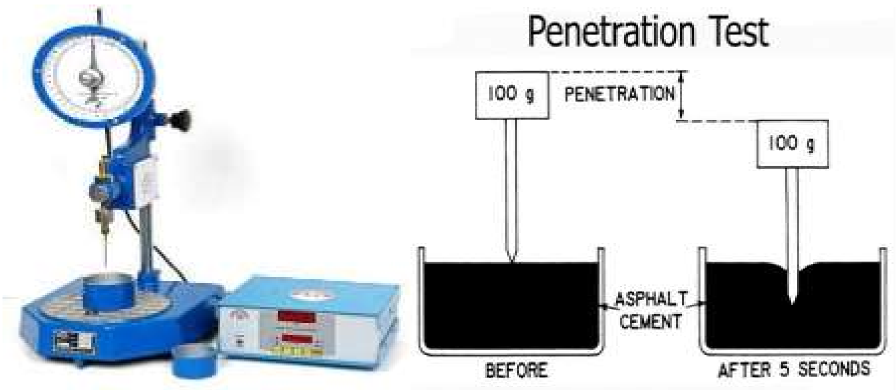


Figure 3.10 Penetrometer apparatus

3.4.3 Softening Point Test

It is performed in accordance with (ASTM D36, 2006) and (AASHTO T 53-92, 2008) using apparatus as shown in Figure 3.11. Even though it's a viscoelastic material, the bitumen becomes softer and dries more quickly as it gets hotter. The water temperature at which a specimen of asphalt binder can no longer hold a 3.5g steel ball. Consequently, the mean temperature at which two bitumen discs become soft enough to allow steel balls to fall 25mm is determined. The first step was to heat the binder to a temperature that would enable it to flow while keeping its properties. Then, using a mold, it was formed into horizontal discs. After being inserted into the machine, the balls were positioned on the discs. To achieve the above-mentioned fall distance, we increased the temperature of our binder placed in water beaker.

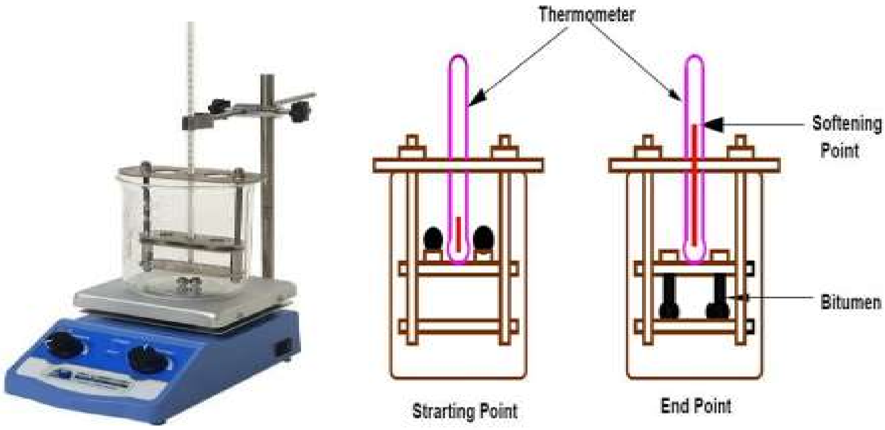


Figure 3.11 Bitumen softening point apparatus

3.4.4 Ductility Test of Bitumen

It is carried out according to (ASTM-D-113, 1999) and (AASHTO T51-93, 2017) by equipment shown in Figure 3.12. Determined by length of asphalt binder's thread when stretched in centimeters under normal test circumstances. Due to their elasticity, asphalts with low ductility are thought to have poor adhesion properties, whilst asphalts with high ductility are more vulnerable to temperature fluctuations.

This test assesses the binder's ability to stretch and adhere. One of the most important properties of bitumen is its flexibility. It shows how bitumen behaves as the temperature varies. 25 °C was the temperature of choice for this experiment. At a rate of 5cm/min using standard-sized binder specimen (a briquette with a 1 in 2 cross-sectional area) is pulled apart, and the extent to which it elongates without fracturing is termed ductility, which is measured in millimeters. The ductility test requires a sample that is at least 100 cm long.

Figure 3.12 Ductility test of bitumen

3.5 PHASE-II Cementitious Grout

The cementitious grouts were produced in accordance with ASTM C305 [34] using a Hobart mortar mixer. In this procedure, the dried binders were added to the mixing basin and stirred at a moderate speed for one minute. The dry binder should be mixed with two thirds (3/3) of water for two minutes at a low pace. Superplasticizer (SP) and the remaining water were combined for five minutes at a low pace. The grouts were also blended at high speed for an extra three minutes. The bottom and sides' adhesive substance was mixed and gently scraped off. To achieve homogeneity, the grouts was then mixed for a further minute at a high speed. Grout design was completed in two stages. Cement grouts were created in the first phase using a variety of water-to-cement ratios (0.35 to 0.50) and SP doses (0.5%), their flow and compressive strength were then assessed (7-day & 28-day tests). Based on the qualities of the flow and compressive strength, as well as the bleeding effect, an appropriate combination of w/c ratio and SP was established. The w/c and SP produced in the first step are used in the second stage, and further grouts are made by partly replacing cement with various percentages of marble dust (MD). In order to determine the ideal compositional combination, these cement grouts were tested for flowability and compression strength (7 days and 28 days) respectively. In the next subsections, it is explained how RSM is used to assess and improve grouts in the second stage.

3.5.1 Tests on Cementitious Grouts

Flow testing, compressive testing after curing of 7 and 28 days and microstructure analysis are all examples of tests that may be performed on cementitious grouts. The subsequent subheadings each include an explanation of a specific aspect of these examinations.

3.5.2 Flow of Grouts

Fresh cementitious grouts are evaluated for their flowability using a flow test. The procedure was conducted according to the ASTM C939/C939M Flow Cone Method [35] specifications. As shown in Figure 3.13, this technique included pouring 1725 milliliters of freshly mixed grout into the flowability cone while sealing the outlet at the bottom. Following the pouring of the grout, the subsequent step was the opening of the lower orifice, wherein the duration of the grout's outflow was measured in seconds. The aim of the flow-out time, according to [36] is to ensure that grouts have adequate flowability to fill voids in an open-graded bitumen mixture. The acceptable range for the duration is limited to a minimum of 11 seconds and a maximum of 16 seconds. There exists an inverse correlation between the workability of cementitious grouts and their flow-out time. Specifically, grouts with improved workability, attributed to reduced viscosity, exhibit shorter flow-out times.

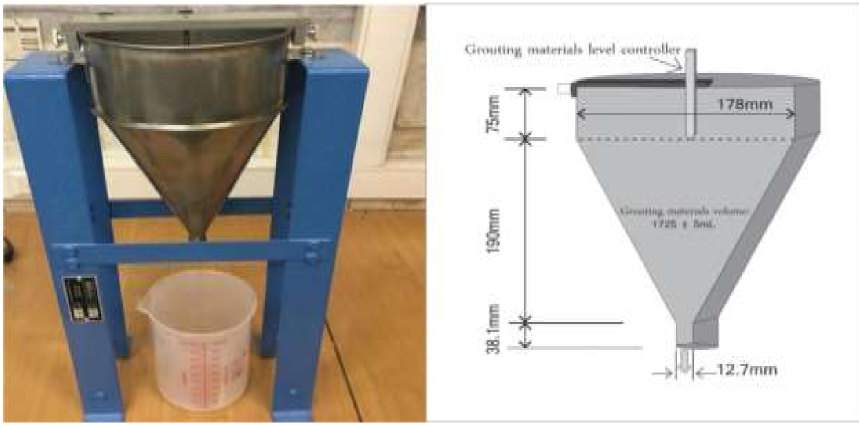


Figure 3.13 Fluidity test procedure and flow cone geometry [36]

3.5.3 Compressive Strength

A MATES – Universal Testing Machine 3000 KN and rate of loading of 1.350 KN/s was utilized to measure the compressive strength of cement grouts. A specimen's dimensions 2 cubic inches cubes of each grout type were made in accordance with ASTM C109 [37], and compressive strength tested at of 7 and 28 days in triplicate specimens. There is currently no standard handbook that specifies the range of compressive strength criteria for cement grouts for applications involving semi-flexible surfaces. Very limited commercial grouts are available that are suggested for semi flexible paving surfaces. One such form is DuraTough®, which has compressive strengths of 7 Mpa after one day, 35 Mpa seven days, and 60 Mpa at 28 days respectively. The present research aims for compressive strengths of cementitious grout accordingly compressive strength tested at of 7 days and 28 days for the development of cementitious grout. The specimens and testing equipment are shown in Figure 3.14 in accordance with UTM.

Figure 3.14 Specimens and Test setup

3.5.4 Microstructural Characterization of Cement Grouts

Microstructure analysis like SEM and EDS is performed to figure out surface shape and elemental analysis. EDS is special because it can do many kinds of elemental analysis, like line, point, spectrum, and compositional mapping. At the National Centre of Excellence in Geology at the University of Peshawar, a SEM was used to look at the surface shape and substructure of hardened cement grout. SEM Model: JSM-IT-100 tool facility was used for this. At different ultra-high picture levels, the surface shape was caught. Figures 3.15 show SEM facility at NCEG- UOP, Peshawar.

Figure 3.15 SEM facility at NCEG- UOP, Peshawar

3.6 PHASE III: Preparation of OGA Mixture

3.6.1 Open-Graded Asphaltic Mixture

The Open-graded asphalt (OGA) mixes for SFPs are created and prepared differently from OGA mixtures used as the wearing course in asphaltic pavements. The minimum air voids in OGA mixes used in semi flexible pavements is 20%; in practical applications, this rises to 30–35% [16], [38], [18]. Highly flowable cementitious grouts are often put on top of the open graded asphaltic skeleton (OGAS) holding 20-35% air voids to create semi flexible pavement surface. The gradation method for SFP surfacings, as shown in Figure 3.16 [12] has not been the subject of many investigations. The performance properties of semi flexible pavement is significantly influenced upon choice of aggregates. The most suitable asphaltic skeleton for semi-flexible pavements, according to Saboo N [13], may be chosen from one of the following three mixtures: Densiphalt 8-4%, BSI-4%, and Densiphalt 12-4.5%. The most suitable Densiphalt Type-12 gradations were chosen based on the literature that was accessible, as shown in Table 3.7.

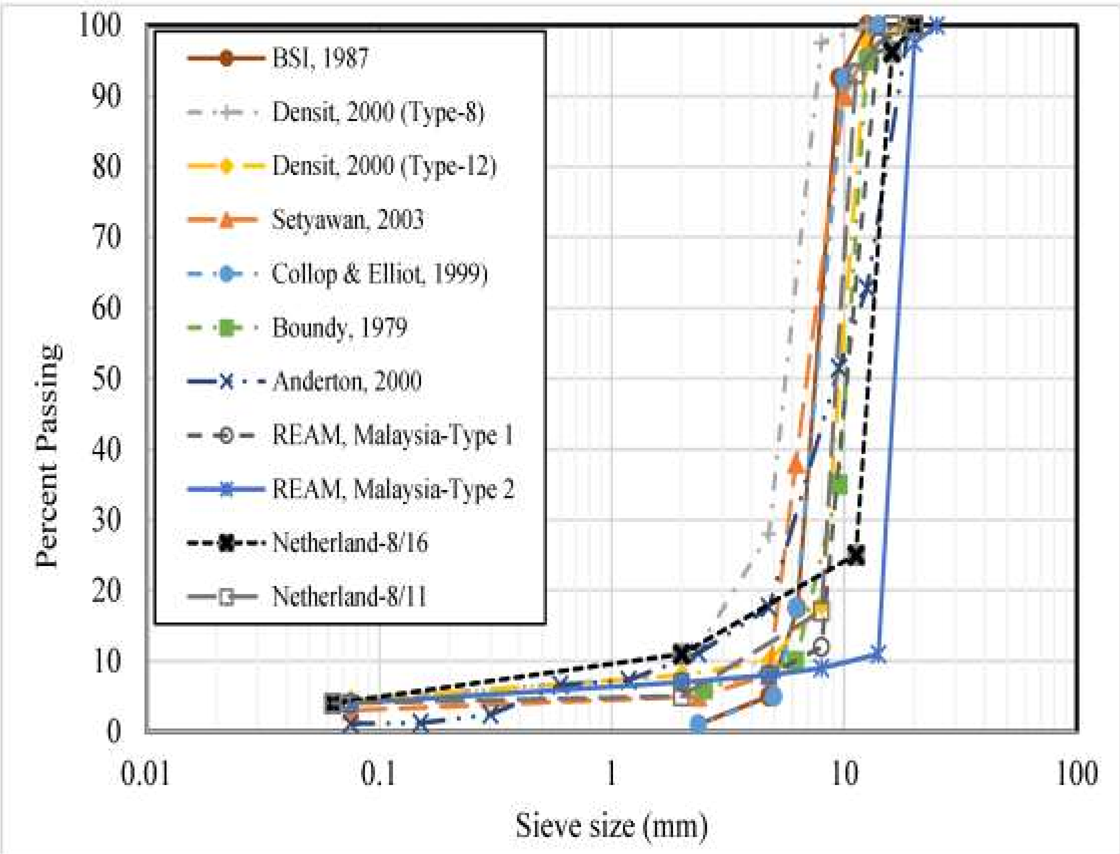


Figure 3.16 Porous aggregate gradation used in past studies

Depending on the thickness of the Densiphalt® coating, Densit a/s recommends using one of two gradation types [39]. This leads to the specification of Type 8 aggregate for thicknesses between 30 and 50 mm and Type 12 aggregate for thicknesses between 40 and 60 mm [17]. For further information on the mentioned gradation, see Table 3.6.

Table 3.6 Open-Graded Asphalt Mixtures (Densiphalt-12)

Densiphalt Type-12 Gradation for OGAS		
Sieve size (mm)	% Passing	% Retained
3/4" (19 mm)	100	0
1/2" (12.5 mm)	97.5	2.5
3/8" (9.5 mm)	18	79.5
#4 (4.75 mm)	10	8
#8 (2.36 mm)	8	2
# 200 (0.075 mm)	4.5	3.5
Filler (Passing # 200 sieve)		4.5
Total		100

3.6.2 Determining Initial Optimum Binder Content

In order to establish the optimum bitumen content (OBC) to be included in open-graded asphalt mix, Roffe (1989) recommended using Equation 2.1 (refer to Anderton, 2000) [29]. Based on previously recognized aggregate features, the following equation, was used to achieve this. Details are previously given in this study's chapter 2, subsection 2.4.

3.6.3 Test on Binder Draindown

The test is necessary to figure out how much bitumen may leak out of a porous asphalt mixture while being handled and transported from the manufacturer to the project site. The binder draindown test is carried out in accordance with ASTM D6390 [193]. The combination is made in the manner described in section 3.4.2. On a pre-weighed paper plate, the completed loose mixture is put into a wire basket. After that, the whole structure is cooked for an hour in a preheated oven. Equation 3.1 is used to calculate the quantity of bitumen that has been drained after one hour, after which the complete assembly is taken apart and weighed.

$$Draindown = \frac{W2 - W1}{Wm} \tag{3.1}$$

Where,

W1-weight of the empty paper plate before a test, W2-weight of the paper plate after test,

Wm-initial weight of the mixture.

3.6.4 Preparation of Cylindrical Specimens

The open-graded asphalt mixture was made as described in section 3.6.4 and put into pre-heated gyratory 100 millimeter in dia and 200 millimeter in height molds. The asphalt mix filled molds were put in a gyratory compaction machine, and each specimen was compacted with 50 gyrations. The number of gyrations (i.e. 50 gyrations) was acquired by several attempts by achieving air voids close to 30% (the required is 25% to 35%). After the gyrations were completed, the compressed specimens in molds were left in the open air to cool before being retrieved from the molds. Specimens were kept at room temperature for 24 hours prior to testing.

3.6.5 Air Voids Determination in Compacted Specimens

The most crucial mixture design factors for open-graded asphalt mixes is the presence of interconnected void in finished specimens. It should be ensured that air voids are 25 to 35 percent of the whole mixture [39], [38], [13]. Because to void dysconnectivity, a lower percentage of voids will hinder cementitious grout penetration. Bulk specific gravity and maximum theoretical specific gravity are used to compute the fraction of voids [22]. According to ASTM D1188, D2041, D2726, and D3549, the volumetric analysis was performed. The computations were carried out as planned. The formulae are detailed in Appendix (Equations Al-A4). The draindown test and volumetric analyses were then used to compute the final optimal bitumen content (OBC). Figures 3.17 and 3.18 illustrate porous skeletal samples.

Figure 3.17 Voids analysis of porous skeleton.

Figure 3.18 Voids analysis of porous skeleton.

3.7 PHASE IV: Preparation and Evaluation of Semi flexible Specimens

In the next subsections, you will find an explanation of the preparation of semi flexible specimens and their performance properties.

3.7.1 Semi-flexible specimen preparation

Prior to grouting, the prepared compacted specimens were left in molds for 24 hours to cool down at room temperature. To avoid leakage of highly flowable cement grouts, the specimens containing porous asphalt mixes were covered with polythene sheets. The pre-designed cement grout components (control grout, WMD-based grouts) were mixed and prepared using the same technique as described in section 3.5. The needed amount of grout was put on top of the gyratory specimen, followed by a little vibration. The grout was applied in the manner seen in Figure 3.21. The removal and leaking of air bubbles were constantly monitored. The specimen was covered with a plastic sheet after being poured with gout. After holding period, the samples had been demolded and covered in water-resistant sheets of polythene for curing. Cores of 100+10 mm dia cylinders were extracted from gyratory specimens. Marshall stability, compression test, tensile strength ratio, stiffness modulus (ITSM), and the cylindrical specimens were used for all fuel resistance tests. Figure 3.19 depicts the step-by-step approach.

Figure 3.19 Preparation of semi-flexible specimens

3.7.2 Preparation of HMA Specimens

The characteristics of semi-flexible and conventional HMA hot mix asphalt specimens were compared. Figure 3.20 [48] shows the HMA (ACWC-Class-B) grading scale that was adopted from National Highway Authority-Pakistan. Specimens were compacted with 125 gyrations of gyratory machine. The ideal bitumen concentration of 4.1% was established following the marshall mix design procedure for preparation of conventional HMA samples. The performance properties of HMA samples prepared at OBC 4.1% are listed in Table 3.7.

Table 3.7 Results of HMA Sample at OBC

Property	**Results**	**Specification Limits**
Binder Content, %	4.1	Min 3.5%
Air Voids, %	4.8	4-7
Mineral aggregate VMA%	13.66	> 13%
Asphalt-filled voids, VFA%	64.7	60-70%
Marshall Stability (N)	1204	1000 Kg (Min)
Flow, mm (0.25mm)	13.2	8-14

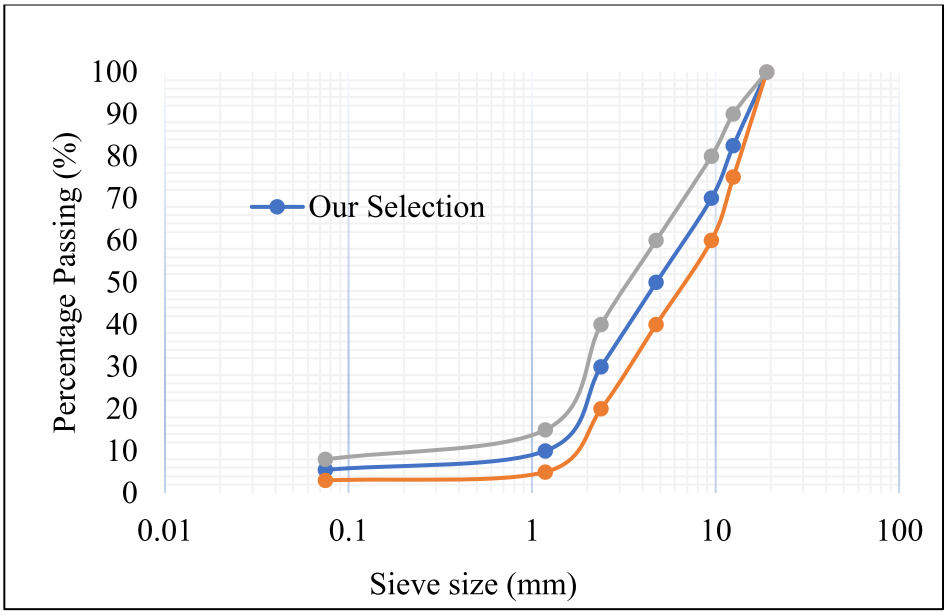


Figure 3.20 NHA class B gradation for conventional HMA mixture

3.7.3 Tests on Semi-flexible Specimens

In addition to being tested for resistance to oil leakage, the semi-flexible specimens (cores) were also assessed for grout saturation level, marshall stability, tensile strength ratio, stiffness modulus, dynamic modulus and compressive characteristics [39], [1], [13]. The next sections go into further depth about these tests.

3.7.3.1 Grout Saturation Level

The Grout Saturation Level following grouting in semi-flexible pavement surfacings are critical factors to guarantee that the air gaps are linked and adequately filled with cement grouts. These variables are associated with the efficiency of semi-flexible pavement surfacings under traffic stress and weathering circumstances [36]. Researchers have proposed a grout saturation level of 94- 97% [40], [41], [42]. Equation 3.2 was used to calculate grouting saturation by analyzing the amount of grout filling the gaps.

$$Sg = \frac{(m2 - m1)}{\rho \times V \times VV} \tag{3.2}$$

where ‘V’ is the specimen's volume (centimeters), Sg is saturation level of the grout (percent), m1 & m2 are the before and after weight of specimens, p is the density of grout (grams per cubic centimeter), and VV is the quantity of voids in the OGA mixture [36].

3.7.3.2 Marshall Stability

According to ASTM D6926 guidelines, the Marshall stability test was conducted to evaluate the flowability and stability of semi-flexible mixtures [43]. Numerous stability tests were performed on the core samples that were taken from different gyratory specimens. The specifications required that the samples be conditioned in a water immersion heated to sixty degrees Celsius for thirty minutes prior to the tests. The stability and flow measurements were shown on the instrument's screen while applied loading rate was 50mm/min. Marshall stability of a cylindrical specimen is the maximum load it can sustain before collapsing, and the peak load deformation that is seen is known as the specimen's flow. HMA samples were also examined under the same circumstances to allow comparisons.

3.7.3.3 Tensile Strength Ratio

Indirect tensile strength is outstanding predictor of mixture cohesiveness and a measure of tensile strength. It is anticipated that the asphalt matrix would give the majority of the tensile qualities to the mix in the grouted macadam[44]. These attributes are important for the mix's ability to resist cracking. An indirect tensile test, also known as an ITS, was carried out using the exact same apparatus shown in Figure 3.21 depicts the test setup that will be used for ITS. At a pace of 50.8 millimeters per min, the force applied until the specimen could no longer withstand it. This test was conducted according to ASTM D6931. There were two different groups of specimens that needed to be processed. One group was preconditioned in a 25-degree Celsius water immersion for thirty minutes (ITS-dry) prior to the test. The second batch of samples were treated in a 60-degree Celsius water bath for twenty-four hours before being moved to a second water bath heated to 25 degrees Celsius for the duration of the ITS-wet test. By applying the following Equation 3.3 to the data, the ITS was calculated.

$$ITST = \frac{2000 \times P}{\pi \times t \times D} \quad (3.3)$$

P, t, and D, respectively, stand for peak load, sample thickness, and sample diameter.

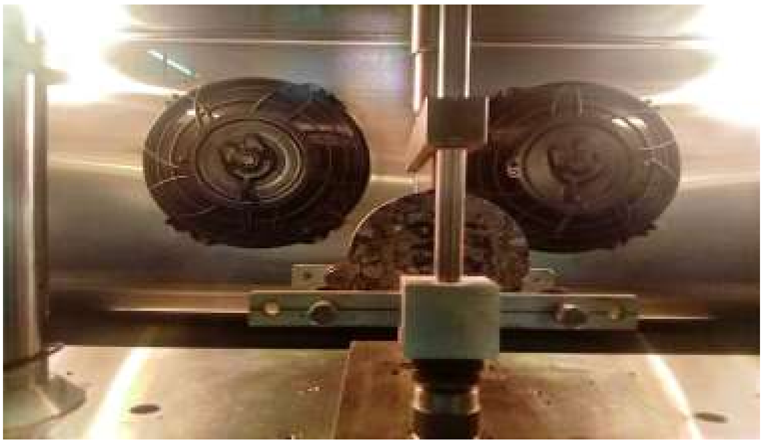


Figure 3.21 Test set-up for indirect tensile strength

In Equation 3.4, tensile strength ratio was determined by dividing ITS $_{wet}$ over ITS_{dry}. The TSR value reflects mixture moisture sensitivity after 24 hours in a water bath at high temperatures. Figure 3.18 shows the specimen test setup.

$$TSR = \frac{\mathrm{ITS}_{wet}}{\mathrm{ITS}_{dry}} \times 100 \quad (3.4)$$

3.7.3.4 Indirect Tensile Stiffness Modulus

The stiffness of the asphalt material is one of the most important input factors for the design of the structure pavement layers. The stiffness of a mix is a measure of how well its lower levels are able to handle the traffic load. The stiffness attribute is also utilized in this test to rate various asphalt mixes. Pavement's structural behavior may also be evaluated using the stiffness modulus [45]. In the present investigation, a UTM-100 (Universal testing machine) was used to carry out the ITSM evaluation. Figure 3.22 depicts the UTM and testing apparatus configuration.

Figure 3.22 ITSM testing and sample positioning

The test was done on two different kinds of mixtures: (i) semi-flexible mixtures with grout made from marble dust (SFM-MD) and (ii) regular hot mix asphalt (HMA). The reason for finding out how stiff HMA was to compare it to semi-flexible mixes. Following the BS EN 12697-26 standard [45], all of the samples were tested at 25°C, and 40°C temperature. Three sample specimens were to tested from each mixture at each temperature, and the average of the data was used to figure out what was going on. Table 3.8 shows how the conditions were used based on what was put in.

Table 3.8 Test Parameter for ITSM

Description	**Value**	**Description**	**Value**
Temperature (°C)	25 & 40	Poisson ration	0.35
Loading time (ms)	125 ± 5	Width of loading pulse (ms)	250
Pulse repetition period (ms)	3000± 100	Conditioning time (hours)	4
Number of conditioning pulses	5	Total (target) horizontal deformation (μm)	5

The ITSM test was done along two sections of each sample, and Equation 3.5 [45] was used to figure out and record the average stiffness modulus.

$$Sm = \frac{p * (\upsilon + 0.27)}{z * t} \tag{3.5}$$

For this investigation, we use a poison's ratio of 0.35, therefore SM is stiffness modulus in megapascals, P is the peak vertical load in newton, v is the horizontal deformation in millimeters, and t denotes the specimen's thickness in millimeters.

3.7.3.5 Dynamic Modulus Test using SPT

The experiment was conducted according to the guidelines outlined in the AASHTO-TP 62-07. The determination of dynamic modulus was conducted with the Asphalt Mix Performance Tester (AMPT). The alternative designation for this tool is Simple Performance Tester (SPT). Before placing the specimen in AMPT, the studs were fixed using R-Belite epoxy glue. Once the studs were fixed, then clamps were fixed to each specimen. The purpose of this clamp is to accommodate the (LVDT’s) Linear Variable Displacement Transducer, which measures the axial deformation/strain during the test. Figure 3.23 shows the specimen having the LVDTs attached inside the SPT environmental chamber.

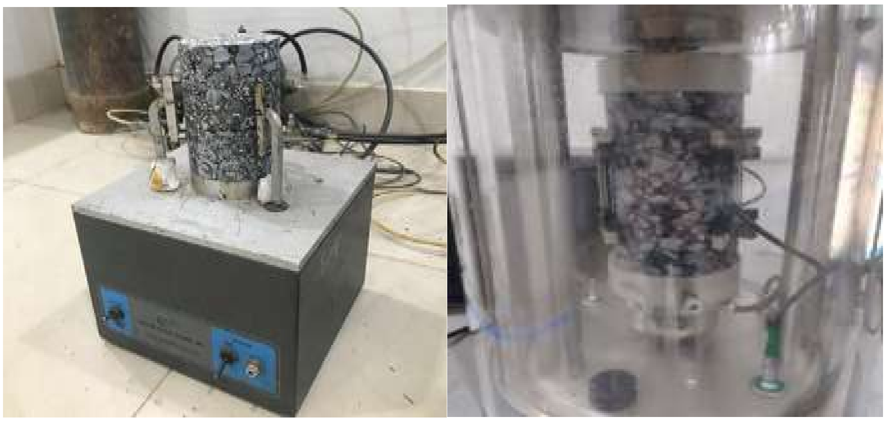


Figure 3.23 Stud fixing and LVDTs attached inside the SPT environmental chamber

Temperature control was maintained within ± 0.5°C of the set point for the sample in the environmental chamber. We used a test method called continuous uniaxial sinusoidal compression stress on our sample. The deformation of the sample was measured using LVDTs fixed at 120 apart. Outcomes were provided by the UTS006 software upon completion of test, and dynamic modulus was noted at corresponding frequencies. Following (AASHTO-TP 62-07, 2009) standards, the environmental compartment is hermetically sealed and allowed to reach thermal equilibrium at the designated test temperature. The minimal optimum condition of temperature is listed in Table 3.9 shown below.

Table 3.9 Times for Conditioning Temperature

Sample Temperature (°C)	**Conditioning Time from normal temperature (Hours)**
4.4	24 Hours (Overnight)
21.1	1 Hours
37.8	2 Hours
54.4	3 Hours

UTS 6 software as shown in Figure 3.24 is used to begin testing the specimen after completing equilibrium temperature times. Once the required temperature has been reached, the intended, 25, 10, 5, 1, 0.5, and 0.1Hz frequencies were selected.

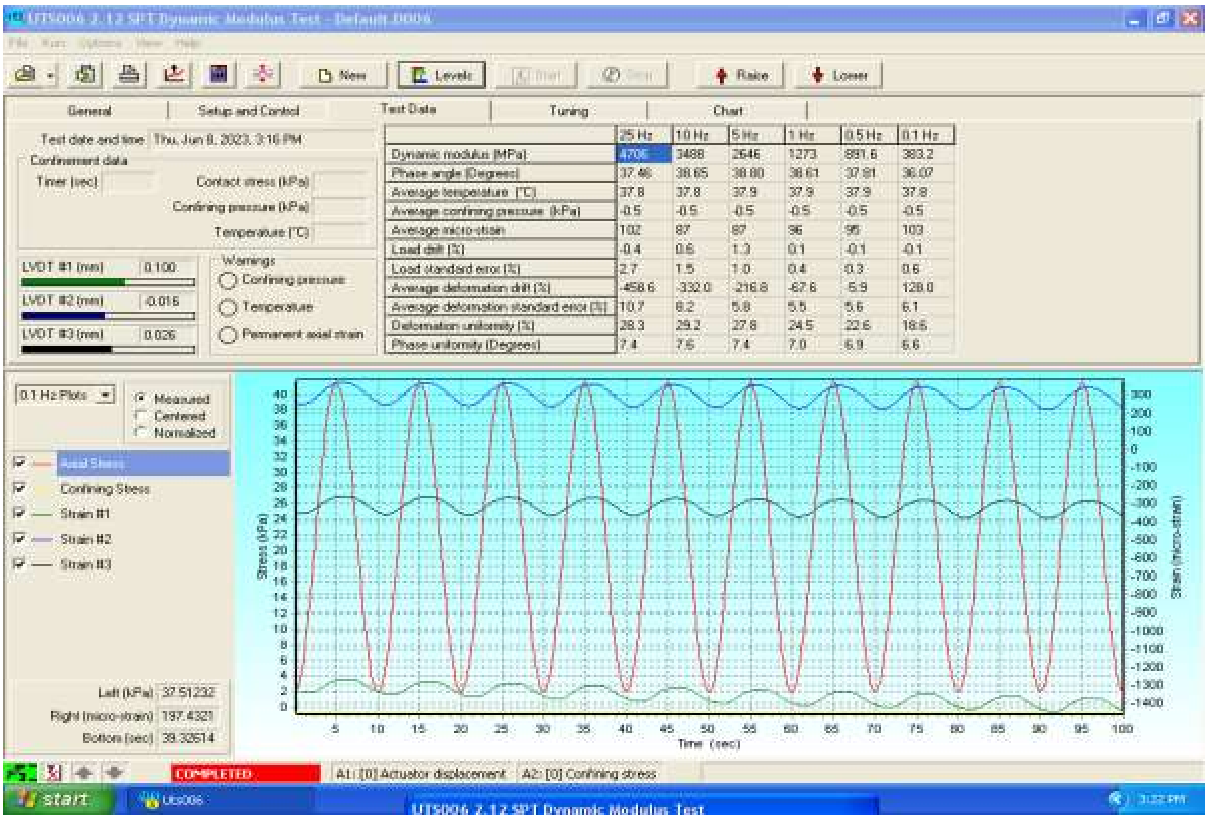


Figure 3.24 UTS 6 software interface

Initial modulus is determined by running a nine-cycle haversine load on the program before commencing the test, which yields the initial modulus. From high to low frequency that is 25Hz to 0.1Hz, the testing technique is built out. When the testing is finished, a report comprising the results of the phase angle and dynamic modulus measured at given frequency and temperature ranges were produced. Triplicate samples are examined at temperatures (4.4, 21.1, 37.8, and 54.4°C) using the identical approach for the dynamic modulus test.

3.7.3.6 Simple Performance Tester (SPT)

The determination of dynamic modulus was conducted with the Asphalt Mix Performance Tester (AMPT). The alternative designation for this tool is Simple Performance Tester (SPT) [46]. The AMPT machine seen in Figure 3.25 was used in this study. For asphaltic pavement structural design, transportation organizations around the world are using AMPT. Asphaltic mixture's in-service performance quality can be predicted using the results of this study. An air-cooled hydraulic pump, refrigerator, and heating unit are all included in this equipment. Another important component of the machine is an air-driven compressor for securing the pressure system. Built-in digital control of the triaxial cell and environmental chamber is included in this piece of equipment. Data is collected and processed by the testing equipment on its own. To evaluate asphalt mixture specimens, this testing machine can apply cyclic stress at various temperatures and frequencies. This system can analyze the parameters of asphalt mixtures to predict their performance. Built- in test modules for each test type are placed in the computer system that is attached to the equipment. Real-time deflections and strains can be viewed on a monitor during the test, together with applied or testing conditions. It is possible to export testing data results in Microsoft Excel file format from a computer hard disk following the test.

Figure 3.25 Simple performance tester (SPT) machine

3.7.3.7 Fuel Spillage Resistance

Fuel leakage is a common problem for parking lot pavement, road intersection pavement, toll plaza pavement, gas station pavement, and airport runway pavement. When diesel, kerosene, and other mineral oils come into contact with standard HMA surfacings in these areas, the bitumen softens and causes raveling-style pavement distresses. Aggregates detach from the surface as a result of this occurrence. This research tests the hypothesis that semi-flexible materials' resistance to fuel is one of its benefits. Both the semi-flexible and the standard HMA samples were subjected to diesel oil. To calculate mass loss, we immersed certain samples in diesel oil for varying amounts of time. Figure 3.26 is a flowchart depicting the steps of this evaluation.

3.7.3.8 Test using partial immersion (mass loss determination)

According to BS EN 12697-43 test specimens were partially immersed up to 35 mm, as indicated in Figure 3.26. Each specimen's mass is calculated prior to immersion and is noted as m1. The specimens were held for a further 24 hours to dry after being submerged for 24 hours. Following the drying phase, the specimen's mass is calculated, recorded as m2, and visually examined. A steel brush that is connected to the Hobart mixer and travels in an epicycloid motion is then used to abrade the specimen (Figure 3.26). After being rubbed with a steel brush for 30, 60, and 120 seconds, the mass of the specimens is measured and noted as m3, m4, and m5, respectively. Each combination had three samples examined, and the average result was utilized for analysis. Based on the prescribed standard (BS EN 12697-24), the determination of fuel resistance level entails the evaluation of two distinct parameters (A and B) subsequent to the occurrence of mass loss caused by immersion and abrasion actions. The parameters A and B are determined by Equations 3.6 and 3.7, and they correspond to the reduction in mass caused by exposure to fuel and the effects of abrasion, respectively.

$$A(\%) = \frac{m1 - m2}{m1} * 100 \tag{3.6}$$

$$B(\%) = \frac{m2 - m5}{m2} * 100 \tag{3.7}$$

By determining “A” and “B”, BS EN 12697-24 sets the following conditions to characterize the material resistance to fuel.

Good resistance = A < 5% & B < 1%

Moderate resistance = A < 5% & B < 5%

Poor resistance = A > 5% & B > 1%

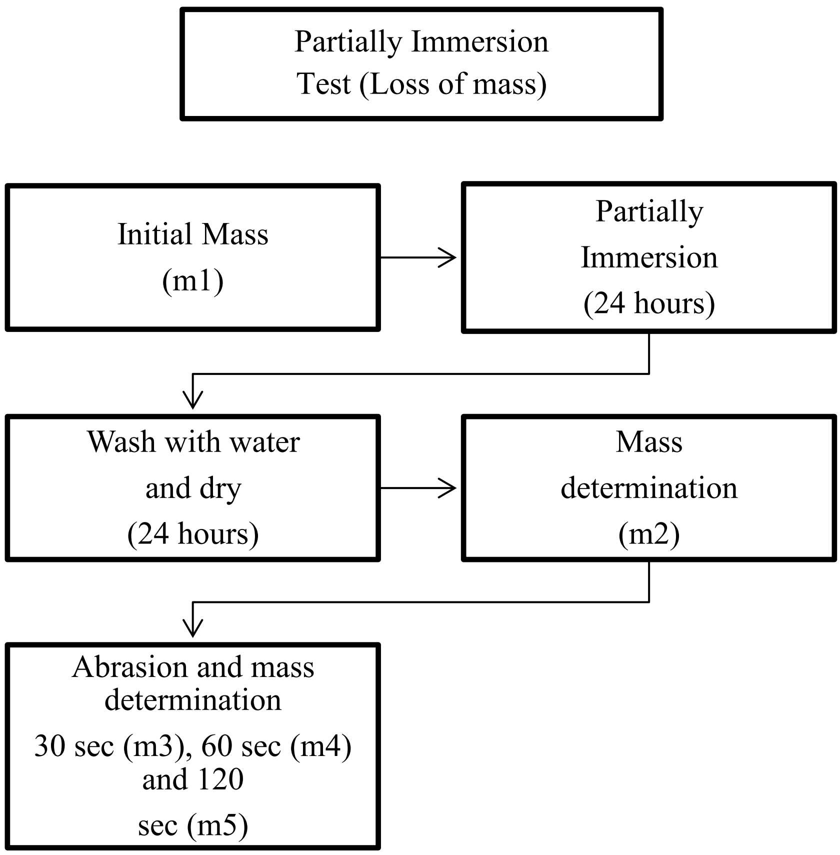


Figure 3.26 Process of loss of mass due to immersion & abrasion

3.8 Summary

This chapter covered the research methods used as well as every job included in the investigation. The methodology was also shown graphically in the form a flow chart.

First PHASE describe Material Selection and Characterization of Material was done in detail. Ordinary portland cement (OPC) of Cherat cement nowshera, Waste marble dust of district Nowshera, Crushed limestone aggregate from the Babuzai quarry site was used with ARL 60/70 Bitumen.

The **Second PHASE** is associated with the production of cementitious grouts, performance evaluation, morphological characterization and finally determined the optimal combination of compositions of grouts having marble dust replacement using optimum water-cement ratio.

In the **Third PHASE** an open-graded asphalt skeleton (OGAS) was selected based on a literature study and available specifications using Densiphalt Type-12 gradation 12.5 NMAS based on volumetric criteria and optimum asphalt content.

In **Fourth PHASE** preparation and performance evaluation of semi-flexible specimens are discussed which includes: grouting ability, Marshall stability, Standard Performance Tester (SPT) using a gyratory compacted sample, tensile strength ratio, moisture resistivity, stiffness modulus, dynamic modulus and fuel resistance.

CHAPTER 4

RESULTS AND ANALYSIS

4.1 Introduction

The design, analysis, and optimization of cementitious grout compositions that use waste marble dust (WMD) as a partial substitution of cement are covered in this chapter. This research study was conducted at NUST-MCE, Military college of engineering Risalpur. At first, the appropriate water to cement ratio and super-plasticizer dose were selected based on the flowability and compressive characteristic at a curing age of 7 and 28 days, while also taking into consideration the bleeding impact. The experimental design and analysis technique known as "RSM-response surface methodology" was utilized throughout the process of designing, analyzing, and optimizing the experiment. Throughout the whole process of experimental design and analysis, flowability and compressive characteristic at a curing age of 7 and 28 days were chosen as a response to measure. This chapter also examines how to establish the proper quantity of bitumen for an open-graded asphalt skeleton that will be used in semi-flexible mix preparation. This topic is covered in more detail later in the chapter. Void analysis and mixed grouting are also topics that are covered in this chapter. This chapter includes a comprehensive description of the semi-flexible specimens that were tested for marshall stability, stiffness modulus, tensile strength ration, dynamic modulus, compressive strength and resistance to fuel leakage.

4.2 PHASE-I Results of Material

In this phase properties and results of material utilized in this research study is presented in detail.

4.2.1 Cement

OPC, or ordinary Portland cement, is a key ingredient in grouting materials., is very certainly what is meant by the term "cement." Purchased from a local vendor of Cherat Cement is the OPC that will be employed in the production of grout for SFP. Chemical composition to cement are listed in Table 4.1

Table 4.1Chemical Composition of OPC [32].

Material	SiO2	Al2O3	Fe203	CaO	MgO	Na2O	K2O	S03	FL	IR	LOI
Cement	21.24	5.56	3.24	63.53	0.93	0.13	0.2	2.55	0.55	0.64	1.24

4.2.2 Waste Marble Dust

This study's main goal was to assess the possibility of utilizing waste marble dust partial substitution of the cement in cementitious grouts. This trash WMD in powder form acquired from the local marble factory in Economic zone Rashakai, which is in Nowshera. In the end, waste WMD powder with a particle size of smaller than 200 microns was utilized as a partial substitute for OPC in cementitious grouts. This was done to complete the study. As can be seen in figure 3.3, a very fine in powder form WMP that was utilized in this investigation. Physical Properties of WMD are tabulated in Table 3.2.

4.2.3 Bitumen Physical Properties

The study made use of the physical attributes of an asphalt binder that was acquired from ARL 60/70 penetration grade. The results of the tests suggest that the bitumen met all the requirements. The conclusions reached are tabulated in Table 4.2

Table 4.2 Binder Properties

Description	Results	Specification	Standard
Penetration Test @ 25 °C	66	60/70	ASTM-D-5
Flash Point (°C)	262	232 °C (Min)	ASTM-D-92
Fire Point (°C)	291	270 °C (Min)	ASTM-D-92
Specific Gravity	1.029	1.01-1.06	ASTM-D-70
Softening Point (°C)	49.6	49 °C to 56 °C	ASTM-D-36
Ductility Test (cm)	108	100 (minimum)	ASTM-D-113

4.2.4 Aggregate Physical Properties

In the study, Babuzai, Katlang crush were used. The results of standard tests on aggregates show that our numbers are in the normal range, so this aggregate was fine to use. Table 4.3 shows an overview of the tests that have been done on groups.

Table 4.3 Aggregate Testing Results

Type of Test		Results %	Specification
Los Angeles Abrasion		21.00	45% (Max)
Flakiness index of Aggregate		10.80	15% (Max)
Elongation Index of Aggregate		3.20	15% (Max)
Impact Value of Aggregate		15.5	30% (Max)
Crushing Value of Aggregate		19.6	30% (Max)
Water Absorption	Fine Aggregate	2.22	3% (Max)
	Coarse Aggregate	0.56	3% (Max)
Specific Gravity	Fine Aggregate	2.55	-
	Coarse Aggregate	2.64	-

4.3 PHASE-II Sustainable Cementitious Grout

Cementitious grouts were prepared to determine their physical and mechanical characteristic; the results of the testing were examined. Flow and compression strength are two of these characteristics. Also, the findings (morphological features) of microstructural characterization were discussed about as well.

4.3.1 Grout Selection Based on W/c Ratio & Compressive Strength

During the initial stage, various ranges of w/c from 0.35 to 0.5 at increment of 0.05 and SP (0.5%) were used to manufacture cement grouts and their flow and compressive strength (7-day and 28-day curing) were evaluated. On the basis of the results, the final w/c ratio and SP dosage were determined. Table 4.4 demonstrates that increasing the w/c ratio significantly decreases the time for flow-out. Likewise, the effect becomes more pronounced when MD is added. As per requirements, the flow out time for 1725 ml grout should fall between 11 and 16 seconds [35]. Cementitious grout flowability is inversely linked to the flow-out time; the shorter the flow time, the better the flowability due to reduced viscosity. By adding water to cement, the interparticle lubricant is increased, resulting in a decrease in viscosity and, consequently, a reduction of grout flow out time [47]. It also applies to this study.

Table 4.4 Grouts' Compressive Strength and Flow

Marble Dust %	S.P %	w/c	Flow (sec	Sample ID	Compressive Strength (Mpa)	
					7-days	28-days
0	0.5	0.35	23	MD0W35	38	55
5	0.5	0.35	21	MD5W35	36	45
10	0.5	0.35	20	MD10W35	33	42
15	0.5	0.35	19.4	MD15W35	32	38
20	0.5	0.35	19	MD20W35	29	36
25	0.5	0.35	18.6	MD25W35	28	36
0	0.5	0.4	16	MD0W40	38	49
5	0.5	0.4	14.8	MD5W40	37	44
10	0.5	0.4	14	MD10W40	36	45
15	**0.5**	**0.4**	**13.2**	**MD15W40**	**35.8**	**46**
20	0.5	0.4	13	MD20W40	35	43
25	0.5	0.4	12.7	MD25W40	27	39
0	0.5	0.45	14.2	MD0W45	29	42
5	0.5	0.45	13	MD5W45	27	38
10	0.5	0.45	12.8	MD10W45	25	36
15	0.5	0.45	12.6	MD15W45	25	35
20	0.5	0.45	12.3	MD20W45	25	36
25	0.5	0.45	12.5	MD25W45	24	34
0	0.5	0.5	13.9	MD0W50	28	38
5	0.5	0.5	13.2	MD5W50	28	36
10	0.5	0.5	12.2	MD10W50	27	33
15	0.5	0.5	11.8	MD15W50	26	33
20	0.5	0.5	11.3	MD20W50	22	32
25	0.5	0.5	12.1	MD25W50	19	27

Similar to this, Table 4.4 demonstrates that compressive strength declined as the w/c ratio rose. The inclusion of a polycarboxylate ether-type superplasticizer improved cement hydration to achieve early strength. The grouts selected based on the desired flow rate (11 to 16 seconds) and compressive strength as tabulated in Table 4.4.

4.3.2 Optimization and RSM Analysis of Cementitious Grouts

Response surface methodology a statistical tool was used for analysis of grout . ANOVA was utilized to analyze the effect at a curing age of 7 days and 28 days of various marble dust (MD) percentages, w/c ratio on flow and compressive strength. RSM then optimized and validated the outcomes. Independent variables are MD and w/c, whereas dependent variables (or responses) are flow and compressive strength. The next parts will provide an explanation of the results.

4.3.2.1 RSM Analysis of Grouts with Partial MD Substitution

As described in Section 2.4.3 (Methodology), Response surface methodology a statistical tool was used for analysis numerous combinations of grouts. Using ANOVA, the effect of various percentages of MD and w/c on flow and compressive strength (7-day and 28-day curing) were analyzed. MD and w/c are independent variables (factors), while flow and compressive are dependent variables (responses). Table 4.5 provides further information on the suggested models for the flow and compressive characteristics of cementitious grouts based on MD. Cubic versus quadratic models are suggested for responses based on a high R2 value (> 90%), and the models' p-values are less than 0.05, indicating that they are significant.

Table 4.5 MD-based Grout Model Validation and ANOVA Analysis

Responses	Flow (sec)	Compressive Strength 7 days	Compressive Strength 28 days
Standard Deviation	0.48	2.60	2.64
Mean	15.48	31.78	40.71
R2	0.94	0.8	0.96
Predicted R2	0.93	0.785	0.94
Adjusted R2	0.94	0.7736	0.95
Adequate Precision	49	23.7	27
Model F-value	52.13	52.13	49.66
Model p-value	<0.0001	<0.0001	<0.0001
Model Remarks	significant	significant	significant
Final selected model	Quadratic	Quadratic	Quadratic

Table 4.5 shows the Analysis of Variance (ANOVA) and model validation for the mechanical and physical characteristics of cementitious grouts in terms of responses. The suggested

models' high F-value (more than 40) as well as low p-value (0.05) demonstrate their significance. R2 is 0.96 for flow, 0.8 and 0.96 for compressive strength over 7 and 28 days, respectively. The sufficiency and validity of the developed models are shown by the coefficient of determination, or R2. R2 > 0.80 indicates a strong fit to the model and excellent agreement between the observed and anticipated responses [48], [49].

As a further indication for confirming the importance of the model, acceptable precision (which assesses signal-to-noise ratio) must be more than 4.0 [48]. Table 4.5 demonstrates that all answers have sufficient precision of larger than 12, demonstrating high agreement across all models. For all replies, the difference between projected R2 and adjusted R2 is less than 0.20, demonstrating a satisfactory level of agreement.

Furthermore, to statistics for model validation and fit, diagnostic diagrams can verify the sufficiency and normal distribution of data. The diagnostics plots, like normal residual plot, actual versus predicted plots, and residual versus runs plots, may be used to evaluate the accuracy of regression statistics [50]. Figures 4.1 (1) and 4.1 (2) depict the residual normal plots for both fluid flow and compressive strength. The figures show a decent link between the very studentized residual and the normal percentage of likelihood, as nearly all of the points for both responses (flow and compressive strength) are situated near close along the path. It suggests that the residual values, which represent the difference between the experimental and anticipated responses, follow a normal distribution. [51].

Figures 4.1 (3) and 4.1 (4) illustrate the correlation between predicted and actual flow and compressive strength data points. Data points' distribution is comparatively near to the line of equality, indicating a satisfactory degree of model fitness and appropriate agreement between observed and predicted outcomes. Figure 4.2 – 4.4 shows RSM analysis in 3d contour maps for flow and compressive strength.

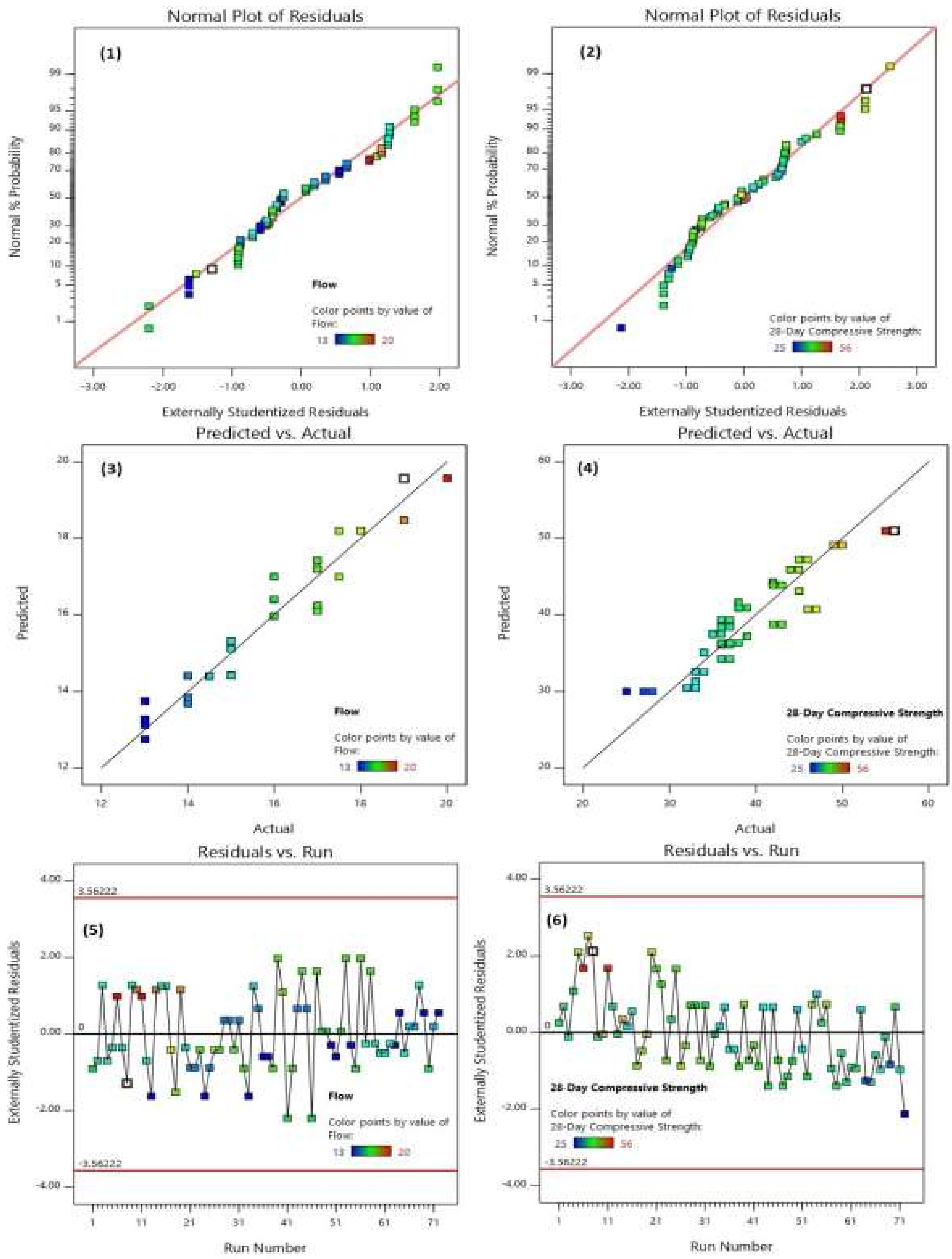


Figure 4.1 Normal plots of residual: (1) flow and (2) 28-days compressive strength; predicted vs actual plots (3) flow and (4) 28-days compressive strength; residual vs run plots (5) flow and (6) 28-days compressive strength

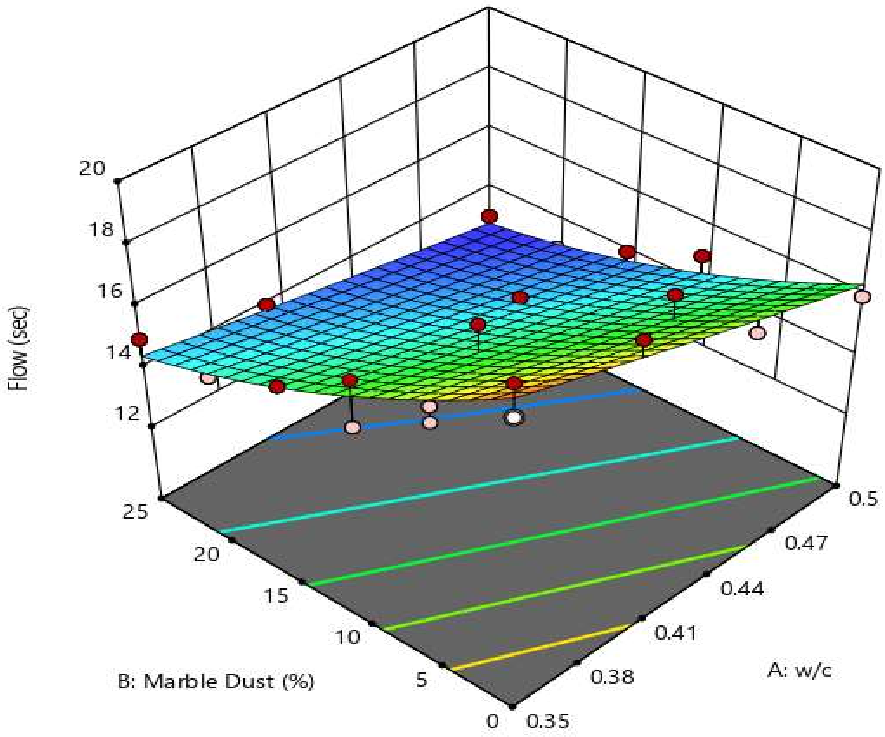


Figure 4.2 RSM analysis in 3d contour for flow

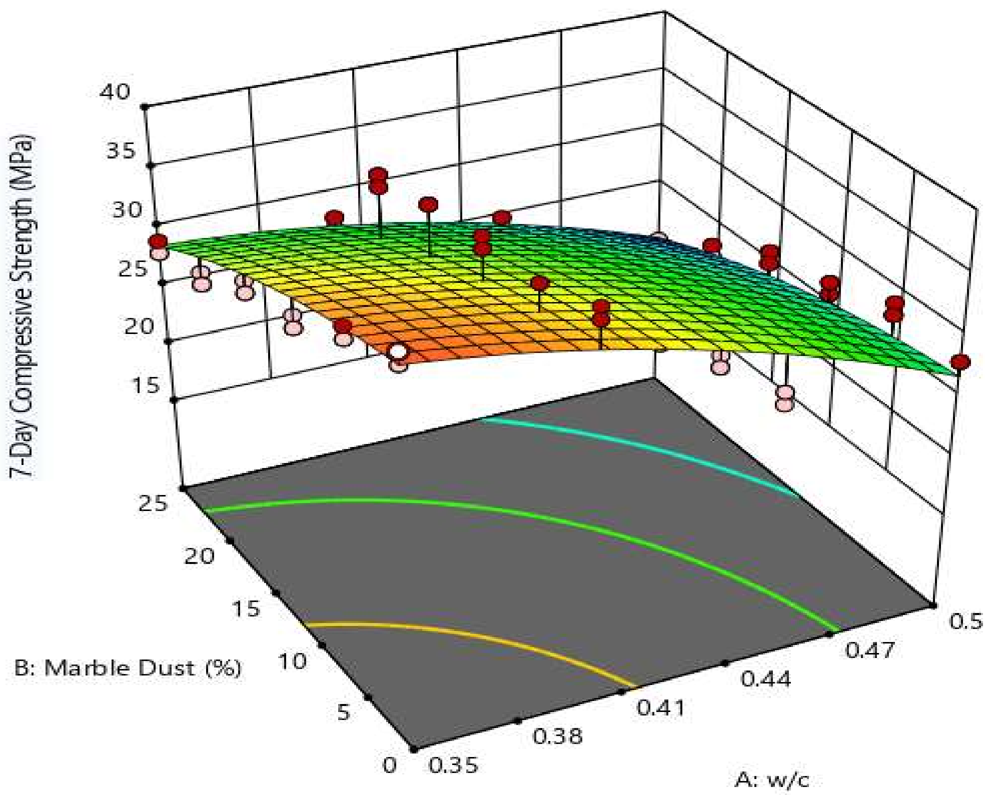


Figure 4.3 RSM analysis in 3d contour for 7 days compressive strength

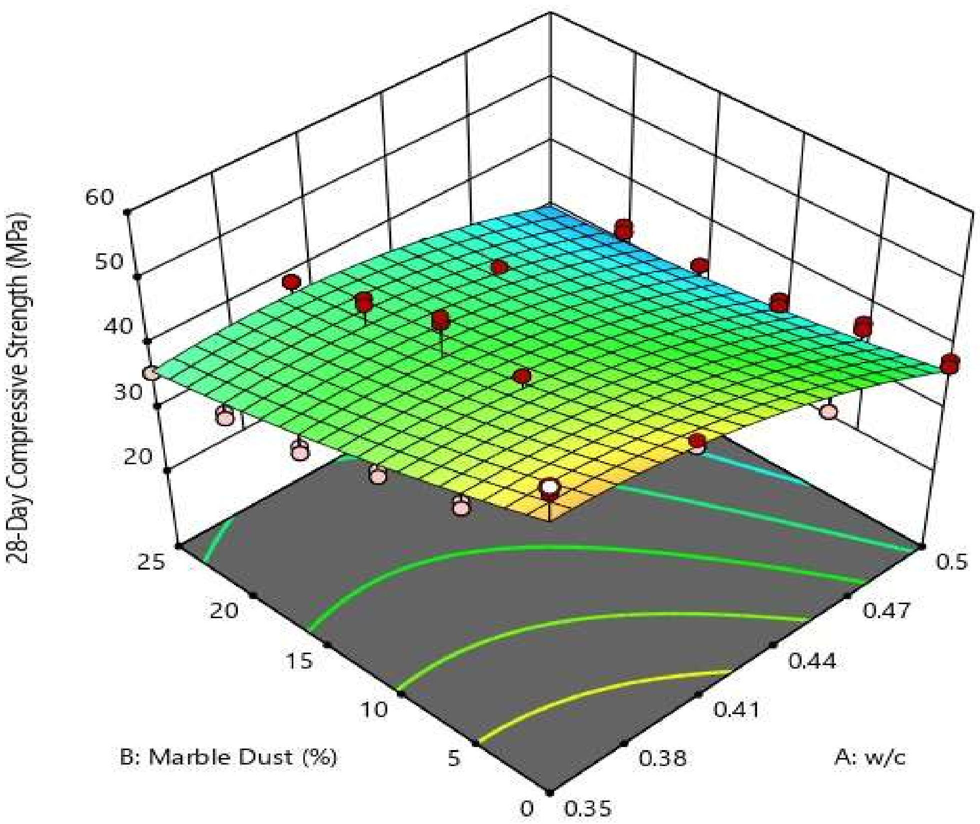
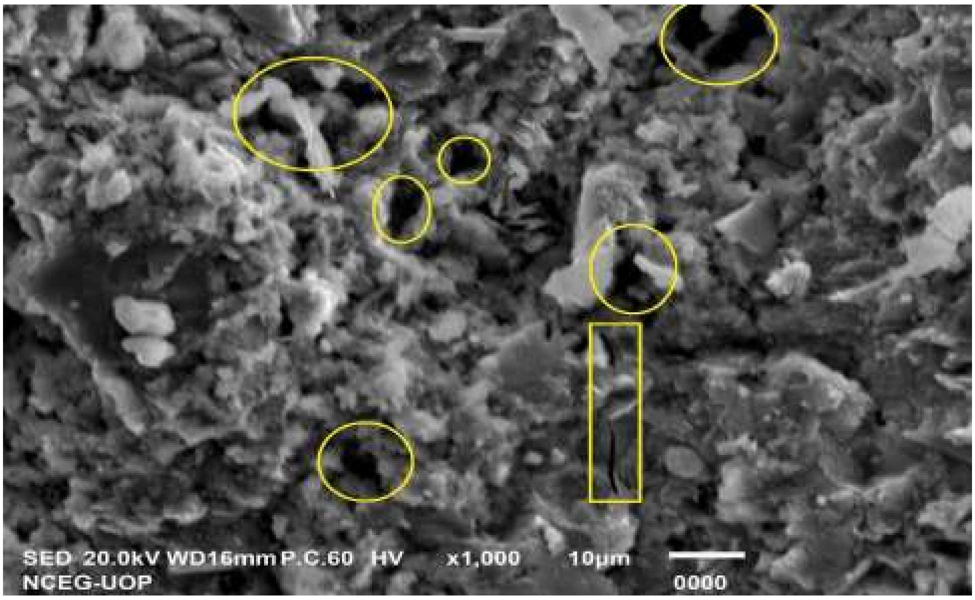


Figure 4.4 RSM analysis in 3d contour for 28 days compressive strength

4.3.2.2 SEM Analysis

The SEM-EDX test was done on the grout of the control sample and the samples that had 15% waste marble dust. Figure 4.5 shows the micrographs and EDX analysis graphs of all the samples. The SEM image of the control grout shows that a lot of CH crystals have formed. When EDX analysis is done, a high Ca/Si ratio of 2.7 shows that CH crystals with a low density have formed in the paste sample control grout. Also, an image of a paste sample made with waste marble dust showed that CH was the main phase, but the crystals were very close together. Ca/Si ratio of 2.45 confirmed the formation of densely packed CH phases. The SEM-EDX data showed that adding waste marble dust causes thick phases to form, which increased the density of grout. This helps to reduce the strength loss caused by adding marble dust.



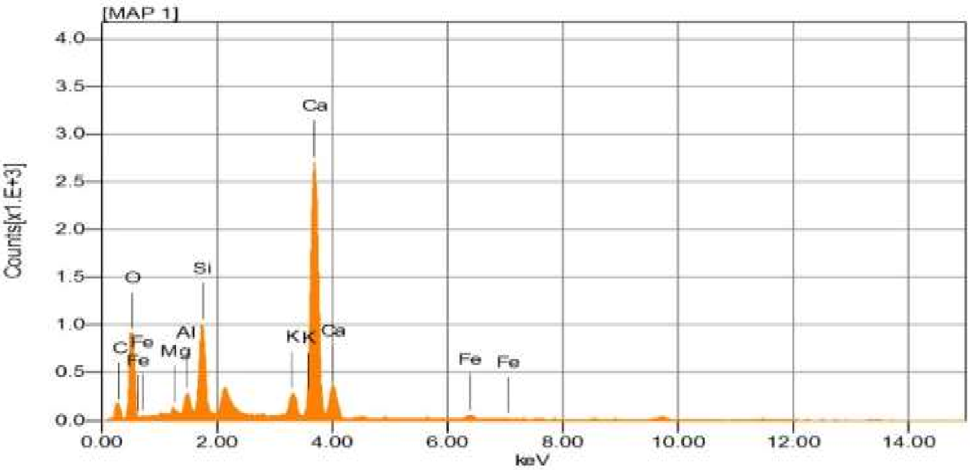


Figure 4.5 SEM in-depth picture and EDS analysis of control grout

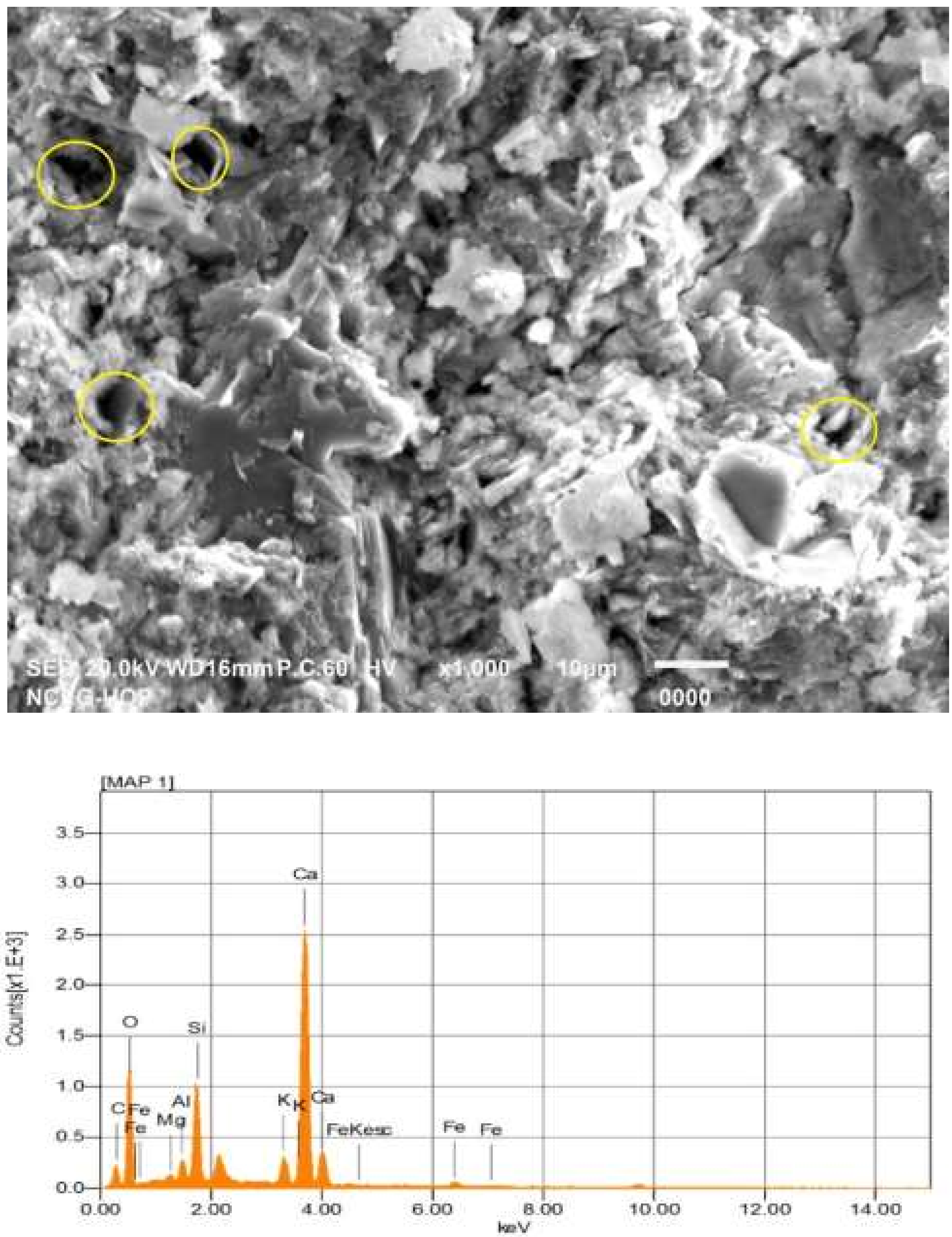


Figure 4.6 SEM in-depth picture and EDS of cement-marble dust grout

On the other hand, as shown in Figure 4.6, the SEM-EDX study shows that adding marble dust reduces the number of CH crystals because it makes the pozzolanic event better upon using CH phases to make more CSH phase. When marble dust was added, the base of the paste became much less porous, which led to better mechanical qualities in the long run. These data show that utilizing waste marble dust in the cement and concrete business in a way that is good for sustainable growth.

4.4 PHASE-III Preparation of Open Graded Asphalt Mix & HMA Specimen

This section describes the fabrication of conventional HMA and semi flexible specimens, including void analysis and grouting, as well as determining the Ideal Bitumen Content Equation 2.1 (section 2.4) was utilized to determine the initial optimum bitumen content (O.B.Ci) at the outset. As shown in Table 4.6, the $OBC_{initial}$ was determined based on aggregate sieve analysis from aggregate stockpiles.

Table 4.6 Components of $OBC_{initial}$ Equation

Parameter	**Value**	**Parameter**	**Value**
G	0.9	$\sum$	0.8586
S	0.033	Gsa	2.72
s	0.012	α	0.9743
f	0.003	$\sum^{0.2}$	0.9700

Hence, Initial $OBC_{initial}$ = 3.07 %

The study [39], proposes building trial porous asphalt specimens utilizing two points above and below this binder % to find the ultimate binder amount, with bitumen concentration assumed to be 3.0 percent. The optimal bitumen concentration was determined by conducting experiments with bitumen contents of 2.60%, 2.80%, 3.0%, 3.20%, and 3.50% based on the weight of aggregates.

4.4.1.1 Open-graded asphalt mixture air voids content

The amount of air that was found in the porous asphalt compacted mixes was measured during the experiment for the bitumen content, and the results may be found in Table 4.7.

Table 4.7 Air Voids of OGA Mixtures

Bitumen Content (%)	**Air Voids (%)**
2.6	29
2.8	28
3.0	26
3.2	24
3.5	21

The findings show that when bitumen concentration rises, air voids are dramatically decreased. The standards state that the porous specimen should include 25% to 35% voids with a suggestion of about 30% [8]. 3% bitumen content by weight of aggregate is used as the ultimate OBC for asphaltic skeletons to be taken into consideration for semi-flexible pavement surfacings based on the findings of the draindown test and examination of air voids.

4.4.1.2 Degree of Grouting Saturation

Cylindrical specimens were analyzed for voids using volumetric measures. Table 4.7 displays findings. Air voids are essential in an open-graded bitumen composition for semi-flexible pavement surfaces. Below 25% air cavities will disconnect the mixture and limit cement grout penetration. In addition, it may cause non-uniform grout dispersion in specimens and diminish the layer's mechanical performance and load-bearing capability [36]. A greater proportion of voids (say, greater to 35%) necessitates larger volumes of cement grouts, thus the specimen becomes brittle and stiffer. In addition, the grout saturation degree (Table 4.8) verifies the connectivity of the interior cavities of the mixture. According to the scientific research, void interconnectivity and homogenous penetration can be assured at grout saturation levels between 94 and 97% [41], [36], [52], [53]. According to the findings of the present study, the grout saturation level ranges between 94% and 97% (Table 4.8). This indicates that the cavities were filled and that the cement grout is distributed effectively.

Table 4.8 Grout Saturation of OGA-Specimens

Mixture Type	Degree of grout saturation (%)
OGA-Specimen-1	0.96
OGA-Specimen-2	0.95
OGA-Specimen-3	0.97
OGA-Specimen-4	0.96
OGA-Specimen-5	0.94
OGA-Specimen-6	0.94
OGA-Specimen-7	0.95
OGA-Specimen-8	0.97
OGA-Specimen-9	0.94

4.5 PHASE-IV Performance Testing of Semi-flexible and Conventional HMA Mixture

4.5.1 Marshall Stability of Specimens

Semi-flexible mixes' stability was assessed and compared with HMA's. Reasonably, semi-flexible mixes' Marshall stability value is much higher than HMA. According to Table 4.9, the stability of HMA ranged between 12 to 13 kN, while semi-flexible mixtures increased this value by 160 to 180 percent. Cement grout added to semi-flexible mixes increases their stability in comparison to HMA combinations as shown in Figure 4.7. Semi-flexible pavement surface materials do not yet have any recognized design stability criteria; despite this, this research was performed for comparative reasons. Other investigations [6], [40] have shown that stability values of semi-flexible mixtures are more than double those of HMA mixtures.

Table 4.9 Marshall Stability of Conventional HMA and Semi-Flexible Mixtures

Mix Type	Stability (KN)	Flow (mm)
HMA – 1	13.3	3.2
HMA – 2	12.7	3.3
HMA – 3	12.5	3.5
SFM-1	20.5	5
SFM-2	21.66	4.5
SFM-3	24	4.2

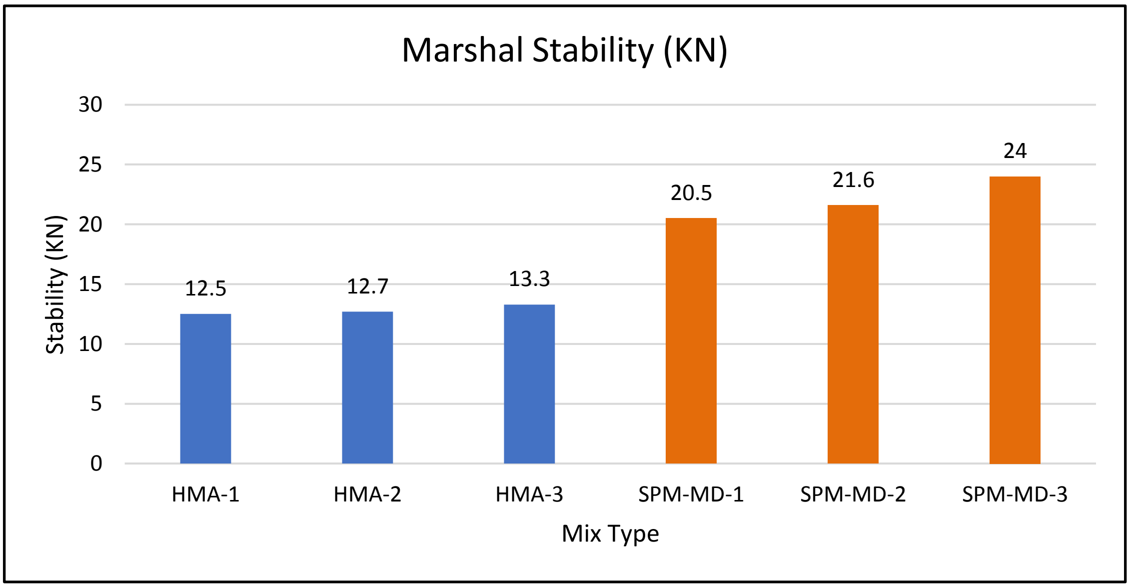


Figure 4.7 Marshall stability of HMA and semi flexible specimens

4.5.2 Tensile Strength Ratio-TSR

The TSR of HMA and semi-flexible blends are displayed in Table 4.10. Semi-flexible formulations containing marble dust-based grouts (SFM-MD) exhibit higher TSR values than HMA specimens. In addition, the moisture resistance of each mixture was determined by immersing specimens in a 60°C water immersion and then conducting the ITS test. Figure 4.8 demonstrates the results (ITS_{wet}). Similar to ITS_{dry}, ITS_{wet} findings follow a similar trend. By figuring out the TSR for each mix, which represents the resistance to moisture damage is determined. By looking at the outcomes, it is possible to conclude that all semi-flexible mixes have a TSR value close to 0.91. However, as compared to semi-flexible composites, HMA showed lower TSR value of 0.71. The TSR values found in this investigation (about 0.9) closely match those found in other studies (ranging from 0.9 to0.97) for semi flexible mix using different materials and additive [54], [55]. In conclusion, semi-flexible composites outperformed traditional HMA in terms of moisture resistance and effectiveness against moisture damage.

Table 4.10 Results of TSR

Test	HMA	SFM-MD
TSR (%)	71.1	90.1

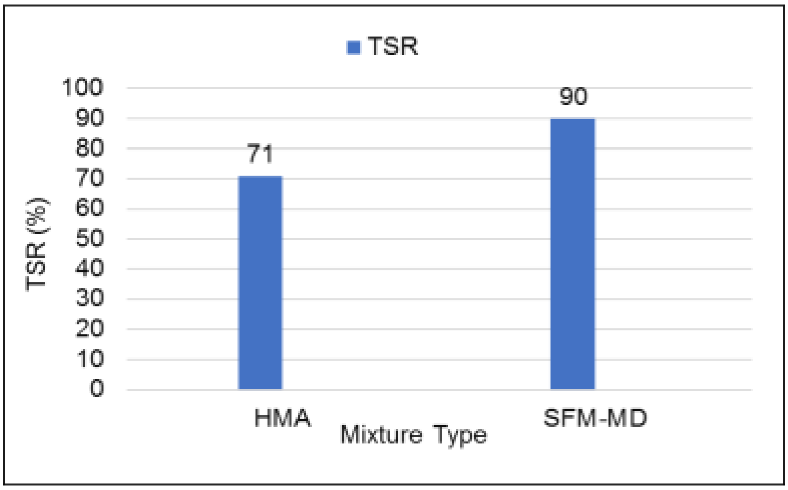


Figure 4.8 Tensile strength ratio

4.5.3 Fuel Resistivity of Semi-flexible Specimens

Fuel resistivity of a semi-flexible specimen is measured by mass loss as a result of partial immersion and loss of strength after full submersion. The detailed discussion of results is described in the following subsections.

4.5.3.1 Results of Partial Immersion

Resistance of mixes to oil and fuel spills is determined by partly immersing specimens for 24 hours in Diesel oil, followed by a washing and drying phase (another 24 hours), and then abrasion with a steel brush. For semi-flexible mixes and HMA, Figure 4.9 displays the mass loss from fuel following Parameters A and B. Parameter "A" represents effects of diesel oil immersion on the samples, whereas the parameter "B" reveals the washing and abrasion effects. Conventional HMA specimens that had been exposed to diesel for a portion of the time were severely harmed and had lost a considerable quantity of mass. The semi-flexible mixes, on the other hand, demonstrated outstanding diesel resistance and underwent minimal loss of mass throughout its immersion duration.

Additionally, it has been shown that the amount of mass lost for HMA specimens rises with immersion time. The mass loss was 2.5% on day 1 and 21% on day 7, respectively. Following seven (7-day immersion) immersion cycles, this demonstrates a 755% increase in mass loss. Alternatively, semi-flexible demonstrated a little increase in mass loss as immersion days increased.

As shown by Parameter "B," the mass loss brought on by abrasion (with a steel brush) was also much higher for HMA combinations. Up to five exposure cycles, the mass loss rises before starting to decline for the subsequent cycle. After six cycles, there is a constant loss of mass. When a steel brush was used to abrade the specimen's surface, the bitumen and other fine particulates were promptly removed. After six cycles, the exposed coarse aggregates were firmly entrenched in the specimens, preventing any mass loss due to abrasion. SFM, on the other hand, did not noticeably lose bulk with more frequent immersion cycles. When "A" and "B" were computed and compared to the (See section 3.5.3.8) BS EN 12697-43, HMA combinations showed very little fuel resistance, while all semi-flexible blends exhibited substantial resistance. The images show how the HMA specimen significantly loses mass after being exposed to diesel and abrasion impacts. More aggregates were removed from the mixture and the mass loss increased with each immersion session. On the other hand, it was shown that no semi-flexible combinations produced any significant diesel effects.

Figure 4.9 Loss of Mass Test (Partial Immersion)

Finally, the semi-flexible surface materials demonstrated higher resistance to gasoline spills. As a result, these surfaces may be effectively deployed in places prone to gasoline spills, such gas stations, runways at airports, refineries, and industrial areas.

4.5.4 Stiffness Modulus of Specimens (ITSM)

The stiffness modulus of specimens was assessed using a series of indirect tensile stiffness modules test measurements. To provide a comparison, the stiffness modulus of conventional hot mix asphaltic (HMA) specimens was also assessed. The ITSM test was performed at two different temperatures 25°C and 40°C, four samples of each kind of combination and temperature were tested. For the study, the average outcomes at each temperature were considered. Table 4.11 lists the average stiffness modulus for each combination for each of the two temperatures, accompanying standard deviation values. Furthermore, each kind of semi-flexible behavior in comparison to traditional HMA mixes, the average data is also shown in Figure 4.10.

HMA mixes and semi-flexible mixtures both experience a drop in stiffness modulus as a function of temperature. The behavior of HMA as a visco-elastic material and how temperature affects its properties are well-known facts. However, based on the conditions and the type of test, semi-flexible behaves differently. From stiffness properties, it can be concluded that semi-flexible material also behaves as a visco-elastic because the stiffness modulus is significantly influenced by an increase in temperature. The reduction in stiffness modulus is the evidence that semi- flexible have visco-elastic nature and, therefore, can directly be compared with the stiffness characteristics of traditional HMA mixes. Similar results of the stiffness modulus for semi-flexible specimens (i.e., decreasing with increased temperature) were also observed in the literature [6], [39]. Stiffness modulus of the SFM and HMA mixes discovered in the current investigation is shown in Table 4.11.

Table 4.11 Semi-Flexible Specimens and HMA's Stiffness Modulus

Temperature (C)	SFM-MD		HMA	
	Stiffness (MPa)	Std. dev	Stiffness (MPa)	Std. dev
25	3792	86	3540	93.6
40	2758	108	1356	21

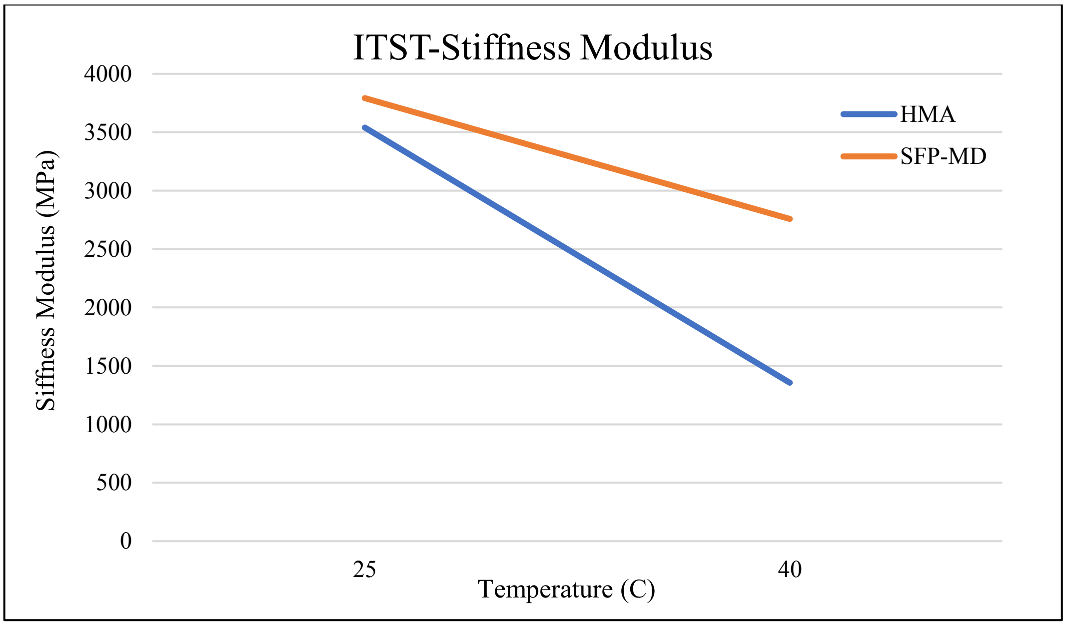


Figure 4.10 Semi-Flexible Specimens and HMA's Stiffness Modulus

It appears from stiffness results that semi-flexible surfacing materials behave closer to bituminous material than rigid pavement material.

4.5.5 Master Curve for Dynamic Modulus

The information provided by AMPT was used to create a master curve for the pavement design procedure. Results were combined using the time-temperature superimposition technique at 21.1 °C for the HMA & SFM-MD combination. Master curve was created using the NCHRP Project 9 29 procedures. To generate the best fit line in MS Excel, the master curve was built using a solver add-in that restricts sum square error (SSE). Figures 4.11, which illustrate the dynamic modulus response at low and high frequencies, show the master curve for HMA and SFM-MD mixes. Where low and high frequencies, respectively, correspond to high and low temperatures [56].

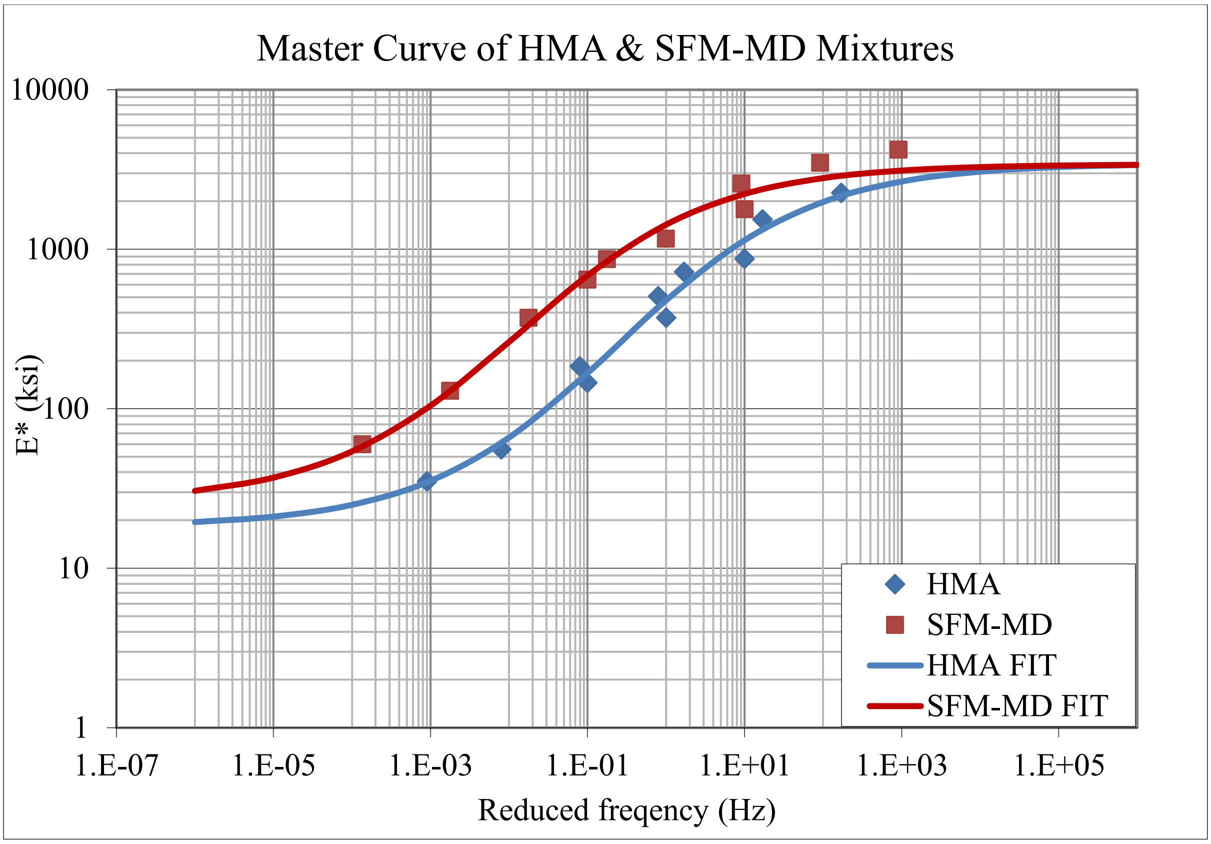


Figure 4.11 Dynamic modulus master curve for HMA & SFM-MD

4.5.6 Sensitivity Analysis

A sensitivity analysis is used to determine how different independent factors affect dependent parameters in the context of a given set of criteria. It is assessed under predefined boundary conditions that specify the input variables. Sensitivity analysis shows the extent to which the dependent variable is sensitive to certain independent variables or change in input parameters. It may be quite helpful for verifying the resilience of models or outputs that are dependent on some input factors. The independent parameters for this research are temperature and frequency, while the dependent variable is |E*|.

It can be inferred from the results of sensitivity analysis that the dynamic modulus has a negative correlation with temperature, meaning that as the temperature decreases, the dynamic modulus tends to increase, and vice versa. The opposite relationship is observed for frequency, a increase in frequency results in a increase in dynamic modulus values. Changes in dynamic modulus values has been noticed, indicating severe sensitivity to higher temperatures and prone to inaccuracy. Therefore, when testing at higher degrees, considerable care should be used, and samples should be treated for equilibrium periods until the appropriate test temperatures are obtained. Once the desired temperature has reached its equilibration point, the test should be performed.

Isothermal and isochronal curves are used to depict the average test findings graphically. It is evident from Figure 4.12-4.13 that dynamic modulus increases as frequency increases from 0.1Hz to 25Hz and temperature decreases 54.4oC to 4.4oC. The ratio of stress to maximal recoverable strain is known as dynamic modulus, as was previously mentioned; therefore, it has been ascertained that at lower temperatures i.e., 4.4oC the |E*| values are significantly greater as compared other to high temperatures, as strain is temperature-dependent, resulting in increased stiffness at 4.4oC and greater flexibility at high temperatures i.e., 54.4oC. That is why the dynamic modulus is high at 4.4 °C; as the temperature increases, the dynamic modulus tends to fall dramatically.

From Figure 4.14 and Figure 4.15, it is evident that SFM-MD has greater dynamic modulus values as compared to HMA. Moreover, at high temperature, these is no significant variation in dynamic modulus values.

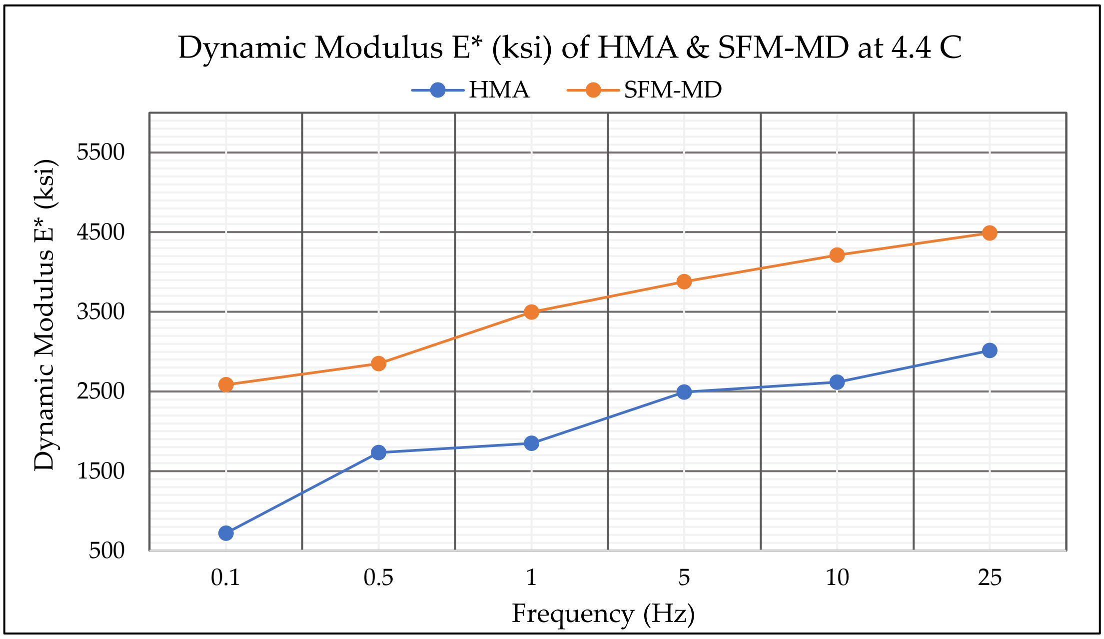


Figure 4.12 Dynamic modulus - Isochronal curves (HMA & SFM-MD)

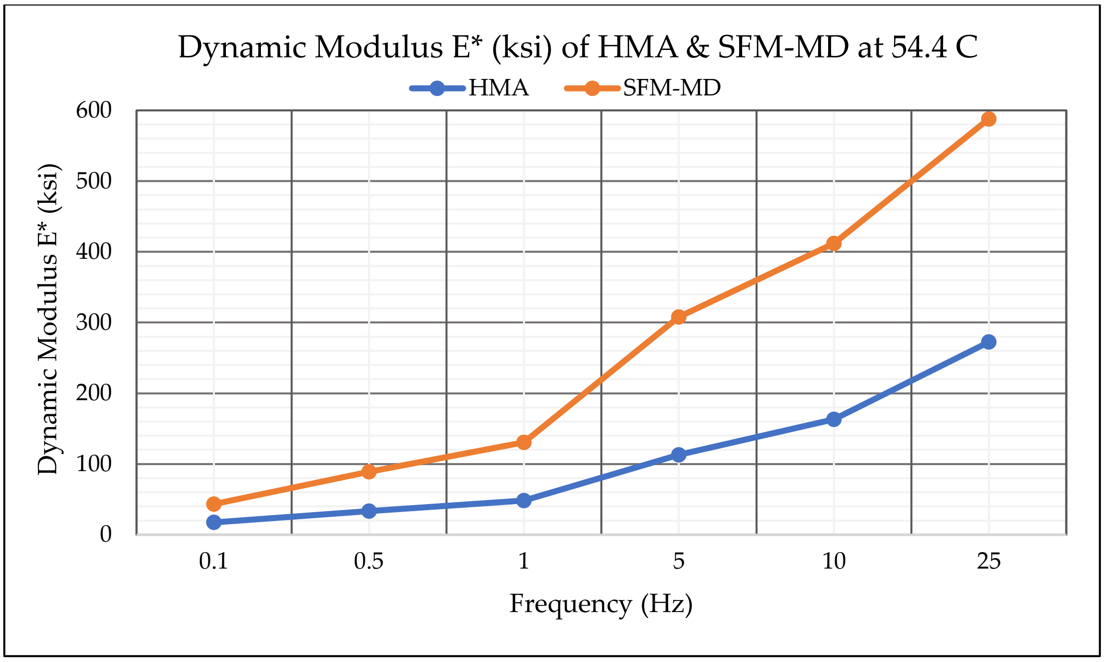


Figure 4.13 Dynamic modulus - Isochronal curves (HMA & SFM-MD)

Due to the fact that dynamic modulus is represented by a stress-strain relationship and that the frequency of loading determines how long the tire is in contact with the pavement, Figure 4.13 shows that dynamic modulus increased with increasing frequency, ultimately leading to an increase in |E*|.

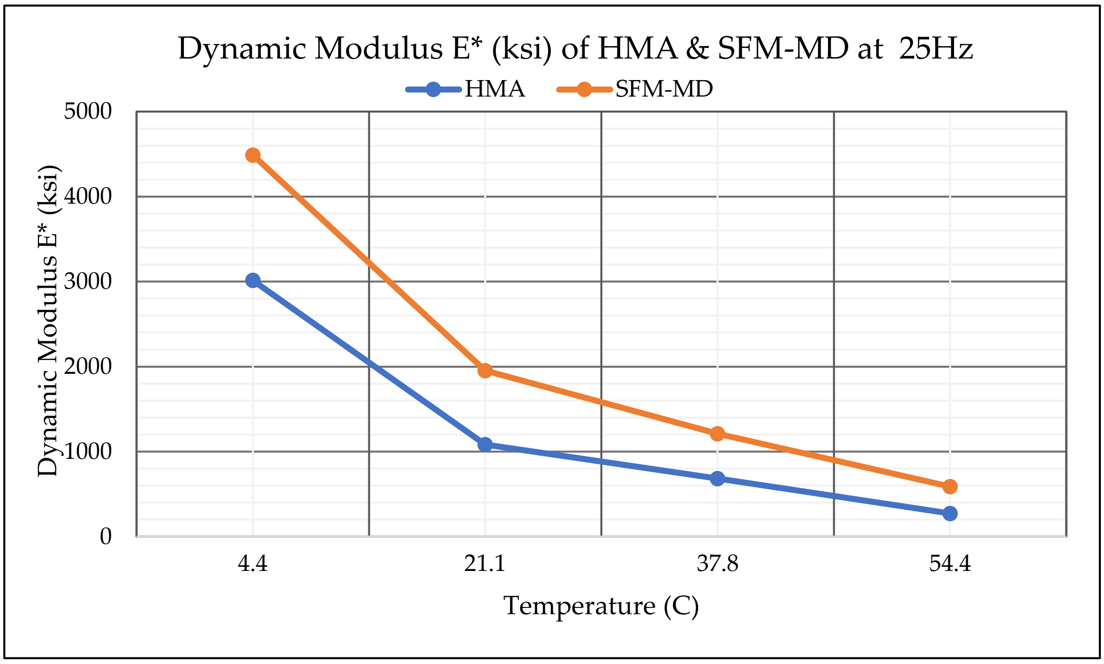


Figure 4.14 Dynamic modulus - Isothermal curves (HMA & SFM-MD)

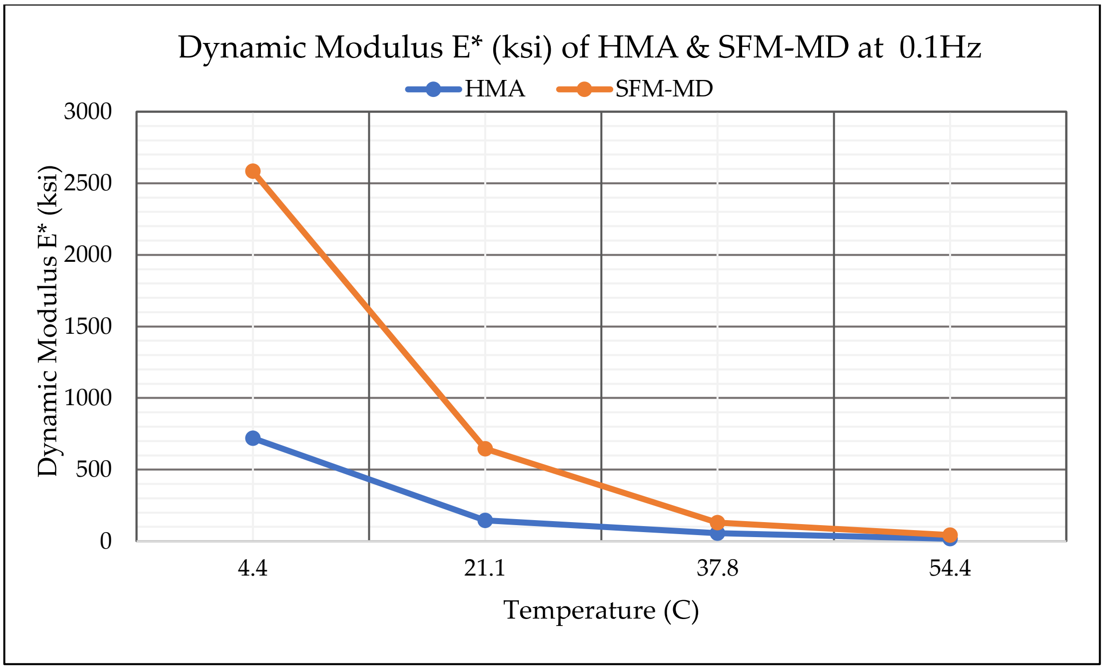


Figure 4.15 Dynamic modulus - Isothermal curves (HMA & SFM-MD)

From Figure 4.15, it is evident that SFM-MD has greater dynamic modulus values with respect to HMA. Moreover, the pattern it follows is quite obvious, that at higher frequencies modulus is improved. We know that high frequency has lower wavelength so less effect on pavement, depicts fast moving vehicle and vice versa for lower frequencies values.

4.5.7 Compressive Strength of SFM-MD

For evaluating concrete materials, compressive strength properties are often used, and this measurement is considered as the most important indicator of concrete quality. Since these materials are often significantly stronger in compression than in tension, the tensile and flexural strengths are the most crucial material characteristics for designing rigid pavements. This is because under certain loading situations, tensile failure will occur before compressive failure. However, since it is easier to perform than other tests and because there are many relationships between compressive strength values and other material parameters, compressive strength is the most used strength test for rigid pavements. Because semi-flexible pavements have mechanical characteristics that fall somewhere between those of bituminous mixes and those of concrete, the compressive qualities of the grouted macadams built for this research were examined, and the findings are described in this publication. Compressive strength measurements were performed in line with ASTM C39/C39M-21 [29]. For the compressive strength test after 28 days, cubes with dimensions of 100 millimeters in diameter and 50 millimeters in thickness were created. At a constant filling rate of 1.25 KN/second and ambient temperature, the tests were run. By dividing the maximum force obtained during the test by the cross-sectional area of the specimen, the compressive strength of the material was calculated. Figure 4.16 displays the findings of the compressive strength assessment.

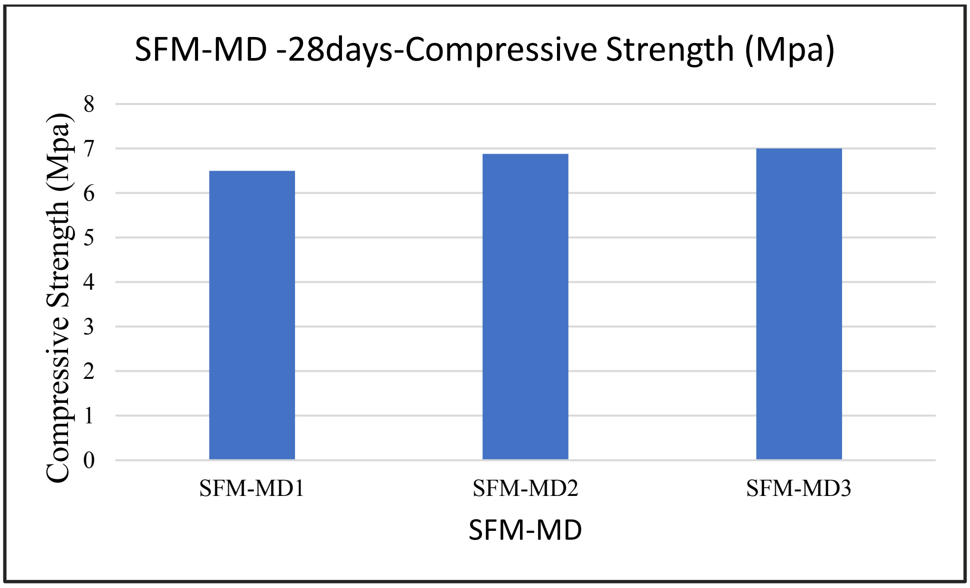


Figure 4.16 SFM-MD -28days-Compressive Strength (Mpa)

4.6 Summary

Evaluation and analysis on cementitious grouts containing waste MD suggest that there is a considerable drop in compressive strength when cement was substituted in excess by MD. This was found to be the case when the grouts were tested. When compared to a standard HMA mixture, semi-flexible mixes that contained waste MD based grouts showed improvement in marshall stability performance, tensile strength ratio, stiffness, and dynamic modulus, as well as resistance against moisture and fuel spills. This was the case even though the semi-flexible mixtures also contained waste MD.

If you were to replace cement with a greater quantity of waste MD, this would lead to an increase in the recycling of waste MD for use as a substitute for cement. A reduction in cement usage and recycling of waste MD would further promote sustainability, reduce emissions of greenhouse gases, and maybe bring about economic effectiveness while developing of pavement.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Introduction

In this research study, waste marble dust, often known as WMD, was used in lieu of cementitious grout in applications involving semi-flexible paving surfaces. The objective of this research was to investigate the efficiency of waste marble dust (WMD) on the strength property of grouts in contrast to conventional cement grout. To determining flowability and compressive strength values, the testing on grouts was carried out. It was also determined how well semi-flexible mixes that had the best possible combination of grout compositions performed. The findings of this study have the potential to present stakeholders and road construction agencies with options that are both economically and environmentally beneficial option of waste marble dust (WMD) in construction of semi-flexible pavement surface. It also has the potential to offer an efficient method of recycling of industrial byproducts which would otherwise be disposed of in open landfills and flowing rivers. These factors regarding the recycling of waste marble dust (WMD) might be of assistance to the authorities in the effective management and disposal of trash. As a consequence of this, it has the potential to lessen the strain placed on landfills, lessen its impact on the environment, and create a possible cash stream for other companies. Some of the inferences that can be drawn are as follows:

5.2 Conclusions

Based on the above performance tests performed on conventional HMA and Semi flexible mixture specimens, conclusions drawn from this research study include the following:

1) Cement replacement with a high content of waste marble dust (WMD) decreases compression strength at curing age of 7 days and 28 days as compared to the neat mixture. In cementitious grout, WMD as a substitute for up to 15% of the cement and maintaining a w/c ratio up to 0.4 produced results that were near identical to those of the control grout.

2) Higher R^2 ($R^2 > 0.90$), the suggested models' high F-value (more than 40) as well as low p-value (0.05) demonstrate their significance.

3) Utilizing waste marble dust in grouts resulted in improved density. No cracks at the interface were seen in grouts containing WMD by SEM analysis.

4) As a result of open-graded asphalt mixtures having voids that are in acceptable range (25-35%), the designing criterion for semi-flexible pavement mix has been satisfied. Also, a grout saturation level ranging between 0.945 and 0.975 suggested that the components of grout have been appropriately formulated and the voids are interconnected.

5) Marshall stability of semi-flexible mix increased by around 70% as compared to conventional HMA. As a result, semi-flexible pavement surfacings might be an alternative worth considering in situations in which the pavement is subjected to heavy load and stresses. A same pattern was noticed while looking at the findings of the indirect strength results.

6) Semi-flexible mixes have a greater tensile strength ratio than HMA mixtures, which suggests that they are more resilient to the negative effects of moisture.

7) The resistance of semi-flexible surfacings to fuel spills is the most essential and important property. The semi-flexible mixes utilized in the study demonstrated improved resistance against fuel in terms of mass loss (less than 3% loss) and preserved strength. HMA mixes, on the other hand, performed poorly, with more than 21% loss of mass following a 7^{th} immersion cycle.

5.3 Recommendations

To fully characterize the mixes adopted for this research, more performance tests, such as Hamburg wheel tracker, indirect tensile fatigue test must be performed to measure resistance to fatigue cracking. A realistic field test section shall be constructed to investigate the performance against traffic and environmental stresses. The life cycle cost analysis can also be estimated using the field test section data. Furthermore, the serviceability and distresses can be evaluated during the test period and proper maintenance procedures can be outlined accordingly.

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APPENDIX A

Table A-1: Aggregate Testing Results

Type of Test		Results %	Specification
Los Angeles Abrasion		21.00	45% (Max)
Flakiness index of Aggregate		10.80	15% (Max)
Elongation Index of Aggregate		3.20	15% (Max)
Impact Value of Aggregate		15.5	30% (Max)
Crushing Value of Aggregate		19.6	30% (Max)
Water Absorption	Fine Aggregate	2.22	3% (Max)
	Coarse Aggregate	0.56	3% (Max)
Specific Gravity	Fine Aggregate	2.55	-
	Coarse Aggregate	2.64	-

Table A-2: Test Results Performed on Binder

Description	Results	Specification	Standard
Penetration Test @ 25 °C	66	60/70	ASTM-D-5
Flash Point (°C)	262	232 °C (Min)	ASTM-D-92
Fire Point (°C)	291	270 °C (Min)	ASTM-D-92
Specific Gravity	1.029	1.01-1.06	ASTM-D-70
Softening Point (°C)	49.6	49 °C to 56 °C	ASTM-D-36
Ductility Test (cm)	108	100 (minimum)	ASTM-D-113

APPENDIX B

Table B-1: Flowability and Compressive Strength of Grouts

Marble Dust %	S.P %	w/c	Flow (sec	Sample ID	Compressive Strength (Mpa)	
					7-days	28-days
0	0.5	0.35	23	MD0W35	38	55
5	0.5	0.35	21	MD5W35	36	45
10	0.5	0.35	20	MD10W35	33	42
15	0.5	0.35	19.4	MD15W35	32	38
20	0.5	0.35	19	MD20W35	29	36
25	0.5	0.35	18.6	MD25W35	28	36
0	0.5	0.4	16	MD0W40	38	49
5	0.5	0.4	14.8	MD5W40	37	44
10	0.5	0.4	14	MD10W40	36	45
15	**0.5**	**0.4**	**13.2**	**MD15W40**	**35.8**	**46**
20	0.5	0.4	13	MD20W40	35	43
25	0.5	0.4	12.7	MD25W40	27	39
0	0.5	0.45	14.2	MD0W45	29	42
5	0.5	0.45	13	MD5W45	27	38
10	0.5	0.45	12.8	MD10W45	25	36
15	0.5	0.45	12.6	MD15W45	25	35
20	0.5	0.45	12.3	MD20W45	25	36
25	0.5	0.45	12.5	MD25W45	24	34
0	0.5	0.5	13.9	MD0W50	28	38
5	0.5	0.5	13.2	MD5W50	28	36
10	0.5	0.5	12.2	MD10W50	27	33
15	0.5	0.5	11.8	MD15W50	26	33
20	0.5	0.5	11.3	MD20W50	22	32
25	0.5	0.5	12.1	MD25W50	19	27

Table B-2: MD-based Grout Model Validation and ANOVA Analysis

Responses	Flow (sec)	Compressive Strength 7 days	Compressive Strength 28 days
Standard Deviation	0.48	2.60	2.64
Mean	15.48	31.78	40.71
R2	0.94	0.8	0.96
Predicted R2	0.93	0.785	0.94
Adjusted R2	0.94	0.7736	0.95
Adequate Precision	49	23.7	27
Model F-value	52.13	52.13	49.66
Model p-value	<0.0001	<0.0001	<0.0001
Model Remarks	significant	significant	significant
Final selected model	Quadratic	Quadratic	Quadratic

APPENDEX C

Table C-1: Open-Graded Asphalt Mixtures (Densiphalt-12)

Densiphalt Type-12 Gradation for OGAS		
Sieve size (mm)	% Passing	% Retained
3/4” (19 mm)	100	0
1/2” (12.5 mm)	97.5	2.5
3/8” (9.5 mm)	18	79.5
#4 (4.75 mm)	10	8
#8 (2.36 mm)	8	2
# 200 (0.075 mm)	4.5	3.5
Filler (Passing # 200 sieve)		4.5
Total		100

APPENDIX D

Table D-1: Marshall Stability & Flow of Conventional HMA Specimens

Mix Type	Stability (KN)	Flow (mm)
HMA - 1	13.3	3.2
HMA – 2	12.7	3.6
HMA – 3	12.5	3.8
SFM-1	20.5	5
SFM-2	21.66	4.5
SFM-3	24	4.2

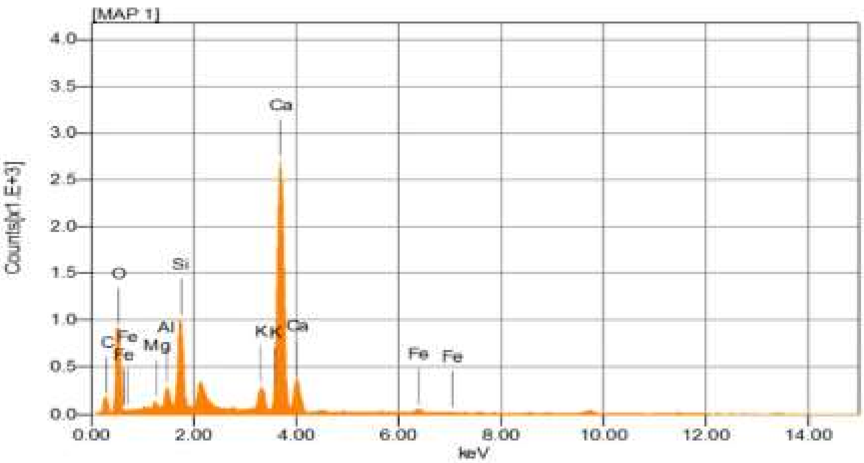
Table D-2: Results of Tensile Strength Ratio (TSR)

Test	HMA	SFM-MD
TSR (%)	71.1	90.1

Table D-3: Semi-Flexible Specimens and HMA's Stiffness Modulus

Temperature (C)	SFM-MD		HMA	
	Stiffness (MPa)	Std. dev	Stiffness (MPa)	Std. dev
25	3792	86	3540	93.6
40	2758	108	1356	21

APPENDIX E



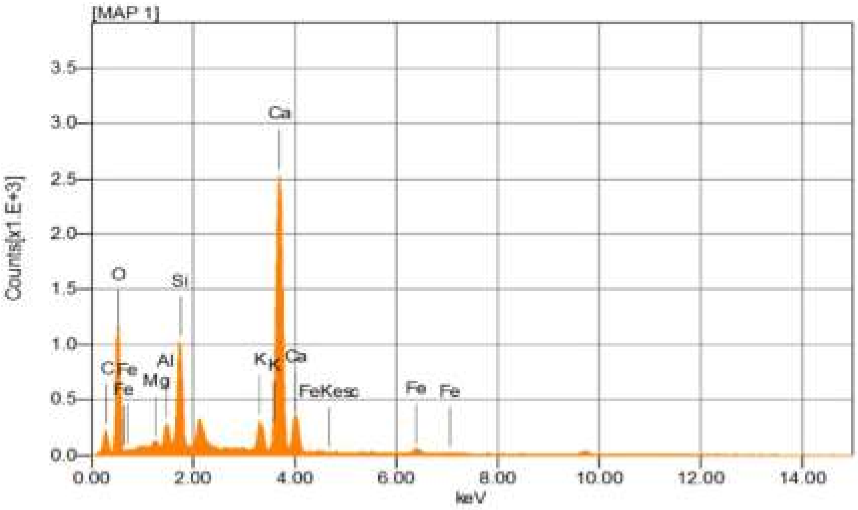
Formula	mass%	Atom%	Sigma	Net	K ratio	Line
C	6.11	10.76	0.03	4002	0.0015686	K
O	47.52	62.83	0.23	24423	0.0437411	K
Mg	0.51	0.44	0.04	1819	0.0012718	K
Al	1.70	1.33	0.05	7847	0.0043859	K
Si	6.84	5.15	0.08	33492	0.0180833	K
K	2.93	1.59	0.05	13258	0.0109629	K
Ca	32.71	17.26	0.13	148060	0.1287081	K
Fe	1.68	0.64	0.06	2911	0.0053756	K
Total	100.00	100.00				

Acquisition Condition
Instrument : IT100LA
Volt : 20.00 kV
Current : ---
Process Time : T2
Live time : 19.31 sec.

JEOL EDS System JEOL

Figure E-1: SEM-EDS Report of control sample (0% MD)

APPENDIX E



Formula	mass%	Atom%	Sigma	Net	K ratio	Line
C	7.21	12.24	0.03	4171	0.0019939	K
O	50.58	64.49	0.25	24455	0.0534273	K
Mg	0.50	0.42	0.04	1573	0.0013420	K
Al	1.57	1.19	0.05	6328	0.0043141	K
Si	6.56	4.77	0.08	28090	0.0185002	K
K	2.80	1.46	0.05	11096	0.0111925	K
Ca	29.16	14.84	0.13	115863	0.1228603	K
Fe	1.61	0.59	0.06	2465	0.0055537	K
Total	100.00	100.00				

Acquisition Condition
Instrument : IT100LA
Volt : 20.00 kV
Current : ---
Process Time : T2
Live time : 19.32 sec.
Real Time : 19.65 sec.
DeadTime : 1.00 %
Count Rate : 4863.00 CPS

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Figure E-2: SEM-EDS Report of Modified sample (15% MD)

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DEVELOPMENT OF MARBLE DUST (MD) BASED SUSTAINABLE CEMENTITIOUS GROUT FOR SEMI FLEXIBLE PAVEMENT APPLICATION

MUHAMMAD NOUMAN KHAN

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PAGE 4

PAGE 5

PAGE 6

PAGE 7

PAGE 8

PAGE 9

PAGE 10

PAGE 11

PAGE 12

PAGE 13

PAGE 14

PAGE 15

PAGE 16

PAGE 17

PAGE 18

PAGE 19

PAGE 20

PAGE 21

PAGE 22

PAGE 23

PAGE 24

PAGE 25

PAGE 26

PAGE 27

PAGE 28

PAGE 29

PAGE 30

PAGE 31

PAGE 32

PAGE 33

PAGE 34

PAGE 35

PAGE 36

PAGE 37

PAGE 38

PAGE 39

PAGE 40

PAGE 41

PAGE 42

PAGE 43

PAGE 44

PAGE 45

PAGE 46

PAGE 47

PAGE 48

PAGE 49

PAGE 50

PAGE 51

PAGE 52

PAGE 53

PAGE 54

PAGE 55

PAGE 56

PAGE 57

PAGE 58

PAGE 59

PAGE 60

PAGE 61

PAGE 62

PAGE 63

PAGE 64

PAGE 65

PAGE 66

PAGE 67

PAGE 68

PAGE 69

PAGE 70

PAGE 71

PAGE 72

PAGE 73

PAGE 74

PAGE 75

PAGE 76

PAGE 77

PAGE 78

PAGE 79

PAGE 80

PAGE 81

PAGE 82

PAGE 83

PAGE 84

PAGE 85

PAGE 86

PAGE 87

PAGE 88

PAGE 89

PAGE 90

PAGE 91

PAGE 92

PAGE 93

PAGE 94

PAGE 95

PAGE 96

PAGE 97

PAGE 98

PAGE 99

PAGE 100

PAGE 101

PAGE 102