



ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF GRADUATE STUDIES

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

LABORATORY STUDY ON THE MIXTURE DESIGN OF GROUTED MACADAM

By

Mubarek Zeyne

A Thesis Submitted to School of Graduate Studies in Partial
Fulfillment of the Requirement for Degree of Master of Science
In
Road and Transport Engineering

Adviser

Dr. Habtamu Melese

Addis Ababa, Ethiopia

April, 2017

ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

M.Sc. Thesis on
Laboratory Study on Mixture Design of Grouted Macadam

By
Mubarek Zeyne Hulala

Addis Ababa Institute of Technology
School of Civil and Environmental Engineering

Approved by Board of Examiners

Dr. Habtamu Melese (PhD.,P.E.)
Advisor *Signature* *Date*

Eng. Ephrem G/Egziabeher
External Examiner *Signature* *Date*

Eng. Asres Simeneh
Internal Examiner *Signature* *Date*

Dr. Agizew Nigussie
Chairman *Signature* *Date*

ABSTRACT

Grouted macadam is a composite material which consists of porous asphalt concrete with 25–35% air voids, in which a designed cementitious grout is filled. This research tried to design grouted macadam mixtures from local materials and evaluate the contribution of cementitious grout in the resultant grouted macadam. The study utilized laboratory-based experimentation program with three phases.

The cementitious grout mixture involving ordinary Portland cement, silica sand, bagasse ash, megaflow SP1, and water is designed using the Taguchi approach. Based on the results of the first phase of the study, a water to binder ratio of 0.76, silica sand content of 10% replacement by weight of cement, and bagasse ash content of 10% replacement by weight of cement, and megaflow SP1 1.5% by weight of the binder is proposed for use in the grouted macadam.

Using penetration grade 60/70 bitumen, the porous asphalt concrete is designed to have a target air voids content of 30%. The grout mixture that was proposed above is prepared and applied to the 65mm thick porous asphalt concrete specimens that were prepared with bitumen contents of 3.1% and 3.6%. It is observed that all these specimens are fully penetrated by the grout. Marshal stability and indirect tensile strength (ITS) tests are conducted on the grouted macadam and maternal porous asphalt specimens. At the 3rd day of air-curing, the Marshal stability result of grouted macadam is found to be 91.5% higher than that of maternal porous specimens. At the 28th day of air-curing, the tensile strength result of grouted macadam is found to be 81.75% and 84.85% higher than that of maternal porous specimens, at 25 °C and 40 °C respectively. Cementitious grout is the cause for these improvements.

The research concludes that the grout mix proportion proposed in this study, has good grouting ability and its contribution in the grouted macadam material is high. The Marshal stability and ITS tests indicated that the grouted macadam mixtures have promising performances.

Keywords

GROUTED MACADAM, CEMENTITIOUS GROUT, TAGUCHI APPROACH

DECLARATION

I certify that this research work titled “Laboratory Study on the Mixture Design of Grouted Macadam” is my own work. The work has not been presented elsewhere for assessment and award of any degree or diploma. Where a material that has been used from other sources, it has been properly acknowledged.

Mubarek Zeyne
Name

.....
Signature

.....
Date

ACKNOWLEDGEMENT

Alhamdulillah, this research has been very helpful for me to grasp great knowledge, skills and experimentation experiences. During the course of the study, many institutions and individuals helped me in solving challenges and obstacles I had faced.

I would like to give my thanks to Wollo University for granting me MSc Scholarship. Also to Addis Ababa University, for building my academic career starting from undergraduate to postgraduate studies.

I would like to express my heartfelt gratitude to Dr. Habtamu Melese, (P.E.), who is my adviser. His guidance, suggestions, and feedbacks were valuable.

My appreciation goes to IFH Addis Engineering PLC, for their all supports and permission to conduct almost all tests in their Central Laboratory. Special thank goes to Mr. Feijianwen, Material Engineer at IFH Engineering, who provided me laboratory apparatus and arranged personnel to assist me in conducting tests. And to supportive and motivating Ethiopian staffs: Sisay G., Girma S., Tewodros Y., Kelem M., Robel E., Yonas Y., Habtamu E., Ayub E., Rahel, Ayele, and Tesfa, for their guidance in operating laboratory equipment, and assistance in taking test readings throughout the laboratory work. Their support was great!

Also, my appreciation goes to Licon Manufacturing PLC, for providing me a sample of megaflo SP1 superplasticizer. And I appreciate the permission and support given by Wenji Shewa Sugar Factory while taking bagasse ash samples from this factory.

Thanks to friends: Berihun W., Yohannes G. and others for their comments, suggestions, and experience sharing in writing this report.

Finally, thanks to Yared Seid and to my brothers and sisters: Arafat, Amir, Nejat and Siti whose motivation and support was great.

TABLE OF CONTENTS

ABSTRACT.....	i
DECLARATION	ii
ACKNOWLEDGMENTS	iii
TABLE OF CONTENTS.....	iv
LIST OF TABLES.....	vi
LIST OF FIGURES.....	vii
LIST OF ABBREVIATIONS	viii
1. INTRODUCTION.....	1
1.1. Background	1
1.2. Rational of the Research	2
1.3. Research Objective	3
1.4. Research Approach.....	4
1.5. Scope and Limitation of the Research.....	4
2. LITERATURE REVIEW	5
2.1. General Introduction	5
2.1.1. Composition of grouted macadam	7
2.1.2. Field construction considerations.....	9
2.2. Mechanical Properties of Grouted Macadam	10
2.3. Design Approach for Pavements incorporating Grouted Macadam.....	16
2.4. Porous Mix Design Considerations.....	16
2.5. Grout Mixture Design Considerations.....	20
2.5.1. Cementitious grout composition	20
2.5.2. Potentially available cementitious grout ingredients in Ethiopia.....	24
3. Materials, Methods, and Procedures.....	30
3.1. Introduction	30
3.2. Experimental Programme	31
3.3. Materials	32
3.3.1. Materials used in the mixture design of cementitious grout	32
3.3.2. Materials used in the mixture design of porous asphalt concrete	36
3.4. Experimental Phase I.....	37
3.4.1. About Design of Experiments using the Taguchi Approach.....	37
3.4.2. Cementitious grout mixture Design using the Taguchi approach.....	39
3.4.3. Evaluation tests and measurements on the grout mixtures	46

3.5. Experimental Phase II	49
3.5.1. Selection of aggregate gradation	49
3.5.2. Estimation of design bitumen Content	50
3.5.3. Marshal Method of Specimen Preparation.....	51
3.5.4. Density –void relationship of porous asphalt concrete.....	51
3.5.5. Considerations in the selection of optimum binder content.....	53
3.6. Experimental Phase III.....	54
3.6.1. Grouting ability of cementitious grout.....	54
3.6.2. Marshal Stability flow test	54
3.6.3. Indirect tensile strength test.....	55
3.6.4 Analysis approach of the test results	56
4. LABORATORY TEST RESULTS, ANALYSIS AND DISCUSSION.....	57
4.1. Test Results, Analysis and Discussion on Experimental Phase I.....	57
4.1.1. Determination of optimal condition for individual evaluation criteria	57
4.1.2. Optimal condition for overall evaluation criteria	65
4.1.3. Adjustments on the factor levels based on the Marsh cone viscosity	69
4.1.4. Cost comparison of grout mix ingredients.....	71
4.2. Test Result, Analysis, and Discussion on Experimental Phase II.....	72
4.2.1. Weight-volumetric properties of porous asphalt concrete	72
4.2.2. Determination of optimum bitumen content	73
4.3. Test Results, Analysis, and Discussion on Experimental Phase III.....	74
4.3.1. Grouting ability of the cementitious grout.....	74
4.3.2. Marshal Stability-Flow Test.....	75
4.3.3. Indirect tensile strength test.....	78
5. CONCLUSION.....	82
5.1. Conclusion on Phase I.....	82
5.2. Conclusion on Phase II.....	82
5.3. Conclusion on Phase III.....	83
6. RECOMMENDATION.....	84
6.1. Future Works.....	85
7. REFERENCES.....	86
APPENDIX 1.MATERIALS TEST RESULT.....	89
APPENDIX 2. TEST RESULTS.....	93
Appendix 2.1. Test Result of Experimental Program I.....	93
Appendix 2.2. Test Result of Experimental Program II.....	96
Appendix 2.3. Test Result of Experimental Program III.....	98
APPENDIX 3. PHOTO GALLERY.....	102

LIST OF TABLES

Table 1: Comparison of the performances of AC-16 and GMCM (Hou et al., 2016).	12
Table 2: Resin-modified cement slurry grout mixture proportions (UFGS, 2008) ...	21
Table 3: Estimated reserves of silica sand (Mesfin, 2012)	26
Table 4: Chemical composition of silica sand (Mesfin, 2012).....	26
Table 5: Grading of processed silica sand	33
Table 6: Summary of physical tests performed on the processed bagasse ash	35
Table 7: Summarized test results for the aggregate used in asphalt concrete	36
Table 8: Summarized tests results for bitumen PG 60/70	37
Table 9: Individual evaluation criteria definition and their relative weights	40
Table 10: Factors and their levels for the orthogonal array development.....	41
Table 11: Standard orthogonal array $L_9(3^4)$ with factor level assignment.....	42
Table 12: Summary of optimum combination of factor levels for different criteria ..	64
Table 13: Overall evaluation (OEC) criteria definition and related details	65
Table 14: Indexed OEC results per experimental run	67
Table 15: Average of Marshal Stability test result	75
Table 16: Summary of average result of indirect tensile strength (ITS) test.....	78

LIST OF FIGURES

Figure 1: Tensile strength versus temperature for RMP & AC (Anderton,2000).	10
Figure 2: Crack propagation in grouted macadam (Hou et al., 2016)	12
Figure 3: Moisture susceptibility comparison of grouted macadam and asphalt concrete based on MS and ITS tests (Hou et al., 2016)	13
Figure 4: Marshal Stability of various grouted macadam (Afonso et al., 2015)	15
Figure 5: Some of the aggregate gradations obtained from the literature as compared to the aggregate grading for conventional asphalt concrete	18
Figure 6: Flow chart showing the sequential order of experimental phases.....	31
Figure 7: Processed silica sand	32
Figure 8: Photos of bagasse ash sample preparation.....	34
Figure 9: Photos of mixing bowl & its cover lid, mixing paddle, electric driven mixer and Marsh cone funnel.....	43
Figure 10: Dimension of Marsh cone funnel as suggested by Anderton (2000).	47
Figure 11: Cementitious grout being poured into Marsh cone funnel.....	47
Figure 12: Rupture modulus apparatus used in the study.....	48
Figure 13: The selected aggregate gradation with respect to specifications.....	49
Figure 14: Typical grouted macadam specimen immediately after extrusion.....	54
Figure 15: Average result of bleeding test per experimental run.....	58
Figure 16: Trend of influence of factors on the bleeding of grout.....	58
Figure 17: Average result of Marsh cone viscosity test per experimental run	59
Figure 18: Trend of influence of factors on the Marsh cone viscosity	60
Figure 19: Average result of bulk specific gravity test per experimental run	60
Figure 20: Trend of influence of factors on the bulk specific gravity	61
Figure 21: Average result of compressive strength test per experimental run ...	62
Figure 22: Influence of factors on the compressive strength.....	62
Figure 23: Average result of rupture modulus test per experimental run	63
Figure 24: Influence of factors on the rupture modulus.....	63
Figure 25: Plot of average factor effect for indexed OEC results	67
Figure 26: compressive strength development of grout mixture in exp. run 2....	68
Figure 27: Effects of variations of factors on the Marsh cone viscosity.....	70
Figure 28: Air voids content as a function of bitumen content.....	73
Figure 29: Grouted macadam specimens after three days of air curing	74
Figure 30: Impact of cementitious grout on the Marshal stability	76
Figure 31: Box plots of the means of Marshal Stability test result of grouted macadam that were prepared with bitumen contents of 3.1% &3.6%	77
Figure 32: Effect of temperature on the tensile strength of porous asphalt concrete and grouted macadam	80
Figure 33: Box plots of the means of indirect tensile strength test result of grouted macadam that are prepared with bitumen contents of 3.1% and 3.6%. 81	

LIST OF ABBREVIATIONS

AASHTO: American Association of State Highway and Transportation Officials

ASTM: American Society for Testing and Materials

ANOVA: Analysis of variance

BS: British Standards

DOE: Design of experiment

ERA: Ethiopian Roads Authority

gm/cm³: gram per cubic centimeters

ITS: Indirect tensile strength

kg: kilogram

kPa: kilo Pascal

m: meter

m²: Square meter

mm: millimeter

µm: micrometer

ml: millilitre

MPa: Mega Pascal

OEC: Overall evaluation criteria

PLC= Private limited company

QC=S: The smaller is better

QC=N: Nominal value is better

QC=B: The larger is better

RMP: Resin-modified pavement

sec: Second

SP1: Product description of the superplasticizer known by the brand

%: Percent

°C: Degree celsius



1. INTRODUCTION

1.1. Background

In the history of Pavement Engineering, there are two conventional pavement types, intensively used for road construction and rehabilitation. These are flexible and rigid Pavements. Flexible pavements are characterized by their immediate serviceability, good riding quality, and absence of joints. Whereas rigid pavements made of Portland cement are known for their high bearing capacity and a longer life.

Pavement failures associated with the susceptibility of flexible pavements to abrasive loads, fuel spillage, and stripping as well as failures associated with the joints and lack of strains in rigid pavements initiated the search for a material that gives the merits of both Portland cement concrete and hot-mix asphalt (Al-Qadi et al., 1994). One of the advancements in this regard is constructing highly porous asphalt concrete and filling the voids with a cementitious grout. It is usually called grouted macadam. However, it has got different names such as resin modified pavement (RMP), grouted macadam and other brand names; its success is being reported.

This research aims at developing grout mixture proportions from local materials as well as evaluating its contribution in the resultant grouted macadam. While reviewing literature, taking specifications and recommendations, terms such as resin modified pavement, RMP (Anderton, 2000; UFGS, 2008), asphalt-Portland cement concrete composite, APCCC(Al-Qadi et al., 1994) and grouted macadam composite material, GMCM (Hou et al., 2016) and grouted macadam (Olivera, 2006) are used interchangeably and also the term semi-flexible pavement is used to indicate the whole pavement. The term grouted macadam is frequently used in this research. In this study, cementitious grout is prepared and applied to porous asphalt concrete specimens. Marshal stability-flow and indirect tensile strength tests are performed on both porous asphalt concrete as well as grouted macadam specimens. Based on these experimental results, improvements as a result of grout application are calculated with reference to control porous asphalt concrete. Finally, the conclusion is drawn and recommendations have been forwarded.

1.2. Rational of the Research

In the last 50 years, a new pavement technology called semi-flexible pavement emerges where its surface course layer consisted of the bituminous mixture as well as cementitious grout mortar (i.e. grouted macadam). As an alternative to conventional asphalt concrete, the use of grouted macadam as a wearing course layers is suggested for pavements where static, tracked or heavy traffic load is expected. It is getting acceptance in Europe, North America and Asia, as a potential alternative pavement for heavily loaded areas such as airport taxi-ways, intersections, bus stops, warehouses and for areas susceptible to oil and fuel spillage(Ahlich and Anderton,1991; Anderton, 2000; Olivera, 2006). This pavement technology has reached a high level in European countries, and remarkable successes have been achieved with the establishment of pavement specialist companies that are engaged in supplying grout mortar as well as constructing this pavement. It is well-known that pavement construction requires a bulk of materials, experts of pavement design and construction, therefore research is required for a better understanding of emerging pavement technologies as well as for utilizing local materials specially by-products. In this regard, efforts are underway worldwide to get the best of grouted macadam or semi-flexible pavement as a whole.

Whereas in Ethiopia, there is no report on the practice of this pavement type. It is not yet fully understood advancement in the pavement design. On the other hand, Ethiopia is constructing a number of dry ports, airports and industrial parks where heavy goods loading and/or unloading expected. Despite there is no compiled report, local practice showed that they are either flexible or rigid pavements. These pavements have their own drawbacks and limitations associated with the intrinsic nature of the binders that are used in the construction (Al-Qadi et al., 1994; Olivera, 2006). Hence, the grouted macadam which is made of bitumen and cement should be clearly examined and adapted to suit local conditions.

This research will develop grouted macadam mixtures and evaluate achievements that are associated with the grout application with reference to maternal porous mixtures. In this way, the contribution of cementitious grout will be better understood.

The research may show the benefits of grouted macadam, may create awareness and motivate local students, academicians, and research institutes to work further research in the study area.

1.3. Research Objective

The main objective of this research is to design grouted macadam mixtures and evaluate the contribution of cementitious grout in the resultant grouted macadam with reference to maternal porous asphalt concrete.

The specific objectives are:

- I) Determining the optimum grout mix proportions from ordinary Portland cement, silica sand, bagasse ash, megaflo SP1 and water using the Taguchi approach. Cementitious grout mix proportions based on these local materials is to be proposed for semi-flexible pavement applications.
- II) Checking the grouting ability of mix proportions proposed above by designing porous asphalt concrete with air voids content close to 30%.
- III) Examining the improvement in Marshal stability as well as indirect tensile strength associated with the grout application to the porous asphalt concrete. The improvements are to be determined based on Marshal stability and indirect tensile strength of grouted macadam mixtures with reference to maternal porous mixtures that are not filled with the grout (control). The research considers these improvements as indicators for the contribution of cementitious grout to the performance property of the resultant grouted macadam material.

1.4. Research Approach

The study reviewed literature related to the research. In order to achieve the objectives of this research, the laboratory-based experimental program is adopted. During site reconnaissance, samples for laboratory testing are collected. First of all, relevant material quality tests are conducted. Based on the established experimental program, detailed design of mixtures and related performance tests are performed. Finally, results are analyzed and then research findings are reported.

1.5. Scope and Limitation of the Research

The research reported herein is primarily based on the laboratory study work. In the evaluation of different mixtures, different engineering properties are considered. These properties are listed for the corresponding mixtures as shown below.

- 1) For grout mixture
 - Bleeding, Marsh cone viscosity, and bulk specific gravity at fresh state whereas compressive strength and rupture modulus at the hardened state of the grout.

N.B:- In the case of grout mixtures that involves the bagasse ash filler; it was challenging to read the exact thickness of the bleed layer.
- 2) For porous asphalt concrete mixtures
 - Density-void relationship of compacted specimens with the size of 101.6mm in diameter.
- 3) For grouted macadam mixtures
 - Marshal Stability at 3rd day of air-curing age
 - Indirect tensile strength at 28th day of air- curing age

Generally, for all mixtures and corresponding evaluation properties listed above, triplicate sample specimens have been prepared and evaluated accordingly.

Finally, the findings of this research that are associated with the grout are limited to only one source of cement, silica sand, bagasse ash, and chemical admixture called megaflow SP1. The findings associated with grouted macadam are also limited to one source of aggregate and aggregate grading. The hardened state performance property of both grout and grouted macadam are evaluated by air curing the specimens at room temperature.

2. LITERATURE REVIEW

2.1. General Introduction

Pavement structures usually defined as a multilayer load bearing structures that are designed and constructed to withstand expected loads as well as adverse climatic conditions. The top surface layer is also known as the surface course is designed to have high bearing capacity in such a way it spread the loads and dissipate the stresses to base course and/or sub-base layers which in turn transfers these stresses (an acceptable value) to the subgrade. In addition to strength, the surface course is required to have an adequate evenness and skid resistance to vehicles, to provide sufficient comfort and safety for the users, and to be impermeable to water, oils, and others.

According to Olivera (2006), pavements usually classified into flexible, rigid, and semi-rigid pavements, based on the nature of the material that comprises the upper layers. The mechanical properties of these top layers determine the performance of the whole pavement. Flexible (also called asphalt concrete) pavement is a pavement where the top layers are constructed from bitumen bound materials. It is immediately opened to traffic and generally known for its high recoverable deformation, and good riding quality (Olivera, 2006). Rigid pavements also called Portland cement concrete (PCC) are pavements which consist of cement bound layers as the top layers. It is known for its high compressive and flexural strength, longer service life. As a disadvantage it requires a longer time before opening to traffic, requires joints and/or reinforcement bars to accommodate differential expansion and contraction movements (Olivera, 2006). Semi-rigid pavement, also known as composite pavement, which consists of bituminous layers as a surface course and cement concrete (or cement bound mixtures) layers as a base. It will combine the good bearing capacity of rigid pavements and the good riding quality of flexible pavements. However, reflective cracking associated with cracking of the base may result in premature failure of the pavement (Olivera, 2006).

According to Olivera (2006), it is more likely develop permanent deformation within the pavement structure when flexible pavements are subjected to heavy and slow loads, often canalized traffic, such as bus lanes, airport aprons, and taxiways or distribution centers. So, rigid pavements can be the natural choice for such special areas. However, the major disadvantages of rigid pavements, as compared to flexible pavements, are related to the curing time of cement concrete and the necessity of joints to allow the thermal movements of the concrete layer (Olivera, 2006). In order to avoid these limitations, a new type of material has been devised to create a semi-flexible surface layer, rut-resistant and free from joints or cracks (Al-Qadi et al., 1994; Olivera, 2006). The term grouted macadam is often used to characterize the construction process of this semi-flexible layer. When the upper layer of a pavement constructed with this semi-flexible material (i.e. grouted macadam), generally the pavement is called Semi-flexible pavement (Olivera, 2006).

A typical grouted macadam composed of a combination of an asphalt mixture and a cementitious grout in the same layer. Porous asphalt concrete is placed first and in another day its voids are filled with cementitious grout. The resultant composites combine the flexibility of the bituminous component with the strength and rigidity of the cementitious component. As a result, the composite material has the potential to combine some of the best qualities of flexible and rigid pavements, namely absence of joints, long life and high bearing capacity. Since, it has an impermeable surface which provides good protection against infiltration of water, fuels and oils (Ahlrich and Anderton, 1991; Anderton, 2000; Olivera, 2006; Setyawan, 2013; Zoorob et al, 2002).

The historical background of this pavement indicated that it is started in 1960`s with the name resin modified paving (RMP) or Saliviaticim process. This process is developed by the French construction company Jean Lefebvre Enterprises as a protection of asphalt concrete surface course against the attack of waste oils and fuels. This company developed a proprietary product called Prosaliva-7 as a resin additive for cementitious slurry preparation and successfully constructed many military bases for tracked vehicles as well as industrial floors with this pavement (RMP) in Europe and USA (Ahlrich and Anderton,1996; Anderton,1996).

This type of pavement demands a two stage construction. Nonetheless, the time required before opening to traffic is still considerably less than that needed when using cement concrete. Ahlrich and Anderton (1991) stated a curing period of 1 to 28 days is required depending on the grout mortar (or cement) used. Several studies proved that RMP as a fuel and abrasion resistant surfacing material. It is a cost-effective alternative to Portland cement concrete for special pavements (Anderton, 1996; Anderton, 2000). Anderton (2000) reported that resin modified pavement (RMP) is constructed in more than 25 countries. Based on the 1990 data, about 8,356,000 m² in France; 962,000 m² in Portugal; 602,000 m² in Japan; 307,000 m² in Great Britain, and in others including African countries.

Grouted macadam can be used as a wearing course layer between 25 mm to 75 mm in thickness. It can be constructed over bridge decks as an overlay. Also, it can be laid on top of new or old bituminous courses (Deshmukh, 2011). Currently, semi-flexible pavement gained popularity across Europe, USA, and Japan. This pavement has got various names such as resin modified pavement (RMP) in the USA, Salviacim in France, Rut proof (RP) pavement in Japan and different brands of names associated with the grout products. Some of the brand names are Betophalt, Confalt, Hardicrete, Ulticrete, Densiphalt, Eucopave, etc. (Olivera, 2006).

2.1.1. Composition of grouted macadam

Grouted macadam by Read & Whiteoak (2003) described as a proprietary product which is being used in areas where loading is particularly heavy or concentrated, where it is likely for the spillages of aggressive materials or in areas that require high surface rigidity. Based on the nature of the grout it can be categorized into two: cementitious grouted macadam (where cement is the binding agent in the grout) and asphaltic grouted macadam (bitumen as a binding agent in the grout).

A conventional grouted macadam consists of bitumen coated aggregates (porous asphalt skeleton) with 25–35% air voids, in which a highly flowable cementitious grout is filled (Deshmukh, 2011; Hou et al., 2016, Olivera, 2006).

Porous asphalt concrete matrix

According to Hou et al.(2016), porous asphalt mix skeleton mainly consists of more coarse aggregate (with size greater than 2.36 mm, around 90% of the total aggregate) and less bitumen than that of conventional dense bituminous mixtures. The use of coarse aggregates with the higher crushed surface is advantageous to increase the stability of aggregate to the aggregate skeleton. It means increasing contact points among coarse aggregate, thereby increasing the load carrying capacity of the compacted skeleton. The reason to decrease fine aggregate content is to have high air voids content and to make most air voids are interconnected (Hou et al., 2016). Generally, it is prepared justlike hot-mix, hot-laid type of mixtures. But, a study conducted by Zoorob et al. (2002) showed that it is possible to prepare cold-mix, cold laid porous asphalt concrete using asphalt emulsions. The resultant grouted macadam is reported to have satisfactory performance (Zoorob et al.2002). Afonso et al. (2015) studied the use of reclaimed asphalt pavement (RAP) and altered granite as an aggregate for hot and cold-mix porous asphalt concrete preparation.

Cementitious grout network

When cementitious grout is applied to porous asphalt concrete, the air voids are filled with the grout by the gravitational action. As the cement hydrates, the hardened grout mortar “forms a spatial crystalline lattice network to play a role of reinforcement and crosslink in the porous mix skeleton” (Hou et al., 2016). These authors added, “As a result, a three-dimensional coagulation-crystalloid matrix is generated. Both the hardened paste network and asphalt mix skeleton forms an integral structure via the interfacial adhesion together to bear vehicle loads”. As examined by scanning electron microscope (SEM), fibre-like hydrated products of fresh cement slurry on the bitumen film surface are formed. As a result of the toughening and bridging effects of these fiber-like products, the interfacial bond between bitumen and hardened cement mortar is increased. This bond could contribute to the overall performance of grouted macadam (Hou et al., 2016).

2.1.2. Field construction considerations

Grouted macadam can be constructed on any clean, sound and level existing or newly constructed surfaces (Read & Whiteoak, 2003). The construction involves a two-stage procedure. Since, it is necessary to allow the asphalt layer to cool down before applying the grout into its voids. Thus, construction is normally carried out on two consecutive days (Anderton, 2000; Zoorob et al, 2002).

According to UFGS (2008) using either a conventional batch plant or drum-mix plant, porous asphalt concrete can be mixed. Immediately before placing this HMA, heavy application of tack coating is applied to cleaned surfaces. Then the asphaltic concrete mixture is placed to 50mm (2-in) thickness with standard AC paving equipment but is compacted with a smallsteel-wheel roller. The rollers should be operated at slow speeds without vibration to avoid the formation of cracks or tracks and displacement of mixtures (UFGS, 2008). Generally, this specification stated, "The amount of rolling required to achieve the required voids total mix criteria is usually 1 to 3 passes of the 1.8-metric ton to 2-ton tandem steel wheel roller in the static mode. The appropriate temperature of the freshly placed bituminous mixture required for preventing undue shoving and cutting by the roller is usually in the 50 to 70 °C range."

The slurry grout can be thoroughly mixed using a batch plant, portable mixer and/or ready-mix truck mixing shall be accomplished by rotating the mixing drum at the maximum allowable revolutions per minute. It can be mixed for a minimum of 10 minutes. When the porous asphalt concrete cooled to below 38 °C, cementitious grout can be poured onto the asphaltic material and it is spread over the surface with a mechanical spreader or rubber squeegees. Finally, to assist full impregnation of the asphaltic mixture by the grout, the small tandem steel wheel roller (1.8 metric ton to 2-ton maximum) is passed in vibrating mode, in this case. After 2 hours of grout applications, two coats of curing compound is to be applied and allowed to cure for 21 days before opening to traffic (UFGS, 2008).

2.2. Mechanical Properties of Grouted Macadam

A study conducted by Anderton (2000) is one of the detailed works to characterize the mechanical properties of resin modified pavement (RMP) material that is prepared in the laboratory as well as cored from construction projects. In that study, strength, and stiffness related tests such as indirect tensile strength, split tensile strength, flexural strength, compressive strength, resilient modulus and thermal properties have been studied and compared with the mechanical properties of conventional asphalt and cement concrete(Anderton, 2000).

Based on resilient modulus tests conducted at 5, 25 and 40 °C, Anderton (2000) concluded, “RMP behaves like a very stiff asphalt concrete mixture in low to moderate pavement temperatures; but at high pavement temperatures, RMP generally has two to seven times the stiffness of asphalt concrete.” Similarly, Anderton (2000) conducted indirect tensile strength on samples of asphalt concrete (AC) as well as resin modified pavement (RMP) cured for more than 28 days in lab & field projects (i.e. Altus and McChord). The results can be seen in the Figure below.

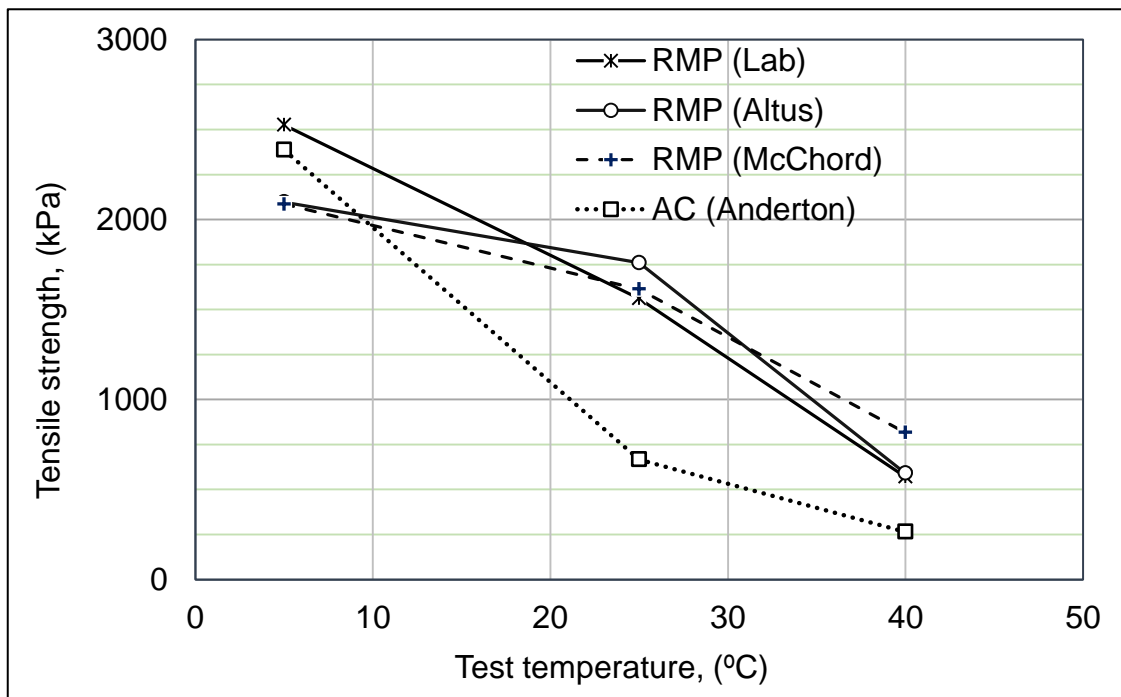


Figure 1: Tensile strength versus temperature for RMP & AC (Anderton, 2000)

As shown in Figure 1, grouted materials such as RMP can have a similar indirect tensile strength as dense asphalt concrete mixtures (AC) at cold temperatures. However, these materials can have about two to three times the strength of asphalt concrete at moderate to hot pavement temperatures. Like dense bituminous mixtures, a similar loss in tensile strength with increasing temperature might indicate the visco-elastic nature of grouted material (Anderton, 2000).

Anderton (2000) is suggested a Poisson ratio of 0.27 for RMP design which was the test result at high temperatures, whereas 0.2 and 0.35 are for cement concrete and asphalt concrete, respectively. Based on thermal coefficient studies, Anderton(2000) also concluded that the damping effect as a result of bitumen surrounding and between each aggregate made the thermal coefficients of RMP less sensitive to aggregate type as compared to Portland cement concrete (PCC).

Another detailed material characterization of grouted macadam based on stiffness, fatigue (four-point bending) and thermal tests is presented in Olivera (2006). However, this study uses commercial grout mortar named densiphalt, tried to evaluate the effect of aggregate size and gradation, bitumen type and content, grout type (strong or weak), and others on the performance of grouted macadam.

Based on the observations during the fatigue testing of specimens that were prepared with bitumen contents of 1.5%, 3% and 4.1%, Olivera (2006) noted an extended fatigue life of grouted macadam as compared to bituminous macadam and pointed out, "Fatigue performance of grouted macadams is more dependent on the length that a crack has to travel, rather than on the binder film thickness." For this observation, Olivera (2006) argued that in grouted macadam, cracking most likely to propagate along the weak spots through the bitumen film surrounding the aggregates and the grout, only going through the grout at thin spots. This crack propagation is lengthy, which might enable grouted macadam further fatigue life. This may not be the case in bituminous macadam in which cracking propagate through the asphalt mortar between the larger aggregate (Olivera, 2006).

A comparative study between grouted macadam (called grouted macadam composite material, GMCM by the authors) and asphalt concrete (AC-16) is reported by Hou et al. (2016). It is summarized in Table 1 shown below. Based on the beam bending test Hou et al. (2016) reported that the tensile cracking is initiated at the bottom center of beam specimen as shown in Figure 2(a) and the crack propagation path is along the interface between aggregates and hardened cement slurry as shown in Figure 2(b) (Hou et al., 2016).

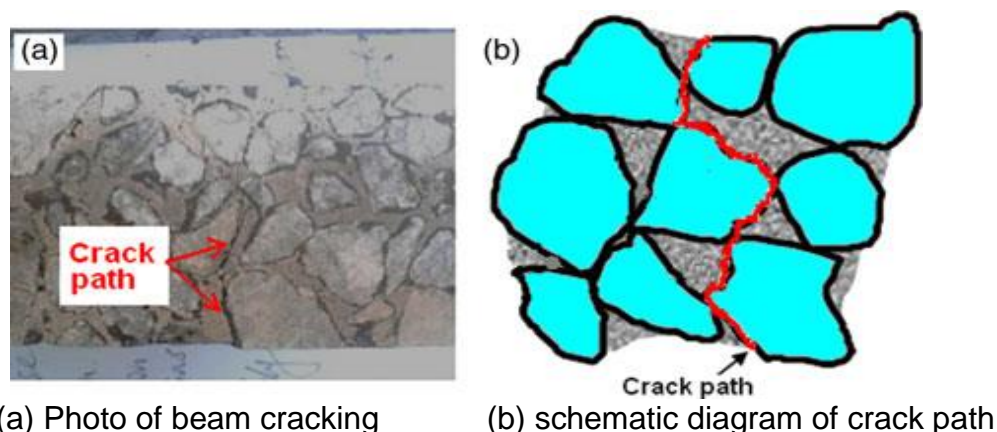


Figure 2: Crack propagation in grouted macadam (Hou et al., 2016)

As it can be seen from Table 1 shown below, grouted macadam specimens are reported to have superior performance than asphalt concrete, except flexural strength and tensile strain which were measured for checking low temperature cracking resistance by conditioning for 3 hours at a test temperature of -10 °C.

Table 1: Comparison of the performances of AC-16 and GMCM (Hou et al.,2016)

Test method	Test items	AC-16	GMCM @28 th day of curing
Wheel tracking test	Rut depth (mm)	0.553	0.040
	Dynamic stability, DS (cycle/mm)	1140	15,750
Beam bending test	Max. flexural strength (MPa)	6.63	5.2
	Flexural-tensile strain($\mu\epsilon$)	2267	2116
Fatigue test	Fatigue life at 0.3 stress ratio (cycles)	33,030	55,523
	Fatigue life at 0.4 stress ratio (cycles)	11,463	20,493
	Fatigue life at 0.5 stress ratio (cycles)	5238	5827
Moisture susceptibility test	Retained Marshal Stability (RMS)	87.8%	110.1%
	Tensile Strength Ratio (TSR)	81.8%	85.5%

For the case of low tensile strain, Hou et al. (2016) argued based on the suggestion of Aliha et al. (2014). Aliha et al. (2014) suggested that at low temperature, the relative brittleness of grouted macadam is increased mainly related to the hardened cement paste filled in the porous asphalt mix (Hou et al., 2016). The tensile strain of grouted mixtures is about 2116 $\mu\epsilon$ and is reported to fulfill the permissible lowest strain criteria of 2000 $\mu\epsilon$ for asphalt pavement in China (Hou et al., 2016).

Hou et al. (2016) also studied and compared the moisture susceptibility of both types based on Marshal Stability and Indirect tensile strength, which is shown in Figure 3 below. As it can be seen in Figure 3(a) conditioned specimens of grouted macadam (i.e. GMCM) are found to have higher Marshal Stability (MS) than those controlled (unconditioned) specimens. Hou et al. (2016) argued for this, as the cement is hydraulic material, and shows an increasing trend in strength with the extension of curing time. The conditioned specimens were soaked in water at 60 °C for 48 hours which means the curing time of conditioned specimens is much longer than that of the controlled ones(i.e. immersed in water at 60 °C for 30 minutes). At this temperature and humidity conditions, the cement hydration continues which lead to an increase in the strength of cement paste (Hou et al., 2016).

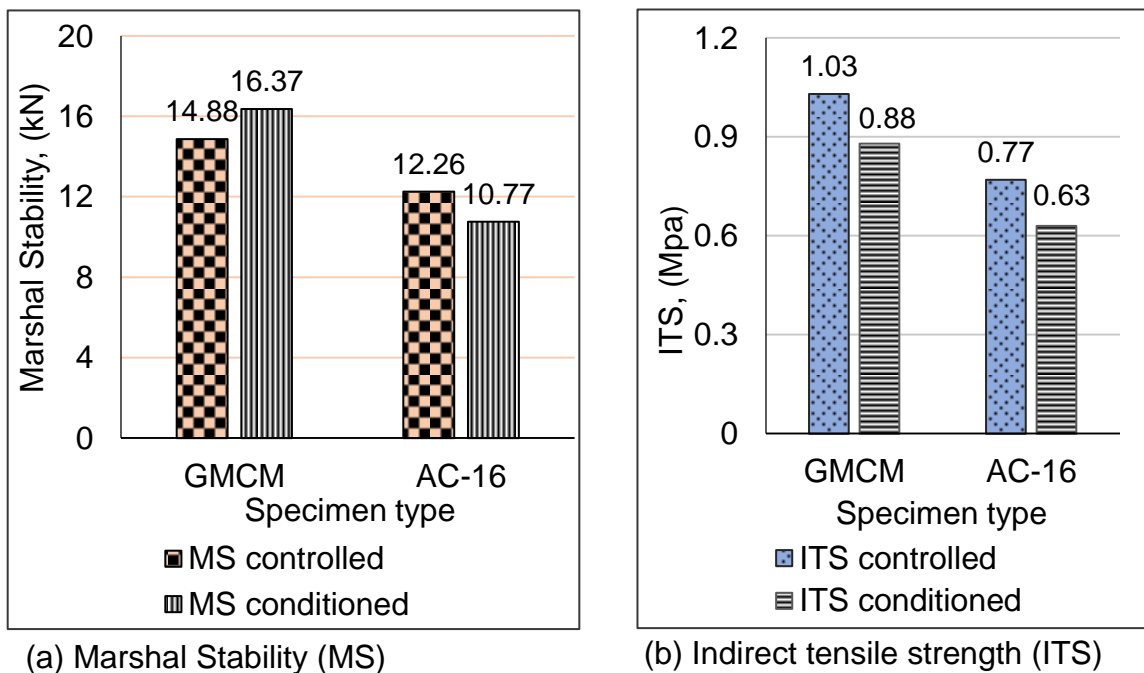


Figure 3: Moisture susceptibility comparison of grouted macadam and asphalt concrete based on MS and ITS tests (Hou et al., 2016)

As it is seen in Table 1 shown above, 110.1% retained Marshal Stability (RMS) for grouted macadam indicating that it is not moisture susceptible. But, RMS for AC-16 is 87.8% which indicated AC-16 is slightly moisture susceptible. Where RMS is the ratio of MS of conditioned to MS of controlled (Hou et al., 2016).

Another important comparison is presented in Figure 3(b) based on indirect tensile strength (ITS) test. Hou et al. (2016) clarified, "The conditioned specimens were first conditioned by vacuum saturation for 15 min with distilled water. Then these specimens were placed in a freezer at -18 °C for 16 hours followed by soaking in distilled water at 60 °C for 24 hours. ITS tests were conducted at the end of freeze-thawing cycle". As it is seen in Figure 3(b) ITS of conditioned specimens is less than ITS of controlled for both material types. This signifies water have an effect on both materials whenever it is percolated. Tensile strength ratio, TSR is the ratio of ITS of conditioned to ITS of controlled. As shown in Table 1 above, in comparison, TSR of grouted macadam is higher than TSR of AC-16 specimens. This is associated with lesser porosity in grouted macadam than asphalt concrete, AC-16 (Hou et al. 2016).

A study by Afonso et al. (2015) evaluated the engineering properties of grouted macadams that were prepared from hot mix and cold mix asphalt and different grout mixtures. This study indicated that Marshal Stability, stiffness modulus, and compressive strength are predominantly affected by the grout type. The effect of the grout type, porous asphalt type and aggregate quality on the Marshal stability of grouted macadam mixture is shown in Figure 4 below. As it can be seen from this Figure, hot mixtures filled with the strong grout(S) have higher stability values than those hot mixtures which filled with the weaker grout (W). Similarly, grouted macadams that were consisted of 8/12.5 cold mixtures with altered granite, and filled with S30MG (i.e. strong grout with 30% milled glass) have significantly higher stability values than those made of 8/12.5 cold mixtures- recycled asphalt pavement (RAP), and filled with geopolymer grout (GEOI). Grouted macadams that were made of cold mixtures found to have significantly lower stability than those prepared with the hot mixture (Afonso et al., 2015).

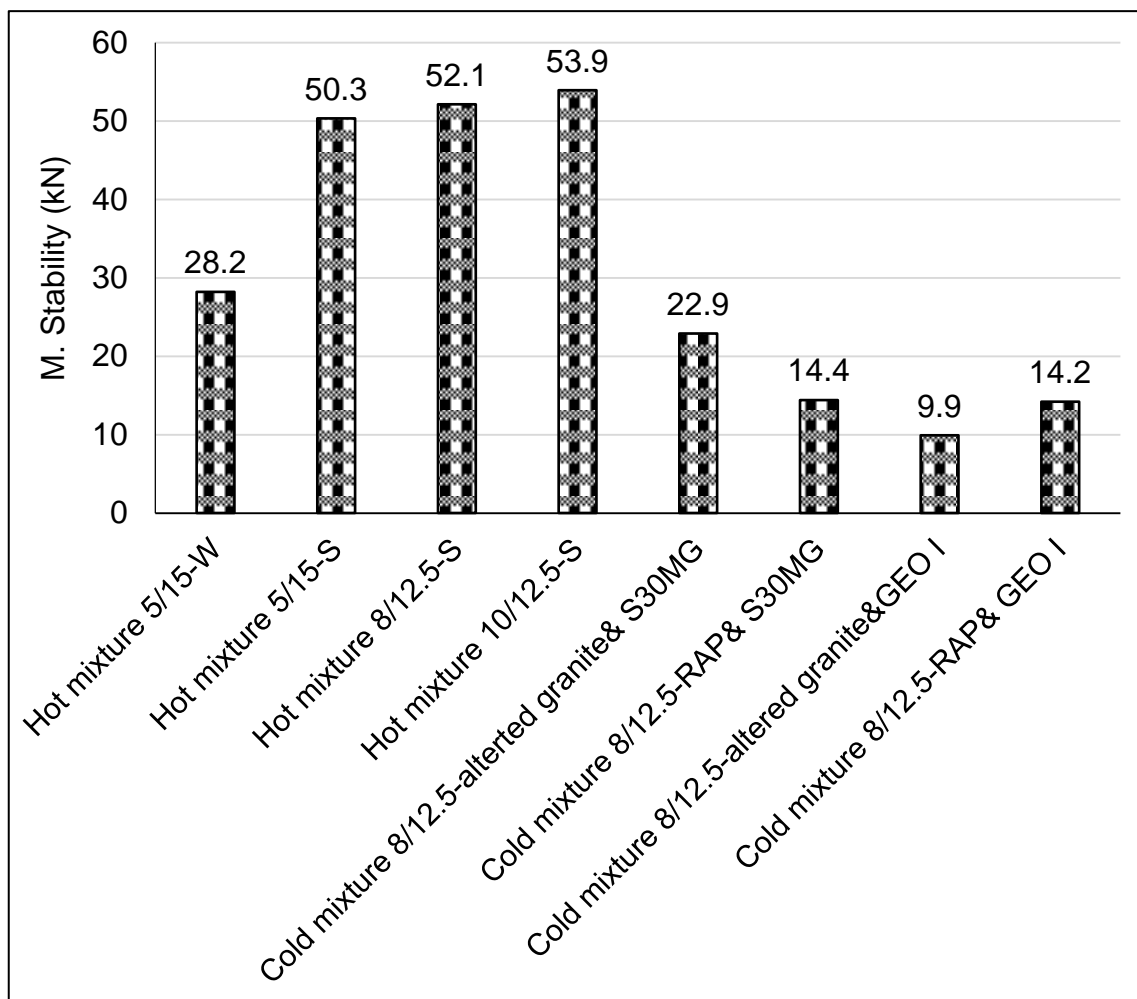


Figure 4: Marshal Stability of various grouted macadams (Afonso et al., 2015)

As a result of variation in grout type, a similar trend of variation in compressive strength and indirect tensile stiffness modulus (ITSM) properties of grouted macadam is reported by this study. Based on wheel tracking test, Afonso et al. (2015) concluded that grouted macadams are generally resistant to permanent deformations, regardless of grout type.

Setyawan (2013) studied the compressive properties of the grout macadams in relations to porous asphalt mix type (i.e. hot and cold), grout type, aggregate type and size as a function of curing age. This study showed that as the curing age of grouted macadam increased, the compressive strength of grouted macadam increased. The mechanical property of grouted macadam is in between bituminous mixtures and cement concrete (Anderton, 2000; Setyawan, 2013; Hou et al., 2016).

2.3. Design Approach for Pavements incorporating Grouted Macadam

AFCESA (2001) recommended an elastic layered method of flexible pavement design, in particular, the fatigue failure criterion used in the design of airfield pavements. More specifically, the whole pavement is designed as if a flexible pavement and finally, top 50mm part of the asphalt concrete is to be replaced by resin modified material (in this case, grouted macadam). A minimum thickness of 50 mm of asphalt concrete (AC) is required beneath the resin modified (grouted macadam) layer. When the combined RMP layer and AC thickness exceeds the design thickness of AC surfacing in the traditional flexible pavement design, then using standard AC equivalency factors, the thickness of base or sub-base layers can be reduced (Anderton,2000; AFCESA,2001).

A comparative study between the “traditional” fatigue failure criterion approach and an iterative approach (considering the real or actual damage accumulation within the material) is conducted by Olivera et al. (2008). The fatigue failure criterion used in flexible pavement is determining the number of load applications that the materials can be subjected to before failure, at a particular stress or strain level (Olivera, 2006).

Olivera et al. (2008) designed pavement which consists of grouted macadam layer using the “traditional” failure criterion established for flexible pavement as well as using an analytical pavement design called an iterative approach. Based on the fatigue performance evaluation of these pavements, Olivera et al. (2008) indicated that the “traditional” fatigue failure criterion can be used conservatively, in which grouted macadam expected to have an extended fatigue life.

2.4. Porous Mix Design Considerations

Air voids content

Porous asphalt concrete is required to have adequate porosity and voids interconnectivity to facilitate rapid impregnation with highly flowable cementitious grouts. A study by Yang and Weng (2015) showed that air voids content of maternal asphalt mixture is found to affect the performance of the resultant composite material.

Air voids contents recommended by most researchers conducted in this area falls within the range of 25-35 % (Anderton, 2000; Hou et al., 2016; Olivera, 2006; Setyawan, 2005; Yang and Weng, 2015). It is good to consider variations that might happen during construction, hence it is appropriate to select porous mixtures with a target air voids content of 30% when conducting the laboratory mix design (Olivera et al, 2008; Anderton, 2000). To achieve the desired level of porosity, factors that need to be considered are aggregate gradation, filler content, bitumen type, and bitumen content. In addition to air voids content, mechanical properties of porous asphalt concrete skeleton need to be considered for proving its capacity to serve expected traffic during the construction phase (Setyawan, 2005). In the selection of optimum bitumen content and bitumen type for the porous asphalt skeleton, Setyawan(2005) suggested the evaluation of the following hot mix performance parameters namely hydraulic conductivity, indirect tensile strength, indirect tensile stiffness modulus, unconfined compressive strength and resistance to abrasion tests.

Aggregate gradation

The type, size, and properties of the aggregate used for the production of grouted macadam vary according to the patent or the guidelines produced by authors or grout suppliers (Olivera, 2006). To achieve high air voids content of above 25%, uniform gradation or a single-sized aggregate of nominal size: 8, 10, 14 & 20 mm was used by different researchers.

Olivera (2006) evaluated the effect of aggregate grading using 10 mm, 14 mm, and 20 mm single sized aggregate, and more continuous grading on the stiffness and fatigue performance of grouted macadam. As compared to conventional asphalt concrete, the aggregate for grouted macadam should primarily composed of coarser fractions. It is important to select single sized aggregates in order to ensure voids interconnectivity (Olivera, 2006). Also, Deshmukh (2011) suggested the use of coarser aggregate fractions that have 5mm to 15mm particle size in general.

Some of the aggregate gradations obtained from the literature are summarized in the Figure shown below.

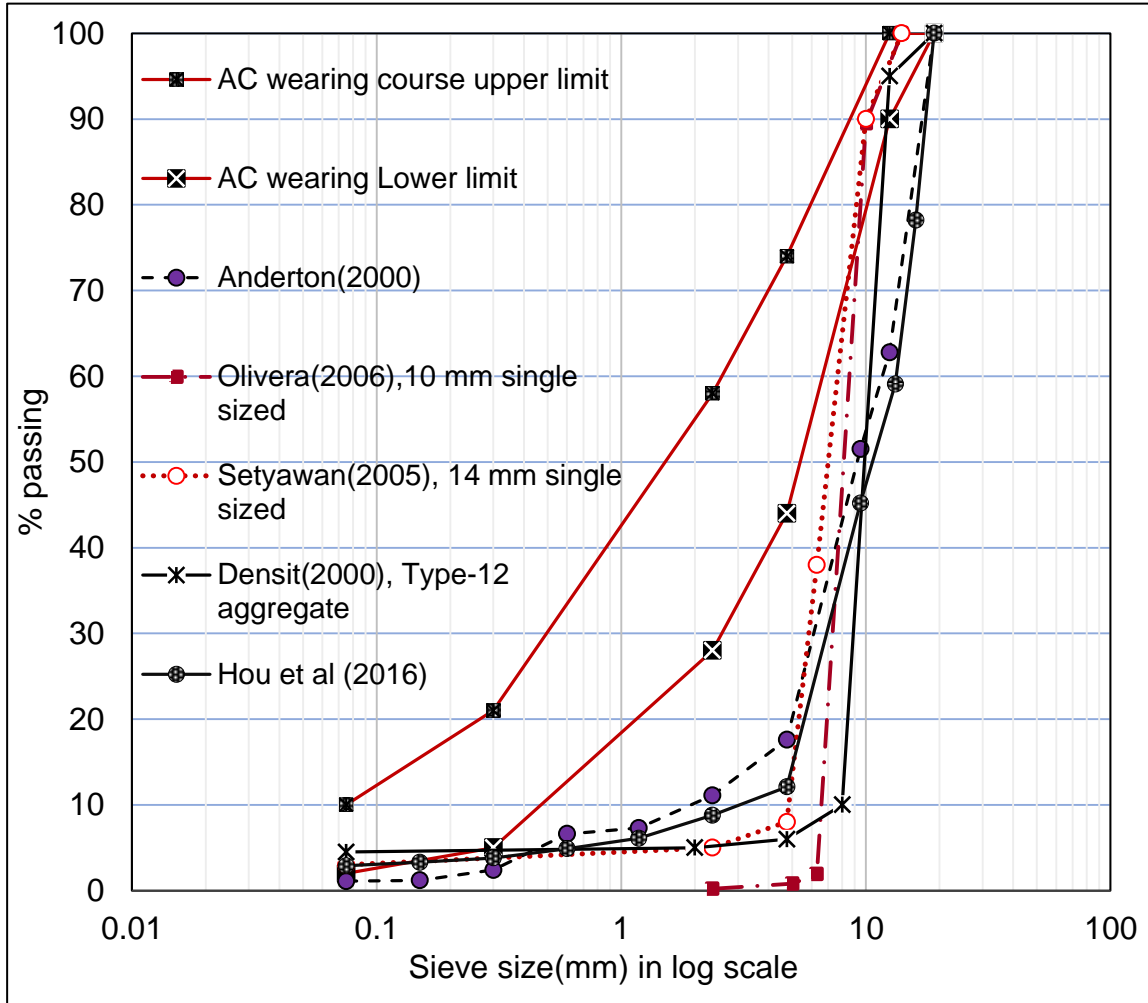


Figure 5: Some of the aggregate gradations obtained from the literature as compared to the aggregate grading for conventional asphalt concrete

For a similar maximum aggregate size, it is clear that the aggregate grading for porous asphalt concrete is out of the gradation band for 19mm maximum size aggregate of dense graded asphalt concrete (AC) wearing course layer that is suggested by Asphalt Institute (1995). As it seen in Figure 5 above, the aggregate grading for grouted macadam is a single sized aggregate.

Bitumen type and content

In the production of porous asphalt concrete various binder types (straight run or modified bitumen) are suggested by different authors and specifications. Densit (2000) stated that (as cited in Olivera, 2006) bitumen type is to be selected based on the locations indoors or outdoors, climatic conditions, and whether the asphalt is to be laid by machine or manually.

Anderton (2000) suggested a penetration grade (PG) bitumen with penetration value in the range of 40 to 100 at 25 °C and used PG 85/100 with a penetration value of 89 in that laboratory study. After analyzing air voids content, for preparing resin modified specimens a bitumen content of 3.8% is used in that study.

Olivera et al.(2008) for the investigation of fracture and fatigue strength of grouted macadam, used a nominally single-sized 10mm granite aggregate (75% by mass between 6.3mm and 10mm) with 4.1% of 200 penetration bitumen, with 3.7% fibers (by mass of binder) to prevent binder drainage.

Penetration grade (PG) 60/70 bitumen with bitumen contents in the range of 3.8% to 4% by weight of the total mixtures is suggested by Deshmukh (2011).

It can be said that there is a better consensus seems to be found on bitumen content among various authors and specifications, with bitumen contents ranging from 3.5 to 4.6% by mass of mixture (Anderton, 2000; Densit, 2000; Koting et al, 2011; UFGS, 2008; Setyawan, 2005; and others).

Roffe (as cited in Anderton, 2000) presented a correlation model based on the relationship studies between optimum bitumen content and aggregate properties i.e. grading & specific surface area. According to this model, the optimum bitumen content (OBC) can be estimated by the following equation (Anderton, 2000):

$$OBC=3.25(\alpha)\Sigma^{0.2} \dots\dots\dots(2.1)$$

Where: $\alpha= 2.65/G_{sb}$;

G_{sb} =apparent specific gravity of aggregate blend;

Σ = conventional specific surface area = $0.21G + 5.4S + 7.2s + 135f$;

G= percentage of material retained on 4.75 mm sieve;

S= percentage of material passing 4.75 mm sieve and retained on 600 μ m sieve;

s= percentage of material passing 600 μ m sieve and retained on 75 μ m sieve;

f= percentage of material passing 75 μ m sieve.

Binder drain-off

Binder drain-off is the condition when excess bitumen with fillers (asphalt mortar) drains off the aggregate skeleton. Densit (2000) (as cited in Olivera, 2006) suggested that binder drainage should be limited to 0.3% maximum by weight of mixtures.

Conventionally the asphaltic mixture consists of aggregate, filler and bitumen, but in some cases, it incorporates cellulose fiber in order to reduce binder drain down (Setyawan, 2005). Binder drainage is also considered for engineering as well as economic justification (Ahlrich and Anderton, 1991).

2.5. Grout Mixture Design Considerations

2.5.1. Cementitious grout composition

According to literature obtained, the main difference among researchers is in the grout composition. Most of the commercial grouts are supplied as grout mortar and their composition is confidential where water is to be added in the prescribed percent by weight of grout mortar at the job site. On the other hand, recent studies suggested different composition of cement-based grout, epoxy-based grout as well as geopolymeric grout. Based on recent studies, it can be said that the use waste materials such as industrial by-products are getting attention to reduce the cost of grouted macadam in general.

Research papers from the academic areas suggested grout composition with different ingredients in addition to cement. In this regard, Hassan et al.(2002) prepared different types of cementitious grouting materials by using ordinary Portland cement, silica fume, fly ash and silica sand in different combinations. In order to improve fluidity and strength properties of grout mixtures, Hassan et al. (2002) added chemical admixture to this mixtures by weight of the binder. Water to binder ratio as low as 0.28 is reported in that study. In this case, the binder is defined to be the binding material consists of cement and supplementary cementitious materials such as silica fume, fly ash, etc. Cementitious grout with a better mobility while maintaining higher strength at 28 days is prepared by Hassan et al. (2002).

Koting et al. (2011) prepared cementitious grout from ordinary Portland cement, silica fume and fly ash in different combinations with chemical admixtures. The study adopted two types of polycarboxylic ether polymer and one type of sulphonated naphthalene formaldehyde origin prepared cementitious grouts with high strength and high fluidity and analyzed the effects of different doses of additives on the performance of grout.

Yang and Weng (2015) used fine sand content of 20% with water to binder ratio of 0.7 and 0.75, for the preparation of semi-flexible material.

However, cementitious grout mixtures suggested by above papers are entirely based on laboratory design and the success of field construction is yet not reported.

On the other hand, a detailed cementitious grout composition of resin modified pavement (the USA version of grouted macadam) is released for the public from US Army Corps of Engineers. The success of this grout composition as designed to different field project is also reported. Besides the design of resin modified pavement, its detailed construction procedure is well documented based on experiences gained from previous projects.

According to Unified Facilities Guide Specification (UFGS, 2008) of US Army Corps of Engineers, enough water is added to produce cementitious slurries with water to cement ratio in the range of 0.65 to 0.75.

Table 2: Resin-modified cement slurry grout mixture proportions (UFGS, 2008)

Material	Percent by weight
Portland cement	34-40
Silica sand	16-20
Class F fly Ash	16-20
Cross polymer resin (Resin modifier)	2.5-3.5
Water	22-26

The cross polymer resin (latex additive) acts as a plasticizer to reduce the slurry grout viscosity for better penetration and as a strength producing agent. The combination of ingredients shown in Table 2 is standardized, can produce a slurry grout which is very fluid and only slightly more viscous than water (Anderton, 2000).

2.5.2. Desired performance requirements of cementitious grout

As a binding material, cement reacts with water and additives added onto it. After hydration of cement, the paste or mortar hardens and gets its strength. Adequate water is required for full hydration of cement, to recover loss of water associated with evaporation and to satisfy workability requirements (Neville and Brooks, 2010).

The design of cementitious of grout primarily focuses on designing a material that is easily flowable into the voids of porous asphalt skeleton, and a material that provides adequate strength (to resist the application of stresses and strains) when it hardened (Anderton, 2000; Olivera, 2006). Some of the important properties of cementitious grout are discussed below.

Bleeding

It is one of the fresh state performances of grout. It can indicate the stability of grout at fresh state. Lombardi (1985) stated (as cited in Tan, 2005) a grout is considered stable when the final bleeding is less than 5% after 120 minutes from which the grout is allowed to settle. However, this value is suggested for the grouts to be used in geotechnical applications.

Marsh cone viscosity

Viscosity indicates the liquidity level of cementitious grout which can be considered as the workability of grout for a particular application. In order to obtain full penetration of the air voids in the asphalt skeleton, it is the most important property need be controlled during design (Olivera, 2006). Based on the purpose and testing approach: Marsh cone viscosity (Anderton, 2000; Olivera, 2006 and UFGS, 2008), flow time or flow cone time by ASTM C-938 (Al Qadi et al., 1994), fluidity (Pei et al., 2016 and Zhang et al., 2016), and Leeds cone viscosity (Hou et al., 2016) are some of the terms used in characterizing the workability performance of grout for semi-flexible pavement applications.

In a similar way, the value of viscosity that were suggested by specifications and previous authors are also different in relation to the difference in cone dimension as well as the volume of grout used in the test.

Generally, the grout or slurry material is required to have high fluidity at the beginning stage, and maintain this fluidity for a certain period during the whole grouting process, to ensure enough time for grouting (Pei et al., 2016).

According to Anderton (2000), Marsh cone viscosity is the time flow (efflux) of 1000ml of grout through Marsh cone funnel. In this regard, to assure flowability of cementitious grout, Marsh cone viscosity is required to be in the range of 8 to 10sec slightly higher than the viscosity of water, i.e. 6 sec (Anderton, 2000; UFGS, 2008).

Compressive strength

Compressive strength is one of the hardened state performances of grout mixtures that are commonly used in comparing different grout compositions. Studies showed that the compressive of grouted macadam is more influenced by the strength of cementitious grout. Grout with higher strength, resulted in the higher strength of grouted macadam (Afonso et al., 2015; Koting et al.2011 and Setyawan, 2013).

Where grouts with low water to cement ratio and most commercial grout products reported to have high strength, hence classified as strong grout. Whereas grout with high water to cement ratios such as grouts used in resin modified pavement (RMP) categorized under weak grout (Afonso et al., 2015; Olivera, 2006). Anderton (2000) reported the compressive strength for resin modified specimens to be about 22.8 MPa at the 28th day of air-curing age. It is necessary to investigate the strength development of cementitious grout in order to investigate the impact of grout on the strength property of the resultant grouted macadam material.

Rupture modulus

It is also known as flexural strength of grout (Zhang et al., 2016). As the cementitious grout expected to contribute to the tensile strength of grouted macadam, knowing the tensile strength of grout is important.

Drying shrinkage

As a result of hydration of cement as well as loss of water in cementitious grout will lead to shrinkage of mortar. Hassan et al. (2002) reported the use of silica fume and fly ash in grout reduces drying shrinkage by 12-15% as compared to grout with cement only. And these fillers are reported to reduce the porosity of hardened grout.

Grouting ability

According to Pei et al. (2016) grouting ability is defined as the grouting material's ability to be fully and smoothly poured into the matrix mixture. It is directly related to the fluidity level of the grout. It can be estimated, based on the volume of grout infiltrated into porous media in per unit area, depth of grout penetration achieved and residual porosity of grouting composites (Pei et al., 2016). In this regard, the full depth of grout penetration and more than 95% of impregnation porous asphalt concrete by the grout (Anderton, 2000; Olivera, 2006 and UFGS, 2008).

Other performances of grout such as unit mass, durability, sulfate attack resistance, and moisture resistance are recommended to be tested by some authors.

2.5.2. Potentially available cementitious grout ingredients in Ethiopia

Portland cement

Portland cement, according to Neville and Brooks(2010), is the name given to a cement obtained by intimately mixing together calcareous and argillaceous, or other silica(SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3)- bearing raw materials, burning them at a clinkering temperature, and finally grinding the resulting clinker. It is also called hydraulic cement, because when it is mixed with water forms a paste which sets and hardens by means of hydration reactions and processes and which, after hardening, retains its strength and stability even under water.

According to UFGS (2008), Portland cement conforming to ASTM C150/C150M, Type I, II, III, and V, can be used in the cementitious grout. These types are:

- ✚ Type I: Ordinary Portland cement that is used in general concrete construction where special properties of other cement types are not required.
- ✚ Type II: Portland cement used in general concrete construction exposed to moderate sulfate action, or where a moderate heat of hydration is required.
- ✚ Type III: Rapid hardening cement, used when high early strength gain is required
- ✚ Type V: Sulfate resisting cement that is often used when high sulphate resistance is required.

According to the study by FDRE Ministry of Industry, MOI (2015), the cement production is started in 1936 in the city of Dire-Dawa. Since then the cement production in the country has started to grow substantially to satisfy local cement demand. However, due to a construction boom in 2004, a severe shortage of cement is observed up to 2011. There was price escalation of cement, as a result of this shortage. This led to further expansion projects and private investments in the cement industry.

“An aggressive expansion of the cement industry in 2012 onwards resulted in inflaming excess capacity” (MOI, 2015). In 2014, the consumption and installed capacity are about 5.47 and 11.2 metric ton per annum, respectively. It means the industry at only 49% capacity utilization rate. Currently, the country has more than 16 cement plants. When all cement factors become fully operational, the overall installed cement production capacity will be expected to reach 17.15 metric ton per annum. In order to utilize its capacity, the cement industry is calling the government to take measures which stimulate the market for cement (MOI, 2015). Nowadays, Portland cement is locally available at an affordable price.

Silica sand

Silica is the name given to a group of minerals composed solely of silicon and oxygen, known by the chemical formula, SiO_2 . It is hard, chemically inert and has a high melting point, attributable to the strength of the bonds between the atoms. Silica exists in many different shapes and crystalline structures. The three major forms of crystalline silica that are stable at different temperatures namely quartz, tridymite, and cristobalite. For industrial and manufacturing applications, deposits of silica-yielding products of at least 95% SiO_2 are preferred (Mesfin, 2012).

Silica sand is usually exploited from sandstones, quartzite rock and loosely cemented or unconsolidated sand deposits. In Ethiopia, huge deposits of silica sand proved to exist in the localities namely in the Mughher Valley, in the Jemma-Wonchit River basin, and in the Enticho units of Adigrat Group of Mountains (Mesfin, 2012).

Table 3: Estimated reserves of silica sand (Mesfin, 2012)

ID	Location	X	Y	Reserve (Metric tons)
1	Fetra	485908	1107781	212.5
2	Mughher	454244	1031638	3.413
3	Enticho	571865	1593770	

According to Mesfin (2012), use of silica sand for particular applications might require beneficiation processes such as washing, screening, attrition scrubbing, acid leaching, heavy mineral separation and magnetic mineral separation are vital in reducing iron and titanium content. Silicate analysis conducted in the Geological survey of Ethiopia, for samples taken from the above-mentioned localities is shown in Table 4 below.

Table 4: Chemical composition of silica sand (Mesfin, 2012)

ID	Location	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	Cr_2O_3
1	Fetra (unwashed)	91.15	0.75	5.29	0.4	
2	Fetra (washed)	97.90	0.65	0.8	0.2	
3	Mughher	96.43	0.20	1.37		<0.02
4	Enticho	99.0	0.21	0.35		

Silica sand for grouting application is required to be clean, sound and free from clay or any objectionable matter. It should consist of grains with a particle size in the range of 0.075 mm to 0.6mm (Anderton, 2000; UFGS, 2008). To achieve this grading requirement, simple beneficiation such as attrition washing and screening might be enough to upgrade the quality of sandstone deposits. Whereas high purity silica sand can be obtained through crushing of quarzitic rock.

Based on the information gathered, it is understood that Muger Cement Enterprise is the first to exploit silica sand in Muger valley in a village called Derba. Currently, this Enterprise is selling processed silica sand at a factory gate price of 384.2 Birr/tonne. This price includes all taxes but does not include transportation costs. Glass Factories, Akaki Basic Metals Industry, Paint Factories and others are exploiting silica sand from quarries in Ethiopia.

Supplementary cementitious materials

According to Kosmatka and Wilson (2011), supplementary cementitious materials (SCMs) are materials that, when blended with Portland cement, contribute to the properties of concrete through hydraulic activity, pozzolanic activity, or both. Hydraulic activity occurs when phases (oxides) in the SCM chemically react with water, forming cementitious hydration products similar to those formed through hydration of Portland cement. In contrast to this, pozzolanic activity, which is characterized by the reaction between siliceous or aluminosiliceous material in the SCM with calcium hydroxide (a reaction product from the hydration of Portland cement), forming calcium silicate hydrate and other cementitious compounds (Kosmatka and Wilson, 2011). Some of the commonly used SCMs are fly ash, ground granulated blast slag, silica fume, and natural pozzolans such as calcined shale, metakaolin, or other calcined clays (Kosmatka and Wilson, 2011). Most of the time, associated with the improvements obtained by incorporating these materials into concrete mixtures, they are referred to as mineral admixtures.

Bagasse fiber is the waste obtained after extraction of sugar juice from sugar cane. For energy production purpose, this waste is transported to combustion furnace. It is burnt there and its ash is collected at the outlets of the furnace.

Bagasse ash is the common by-product of sugar and alcohol factories (Biruk, 2011; Cordeiro et al., 2008).

Many researchers evaluated bagasse ash as a cement replacing material or as a supplementary cementitious material. It is reported that concrete mixtures incorporating bagasse ash were found to have improved performances. These researchers suggested that it is because of the pozzolanic activity of the bagasse ash which in turn associated with the high amount of silica, i.e. SiO_2 (Biruk, 2011; Cordeiro et al., 2008; Ganesan et al., 2007). Cordeiro et al. (2016) added that the effectiveness of bagasse ash as a pozzolanic material is highly related to its silica content, and mainly to the crystallinity of silica. Amorphous or partially crystalline silica and amorphous alumina are essential for the development of pozzolanic reactions with calcium hydroxide which is liberated during hydration reaction of cement (Cordeiro et al 2009). Whereas crystalline silica is an inert compound that it can be found in two forms namely cristobalite and quartz. Cristobalite is produced when the bagasse ash is burnt at high temperatures (above $800\text{ }^\circ\text{C}$) and/or long periods of burning. Also, quartz (another stable form of silica) reported to exist in the ash associated with sand adhered to the sugar cane and harvested along with it (Cordeiro et al., 2009).

A study by Cordeiro et al. (2008) showed that bagasse ash as a mineral admixture can provide both physical and chemical effects. As a filler, bagasse ash improves the packing characteristics of the mixtures, which is known to be its physical effect. The size, shape, and texture of the ash particles have a direct influence on its physical effects. According to this literature, the amorphous silica (SiO_2) and alumina (Al_2O_3) in the bagasse ash will chemically react with calcium hydroxide ($\text{Ca}(\text{OH})_2$) to form an additional cementitious product called calcium silicate hydrates (C-S-H). This reaction is described as the chemical effect of bagasse ash. The chemical effect (reactivity) of bagasse ash is dependent on the degree of crystallinity of silica, size, and fineness of the particles (Cordeiro et al., 2008). Cordeiro et al. (2016) investigated the means of improving the pozzolanic activity of bagasse ash. The separation of coarse waste (i.e. quartz-rich waste) by grinding the bagasse ash with a ball mill and screening it by air-classifier in two successive operations is reported to improve the homogeneity and pozzolanic activity of bagasse ash (Cordeiro et al.; 2016).

During the first Growth and Transformation Plan (GTP I), Ethiopia started construction of eight new sugar factories as well as expansion projects on the existing factories (Biruk, 2011). At this time, some of these new and expansion projects started production. Thus, bagasse ash production in Ethiopia is being increased. According to MSc thesis research conducted by Biruk (2011), bagasse ash potential might reach to 0.94 million ton per year when all projects started sugar production.

Chemical admixtures

There are different kinds of chemical admixtures which are produced for different purposes such as to reduce water, to retard or accelerate setting time of cement, to reduce shrinkage, to reduce corrosion of re-bars, to control air content, and to modify other properties of concrete mixtures((Kosmatka and Wilson, 2011).

According to ASTM C-494, chemical admixtures are classified into seven types depending on the purpose and their effects on hydraulic-cement concrete mixtures. These are:-

- ✚ Type A—Water-reducing admixtures,
- ✚ Type B—Retarding admixtures,
- ✚ Type C—Accelerating admixtures,
- ✚ Type D—Water-reducing and retarding admixtures,
- ✚ Type E—Water-reducing and accelerating admixtures,
- ✚ Type F—Water-reducing, high range admixtures, and
- ✚ Type G—Water-reducing, high range, and retarding admixtures.

Water reducing admixtures also called plasticizers which are added to concrete mixtures in order to reduce the amount of water for a given consistency of mixtures. Whereas high range water-reducing admixtures are also called superplasticizers which can enable reduction of the amount of water by 12% or more (ASTM C-494). Superplasticizers are more recent and more effective type where higher dosage can be used with minimum side effects(Neville and Brooks, 2010).

In Ethiopia, different brands of chemical admixtures are being manufactured. Also, different brands of imported admixtures are available in the local market.

3. Materials, Methods, and Procedures

3.1. Introduction

The objectives of this research are to design cementitious grout & porous asphalt concrete and prepare grouted macadam mixtures. In addition, to evaluate improvements achieved after grouting porous asphalt concrete with reference to maternal porous asphalt concrete.

First, samples of all necessary materials have been collected and relevant quality tests have been performed. In order to meet the objectives of this study, it is required to design the cementitious grout and porous asphalt concrete. Then after it is required to prepare and test grouted macadam as well as control specimens. Depending on the mixture type, it is opted to use laboratory-based experimentation with three phases.

In phase I, mixture design of cementitious grout is performed. In this design, it is decided to include five grout mixture ingredients namely cement, silica sand, bagasse ash as a pozzolanic filler, water, and megaflo SP1 as a chemical admixture. It is expected that each of these ingredients might have a contribution to improve some of the engineering properties of the grout. As the same time, each of them might have a negative influence on the other properties. Hence, for selecting the best combination of these ingredients, the Taguchi approach is followed.

Whereas, design of porous asphalt concrete is performed in phase II. The design approach used by US Army Corps of Engineers is followed in mixture design of porous asphalt concrete. In this approach, Marshal Method of hot mix asphalt concrete specimen preparation is used except modification in the number of blows as recommended by Anderton (2000).

After the two design phases, preparation and testing of both control and grouted macadam specimens are carried out in phase III of this study. The details of each experimentation phases are presented in the subsections below.

3.2. Experimental Programme

After each material has been collected, relevant quality tests have been performed. The main experimental work is carried out in three phases. The sequential order of these phases and procedures is summarized in the flowchart shown below.

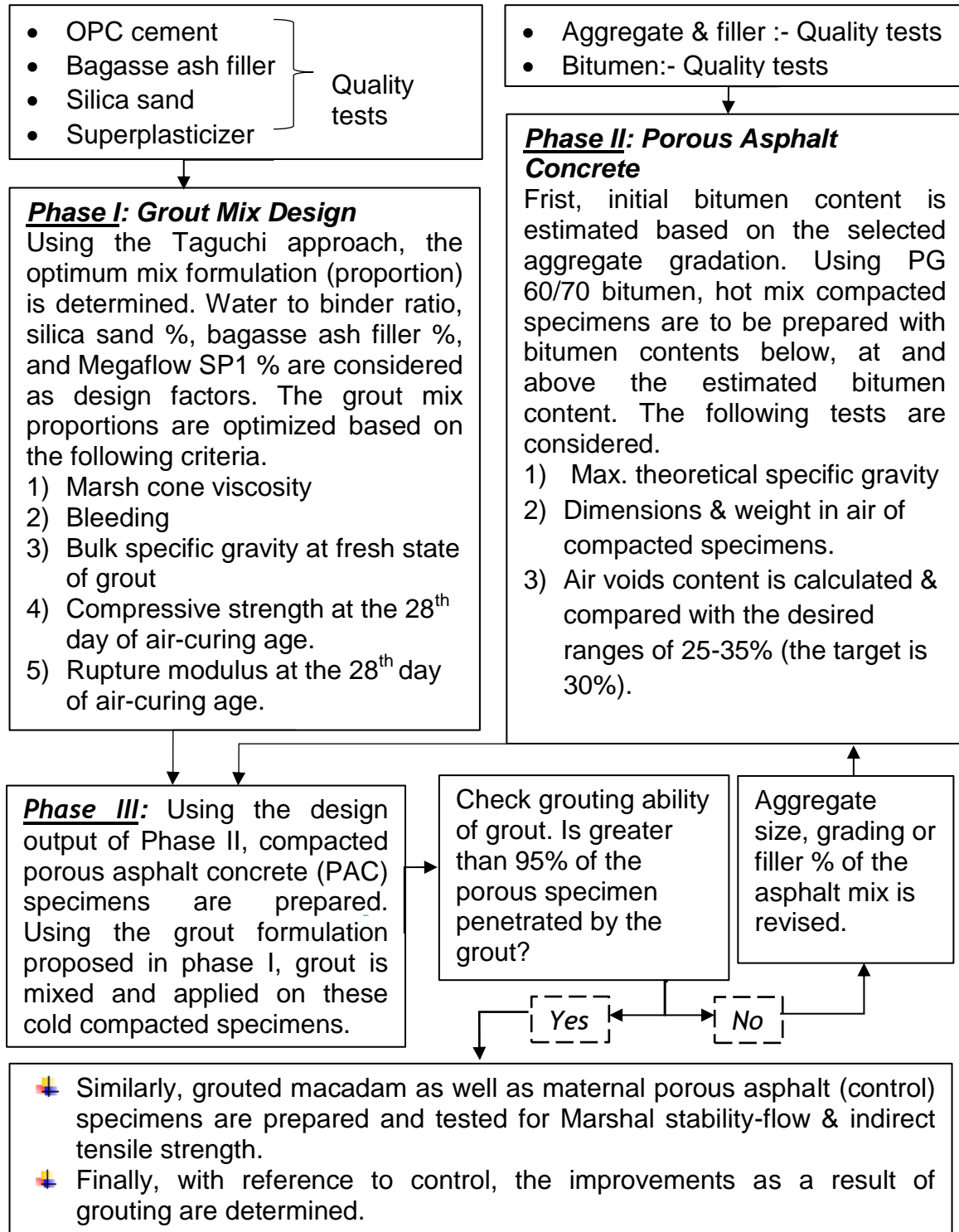


Figure 6: Flow chart showing the sequential order of experimental phases

3.3. Materials

This study is carried out after collecting adequate samples of materials but not limited to the following: Type I cement (OPC), sugar cane bagasse ash as a pozzolanic filler, silica sand, megaflow SP1 as a chemical admixture, bitumen, and aggregate. The samples of these materials are tested for physical and chemical tests where necessary. The material description, sample source, and sample preparation are discussed in the sub-headings below.

3.3.1. Materials used in the mixture design of cementitious grout

Ordinary Portland cement

Ordinary Portland cement manufactured by Dangote Cement Ethiopia PLC is used throughout the study. A quintal of this brand cement is purchased at a price of 280 birr/quintal from a local shop located around Saris Abbo, Addis Ababa.

According to the test results, Dangote ordinary Portland cement has a normal consistency of 27% and has a specific surface area of 2950 cm²/gm as tested by air permeability apparatus. A test performed by using Vicat needle shows that it has an initial and final setting time of 2.5 hours and 4 hours, respectively. It can satisfy ASTM C 150 requirement of Type I cement.

Silica sand

In order to obtain fine silica sand, samples of sandstone are collected from the middle of sandstone pile which is brought from Mughher valley. These samples are washed on 75µm sieve size where silt & clay particles are removed and then washed sand is oven dried to constant weight. After oven drying, the coarser particles are screen out by sieving with 600µm. It is a quartz sand having white to rose color.



Figure 7: Processed silica sand

Processed silica material around 50 kg is prepared. A sample taken from processed silica sand has shown that it has a specific gravity of 2.625 and a grain size as shown in Table below. As it is free from clay, silt, or other objectionable matter, this sand can satisfy all the requirement of Unified Facilities Guide Specification (UFGS) which is published August 2008.

Table 5: Grading of processed silica sand

Sieve size (mm)	Cumulative pass, (%)	Requirement by UFGS(2008)
1.18	-	100
0.60	100	95-100
0.30	59.76	-
0.15	6.29	-
0.075	0.24	0-2

According to information gathered, Mughher Cement Enterprise is processing silica sand in a village called Derba, located in Mughher Valley. It is selling this processed silica sand at a factor gate price of 384.2 birr/ tone including all taxes.

Sugar cane bagasse ash filler

In the design of cementitious slurry, sugar cane bagasse ash is chosen as filler for two reasons. First, the use of pozzolanic fillers such as silica fume, fly ash, in cementitious grout contributed for the reduction of drying shrinkage and porosity (Hassan et al., 2002). Research that was done on bagasse ash showed that it can be used as pozzolanic filler (Cordeiro et al., 2008; Ganesan et al., 2007). Second, bagasse ash is being produced as a by-product in the sugar factories in Ethiopia (Biruk, 2011). However, it is difficult to obtain bagasse ash for immediate use. Therefore, it is decided to take samples from the rehabilitated sugar factory called Wonji Shewa. This factory is now located near to Awash Melkasa town on the road to Assela.

In this factory, the following observations have been made. After extraction of sugar juice, the waste fiber and straw are transported to a combustion furnace, burned there. From the outlets of the combustion furnace, hot ash is transferred onto the conveyor belt which was water wetted before. The conveyor transports it to the discharging outlet where tractors stood and collect the ash. Then each loaded tractors move it to sugarcane fields and dump it there.

Since bagasse ash production is a continuous process, with the help of shovel the bagasse ash samples were collected at discharging point randomly. During sample collection time, two trial samples were placed on hand, squeezed and examined visually. From these observations, it is understood that the ash contains a high amount of water. The technicians told that it is because of the water sprayed on the conveyor to cool and minimize air blown ash particles and also they said that the bagasse ash is being burnt at a temperature of 700 °C. Adequate samples of the ash packed in three sacks and transported to central laboratory of IFH Addis Engineering PLC. In this laboratory, these samples were air dried for two days as shown in Figure 8(a). After air drying, the sample for the chemical test is taken to Geological Survey of Ethiopia. The chemical test called complete silicate analysis is conducted. However, for this test, only one trial is performed due to financial constraints. This chemical test report is presented in Appendix 1. As it can be seen in this Appendix, the sum of SiO_2 , Fe_2O_3 , and Al_2O_3 content is 62.76% which is slightly less than ASTM C-618 class F fly ash minimum requirement of 70%. And the loss on ignition value is reported to be 21.96% again it is greater than the maximum 12%. The higher value of loss on ignition is an indicator for the presence of significant amount of unburned matter in the ash. For this reason, it is decided to process the bagasse ash by oven drying it to constant weight. Then the oven dried samples are sieved using 75 μm sieve size. Those particles passing the 75 μm sieve size are collected. As shown in Figure 8(b), the processed bagasse ash is gray to black in color.



(a) Bagasse ash samples being air-dried



(b) Processed bagasse ash ready for use

Figure 8: Photos of bagasse ash sample preparation

Table 6: Summary of physical tests performed on the processed bagasse ash

Test name	Test result
Specific gravity	2.13
Blain specific surface area (cm ² /gm)	2280
Fineness by 45 µm sieve, % retained	26.2
Liquid limit, %	123.6

As shown in 6 above, the physical property of the processed bagasse ash can satisfy the requirement of ASTM C-618 class F fly ash, except for the water requirement. Based on the liquid limit test result, the bagasse ash has higher water requirement than the water requirement (i.e. 105% maximum) specified for Class F fly ash. In this case, this bagasse ash has a high amount of SiO₂ content (above 50%) and low CaO content. The physical properties such as particle size and fineness suggest that it can be used as pozzolanic filler.

Chemical admixture

Locally manufactured chemical admixture called megaflo SP1 is selected. It is one of the construction materials that are being produced by Licon Manufacturing PLC. It is in liquid form with a specific gravity of 1.20. Five liters of Megaflo SP1 sample is proudly supplied by the manufacturer free of charge.

According to the manufacturer's specification, megaflo SP1 is a highly effective water reducing superplasticizer and an extremely power deflocculating agent based on the soluble salt of polymeric naphthalene sulphonate. It complies with Type F standards of ASTM C-494, BS EN 934-2. It can be used with any types of cement and cementitious materials like fly ash, slag, micro silica, etc. It should not be premixed with other admixtures. The recommended dosage of megaflo SP1 is 0.5-3% by weight of cementitious material. It should be dispensed into the concrete mixer together with the mixing water. It has a shelf life of 12 months from the date of manufacture when stored under warehouse conditions.

Water used

Distilled water that is supplied by Addis Ababa City Water and Sewerage Authority is used throughout the experiments where water is necessary.

3.3.2. Materials used in the mixture design of porous asphalt concrete

Aggregate and filler

It is required that the aggregate particle fractions be dominated by coarser sizes (Setyawan, 2005). After reviewing literature written in the study area, a specification provided by Corps of Engineers, Unified Facilities Guide Specification, i.e. UFGS (2008) is followed and the maximum aggregate size is decided to be 19mm. Then aggregate samples are taken from stockpiles of asphalt concrete batch plant of IFH Addis Engineering PLC. For this study, AASHTO T-84 and T-85 aggregate particle size definition are used. Where coarse aggregate particles are those retained on 4.75mm, fine aggregate particles are finer than 4.75mm and retained on 75 μ m sieve size. Rock dust particles finer than 75 μ m sieve size are described as mineral fillers.

By conducting dry sieving, aggregate particles retained on each sieve series are separated. Whenever it is required, aggregate particles retained on each sieve size are included for quality testing and mixture preparation.

Table 7: Summarized test results for the aggregate used in asphalt concrete

Type of test	Test Method	Test result	Specification (ERA, 2013)
Aggregate Crushing Value, (%)	BS 812 part 110	12.5	<25
Los Angeles Abrasion Value, (%)	AASHTO T-96	14	<30
Flakiness Index (%)	BS 812 part 105.1	21	<45
Elongation Index (%)	BS 812 part 105.1	18	
Soundness test by Na ₂ SO ₄ , loss (%)	AASHTO T-104	4.5	<12
<i>Coarse aggregate (19 - 4.75mm)</i>			
Bulk specific gravity(dry)	AASHTO T-85	2.60	
Bulk specific gravity (SSD)		2.65	
Apparent specific gravity		2.73	
Water absorption (%)		1.75	<2
<i>Fine aggregate & filler (<4.75mm)</i>			
Bulk specific gravity	AASHTO T-84	2.51	
Bulk specific gravity (SSD)		2.58	
Apparent specific gravity		2.70	
Water absorption (%)		2.81	

Bitumen

A sample of penetration grade (PG) 60/70 is taken from Shewa Robbit Road Project, with due support by Ethiopian Water Works Corporation Enterprise. The quality test results are summarized in the Table shown below.

Table 8: Summarized tests results for bitumen PG 60/70

Type of test	Test method	Test result	ERA (2013) Specification
Penetration at 25 °C, 100g, 5 sec	AASHTO T 49	66	60-70
Ductility at 25 °C (cm)	AASHTO T 51	106	
Softening point (°C,)	AASHTO T 53	50.6	46-56
Solubility in Trichloroethylene (%)	AASHTO T 44	99.8	99
Flash and Fire point, resp. (°C)	AASHTO T 48	265,315	232
Specific gravity at 25 °C	AASHTO T 228-06	1.02	

3.4. Experimental Phase I

Studying each effect of each grout ingredient will require full factorial experimentation which will be costly and time-consuming. According to Roy (2001), Taguchi method of experimentation design is a better alternative to minimize cost and time budget of experiments. It is an approach in the design of experiments where less number of experimental runs are to be designed & conducted as compared to the full factorial design of experiments (Roy, 2001). The objective of this phase of the study was to determine the optimum combination of ingredients that result in a grout with overall best performance. To this end, the Taguchi approach is followed. Then, final adjustment on the factor level is done based on Marsh cone viscosity.

3.4.1. About Design of Experiments using the Taguchi Approach

Design of experiment (DOE) is a statistical tool used for studying the effects of multiple factors (variables) simultaneously (Roy, 2001). The name Taguchi is associated with the DOE technique is because of the Japanese researcher Dr. Genechi Taguchi who has offered unique concepts in combining engineering and statistical methods to improve cost and quality.

Cementitious slurry with low water to cement ratio might have high compressive strength, but it might have high flow cone viscosity (Koting et al., 2011). In this case, having high strength may be the desired performance whereas having high Marsh cone viscosity implies low workability (i.e. cementitious slurry may not flow). In comparison, the former require lower water to cement ratio than the latter case. Higher water to cement ratio might produce a flowable grout, but it may result in a reduction of compressive strength. Selection of this design input parameter will be a dilemma. This dilemma leads to a compromise between strength and flowability measured characteristics of the cementitious slurry. Thus, the selection of water to cement ratio for this particular case requires balancing these opposite performance properties. In other words, it means balancing the positive and negative effect of water, before selecting design water to cement ratio. This kind of optimization is usually referred to as parameter design (Roy, 2001). For a selected factors and factor level values, Taguchi method of experimentation design will result in less number of experimental trials than full factorial experiments. Hence, using the results of these experiments, product optimization can be done with minimum effort (Roy, 2001).

According to Roy(2001), the term result is defined as a measured value of the performance and its unit of measurement. In Taguchi approach, an additional term called quality characteristics is frequently used. Quality characteristic (QC) is the sense of desirability of the result in the process of evaluation (Roy, 2001).

Evaluation refers to a process in which the performance (result or status of product) is measured using the objective method and expressed in quantitative terms. For a given performance parameter, the method and processes that are used in determining results are called evaluation criteria. In individual evaluation criteria, the result is always compared with what the standard is, or what the desirable values are. The quality characteristic (QC) indicates the direction of the desirability of the criterion being evaluated (Roy. 2001).

In whatever conditions, there could be three different kinds of quality characteristics (Roy, 2001). These are:

- 1) Smaller is better ($QC=S$): the smallest value is always preferred over the others.
- 2) Nominal is best ($QC=N$): In this case, a fixed value is targeted (desired) and results are compared with this target.
- 3) Bigger is better ($QC=B$): where the highest value is always preferred over others.

Depending on predefined evaluation criterions, these quality characteristics are used in the analysis of experimental results.

There are five main steps (phases) in this approach. These are experiment planning, designing, conducting, analyzing, and confirming predicted results. Experiment planning is the most valuable phase that determines the success of experimentation projects. Trial and error scheme (the old approach) should be avoided through proper planning of experiments (Roy, 2001).

3.4.2. Cementitious grout mixture Design using the Taguchi approach

Step-1: Experimental plan

The aim of this experimentation is finding out the optimum grout formulation (mixture proportions) that produces highly flowable grout with high strength. The ingredients considered in this design are cement, silica sand, bagasse ash filler, megaflowSP1, and water. Determining the amount of these materials for overall best performance condition requires combining multiple performance evaluation criteria.

In Taguchi approach, an Overall evaluation criterion (OEC) is defined by combining individual evaluation criteria through their relative weight. The relative weight of each individual criteria is determined through team discussion based their relative influence or importance (Roy, 2001). For this case, it is decided to use five evaluation criterion and their relative weights as shown in the Table below.

Table 9: Individual evaluation criteria definition and their relative weights

Item no.	Evaluation criteria	Quality characteristics		Relative weight
		Description	Designation	
1	Bleeding	Smaller is better	QC=S	20
2	Marsh cone viscosity	Nominal is best	QC=N, N=9 sec	20
3	Bulk specific gravity	Bigger is better	QC=B	10
4	Compressive strength	Bigger is better	QC=B	25
5	Rupture modulus	Bigger is better	QC=B	25
Total				100

Previous studies showed that the success of grouted macadam primarily dependent on the flowability of cementitious grout. As measured with 10mm orifice Marsh cone funnel, for 1000ml grout a time efflux of 8-10 seconds is recommended (UFGS, 2008). Anderton (2000) proposed and used a grout formulation with Marsh cone viscosity of 9 seconds, for studying other performance of grout. That is why it is given a target value of 9 seconds. It is given equal weight for both fresh state tests and hardened state performance testing of grout mixtures.

Step-2: Experimental Design

Generally, factors are the ingredients that the system requires to produce the intended objectives. However, factors considered in the design of experiments (DOE) are those included in the investigation which might be because of their direct influence on the output. The factors that are required to be controlled by the experimenter are said to be control factors. Whereas those factors that are not included in the study or if they are uncontrollable by the experimenter, they are considered to be as a fixed components in the system.

Control Factors

Experiments involving a higher number of factors and factor level might be expensive, but produces a bulk of information which is useful for the design. So, determining the number of factors and factor levels requires a trade-off between the amount of information to be gathered and experimental costs (Roy, 2001). So, the number of factors and factor levels are to be established.

LABORATORY STUDY ON THE MIXTURE DESIGN OF GROUTED MACADAM

In many cement concrete mix designs, water is calculated as a function of cement or cementitious material (Kosmatka and Wilson, 2003). Since this study involves the design of flowable grout, and the bagasse ash has high liquid limit value, it is decided to consider water to binder (cement+bagasse ash) as one factor. Based on preliminary mixes involving bagasse ash, water to binder ratio of 0.8, 0.85, and 0.9 is proposed. By considering cement as the basic material, fine sand and bagasse ash are included by replacing cement each at 0%, 10%, and 20%. In so doing constant weight of dry solids is maintained in all the experimental runs. Based on previous studies conducted on similar superplasticizer, the level values of megaflow SP1 is determined to be 0%, 1.5% and 2.5% as a percentage of binder. So, water to binder ratio, silica sand, bagasse ash and megaflow SP1 content are the control factors considered in the design of cementitious grout.

Table 10: Factors and their levels for the orthogonal array development

Factors		Level		
Name	Designation	1	2	3
Water to binder (W/B) ratio	A	0.8	0.85	0.90
Sand content by wt. of cement replacement	B	0	10	20
B. ash content by wt. of cement replacement	C	0	10	20
M. SP1% by wt. of binder	D	0	1.5	2.5

Note 1) Binder, in this case, the sum of cement and bagasse ash content

2) A constant weight of dry solids (Cement + silica sand + bagasse ash filler) is considered throughout the study.

As shown in the above Table, there are four factors ($f=4$), each of them has three level values ($n=3$). In order to study the effect of one factor at a time, the full factorial combination can be used. But, it requires $81(3^4=3*3*3*3)$ possible combinations which might lead to expensive experimentation. On the other hand, Taguchi approach has several orthogonal arrays (OA) depending on the number of factors and factor levels. These arrays are designed with the objective of reducing the number of combinations. These are usually designated by notation L and a subscript, which indicates the number of combinations that will be prescribed (Roy, 2001). They are part of a set of arrays which can be used to lay out the experiment following the Taguchi method. For this particular case of four factor with three levels, the standard arrays $L_9(3^4)$ is selected.

The subscript 9 implies that only nine experimental runs are required to be investigated. The test results of these runs (trials) are to be used in determining the best combination that results in a grout with overall best performance. This is the primary advantage of DOE using the Taguchi approach as compared to the full factorial DOE. The detailed layout of factor`s level combination is presented in Table 11 shown below.

Table 11: Standard orthogonal array $L_9(3^4)$ with factor level assignment

Experimental run (E.R.#)	Factors			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

As shown in the Table above, the columns of the array correspond to the factors, each one containing the three levels determined for the factor, while the rows represent the experimental combinations with the factor levels to be tested. Each level of a given factor is represented equally in that column.

Because of time and other constraints, two mixing operations per experimental run are planned. These mixes are designated by mix1 and 2.

Others factors

In order to minimize the variations as a result of unseen factors, efficient mixing equipment & consistent operations (order of adding ingredients, mixing procedure, and order of grout sampling for tests, and curing condition) are considered during experimentation. Thus, an electrically driven mixer which was designed for blending paints and stainless mixing bowl are purchased from a local market called Piassa. Moreover, Marsh cone funnel is also made from galvanized steel sheets in consultation professionals in the area. These materials are shown in Figure below.



Figure 9: Photos of mixing bowl & its cover lid, mixing paddle, electric driven mixer and Marsh cone funnel

Step-3: Conduct the experiments

Once experiments are designed, no more change is allowed on factors or factor level values. Experimentation is carried out by arranging experimental runs in random order. In this case, experimentation is carried out in the order of experimental run number 3, 5, 1, 7, 9, 2, 8, 4, and 6.

A similar method of mixing and order of sampling of grout as specified in ASTM C-938 is followed except some modifications.

Mixing procedure:-

- ✚ Bagasse ash, cement, and silica sand in this order are weighed & added for dry mixing in an air-tight container. Then dry mixed for one minute.
- ✚ Mixing water is weighed and added to the mixing bowl in the first place. Similarly, megaflow SP1 is added on to the mixing water as prescribed by the manufacturer.
- ✚ Then dry mixed solids are added into the mixing bowl. Finally, these ingredients are mixed at the rotational speed of 300 rpm for about 5 minutes (UFGS, 2008).

Order of sampling of grout for tests

Immediately after mixing, the samples for Marsh cone viscosity, bleeding, & bulk specific gravity tests are taken from both mixing operations, respectively. At last, nine grout cubes for compressive strength test are casted using grout from mix 1. Similarly, three grout beams for flexural strength test is casted by taking grout samples from mix 2. While taking samples, grout is continuously stirred and agitated. Thus, for the nine experimental runs each with two mixing replications, therefore a total of 18 mixing operations are performed. A total of 83 cubes is casted for compressive strength test at age of 3rd, 7th and 28th day of air curing while 27 beams are casted for rupture modulus testing at age of 28th day of air curing.

Step-4: Analysis the results

In Taguchi approach two analysis options are available. These are the standard analysis and signal to noise ratios (S/N) analysis. In the standard analysis, the mean result of each experimental run is to be calculated and then used in the optimization. Whereas in the signal to noise ratios (S/N) analysis, hereafter it is called the S/N analysis, uses the signal to noise ratios of experimental results. In the S/N analysis, first, the mean square deviation (MSD) of the results in each experimental run is calculated. It is dependent on the quality characteristic (QC) of evaluation criteria defined in the planning phase. It is calculated as follows (Roy, 2001):

i) For smaller is better (QC=S), $MSD = \frac{\sum_{i=1}^n (Y_i^2)}{n}$(3.1)

ii) For nominal is best (QC=N), $MSD = \frac{\sum_{i=1}^n (Y_i - Y_0)^2}{n}$(3.2)

iii) For larger is better (QC=B), $MSD = \frac{\sum_{i=1}^n (1/(Y_i^2))}{n}$(3.3)

Where MSD is the average of the square of deviations of the results (Y_i) per experimental run, n is the number of replications in an experimental run. In the case of QC=N, the Y₀ is the target value specified in the planning step.

Since, the mean square deviation, hereafter called MSD is always required to be small, i.e. its quality characteristic is the smaller is better, hereafter designated by $QC=S$. Now comparing among experimental run is possible. However, for linearity purpose, and to accommodate a wide range of data, the logarithmic transformation of MSD called signal to noise(S/N) ratio can be used. As it is shown in equation (3.4) below, for changing the quality characteristic from $QC=S$ to $QC=B$, a negative sign with a multiplying factor of 10 is introduced (Roy, 2001).

$$\frac{S}{N} = -10\log(\text{MSD})\dots\dots\dots(3.4)$$

Where: S/N=signal to noise ratio,

MSD= mean of the square of deviations of results per trial run

In fact, Taguchi approach focuses primarily on the main effects of the factors. The main effects of factors are also called factor average effects (Roy, 2001). In order to know the main effects of factors, first, either S/N value or mean value (arithmetic average) of results per trial combination is determined. Then the factor average effect at each factor level is determined by considering the mean value of the trial (experimental run) which contain that factor level. Then the trend of influence of a selected factor can be seen by plotting the factor average effects (main effects) versus factor level values. It is known to be the plot of main effects. If the factors all behave independent of each other, the trend of influence may not change no matter which another factor it is with. However, factors will have some kind of interaction with other factors that are included in the experiments. If the trend of influence of factor changes from expected or changes from increasing trend to decreasing abruptly then it is because of interactive effect among factors (Roy, 2001).

It is important to recognize that this phase of the research is devoted to optimization study. Hence, studying individual factor effect and factor interaction is not of interest. For each quality evaluation criteria, it is possible to determine the contribution of each factor, optimum condition (combination), expected response (prediction of performance is performed), etc. (Roy, 2001).

Step-5: Conduct confirmation testing at optimum proportions of control factors

Whenever required additional confirmation tests with the factor combinations at the optimum condition need to be conducted in order to compare the results with the predicted performance values (Roy, 2001).

3.4.3. Evaluation tests and measurements on the grout mixtures

Bleeding

Bleeding is a form of segregation in which some of the water in the mix tends to rise to the surface of freshly placed mixtures. It is the possible cause for the weak layers in the concrete (Neville and Brooks, 2010).

The objective of this test is to examine the fresh consistency of grout in terms of its stability with respect to time. In accordance with ASTM C-940, however using 250ml graduated cylinder, a 200ml grout is poured into it. In order to prevent loss of bleed water, it was covered with a polyethylene sheet and kept on the non-vibrating table. Readings were taken every 15minutes for the first hour and then afterward hourly for two hours from mixing time. It should be noted that the top layer of water with fine suspended particles is taken as a bleed in this study. The height of this top layer as a percentage of original grout height is calculated and accordingly reported in percent.

Marsh cone viscosity

Marsh cone viscosity test is the test conducted to study the fluid consistency of grout (Pei et al., 2016 and Zhang et al., 2016). The Marsh cone funnel and the testing procedures that were suggested by Anderton (2000) are found to be appropriate for this study. Marsh cone funnel is prepared in accordance with the dimensions recommended by Anderton (2000), which are shown in Figure 10 shown below. Then, it is calibrated by water in which the time of flow for 1 liter of water is 6 seconds. The procedure is blocking the flow cone outlet by simply placing one's finger over the outlet opening, then pouring about 1100 to 1200ml of grout into the Marsh cone funnel as shown in Figure 11 below. Finally, the opening outlet is released and stopwatch timer is started simultaneously. The time of flow for 1 liter of grout from the flow cone is recorded (Anderton, 2000; UFGS, 2008).

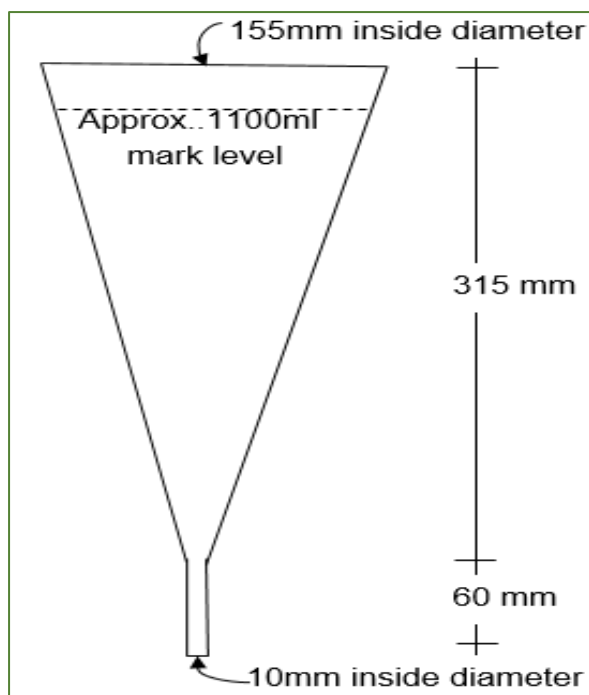


Figure 10: Dimension of Marsh cone funnel as suggested by Anderton (2000)



Figure 11: Cementitious grout being poured into Marsh cone funnel

Bulk Specific gravity

It is included in the evaluation because the mix design is batching by weight and the difference in specific gravity of cement and bagasse ash is about 1.02 (3.15 - 2.13). When cement is replaced by bagasse ash, this difference is found to be significant in volumetric measurements. After the grout is mixed, poured into a container of known volume, tapped inside lightly five times a tapping stick, and finally, its weight is taken in accordance with ASTM C-185. Similarly, water is poured into this container and mass is recorded. For the same volume, dividing mass of grout by mass of water can give a bulk specific gravity of grout.

Compressive Strength of grout

In order to investigate the strength development of grout over time, compressive strength testing is performed at 3rd, 7th and 28th days of curing age. Before the mixing operation started, the mold elements are cleaned, joined and firmly bolted by keeping square ends. In order to prevent leakage of grout, the joints are filled with grease, and finally, internal space painted internal by releasing agent.

Then the grout is prepared and poured to cells of 50*50*50mm steel molds in two layers where each layer was tamped 25 times and finally leveled with a trowel. After two days of curing in a mold, each grout cube is demoulded, labeled, given a date of manufacture and placed in ambient room conditions to represent the worst curing condition. Then for each curing time, the specimens were measured for dimensions, weighed and crushed using compressive strength testing machine at an increasing compression rate to 3kN/s. Finally, the failure load is recorded. Compressive strength is calculated by dividing this failure load by the specimen cross-sectional area.

Rupture modulus test

It is also known as flexural strength test in which it is used to determine the tensile strength of a given material. For preparing grout beams, the procedures from mixing to grout curing, used in compressive strength are repeated here, however with a mold size of 40X40X160mm. These beams are air cured to the 28th day of age. At this age, the beams are measured for dimensions and weight. Then after, they are subjected to flexural load by using the Chinese electric flexure testing machine called DKZ-5000. In this case, as shown in Figure 12(a), it is a single lever arm (1:10 ratio) type, in which it has scales to read failure load as well as corresponding rupture modulus. Just at the instant of the specimen failure, rupture modulus value is recorded.



(a) Loading arm is raised to 1:10 (b) beam is inserted (c) beam after failure

Figure 12: Rupture modulus apparatus used in the study

3.5. Experimental Phase II

3.5.1. Selection of aggregate gradation

As shown in the literature review, resin modified pavement (RMP) specification is well documented, and construction projects designed to this specification are evaluated and reported to be in good performance. Hence, the aggregate gradation for porous asphalt mix preparation is selected to be the midpoint of RMP specification (UFGS, 2008). As shown in the Figure below, except for a sieve size less than 600 μ m, it is also within 20mm single sized aggregate gradation for porous asphalt surface course specification of British Standard (BS4987-2-2001).

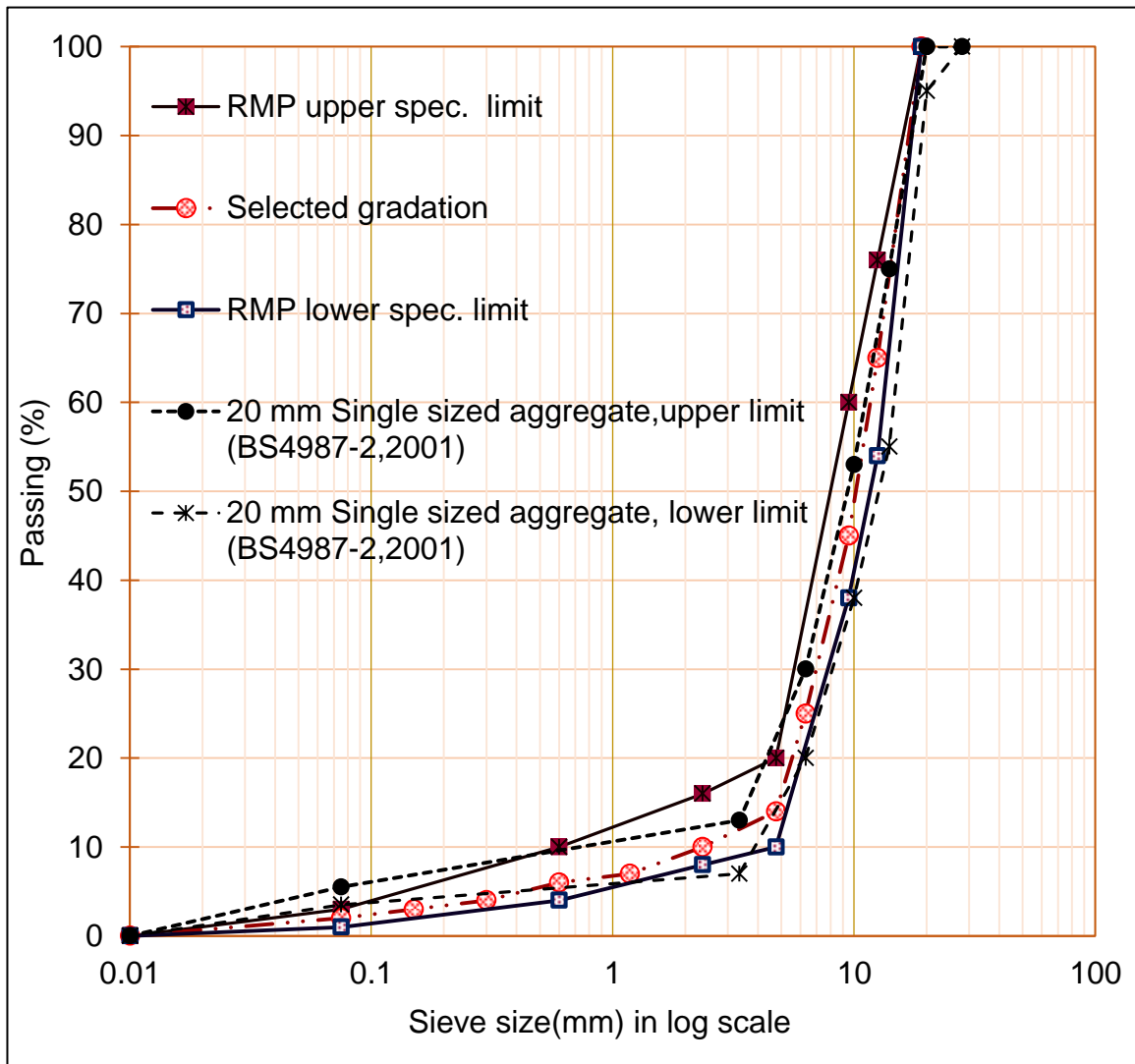


Figure 13: The selected aggregate gradation with respect to specifications

3.5.2. Estimation of design bitumen Content

Frist, the apparent specific gravity of the combined aggregates representing the aggregate blend of the selected gradation is determined. The apparent specific gravity of the aggregate blend is calculated as follows (Asphalt Institute, 1995).

$$G_{sb} = \frac{100}{\frac{P_1}{G_1} + \frac{P_2}{G_2} + \dots + \frac{P_n}{G_n}} \dots\dots\dots(3.5)$$

Where: G_{sb} = Apparent specific gravity of aggregate blend
 P_1, P_2, \dots, P_n = Respective percentages of aggregate stockpiles 1, 2, etc.
 G_1, G_2, \dots, G_n = Respective apparent specific gravity of aggregate stockpiles 1, 2, etc.

As summarized in Table 7, the coarse aggregate and fine aggregates including fillers have an apparent specific gravity of 2.73 and 2.70, respectively. From the selected gradation shown above, the coarse aggregate is 86 percent by weight of the combined aggregate. The specific gravity of this aggregate blend, G_{sb} is as follows:

$$G_{sb} = \frac{100}{\frac{86}{2.73} + \frac{14}{2.70}} = 2.726$$

Then the optimum bitumen content (OBC) is estimated using equation (2.1) as follows: $OBC=3.25(\alpha)\Sigma^{0.2}$;Where: $\alpha= 2.65/G_{sb}$;

G_{sb} = apparent specific gravity of aggregate blend; $G_{sb}=2.726$

Σ = conventional specific surface area = $0.21G + 5.4S + 7.2s + 135f$;

G = percentage of material retained on 4.75 mm sieve= $35+20+20+11=86\%$

S = percentage of material passing 4.75 mm sieve and retained on 600 μ m sieve;
 $S=14-6=8\%$

s = percentage of material passing 600 μ m sieve and retained on 75 μ m sieve;
 $s=6-2=4\%$

f = percentage of material passing 75 μ m sieve, $f=2\%$

i.e. $\alpha= 2.65/2.726=0.972$; $\Sigma=0.21G + 5.4S + 7.2s + 135f$

$$\Sigma = 0.21*0.86+5.4*0.08+7.2*0.04+135*0.02=3.6$$

$$OBC=3.25(\alpha)\Sigma^{0.2}=3.25*0.972*(3.6)^{0.2} ;$$

OBC=4.08%

3.5.3. Marshal Method of Specimen Preparation

Ahlich and Anderton have conducted a study by varying the number of blows of compaction in order to determine the proper laboratory compactive effort to the USA practices. This study showed that the 25 blows applied to only one side of the specimens are found to be an appropriate compaction effort to produce air voids contents in the range of 25 to 30 percent. This compaction effort is validated by the Waterway Experiment Station (WES) laboratories (Ahlich and Anderton, 1991).

In this research, the estimated optimum asphalt content is used along with one asphalt contents above this value and two asphalt contents below this value to produce hot mix samples in the laboratory. These bitumen contents are 3.1, 3.6, 4.1, and 4.6% by weight of total mixture. Using these bitumen contents and the aggregate gradation, the dried & sieved individual aggregate batches are blended through weight measurement, and the blend is heated in an oven at 150 °C. Similarly, the bitumen is preheated to 160 °C. Then the heated aggregates and heated bitumen are blended in a mechanical mixer for approximately 35 sec to thoroughly coat all aggregate with the bitumen. Immediately after mixing, compacted specimens are prepared by applying 25 blows of 4.5 kg marshal compaction hammer to one side of the specimen as suggested by Anderton (2000). These specimens are allowed to cool in the moulds for overnight. Then after, they are extracted from molds. Each specimen's height and dry weight in air are measured and used in the calculation of air voids content.

3.5.4. Density –void relationship of porous asphalt concrete

In this study, 101.6mm diameter specimens were prepared using 25 blows compactive effort to one side only. The specimens were air-cured for more than 8 hours in the mold and then carefully extracted from the molds. In accordance with ASTM D3549, height measurements are taken and averaged. Similarly, diameters of the specimens are measured and averaged. According to ASTM D3203, bulk densities of compacted open bituminous are calculated using its dry mass (in grams) and its volume (in cubic centimeters).

The density of water can be round off to 1.0; therefore bulk specific gravity of compacted mixtures (G_{mb}) is taken to be its corresponding bulk density.

The maximum theoretical specific gravity test is performed for a bitumen content of 3.6% and 4.1% according to ASTM D 2041. Using each of these bitumen contents, the effective specific gravity of the aggregate is calculated and used for calculating maximum theoretical specific gravity for bitumen contents of 3.1% and 4.6%.

The effective specific gravity of aggregate (Asphalt Institute, 1995):

$$G_{se} = \frac{P_{mm} - P_b}{\frac{P_{mm}}{G_{mm}} - \frac{P_b}{G_b}} \dots\dots\dots(3.6)$$

Where:

G_{se} =effective specific gravity of aggregate

G_{mm} =maximum specific gravity (ASTM D 2041) of paving mixture (no air voids)

P_{mm} = percent by weight of total loose mixture, i.e. $P_{mm}=100$

P_b =asphalt content at which ASTM D 2041 test was performed, percent by total weight of mixtures.

G_b = specific gravity of asphalt

The asphalt absorption does not vary appreciably with variation in bitumen content (Asphalt Institute, 1995). It is as expected that the variation among calculated effective specific gravities is so small. So the maximum theoretical specific gravities for the other bitumen contents can be estimated as follows (Asphalt institute, 1995):

$$G_{mm} = \frac{P_{mm}}{\frac{P_s}{G_{se}} + \frac{P_b}{G_b}} \dots\dots\dots(3.7)$$

Where, G_{mm} = maximum specific gravity of paving mixture (no air voids)

P_{mm} = percent by weight of total loose mixture=100

P_s = aggregate content, percent by total weight of mixture

P_b = asphalt content, percent by total weight of mixture

G_{se} =effective specific gravity of aggregate

Air voids content is the total volume of air pockets between the coated aggregate particles throughout a compacted asphalt concrete mixture, expressed as percent of the bulk volume of the mixture (Asphalt Institute, 1995). For each compacted specimen, it is calculated as follows (Asphalt institute, 1994):

$$\text{Air voids, \%} = (G_{mm} - G_{mb}) * 100 \dots\dots\dots (3.8)$$

Where, G_{mm} = maximum theoretical specific gravity of loose mixture, determined in accordance with ASTM D 2041.

G_{mb} = bulk specific gravity of compacted mixture, i.e. $G_{mb} = W_{air} / \text{Volume}$

W_{air} = dry weight of specimen,

$$\text{Volume} = \pi * D^2 * H / 4;$$

Where: D and H are average specimen diameter & height, respectively.

3.5.5. Considerations in the selection of optimum binder content

According to Anderton (2000), a bitumen content that corresponds to an air void content of 30 is preferred in the laboratory design. A mixture designed with air voids content more close to the upper limit of specifications might ensure impregnation of cementitious grout during field construction (Anderton, 2000; Olivera et al, 2008).

Another important consideration is binder drainage. Because the open-graded paving mixtures have large air pockets, the bitumen binder with fillers drain-off through the aggregate skeleton. In this study, significant binder drainage was observed at a bitumen content of 4.1 and 4.6%. When the bitumen contents decreased down to 3.6% & 3.1%, the binder drainage becomes negligible. At bitumen contents of 3.1% and 3.6%, the coating of the aggregates in the mixes is checked visually. The aggregates are fully coated with sufficient bitumen film thickness.

3.6. Experimental Phase III

3.6.1. Grouting ability of cementitious grout

For this phase of the study, proposed design mixture proportions from phase I & II are used. In order to check grouting ability of cementitious grout in the porous specimens, compacted specimens of 101.6mm in diameter and with a target height of 65mm are prepared using 3.1% and 3.6% bitumen content. These specimens are allowed to cool in the moulds for overnight. Keeping these specimens in the moulds, the bottoms of these moulds are firmly covered with plastic tape as to prevent leakage of grout. While specimens are in the molds, cementitious grout is prepared and applied to them. The grout has infiltrated down by the gravity action. After three days of air curing in the moulds, the specimens are extruded. As it is seen in the Figure shown below, the depth of penetration & coverage by the grout is examined visually.



Figure 14: Typical grouted macadam specimen immediately after extrusion

3.6.2. Marshal Stability flow test

This test is performed in accordance with Marshal Method of mixture design. For this test, grouted macadam specimens are prepared and allowed to be air-cured for 3 days, and corresponding maternal porous mixtures are also prepared. After measuring the average diameter, height and weight, the specimens are immersed in a water bath at $60\text{ }^{\circ}\text{C} \pm 1^{\circ}\text{C}$ for 35 ± 5 minutes. Porous compacted specimens are placed on a tray in the bath. Each specimen is then removed from the bath and tested on a Marshall crushing apparatus to determine the stability and flow values.

3.6.3. Indirect tensile strength test

In order to estimate the strength of pavements, so far different testing approaches being used. These are compressive strength, indirect tensile strength, flexural strength, split tensile strength and others are commonly practiced. In rigid pavement design, the tensile or flexural strengths are the critical properties that characterize the cement bound materials, as the traffic loading conditions may cause a tensile failure before compressive failure (Setyawan, 2013). Surfacing materials such as resin modified pavement materials are generally much stronger in compression than in tension. Knowing tensile strength is so important (Anderton, 2000). Generally, grouted macadam possesses mechanical properties in between bituminous mixtures and Cement concrete (Setyawan, 2013).

In this study, indirect tensile strength testing approach is preferred for estimating tensile strength. Test temperatures of 25 °C and 40 °C are selected to simulate moderate and hot pavement temperatures, respectively. Grouted macadam specimens that were prepared with 3.1% and 3.6% bitumen contents are air-cured for 28 days. Similarly, fresh porous asphalt concrete specimens at these bitumen contents are prepared for the test as a control. The specimens were conditioned at the respective temperatures for 24 hours in the oven. The test is done by placing a cylindrical specimen horizontally between two loading plates and by applying vertical load on the specimen across its diameter until failure. The test needs to be completed within two minutes from which the specimens are out from the oven. The vertical load is applied in such a way that it produces a constant deformation rate of 50 mm per minute. The ultimate load is recorded at failure and is used to calculate tensile strength with the following equation (Anderton, 2000):

$$TS = 2P / \pi TD \dots \dots \dots (3.9)$$

Where:

- TS = tensile strength, Pa
- P = ultimate load required to fail specimen, N
- T = thickness of specimen, m
- D = diameter of specimen, m

3.6.4 Analysis approach of the test results

First of all, the average of Marshal Stability test results is determined for grouted macadam specimens as well as for maternal porous asphalt concrete specimens that are made of bitumen contents of 3.1% and 3.6%, respectively. Then as compared to maternal control specimens, the percent increase of stability as a result of grout application is determined. Similarly, using indirect tensile strength test results, the percent increase of tensile strength as a result of grouting is calculated in comparison with maternal porous specimens.

For the objective of evaluating the effect of bitumen content and choosing the design bitumen content based on the performance of grouted macadams, a statistical analysis is required. Therefore, the sample means of Marshal Stability of grouted macadams that are calculated based on the two bitumen contents are to be tested for the following hypotheses with a significance level of 0.05. These are: The two sample means equal (null hypothesis, H_0), or the means are different (alternative hypothesis, H_1).

More clearly,

- H_0 : As the bitumen content of grouted macadam decreased from 3.6% to 3.1%, the difference in stability of grouted macadam is insignificant.
- H_1 : This difference is significant

The two sample t-test is done with help of Minitab Software. The test significance level (α) of 0.05 is compared with the P-value which is the out from Minitab Software. In this case, the P-value is defined as the smallest significance level that would lead to rejection of the null hypothesis (H_0) with the given data (Montgomery and Runger, 2003). Similarly, it is done for indirect tensile strength result for both test temperatures as well.

Finally, for the selected aggregate quality and gradation, the design bitumen content for semi-flexible pavement application is proposed.

4. LABORATORY TEST RESULTS, ANALYSIS AND DISCUSSION

4.1. Test Results, Analysis and Discussion on Experimental Phase I

In this phase, cementitious grout mixture is designed using the Taguchi approach. The five performance properties namely bleeding, Marsh cone viscosity, bulk specific gravity, the compressive strength and rupture modulus at 28th day of curing age are taken as individual evaluation criteria. For each of these evaluation criteria, average factor effects (main effects) is calculated and plotted as a function of factor level value. As this plot shows the nature of the trend of influence of the factor to the result, it is used primarily in the selection of a level value (from among those levels included) of the factor under consideration. Based on the average results, the optimal combination of factor level is determined for each of individual evaluation criteria. Finally, optimal combination for overall best performance is determined by normalizing and combining individual criterion test results in indexed overall evaluation criteria (OEC) results. The details of the test results of each performance criteria are given in Appendix 2.1.

4.1.1. Determination of optimal condition for individual evaluation criteria

Determining the optimum combination of factor levels for each criterion may be important for knowing of the role of ingredients that are used in the grout. Also, the compatibility of the level values can be evaluated.

Optimal condition for bleeding criteria

For each experimental run, two similar mixing operations have been performed and then bleeding test is carried out by taking samples from each mixing operations. Based on these sample test results, an average result is calculated for each experimental run. These average results are shown in Figure 15 shown below. Among the nine experimental runs (combinations), experimental runs 3, 5, 7, and 9 are found to stable grouts as they are at & below the maximum bleeding requirement of 5 % (Lombardi, 1985). Whereas experimental runs 1, 6, and 8 are those with an extremely high value of bleeding. Experimental run 1 grout showed a clear water level as cement particles settled.

While calculating average factor effect, the interaction between factors is observed. Studying interactive effect is not of interest.

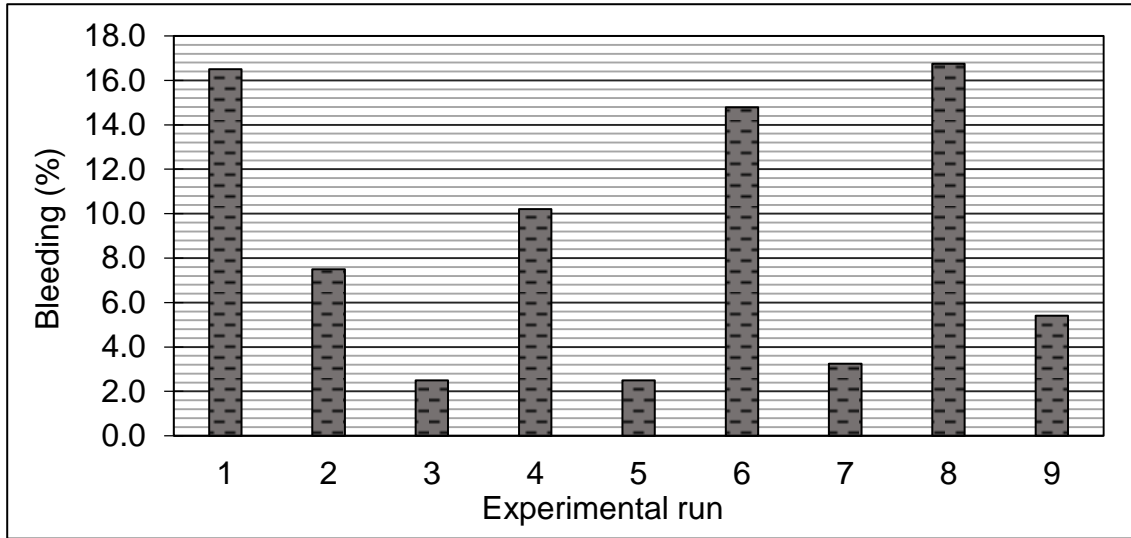


Figure 15: Average result of bleeding test per experimental run

Thus, the average effects of a factor are calculated by neglecting extreme values associated with interactions. The calculated average factor effects are plotted as a function of corresponding factor levels, which is shown in Figure 16 below. This plot is important for visual interpretation of main effects of factors. As it can be seen in Figure 16 above, bagasse ash is found to have the largest contribution in reducing bleeding. Whereas, megaflow SP1 and water to binder (W/B) ratio have an increasing effect. In the planning stage, the quality characteristic of bleeding is defined to be $QC=S$.

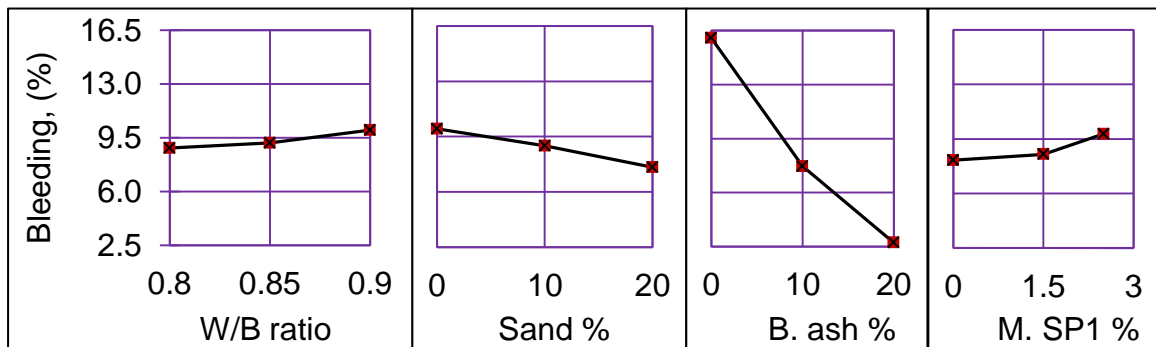


Figure 16: Trend of influence of factors on the bleeding of grout

As it seen in Figure shown above, the minimum bleeding will be observed when water to binder ratio of 0.8, sand content of 20% and bagasse ash content of 20% replacement by weight of cement, and megaflow SP1 content of 0% by weight of the binder.

Optimal condition for Marsh cone viscosity criteria

Similarly, average results of Marsh cone viscosity test is plotted as a function of the experimental run which is shown in Figure below. The desired range of Marsh cone viscosity is 8-10 seconds as recommended by Anderton (2000). As compared to the target 9 seconds, the factor level combination under experimental run 2, 7 and 9 are in close range to this target. As it can be seen in Figure 17, the factor combinations under experimental run 3 and 5 are found to have extremely high viscosity time of 35 sec and 39 sec, respectively. Upon analysis and review of the orthogonal array, these extreme values are because of bagasse ash with 20% replacement by weight of cement.

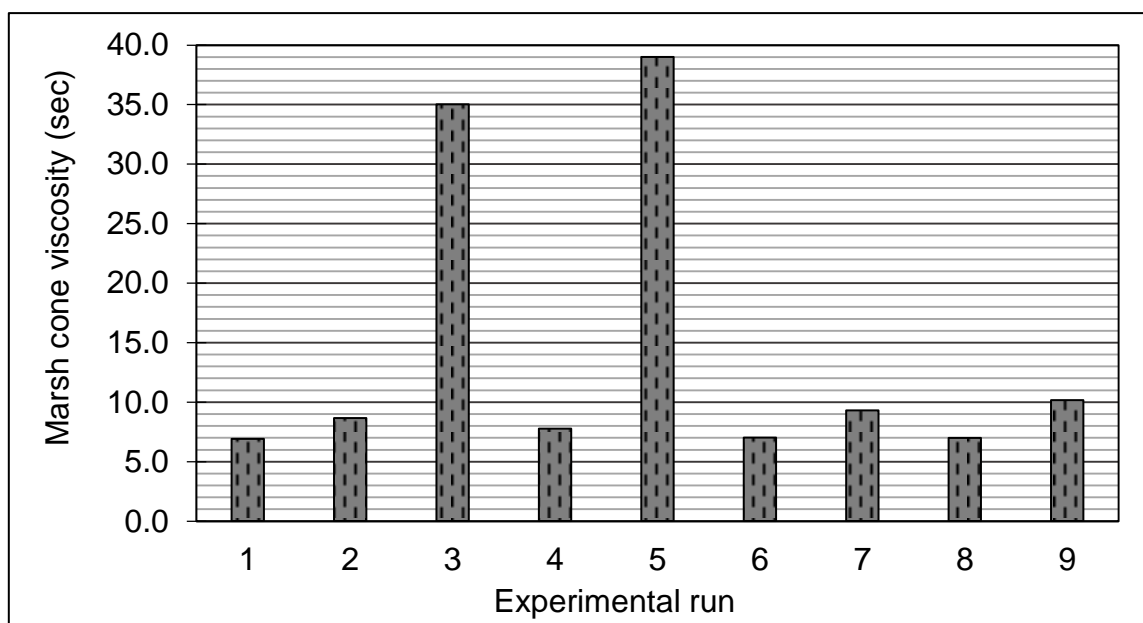


Figure 17: Average result of Marsh cone viscosity test per experimental run

Marsh cone viscosity is predominantly affected by bagasse ash. Whereas other factors behaving differently as their level values change. This is can be seen in the Figure below. It can be concluded that there is interactive effect between factors. As the objective is to determine the optimum combination of factor levels for the Marsh cone viscosity criteria, therefore studying factor interactions are not of interest. However, there is interaction among factors; it is possible to select the combination that results in a target Marsh cone viscosity of 9 seconds. This target is marked by the broken arrow in Figure 18 below.

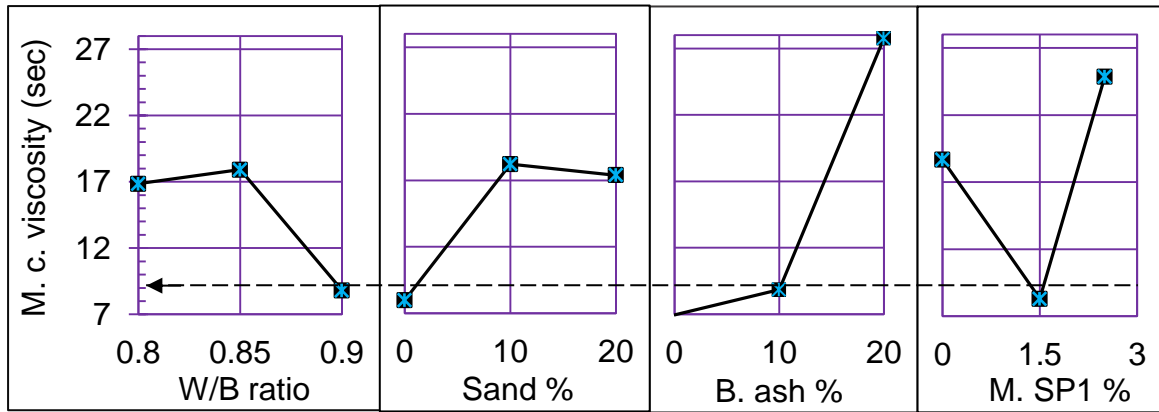


Figure 18: Trend of influence of factors on the Marsh cone viscosity

Hence, the optimal condition for Marsh cone viscosity with $QC=9$ seconds is determined by seeing the level value that resulted in main effect close to 9 seconds. In so doing, the water to binder ratio of 0.9, sand replacement of 0% and bagasse ash replacement of 10% by weight of cement, and megaflow SP1 with 1.5% by weight of the binder is found to be the optimal condition.

Optimal condition for bulk specific gravity

Bulk specific gravity is also the fresh state measurement which is carried out immediately after mixing. Because bagasse ash is light weight as compared to sand and cement, the partial replacement of cement by bagasse ash results in different volumetric properties of grout. For this reason, bulk specific gravity is considered as one performance criteria with $QC=B$. For each experimental run, two bulk specific gravity measurements are conducted on samples from the two mixing operations. The average of these measurements is presented in Figure shown below.

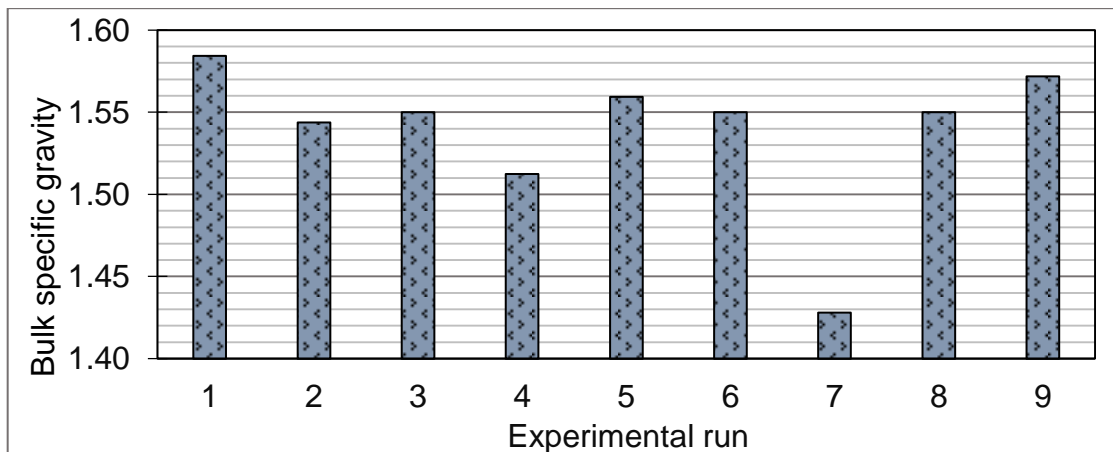


Figure 19: Average result of bulk specific gravity test per experimental run

As shown in Figure 20 below, the bulk specific gravity is found to decrease when water to binder ratio and bagasse ash contents have increased. Whereas it increased when sand content has increased.

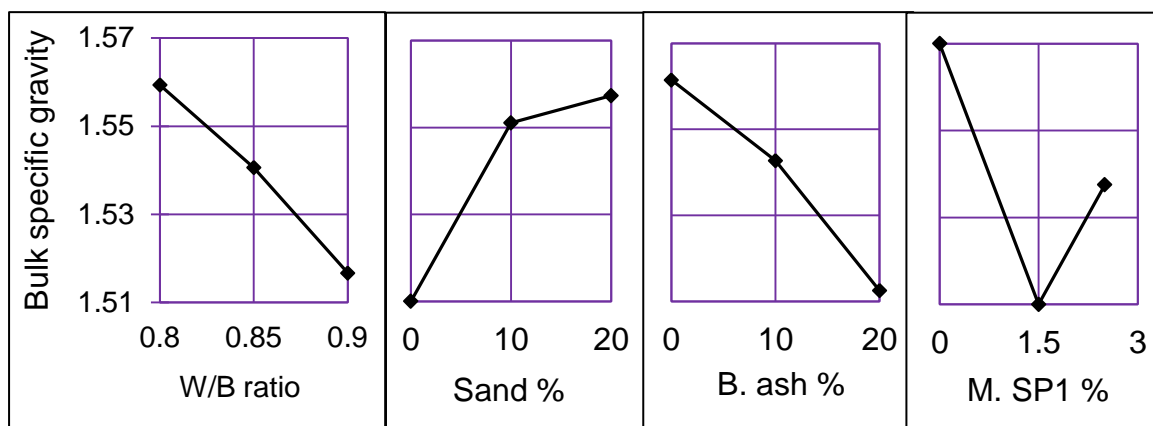


Figure 20: Trend of influence of factors on the bulk specific gravity

For $QC=B$ criteria of bulk specific gravity, the optimum combination is water to binder ratio of 0.8, the sand content of 20% and bagasse ash content of 0% replacement by weight of cement, and megaflow SP1 content of 0% by weight of the binder.

Optimal condition for compressive strength

To investigate the strength development of cementitious grout, 50X50X50 mm grout cubes casted for the 3rd, 7th and 28th day of compressive strength testing. These cubes are air cured at room temperature. At each test age, the cubes are subjected to a compressive load at an increasing loading rate to a maximum of 3kN/s. The detail of this test for each experimental run is provided in Appendix 2.1.

In order to determine optimal combination based on compressive strength criteria, the 28th day compressive strength test result is considered. For each experimental run, the average test results of compressive strength at 28th day of air curing are summarized as shown in Figure below.

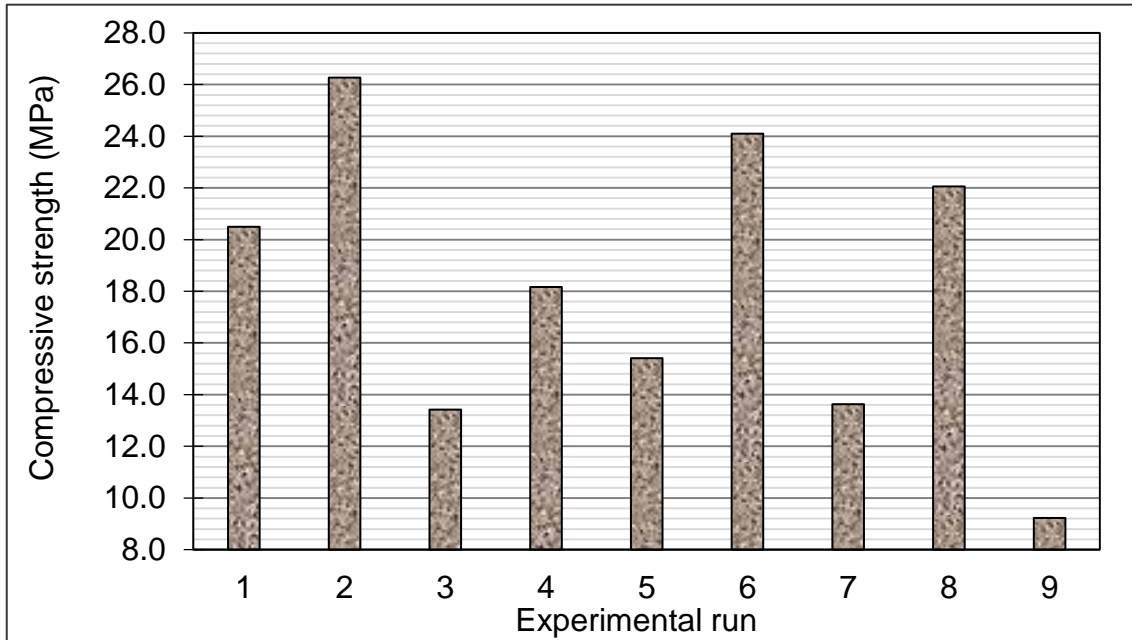


Figure 21: Average result of compressive strength test per experimental run

To select the optimal combination, the main effects of the factors are calculated and plotted as a function of corresponding factor level values. The quality characteristic (QC) defined for compressive strength is $QC=B$. It is easy to select the optimal level of any factor by looking for a maximum effect in the plot of main effects.

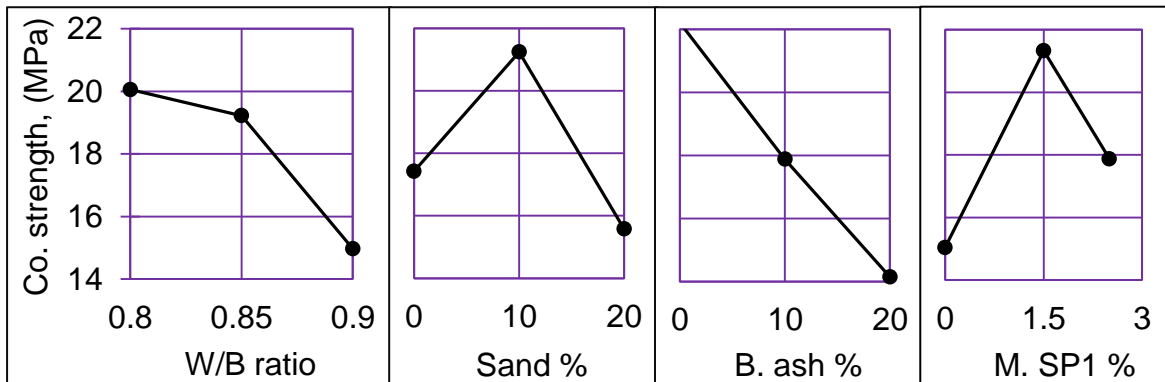


Figure 22: Influence of factors on the compressive strength

As seen in the Figure above, the optimal combination is when water to binder (W/B) ratio of 0.8, the sand content of 10% replacement by weight of cement, bagasse ash content of 0% replacement by weight of cement and megaflow SP1 of 1.5% by weight of the binder.

Optimal condition for rupture modulus

Tensile strength is also one of the performance criterion considered in the design of cementitious grout. For the nine experimental runs, a total of 27 grout beams with 40X40X160 mm dimensions are tested at the 28th day of air-curing age. The details of this test results are provided in Appendix 2.1. For each experimental run, the average of rupture modulus values is taken as shown in the Figure below.

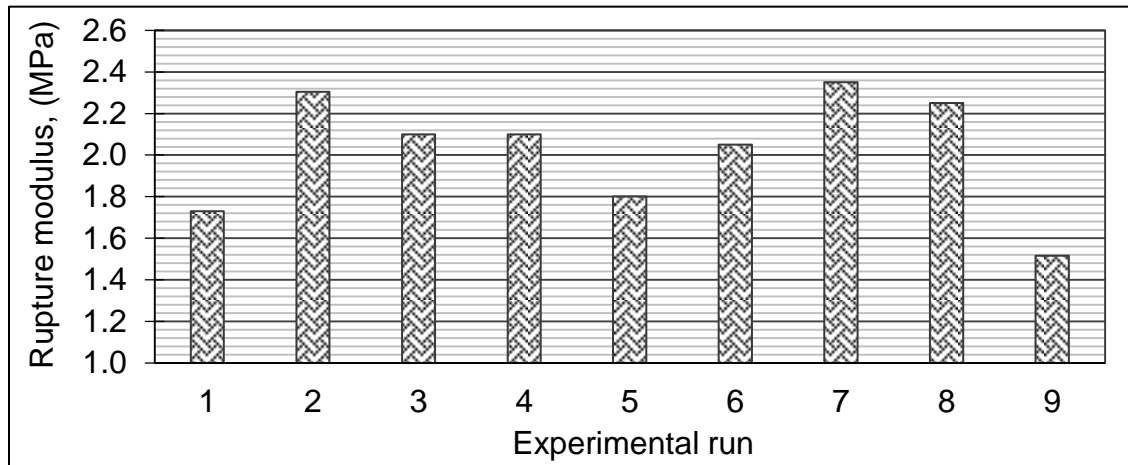


Figure 23: Average result of rupture modulus test per experimental run

Based on the average results shown in the Figure above, in comparison, the factor combination in experimental run 7,2,8 are found to have higher tensile strength values of 2.35, 2.30, 2.25 MPa, respectively. Similarly, average factor effects are determined and plotted as shown in Figure below.

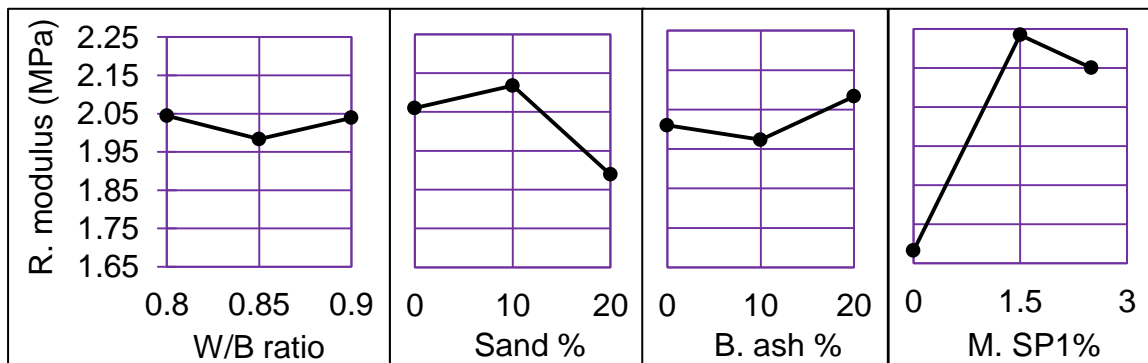


Figure 24: Influence of factors on the rupture modulus

For $QC=B$, the optimal combination of factor level values for rupture modulus is at the water to binder ratio of 0.8, the sand content of 10% replacement by weight of cement, bagasse ash content of 10% replacement by weight of cement, bagasse ash content of 20% and megaflow SP1 content of 1.5% by weight of the binder.

Summary of optimal condition for individual evaluation criteria

As presented in Table 12 shown below, analysis based different evaluation criterion led to a different combination of control factors. The desirable condition for a given criteria is not the desirable combination for the other evaluation criterion.

Table 12: Summary of optimum combination of factor levels for different criteria

Individual evaluation criteria	Factors & corresponding optimal level			
	A: Water to binder ratio	B: Silica sand, %	C: Bagasse ash, %	D: Megaflow SP1, %
Bleeding ($QC=S$)	0.8	20	20	0
Marsh cone viscosity ($QC=9$ sec)	0.9	0	10	1.5
Fresh bulk specific gravity ($QC=B$)	0.8	20	0	0
Compressive strength at 28 th day ($QC=B$)	0.8	10	0	1.5
Rupture modulus at 28 th day ($QC=B$)	0.8	10	20	1.5

The main objective is determining the optimal condition for the overall best performance of grout. It is determined in the section below.

4.1.2. Optimal condition for overall evaluation criteria

In order to optimize grout performance properties, the relative weight of each criterion is defined in the experimental planning stage. The average result of each performance test is used in this stage and the best result and worst result values are sorted out as shown in Table below.

Table 13: Overall evaluation (OEC) criteria definition and related details

Criteria no.	Individual evaluation criteria Name	Relative weight,		Best Result	Worst result
		Designation, R _j	%		
C ₁	Bleeding (QC=S)	W _{,1}	20	2.50	16.75
C ₂	Marsh cone viscosity (QC=N, N=9 Sec)	W _{,2}	20	9.00	39.00
C ₃	Bulk specific gravity (QC=B)	W _{,3}	10	1.58	1.43
C ₄	Compressive strength at 28 th day (QC=B)	W _{,4}	25	26.27	9.22
C ₅	Rupture modulus at 28 th day (QC=B)	W _{,5}	25	2.35	1.52
Total			100		

In order to convert the above five different evaluation criteria into a single indexed overall evaluation criterion (OEC), the following normalization technique, which is provided by Roy (2001) is adapted.

The normalization technique is as follows (Roy, 2001):

$$X_i = \left(\frac{|\text{Test result}(x),i - \text{Smaller of best or worst result}|}{|\text{Best result} - \text{Worst result}|} \right) \dots\dots\dots(4.1)$$

Where: (x) is the performance test result and X is the corresponding normalized test result, for a given experimental run (i). For a given performance criteria, the corresponding best and worst results are determined as discussed below.

For :

- i) QC=N, best result is the target value considered; whereas the worst result is the most deviant value from the target.
- ii) QS=S, best result is the smallest of the test result (performance reading); the worst result is the largest of all test results.
- iii) QC=B, best result is the largest of all results; whereas the worst reading is smallest of all the test results under a given criteria.

The best and worst result values are summarized in Table 13 shown above.

The normalized test result, X_i is unitless and can be combined with other normalized terms to form a single indexed overall evaluation criteria (OEC) result. The quality characteristic of OEC is defined to be the larger is better ($QC=B$). The normalization of the test result is important for combining different criterion and for changing other quality characteristics to $QC=B$.

For each experimental run (i), the normalization and conversion of other quality characteristic to $QC=B$ are done as follows:

$$\begin{aligned}
 OEC_j = & \left(1 - \frac{|\text{Bleeding result, } i - 2.50|}{|2.50 - 16.75|} \right) * w_1 + \\
 & \left(1 - \frac{|\text{M.c. viscosity result, } i - 9.0|}{|9.0 - 39.0|} \right) * w_2 + \\
 & \left(\frac{|\text{B. sp. gravity result, } i - 1.43|}{|1.58 - 1.43|} \right) * w_3 + \\
 & \left(\frac{|\text{Comp. strength result, } i - 9.22|}{|26.27 - 9.22|} \right) * w_4 + \\
 & \left(\frac{|\text{Rupture modulus result, } i - 1.52|}{|2.35 - 1.52|} \right) * w_5 \dots\dots\dots(4.2)
 \end{aligned}$$

Where: The number inserted in equation (4.2) are the best and worst result values summarized in Table 13 shown above for the respective criteria.

w_1, \dots, w_j are the relative weights in which the values are to be taken from this Table 13 shown above.

Using the test result of each experimental run, the indexed overall evaluation criteria (OEC) is calculated and summarized in Table 14 shown below.

A typical calculation for experimental run 1 using equation (4.2):

$$\begin{aligned}
 OEC_{,1} = & \left(1 - \frac{|16.5 - 2.50|}{|2.50 - 16.75|} \right) * 20 + \left(1 - \frac{|6.90 - 9.0|}{|9.0 - 39.0|} \right) * 20 + \left(\frac{|1.58 - 1.43|}{|1.58 - 1.43|} \right) * 10 + \\
 & \left(\frac{|20.49 - 9.22|}{|26.27 - 9.22|} \right) * 25 + \left(\frac{|1.73 - 1.52|}{|2.35 - 1.52|} \right) * 25
 \end{aligned}$$

$$\begin{aligned}
 OEC_{,1} = & (1-0.9824)*20+ (1-0.07)*20+1*10+0.661*25+0.253*25 \\
 = & 0.35+18.6+10+16.54+6.33 \\
 = & 52.10
 \end{aligned}$$

LABORATORY STUDY ON THE MIXTURE DESIGN OF GROUTED MACADAM

In a similar way, OEC for other experimental runs is calculated using spreadsheets. It is summarized in the Table shown below.

Table 14: Indexed OEC results per experimental run

Criteria no.	E.R.# 1	E.R.# 2	E.R.# 3	E.R.# 4	E.R.# 5	E.R.# 6	E.R.# 7	E.R.# 8	E.R.# 9
C ₁	16.50	7.50	2.50	10.21	2.50	14.79	3.25	16.75	5.40
C ₂	6.90	8.65	35.00	7.75	39.00	7.00	9.30	6.98	10.15
C ₃	1.58	1.54	1.55	1.51	1.56	1.55	1.43	1.55	1.57
C ₄	20.49	26.27	13.42	18.16	15.41	24.10	13.63	22.05	9.22
C ₅	1.73	2.30	2.10	2.10	1.80	2.05	2.35	2.25	1.52
OEC i	52.10	88.92	54.29	64.43	46.13	67.19	70.33	67.46	44.72

Note: C₁, C₂, C₃, C₄ and C₅ are the criteria number defined in Table 13.

By using the indexed OEC results as if they are experimental run results, average factor effect is calculated just like it is done for individual evaluation criteria. The plot of average factor effect is shown in the Figure below.

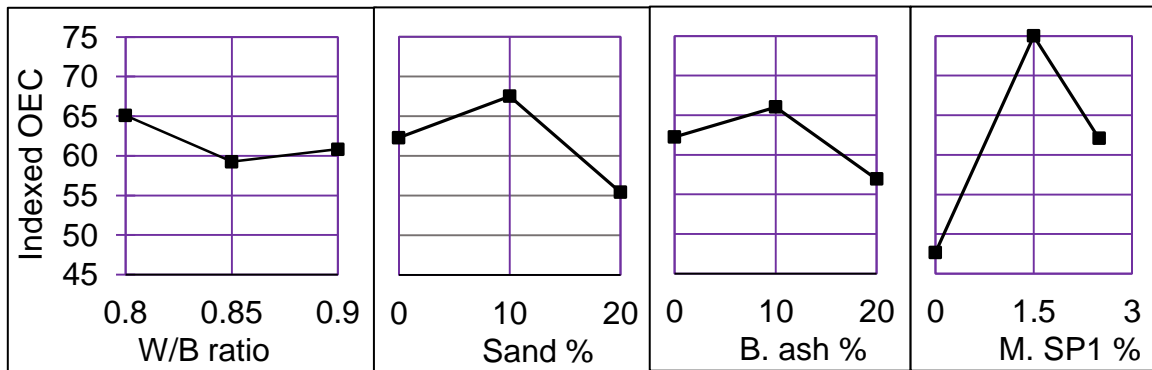


Figure 25: Plot of average factor effect for indexed OEC results

Therefore, based on the test results and the five evaluation criterion with defined relative weight, the combination for overall best performance is determined. As the quality characteristic of OEC is defined to be QC=B, the factor level that results in the larger effect is taken. As it can be seen in Figure above, water to binder ratio of 0.8, sand content of 10% replacement by weight of cement, bagasse ash content of 10% replacement by weight of cement and megaflow SP1 content of 1.5% by weight of binder is found to be the optimal combination for overall best performance of the grout.

By chance, it is the combination already tested under experimental run 2 (E.R. #2). Therefore confirmation tests are not required. As discussed earlier, the combination of factor levels under experimental run 2 is found to have an average bleeding value of 7.5%, Marsh cone viscosity of 8.65 seconds, bulk specific gravity of 1.54, 28th day compressive strength of 26.27 MPa and rupture modulus of 2.30 MPa. Except bleeding, other performance criterion are as desired. The bleeding is slightly higher than the maximum 5% recommended for stable grout. The strength development of this grout combination is plotted by taking an average of compressive strength test conducted at the 3rd, 7th, and 28th day of curing age. As it is provided in Appendix 2.1, these average compressive strength values are 6.11 MPa, 15.71 MPa, and 26.27 MPa for 3rd, 7th, and 28th days of curing age, respectively.

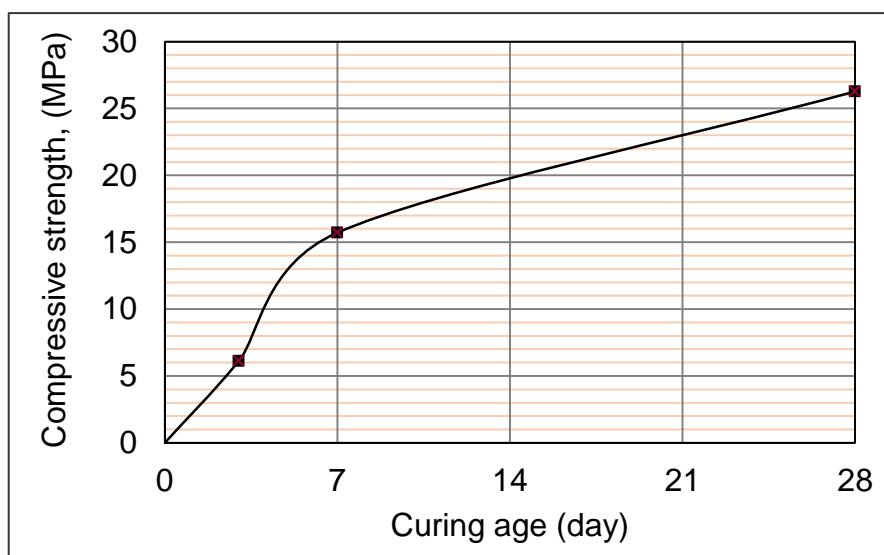


Figure 26: compressive strength development of grout mixture in exp. run 2

As it can be seen in the Figure above, the rate of strength gain is higher for the first seven days and then it is found decreasing for the rest of curing days. This result is entirely based on air-curing of grout cubes at room temperature. So, the combination of factor levels that are used in experimental run 2 can be taken as the optimum condition for overall evaluation criteria.

However, in order to reduce the bleeding of the grout, further adjustments can be made by studying the sensitivity of Marsh cone viscosity criteria to small variations of factor levels. This is discussed in the section below.

4.1.3. Adjustments on the factor levels based on the Marsh cone viscosity

Successful grouted macadam is obtained whenever the grout infiltrates down to the full depth of porous asphalt concrete. The depth of grout infiltration directly related to grout flowability as well as air voids content of the porous asphalt concrete. Grout flowability plays an important role in determining the effectiveness of grouted macadam. As a design requirement for grout mixtures, a flow time of 8-10 seconds is recommended by Anderton (2000) when it is measured by 10mm orifice Marsh cone funnel.

In the laboratory, it may be possible to control input mixtures as designed. However, this may not be the case in actual field practices where ingredients to be added in bulk. Any variation in input factors (ingredients) of grout might lead to variation in grout properties. At this stage, variations that might increase flow value are assessed based on the Marsh cone viscosity.

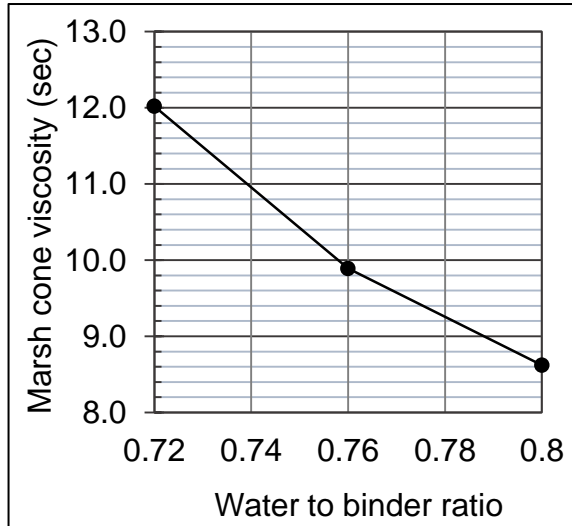
As compared to optimum condition (water to binder ratio of 0.8, sand content of 10% replacement by weight of cement, bagasse ash content of 10% replacement by weight of cement and megaflow SP1 content of 1.5% by weight of binder) the following conditions are studied by keeping other factors constant.

- a) Reduction of water by 0 % (control), 5% and 10%. Where 0%, 5% and 10% reduction of the amount of water indicate that the water to binder ratio is 0.8 (control), 0.76 and 0.72.
- b) Reduction of Megaflow SP1% from 1.5% (control) to 0.75% and 0%.
- c) Sand content is increased from 10 % (control) to 11%, 12, and 13%.
- d) Bagasse ash content is increased from 10% (control) to 11% and 12%.

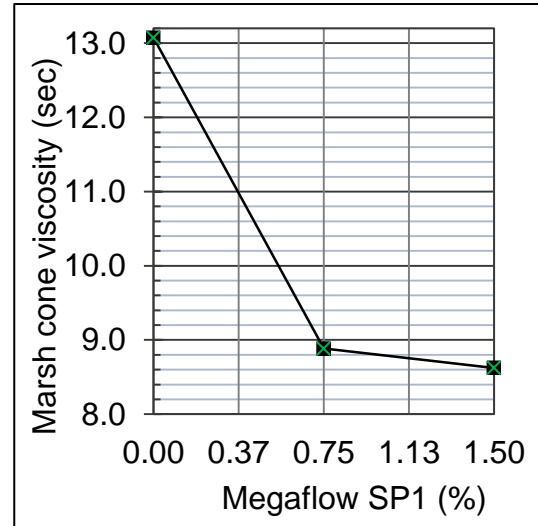
Then four samples were tested using Marsh cone funnel. The details of these results are provided in Appendix 2.1.2. The average result of each condition tested can be seen in the Figure shown below. As it can be seen in Figure 27 shown below, both reduction in water to binder ratio and megaflow SP1 content results in an increase of Marsh cone viscosity. Also, an increase of sand and bagasse ash content led to increasing in Marsh cone viscosity.

LABORATORY STUDY ON THE MIXTURE DESIGN OF GROUTED MACADAM

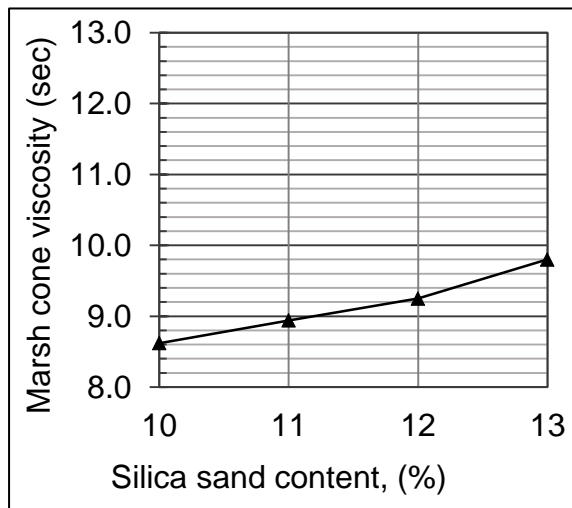
If it is required to change one of the factors, by keeping others constant then the following adjustments can be taken. As compared to the upper specification of 10 seconds, the water to binder ratio should be reduced to 0.76 and Megaflow SP1 content can be reduced to 0.50% by weight of the binder. Whereas an increase in sand and bagasse ash content should be limited to 13% and 11% replacement by weight of the binder, respectively.



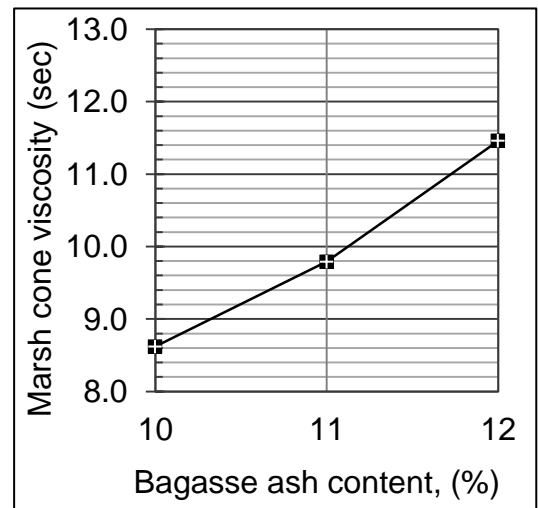
(a) Effect of decreasing water to binder ratio



(b) Effect of decreasing megaflow SP1 content



(c) Effect of increasing sand content



(d) Effect of increasing bagasse ash content

Figure 27: Effects of variations of factors on the Marsh cone viscosity

Based on these adjustments, reduction of water to binder ratio to 0.76 can be allowed without affecting other performance properties of the grout.

4.1.4. Cost comparison of grout mix ingredients

In the design of grout mixtures, cement is considered as the basic ingredient whereas bagasse ash and silica sand are considered as a replacing material of cement for improving performance and economic reasons. The evaluation based on the selected performance properties of grout mixtures suggests the use of silica sand and bagasse ash each 10% replacement by weight of cement, megaflow SP1 1.5% by weight of the binder and water to binder ratio of 0.76.

In any design work cost comparison may be important for the final decision. This comparison may involve qualitative and quantitative analysis of direct and indirect costs. This kind of analysis can be done easily if there is a previous experience over similar projects or if there is detailed material cost of all ingredients and related direct and indirect costs. In this case, there is no local experience. And also at this moment, it is difficult to estimate costs for some processes such as drying and screening of bagasse ash, mixing operation of the cementitious grout, grout application to the laid porous asphalt concrete, etc.

Therefore, it is opted to do cost comparison of grout ingredients based on the available data. Since, the amount of megaflow SP1 required for a batch of mixtures is small and also the relative price of water is small, therefore, in this qualitative analysis, the prices of these materials are neglected. Thus, it is decided to do simple cost analysis based on material and transportation costs of silica sand and bagasse ash as compared to cost of cement.

Cement is being produced in Addis Ababa and also it is available in other cities at a reasonable price; therefore, it is assumed that cement is available at a negligible hauling distance.

The material price of ordinary Portland cement and silica sand is taken from sales department of Muger Cement Enterprise and transportation cost is taken from Derba Transport PLC. These are:

Factor gate price of Muger ordinary Portland cement =250 Birr/quintal

Price of Muger processed silica sand at Derba village= 38.42 Birr/quintal

Freight Transportation by Derba Transport =0.3 Birr/(quintal*km)

Therefore, replacing of silica sand at the specified percentage is economical when the hauling distance (X, km) satisfies the inequality:

$$38.42 \text{ Birr/quintal} + X, \text{ km} * 0.3 \text{ birr}/(\text{quintal} * \text{km}) \leq 250 \text{ Birr/quintal} \dots(4.3)$$

Maximum value of X, km that satisfies the above inequality is 705 km.

Therefore, it is economical to use silica sand at 10% replacement by weight of cement when the project site is within a radius of 705 km from the source of silica sand(in this case Derba village, Mughher Valley).

In the case of bagasse ash, the material price is not specified due to the fact that it is a byproduct and dumped as a solid waste. However, it requires drying, and screening to collect those particles that have size less than 75 μ m. If this processes cost is similar to the material cost of silica sand, thus, it is economical to use bagasse ash at 10% replacement by weight of cement when the hauling distance (X, km) is 705 km from the source of bagasse ash (in this case Wenji Shewa Sugar Factory). Since, detailed economic analysis is not the interest of this research; it is suggested to be carried out in future research works.

4.2. Test Result, Analysis, and Discussion on Experimental Phase II

This phase of the study was devoted to mixture design of porous asphalt concrete in which to propose design bitumen contents for the grouted macadam specimen preparation. Air voids content and binder drain-off are considered in the design of porous asphalt concrete. First, an aggregate gradation was selected in mid-point specification of resin modified pavement (UFGS, 2008). Using this gradation and aggregate specific gravity of the combined aggregate blend, initial design bitumen content of 4.08% was estimated. Marshal method of specimen preparation except some modifications was used in preparing hot mixtures at 3.1%, 3.6%, 4.1% and 4.6%. The details of this test result are presented in the sections below.

4.2.1. Weight-volumetric properties of porous asphalt concrete

At the specified bitumen contents, maximum theoretical specific gravity (G_{mm}) of the mixtures is determined first. Then Marshal specimens are prepared, air-cured in the molds, and carefully demoulded. Then after measurements for height (H) & dry weight (W_{air}) are taken. Bulk specific gravity of these specimens is determined and used in calculating corresponding air voids content.

Air voids content, in this case, refers to the total volume of interconnected pockets of air between the coated aggregate particles throughout a compacted bituminous mixture, expressed as percent of the bulk volume of the compacted bituminous mixture. These weight-volumetric measurements and tests are summarized in Appendix 2.2.1.

4.2.2. Determination of optimum bitumen content

In the design of porous asphalt mixtures for semi-flexible applications, the primary design requirement is air voids content. Because these air voids are required to the interconnected cavities which are going to be filled with cementitious grout. The bitumen content that resulting in an air voids content in the range of 25-32% should be selected. A bitumen content with air voids content close to 30% is preferably selected during laboratory design (Anderton, 2000 and Olivera et al, 2008). Another important consideration is binder drainage. It is the condition where drain down of excess asphalt mortar (bitumen& filler) from the aggregate skeleton. It is required to be less than 0.3% by weight of total asphaltic mixture (Olivera, 2006).

From Appendix 2.2.2., average air voids content is taken for further analysis and it is as shown in Figure below.

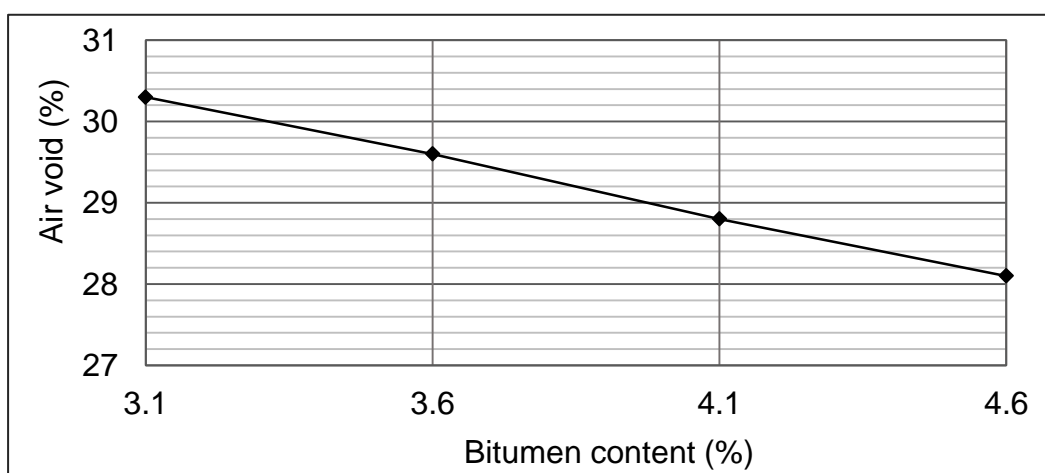


Figure 28: Air voids content as a function of bitumen content

As shown in the Figure above, however, the difference is small; air void content is found to decrease as bitumen content increased. All calculated bitumen contents are within the desired range of 25-32%.

However, a specific test is not performed for binder drainage requirement; significant binder drainage is observed at hot mixtures that were prepared with 4.1% and 4.6% bitumen content. During mixing at both bitumen contents, drained binder is observed on mixing bowl. Whereas at the bitumen content of 3.1% and 3.6%, no significant binder drainage is observed. Hence, for a comparative study in phase III bitumen contents of 3.1% and 3.6% are proposed.

4.3. Test Results, Analysis, and Discussion on Experimental Phase III

The main objective of this phase of the study was to evaluate the impact of cementitious grout on Marshal Stability and indirect tensile strength of porous asphalt concrete. The percent increase in Marshal stability and indirect tensile strength as a result of cementitious grout application to porous asphalt concrete was required.

4.3.1. Grouting ability of the cementitious grout

According to the literature reviewed, the success of grouted macadam is entirely dependent on the fluidity (grouting ability) of cementitious grout and air voids content of porous asphalt concrete. It is required that more than 95% of grout penetration and coverage of porous asphalt concrete (Anderton, 2000; Olivera, 2006). According to Pei et al. (2016), grouting ability can be estimated, based on the volume of grout infiltrated, depth of grout penetration achieved and residual porosity (air voids) of grouted macadam. In this study, after three days of air curing, the grouted macadam specimens are extruded from molds and examined visually. It is observed that all these 65mm thick specimens are fully penetrated by the grout. This can be seen in Figure 29 shown below.

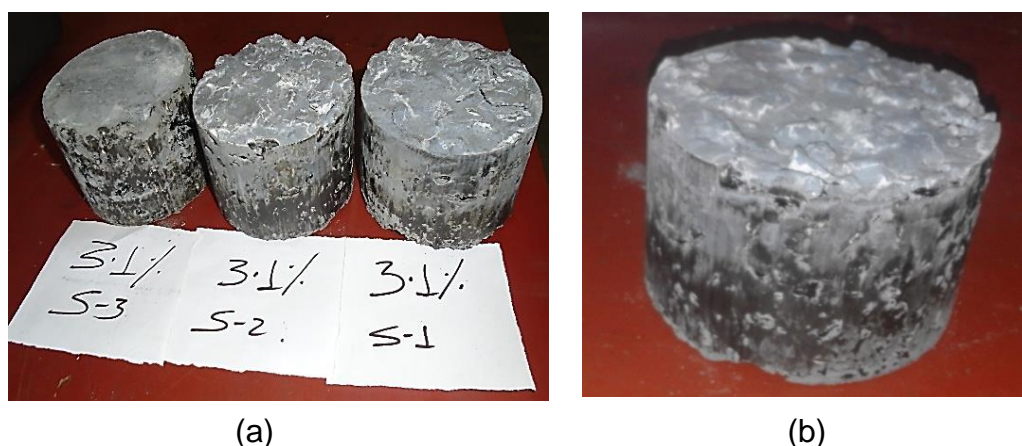


Figure 29: Grouted macadam specimens after three days of air curing

In addition, the bulk specific gravity of the porous asphalt concrete specimens is around 1.78. This is increased to an average bulk specific gravity value of 2.09 for grouted macadam specimens. The details of these values can be seen in Appendix 2.3.1. This increase in specific gravity also indicates that the porous asphalt concrete is well impregnated by the grout.

4.3.2. Marshal Stability-Flow Test

Marshal stability-flow testing of grouted macadam specimens, as well as corresponding maternal porous mixtures, is performed. However, this test was not carried out on grouted macadam specimens that were air cured for seven and 28 days. It is because the available Marshal Stability testing machine has a ring capacity which is limited to 28kN.

The details of the Marshal stability-flow test results are presented in Appendix 2.3.1. The maternal porous asphalt specimens (control) have shown a stability value in the range of 0.81 kN to 2.18kN as tested by conditioning specimens in a water bath at a temperature of 60 °C for 30 minutes. Even though these values are so small, grouting can increase these values to higher stability values. But, this increase is a function of the curing time of grout. As it can be seen in Appendix 2.3.1., grouted macadam specimens that were air-cured for three days, have Marshal stability in the range of 14.41kN to 24.36 kN. For heavy traffic, Asphalt Institute (1995) suggests a minimum stability value of 8kN. Similarly, ERA (2013) specifies the minimum stability of 9kN for a very heavy traffic class. In comparison at age of three days, grouted macadam has higher stability values than that is required from dense bituminous mixtures. Average of Marshal stability test result is determined corresponding to each bitumen contents is shown in the Table below.

Table 15: Average of Marshal Stability test result

Bitumen content (%)	Average Marshal stability (kN) [Appendix 2.3.2.]		Percent increase in stability	
	Control porous HMA	Grouted macadam specimens that are air-cured for 3 days	(kN)	(%)
3.1	1.53	19.14	17.61	92
3.6	1.70	18.52	16.83	91

Anderton (2000) presented the reports of Strategic Highway Research Program (SHRP). According to this report, RMP specimens that were air-cured for 28 days are found to have an average stability value of 19 kN. As compared to this value, the stability results of grouted macadam specimens are promising.

Impact of grout on the Marshal stability

As shown in Table above, as a result of cementitious grouting, on average 92 and 91 percent increase in stability are obtained. It is calculated as compared to maternal mixtures that were prepared with bitumen contents of 3.1% and 3.6%, respectively. As an alternative, this can be seen in the Figure shown below.

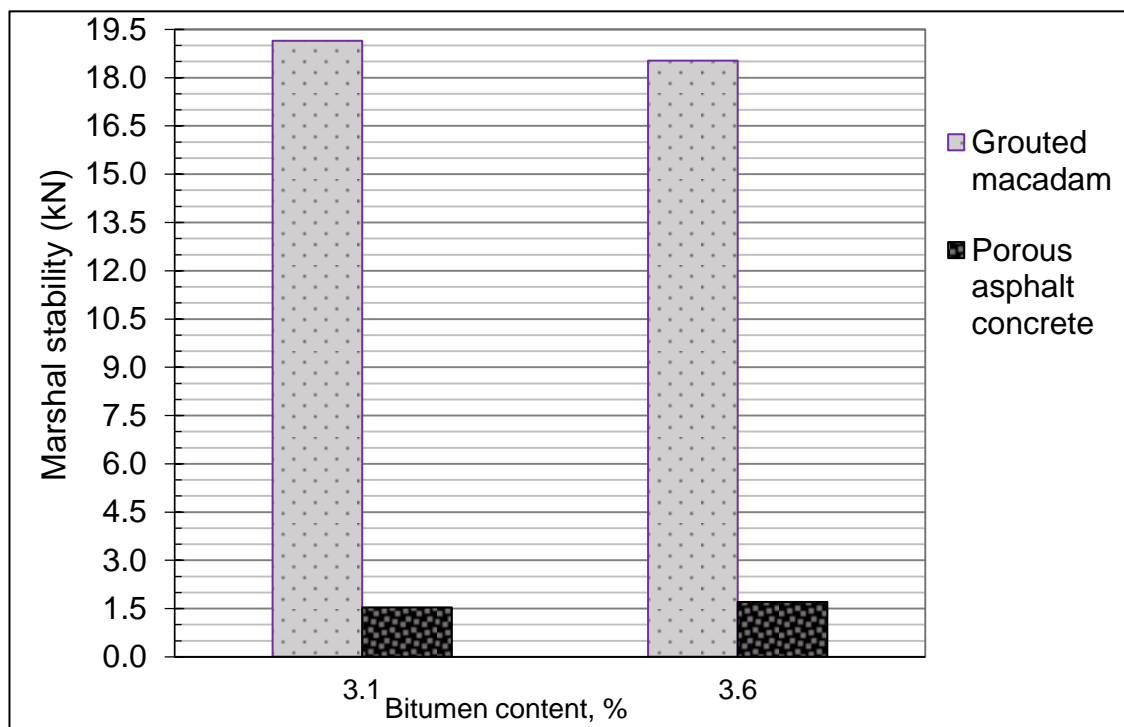


Figure 30: Impact of cementitious grout on the Marshal stability

In both bitumen contents around 30% of the grouted macadam is taken up by cementitious grout. As it can be seen in Appendix 2.1.1., this grout has an average compressive strength of 6.11 MPa, 15.71 MPa, and 26.27 MPa at 3rd, 7th, and 28th days of air-curing, respectively. Based on the average compressive strength of grout, it is possible to say that the average compressive strength this grout at 7th day and 28th day is 2.57 and 4.3 times that of the 3rd-day strength, respectively. It can be concluded that the Marshal stability of grouted macadam specimens could be much higher at 7th and 28th days of curing age than the value obtained at the 3rd day of curing age.

Effect of bitumen content

As it seen in Table shown above, the average value of stability for porous specimens prepared at bitumen content of 3.1% and 3.6% are 1.53 kN & 1.70 kN, respectively. However, the difference is small; there is an increase in stability of porous asphalt concrete as the bitumen content increased. It is the fact that air voids space will be taken up by bitumen, i.e. voids filled with asphalt is increased. This might increase the stability value of the porous mix as bitumen contents increased. But, as the bitumen content increased from 3.1% to 3.6%, the average stability of grouted macadam specimens slightly decreased from 19.14kN to 18.52kN. This can be seen in the Figure below. It is because of the fact that as bitumen contents decreased; more space will be taken up by higher strength cementitious grout.

To say this difference is significant, a statistical test is performed using Minitab Software. The output is given in Appendix 2.3.3. The box plot of the two means can be seen Figure 31 below.

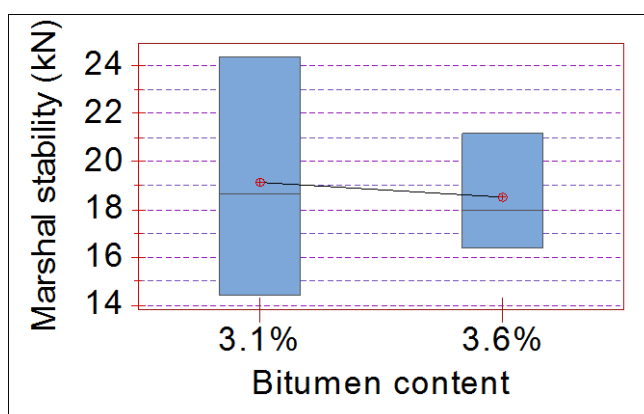


Figure 31: Box plots of the means of Marshal Stability test result of grouted macadam that were prepared with bitumen contents of 3.1% & 3.6%

Based on t-test, P-value of 0.864 is obtained. A significance level of 0.05 is considered in this study. Therefore, in this case, there is no enough test data to reject the null hypothesis (H_0), which is as bitumen content of grouted macadam decreased from 3.6% to 3.1%, the difference in Marshal stability of grouted macadam is insignificant. Therefore, the average improvement in Marshal stability associated with this grout can be estimated by averaging the percent increase in Marshal stability calculated at the two bitumen contents, i.e. 92% & 91%. Thus, the average improvement in Marshal stability is about 91.5%.

4.3.3. Indirect tensile strength test

In order to examine the indirect tensile strength of grouted specimens in comparison with control porous specimens, grouted macadam specimens at bitumen contents of 3.1% and 3.6% are prepared and air-cured to 28th days of curing age. Then for each respective test temperature of 25 °C and 40 °C, triplicate specimens are conditioned in the oven for 24 hours. After conditioning, the specimens are crushed with a load at a constant strain rate of 50 mm/min. The details of this test results are presented in Appendix 2.3.3. The percent increase in indirect tensile strength as compared to control porous specimens is calculated at the two test temperatures and presented in the Table shown below.

Table 16: Summary of average result of indirect tensile strength (ITS) test

Test temp (°C)	Bitumen content (%)	ITS, kPa [Appendix 2.3.3]		Increase in ITS (kPa)	Percent increase (%)
		Porous specimens	Grouted macadam specimens @28 th day		
25	3.1	174.62	1018.27	843.65	82.9
	3.6	183.60	947.84	764.24	80.6
40	3.1	49.87	432.41	382.54	88.5
	3.6	70.69	375.94	305.25	81.2

Impact of cementitious grout on the indirect tensile strength

As it can be seen in Table 16 shown above, at 25 °C the average indirect tensile strength (ITS) of porous asphalt concrete specimens are 174.62 kPa and 183.60 kPa at 3.1% and 3.6% bitumen contents, respectively. Whereas at 40 °C, porous specimens have so small indirect tensile strength which is an average value of 49.87 kPa and 70.69 kPa at 3.1% and 3.6% bitumen contents, respectively.

As it is given in Appendix 2.1.1, the cementitious grout prepared has an average rupture modulus of 2.30 MPa which is the beam tensile strength tested to failure at room temperature. However, different testing procedures and temperatures, the tensile strength of grout is much more than porous asphalt concrete where tensile strength is primarily gained from bitumen.

As it is seen in Table above, at 25 °C, on average the tensile strength of grouted macadam specimens is 843.65 kPa and 764.24 kPa higher than the corresponding porous specimens that were prepared with bitumen contents of 3.1% and 3.6%, respectively. This increase in tensile strength, of course, the contribution of cementitious grout is 82.9% and 80.6% as calculated with reference to maternal porous asphalt mixtures that were prepared with bitumen contents of 3.1% and 3.6%, respectively. Whereas at 40 °C, on average the tensile strength of grouted macadam specimens is 382.54 kPa and 305.25 kPa higher than the maternal porous mixtures that were prepared with bitumen contents of 3.1% and 3.6%, respectively. It is about 88.5% and 81.2% increase in tensile strength as compared to maternal porous mixtures that were prepared with bitumen contents of 3.1% and 3.6%, respectively.

Effect of test temperature

The effect of temperature on the indirect tensile strength of grouted macadam is also evaluated, in order to examine the high temperature susceptibility of this composite material.

As it can be seen from Figure 32(a)&(b) shown below, at both bitumen contents a similar trend of decrease in indirect tensile strength is observed for both porous as well as grouted macadam specimens as the conditioning temperature is increased from 25 °C to 40 °C. As compared to 25 °C, tests done at 40 °C showed a reduction of indirect tensile strength by 58% and 60% is observed on grouted macadam specimens that were prepared with bitumen contents of 3.1% and 3.6%, respectively.

The decrease in tensile strength of grouted materials is high at high temperatures just like dense bituminous mixtures. However, at high temperatures, grouted materials can have two to three times higher tensile strength than that of dense bituminous mixtures (Anderton, 2000). According to this author, the reduction in tensile strength is because of the viscoelastic nature of bitumen that coated the aggregate. These results indicate that the performance of grouted macadam is temperature dependent.

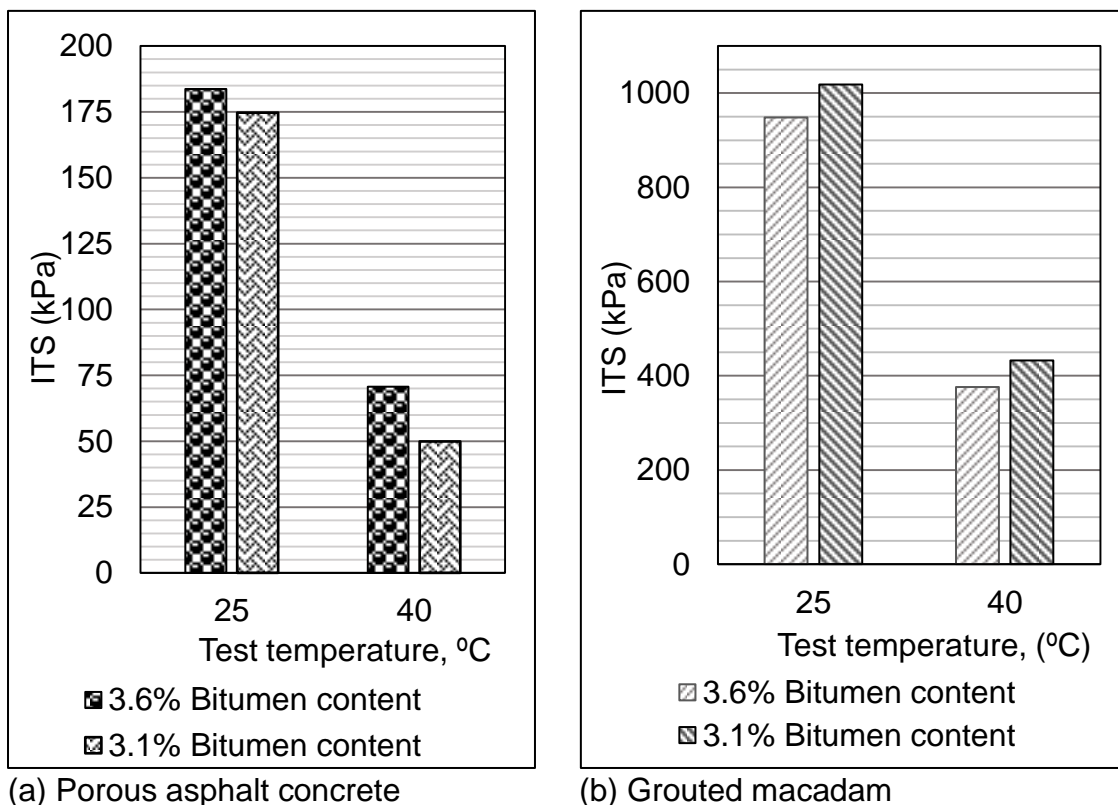


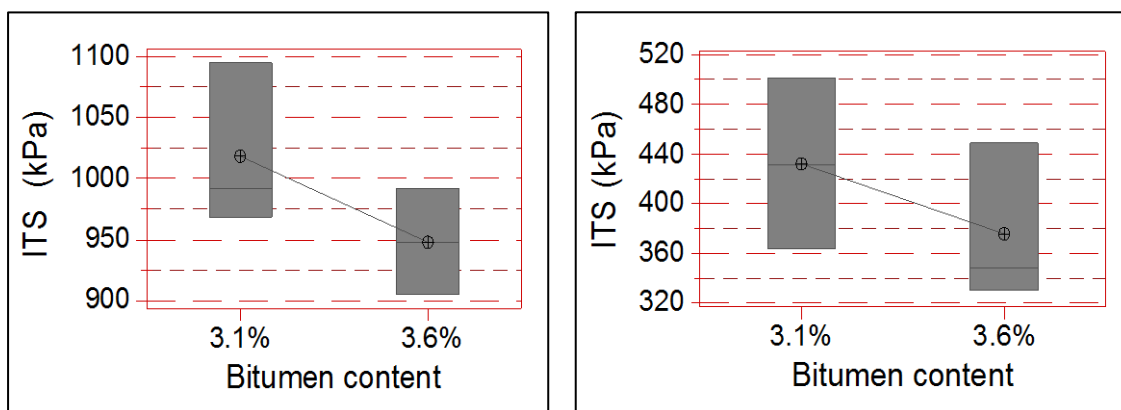
Figure 32: Effect of temperature on the tensile strength of porous asphalt concrete and grouted macadam

Effect of bitumen content

The effect of bitumen content is similar to the effects observed in Marshal Stability of both porous and grouted macadam specimens. As shown in Figure 32(a) above, at both test temperatures, the average indirect tensile strength of porous asphalt specimens that were prepared with a bitumen content of 3.6% is higher than those of specimens that were prepared with 3.1% bitumen content. However, the difference is small, this trend is reversed which can be seen in Figure 32(b) shown above. It is because as bitumen content decreased, more air void would be available which in turn filled by cementitious grout, resulting in the high tensile strength of grouted macadam. Similarly, the t-test is performed in order to check whether the difference in tensile strength is significant or not as bitumen content decreased from 3.6% to 3.1%. Similarly, the details can be seen in Appendix 2.3.3.

Based on the t-test analysis on the means of ITS of grouted macadam at a test temperature of 25 °C, a P-value of 0.226 is obtained. Whereas at 40 °C, a P-value of 0.374 is obtained. According to Montgomery and Runger (2003), if P-value is less than the considered significant level (α), then there is strong evidence to reject the null hypothesis (H_0). In this case, all the P-value is greater than the significance level (α) of 0.05. Therefore, there is no strong evidence to reject the null hypothesis. It is as the bitumen content of grouted macadam decreased from 3.6% to 3.1%, the difference in tensile strength of grouted macadam is insignificant.

The box plot of the two-sample means is presented in Figure 33(a) for means at the test temperature of 25 °C and also in Figure 33(b) for means at the test temperature of 40 °C. As it can be seen in these Figures, in both test temperatures, it seems that the tensile strength of grouted macadam tends to increase as the bitumen content decreased from 3.6% to 3.1%. But, to say it is significant, additional test data are required.



(a) At a test temperature of 25 °C

(b) At a test temperature of 40 °C

Figure 33: Box plots of the means of indirect tensile strength test result of grouted macadam that are prepared with bitumen contents of 3.1% and 3.6%

Based on the available data shown in Table 16 above, the average improvement in tensile strength associated with this grout can be estimated by averaging the percent increase in tensile strength that were calculated at the two bitumen contents and temperatures. Thus, the average improvement in tensile strength is 83.3%.

5. CONCLUSION

In this research, cementitious grout and porous asphalt concrete mixtures are designed in phase I and II of the study, respectively. In phase III, grouting ability of the grout mix proportion proposed in phase I is evaluated. Finally, the improvements in Marshal stability and indirect tensile strength (ITS) as a result of this grout application to the porous asphalt concrete are determined.

5.1. Conclusion on Phase I

Design of cementitious grout involving ordinary Portland cement, silica sand, bagasse ash, megaflow SP1, and water is carried out using the Taguchi approach. The factor levels considered are: Water to binder ratio, A (0.80,0.85,& 0.90), silica sand replacement by weight of cement, B (0%,10%,& 20%), bagasse ash replacement by weight of cement, C(0%,10%,& 20%) and megaflow SP1 by weight of the binder, D(0%, 1.5% and 2.5%). Finally, the optimum combination of the factor levels for the overall best performance of the grout is determined. Based on the analysis of test results in phase I, the following can be concluded.

- ✚ Following the Taguchi approach, the optimum condition for the defined overall evaluation criteria is 0.80, 10%, 10% and 1.5% for the factor A, B, C, and D respectively. Further adjustment is made on this optimum condition based on Marsh cone viscosity test. Based on this test result, the water to binder ratio (A) can be decreased to 0.76 without affecting other performance properties. Therefore, a water to binder ratio of 0.76, silica sand 10% & bagasse ash 10% replacement by weight of cement and megaflow SP1 1.5% by weight of the binder is proposed for use in the grouted macadam.

5.2. Conclusion on Phase II

Based on the test results done in phase II, the following can be concluded.

- ✚ Porous asphalt concrete mixtures that were prepared with bitumen contents of 3.1% and 3.6% by weight of the total mixture have an average air voids content of 30.3% and 29.6%, respectively. For the selected aggregate grading and targeted air voids content of 30%, these bitumen contents are suggested for the preparation and evaluation of their effect on the grouted macadam.

5.3. Conclusion on Phase III

Based on the test results in phase III, the following conclusion is given.

- ✚ Using the proposed grout mix proportion in phase I, cementitious grout is prepared and poured into the porous asphalt specimens that were prepared with bitumen contents of 3.1% and 3.6%. The grout mix is proven to be highly flowable and it has the capability to percolate a 65mm thick porous asphalt concrete.
- ✚ Marshal stability-flow and ITS tests are conducted on both grouted macadam and corresponding maternal porous asphalt mixtures that were prepared with bitumen contents of 3.1% and 3.6%. Based on the t-test of these tests data, it can be said that grouted macadam specimens haven't shown any significant variation in Marshal stability and indirect tensile strength with respect to the difference in bitumen content. Thus, by neglecting the effect of bitumen content, the average improvement associated with the grout is determined for both properties.
- ✚ At the 3rd day of air-curing age, grouted macadam specimens are found to have Marshal stability more than 14.41kN. At this age, on average the Marshal stability is improved by 91.5%.
- ✚ Whereas ITS test is conducted on grouted macadam specimens aged 28th days and control specimens by conditioning them at the respective test temperature of 25 °C and 40 °C for 24 hours. Associated with the grout application, the test result analysis shows that the average improvement in tensile strength is about 81.75% and 84.85%, at 25 °C and 40 °C, respectively.
- ✚ Since about 30% of the grouted macadam volume is taken up by the cementitious grout, it can be said that the improvements achieved in both Marshal stability and ITS values are high. These improvements are indicating that the contribution of cementitious grout to the performance of the resultant grouted macadam is significantly high. Therefore, adequate care should be given in the design and application of the grout mixtures.
- ✚ Marshal stability and ITS tests indicated that the resultant grouted macadam mixtures have promising performance. Therefore, it should be given attention as an alternative wearing course pavement material.

6. RECOMMENDATION

For the last five decades, an alternative pavement surfacing material to conventional asphalt concrete or Portland cement concrete is being investigated in order to have a layer with the best qualities of the two materials namely flexibility from asphalt and rigidity from the cement-based mixtures. One of the promising alternative solutions is the grouted macadam (called resin modified pavement in the USA).

Nowadays, the research more focuses on mixture design of cementitious grout and performance evaluation of the grouted macadam. There is a pressing need for best grout composition involving low-cost industrial byproducts. During this research, it is found that there is no agreed practice in the design of cementitious grout, especially on the grout ingredients. Further research is required in the study area.

With regard to this research work, the following recommendations are given. These are:

- ✚ The grouted macadam mixtures designed in this study can be laid as a wearing course or as an overlay over existing or newly constructed bituminous layers. It can also be laid over thick cement or lime-cement stabilized base courses. Therefore, it is suggested for wearing course layers of special pavement areas such as airport taxiways (apron), intersections, bus stops, industrial compounds, channelized sections, heavy vehicle parking locations and other areas that are susceptible to rutting and chemical attack. Road authorities, dry port administrations and airport facility managements should allow, finance and promote the development of field test strips. Basically, construction of field test strip is important for the evaluation of field performance of this grouted macadam mixture and also for studying its economic feasibility for use in future projects.

6.1. Future Works

- ✚ Further studies on porous asphalt concrete involving different bitumen grade, different maximum aggregate size, filler content and others, can be carried out.
- ✚ Detailed studies may be required on the grout properties such as drying shrinkage, sulphate or chloride attack resistance, etc.
- ✚ Research on the residual porosity, fuel resistance, durability, resilient modulus, fatigue resistance and other property of grouted macadam should be done.
- ✚ The by-product bagasse ash should not be used in the grout as it is received. It requires processes such as drying, screening, and milling. Therefore, academicians in the Universities should work research in conjunction with Sugar Factories to process the byproduct called bagasse ash as it is directly discharged from combustion furnace.
- ✚ It is important to work collaborative research in consultation with local Cement Factories in order to develop special cement (micro-fine cement, rapid setting cement or any other suitable cement) and process locally available different pozzolanic fillers for use in the grout mixture. This kind of research enables the development of grout mortar powder that can be readily available for immediate use for grouting application.

7. REFERENCES

Afonso, M.L., Dinis-Almeida, M., Pereira-de-Oliveira, L.A., Castro-Gomes, J., Zoorob, S.E., 2016. Development of a semi-flexible heavy duty pavement surfacing incorporating recycled and waste aggregates – Preliminary study. *Construction and Building Materials* 102, pp.155-161

AFCESA, 2001. Engineering Technical Letter (ETL) 01-8: Resin Modified Pavement (RMP) Design and Application Criteria. Air Force Civil Engineer Support Agency, Tyndall AFB.

Ahlrich, R.C. and Anderton, G.L., 1991. Construction and Evaluation of Resin Modified Pavement. Technical Report GL-91-13. US Army Corps of Engineers Waterway Experiments Station. Vicksburg.

Al-Qadi, I.L., Gouru, H., and Weyers, R. E., 1994. Asphalt Portland Cement Concrete Composite: Laboratory Evaluation. *ASCE Journal of Transportation Engineering*, 120(1), pp. 94-108.

Anderton, G.L. and Ahlrich, R.C., 1994. Design, Construction, and Performance of Resin Modified Pavement at Fort Campbell Army Airfield, Kentucky. US Army Corps of Engineers Waterways Experiment Station. Vicksburg.

Anderton, G. L., 1996. User's Guide: Resin Modified Pavement. US Army Engineer Waterways Experiment Station. Vicksburg.

Anderton, G. L., 2000. Engineering Properties of Resin Modified Pavement (RMP) for Mechanistic Design. ERDC/GL TR-00-2. Army Corps of Engineers. Vicksburg.

Asphalt Institute, 1995. The Asphalt Handbook. Manual Series No. 2 (MS-2).

ASTM, 2000. American Society for Testing and Materials

AASHTO, 1998. American Association of State Highway and Transportation Officials

Biruk, B., 2011. Bagasse ash a cement replacing material. MSc Thesis report. Addis Ababa University. Addis Ababa. Ethiopia

BSI, 2001. British Standards Institute. London. UK

Cordeiro, G.C., Toledo Filho, R.D., Tavares, L.M., Fairbairn, E.M.R., 2008. Pozzolanic activity and filler effect of sugar cane bagasse ash in Portland cement and lime mortars. *Cement & concrete composites*, Volume 30, pp. 410-418.

Cordeiro, G.C., Toledo Filho, R. D., Tavares, L.M., Fairbairn, E.M.R., 2009. Ultrafine grinding of sugar cane bagasse ash for application as a pozzolanic admixture in concrete. *Cement and Concrete Research* 39, pp. 110–115

Cordeiro, G.C., Tavares, L.M., Toledo Filho, R.D., 2016. Improved pozzolanic activity of sugar cane bagasse ash by selective grinding and classification Cement and Concrete Research 89, pp. 269–275

Deshmukh, V.V., 2011. Grouted Macadams: Successful Technology for Rehabilitation of Bituminous Roads [On line]. Available: <http://concretetechnologies.blogspot.com/2011/07/grouted-macadam-bsuccessful-technology.html>. Access date: 3/3/2017

ERA, 2013. Ethiopian Roads Authority, Pavement Design Manual Volume I: Flexible Pavements.

Ganesan, K., Rajagopal, K., Thangavel, K., 2007. Evaluation of bagasse ash as supplementary cementitious material. Cement & Concrete Composites, Volume 29, pp. 515–524.

Hassan, K.E, Setyawan, A., Zoorob, S.E, 2002. Effect of Cementitious Grout on the Properties of Semi-flexible bituminous Pavements. In: Zoorob, S.E., Collop, A.C. & Brown, S.F. (Editors), Proceedings of the 4th European Symposium on Performance of Bituminous and Hydraulic Materials in Pavements, BITMAT 4, pp. 113-120. A.A. Balkema, The Netherlands.

Hou, S., Xu, T. and Huang, K., 2016. Investigation into Engineering Properties and Strength Mechanism of Grouted Macadam Composite Materials. International Journal of Pavement Engineering 17:10, pp. 878-886.

Kosmatka, S.H. and Wilson, M.L., 2011. Design and Control of Concrete Mixtures: The guide to applications, methods, and materials, 15th edition. Portland Cement Association. USA

Koting, S., Karim, M.R., Mahmud, H., Abdul Hamid, N.A., 2011. Development of Cement-Bitumen Composites for Semi-Flexible Pavement Surfacing. Proceedings of the Eastern Asia Society for Transportation Studies, Volume 8.

Mesfin T., 2012. Opportunities for Silica Sand development in Ethiopia. Geological Survey of Ethiopia

MOI, 2015. FDRE Ministry of Industry, Ethiopian Cement Industry Development Strategy 2015-2025. Addis Ababa. Ethiopia

Montgomery, D.C., Runger, G.C., 2003. Applied Statistics and Probability for Engineers, 3rd edition. John Wiley & Sons, Inc., USA. pp 327-347

Neville, A.M. and Brooks, J.J., 2010. Concrete Technology, Second edition. Pearson Education Limited. England.

Oliveira, J. R. M., 2006. Grouted Macadam – Material Characterization for Pavement Design. PhD thesis. University of Nottingham. Nottingham.

Oliveira, J.R.M., Thom, N.H., Zoorob, S.E., 2008. Design of Pavements incorporating Grouted Macadams. ASCE Journal of Transportation Engineering, 134, pp. 7-14.

Pei, J., Cai, J., Zou, D., Zhang, J., Li, R., Chen, X., Jin, L., 2016. Design and Performance validation of high-performance cement paste as a grouting material for Semi-flexible pavement. Construction and Building Materials 126, pp. 206-217.

Read, J. and Whiteoak, D., 2003. The Shell Bitumen Handbook, fifth edition. Thomas Telford Ltd. London.

Roy, R. K., 2001. Design of Experiments using the Taguchi Approach 16 steps to product and process improvement. John Wiley & Sons, Inc. New York

Setyawan, A., 2005. Design and Properties of hot mixture porous asphalt for Semi-flexible pavement applications. Surakarta. Indonesia.

Setyawan, A., 2013. Assessing the Compressive Strength Properties of Semi-Flexible Pavements. Procedia Engineering 54, pp.863 – 874.

Tan, O., Zaimoglu, A. S., Hınıslıoglu, S., and Altun, S., 2005. Taguchi approach for optimization of bleeding on cement based grouts. Tunneling and Underground Space Technology 20, pp.167-173.

UFGS, 2008. Unified Facilities Guide Specifications. US Army Corps of Engineers. Vicksburg. USA

Yang, B. and Weng, X., 2015. The influence on the durability of semi-flexible airport pavement materials to cyclic wheel load test Construction and Building Materials 98, pp. 171–175

Zhang, J., Cai, J., Pei, J., Li, R., Chen, X., 2016. Formulation and performance comparison of grouting materials for semi flexible pavement. Construction and Building Materials 115, pp. 582–592.

Zoorob, S.E., Hassan, K.E. and Setyawan, A., 2002. Cold-mix, cold laid semi-flexible Grouted Macadams, mix design and properties. In: Zoorob, S.E., Collop, A.C. & Brown, S.F. (Editors), Proceedings of the Fourth European Symposium on Performance of Bituminous and Hydraulic Materials in Pavements. BITMAT 4, pp.105-112. A.A. Balkema, The Netherlands.

APPENDIX 1. MATERIALS TEST RESULT

1.1. Ordinary Portland cement properties

1.1.1. Normal consistency

Cement (gm)	650	650	650
Water % by wt. of cement	26	27	28
Water (gm)	170	175.5	182
Penetration by Vicat apparatus(mm)	8	11	14

For 10mm penetration, the normal consistency of this cement is about 27%.

1.1.2. Initial and final setting time

Time, min	30	45	60	75	90	105	120	135	150	165	180	195	210	225	240
Pen., mm	40	40	38		35	33	30	28	24	20	17	12	8	2	0

✓ Initial and final setting time of this cement is 150minutes (2.5 hours) and 240 minutes (4 hours) respectively, as measured from the beginning of mixing.

1.1.3. Fineness of cement by air permeability apparatus

$$S = S_s \cdot (T/T_s)^{0.5}$$

Where S= Blain surface area,

T= Time measured in seconds

T_s=Standard time measured for standard cement, T_s=29.77 sec

S_s=Surface area of Standard cement, S_s=3774 cm²/gm

Mass of cement sample=2.917 gm		
Time Reading, T (sec)	17.94	17.92
$S = 3774 \cdot (T/29.77)^{0.5}$	2929.7	2828.07
Average surface area, S	2929	

✓ The fineness of this cement in terms of Blain surface area is about 2950 cm²/gm.

1.2. Bagasse ash properties

1.2.1. Physical properties of bagasse ash

A) Specific gravity

Trial number	1	2
Mass of oven dried sample, M _o	10.5	10.6
Mass of Pycnometer & lid filled with water, M _A	155.3	155.3
Mass of Pycnometer, lid + sample filled with water, M _B	160.8	161.0
Specific gravity (G _S) = M _o / (M _o + (M _A - M _B))	2.100	2.163
Average specific gravity (G _S)	2.132	

LABORATORY STUDY ON THE MIXTURE DESIGN OF GROUTED MACADAM

B) Fineness of processed bagasse ash by air permeability apparatus

Bagasse ash is filled to the plunger (to full level)		
Time Reading, T (sec)	10.87	10.83
$S=3774*(T/29.77)^{0.5}$	2280.5	2276.3
Average surface area, S	2278.4	

This bagasse ash has a Blain surface area of 2280 cm²/gm

- Fineness of processed bagasse ash as sieved by 45µm sieve size

Weight before test, W_o=10gm

Weight retained on the sieve after test, W_r

Fineness is calculated by:- $Fineness = W_r * 100 / W_o$

Trial1	W _r =2.42	Fineness=2.42*100/10=24.2%
Trial 2	W _r =2.81	Fineness =2.81*100/10=28.1%
Average		24.2%+28.1%= 26.15%

Thus, it can be said that 26.2% of the bagasse ash will retain on 45µm sieve size. This value below the maximum 34% of ASTM C-618 class F fly ash requirement.

C) Water requirement (Liquid and plastic limit)

<i>Liquid limit data</i>				
Container no.	14	3	80	92
depth of penetration of Penetrometer	13.6	15.4	17.2	20.6
Wt. of container+wet sample(gm)	36.15	32.88	44.17	32.25
Wt. of container+Oven dried sample(gm)	25.92	23.49	27.66	22.97
Wt. of container weight (gm)	17.48	15.88	14.34	15.6
Wt. of oven dried sample	8.44	7.61	13.32	7.37
Wt. of water	10.23	9.39	16.51	9.28
Moisture %	121.21	123.39	123.95	125.92
Average moisture content, %	123.62			
<i>Plastic limit data</i>				
Container no.	5		6	
Number of blows (depth of penetration)				
Wt. of container+wet sample(gm)	22.88		26.15	
Wt. of container+Oven dried sample(gm)	18.91		19.7	
Wt. of container weight (gm)	15.57		14.32	
Wt. of oven dried sample	3.34		5.38	
Wt. of water	3.97		6.45	
Moisture %	118.86		119.89	
Average moisture content, %	119.38			
	<i>Penetration Index (PI)=4.24</i>			

LABORATORY STUDY ON THE MIXTURE DESIGN OF GROUTED MACADAM

1.2.2. Chemical composition of bagasse ash sample as received from Wonji Shewa Sugar Factory

Geological Survey of Ethiopia:Geochemical Laboratory Directorate

Geochemical Laboratory Complete Silicate Analysis Report Format

Form G0004

FILE ID ;7388/16 pvt

Originator :-Mubarek Zeyne

Sample type; Bagasse Ash

Date Submitted;11/22/2016

Preparation :-200 MESH

Number of Sample: 1

Element to be determined Major Oxides & Minor Oxides

Analytical Method: LiBO2 FUSION , HFattack,GRAVIMETERIC,COLORIMETRIC and AAS

Analytical Results in PERCENT

FIELD NO	Lab No	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	MnO	P ₂ O ₅	TiO ₂	H ₂ O	LOI
BA	7388/16	50.12	7.90	4.76	2.20	2.32	4.72	4.36	<0.01	0.44	0.13	2.55	21.96

Analysts

Yohannes Getachew

Tizita Zemene

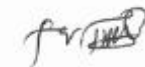
Dessie Abebe

H/gebriel Asmare

Yirgalem Abreham

Tamiru Siraye

Checked by



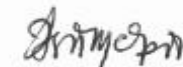
Gosa Haile

Approved by



Demisew Lema

QUALITY CONTROL



Zinash Marcos

DATE REPORTED

02/01/2017



1.3. Silica sand

1.3.1. Specific gravity of silica sand

Trial number	1	2
Mass of oven dried sample, M_o	50.0	50.0
Mass of Pycnometer & lid filled with water, M_A	156.1	156.1
Mass of Pycnometer, lid + sample filled with water, M_B	187.1	187.0
Specific gravity(G_S)= $M_o/(M_o+(M_A-M_B))$	2.632	2.618
Average specific gravity(G_S)	2.625	

1.4. Megaflow SP1



Typical properties at 25 °C (Manufacturer`s specification)

Property	Test method	Value
Component	-	Single
Form	-	Liquid
Colour	-	Brown
Specific gravity	ASTM C494	1.20 +/- 0.02
Air entrainment	-	Up to 1% over control mix
Chloride Content	BS EN 480- 10	Nil to BS EN 934-2
PH	ASTM C494	7-9

APPENDIX 2. TEST RESULTS

Appendix 2.1. Test Result of Experimental Program I

2.1.1. Test result details of all experimental run

A. Details of tests results (at fresh state of grouts)

E.R. #	Bleeding test data, (%)			Marsh cone viscosity,(sec)			Bulk Specific gravity		
	Mix 1	Mix 2	Avg	Mix 1	Mix 2	Avg	Mix 1	Mix 2	Avg
1	16.0	17.0	16.5	6.75	7.05	6.9	1.581	1.588	1.584
2	8.0	7.0	7.5	8.5	8.8	8.7	1.556	1.531	1.544
3	2.5	2.5	2.5	36	34	35.0	1.531	1.569	1.550
4	10.0	10.4	10.2	7.5	8	7.8	1.538	1.488	1.513
5	2.5	2.5	2.5	40	38	39.0	1.581	1.538	1.559
6	15.0	14.6	14.8	6.85	7.15	7.0	1.544	1.556	1.550
7	4.0	2.5	3.3	9.5	9.1	9.3	1.406	1.450	1.428
8	17.5	16.0	16.8	7.2	6.75	7.0	1.563	1.538	1.550
9	5.6	5.2	5.4	10.5	9.8	10.2	1.569	1.575	1.572

Note:- E.R.# is experimental run or trial combinations designations as designed using the Taguchi approach

LABORATORY STUDY ON THE MIXTURE DESIGN OF GROUTED MACADAM

B. Details of tests results (at hardened state of grouts)

E. R. #	Compressive Strength,(MPa) (at 3 rd age)				Compressive Strength,(MPa) (at 7 th age)				Compressive Strength,(MPa) (at 28 th age)				Rupture Modulus. (MPa) (at 28 th age)			
	Cube 1	Cube 2	Cube 3	Avg.	Cube 1	Cube 2	Cube 3	Avg.	Cube 1	Cube 2	Cube 3	Avg.	Cube 1	Cube 2	Cube 3	Avg.
1	8.17	7.47	8.23	7.96	16.53	13.01	16.37	15.30	20.75	21.61	19.12	20.49	1.48	1.71	2.00	1.73
2	5.92	5.53	6.89	6.11	14.82	15.85	16.47	15.71	29.96	25.00	23.83	26.27	2.47	1.94	2.50	2.30
3	4.63	4.73	4.22	4.53	7.01	6.90	6.31	6.74	12.54	13.15	14.56	13.42	2.10	2.20	2.00	2.10
4	3.33	4.29	5.16	4.26	10.36	15.84	11.38	12.53	18.92	18.80	16.77	18.16	2.10	1.95	2.25	2.10
5	5.04	5.01	5.15	5.07	9.13	9.41	8.96	9.17	15.13	15.75	15.34	15.41	1.80	1.90	1.70	1.80
6	6.00	6.86	6.93	6.60	13.75	11.47	12.80	12.67	25.98	22.81	23.50	24.10	2.25	2.05	1.85	2.05
7	4.48	6.16	5.42	5.35	8.57	9.80	7.57	8.64	12.40	10.96	17.52	13.63	2.40	2.15	2.50	2.35
8	6.53	6.60	5.28	6.13	17.69	14.62	13.28	15.20	15.94	28.43	21.80	22.05	2.05	2.10	2.60	2.25
9	4.46	3.60	3.75	3.94	6.12	6.94	6.89	6.65	10.23	9.00	8.44	9.22	1.55	1.65	1.35	1.52

Note:- E.R. # is experimental run number or trial combinations designation as designed using the Taguchi approach

LABORATORY STUDY ON THE MIXTURE DESIGN OF GROUTED MACADAM

2.1.2. Test results for the adjustments of factor levels based on Marsh cone viscosity

<i>a) Effect of decrease in water to binder ratio</i>								
Water to binder ratio	Designation	Sample 1 (sec)	Sample 2 (sec)	Sample 3 (sec)	Sample 4 (sec)	Sample mean	Standard deviation	Coefficient of variation (%)
0.80	Control	8.5	8.65	8.76	8.58	8.62	0.095	1.11
0.76	-5%	9.83	9.88	10.06	9.8	9.89	0.101	1.02
0.72	-10%	11.85	12.09	12.2	11.95	12.02	0.133	1.11
<i>b) Effect of presence of megaflow SP1</i>								
Megaflow SP1 by wt. of binder	Designation	Sample 1 (sec)	Sample 2 (sec)	Sample 3 (sec)	Sample 4 (sec)	Sample mean	Standard deviation	Coefficient of variation (%)
0.00	SP1 0%	13.26	13.15	12.77	13.12	13.08	0.184	1.41
0.75	SP1 0.75%	8.78	9.01	8.9	8.85	8.89	0.084	0.94
1.50	SP1 1.5%	8.5	8.65	8.76	8.58	8.62	0.095	1.11
<i>c) Effect of increase in sand content</i>								
Sand content by wt. of cement (%)	Designation	Sample 1 (sec)	Sample 2 (sec)	Sample 3 (sec)	Sample 4 (sec)	Sample mean	Standard deviation	Coefficient of variation (%)
10	Control	8.5	8.65	8.76	8.58	8.62	0.095	1.11
11	Sand+10%	8.96	8.78	8.97	9.03	8.94	0.093	1.05
12	Sand+20%	9.26	9.22	9.28	9.24	9.25	0.022	0.24
13	Sand+30%	10.01	9.61	9.7	9.86	9.80	0.153	1.56
<i>d) Effect of increase in bagasse ash content</i>								
Bagasse ash content by wt. (%)	Designation	Sample 1 (sec)	Sample 2 (sec)	Sample 3 (sec)	Sample 4 (sec)	Sample mean	Standard deviation	Coefficient of variation (%)
10	Control	8.5	8.65	8.76	8.58	8.62	0.095	1.11%
11	BA+10%	9.65	9.81	9.95	9.75	9.79	0.109	1.11%
12	BA+20%	12.09	11.39	11.29	11.05	11.46	0.387	3.38%

Appendix 2.2. Test Result of Experimental Program II

2.2.1. Maximum Theoretical Specific gravity of loose hot mixtures

Test Method: ASTM D2041-00

<i>i) At 3.6% asphalt content by weight of total mixture</i>		
Mass of Jar	A	B
A: Mass of dry sample in air	2500	2500
B: Mass of Jar filled With water	4657	4634
C: Mass of Jar & sample filled With water	6169	6146.5
Water temperature	25 °C	
Maximum theoretical specific gravity (Gmm)= $K \cdot A / (A+B-C)$	2.530	2.532
<i>Average maximum theoretical specific gravity (Gmm)</i>	<i>2.531</i>	
<i>ii) At 4.1% asphalt content by weight of total mixture</i>		
Mass of Jar	A	B
A: Mass of dry sample in Air	2500.8	2500
B: Mass of Jar filled With Water	4657	4634
C: Mass of Jar filled With Water +Sample	6160.5	6139
Water temperature	25 °C	
Maximum theoretical specific gravity(Gmm)= $K \cdot A / (A+B-C)$	2.509	2.513
<i>Average maximum theoretical specific gravity (Gmm)</i>	<i>2.511</i>	
<i>iii) At 3.1% asphalt content by weight of total mixture</i>		
<i>Calculated maximum theoretical specific gravity (Gmm)</i>	<i>2.550*</i>	
<i>iv) At 3.1% asphalt content by weight of total mixture</i>		
<i>Calculated maximum theoretical specific gravity (Gmm)</i>	<i>2.492*</i>	

Water tem.°C	18	19	20	21	22	23	24	25	26	27
Correction ,K	1.0016	1.0014	1.0012	1.001	1.0007	1.0005	1.0003	1	0.9997	0.9995

* Gmm is calculated value.

2.2.2. Weight-volume measurement result of compacted Marshal Specimen

Asphalt (%)	Designation	G _{mm}	W _{air} (gm)	Diameter, D (cm)	Height, H (cm)	Volume (cm ³)	G _{mb}	Air voids (%)
3.1	S-1	2.550	942.2	10.16	6.55	531.0	1.77	30.4
	S-2	2.550	948.7	10.16	6.56	531.8	1.78	30.0
	S-3	2.550	940.8	10.16	6.55	531.0	1.77	30.5
<i>Average</i>								30.3
3.6	S-1	2.531	946.5	10.16	6.56	531.8	1.78	29.7
	S-2	2.531	951.5	10.16	6.56	531.8	1.79	29.3
	S-3	2.531	943.4	10.16	6.55	531.0	1.78	29.8
<i>Average</i>								29.6
4.1	S-1	2.511	950.0	10.16	6.55	531.0	1.79	28.8
	S-2	2.511	952.0	10.16	6.56	531.8	1.79	28.7
	S-3	2.511	948.0	10.16	6.55	531.0	1.79	28.9
<i>Average</i>								28.8
4.6	S-1	2.492	953.1	10.16	6.56	531.8	1.79	28.1
	S-2	2.492	950	10.16	6.55	531.0	1.79	28.2
	S-3	2.492	955.3	10.16	6.56	531.8	1.80	27.9
<i>Average</i>								28.1

LABORATORY STUDY ON THE MIXTURE DESIGN OF GROUTED MACADAM

Appendix 2.3. Test Result of Experimental Program III

2.3.1. Marshal Stability-Flow Test results

<i>A. Marsh stability-flow test result of porous asphalt concrete</i>										
Asphalt by wt. of total mix (%)	Designation	G _{mm}	Wt. _(air) (gm)	Diameter (cm)	Height (cm)	Volume (cm ³)	G _{mb}	VTM (%)	Stability (kN)	flow (0.1 mm)
3.1	S-1	2.550	942.2	10.16	6.55	528.6	1.77	30.4	2.18	5.03
	S-2	2.550	948.7	10.16	6.56	528.6	1.78	29.7	1.59	6.41
	S-3	2.550	940.8	10.16	6.55	528.6	1.77	30.3	0.81	-----
<i>Average</i>								30.3	1.53	
3.6	S-1	2.531	946.5	10.16	6.56	528.6	1.78	29.6	1.61	5.35
	S-2	2.531	951.5	10.16	6.56	528.6	1.79	29.6	2.03	2.75
	S-3	2.531	943.4	10.16	6.55	528.6	1.78	29.3	1.46	7.42
<i>Average</i>								29.6	1.70	5.17
<i>B. Marshal stability-flow test result of grouted macadams (@ 3rd day of curing)</i>										
Asphalt content (%)	Designation	Wt. _(air) (gm)	Diameter (cm)	Height (cm)	Volume (cm ³)	G _{mb}	Stability (kN)	Flow (0.1 mm)		
3.1	S-1	1182.3	10.16	7.04	570.7	2.07	18.66	-----		
	S-2	1178.1	10.16	7.02	569.1	2.07	14.41	4.48		
	S-3	1145	10.16	6.9	559.4	2.05	24.36	3.1		
<i>Average</i>							19.14			
3.6	S-1	1186.9	10.16	7.02	569.1	2.09	21.19	3.32		
	S-2	1173.8	10.16	7.00	567.5	2.07	16.37	-----		
	S-2	1199.8	10.16	7.02	569.1	2.11	18	5.93		
<i>Average</i>							18.52			

LABORATORY STUDY ON THE MIXTURE DESIGN OF GROUTED MACADAM

2.3.2. Indirect tension test results (@ a constant strain rate of 50mm/min)

A. Indirect tensile strength of porous asphalt concrete

<i>i) After conditioned for 24 hours at test temperature of 25 °C</i>											
Asphalt content (%)	Designation	G _{mm}	Wt _(air) (gm)	Diameter (cm)	Average height (cm)	Volume (cm ³)	G _{mb}	VTM (%)	Gauge reading (division)	Load (N) div*25.5	ITS (kPa)
3.1	S-1	2.550	953.1	10.16	6.7	543.19	1.75	31.2	79	2015	188.40
	S-2	2.550	951.3	10.16	6.65	539.14	1.76	30.8	58	1479	139.36
	S-3	2.550	949.8	10.16	6.6	535.08	1.78	30.4	81	2066	196.10
<i>Average</i>								30.8	<i>Average</i>		174.62
3.6	S-1	2.531	951.7	10.16	6.7	543.19	1.75	30.8	72	1836	171.71
	S-2	2.531	948.1	10.16	6.55	531.03	1.79	29.5	76	1938	185.40
	S-3	2.531	957.1	10.16	6.6	535.08	1.79	29.3	80	2040	193.68
<i>Average</i>								29.9	<i>Average</i>		183.60
<i>ii) After conditioned for 24 hours at test temperature of 40 °C</i>											
3.1	1	2.550	950.6	10.16	6.6	535.08	1.78	30.3	15	382.5	36.32
	2	2.550	954.1	10.16	6.65	539.14	1.77	30.6	27	688.5	64.88
	3	2.550	951.9	10.16	6.6	535.08	1.78	30.2	20	510	48.42
<i>Average</i>								30.4	<i>Average</i>		49.87
3.6	1	2.531	960.7	10.16	6.75	547.25	1.75	30.6	29	739.5	68.65
	2	2.531	948.1	10.16	6.55	531.03	1.79	29.5	32	816	78.06
	3	2.531	957.1	10.16	6.6	535.08	1.79	29.3	27	688.5	65.37
<i>Average</i>								29.8	<i>Average</i>		70.69

LABORATORY STUDY ON THE MIXTURE DESIGN OF GROUTED MACADAM

B. Indirect tensile strength of grouted Macadams

<i>i) After conditioned for 24 hours at test temperature of 25 °C</i>									
Asphalt (%)	Designation	Wt _(air) (gm)	Diameter (cm)	Average height (cm)	Volume (cm ³)	G _{mb}	Gauge reading (div.)	Load (N) (div*25.5)	ITS (kPa)
3.1	S-1	1143.8	10.16	6.75	555.35	2.06	409	10430	968.19
	S-2	1155.7	10.16	6.8	569.14	2.03	466	11883	1095.01
	S-3	1155.1	10.16	6.8	569.14	2.03	422	10761	991.61
<i>Average</i>									<i>1018.27</i>
3.6	S-1	1242.7	10.16	7.15	579.67	2.14	424	10812	947.54
	S-2	1207.5	10.16	7.06	572.38	2.11	438	11169	991.31
	S-3	1167.5	10.16	6.8	551.30	2.12	385	9818	904.67
<i>Average</i>									<i>947.84</i>
<i>ii) After conditioned for 24 hours at test temperature of 40 °C</i>									
Asphalt (%)	Designation	Wt _(air) (gm)	Diameter (cm)	Average height (cm)	Volume (cm ³)	G _{mb}	Gauge reading (div.)	Load (N) div*25.5	ITS (kPa)
3.1	1	1184.4	10.16	6.85	555.35	2.13	185	4718	431.54
	2	1193.8	10.16	6.85	555.35	2.15	215	5483	501.52
	3	1210	10.16	7.02	569.14	2.13	160	4080	364.19
<i>Average</i>									<i>432.41</i>
3.6	1	1176.9	10.16	6.65	539.14	2.18	187	4769	449.32
	2	1211.8	10.16	7.01	568.32	2.13	145	3698	330.51
	3	1154.4	10.16	6.75	547.25	2.11	147	3749	347.98
<i>Average</i>									<i>375.94</i>

2.3.3. Two-Sample T-test analysis output of Minitab Software

I) For Marshal stability test result of grouted Macadam

Two-sample Test on the means of stability(kN) of grouted macadam with bit.content 3.1% vs 3.6%

Bit.Content	N	Mean	StDev	SE Mean
3.1%	3	19.14	4.99	2.9
3.6%	3	18.52	2.45	1.4

Difference = μ (3.1%) - μ (3.6%)
 Estimate for difference: 0.62
 95% CI for difference: (-13.19, 14.44)
 T-Test of difference =0 (vs \neq):T-Value =0.19 P-Value =0.864 DF = 2

II) For indirect tensile strength test result of grouted macadam @ 25 °C

Two-sample Test on the means of ITS(kPa) of grouted macadam with bitumen content 3.1% vs 3.6%

Bit.content	N	Mean	StDev	SE Mean
3.1%	3	1018.3	67.5	39
3.6%	3	947.8	43.3	25

Difference = μ (ITS of 3.1%) - μ (ITS of 3.6%)
 Estimate for difference: 70.4
 95% CI for difference: (-76.9, 217.8)
 T-Test of difference =0 (vs \neq):T-Value =1.52 P-Value =0.226 DF =3

III) For indirect tensile strength test result of grouted macadam tested @40 °C

Two-sample Test on the means of ITS(kPa) of grouted macadam with bitumen content 3.1% vs 3.6%

Bit.content	N	Mean	StDev	SE Mean
3.1%	3	432.4	68.7	40
3.6%	3	375.9	64.1	37

Difference = μ (3.1%) - μ (3.6%)
 Estimate for difference: 56.5
 95% CI for difference: (-116.2, 229.1)
 T-Test of difference=0 (vs \neq):T-Value = 1.04 P-Value =0.374 DF =3

APPENDIX 3. PHOTO GALLERY



Ordinary Portland cement



Distilled water



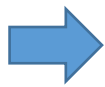
Silica sand



Bagasse ash



Megaflow SP1



All ingredients added and being mixed



Cementitious grout



Grout mortar cubes and beams that are casted and being air cured.



Typical cube under compressive



Beam under flexure test



Cubes after compressive failure



Typical specimen after tensile failure



Porous asphalt mixtures before mixing



Loose samples for max. theoretical specific gravity (Gmm)



Weight measurement for Gmm



Gmm samples under vacuum suction



Covered at the bottom with plastic sheets

Compacted porous specimens ready for grouting



Grouted porous specimens immediately after two hours grouting



Grouted macadam & porous asphalt specimens in a water bath @60 °C before Marshal test



Typical porous specimen under Marshal stability-flow test

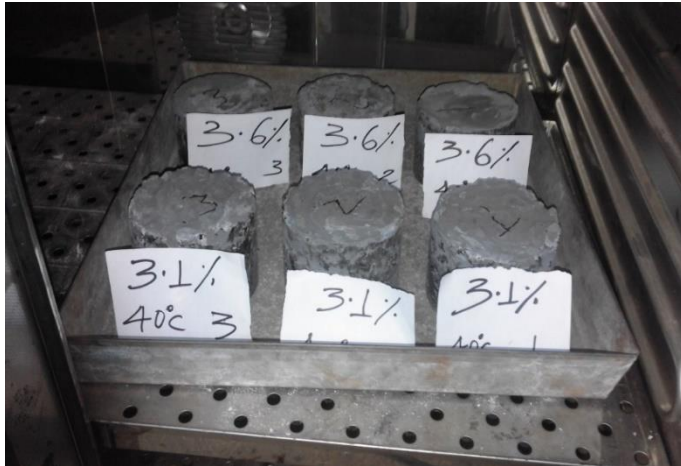


Typical grouted specimen after Marshal stability-flow test

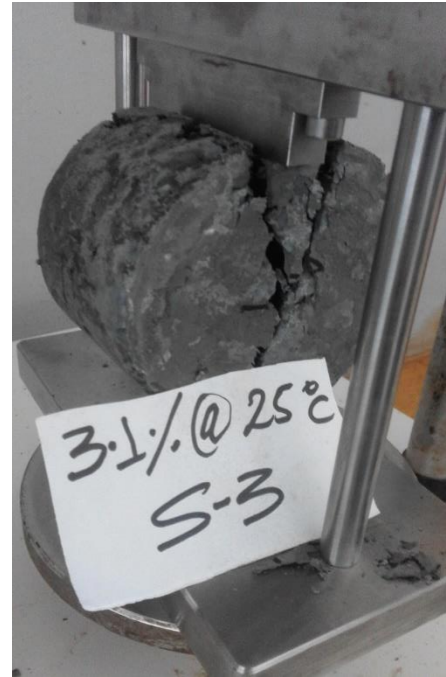


Typical porous asphalt concrete ready for conditioning in the oven before ITS test

LABORATORY STUDY ON THE MIXTURE DESIGN OF GROUTED MACADAM



Grouted macadam specimens that are being conditioned @40 °C in oven for ITS test



Typical grouted specimen immediately after failure



Grouted macadam specimens after ITS test



Close-up view of the internal structure of grouted macadam specimen after ITS test



Typical porous specimen immediately after ITS test