Creep Properties of Geopolymer Bituminous Mixtures

by

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Dissertation submitted in partial fulfillment of

the requirements for the

Bachelor of Engineering (Hons)

(Civil Engineering)

SEPTEMBER 2011

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Civil Engineering Programme Universiti Teknologi PETRONAS
in partial fulfillment of the requirement for the
BACHELOR OF ENGINEERING (Hons) (CIVIL ENGINEERING)

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TRONOH, PERAK
SEPTEMBER 2011

ACKNOWLEDGEMENT

First and foremost, I would like to thank God the Almighty, for only with his willing and blessing I am able to complete my Final Year Project and achieve what have been done in this work.

A special acknowledgement goes to my supervisor, AP. Ir. Dr. Ibrahim bin Kamaruddin, for the guidance and knowledge he has given to me throughout the completion of this project. I would also like to thank AP. Dr. Madzlan Bin Napiah for his invaluable input, useful suggestion and advice to this work.

My sincere appreciation also extends to the Mr. Iskandar and Mr Azran, the two technicians of Highway and Transportation Laboratory for their willingness to assist me during my entire laboratory work. I am also thankful to Mrs. Noor Zainab Habib for finding the time to help me with my work despite her busy schedule, and my fellow friend Ameer Mustakim for sticking with me through thick and thin in overcoming the many challenges we had to meet in the course of completing this project.

I wish to express my heartfelt gratitude and love to my beloved father Ismail Yusof for his wise thoughts and opinion, and my mother Rohana Ahmad for always being there to lift me up and give me comfort whenever I faced difficulties, and all my family who have never ceased giving me their support and encouragement all the way until the finish of this project.

Last but not least, I would like to convey my thanks to everyone who have directly or indirectly contributed in helping me finish my project and making this study a success.

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND OF PROJECT

A study was previously conducted in Universiti Teknologi Petronas(UTP) on the uses of geopolymer in porous asphalt, and it was discovered that using adding geopolymer on porous asphalt gives the substance a higher value of stiffness and stability compared to conventional pavement being used nowadays. This finding sparks the initiative to further investigate the properties of geopolymer bituminous mixtures, with the ultimate goal to study the potential capability of the substance to commercially replace the use of conventional pavement. The project "Creep Properties of Geopolymer Bituminous Mixtures" is a continuation of the previous study, with the aim to investigate the creep properties of geopolymer bituminous mixtures, and thus predicting the rut potential of the material. This project is an important component in an effort to investigate the suitability of geopolymer bituminous mixtures for its potential commercial use in the future.

Much of the drive behind research carried out in academic institutions these days is to investigate the development of geopolymer cements as a potential large-scale replacement for concrete produced from Portland cement. This is due to geopolymers' alleged lower carbon dioxide production emissions, greater chemical and thermal resistance and better mechanical properties at both ambient and extreme conditions. Addition of geopolymer to porous asphalt to produce a new type of pavement material is a new idea which seeks to exploit these valuable properties of geopolymer, which is beneficial in pavement design. In short, the use of geopolymer on bituminous mixtures therefore carries the prospect of combining these properties of geopolymer and porous asphalt to develop a material that is environmental friendly and durable at a competitive cost for use in pavement.

1.2 PROBLEM STATEMENT

Rutting, also known as permanent deformation, can be defined as the accumulation of small amounts of unrecoverable strains as a result of applied loading to a pavement. Rutting occurs when the pavement under traffic loading consolidates or there is a lateral movement of the hot-mix asphalt (HMA). The lateral movement is a shear failure and generally occurs in the upper portion of the pavement surface. Rutting is considered as a problem for some reasons. One of them is because pavement service life is reduced as a result of rutting, and thus will cost extra money for repairing purposes. Another reason is because if the rutting depth is significant then water may accumulate in the rutted area, which can lead to vehicle hydroplaning or skidding, making lane-changing a dangerous maneuver and possibly cause accident to road users.

Increase in cars and trucks, combined with various environmental effects has caused road surfaces to be exposed to the high traffic that causes constant and excessive stresses, which is the cause for permanent deformation (Chavez-Valencia et al, 2007, Wu et al, 2007, Abo-Qudais and Shatnawi, 2007, Tayfur et al, 2007). Therefore it is important to design a material that can withstand the stress and has greater durability than the existing conventional pavement, which is what could be achieved by geopolymer bituminous mixtures. Investigating the creep properties of the substance could help us determine its rut potential and in turn could justify its suitability to be used in pavement. Knowing the rut potential can also help us in devising an optimum design of the pavement, thus avoid unnecessary cost in case of over design, or repair cost because of under design.

Figure 1.2: Rutting in pavement

1.3 OBJECTIVE

i. To determine the creep properties of geopolymer bituminous mixtures
ii. To predict the rut potential of geopolymer bituminous mixtures

1.4 SCOPE OF STUDY

This project involves research work and laboratory work. Research work includes literature review and finding information on geopolymer, understanding creep properties of bituminous mixtures, and finding information on relevant tests to be conducted to determine creep properties of bituminous mixtures.

Laboratory work will be conducted in Highway Engineering Laboratory in UTP. Two tests will be conducted in order to obtain the creep properties of geopolymer bituminous mixtures, which are Dynamic Creep Test and Wheel Tracking Test. Both these tests were conducted based on standard specification of British Standard (BS) code.

CHAPTER 2

LITERATURE REVIEW

2.1 GEOPOLYMER

2.1.1 What is Geopolymer

Geopolymers are a class of inorganic polymer formed by the reaction between the reaction between an alkaline solution and an aluminosilicate source or feedstock. The hardened material has an amorphous 3-dimensional structure similar to that of an aluminosilicate glass. However unlike glass these materials are formed at low temperature and as a result can incorporate an aggregate skeleton and a reinforcing system if required, during the forming process.

2.1.2 Geopolymerization

As with conventional organic polymerization, the process involves forming monomers in solution then thermally triggering them to polymerize to form a solid polymer. The geopolymerization process involves three separate but inter-related stages.

i. During initial mixing the alkaline solution dissolves silicon and aluminium ions from the amorphous phases of the feedstock. The binder is the primary feedstock but any amorphous phases in the aggregate skeleton (stone or sand particles) will also react during this stage.

ii. In the solution, neighboring silicon or aluminium hydroxide molecules then undergo a condensation reaction where adjacent hydroxyl ions from these near neighbors condense to form an oxygen bond linking the molecules, and a free molecule of water; $OH^- + OH^- \rightarrow O^{2-} + H_2O$. The "monomers" so formed in solution can be represented in 2-dimensions by;-

- Si – O – Al – O - (poly[silalate]),

or, - Si – O – Al – O – Si – O - (poly[silalate-siloxi]),

where each oxygen bond, formed as a result of a condensation reaction, bonds the neighboring Si or Al tetrahedra.

iii. The application of mild heat (typically ambient or up to 90 degrees C) causes these "monomers" and other silicon and aluminium hydroxide molecules to poly-condense or polymerize, to form rigid chains or nets of oxygen bonded tetrahedra.

Higher "curing" temperatures produce stronger geopolymers. As each hydroxyl ion in the tetrahedral is capable of condensing with one from a neighboring molecule it is theoretically possible for any one silicon ion to be bonded via an oxygen bond to 4 neighboring silicon or aluminium ions, so forming a very rigid polymer network. Aluminium ions in such a network require an associated alkali metal ion (usually Na) for charge balance.

2.1.3 Application of Geopolymer

The properties of geopolymers are being explored in many scientific and industrial disciplines: modern inorganic chemistry, physical chemistry, colloid chemistry, mineralogy, geology, and in all types of engineering process technologies. The wide variety of potential applications includes: fire resistant materials, low energy ceramic tiles, refractory items, thermal shock refractory, foundry applications, cements and concretes, composites for infrastructures repair and strengthening, high-tech composites for aircraft interior and automobile, high-tech resin systems, radioactive and toxic waste containment, arts and decoration, cultural heritage, archeology and history of sciences. (Davidovits J., 2008).

2.1.4 Advantages of using Geopolymer

Geopolymer can provide comparable performance to traditional cementitious binders in a range of applications, but with the added advantage of significantly reduced Greenhouse emission (Gartner E., 2004). Depending on the raw material selection and selection and processing conditions, geopolymers can exhibit a wide variety of properties and characteristics, including high compressive strength, low shrinkage, fast or slow setting, acid resistance, fire resistance and low thermal conductivity.(P Duxon et al, 2006). Advantages of geopolymer in term of waste consumption and greenhouse emission are further explained below:

i. Waste Consumption

Geopolymer cements can be made from binders which are basically waste products;-

- fly ash and bottom ash produced in black coal fired power stations. ground granulated blast-furnace slags,
- bauxite processing residues,
- kaolinitic clays,
- certain mine wastes,
- naturally occurring pozzolans,

or any fine materials that contain significant amounts of silicon and aluminium in an amorphous form. Most current formulations use a mixture of sodium hydroxide and/or sodium silicate (or the potassium alternatives) as the alkaline activator, but any strongly alkaline waste liquor can be used as a partial or full substitute.

ii. Greenhouse gas emission

Wide-scale acceptance of Geopolymer Cements (GC) and the concretes they form could reduce the requirement for Ordinary Portland Cement (OPC). This represents a significant opportunity to reduce global carbon dioxide emissions as;-

- given that the production of OPC requires the calcining of limestone to form the calcium components of OPC, the production of 1 tonne of OPC (by milling OPC clinker) liberates approximately 1 tonne of carbon dioxide to the atmosphere.
- global OPC production accounts for about 5 to 10% of worldwide CO_2 emissions.
- assuming the use of a waste binder such as fly ash and standard chemical activators, the production of 1 tonne of geopolymer cement liberates just 0.16 tonnes of CO_2. The use of waste alkalis would clearly reduce this further.

The conclusion is that substituting GC for OPC would reduce cement generated CO_2 emissions by some 80% or more. For total replacement of OPC by GC, this potential saving represents some 4 to 8% of current world CO_2 emissions. (Davidovits J., 1994)

2.2 CREEP PROPERTIES OF ASPHALT MATERIALS

Viscoelastic materials, such as plastics, exhibit flow in addition to their elastic characteristics. Such behaviour is also common for asphalt concrete. This kind of flow under applied load pattern is called creep. Creep is defined as time dependent deformation characteristic of a viscoelastic material subjected to load.(Tapkin et al, 2009).

Asphalt concrete under constant stress condition exhibits a typical deformation characteristic which can be explained in four stages as shown below (Tapkin et al, 2009):

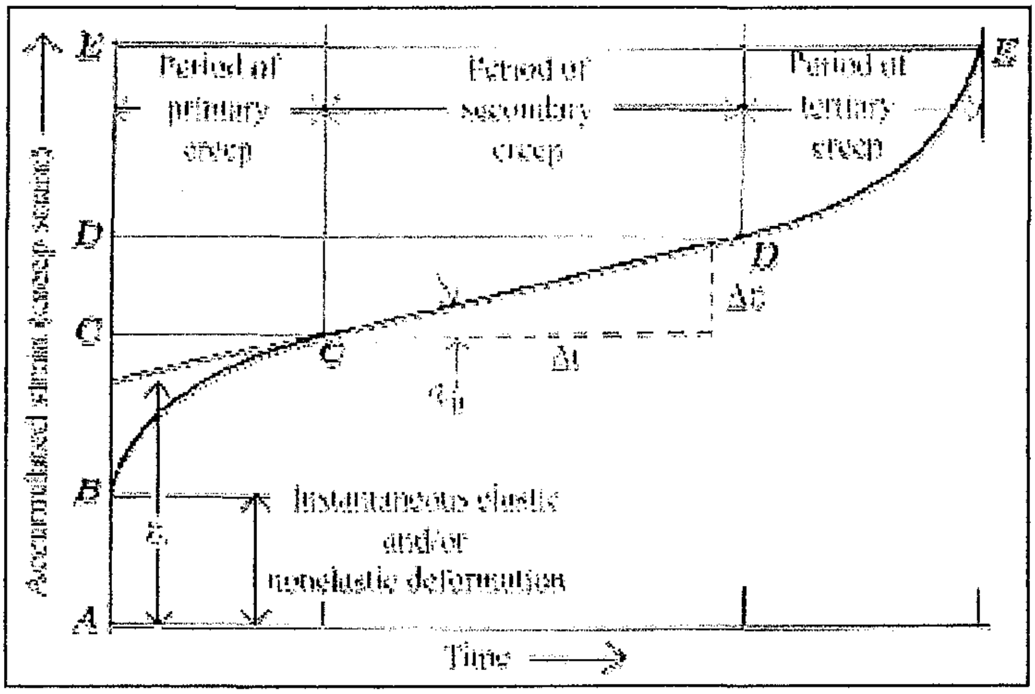

Figure 2.2: Typical creep curve for asphalt materials

1. Instantaneous elastic and/or non-elastic deformation: with the application of load, there is an immediate deformation. Upon the removal of the load through this stage, a portion of the deformation is recovered instantaneously. The amount of recovery is not necessarily equal to the instantaneous deformation that has occurred due to the application of the initial load.

2. Primary creep: if the load on the system is not removed, the material deforms further, but with a decreasing rate. Observed deformation at this stage has both recoverable and unrecoverable portions.

3. Secondary creep: at this region the slope of deformation is linear. The deformation that exhibits at this stage is unrecoverable.

4. Tertiary creep: at this stage represents the complete plastic failure of the material. At this stage deformation has an accelerated increasing rate.

Basically, there will be two tests conducted to determine the creep properties of geopolymer bituminous mixtures, which are Dynamic Creep Test and Wheel Tracking Test.

2.2.1 Dynamic Creep Test

A repeated load test applies a repeated load of fixed magnitude and cycle duration to a cylindrical test specimen. The specimen's resilient modulus can be calculated using its horizontal deformation and an assumed Poisson's ratio. Cumulative permanent deformation as a function of the number of load cycles is recorded and can be correlated to rutting potential. Tests can be run at different temperatures and varying loads. The load varies is applied in a short pulse followed by a rest period. Repeated load tests are similar in concept to the triaxial resilient modulus test for unconfined soils and aggregates. Repeated load tests correlate better with actual in-service pavement rutting than static creep tests.

2.2.2 Wheel Tracking Test

Laboratory wheel-tracking devices are used to run simulative tests that measure HMA qualities by rolling a small loaded wheel device repeatedly across a prepared HMA specimen. Performance of the test specimen is then correlated to actual in-service pavement performance. Laboratory wheel-tracking devices can be used to make rutting, fatigue, moisture susceptibility and stripping predictions. Some of these devices are relatively new and some have been used for upwards of 15 years like the French Rutting Tester (FRT).

In general, these wheel tracking devices have potential for rut and other measurements but the individual user must be careful to establish laboratory conditions (e.g., load, number of wheel passes, temperature) that produce consistent and accurate correlations with field performance.

2.3 PERMANENT DEFORMATION

Verstraeten (1995) mentioned that a distinction should be made between three permanent deformation mechanisms which lead to rutting:

i. The first is the result of the individual deformation of one or more layers (including the subgrade) underlying the bituminous courses, due to load-induced stresses which exceed material strength. This is referred to as **structural rutting,** and the resulting ruts are wide and do not have humps to their sides (V profile).
ii. The second mechanism is the result of the individual deformation of the bituminous courses due to load induced stresses exceeding the stability threshold of the material. This is called **flow rutting,** and the resulting ruts have humps to their sides (W profile under the action of dual tires, and asymmetric under the action of wide-based single tires.) Flow ruts are most often formed on ascending gradients, on junction approaches and in bends, i.e. where heavy lorries have to reduce speed and tangential stresses in the tire pavement contact area are higher.
iii. The third mechanism is the result of actual wear of the pavement due to the use of studded tires in winter. This is termed **wear rutting,** and the resulting ruts have a transverse profile characterized by neat discontinuity.

These three mechanisms may act independently of each other or simultaneously.

2.3.1 Structural Rutting

Structural rutting generally occurs in pavements inadequately designed for actual traffic conditions. It may also be due to the use of unsuitable or incorrectly laid (e.g. poorly compacted) materials, to inadequate drainage, to poor design against freezing and thawing effects – in fact anything that may affect the bearing capacity of the subgrade in the layers in the pavement during its projected service life.

The measures to avoid this type of distress are at present well known (design methods for loads, design methods against freezing and thawing, recommendations for the use and laying of materials and for subsoil, subsurface and surface water drainage). The most typical case is probably that of an initially well-designed pavement with traffic conditions becoming sever than anticipated. The solution called for in this case is strengthening, for which there are design methods that account for the residual bearing capacity of the existing pavement. This bearing capacity is generally determined from surface deflection under a known load. (Verstraeten, 1995)

2.3.2 Flow rutting

This type of rutting has to do with mix design rather than structural design. The relevant factors are the characteristics of the various constituents, their proportions in the mix, and laying. The only valid solution in this case is to replace the affected course either with new materials or with materials recycled and corrected on site or central plant. (Verstraeten, 1995)

2.3.3 Wear Rutting

Rutting by wear of the pavement is caused by the action of studded tires in winter. It occurs more particularly in Nordic countries and the main parameter to be considered is aggregate hardness. This mechanism is becoming less frequent as the use of studded tires has been restricted or prohibited since the first damage was observed. (Verstraeten, 1995)

CHAPTER 3
METHODOLOGY

There are three main stages in this project:

- i. Research/literature review
- ii. Laboratory work
- iii. Data analysis and interpretation

The details of each stage will be further explained below:

3.1 RESEARCH/LITERATURE REVIEW

In this stage is where information regarding the project is gathered and analyzed. This phase is also the time to fully understand the purpose and the prospect of the project.

3.2 LABORATORY WORK

Two experiments will be conducted in this project, namely Dynamic Creep Test and Wheel Tracking Test. The flow of the lab work is as below:

1. Preparing porous asphalt. For this project porous asphalt will be used because the pores in the pavement mixture are important as it provides void or space for geopolymer slurry to be poured into. The gradation of aggregates for porous asphalt as obtained from Jabatan Kerja Raya (JKR) Malaysia specification:

BS Sieve Size, mm	Percentage Passing, by weight	
	Grading A	Grading B
20.0	-	100
14.0	100	85 - 100
10.0	95 - 100	55 - 75
5.0	30 - 50	10 - 25
2.36	5 - 15	5 - 10
0.075	2 - 5	2 - 4

Table 3.2.1: Gradation limit of combined aggregates for porous asphalt

The materials for porous asphalt (specified by JKR):

❖ ***Coarse Aggregate :***

The coarse aggregate used shall be screened crushed rock, angular in shape and free from dust, clay, vegetative, organic matter, and other deleterious substances. They shall conform to the following physical and mechanical quality requirements:

a) The loss by abrasion and impact in the Los Angeles machine when tested in accordance with ASTM C 131 shall be not more than 25%.
b) The weighted average loss of weight in the magnesium sulfate soundness test (five cycles) when tested in accordance with AASHTO T 104 shall be not more than 18%
c) The flakiness index when tested in accordance with MS 30 shall be not more than 25%
d) The water absorption when tested in accordance with MS 30 shall be not more than 2%
e) The polished stone value when tested in accordance with MS 30 shall be not less than 40.

Notwithstanding compliance with the aforementioned requirements, crushed or uncrushed limestone and gravel shall not be permitted.

❖ *Fine Aggregate :*

The fine aggregate shall be screened quarry fines. They shall be non-plastic and free from clay, loam, aggregations of material, vegetative and other organic matter or deleterious substances. They shall conform to the following physical and mechanical quality requirements:

a) The sand equivalent of aggregate fraction passing the No.4 (4.75mm) sieve when tested in accordance with ASTM D 2419 shall be not less than 45%
b) The fine aggregate angularity when tested in accordance with Ohio Department of Transportation Standard Test Method shall be not more than 10mg/g
c) The weighted average loss of weight in the magnesium sulfate soundness test (five cycles) when tested in accordance with AASHTO T 104 shall be not more than 20%
d) The water absorption when tested in accordance with MS 30 shall be not more than 2%

❖ ***Mineral Filler :***

Mineral filler shall be incorporated as part of the combined aggregate gradation and it shall be of finely divided mineral matter of hydrated lime (calcium hydroxide). At the time of mixing with bitumen, the hydrated lime shall be not less than 70% by weight shall pass the BS 75 μm sieve. If hydrated lime is not available, ordinary Portland Cement shall be used as alternative, subject to approval by the S.O. the amount of mineral filler to be added shall be not less than 2% by weight of the combined aggregates. However, the amount shall be limited to not more than 2% if hydrated lime is used.

- ***Bituminous Binder :***

The bituminous binder for use with porous asphalt in this project is of grade 80/100. The optimum bitumen content for porous asphalt is 5% (Habrah, 2011).

Figure 3.2.1: Creep Test sample

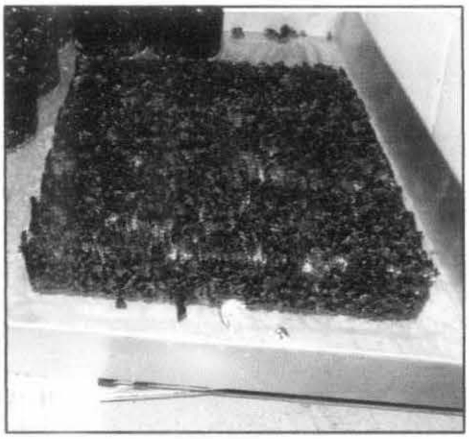

Figure 3.2.2: Wheel Tracking sample

2. Adding/ mixing geopolymer to porous asphalt sample. The type of geopolymer used in this project is fly-ash based and the mixture used to produce the geopolymer is specified in the tables below:

Fly Ash	**NaOH**		**Na_2SIO_3**	**Extra Water**	
kg/m^3	**kg/m^3**	**Mol**	**kg/m^3**	**kg/m^3**	**%**
350	41	8	104	35	10

Table 3.2.2: Proportion of geopolymer in density Parameter

Volume	**Fly Ash**	**NaOH**		**Na_2SIO_3**	**Extra Water**	
m^3	**kg**	**kg**	**Mol**	**kg**	**kg**	**%**
0.002	0.7	0.082	8	0.208	0.07	10

Table 3.2.3: Proportion of geopolymer in weight (kg)

The geopolymer is in slurry form and is added onto the samples on a vibrating table. The vibration ensures that the slurry will seep in and fill the voids inside porous asphalt sample. 150ml of geopolymer slurry is added to each creep sample, while 750ml is added to wheel tracking sample. Samples are left for seven days to harden before any test is performed.

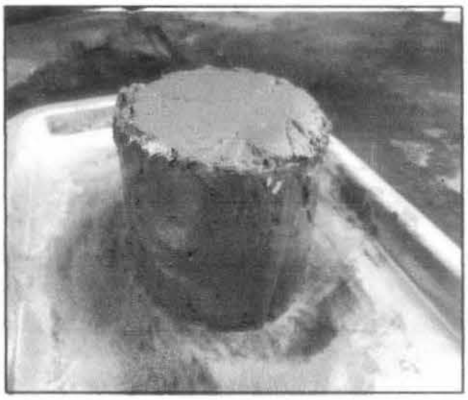

Figure 3.2.3: Geopolymer mixed porous asphalt for creep test

Figure 3.2.4: Geopolymer mixed porous asphalt for wheel tracking test

3. Conducting **Dynamic Creep Test** and **Wheel Tracking Test**

❖ ***Dynamic Creep Test:***

It applies a repeated pulsed uniaxial stress/load to a mixture specimen and measures the resulting deformations in the same axis using Linear Variable Displacement Transducers (LVDTs). The conditions of the test are; the temperature was 40 0C, 2 minutes for preloading at 12 kPa, and 1hour for loading options (Ahmedzade and Yilmaz, 2007; Cabrera and Nikolaides, 1988). The data of the creep test were plotted to show the relationship between permanent deformations (mm) versus cycles. Creep Test will be conducted in laboratory using Universal Testing Machine (UTM).

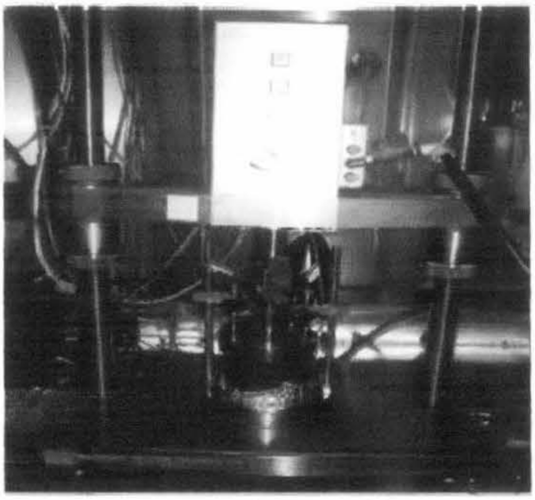

Figure 3.2.5: Dynamic Creep Test apparatus

❖ ***Wheel tracking test***

Wheel tracking test is a test to measure the rutting behavior of bituminous mixtures. This test will be done using Wessex wheel tracking machine available in UTP. The test should be conducted at 40°C, with an actual 200mm diameter and 50mm width with a total wheel load of 520 N applied on specimen prepared for the test. The wheel will be run backward and forward across the centre of the specimen with a specified frequency, with a maximum of 2000 passes. The total rut depth will be recorded using Wessex software that came together with the testing machine. All the parameters mentioned conform to the specification of BS 598 110: 1998.

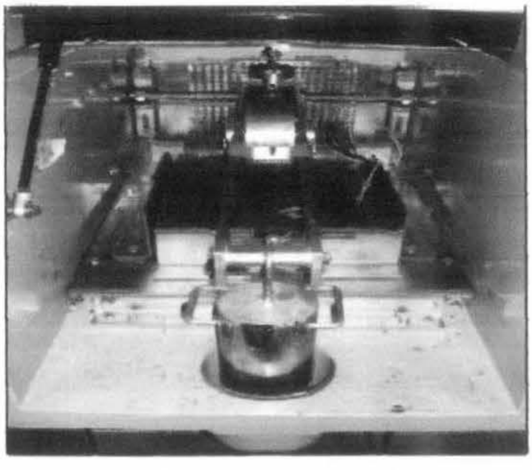

Figure 3.2.6: Wessex Wheel Tracking Machine

3.3 DATA ANALYSIS AND INTERPRETATION

This stage requires analysis of data obtained from Dynamic Creep Test and Wheel Tracking Test that have been completed. For Dynamic Creep Test, the rut depth versus standard axle repetitions graph for geopolymer bituminous mixtures will be plotted and compared to conventional pavement, while for Wheel Tracking Test the rut depth and deformation rate will be measured and compared to the performance of conventional pavement as well.

3.4 GANTT CHART

No	Activities	Semester May 2011				Semester Sep 2011			
		Month				Month			
		May	Jun	Jul	Aug	Sep	Oct	Nov	Dis
1	Selection of project topic	🟨							
2	Submission of project proposal		🟨						
3	Literature review research		🟨						
4	Project work		🟨	🟨					
5	Submission of progress report			🟨					
6	Project work continues			🟨	🟨				
7	Submission of interim report				🟨				
8	Oral Presentation				🟨				
10	Project work continue				🟨	🟨	🟨	🟨	
11	Submission of progress report II							🟨	
12	Project work continue							🟨	🟨
13	Submission of final dissertation draft								🟨
14	Poster presentation								🟨
15	Submission of final report								🟨

CHAPTER 4
RESULTS AND DISCUSSION

4.1 DYNAMIC CREEP

The result presented below is the average values obtained from three specimens. These mixtures were made at optimum binder content in order to obtain better creep properties. Figure 4.1.1 below shows the result of dynamic creep test in terms of creep modulus against the number of cycles. The graph indicates that creep modulus decreases with increasing loading cycles.

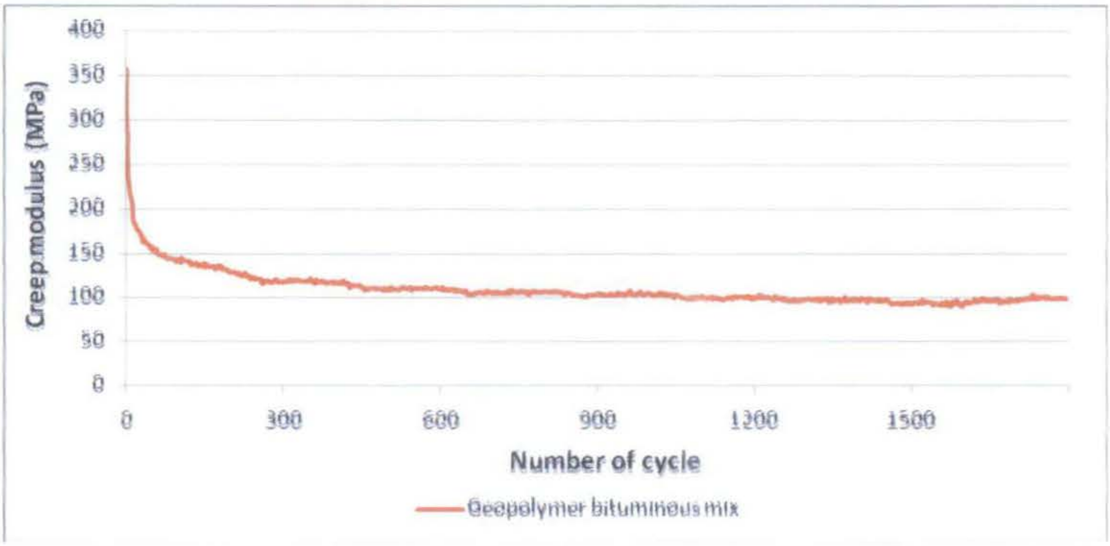

Figure 4.1.1: Creep stiffness of geopolymer bituminous mixture

Figure 4.1.2 shows a graphical presentation of the creep results in term of creep modulus versus number of cycles in logarithmic scales. The slope of the graph which represents the sensitivity of the mixture to creep deformation is then calculated and compared to the performance of conventional pavement. The slopes for both geopolymer bituminous mixture and conventional pavement are tabulated in Table 4.1.1.

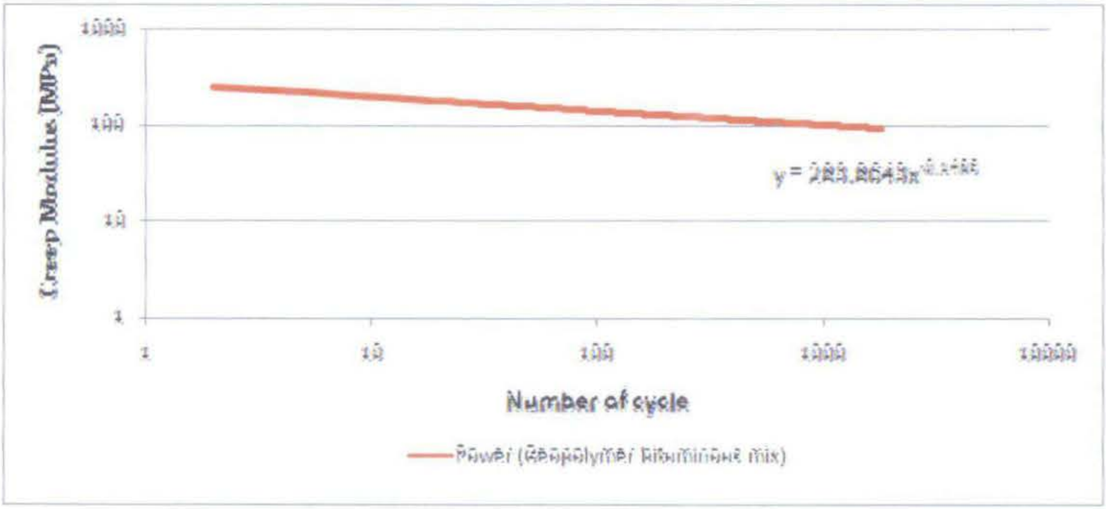

Figure 4.1.2: Creep stiffness vs cycles for geopolymer bituminous mixture

Type of mixture		Slope of graph
Geopolymer bituminous mixture		0.1485
Conventional pavement (ACW20, bitumen 80/100)	Quarry sand	0.1465
	River sand	0.3044
	Mining sand	0.3086
	Marine sand	0.3197

Table 4.1.1: Slope of graph of geopolymer bituminous mix and conventional pavement with various types of fine aggregate

The relationship between the slope of graph and creep susceptibility is that a lower slope of the graph means less susceptible to deformation or better resistance to the creep. From Table 4.1.1, we can see that geopolymer bituminous mixture has second lowest slope compared to all types of conventional pavement. The slope of graphs for conventional pavement (ACW20 with bitumen grade 80/100 as binder) with various types of sand as fine aggregates are obtained from Yasreen(2009). The result shows that geopolymer bituminous mixture has comparable performance to creep with conventional pavement with quarry sand as fine aggregate, which is commonly used type of sand that is used in construction of pavement. The result also indicates that geopolymer bituminous mixture is better than other conventional pavement using various types of fine aggregates other than quarry sand.

Figure 4.1.4 shows typical graph plots of mixture stiffness (S_{mix}) versus bitumen 80/100 stiffness (S_{bit}) in a double logarithmic graph for geopolymer bituminous mix and conventional pavement. Mixture stiffness was measured by Universal Testing Machine at 40°C for 1 hour loading time period and the corresponding bitumen stiffness S_{bit} was calculated by using Van Der Poel's nomograph (Figure 4.1.3).

The resistances to permanent deformation from the creep tests were determined using the slope from the log-log relationship of mixture stiffness versus binder stiffness. Mixture stiffness corresponds to a fixed loading time, or the time to reach a critical strain level. This manner of characterization is based on the fact that more resistant mixtures have stiffness that are greater and decrease rapidly with increasing time.

Loading time, second	Bit. stiffness, S_{bit} (80/100)	Geopolymer bituminous mix stiffness, S_{mix}
4	0.0075	356.9345
8	0.005	272.717
20	0.0015	212.684
40	0.001	183.472
60	0.0008	170.4205
80	0.0006	161.554
100	0.0005	156.167
200	0.0002	143.331
400	0.0001	129.1295
600	0.00009	118.371
800	0.000075	115.327
1000	0.000055	109.9025
2000	0.000025	105.694
3600	0.00002	99.3545

Table 4.1.2: Tabulated value of mixture stiffness, S_{mix} and bitumen stiffness, S_{bit}

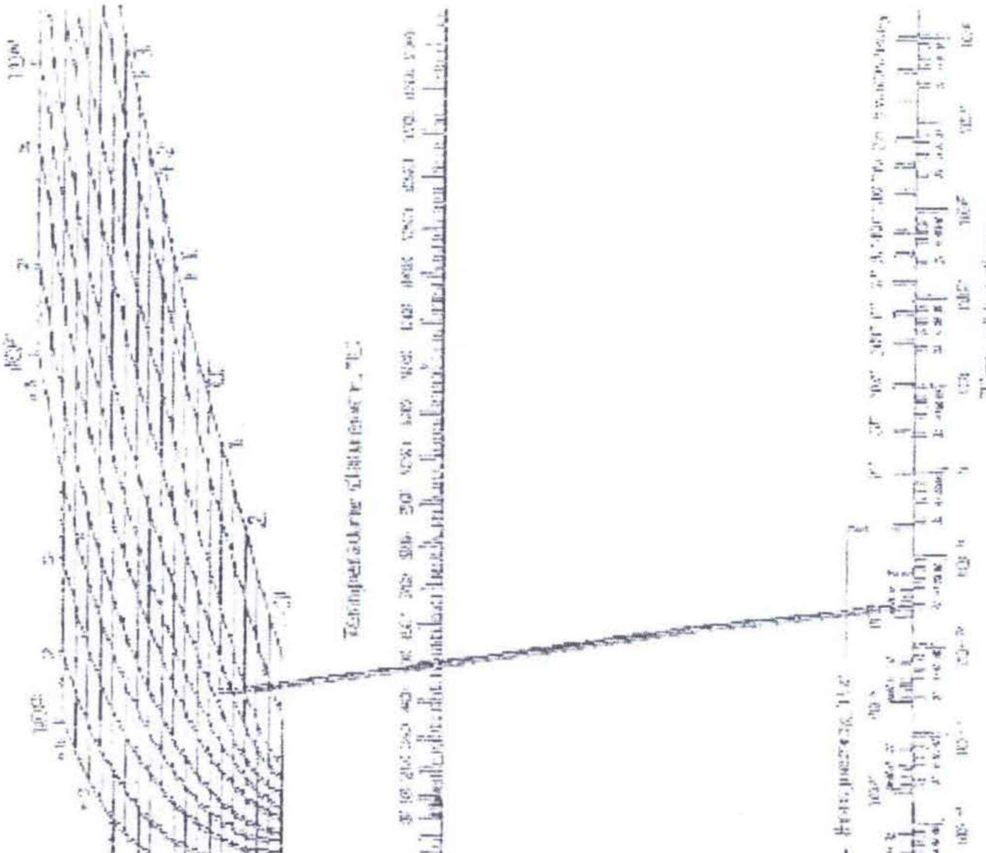

Figure 4.1.3: Van der Pool nomograph for determination of S_{bit}

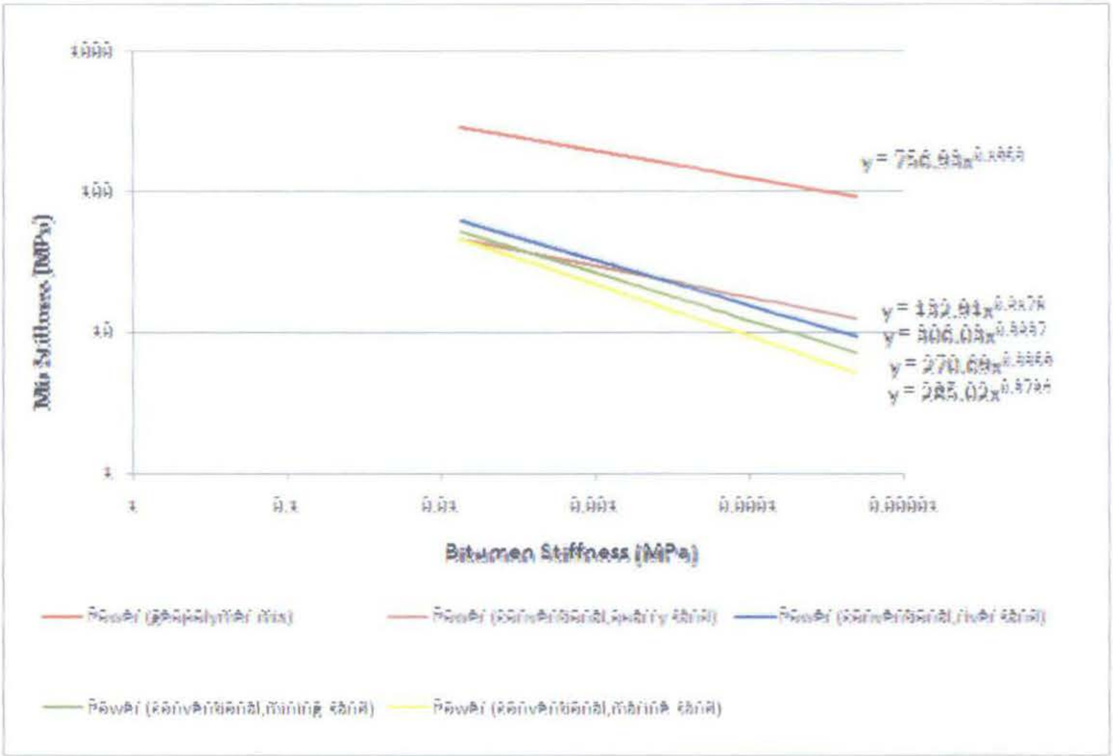

Figure 4.1.4: Mix stiffness, S_{mix} vs bitumen stiffness, S_{bit}

The stiffness of geopolymer bituminous mixture is higher than the stiffness of the mixtures of conventional pavement. The slope of the S_{mix} versus S_{bit} relationship also indicates the mixture's susceptibility to time of loading, the relationship is that smaller value of slope indicates less susceptibility to creep deformation which means better performance. The result in Table 4.1.3 indicates that geopolymer bituminous mixture is least susceptible to loading time in comparison to the conventional mixtures, as it has the lowest slope among all other mixtures.

Mixture		**Formula**	**(a) Value**	**(b) Slope**
Geopolymer bit. mix		$y = 756.93x^{0.1953}$	756.93	0.1953
Conventional pavement	Quarry	$y = 132.91x^{0.2178}$	132.91	0.2178
	River	$y = 306.03x^{0.3237}$	306.93	0.3237
	Mining	$y = 270.69x^{0.3359}$	270.69	0.3359
	Marine	$y = 285.02x^{0.3724}$	285.02	0.3724

Table 4.1.3: Creep results in term of S_{mix} vs S_{bit}

The relationship between stiffness of mixture and stiffness of bitumen can be expressed in form of the equation:

$$S_{mix} = a\,(S_{bit})^{\,b}$$

A good correlation between S_{mix} and S_{bit} can also be seen from the plots. The equation of the lines can be expressed as:

$$Log\,(Y) = Log\,(a) + b\,Log\,(X)$$

or

$$Y = aX^b$$

Where: Y= stiffness of the mix in MPa
a = interception of the line with y-axis
X = stiffness of the binder in MPa
b = slope of the line

In this equation, coefficients "a" and "b" represent the mixture in terms of deformation performance. Mixture stiffness is indicated by the constant "a" and the slope "b" indicates the sensitivity of the mixture to loading time. Therefore, mixture with high value of coefficient "a" and low value of coefficient "b" will exhibit good deformation resistance.

Hills et al (1974) suggested the following equation for determining the stiffness modulus of bitumen corresponding to its viscous part:

$$(Sbit)^{\,v} = 3\eta / N.T_w$$

Where: $(Sbit)^v$ = viscous component of the stiffness modulus of the bitumen

η = viscosity of the binder as a function of PI, and ring and ball temperature (refer figure 4.1.5)

N = number of wheel passes in standard axles (in million)

T_w = time of loading for one wheel pass.

To obtain η, first obtain the penetration index, PI using the formula:

$$\frac{\log 800 - \log pen}{T_{R+B} - T} = \frac{20 - PI}{10 + PI} \times \frac{1}{50}$$

Where: PI = penetration index

pen = measured penetration at temperature T (normally 25°C)

T_{R+B} = softening point temperature

T = penetration test temperature (normally 25°C)

Using value of $pen = 90$, $T_{R+B} = 49°C$, and $T = 25°C$

obtained from Yasreen(2009), the calculated penetration index, PI is 0.0779 and η is approximately 200000 Ns/m^2, obtained from Figure 4.1.5. Then plot the value of $(Sbit)^v$ at N = 1, 100, 10000… 1E+10. Using T_w = 0.02 sec, the tabulated value of $(Sbit)^v$ is:

N	1E+6	1E+8	1E+10	1E+12	1E+14	1E+16
(Sbit) ^{v}**, *MPa***	0.00003	0.0000003	0.000000003	3E-11	3E-13	3E-15

Table 4.1.4: Calculated value of S_{bit}

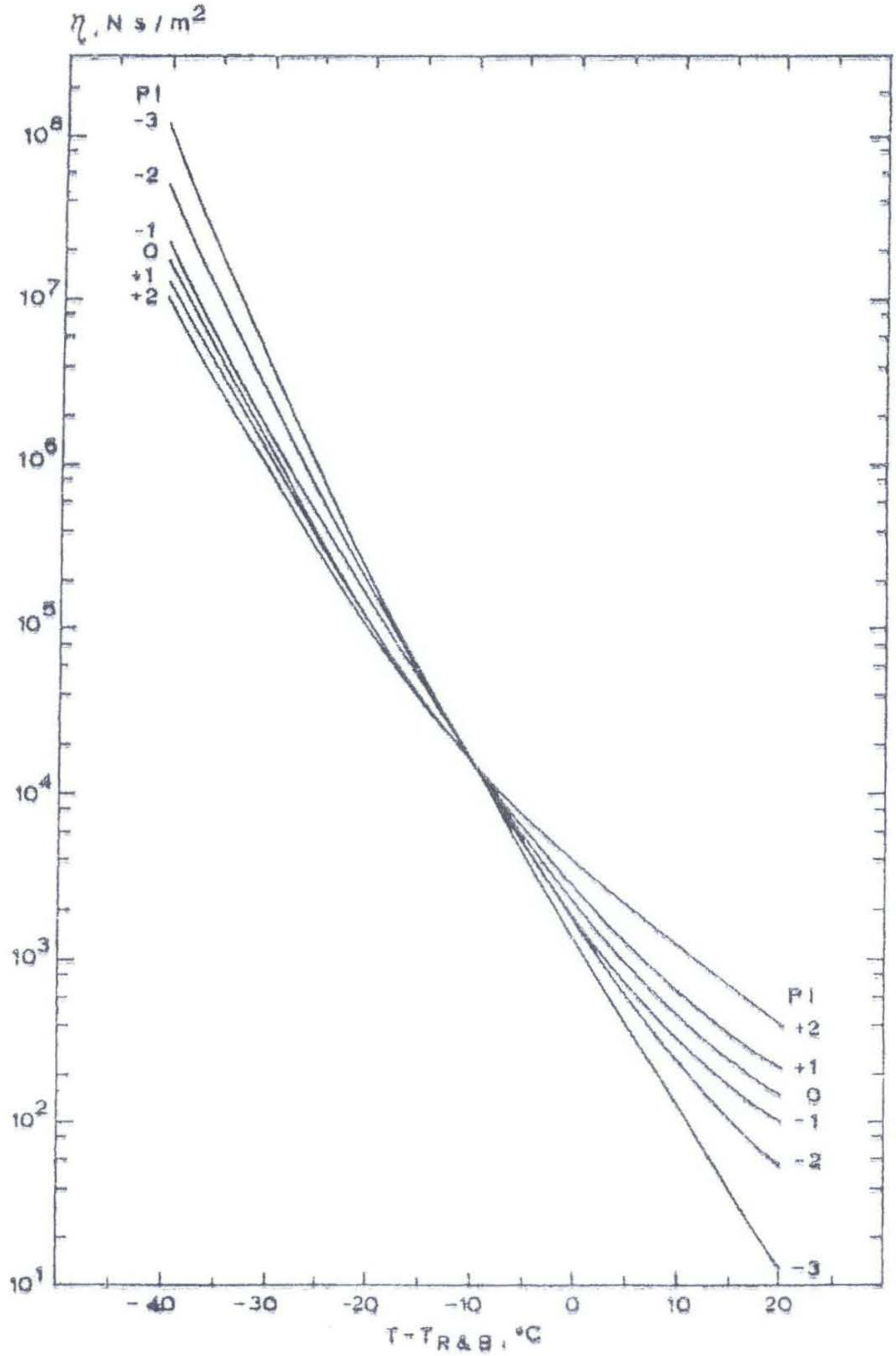

Figure 4.1.5: Viscosity of bitumen as a function of T - T_{R+B} and PI obtained from van der Poel's nomograph

Inserting the values of $(Sbit)^v$ into the equation $S_{mix} = a\ (S_{bit})^{b}$, then we get the value of S_{mix} as in the table below:

N	1E+6	1E+8	1E+10	1E+12	1E+14	1E+16
$(Sbit)^v$, MPa	0.00003	0.0000003	0.000000003	3E-11	3E-13	3E-15
S_{mix}, MPa	99.02332	40.28445	16.388435	6.667108	2.71229	1.103411

Table 4.1.5: Calculated value of S_{mix}

Formula for estimation of rut depth of pavement from laboratory creep test result was initially proposed by Hills et al. and van der Loo:

$$R_d = C_m \times H \times \sigma_{av} / S_{mix\ creep}$$

Where: R_d = calculated rut depth of pavement

C_m = correlation factor for dynamic effect varying between 1.0 and 2.0

H = pavement layer thickness

σ_{av} = average stress in pavement related to wheel loading and stress distribution.

$S_{mix\ creep}$ = stiffness of design mixture derived from creep test at a certain value of stiffness related to the viscous part of bitumen

Using the following numerical assumption:

$$C_m = 1.5,\quad H = 100\text{mm, and}\quad \sigma_{av} = 0.25\text{Mpa}$$

the graph of rut depth versus standard axle repetitions can be plotted as in Figure 4.1.6.

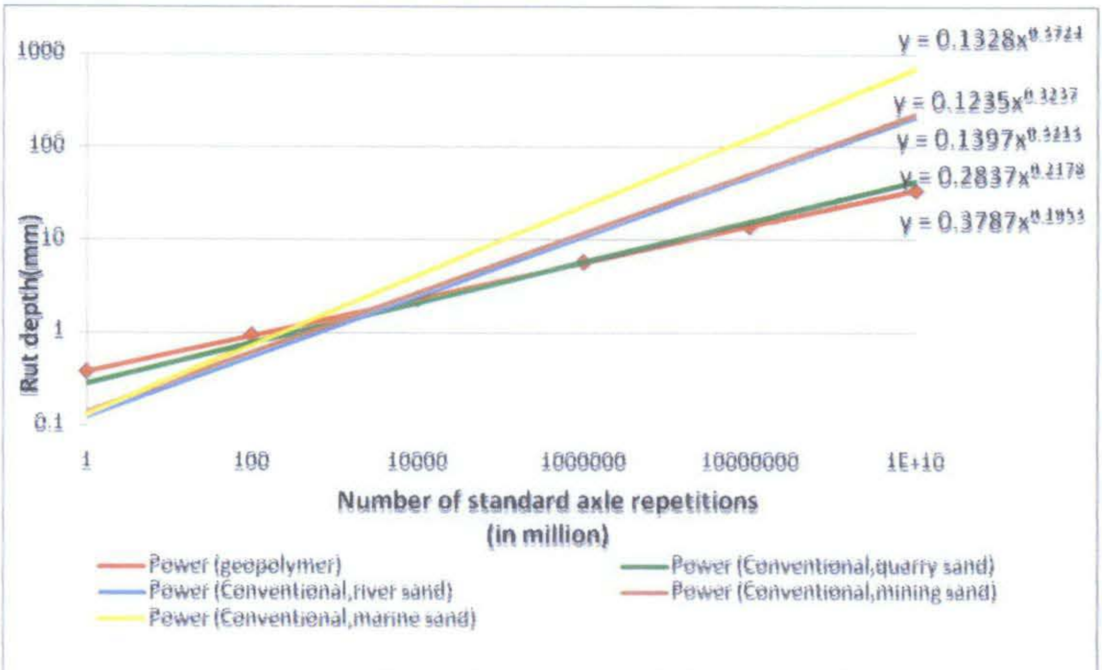

Figure 4.1.6: R_d estimation related to the number of standard axle repetitions

From equation of the line in figure 4.1.6, we can estimate the required number of cycle for the material to arrive at a certain value of rut depth. Table 4.1.6 shows the estimated number of cycle at maximum rut depth allowable in pavement, which is 25mm. It can be seen that geopolymer bituminous mix are able to take more cycles in comparison with conventional mixtures.

Geopolymer mix	**Conventional pavement mix**			
	Quarry sand	**River sand**	**Mining sand**	**Marine sand**
$20758*10^5$	$85227*10^4$	$13326*10^3$	$50885*10^2$	$12833*10^2$

Table 4.1.6: Number of estimated cycles at maximum R_d allowable in the pavement

From Figure 4.1.6 and Table 4.1.6, it can be seen that geopolymer bituminous mixture exhibit better performance compared to conventional pavement. From Figure 4.1.6, although geopolymer mixture has the highest rut depth in the beginning, but it shows greater resistance to rutting in long run, as indicated by the lowest slope and lowest rut depth in the end. This is probably due to the increased density of the mixture after geopolymer has been mixed to the sample. The geopolymer slurry will seep into voids inside the sample and once it has hardened it will occupy the voids, giving less room for displacement of particles to occur when subjected to load, hence increasing its resistance to permanent deformation. High rut depth at the beginning is possibly due to the early settlement of particles upon loading, but once all the particles have consolidated geopolymer mixture shows the best resistance to rutting, slightly edging the performance of conventional pavement using quarry sand as indicated by its slope of line (0.1953) against conventional quarry sand (0.2178). However this difference is proven to be significant when comparing the performance of the mixtures at maximum allowable rut depth (25mm) as indicated in table 4.1.6, with geopolymer mixture able to take $20758*10^5$ cycles while conventional quarry sand only able to withstand estimated $85227*10^4$ cycles.

Severe consolidation of the geopolymer mixture particles which lead to it having high rut depth at early number of standard axle repetitions or early application of load could be caused by high air voids content in the mixture. To check the validity of the aforementioned theory, the air voids content of geopolymer mixtures were checked.

Calculation of percentage air voids content is done using the formula:

$$V_a = \left(1 - \frac{G_{mb}}{G_{mm}}\right) \times 100$$

Where V_a = air void content (%)

G_{mb} = bulk specific gravity of the compacted mixture

G_{mm} = maximum theoretical sepcific gravity of the mixture

The bulk specific gravity of the compacted mixture, G_{mb} is found using the formula:

$$G_{mb} = \frac{W_D}{W_{SSD} - W_{sub}}$$

Where W_D = dry weight of sample

W_{SSD} = saturated surface dry weight of the sample

W_{sub} = weight of sample submerged in water

The values of the parameters were measured on three samples and the resulting G_{mb} are as tabulated below:

Sample	W_D, (g)	W_{sub}, (g)	W_{SSD}, (g)	G_{mb}
1	1390	763.5	1384	2.2401
2	1558	848.4	1568	2.1650
3	1506	825.2	1515	2.1832

Table 4.1.7: Values of W_D, W_{SSD}, W_{sub}, and calculated G_{mb}

The maximum theoretical sepcific gravity of the mixture, G_{mm} is found using the formula:

$$G_{mm} = \frac{1}{\frac{1-P_b}{G_{se}} + \frac{P_b}{G_b}}$$

Where P_b = asphalt content by weight of mix (%)

G_{se} = effective specific gravity of the aggregate

G_b = asphalt binder specific gravity

The values of Pb, Gse and Gb are constant values for all samples. From Habrah, 2011 the obtained values Pb, Gse and Gb, and the calculated value of G_{mm} are tabulated below:

P_b (%)	G_{se}	G_b	G_{mm}
0.05	2.643	1.03	2.4510

Table 4.1.8: Values of P_b, G_{se}, G_b, and calculated G_{mm}

The percentage air voids content, V_a can then be calculated:

Sample	W_D, **(g)**	W_{sub}, **(g)**	W_{SSD}, **(g)**	G_{mb}	G_{mm}	V_a **(%)**
1	1390	763.5	1384	2.2401	2.4510	8.6063
2	1558	848.4	1568	2.1650	2.4510	11.6677
3	1506	825.2	1515	2.1832	2.4510	10.9273
					Average	**10.4004**

Table 4.1.9: Calculated percentage air voids content, V_a

Air voids of geopolymer bituminous mixtures have been determined to be at 10.4%, which is considered high for wearing course in pavement. The result indicates that it is possible that the early consolidation of geopolymer mixture is in fact caused by high air voids content in the mixture. The result (10.4%) has also exceeded the standard specification set by JKR for wearing course to have air void content within the range of 3% – 5%. However, the air void content of geopolymer mix is almost half the air voids content of porous asphalt which is used in this project. One possible cause of the high air voids percentage in geopolymer bituminous mixture is because of improper or inadequate vibration when mixing geopolymer to the sample, which consequently causes the failure of geopolymer slurry to enter or seep into the voids inside the sample. Failure of the slurry to fill in the voids inside geopolymer mixture can also be caused by the properties of geopolymer itself, which is very quick to harden and changes from its original watery/slurry form upon mixing, to very viscous after several minutes. Its high viscosity causes it to fail to penetrate into the voids inside porous asphalt, thus leaving a lot of air voids inside the mixture.

Apart from vigorous or severe early consolidation in the mixture, having a high percentage of air voids content can also lead to another problem. Oxygen which is present in the air would cause oxidation of the bitumen, undermining its binding capabilities and consequently weaken the material further. Therefore although geopolymer mix has better creep resistance, it is possible that it is prone to weakening of structural integrity in the latter part of its service life.

4.2 WHEEL TRACKING

The result of laboratory wheel tracking test can be compared with the actual performance of the road structure because the test was done in conditions similar to actual road conditions. The test machine was set to operate for 46 minutes at 42 cycles per minute. The result of the test is presented in Figure 4.2

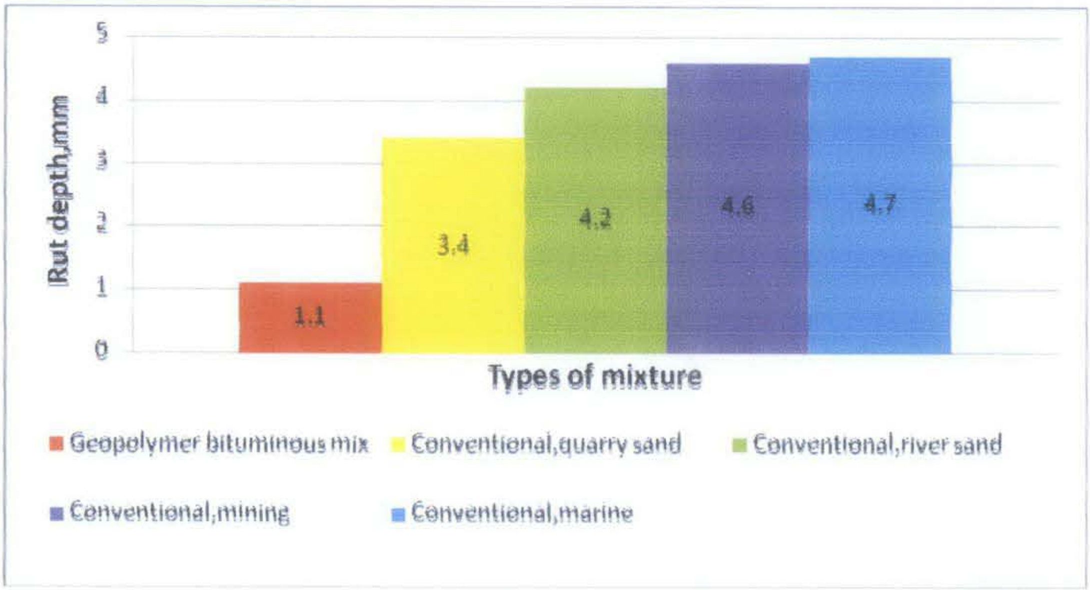

Figure 4.2: Wheel tracking result

From the chart it can be seen that geopolymer bituminous mix has the lowest rut depth compared to all other mixtures. This proves that it has the best resistance towards rutting or permanent deformation. The wheel tracking test result is also supportive of creep test result that has been discussed before. The percentage difference of rut depth between geopolymer bituminous mix and all conventional mixtures are shown in Table 4.2:

Types of mixture	Conventional mix			
	Quarry sand	River sand	Mining sand	Marine sand
% difference	67.6	73.8	76.1	76.6

Table 4.2: Percentage difference of rut depth of conventional pavement in comparison with geopolymer bit mix

From Table 4.2 it can be seen that geopolymer bituminous mix has better rutting resistance to all of the conventional samples, with the largest percentage difference is between marine sand which is at 76.6% and the smallest is between quarry sand at 67.6%.

4.3 OTHER ADVANTAGES AND DISADVANTAGES

Apart from having a high percentage of air voids content, the characteristic of geopolymer which is very quick to harden can also cause another reason for concern; practicality. Having this characteristic limits the period between the time of production of geopolymer and the mixing with pavement, since the geopolymer will become viscous and have reduced workability if it takes too long for transportation or any other activities in between the production and mixing. This causes ready-mix geopolymer to be impossible if the mixing plant is far away from construction site, and leads to extra expenses for in-situ mixing to cover the cost of equipments and expertise.

Another disadvantage of using geopolymer can be found in the method of mixing. The method to mix geopolymer with porous asphalt requires vibration to be applied during the process but there is probably no equipment currently available that is capable of vibrating a whole block of pavement already constructed on road. Vibration ensures that geopolymer would fill in the voids more effectively and so without vibration the air voids content would be higher compared to its already high air voids content (10.4%) which has already exceeded the standard set by JKR at 3% - 5%.

From economic point of view, geopolymer bituminous mixtures would probably have a lower cost of material compared to conventional pavement, since it uses fly-ash or other alternative industrial wastes as one of its source of material and cost of waste materials are usually cheap. However this could be argued if the overall cost; including the cost due to different construction method and production expenses of geopolymer itself are taken into account. On the other hand, its better creep properties can give geopolymer bituminous mixture a longer service life and enhanced resistance to permanent deformation which will cut cost from repair and maintenance, giving it an extra advantage over conventional pavement.

The environmental benefit of using geopolymer bituminous mixture is probably its best advantage over conventional pavement. Usage of industrial waste such as fly-ash can help preserving nature while also cutting cost for disposal. Its longer service life also can also help in preventing consumption of natural resources to be used for the purpose of refurbishment or replacement of damaged roads. This, in turn can also help in preserving our nature.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

From both laboratory tests (Dynamic Creep Test and Wheel Tracking Test) we can draw several conclusions:

1. Geopolymer bituminous mixture has higher creep stiffness and shows better creep resistance compared to various types of conventional pavement mixture as indicated from laboratory dynamic creep test result.

2. Geopolymer bituminous mix shows better rutting resistance compared to various types of conventional pavement mixtures, as indicated from laboratory wheel tracking result.

3. The results from both tests are in tune and both suggesting that geopolymer bituminous mixture has better creep performance or creep properties in comparison with other conventional mixtures.

5.2 RECOMMENDATIONS

It is recommended that further study on the properties of geopolymer bituminous mixtures such as fatigue characteristics could be done to promote more understanding and knowledge of the mixtures. A study on different porosity can also be proposed to find out how it would affect the characteristic of the substance.

Hopefully the continuation on the study of the material will go on as the result so far is very positive and promising. Continuation of study of the material is important; as it needed to be investigated thoroughly and proven wholly before it can be justified to be a better substitute to conventional pavement.

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