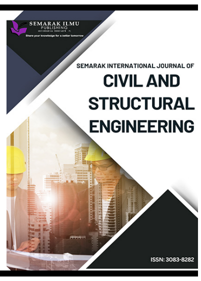
SEMARAK ILMU PUBLISHING
202103268166(003316878-P)

Semarak International Journal of Civil and Structural Engineering

Journal homepage: https://semarakilmu.my/index.php/sijcse/index
ISSN: 3083-8282



Investigating the Density of Granular Materials for Road Base Performance

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ARTICLE INFO

Article history:
Received 13 May 2025
Received in revised form 4 June 2025
Accepted 15 June 2025
Available online 30 June 2025

Keywords:
Granular Materials; Repeated Triaxial Test; Resilient Modulus; MICH-PAVE

ABSTRACT

Inadequate compaction of road base layer can induce to permanent deformation and fatigue cracking in pavement structure which resulted to pavement deterioration and reducing its lifespan. This study focuses on the investigation the effect of density and level of stress on road base granular material under repeated load application. The gradation specification for road base compaction at optimum moisture content was 90% and 95% of maximum dry density. The granular aggregate was poured into a mould of 100 mm diameter and 200 mm height and compacted by applying 4.5 kg hammer at the desire density. The extruded specimens were tested for repeated triaxial load tests using the universal testing machine. The result shows that the increase of 90% to 95% of maximum dry density granular material has increased the resilient modulus value from 2126.0 kg/m^3 to 2246.0 kg/m^3, respectively. The MICH-PAVE analysis shows increasing of granular densification has increase the fatigue life in asphalt pavement and reduced rut depth of the road base layer. This is due to less void between aggregates particles thus increased their density. It can be concluded that the increasing of compaction effort of road base granular material has increased maximum dry density and subsequently improving the resilient modulus value and fatigue life for better resistance to rut depth in road pavement.

1. Introduction

The stability and durability of asphalt pavement to withstand the destructive forces of dynamic wheel loading are depending on the characteristics of the road base. Low performance of road base granular material can reduce the pavement's lifespan and cause high maintenance costs. To ensure effective load distribution and prevent premature wear, a high-quality aggregate material that meets standard road works specifications is necessary to enhance mechanical response and sustain anticipated or actual traffic [1]. Road compaction is requiring process to achieve the degree of density by applying the necessary compaction effort to reduce the porosity

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https://doi.org/10.37934/sijcse.5.1.4454

and increases shear strength. The technique of compaction is essential to ensure the road's load-bearing capacity and maintain a high level of road service [2]. In laboratory works, Proctor test is the most commonly technique used to determine compaction parameters while pavement compacter machine which resulting to enhance the density characteristics and compressive strength of road base may also be utilized [3].

In recent years, the gradual increase in traffic volume is expected to cause road congestion and accelerate pavement deterioration, which ultimately reduces its lifespan. According to Mohamad Taher *et al.,* [4], road pavement will endure to heavy traffic loads that the load frequency and repetitions can lead to permanent deformation and fatigue cracking in the bound layer of the pavement structure. Permanent deformation or rutting is a common failure mode in flexible pavements, resulting from the accumulation of small deformations and repeated shear deformations caused by wheel loads. The lateral movement and consolidation of the bituminous material under traffic are some of the factors that contribute to this type of deformation. A vertical compressive stress from traffic loads as well as a wheel load passes over pavement layers material will experience to behaviour of tensile stress and deformation [5]. Bilodeau *et al.,* [6] stated that a granular material used as road base and sub-bases cannot withstand significant tensile stress. Consequently, these layers will relax under load, resulting in a decrease in the effective elastic modulus of the materials. Road base courses are utilized as base and sub-bases to enhance the load-supporting capacity of the pavement. This is achieved by imparting additional stiffness and resistance to fatigue, as well as constructed relatively thick layers to distribute the load through a finite thickness of pavement [4]. To address this issue, the concept of critical dynamic stress was introduced. This refers to the maximum cyclic stress ratio that can be applied without causing structural damage and has since been widely accepted globally. The road base layer is subjected to cyclic loading throughout its service life, and testing its cyclic loading behaviour is more representative of real-world conditions. Hanandeh *et al.,* [7] reported that various factors can affect the cyclic behaviour of the soil, including confining pressure, cyclic deviator stress amplitudes, fines content, density and moisture content. The repeated load triaxial testing method was widely used to evaluate the material's stiffness characteristics and its ability to withstand permanent deformation accumulation during pulsating loading, which are crucial parameters for assessment.

In another hand, Titi *et al.,* [8] studied the influenced of various factors such as distribution of aggregate particle size, fine aggregate content, stress level application and moisture content, which increasing of density and increases the resilient modulus values. However, parameters such as compaction energy, degree of compaction which relative to proctor test, moisture content, density and void content have an impact on the resilient modulus values. Li *et al.,* [9] conducted a study on the impact of load cycle and permanent deformation on unbound granular material. The study found that confining stress and resilient modulus were affected by axial load, material type, and maximum particle size, with cyclic shear stress having a significant impact on resilient stiffness. Resilient modulus was less affected by principal stresses at low shear stress, but increased with cyclic major principal stress and decreased with increasing initial stress ratio. Density was found to positively correlate with resilient modulus. Stress level was identified as the most prominent factor affecting resilient modulus values, and several regression models have been developed to relate the two. Accurate modeling of the relationship between stress and strain is crucial, as noted by Gu *et al.,* [10].

The resilient modulus test is conducted in laboratory to simulate the elastic response on stiffness characteristics of specimen, but the plastic strains give information about permanent deformation behaviour of specimen. During triaxial test of a cylindrical specimen, the confining pressure is equal to the radial stress and $\sigma_2 = \sigma_3$. The axial stress σ_1 on the other hand is varied to simulate the stress situation caused by the wheel loading [11]. Figure 1 shows the illustrated of general stress regime experienced by an unbound base course element in a pavement structure as the result of a moving wheel load, which the largest part of the strains is caused by the elastic response with only a small part due to plastic behaviour [12].

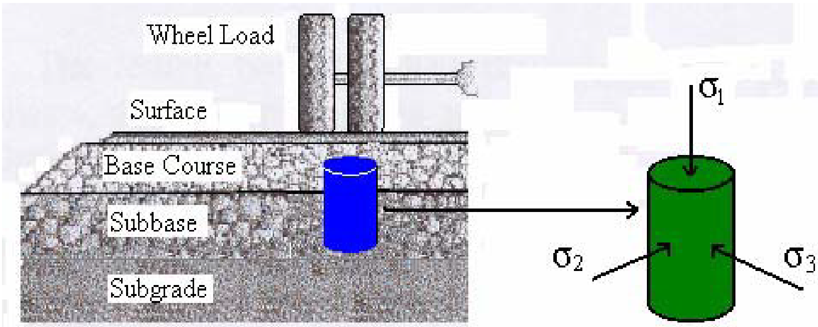

Fig. 1. Stress in an unbound Granular material by Saeed *et al.,* [12]

For instance, cyclic loading triaxial tests are necessary to assess the stress-dependent mechanical behavior of granular materials. Therefore, this study conducted to investigate the effect of density on granular material and level of load stress application to influence on resilient modulus in result reducing the pavement deformation and fatigue life of asphalt pavement. The MICH-PAVE computer program which was developed by Harichandran *et al.,* [13] was applied to predict the performance of pavement layer based on the cubic sample. The analysis is including predicting fatigue life and rut depth on flexible pavement.

2. Materials and Methods

The performances of unbound granular materials for road base are very closely related to the physical properties. The gradation of particle size distribution and properties of the material are factors that significantly influence the response of a granular material. In this study, crushed granite aggregate which obtained from a Quarry Minyak Beku Sdn. Bhd., Batu Pahat, Johor was used, and its physical properties are summarized in Table 1. Crushed granite aggregate was washed, dried, and sieved into selected range of sizes according to the Public Works Department (PWD) [14] for road base of road works specification as shown in Table 2.

Table 1
Physical properties of crushed granite aggregates

Test Properties	Standard	PWD Requirement	Results
Specific Gravity:			
Coarse Aggregate	AASHTO T85	Not Stated	2.486
Fine Aggregate	AASHTO T84	Not Stated	2.422
Flakiness Index	BS 812-105.1:1989	< 25%	12.98%
Elongation Index	BS 812-105.1:1989	Not Stated	4.53%
Aggregate impact value	BS 812-112:1990	< 25%	15.17%
Los Angeles Abrasion Loss	ASTM C131	< 25%	23.53%

Table 2
The gradation limit for road base

Sieve Size (mm)	Percent Passing
50.0	100
37.5	100
28.0	90
20.0	76
10.0	55
5.0	44
2.0	25
0.425	11

2.1 Determination of Optimum Moisture Content

The presence of adequate amount of water has positive influence on the strength and stiffness of unbound road base granular materials. The laboratory compaction test was conducted according to the Modified Proctor test in accordance with AASTHO T-180 [15] standard test procedure with modified rammer of 4.5 kg, 1 litre standard mould and compact each lift with 27 blows for five layers and 450 mm free fall rammer. Figure 2 show the results of moisture content versus dry density of the granular material.

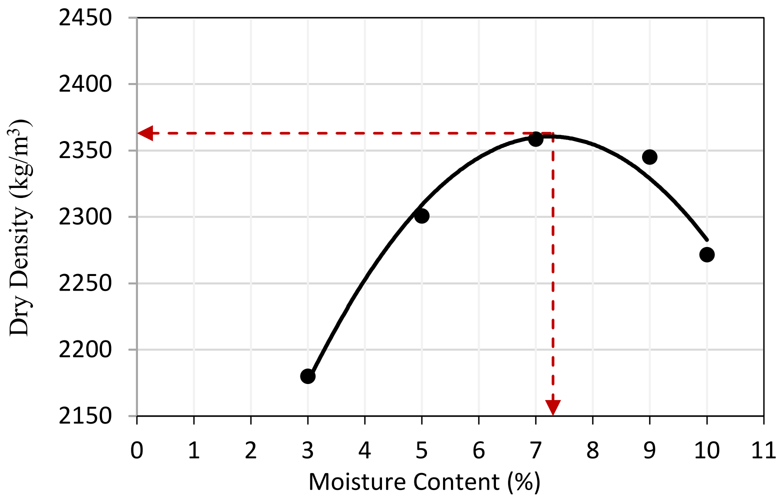

Fig. 2. Dry density and moisture content relationship curve

From Figure 2, the maximum dry density for crush granite aggregates used for road base is 2364.2 kg/m^3 with optimum moisture content is 7.2 %. Based on the result, the dry density for 90% and 95% degrees of density are 2126.0 kg/m^3 and 2246.0 kg/m^3, respectively were selected for further investigation as shown in Table 3.

Table 3
The values of dry density obtained at optimum moisture content

Degrees of Density	Dry Density (kg/m^3)
90%	2126.00
95%	2246.00

2.2 Determination of Compaction Layer of Specimen

A crush granite aggregate prepared according to sieve selected range of sizes in Table 2 for the whole specimens to determining the resilient modulus of aggregate materials according to the AASHTO TP46 [16] standard test procedure. In this study, crush granite aggregate mixed with optimum moisture content were compacted in mould with a diameter of 100 mm and a 200 mm height provided with mould collar to the cell base as described by AASTHO T 307 [17] were compacted in four layers with 4.5 kg weight rammer and 450 mm free height fall to achieve the target volume of specimen base on the dry density condition. For the last layer, the compaction shall be compressed to achieve the target volume of specimen base on the dry density condition. In this study, the compaction effort is determining according to the B.S 1377 [18] compaction test, with standard mould and modified rammer. The number blow/layer determine by trial-and-error compaction is shown as below:

$$\text{Compaction Effort} = \frac{4.50\text{kg}\ (9.81\text{m/s}^2)\ (0.450\ \text{m})\ (5\ \text{layers})\ (27\ \text{blowers/layer})}{1.0 \times 10^{-3}\ \text{m}^3}$$

$$= 2682\ \text{kJ/m}^3$$

where:
Weight of rammer is 4.5 kg
Height free fall is 450 mm
Volume of mould is 1.0×10^{-3} m^3

To determine the number of layers for the 100 mm diameter and 200 mm height specimen:

$$\text{Compaction Layer} = \frac{2682\ \text{kJ/m}^3\ (1.57 \times 10^{-3}\ \text{m}^3)}{4.50\ \text{kg}\ (9.81\ \text{m/s}^2)\ (0.450\ \text{m})\ (50\ \text{blowers/layer})}$$

$$= 4\ \text{layers}$$

2.3 Experimental Design for Stress Level

The experimental design to determine the resilient modulus is described under conditions levels of stress and levels of density. The stress application assigns to the stress situation caused by wheel loading. During triaxial testing of a cylindrical specimen the confining pressure is equal to the radial stress and $\sigma_2 = \sigma_3$. The axial stress σ_1 is varied to simulate the stress situation caused by the wheel loading 550 kPa. The conditioning of stresses was used for testing depend on the stresses applied during the resilient modulus test. Austroads Pavement Research Group [19] recommends that the stress on road base material designed based on the contact stress of wheel tire are shown in the Table 4.

Table 4
The level of stress was applied on repeated triaxial load test

Stress Parameters	Load Application								
	L1	L2	L3	L4	L5	L6	L7	L8	L9
Main Principal Stress [kPa], σ_1	88.0	108.0	228.0	285.0	305.0	325.0	428.0	448.0	468.0
Minor Principal (Confining) Stress [kPa], σ_3	30.0	30.0	30.0	50.0	50.0	50.0	80.0	80.0	80.0
Cyclic Axial Stress [kPa]	58.0	78.0	198.0	235.0	255.0	275.0	348.0	368.0	388.0
Sum of Principal Stress [kPa], $\theta = \sigma_1 + 2\sigma_3$	148.0	168.0	288.0	385.0	405.0	425.0	588.0	608.0	628.0

2.4 Specimens Preparation for Triaxial Test

In this study, the crush granite aggregate batch was oven-dried, sieved into various sizes and stored in closed containers. The aggregate then was weighed and blended to meet the specified gradation proportion as shown in Table 2. In preparing specimen for resilient modulus test, the amount of blended aggregate was weighed based on a desired dry density at 90% and 95% Maximum Dry Density (MDD) and the cylindrical mould volume of 100 mm diameter x 200 mm height. The dry material was mixed thoroughly with an amount of optimum water content and compacted using vibratory hammer compaction according to the B.S 1377 [18] compaction test method. The dimension and weight of the specimen after extrusion from the mould were recorded for density calculation. The final preparation step was to fit a rubber membrane around the specimen, then assembled the upper chamber of tri-axial cell and placed the cell into triaxial testing position.

2.5 Resilient Modulus Test

The Universal Testing machine (UTM 25) at 25 kN designed with a dynamic servo hydraulic and can achieve temperature to 100°C temperature cabinet was used to investigate the unbound materials for triaxial testing of paving materials. This machine was provided with an integrated control and data acquisition system (CDAS) for machine operation and controls an accurate force or displacement waveform generation and the windows based on simulation software, cycle with the maximum 1000 haversine load pulse and 1000 cycles loading. As recommended by Austroads Pavement Research Group [19], specimens were applied the confining pressure and cycle loading for at least 50 cycle per time. In this study, the testing time depends on number of cycles duration and load per level which the haversine shape load pulse consisting of a 0.1 second load duration followed by 0.9 second rest period. During triaxial testing of cylindrical specimens, the confining pressure is equal to the radial stress ($\sigma_2 = \sigma_3$) and the axial stress σ_1 is derived to simulate the stress situation caused by the wheel load. The number of cycles duration was outline in the American Association of State Highway and Transportation Officials (AASHTO) guide for design of pavement structures [20], which for each level of loading the cycle number is 10,000 were used. The loading frequency of 5 Hz was chosen and to verify the repeatability of the test for the whole specimens.

2.6 Physical State Condition

Pavement structure response under load is influence to a property of the materials used in base and subbase layers, and the density level. Resilient modulus (Mr) of the unbound granular material is the fundamental parameter needed in the mechanistic analysis of pavement structure. The resilient modulus behaviour responding to moisture content and density level is the key contribution to the structural strength of road pavement. In other words, the behaviour of granular material is affected by the factor such as stress level, number of load application and sum of principal stress. Therefore, this study focused on the density of 90% and 95% of maximum dry density that recommended by Public Works Department [14] prepared with optimum moisture content. The relationship between resilient modulus and stress state of granular materials was widely accepted in a form of bulk stress equation as presented as ($Mr = K_1\theta^{K2}$), which θ is bulk stress or sum of major principal stress ($\sigma_1 + \sigma_2 + \sigma_3$) and K value is constant value.

2.7 Mich Pave Software

MICH-PAVE is a non-linear finite element program developed by Harichandran [13] for use in design and analysis of flexible pavement structures to investigate the pavement parameters such fatigue life and rut depth, and estimated through empirical equations, although these are currently restricted to three pavement layers with asphalt concrete surface, base and roadbed soil. In the analysis, a finite depth is specified by the user for the last layer (the roadbed). Displacements, stresses, and strains in the last layer are computed only within this depth. The infinite extent of the last layer is model by using a flexible bottom boundary. This enables a considerable reduction in the memory and computational effort required by the program without sacrificing accuracy. In the MICH-PAVE program, a failure criterion is used to characterize the non-linear material response of granular is used improve stresses and strains at layer boundaries.

3. Results

3.1 Effect of Compaction on Density Level

Crushes granite aggregate was sieved according to gradation proportion was compacted with 50 blowers/layer for four layers using the mould volume as 1.57 x 10^{-3} m^{-3}. Furthermore, to determine the dry density of and number of l blowers/layer, the trial and error were conducted on the specimens and compacted with optimum moisture content in four layers with 20 blowers/layer, 30 blowers/layer, 40 blowers/layer and 50 blowers/layer and measure the weight. Based on specimen's dry density in Table 3, the degree of compaction and dry density was plotted with an accuracy of R squared equal to 0.9734 and shown in Figure 3. The density achieved by the specimen compaction with 30 blowers/layer for 90 % dry density, 40 blowers/layer for 95 % of maximum dry density and were used in further investigation.

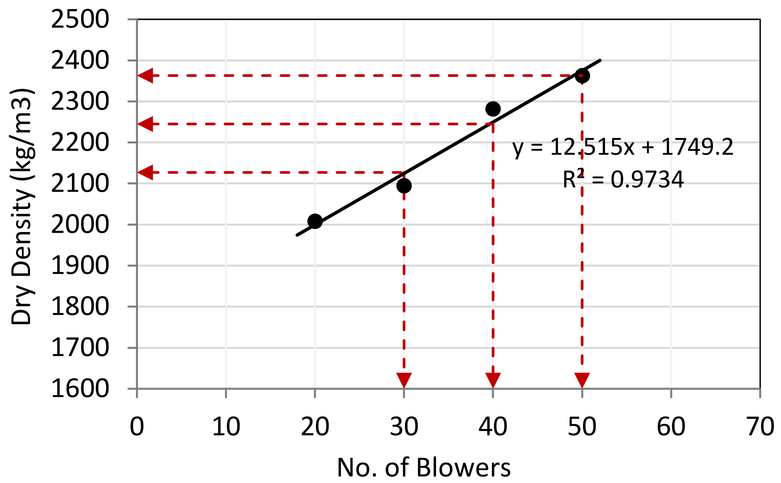

Fig. 3. Determine the Numbers of Blower/Layer by Trial and Error

3.2 Effect of Stresses on Resilient Modulus

Figure 4 shows the effect of level of stresses on resilient modulus values. The level of load application that have been applied is from 1 to 9 at different degree of density which was 90% and 95%. The results showed that the degree of density and level of stress influences resilient modulus. The results indicate a general trend in which the resilient modulus values of aggregate specimens prepared with 90% and 95% maximum dry density were applied for various load level increase as the level of stress increases. The individual bar chart shows that the average resilient modulus values of the compacted specimens for 90% and 95% maximum dry density ranges from 95.7 MPa to 195.8 MPa and 175.6 MPa to 295.7 MPa, respectively. The increasing level of stress to level 9, the resilient modulus increases by 51.1% and 40.6% for 90% and 95% maximum dry density, respectively.

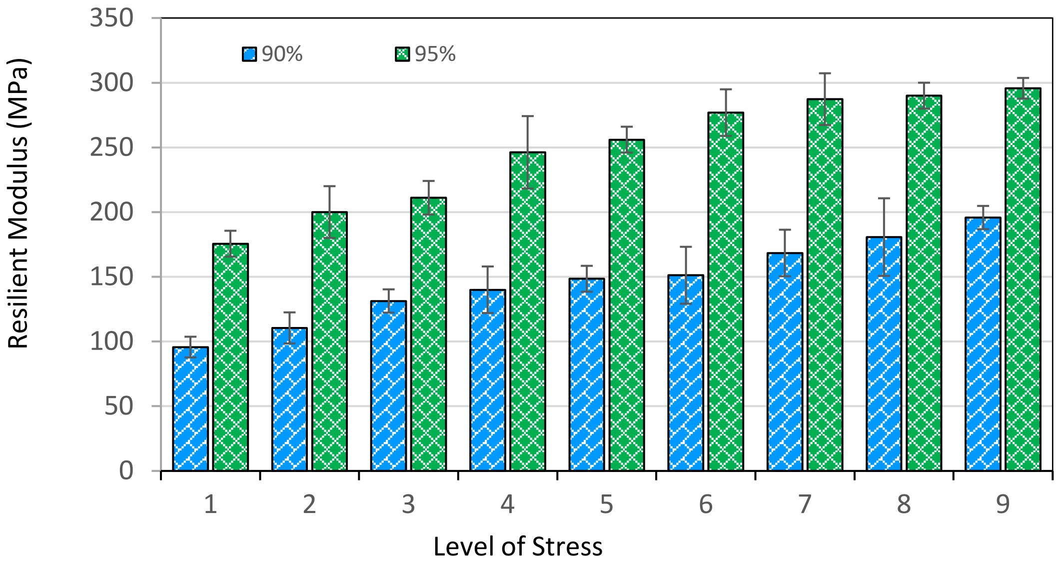

Fig. 4. The comparison of resilient modulus values for 90% and 95% degrees of density

Clearly, the lead to an increase in densification of the specimens and level of stress resulting in higher of resilient modulus value. The resilient modulus increases as the degree of density and level of stress increases. This is due to the number of particle contacts per particle increases greatly with increased density resulting from increasing compaction of the particulate system. The deformation in particle contacts decreases and the resilient modulus increases. According to Lekarp and Dawson [21], the effect of density to be greater for partially crushed than for fully crushed aggregates. The resilient modulus was increase with relative density for the partially crushed aggregate tested, whereas it remained almost unchanged when the aggregate was fully crushed, and density decreased as the fines content of the granular material increased.

3.3 Regression Fitted Model

Fit regression model was used to describe the relationship between the resilient modulus and continuous response of stress level. To determine the K1 and K2 values, the graph was plotted by regression analysis and the model fitted base on Brown and Pell (1967) [22] as $Mr = K1\,(\theta/\theta_0)^{K2}$, which the Mr is resilient modulus, θ is sum of principal stresses, θ_0 is 1 kPa as the reference while K1 and K2 as regression coefficient. From the repeated triaxial load test, the log - log graph was plotted and shown in Figure 5. Table 5 shows the value of K1 and K2 obtained from the regression $Mr = K1\,(\theta/\theta_0)^{K2}$

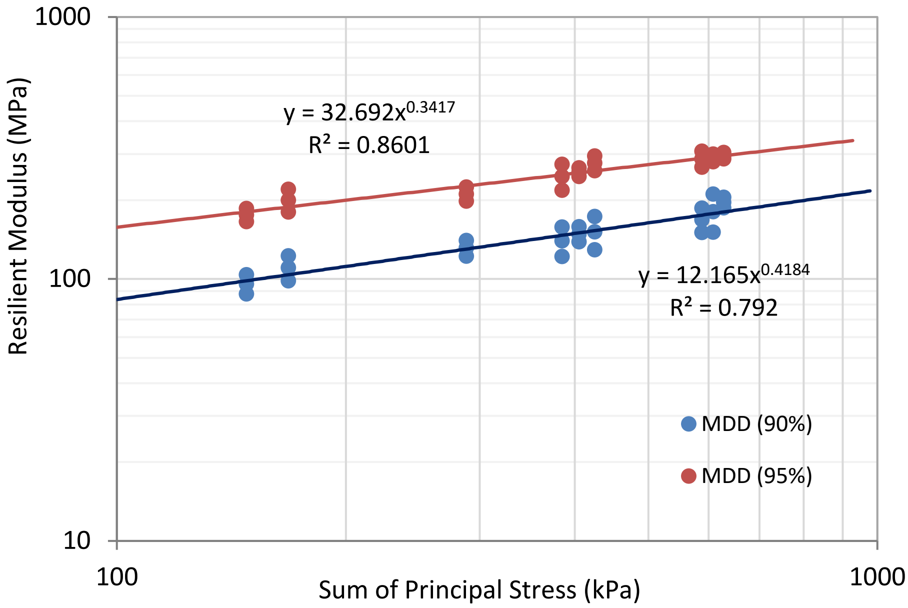

Fig. 5. The effect of density and stress of level on granular material

Table 5 shows the comparison degree of compaction and densification achievement of granular aggregate for road base according to Public Works Department [14] road work specifications to produce the K1 and K2 values.

Table 5
The achieved degrees of compaction and K values

Degree of Density	Weight of Sample (kg)	Wet Density (kg/m^3)	Achieved Degree Density (%)	K1 (MPa)	K2
90%	3.332	2122.5	89.8	62.0	0.695
95%	3.533	2249.5	95.2	172.0	0.337

3.4 MICH-PAVE and Model Analysis

MICH-PAVE is a non-linear finite element program for the analysis of flexible pavement and the design information such as fatigue life and rut depth are also estimated. A three layers pavement consists of with asphalt surface, granular base and sub grade soil were analysed. Displacements, stresses, and strains due to a single circular wheel load were calculated using this software simulation. Typical pavement selected for analysis is based on Manual of Pavement Design (PWD) [14]. The pavement consists of 150 mm, 200 mm granular base course with the California Bearing Ratio (CBR) is not less than 80 %, and the sub grade is 1000 mm below the sub grade surface with not less 3 % of CBR. From the MICH-PAVE, the fatigue life of the asphalt pavement has been observed and the results are as shown in Table 6 for different degree of density.

Table 6
The result from MICH-PAVE program

Descriptions	Level of Density	
	90%	95%
Fatigue life of asphalt pavement (ESAL)	2.279 x 106	2.818 x 106
Total expected rut depth of the pavement (mm)	8.38	7.75
Expected rut depth in the asphalt course (mm)	2.87	2.33
Expected rut depth in the base or subbase course (mm)	0.77	0.63

The increasing of density level shows in reducing of fatigue life and rut depth in road pavement. This may be due to the increasing of densification of granular material used, increasing of surface contacts between stones has reduced the air void, and increasing of road base durability to resistance the load application.

4. Conclusions

The properties of unbound granular aggregates used as road base pavement layers affect the pavement performance. The resilient response of granular material is affected by several factors such as stress level, density, aggregate grading, moisture content and number of load application. From the resilient modulus test result, the resilient modulus increases with the increasing of density level. This is because the number of particle contacts per particle increase greatly with increased density resulting from additional compaction. The level of stress is one of the factors that has most significant impact on resilient modulus of unbound granular material. However, the resilient modulus has effect on the density and load application. It can be seen that the resilient modulus increases when the density and level of stress are increased. This is due to the elasticity of aggregate as unbound material and its non-linear pattern.

Acknowledgements
This research was supported by Ministry of Higher Education (MOHE) through Fundamental Research Grant Scheme (FRGS/1/2019/TK06/UTHM/02/4). We also want to thank for the support received from the Research Management Centre (RMC) and Office for Research, Innovation, Commercialization and Consultancy Management, Universiti Tun Hussein Onn Malaysia (UTHM).

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