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Fibre optic sensing measurement of static surface load distribution on road base layer

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Abstract. Road base layer has a unique way to distribute the stresses. Unlike a concrete layer which relies on its flexural strength, the road base layer transmit its working load by grain-to-grain contact. Many aspects will affect this load transfer system, for example, the aggregate type, shape, and strength. In this research, the fibre optic sensing was used to obtain the strains of the load under the road base layer. By knowing the strains under the road base layer, then the load distribution characteristic on the road base layer can be obtained. Two samples were tested in this research. Sample A was a road base layer constructed from natural crushed aggregate (NCA), and sample B was constructed from recycled concrete aggregate (RCA). The dimensions of the samples are 1 m x 1 m with 200 mm of thickness. A gradual static load was applied on the road base layer surface and the fibre optic sensing will measure the strains at the bottom of the road base layer. A software simulation also conducted as a comparison for the mechanical test. The result shows that the distribution area of road base layer from RCA is smaller than road base layer from NCA which means it distributes less stress than road base layer from NCA. It means that NCA has a better grain-to-grain action compare to RCA.

1. Introduction

Road pavement can be classified into two types based on the structural performance, flexible pavement and rigid pavement. Flexible pavement is the most popular type of pavement for road construction. This type of road pavement will transfer the load stresses to the lower layers by using grain-to-grain transfer through the surface contact of its granular structure [1]. The working load on the pavement surface will be distributed to a wider area and the stresses will decrease along with the pavement depth. These circumstances made the flexible pavement may be constructed by multiple layers with the best quality layer on the top followed by fewer quality layers on the bottom.

Road base is a specific layer which acts as a foundation for road pavement. The working load on the surface of the road pavement will be directly supported by the road base layer. Road base is designed to provide a uniform and stable support for surfacing course (e.g. asphalt pavement) [2]. The simplest way to calculate the load distribution is by means of the 2:1 method [3]. This method assumes that the distributed load over an area increases in width in proportion to the depth below the loaded area. Road base itself is a well-graded material consisting of various size of coarse and fine aggregate [4]. Natural rock that is crushed with rock crushing machine usually used for road base construction. That material commonly called by Natural Crushed Aggregate (NCA). An aggregate made from recycled material (e.g. concrete waste, brick waste, etc.) usually taken as an alternative. The use of the alternative material for NCA has been conducted for over the past decade in any kind of construction projects.

2. Problem Statement and Research Objectives

Road base layer is one of the layer in road construction which is constructed from aggregate. This unbound layer has to be adequate enough to sustain the working load from the surface pavement. Road base layer has a unique way to transmit the working load. The aggregate which has a granular shape will transfer the stresses in a grain-to-grain contact on its surface. This grain-to-grain action is actually similar to the load distribution on the soil mechanic. But in the road base layer, the air void is higher compared to the soil layer because of the materials in construction. The various size of the aggregate for road base layer may also cause a different reaction in load distribution. The grain-to-grain action is a significant for load distribution.

The objective of this research is to determine the load dispersion on the bottom of the road base layer under a static load by using the fibre optic sensing. The fibre optic sensing will measure the strains on the bottom layer of the road base while a static load applied on its surface. The static load then will gradually increase to a certain level of load where the failure appeared.

3. Literature Review

3.1. Flexible Pavement

There are two types of pavement that commonly used in a road pavement construction, the flexible pavement and rigid pavement. Flexible pavement which is the more popular type of pavement compared to the rigid pavement consists of surface, road base or base course, and sub base built over compacted subgrade (natural soil or soil embankment) as shown in **Figure 1**. For some cases, the sub-base layer sometimes is not used, or in a small number of cases, both road base and sub-base are omitted [5].

Figure 1. Structure in flexible pavement.

When the working load applied from the traffic on the surface, the load will be localized under the specific footprint of the working load and distributed into a wider are along with the pavement depth. Each layer receives loads from the above layer, spreads them out, and passes on these loads to the next layer below [6]. The load distribution as shown in **Figure 2** cause the flexible pavement to be constructed from a high-quality material on the upper layer as the same load applied but in a smaller area. In the flexible pavement, the load only considered from one acting wheel of a vehicle because the working load will be localized (one side on one axle). A different approach will occur on the rigid pavement as it will be treated as a plate. Hence, the load on both side of the axle will be considered. The design of flexible pavement is based on some factors, such as traffic density, type of surfacing, and materials for road base, sub-base, and sub-grade. The materials itself have a different standard according to the respective country.

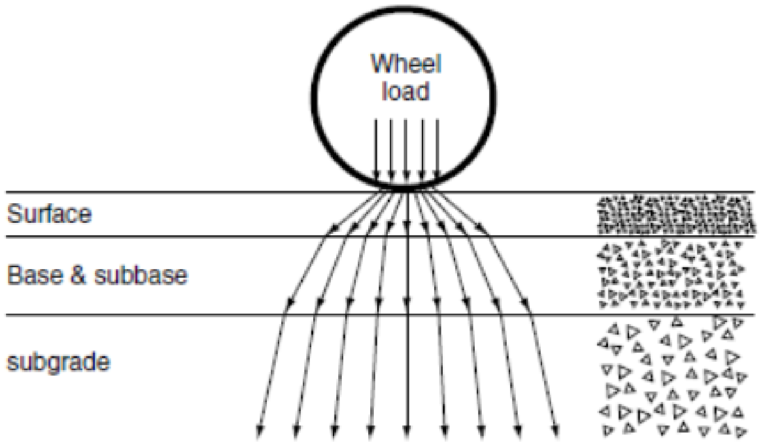


Figure 2. Load distribution is flexible pavement (The Handbook of Highway Engineering, 2006).

3.2. Road Base Materials

Road base of base course is a layer on the flexible pavement which sustain the direct load from the surface pavement. The material for road base must be hard, durable, clean and essentially free from clay and other deleterious materials [7]. The road base material shall be crushed rock, crushed gravel or a mixture of crushed rock and gravel. But now, the recycled concrete aggregate (RCA) already become an alternative material for road base layer.

3.3. Failure Zone and Load Distribution Theories

Failure zone is very well-known in geotechnical engineering. Failure zone is a term for an area which is affected due to the working load. Ludwig Prandtl (1920) was the first to publish the failure mechanism of the solid body due to a strip load [8]. The failure zone consists of three different types of the area which is known as the Prandtl-wedge as shown in **Figure 3**.

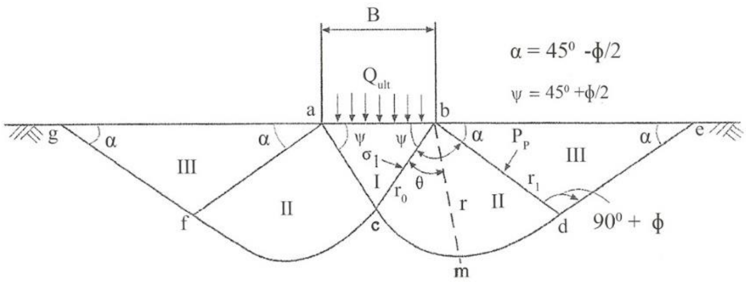


Figure 3. Failure zone of Prandtl.

The Prandtl's analysis has assumptions that the soil is zero cohesion and applicable for footing resting on the surface [9]. In the case of a footing resting on purely cohesive soil, Prandtl's equation leads to an indeterminate quantity. The failure zone in laboratory research can be used to determine the size of the sample which the sample boundary has no effect on the sample due to the applied load.

In 1885, Joseph Valentin Boussinesq or known as a founder of Boussinesq distribution theory solved the problem of load distribution in soils due to the working load on the surface. Some assumptions were made in the solution such as the soil is elastic medium, homogeneous, isotropic, and semi-infinite [10]. From **Figure 4**, the stress at a certain point (σ_z) can be obtained from Equation 1 where K is the influence factor (K_B, for Boussinesq influence factor), Q is single concentrated vertical load and z is the depth.

Influence factor is a function of r/z ratio which is dimensionless. The function of the influence factor is shown in Equation 2. Harold Malcolm Westergaard in 1938 also solved the problem of load distribution under point load. Westergaard suggested that there was a restriction in horizontal expansion. Thus, it is assumed that no lateral displacement implies, or only vertical load that is allowed to impose stress [3]. The same function of Equation 1 is applied for Westergaard distribution theory. Influence factor is the only different variable from the Boussinesq distribution theory. The function of the influence factor for Westergaard's distribution theory is shown in Equation 3.

The equation of vertical stress due to point load can be extended to obtain the vertical pressure under the uniformly loaded circular area from the variables of the radius (a) and load per unit area (q). The concept is to divide the circular area into small parts. In **Figure 5**, a darkened area (δA) is a small part of the whole circular area. The load on that area will be $q\delta A$ and may be considered as a point load. The total vertical pressure at some point of depth (z) in Boussinesq theory is given in Equation 4 whereas Westergaard theory has a slight difference as shown in Equation 5.

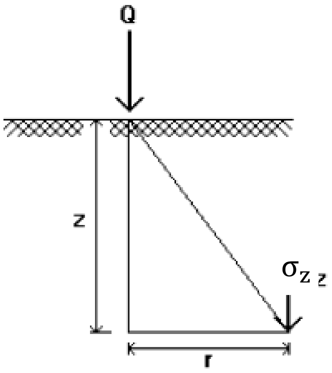


Figure 4. Point load in Boussinesq Theory.

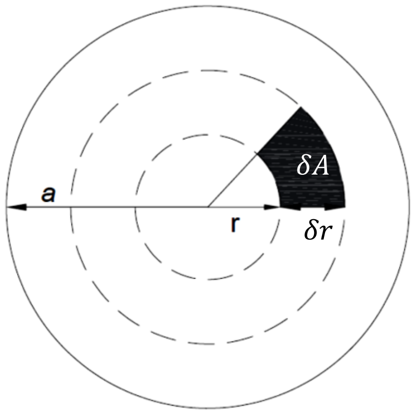


Figure 5. Uniformly circular load in Boussinesq Theory

$$\sigma_z = K\frac{Q}{z^2} \tag{1}$$

$$K = K_B = \frac{3}{2\pi}\left[\frac{1}{1+\left(\frac{r}{z}\right)^2}\right]^{5/2} \tag{2}$$

$$K = K_W = \frac{1}{\pi\left[1+2\left(\frac{r}{z}\right)^2\right]^{3/2}} \tag{3}$$

$$\sigma_z = q.K_B = q\left[1-\left\{\frac{1}{1+\left(\frac{a}{z}\right)^2}\right\}^{3/2}\right] \tag{4}$$

$$\sigma_z = q.K_W = q\left[1-\left\{\frac{1}{1+2\left(\frac{a}{z}\right)^2}\right\}^{1/2}\right] \tag{5}$$

3.4. Fibre Optic Sensing

Fibre optic sensing has been a remarkable method to obtain detail measurements for years. In general, fibre optic sensing uses a laser system as data transmission. The laser system has more ability to transfer very large data compare to the microwave and other electrical systems [11]. An optical fibre is an optical wire made from glass or polymer materials. Each end of the wire are connected into connectors called a pigtail which must maintain the tolerance but in a removable fashion [12]. There are two methods of connecting the wires or splicing, mechanical splicing and fusion splicing. Fusion splicing tends to be used to a permanent join than mechanical splicing. In the fusion splicing, the wires are literally welded to make a very strong connection and low loss [13]. An example operation for fibre optic sensing is when a particular load applied on the optical wires, the intensity of laser wave will change. The changes of the laser wave intensity will be read and recorded by data logger [14]. This research also used the same principle to obtain the load distribution under the road base layer.

4. Samples and Methodology

Two samples of road base layer were tested in this research to have a characteristic comparison between two types of material. Each sample has dimensions of 1 m x 1 m square with 200 mm thickness. Samples were laid and compacted inside a steel frame on a compacted soil represent the subgrade layer as shown in **Figure 6**. The optical wires were laid in between the road base layer and the subgrade layer in two directions. A static load will be placed on the surface of the road base layer with a circular plate in 15 cm diameter. Static load then gradually increase the load capacity at 1 kN increment until the optical wires failed. The strains changes on the optical wires will show the characteristic of the load distribution.

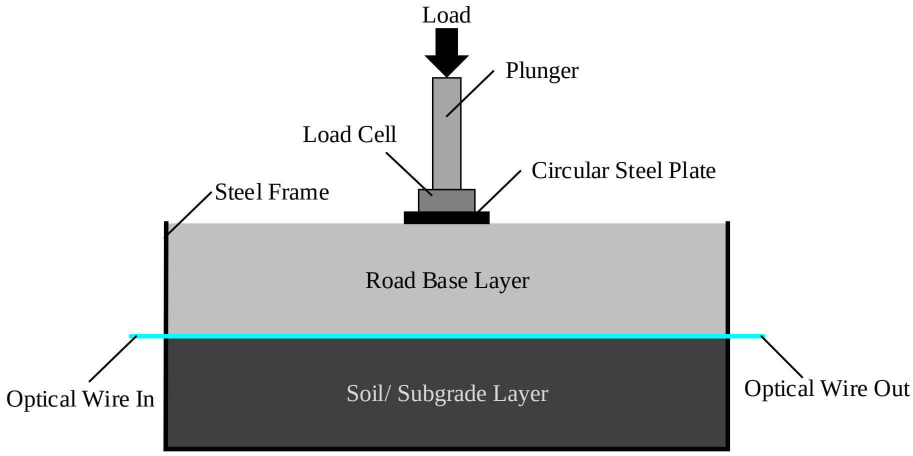


Figure 6. Sample test set up.

Other than the practical test, the load distribution characteristic on the road base layer also studied on the simulation with Plaxis software. Some parameters were needed to run the analysis such as unit weight, material modulus, Poisson's ratio, cohesion, and friction angle. Plaxis software provides parameters for known materials such as rocks and soils [15]. In this study, the only different parameters for the aggregate is the unit weight as NCA and RCA as these materials have a different density. The static load working in this simulation is 20 kN.

5. Results and Analysis

The results from fibre optic sensing under static load show that at 20 kN of load the optical wires were failed. It happened because the optical wires were broke or having a severe crack which makes the laser beam could not pass through. The RCA had a higher strains measurement compare to the NCA as shown in **Figure 7**. It shows that road base sample from RCA material was experiencing higher stress compare to road base sample from NCA material. This situation happened because the load distribution on RCA material was focused under the load source to the subgrade layer. The ease of cracking characteristic of the RCA as studied in previous research makes the aggregate from recycled concrete lack of grain-to-grain action [16]. While on the road base sample from NCA material which has more strength on its aggregate unit may transfer the working load wider and reduce the point load characteristic under the road base layer. In short, NCA has a better grain-to-grain action to disperse the working load. **Figure 7** also shows that the directly affected area is from 0.2 to 0.75 or 0.55 m lengths.

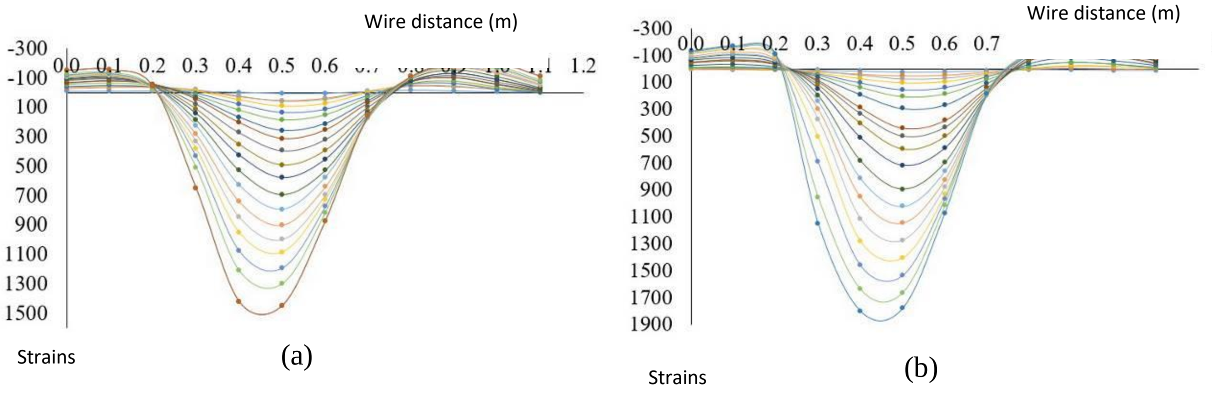
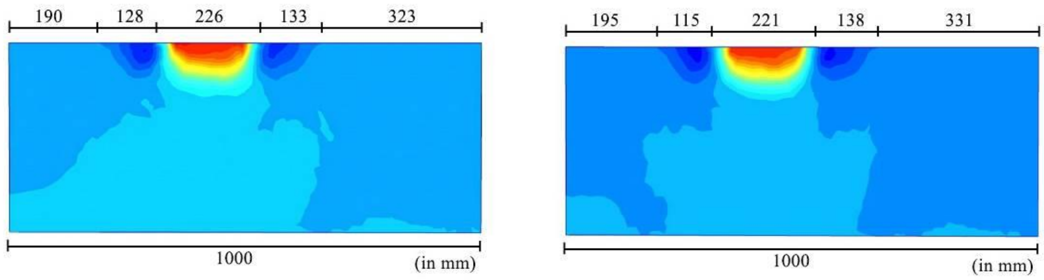


Figure 7. Strains result for NCA (a) and RCA (b).

The dispersion of the working load on both road base samples was also simulated by the Plaxis software. In **Figure 8**, it can be seen that road base sample from NCA tends to distribute the working load wider than the sample from RCA. The results from Plaxis software simulation were consistent with the results from fibre optic sensing. The failure zone or Prandtl-wedge also showed up at the fibre optic sensing and the Plaxis software simulation. In **Figure 8**, the dark blue area outside the red-yellow area is the upward movement of the aggregate which showed as a changing strains value from positive to negative in **Figure 8**.



(a) (b)

Figure 8. Plaxis simulation result for NCA (a) and RCA (b).

6. Conclusion

The conclusion of this research are:

1. The road base sample from natural crushed aggregate (NCA) can distribute the working load wider compared to road base sample from recycled concrete aggregate (RCA). It means the grain-to-grain action between aggregate for NCA has a better performance compared to the RCA. The wider of load distribution is, the better performance will occur for the road base layer.

2. The directly affected area under static load was widened as the depth goes. From the fibre optic sensing, the affected area was approximately 55 cm on the depth of 20 cm or 20 cm circling outside the loading plate which has 15 cm in diameter. This condition makes the theory of 2:1 for load distribution under loading force is not consistent because the ratio from the depth and load dispersion in this study was 1:1 (20 cm : 20 cm).
3. The Prandtl-wedge was proven in this study although it needs further analysis for its load distribution value.

Nevertheless, further research may be conducted to have a better analysis of the load distribution for road base layer under a static load.

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