# STUDY ON RESIDUAL DEFORMATION OF GRADED AGGREGATE BASE IN FLEXIBLE PAVEMENT BY USING ABAQUS SOFTWARE

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**Abstract**

This article presents deformation characteristics and the residual deformation behavior of the graded aggregate base in the flexible pavement under changes of load and elastic modulus of the material layers. The finite element model is presented by using software Abaqus in order to simulate and analyze the influence of several parameters on the accumulating residual deformation of the aggregate layers. The result of the analysis data shows that, when reducing the dynamic elastic modulus of the surface layers or the elastic modulus of the foundation layers, the residual deformation in the graded aggregate base increases a certain amount about (30÷40)%, but when increasing the pressure of wheel acting on the road surface, the residual deformation in the graded aggregate base will increase rapidly about (80÷180)%. Therefore, this is a criterion that should be seriously considered and strictly controlled when designing pavements. The results can be used as the reference database for the calculation, design, and exploitation of this pavement.

***Keywords:*** *Residual deformation; graded aggregate base; flexible pavement; Abaqus software.*

## 1. Introduction

Nowadays, the flexible pavement is used popularly for highways, expressways in Vietnam and other countries. In the pavement, graded aggregate base layer plays an important and effective role, which is indicated from laboratory experiments and field tests that: (1) Graded aggregate base layer can work as a water isolation layer as well as drainage layer; (2) The graded aggregate base can support high loads; stable for water; no spreading cracks appeared on the asphalt surface layer as occurred in case of rigid basement; (3) Under wheel loads, damages appeared in the graded aggregate base is less than those in the surface asphalt layer.

However, the graded aggregate base in flexible pavement construction has some problems such as: It is an unbound granular material layer with small strength, small

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stiffness, large plasticity deformation and limited ability in stress spreading, etc. There are many studies on flexible pavement that have shown that the residual deformation of a pavement structure is a total of residual deformation in the surface asphalt layer, the graded aggregate base layer, and road-bed layer [8, 13]. So, studying the effects of factors (such as loads and materials, etc.) on the residual deformation of the graded aggregate base layer in the flexible pavement construction has a very important significance in improving the construction quality as well as exploiting the structure.

The graded aggregate base is a mixture of unbound granular material, which has the size of the aggregate that comply with the gradation principle. The graded aggregate base layer in the pavement structure is subjected to cyclic loads during its service life. If graded aggregate base layer is considered as perfect elastic-plastic material, the deformation consists of two components: the first component is elastic deformation depending on elastic characteristics of the material, this component will recover after each load cycle; the second component corresponding to plastic characteristics of the material is plastic deformation or residual deformation, this component will accumulate with number of loading cycles. Both the deformation components appear when the stress value is small. The stress-strain relationship for unbound granular material is given by a non-linear curve, and it can be defined the resilient deformation and residual deformation value at each load cycle and is shown in Fig. 1 [3, 5, 10].

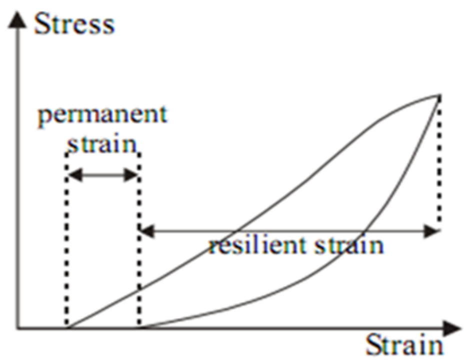


*Fig. 1. The stress-strain curve for granular materials* [5]

Most elastic-plastic material models assume that all the plastic deformations develop at the first loading cycle. After that, if the load level is kept remaining in later loading cycles, the deformation is only elastic. This model behaviour does not simulate the real behaviour of unbound aggregates correctly. In addition, from previous studies it has been shown that, residual deformation accumulates according to an increase of loading cycles.

Some researches showed that the residual deformation development in granular material is affected by several factors such as stress level, stress history, number of load applications, principal stress rotation, moisture content, etc.

Barksdale (1972) investigated the behaviours of the base material by cyclic triaxial tests at a constant confining pressure. It is indicated from this study with $10^5$ loading cycles that the permanent axial strain is linear with the number of loading cycles in logarithm scale [5]. Barksdale also noted that for very low deviatoric stresses the accumulation of plastic strain tends to decrease with the number of load cycles [6]. When the deviatoric stress is larger than a certain limit, the rate of permanent strain development tends to increase with an increase of loading cycles. It is also indicated from this study that after a relatively large number of loading cycles plastic strain accumulation may increase suddenly. Fig. 2 shows the relationship between the plastic strain and the number of loading cycles at different deviatoric stresses for crushed granite.

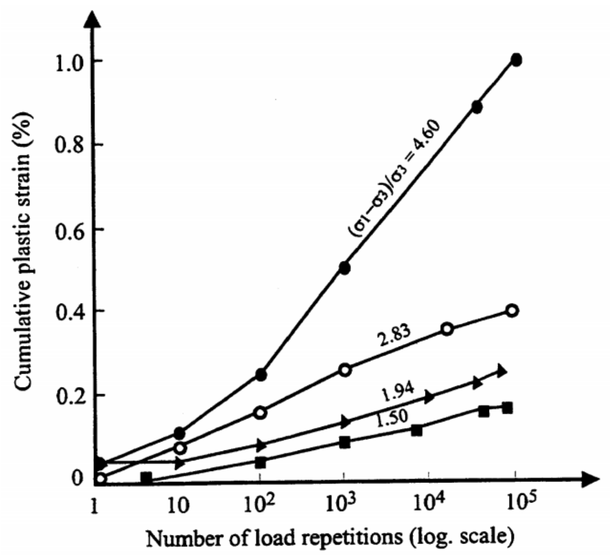


*Fig. 2. Influence of the number of load repetitions and deviator stress ratio on plastic strain in a granite* [5]

A number of limited investigations found in the literature (Chan 1990, [8]) indicate that reorientation of principal stresses due to moving traffic significantly increases the amount of plastic deformation in graded aggregate base.

Paute et al. 1993 [12] proposed a new approach to express the influence of the number of load cycles on the development of residual deformation in unbound granular materials. The modelling approach is based on the assumption that permanent strain increases asymptotically towards a limiting value.

The magnitude of residual deformation in graded aggregate base is also influenced greatly by the presence of water. At high levels of saturation, deformation resistance in the material reduces quite rapidly, probably as positive pore water pressure is generated. Proper drainage in graded aggregate base is, therefore, a necessity for improving performances. The reduction in fines content is likely to achieve this but may conflict with the desire to provide a more deformation-resistant mixture by increasing the fines to promote better packing (e.g. Pham et al. 2015 [13], Liu et al. 2016 [11]).

The above-mentioned results mainly focus on mechanical properties of the graded aggregate base through triaxial compression tests rather than focusing on the characteristics of residual deformation of the graded aggregate base under live load with varying wheel pressure, varying elastic modulus of material layers.

In the next part of the paper, a numerical simulation will be performed for a typical structure of flexible pavement in Vietnam. From there, analyze some effects of load and material parameters on the residual deformation of the graded aggregate base.

## 2. Materials and methods

The residual deformation of the graded aggregate base is evaluated through numerical simulation for a typical structure of flexible pavement in Vietnam, which consists of 5 layers:

+ Layer 1: Asphalt concrete surface is 5 cm;

+ Layer 2: Asphalt concrete intermediate is 7 cm;

+ Layer 3: Graded aggregate base type 1 is 15 cm;

+ Layer 4: Graded aggregate base type 2 is 18 cm;

+ Layer 5: Road-bed.

One of the important tasks when analyzing structures according to finite element method is choosing the appropriate model for each material layer. In the scope of this article, the selection of the model for each material layer is referenced in specialized literature. Specifically, the generalized Maxwell model for the asphalt surface layers [2, 14]; the Drucker-Prager model for graded aggregate base layers [3, 4]; the Mohr-Coulomb model for road-bed layer [3]. At the same time, the initial volumetric deformations of graded aggregate base are not taken into account and the residual deformation is determined at the bottom of the graded aggregate base type 1. Characteristics materials as shown in Table 1 [1]. Harmonic load is used in the calculation model and is shown in Figure 3 [1, 14].

*Tab. 1. Characteristic materials*

| Parameters | Symbol, unit | Layer | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 |
| Model | | MX | MX | DP | DP | MC |
| Mass density | γ, kg/m$^3$ | 2400 | 2400 | 2200 | 2000 | 1800 |
| Young’s modulus | E, MPa | 700 | 1200 | 300 | 250 | 42 |
| Poisson’s ratio | ν | 0.25 | 0.25 | 0.31 | 0.31 | 0.31 |
| Cohesion | c, MPa | - | - | - | - | 0.032 |
| Friction angle | φ, C | - | - | 44 | 40 | 24 |
| Dilatancy angle | ψ, C | - | - | 14 | 10 | 0 |

MX - Maxwell; DP - Drucker Prager; MC - Mohr-Coulomb.

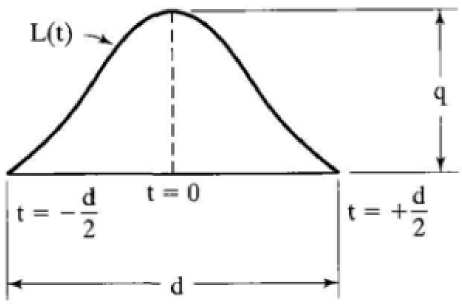


*Fig. 3. Model dynamic loading* [1]

The amplitude of load was computed using Eq. (1):

$$L(t) = q\sin^2\left(\frac{\pi}{2} + \frac{\pi t}{d}\right) \quad (1)$$

where $q$ is the pressure of wheel on pavement (when the axle load is 10 tons, $q$ = 0.6MPa); $d$ is loading time and is determined by Eq. (2):

$$d = \frac{D}{V} \quad (2)$$

where $D$ is diameter of deflection bowl (in this study $D$ = 12R, R is the radius of tyre tracks, R = 0.165m); $V$ is design speed (km/h); $t$ is time (s).

In order to simulate the dynamic wheel load acting on the pavement, the following parameters are applied $V$ = (70÷80) km/h and $d \approx$ 0.1s. Therefore, the amplitude of load is given by Eq. (3):

$$L(t) = 0.6\sin^2\left(\frac{\pi}{2} + 31.4t\right)\text{(MPa)} \quad (3)$$

In this study, the Abaqus software based on the finite element method was used to simulate the three-dimensional pavement structure [4]. In which, the model goes into structural simulations that is subjected to dynamic load when the wheels move on the surface of pavement structure.

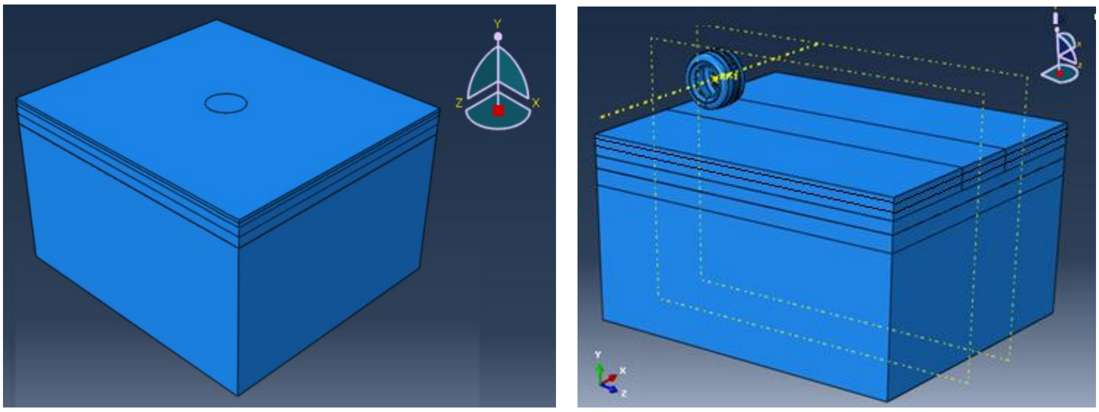

*Fig. 4. Finite element modelling of pavement structure by Abaqus software when the wheels move on the surface*

## 3. Results and discussions

### *3.1. The effect of the number of load cycles on the residual deformation of the graded aggregate base layer*

The effect of the number of load cycles on the accumulation of the residual deformation of the graded aggregate base layer was analysed under wheel pressure $q$ = 0.6 MPa, the number of load cycles N = 10000 times. The residual deformation is recorded at 1; 10; 100; 1000 and 10000 loading cycles [7]. The obtained results are shown in Fig. 5.

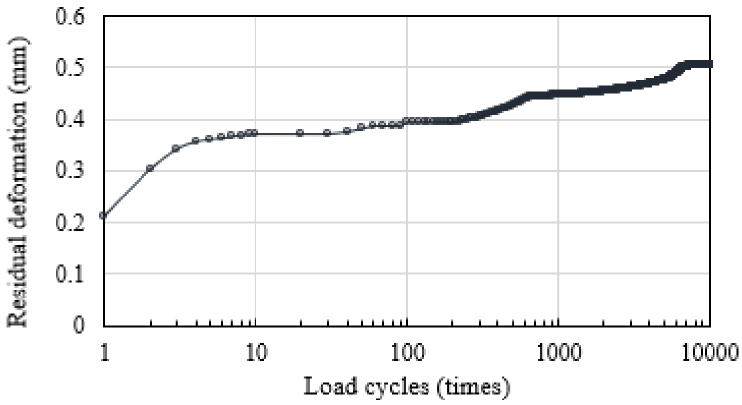


*Fig. 5. The effect of the number of load cycles on the residual deformation of the graded aggregate base layer*

Fig. 5 shows the numerical simulation results of the residual deformation of the graded aggregate base. From Fig. 5, we see that the residual deformation of the graded aggregate base reaches the value of 0.25 mm after the first 1000 cycles. The reason of this can be explained that at the initial time, due to the elastic-plastic deformation characteristic of the material, partial residual deformation exists. Moreover, increasing the number of load cycles to 10000 times, the residual deformation increases a small value (about 0.05 mm). This indicates that the residual deformation almost does not increase and tends to remain constant. Hence, it is found that if the flexible pavement structure works in the normal condition, under the standard load, the effect of residual deformation is relatively small.

### *3.2. The effect of the pressure of wheel on the residual deformation of the graded aggregate base*

The effect of the pressure of wheel on the accumulation of the residual deformation of the graded aggregate base was analysed under the pressures of wheel $q_1$ = 0.2 MPa; $q_2$ = 0.4 MPa; $q_3$ = 0.6 MPa; $q_4$ = 0.8 MPa and $q_5$ = 1.0 MPa; the number of load cycles N = 100 times. The obtained results are shown in Fig. 6.

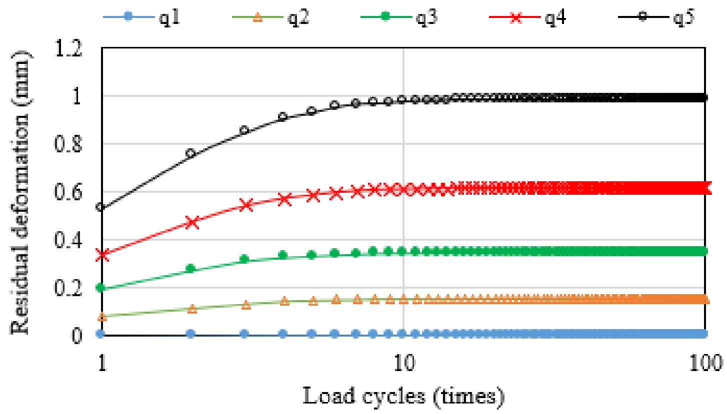


*Fig. 6. Effect of wheel pressure on the residual deformation of the graded aggregate base type 1*

Under wheel load, the residual deformation in the graded aggregate base only increases at some initial cycles and then it tends to remain stable. Under the effect of the load $q_1$ and $q_2$ are lower than the standard pressure $q_3$, the residual deformation is very small and insignificant. However, when increasing the wheel pressure of load to $q_4$ ($1.33q_3$) and $q_5$ ($1.67q_3$), the residual deformation in the graded aggregate base increases significantly and exceeds the deformation of case 3 ($q_3$) by 76.7% and 182.2%, respectively. This means that the rate of residual deformation increase in the graded aggregate base is faster than the rate of increase in the magnitude of the load.

The obtained results are quite consistent with the results of the previous study by Barksdale (Fig. 2).

*Tab. 2. The residual deformation of the graded aggregate base type 1*

| Case | Load | Residual deformation (mm) | Change compares with case $q_3$ (%) |
|---|---|---|---|
| 1 | $q_1$ | 0.038 | 815.8 (-) |
| 2 | $q_2$ | 0.157 | 121.7 (-) |
| 3 | $q_3$ | 0.348 | - |
| 4 | $q_4$ | 0.615 | 76.7 (+) |
| 5 | $q_5$ | 0.982 | 182.2 (+) |

### *3.3. The effect of the dynamic elastic modulus of asphalt concrete on the residual deformation of the graded aggregate base*

In this part, the change of the residual deformation of the graded aggregate base with asphalt concreate specimens having different dynamic elastic modulus at the same temperature will be investigated. The dynamic elastic modulus of asphalt concrete is given at 35ºC for upper surface layer and 30ºC for lower layer. According to [1], the selected values are presented in Tab. 3.

*Tab. 3. Dynamic elastic modulus of asphalt concrete layers*

| Asphalt concrete layer | E (MPa) | | | |
|---|---|---|---|---|
| | Case-1a | Case-2a | Case-3a | Case-4a |
| Upper | 850 | 650 | 550 | 460 |
| Lower | 1200 | 875 | 700 | 565 |

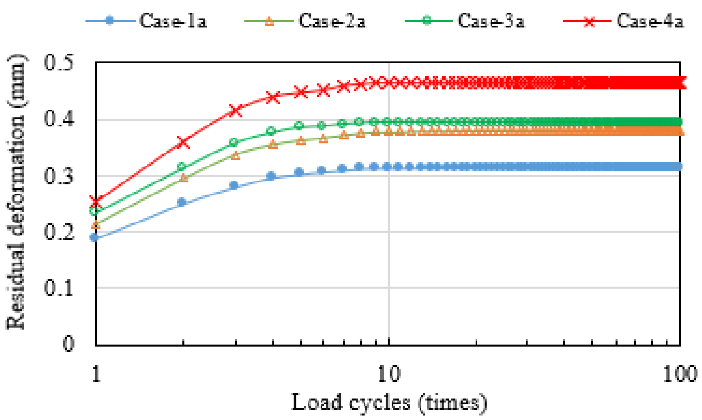


*Fig. 7. The effect of the dynamic elastic modulus of asphalt concrete on the residual deformation of the graded aggregate base.*

It can be seen from Fig. 7 that the residual deformation of the graded aggregate base much depends on the dynamic elastic modulus of asphalt concrete. The residual deformation of the graded aggregate base for case-4a (0.464 mm) is 47.8% larger than that of case-1a (0.314 mm). The residual deformation of the graded aggregate base will result in the rutting on the asphalt concrete surface layer, reducing the quality of the pavement. Therefore, the mechanical properties of the asphalt concrete layer also have a considerable effect on the residual deformation of lower structure layers, including the graded aggregate base layer.

### *3.4. The effect of the elastic modulus of the graded aggregate base layer on the residual deformation*

The development of the residual deformation when changing the elastic modulus of the graded aggregate base layer is investigated for 4 cases. The elastic modulus of each layer is used according to Tab. 4.

*Tab. 4. The elastic modulus of the graded aggregate base layers*

| Layer | Elastic modulus of the graded aggregate base (MPa) | | | |
|---|---|---|---|---|
| | Case-1b | Case-2b | Case-3b | Case-4b |
| Type 1 | 300 | 290 | 270 | 250 |
| Type 2 | 250 | 240 | 220 | 200 |

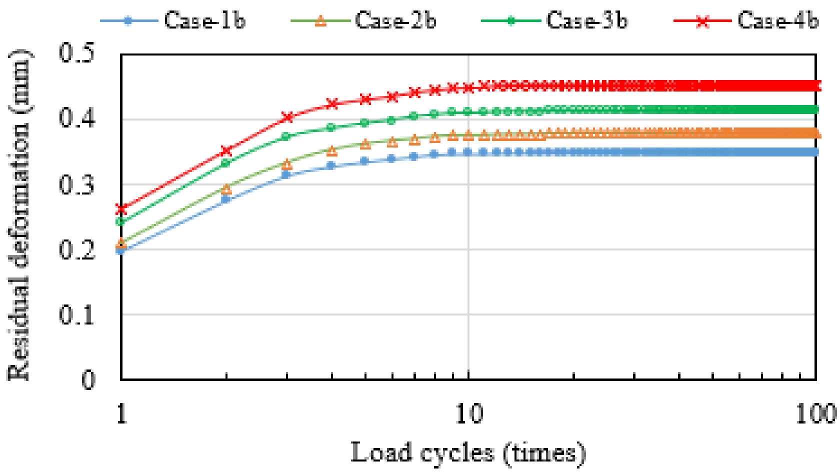


*Fig. 8. The effect of the elastic modulus of the graded aggregate base on the residual deformation*

It can be realized from Fig. 8 that the elastic modulus of the graded aggregate base affects significantly on the residual deformation. However, the effect of the elastic modulus of the graded aggregate base layer is smaller than that of the asphalt concrete layer. It can be explained based on the stress distribution along with the structure depth. The asphalt concrete layers are in direct contact with the wheel loads and the stress in asphalt concrete layers is bigger than that in the graded aggregate base layers. Therefore, the residual deformation of the graded aggregate base will be smaller than that of the asphalt concrete layer. In this study, the residual deformation of the graded aggregate base for case-4b (0.452 mm) is 29.9% larger than that of case-1b (0.348 mm).

## 4. Conclusions

From the obtained results, the following conclusions can be drawn:

- The residual deformation of the graded aggregate depends on the number of loading cycles. In the standard load case, the effect of the number of load cycles on the residual deformation of the graded aggregate base is insignificant. However, the development rate of the residual deformation increases rapidly with the increase of the wheel pressure. It is indicated that one of the main reasons causing the rutting problem is overload wheel pressure comparing with the allowable value.

- The accumulation of the residual deformation is inversely proportional to the elastic modulus of material layers. The effect of the elastic modulus of asphalt concrete layers on the residual deformation is bigger than that of the graded aggregate base layers.

- In the future, it is necessary to conduct experiments to get complete data for each material as well as study the behavior of the structure under different models. In addition, the simulation should be performed with a bigger number of cycles about (1-2 million cycles) to accurately reflect the actual working practices.

- The obtained research results show that the deformation of the pavement is not only controlled by the quality of the input materials but also by a load of vehicles during the operation and exploitation phase. This will prevent damage and increase the service life of the structure.

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# NGHIÊN CỨU BIẾN DẠNG DƯ CỦA LỚP CẤP PHỐI ĐÁ DĂM TRONG MẶT ĐƯỜNG BÊ TÔNG NHỰA BẰNG PHẦN MỀM ABAQUS

***Tóm tắt:*** *Bài báo trình bày nghiên cứu về đặc điểm biến dạng cùng với ứng xử của biến dạng dư trong lớp móng cấp phối đá dăm mặt đường bê tông nhựa khi có sự thay đổi về tải trọng và mô đun đàn hồi của các lớp vật liệu. Thông qua phần mềm Abaqus với phương pháp phần tử hữu hạn để mô phỏng sự ảnh hưởng của một số tham số tới sự tích lũy biến dạng dư trong lớp móng cấp phối đá dăm mặt đường bê tông nhựa đã được phân tích. Số liệu phân tích cho thấy, khi giảm mô đun đàn hồi động của lớp mặt hoặc mô đun đàn hồi lớp móng thì biến dạng dư trong lớp cấp phối đá dăm tăng lên một lượng nhất định (khoảng 30÷40%), nhưng khi tăng áp suất bánh xe tác dụng lên mặt đường thì biến dạng dư trong lớp cấp phối đá dăm tăng lên rất nhanh (khoảng 80÷180%). Đây là một chỉ tiêu cần được nghiêm túc xem xét và khống chế chặt chẽ. Kết quả nghiên cứu có thể làm cơ sở dữ liệu tham khảo cho tính toán thiết kế và khai thác loại mặt đường này.*

**Từ khóa:** Biến dạng dư; cấp phối đá dăm; mặt đường bê tông nhựa; phần mềm Abaqus.

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