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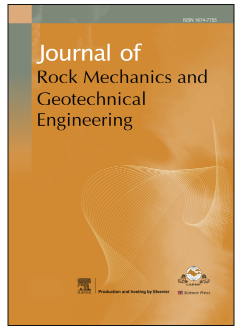

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Effect of Vertical Stress Rest Period on the Deformation Behaviour of Unbound Granular Materials: Experimental and Numerical Investigations

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Effect of vertical stress rest period on deformation behaviour of unbound granular materials: Experimental and numerical investigations

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Abstract: Repeated load triaxial test is used to assess the deformation behaviour of unbound granular materials (UGMs) in flexible road pavements. Repeated load pulse characteristics (i.e. shape, loading period and rest period) are the stress configurations used in the experimental set-up to simulate the passing axle loads. Some researchers and standard testing protocols suggest a rest period of varying durations after a loading phase. A thorough review of existing literature and practices has revealed that there is no agreement about the effect of the rest period of vertical stress pulse on the deformation behaviour of the UGMs. Therefore, the main objective of this study is to investigate the effect of repeated stress rest period on the deformation behaviour of UGMs experimentally. Experiments are conducted, both with and without rest period, using basalt and granite crushed rocks from Victoria, Australia. Furthermore, in order to gain insight of the effect of the rest period, finite element modelling is also developed. Both the experimental and modelling results show that the rest period has a noticeable effect on both resilient and permanent deformation behaviours of UGMs. It is, therefore, recommended to take extra precautions while adopting a particular standard testing protocol and to supplement the results by additional tests with different loading configurations.

Keywords: flexible pavement; unbound granular materials (UGMs); repeated load triaxial test; resilient modulus; permanent deformation; finite element modelling

1. Introduction

Unbound granular materials (UGMs) are used as base and subbase materials in most flexible road pavements. UGMs can be found naturally, such as gravels, or processed, such as crushed rocks and recycled wastes. The role of UGMs in the base layer is to withstand traffic loads imposed at the surface and to spread these loads to the lower layers (Tutumluer and Pan, 2008; Liu et al., 2014). The road pavement is exposed to several stresses from moving wheel loads such as vertical, horizontal and shear stresses (Lekarp et al., 2000; Seyhan and Tutumluer 2000). Therefore, UGMs must possess appropriate stiffness and strength (Yideti et al., 2014). According to the mechanistic and mechanistic-empirical flexible pavement design methods, the mechanical properties (i.e. stress strain behaviour) of each layer in the pavement and the subgrade must be available before designing pavement structure (Englund, 2011). The mechanical response of the UGMs under repeated loads can be described as elastoplastic behaviour (Wolff and Visser, 1994; Uzan, 1999; Werkmeister, 2003; Englund, 2011; Bilodeau and Dore, 2012). The elastic part is called resilient deformation (RD), and the plastic part is the permanent deformation (PD). RD is used to calculate the resilient modulus (M_r) (Cerni et al., 2015) and PD is used to estimate the accumulated rutting (longitudinal depression) (Siripun et al., 2010). Commonly, M_r is defined using Eq. (1) (Zaman et al., 1994):

$$M_\mathrm{r} = \sigma_\mathrm{d}/\varepsilon_\mathrm{r} \quad (1)$$

where M_r is the resilient modulus (MPa), σ_d is the deviatoric stress (kPa), and ε_r is the resilient deformation (μm).

The laboratory tests are performed to simulate the actual field conditions as closely as possible. Repeated load triaxial test (RLTT) is commonly used to assess M_r (Kamal et al., 1993) and to measure the PD of UGMs (Alnedawi et al., 2018). This test is a complex process and not an easy task (Rahim and George, 2005). Axle loads are simulated in the laboratory using a particular loading configuration (pulse shape, loading frequency and number of load repetitions). Several standard testing protocols have been established for this purpose. The protocol from AASHTO (2012) assigns haversine vertical stress pulse with 0.1 s and 0.9 s loading and rest periods, respectively, which results in 1 Hz loading frequency. Austroads (2007) allocated trapezoidal vertical pulse with 1 s and 2 s loading and rest periods, respectively, resulting in loading frequency of 0.33 Hz. Unfortunately, a large disparity in experimental results is detected among different test protocols and practices (Guo and Emery, 2011).

Stress is the most significant factor that influences M_r (Sweere, 1990; Kolisoja, 1997) and PD (Morgan, 1966; Lashine et al., 1971; Brown and Hyde, 1975) of the UGMs. In the laboratory for RLTT, the shape and characteristics of vertical stress pulse are defined in such a way that they simulate actual stresses occurring in the field. Therefore, various efforts have been dedicated to investigating the repeated vertical stress applied. When a moving load is above a specific point on the pavement, the maximum stresses are exerted. If the same wheel load is travelled away from that point, stresses decrease to zero (Huang, 2004). Loading period is the duration of the vertical stress amplitude, and rest period is the period between consecutive loads or amplitudes. The stress during the rest period is zero.

Previous studies have revealed that the vertical loading period is subjected to the speed of vehicle and the depth of the investigated point underneath pavement surface (Barksdale, 1971; Brown, 1973; McLean, 1974; Huang, 2004). On pavement, the vehicle speed and the depth of the examined layer vary considerably. Monismith (1989) concluded that the rest period did not have a significant influence on M_r of asphalt when the ratio of the rest period to loading period exceeded 8. Kim et al. (1992) pointed out that the ratio of the rest period to loading period should be carefully selected since it would directly influence the resilient strain. According to Monismith (1989), a small effect was observed after the ratio of rest period to loading period exceeded 8 and an increase in the rest period resulted in an increase in M_r. Huang (2004) assumed that the pulse rest period between consecutive wheel loads was unknown and might be insignificant. Similarly, Indraratna et al. (2009) found from repeated triaxial experiments that the rest period had an insignificant effect on ballast deformation under repeated loads. MansourKhaki et al. (2015) found that the rest period had no effect on the asphalt deformation at the beginning of second and third phases of fatigue test. Nevertheless, AASHTO (2012) assigned 0.9 s for the rest period and Austroads (2007) allocated 2 s in their RLTT protocols of the UGMs.

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It can be seen from the existing literature and practices that there is no agreement about the influence of the repeated stress rest period on the deformation behaviour of the UGMs. Different pavement design guides and standards have used different testing protocols. A few researchers have also attempted to investigate the effect of the repeated stress rest period on the deformation behaviour of asphalt. However, to the best of authors' knowledge and from the aforementioned literature, the effect of the repeated stress rest period on M_r and PD of UGMs has not been investigated thoroughly.

For this, this study aims to investigate the effect of the repeated stress rest period on the deformation behaviour of UGMs experimentally by testing UGMs both with and without rest period. In order to enhance our understanding of the effect of the rest period and to supplement the experimental results, a finite element model is also developed.

2. Laboratory experimental program

2.1. Materials

Two types of base materials, i.e. basalt and granite, extensively used in Victoria, Australia, were selected for this study. Both rocks were crushed in the quarries to produce Class 2 rocks. Class 2 is a typical unbound granular base material used as a flexible pavement layer in Australia (Alnedawi et al., 2018). The current specifications by VicRoads (Roads Corporation of Victoria) define that Class 2 as a high-quality base material for flexible pavement can be of either basalt or granite origins, within acceptable ranges of properties. Both tested Class 2 rocks were within the limits of specified requirements by VicRoads. The crushed basalt Class 2 rock was collected from Mountain View quarry in Point Wilson, Victoria and the crushed granite Class 2 rock was resourced from Hanson quarry located in Lysterfield, Victoria.

These materials were first tested for main properties such as maximum dry density (MDD), optimum moisture content (OMC) and gradation. Results are listed in Table 1 and shown in Fig. 1.

Table 1. Modified compaction test results.

Class 2 type	OMC (%)	MDD (kg/m^3)
Crushed basalt	7.7	2320
Crushed granite	6	2300

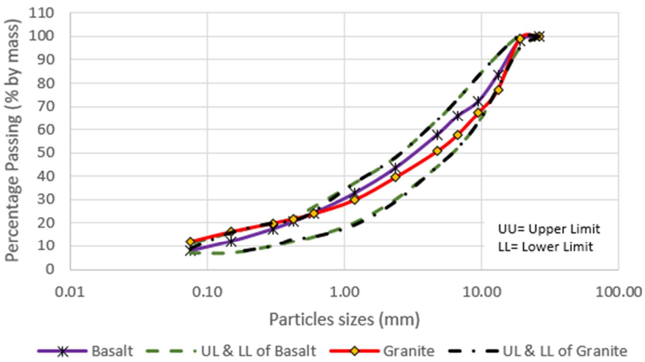
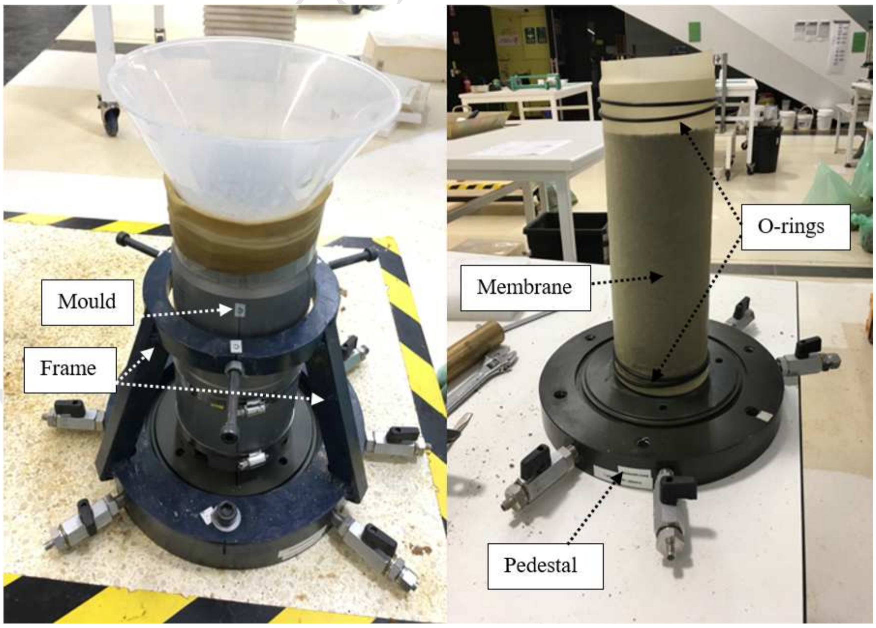


Fig. 1. Gradation of the materials and limits.

2.2. Specimen preparation

All tested specimens were prepared by using modified dynamic compaction procedure. The specimens were all cylindrical measuring 100 mm in diameter and 200 mm long and were prepared with the corresponding MDD and OMC listed in Table 1. A modified compaction effort was applied with 25 blows per layer in 8 layers. Each compacted specimen was mounted on a baseplate and enclosed by a rubber membrane. O-rings were circled at each end of the specimen to hold the ends of the membrane, as shown in Fig. 2. Three replicated specimens were prepared for each case. All preparation process was in accordance with Austroads (2007).



(a) (b)

Fig. 2. Specimen preparation: (a) Moulding and (b) Final specimen.

2.3. Test procedure

The RLTT was used in the experimental investigation. The main components of the system, as shown in Fig. 3, were a pneumatic controller (to control the confining pressure), a digital control system (to collect and store data), load frame, LVDT (linear variable differential transformer), actuator motor (to apply repeated loads), and triaxial chamber (to maintain the confining pressure). The testing procedure included applying repeated deviatoric stress (σ_d)

with a constant confining pressure (σ_3) as tabulated in Table 2. During the test, the LVDT measured the axial deformations (permanent and resilient) at the top of the specimen.

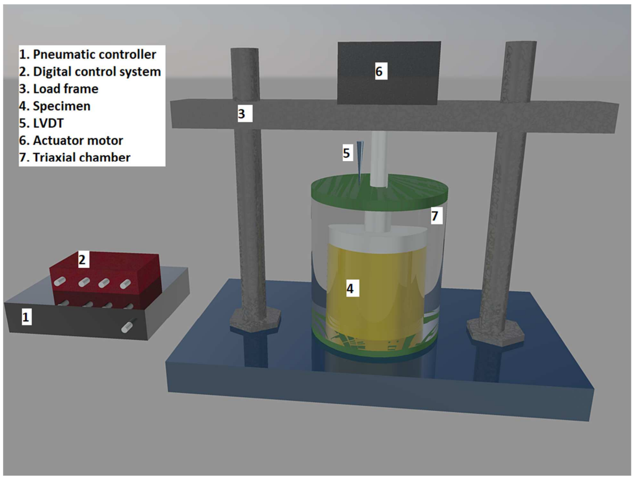


Fig. 3. Components of repeated load triaxial test.

Table 2. Stress sequences for permanent deformation test.

Stage	σ_3 (kPa)	σ_d (kPa)	Number of cycles
1	50	350	10,000
2	50	450	10,000
3	50	550	10,000

To investigate the effect of the vertical stress rest period on the deformation behaviour of the UGMs, two pulses, both with and without rest period, were implemented. This study adopted Austroads (2007) testing protocol for both laboratory testing and finite element modelling (FEM) due to the availability of calibrated RLTT equipment to Austroads (2007) and to adhere to local testing practices in Australia. The first pulse was a standard test protocol by Austroads (2007) (i.e. trapezoidal pulse with 1 s loading and 2 s rest periods) as a controlled case. In this case, the RLTT system applied vertical deviatoric stress during the loading period (amplitude) only, and no vertical stress was induced during the rest period, as shown in Fig. 4. The second pulse was a trapezoidal pulse for 3 s of loading period and no rest period was applied, as shown in Fig. 5. It is important to note that total duration of a cycle was kept constant (i.e. 3 s). Hence, loading frequencies, confining pressures, deviatoric stresses and total number of cycles remained the same for both cases as recommended by Austroads (2007).

3. Finite element modelling

In order to supplement the experimental results and also to have an insight into the deformation behaviour, both with and without rest period, a finite element model is developed. FEM is a continuum numerical modelling method which considers the UGMs as a continuum medium occupying the entire volume (Yohannes et al., 2009). FEM has been used to simulate and analyse several geotechnical problems. Sukumaran et al. (2002) used FEM to determine M_r of the UGMs from California bearing ratio (CBR). Kim and Siddiki (2006) simulated the M_r test for the subgrade materials. The results from the model were similar to the experimental results. Several studies have been conducted to model and analyse the rutting in a pavement structure (i.e. PD) using FEM (Arnold, 2004; Hornych et al., 2007; Ali et al., 2009; Brito et al., 2009; Chazallon et al., 2009; Al-Khateeb et al., 2011; Wu and Chen, 2011; Yang et al., 2011). One of the main limitations of the FEM for UGMs is the problem to model individual granular particles and voids between them. In spite of this issue, most existing pavement design software packages are still using FEM for flexible and rigid pavement designs, including the unbound layers (e.g. CIRCLY, KENPAVE and KENLAYER).

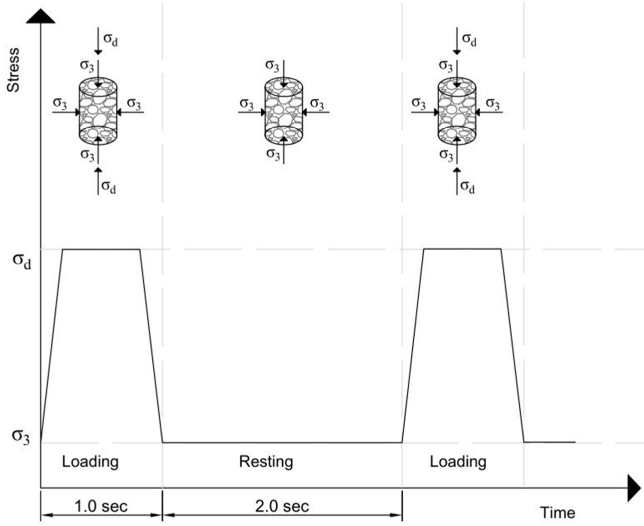


Fig. 4. Trapezoidal pulses with a rest period.

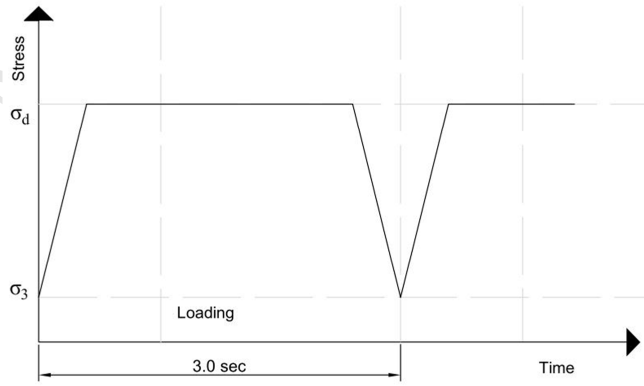


Fig. 5. Trapezoidal pulses without a rest period.

FEM analysis was conducted in this study using the commercial software ABAQUS/CAE 6.14. Two parts of the models were created: three-dimensional (3D) deformable solid part for the cylindrical UGM specimen with 100 mm diameter in the *x*-*y* plane and 200 mm in the *z*-direction and 3D discrete rigid part for the base plate. Simple linearly elastic material property was used to define the elasticity whereas the extended Drucker-Prager model was utilised to define the elastoplastic behaviour of the UGMs. Drucker-Prager model is the best inbuilt model in ABAQUS which can model the elastoplastic behaviour. The general exponent yield criterion function is described by

$$F = q - p\tan\beta - d = 0 \quad (2)$$

where F is the Drucker-Prager yield surface; q is the principal stress difference, and $q = \sigma_1 - \sigma_3$, in which σ_1 and σ_3 are the maximum and minimum principal stresses, respectively; p is the mean normal stress, and $p = (\sigma_1 + \sigma_2 + \sigma_3)/3$, in which σ_2 is the intermediate principal stress; β is the angle of the yield surface in p-q stress space; and d is the q-intercept of the yield surface in p-q stress space. β and d

can be calculated by plotting the values from monotonic shear failure tests in *p*-*q* stress space, as described in Fig. 6.

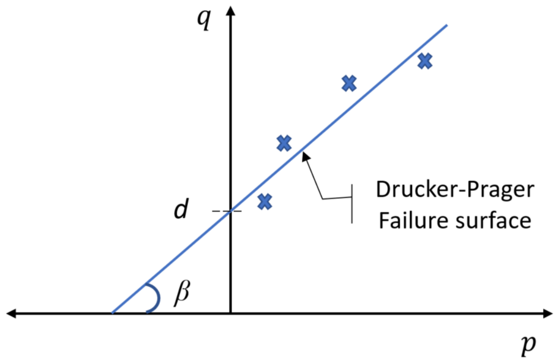


Fig. 6. Drucker-Prager failure surface.

The elastic properties of the cylindrical part (UGMs sample) are defined as per Table 3. To define the Ducker-Prager model, monotonic triaxial test data for crushed rock (i.e. NI Good) as investigated by Arnold (2004) are used in this study and tabulated in Tables 4 and 5. The data from NI Good material are chosen due to the similarities in the physical properties with the Class 2 materials. Both materials are high-quality crushed rocks used in pavement as base layer. NI Good material has OMC and OMC of 1900 kg/m^3 and 5%, respectively, which are the closest properties to the tested materials. Hardening behaviour is also included. Tangent behaviour with friction coefficient of 0.2 and normal behaviour with hard contact are the contact properties between the specimen and the base plate.

Table 3. Elastic properties.

FEM part	Elastic modulus (MPa)	Poisson's ratio
cylinder	120	0.35

Table 4. Monotonic shear failure tests for NI Good material.

Stage	σ_3 (kPa)	q (kPa)
1	25	500
2	50	600
3	75	790
4	100	850

Table 5. Failure surface.

Material	d (kPa)	β (°)
NI Good	135	62

Two magnitudes of pressure are defined and fixed: the vertical uniform stress of σ_d = 350 kPa and the uniform confining pressure of σ_3 = 50 kPa, as suggested by Austroads (2007) for the first stage of RLTT as shown in Fig. 7.

As FEM of the repeated loads is computationally expensive, only the first 6 cycles are simulated to reduce the computation time similar to the study conducted by Al-Khateeb et al. (2011) where only 3 cycles were simulated.

Figs. 8 and 9 show the trapezoidal pulses with and without rest period, respectively. Similar to the experiment, duration of 3 s was used for each stress pulse cycle. The stresses were applied with a total duration time of 18 s.

Encastre type of support is selected as a boundary condition to constrain the base plate. The finite element mesh used for the analysis is shown in Fig. 10. To achieve the convergence in the FEM analysis outputs, a few models of various mesh sizes are run. The convergence is achieved in this study when the total number of elements and nodes in the mesh are 18,080 and 19,885, respectively. A 3D response is simulated by using an 8-node linear brick, which reduces integration (C3D8R) element type. Three elements, bottom (B), middle (M), and top (T), are selected to further investigate the stresses and the deformation at different points, as shown in Fig. 10.

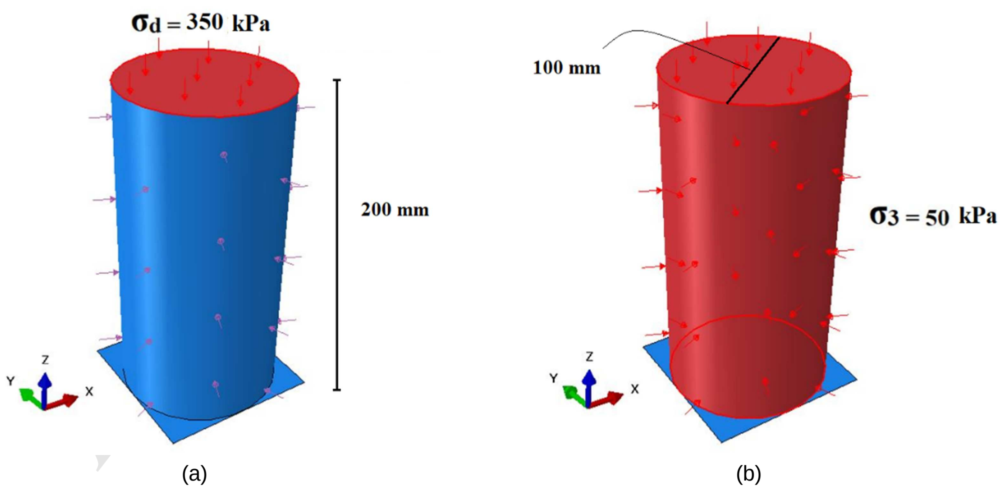


Fig. 7. Applied pressures: (a) Deviatoric stress and (b) Confining pressure.

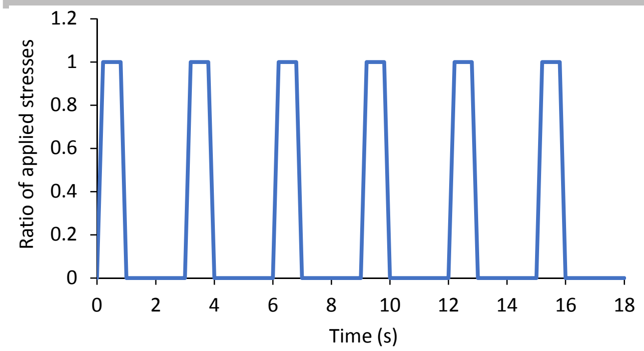


Fig. 8. Loading cycles with rest periods.

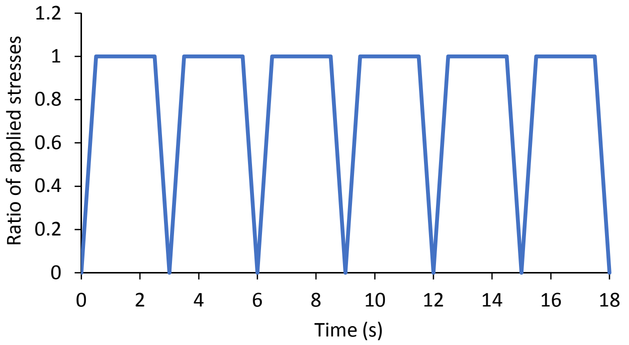


Fig. 9. Load cycles without rest periods.

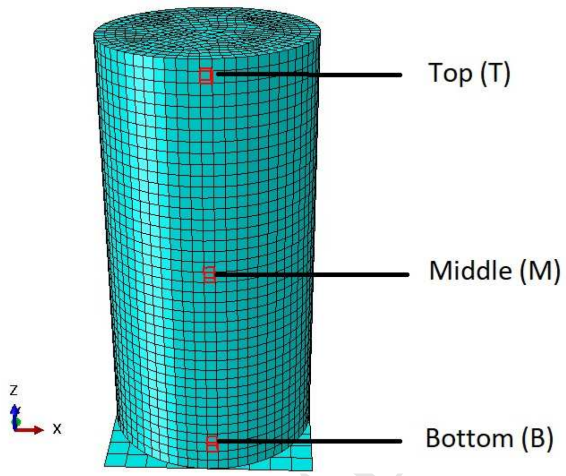


Fig. 10. Finite element mesh and selected three elements.

4. Data analysis and results

4.1. Experimental results

The experimental data were collected from the RLTT. Fig. 11 compares the PDs of both basalt and granite with and without rest period. It can be clearly seen that both basalt and granite have higher PDs when they were tested under repeated load with rest period compared to the case without rest period. At the end of the test (at 30,000 cycles), the PDs for basalt and granite, which were tested under repeated loads with rest period, were 5.6% and 4.1%, respectively, whereas the PDs were 3.9% and 3.2%, respectively when tested under repeated load without rest period. Since the rest period comes after a loading period (Fig. 4), the materials might have recovered. This process could ease the aggregate to segregate resulting in higher PD compared to the same materials without rest period. These findings are not in line with Huang (2004) and Indraratna et al. (2009), as they did not find any effect. Furthermore, it was found that granite had less PD than basalt as also observed by Alnedawi et al. (2017).

Similarly, M_r for basalt and granite with and without rest period is presented in Fig. 12. Basalt and granite had low M_r when they were tested under repeated load with rest period. At 20,000 cycles of load, the M_r values tested under rest period for basalt and granite were 117 MPa and 119 MPa, respectively. Whereas M_r values tested without rest period at the same number of cycles for basalt and granite were 150 MPa and 170 MPa, respectively. This shows a significant increase in M_r without a rest period.

The variation in M_r for these two cases (with and without rest period) is related to the resilient strain as M_r is inversely proportional to the resilient strain, as shown in Eq. (1). A possible explanation for the observed increase in M_r (without rest period) is the low magnitude of the resilient strain. Eliminating the rest period does not result in an adequate time for the material to recover after the load amplitude. This finding is in line with the other studies established on asphalt specimens, such as Kim et al. (1992) and Monismith (1989). It worth mentioning that all three replicated specimens followed the same deformation behaviour.

4.2. Finite element modelling results

4.2.1. Permanent deformation (plastic strain)

As discussed previously, only the first 6 cycles of loading configurations, with and without rest period, were used to model the differences in the UGM behaviours using FEM. Fig. 13 shows the equivalent plastic strain at integrated point (PEEQ) for these two cases with and without rest period after the first 6 loading cycles. It can be seen that specimen under stress with rest period exhibited more PD than the same specimen tested under stress without rest period. The differences in PD is, however, only 2×10^{-5}. The low PD values are expected since only a few initial load cycles were applied. Similar behaviour has been observed in the experimental investigations.

4.2.2. Resilient deformation (elastic strain)

In order to investigate the effect of the rest period on the resilient deformation of the UGMs, the maximum principal elastic strains (EE) were calculated. It can be seen from Fig. 14 that EE is higher by 4×10^{-5} when the specimen is subjected to loading cycles with rest period compared to that without rest period. This leads to low M_r for the case without rest period since the resilient strain is inversely proportional to M_r, as shown in Eq. (1). This result also agrees with the experimental results in Fig. 12.

4.2.3. Comparison between experimental and finite element modelling results

Figs. 15 and 16 compare the elastic strain response of the experimental (basalt and granite) and FEM investigations (B, M, and T) during the first 6 loading cycles with and without rest period. B, M and T are selected elements, as shown in Fig. 10. When rest period exists, EE is high for element B and low for element T, as shown in Fig. 15, which means low to high M_r. The reason behind the high EE at the base of the sample could be because of the encastre support of the base plate which assists reflecting the stresses back to the specimen.

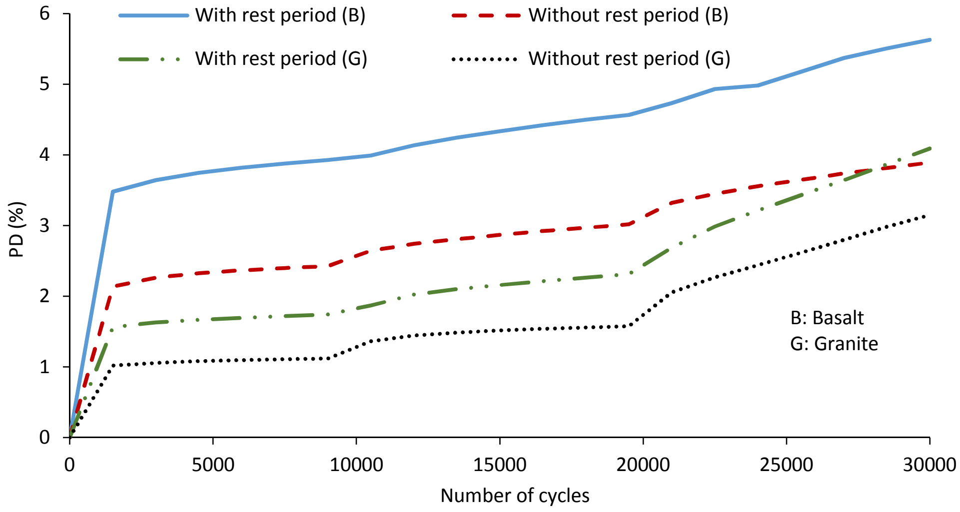


Fig. 11. Permanent deformation of basalt and granite.

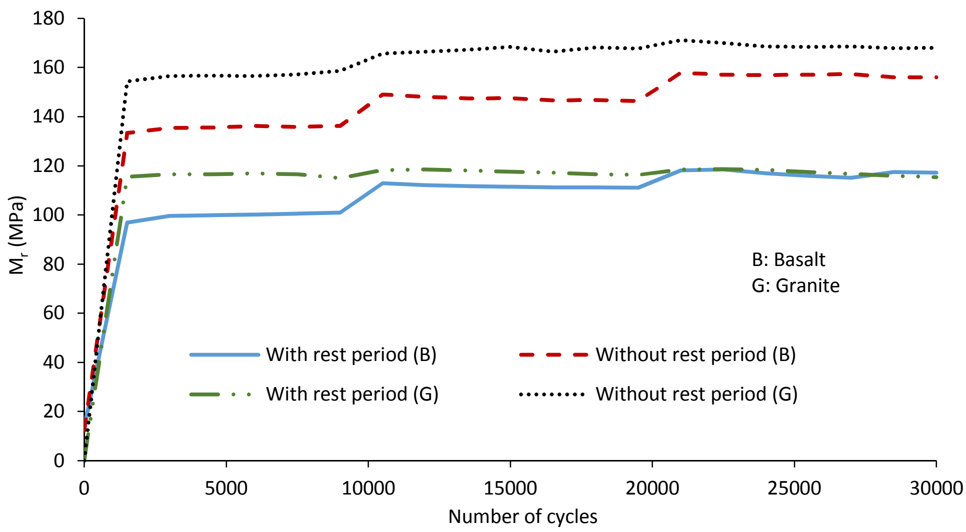


Fig. 12. Resilient modulus of basalt and granite.

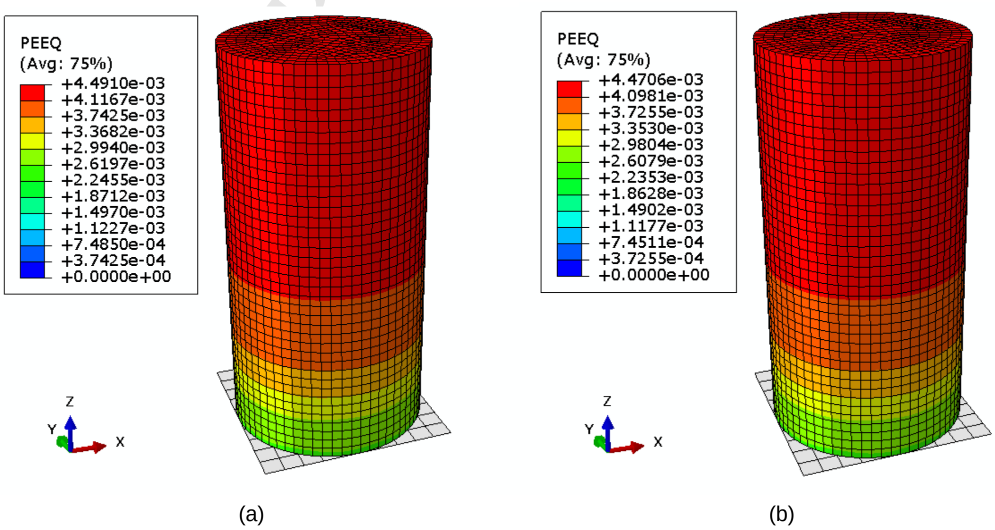


Fig. 13. Permanent deformation (a) with and (b) without rest period.

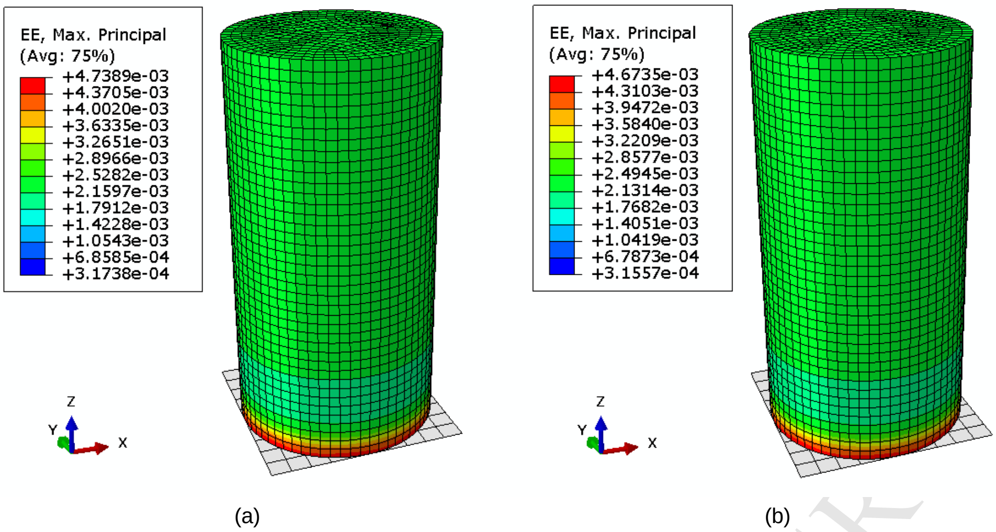


Fig. 14. Elastic strain (a) with and (b) without rest period.

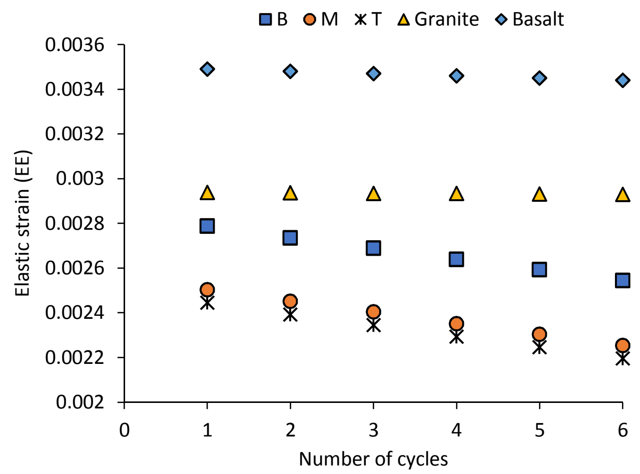


Fig. 15. Elastic strains of experimental and FEM investigations with rest period.

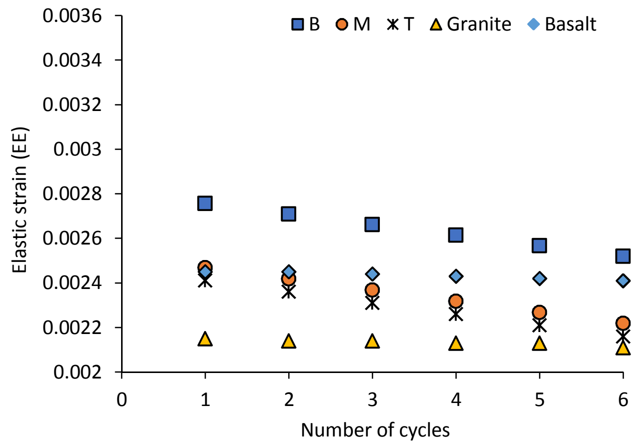


Fig. 16. Elastic strains of experimental and FEM investigations without rest period.

Similarly, when there is no rest period, EE is high for element B and low for element T, as shown in Fig. 16. It is worth mentioning that the FEM is based on boundary conditions from Arnold (2004) as mentioned in Section 3.

Fig. 17 compares the EE of the three elements (B, M, and T) of the FEM with and without rest period. The EE is higher when the specimen is subjected to loading cycle with rest period than the case without rest period. The typical downward trend of the EE could be referred to the effect of the number of cycles. This behaviour can be seen in Fig. 12 that M_r increases slightly as the number of cycles increases. This observation was first highlighted by Moore et al. (1970).

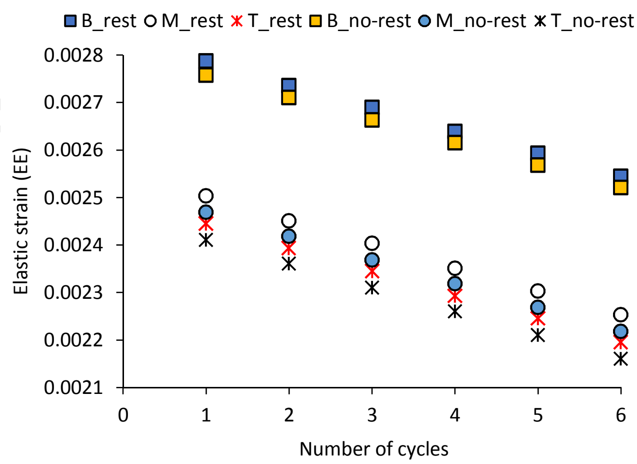


Fig. 17. Elastic strains of FEM investigation with and without rest period.

4.2.4. Displacements under repeated loads

Fig. 18 shows the displacements (U) at the end of the load cycles with and without rest period. The displacements under stress with a rest period are larger compared to those without rest period. For instance, as shown in Fig. 18, the difference in U for both cases at the top of the specimen is 0.4. Higher U at the end of load cycle results in higher resilient strain, since the resilient displacement is the difference between the displacements at the load cycle peak and end. It is worth mentioning that each cycle has stress peak and end, as shown in Figs. 8 and 9. As a result, this finding is in agreement with the experimental finding. The absence of rest period does not allocate an adequate time for the material to recover after applying loads, which results in low resilient strain.

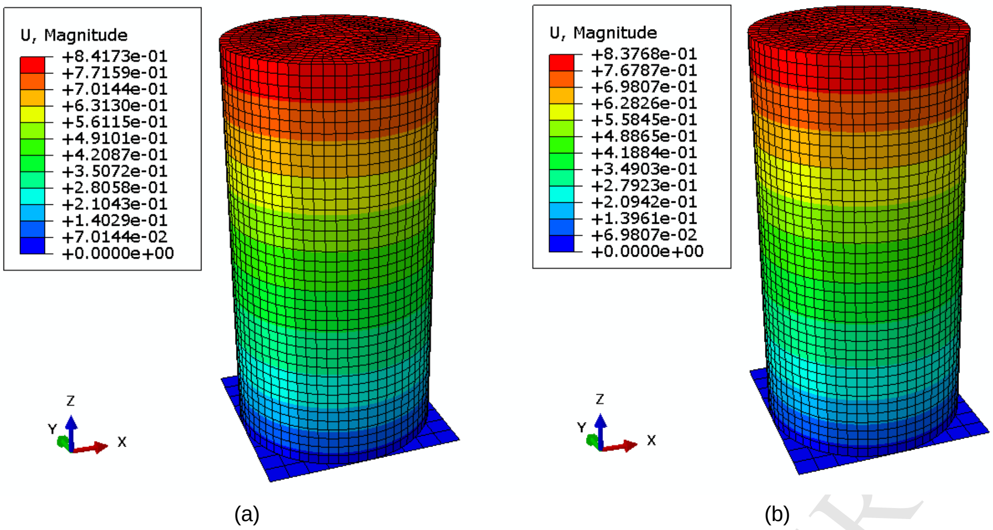


Fig. 18. Displacements (mm) (a) with and (b) without rest period.

4.2.5. Differences between experimental and finite element modelling results

The difference between experimental and FEM results was assessed according to the resilient strain of basalt and granite. The percentage difference in error between experimental and FEM results were estimated and plotted in Fig. 19. The percentage error in the elastic (resilient) strain with rest period is doubled when compared basalt with granite. The closest prediction was observed for element B with an error of 13% compared to the experimental elastic strain for granite. Whilst, the FEM for the elastic strain with no rest period shows better prediction than the case with rest period for both materials. The percentage error difference was 10% or below, compared to both basalt and granite for all elements (B, M, and T). Except for the prediction of element B in comparison to granite, the error was 19%. It was found that the FEM elastic strain values are lower than the experimental values of the basalt. However, when rest period exists, the FEM model showed acceptable prediction to granite. The high percentages of error are expected since the ABAQUS Drucker-Prager model was defined based on material from a different study. Nevertheless, the proposed FEM has the capability to monitor the stress-strain behaviour with acceptable results.

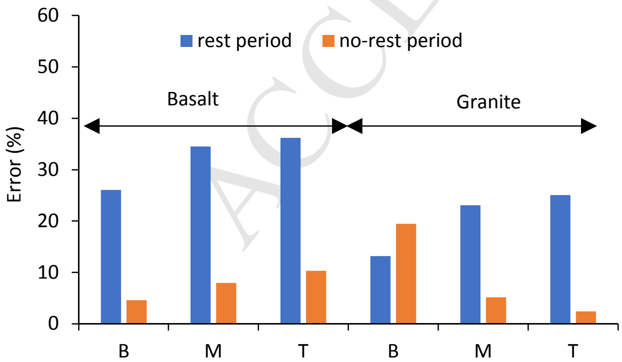


Fig. 19. Errors between experimental and FEM results.

5. Conclusions

This study investigated the effect of rest period of repeated stress pulse on the deformation behaviour of Class 2 basalt and granite crushed rocks. The experiment was conducted using RLTT and used a standard testing protocol as a benchmark. The experimental investigation was further supplemented by FEM.

Experimental results show that the rest period has a noticeable effect on the deformation behaviour of the UGMs. It seems that the rest period allows the materials to recover after loading. This process could ease the material to segregate, resulting in high permanent deformation compared to the same materials without a rest period. Both Class 2 materials (basalt and granite) appeared to have lower resilient modulus when they were tested with repeated loads at a rest period. The observed increase in resilient modulus without rest period could be attributed to the lower magnitude of the resilient strain. It might be because the absence of rest period did not allow an adequate time for the material to recover after the application of loads, which resulted in low resilient strain. Similar behaviours were observed from FEM results. The specimen under stress with rest period exhibited higher permanent deformation than the same specimen when it was tested under stress without a rest period. Moreover, the elastic strain is higher when the specimen is subjected to loading cycle with rest period than the case without rest period, which results in lower resilient modulus. It is recommended to take extra precautions while using a particular standard testing protocol and to supplement the findings using other stress configurations and/or modelling. It is also useful to conduct more tests under several configurations in order to arrive at a concrete conclusion.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interests associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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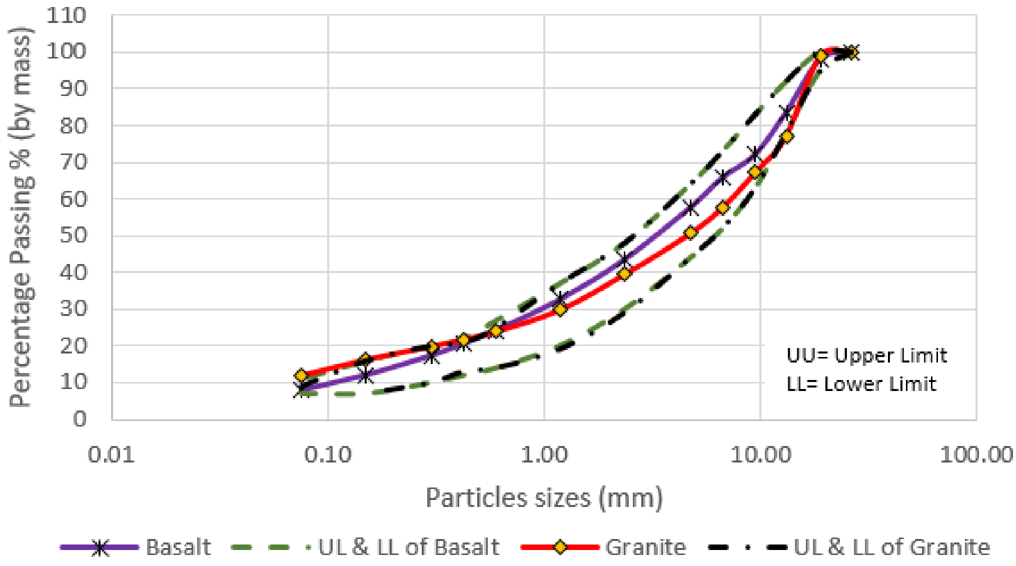
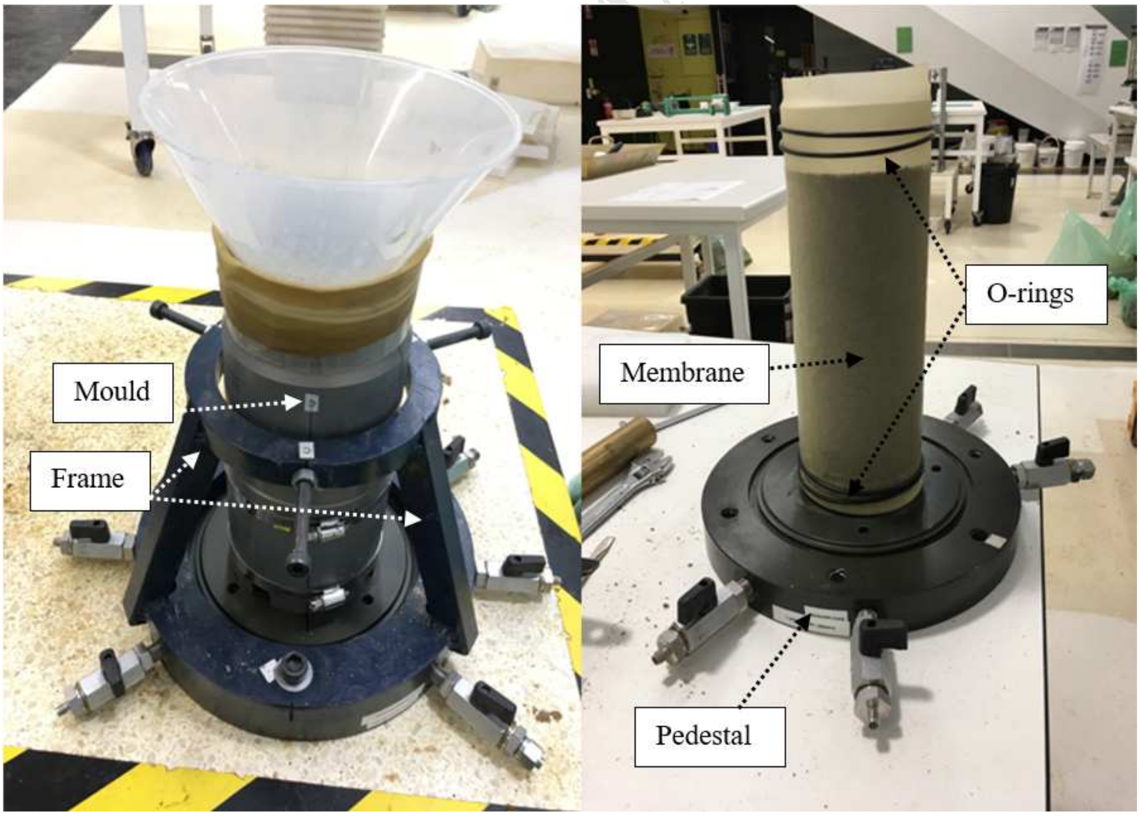


Fig. 1 Gradation of the materials and limits



(a) (b)

Fig. 2 Specimen preparation (a) mouldding (b) final specimen

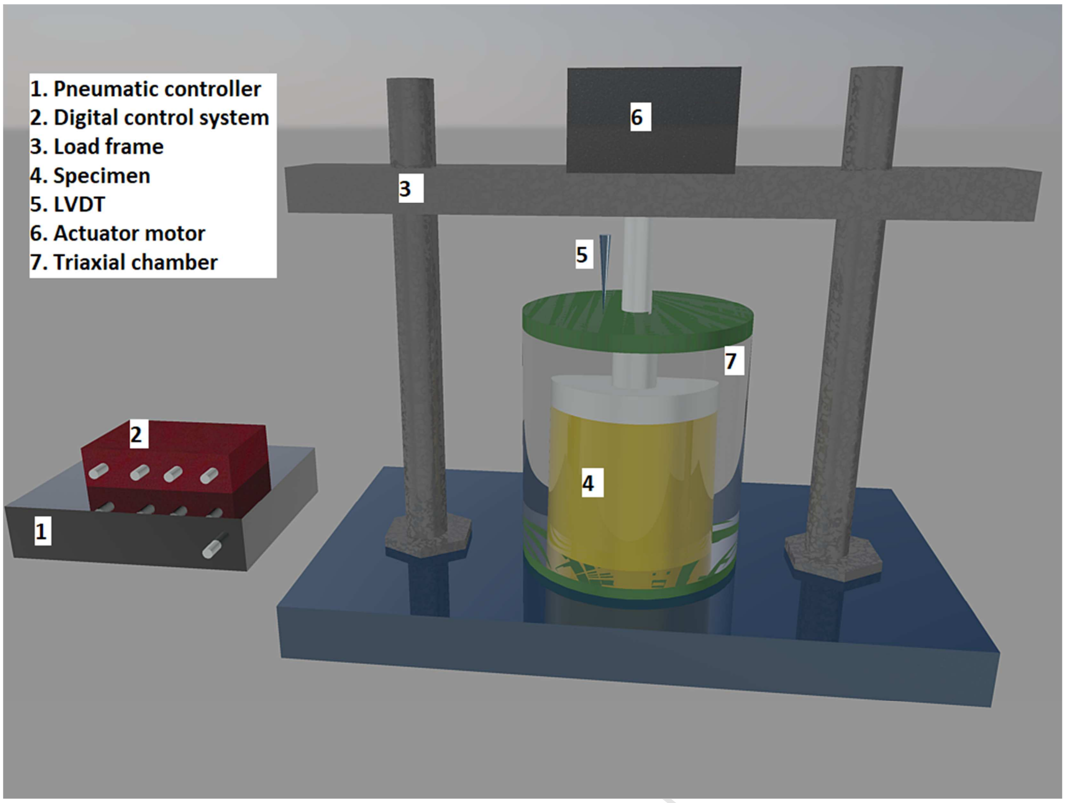


Fig. 3 Components of repeated load triaxial test

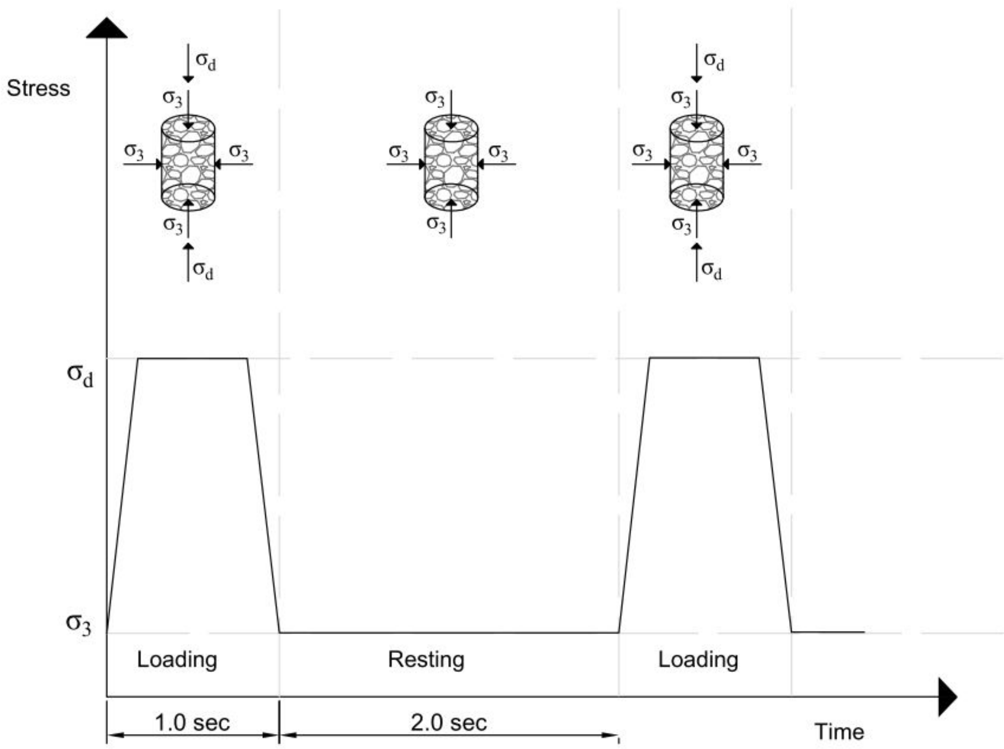


Fig. 4 Trapezoidal pulses with a rest period

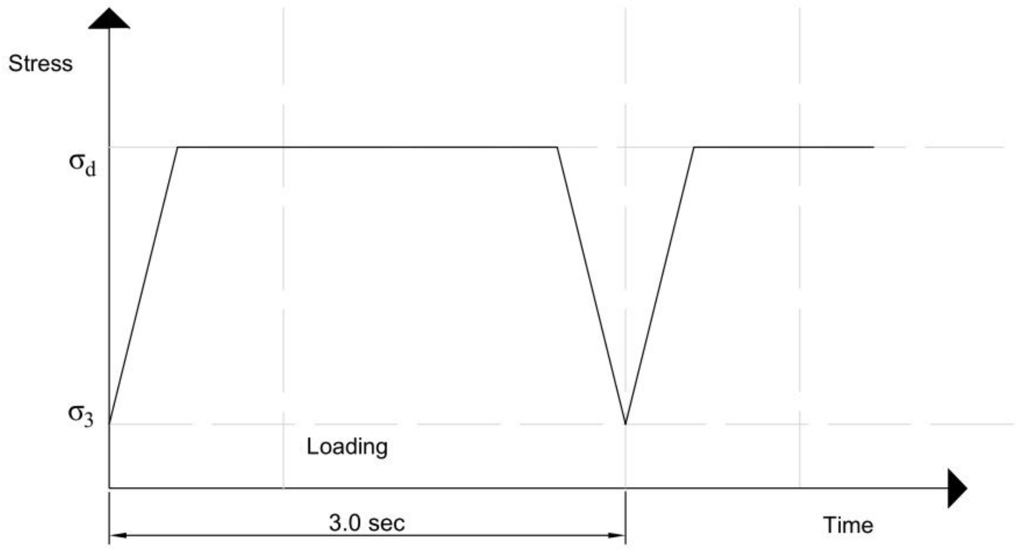


Fig. 5 Trapezoidal pulses without a rest period

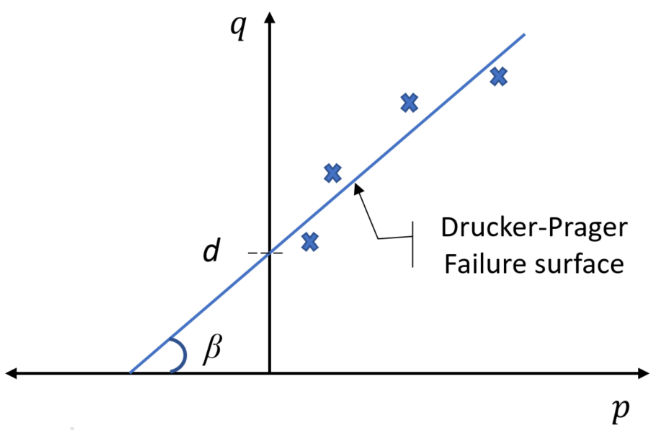
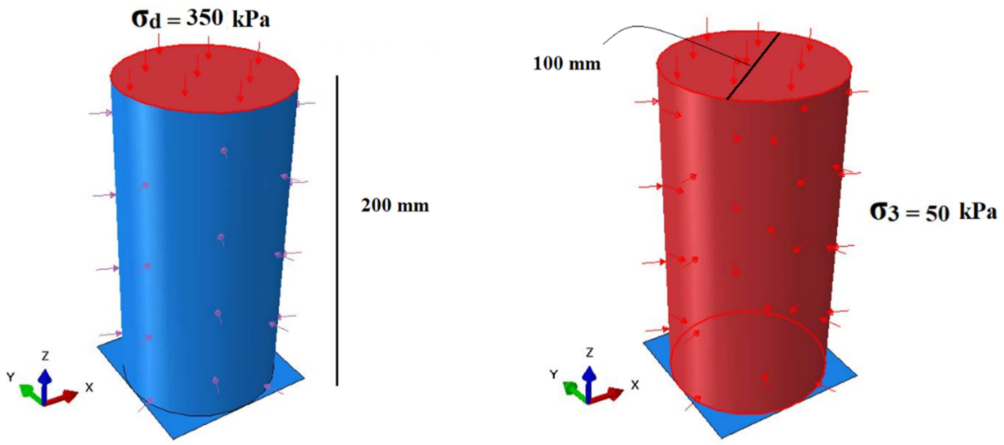


Fig. 6 Drucker-Prager failure surface



(a) (b)

Fig. 7 Applied pressures (a) deviator stress (b) confining pressure

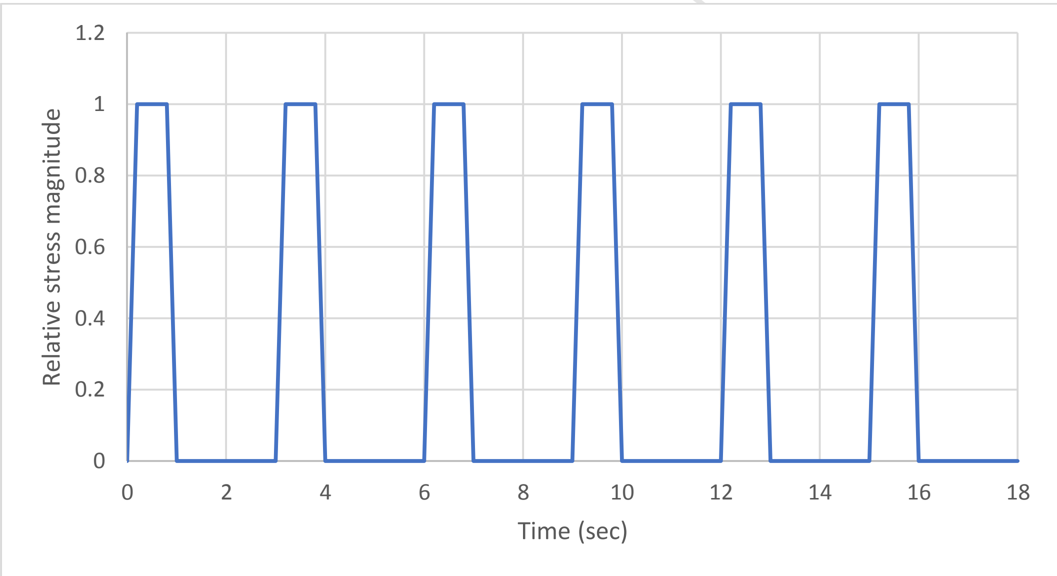


Fig. 8 Loading cycles with rest periods

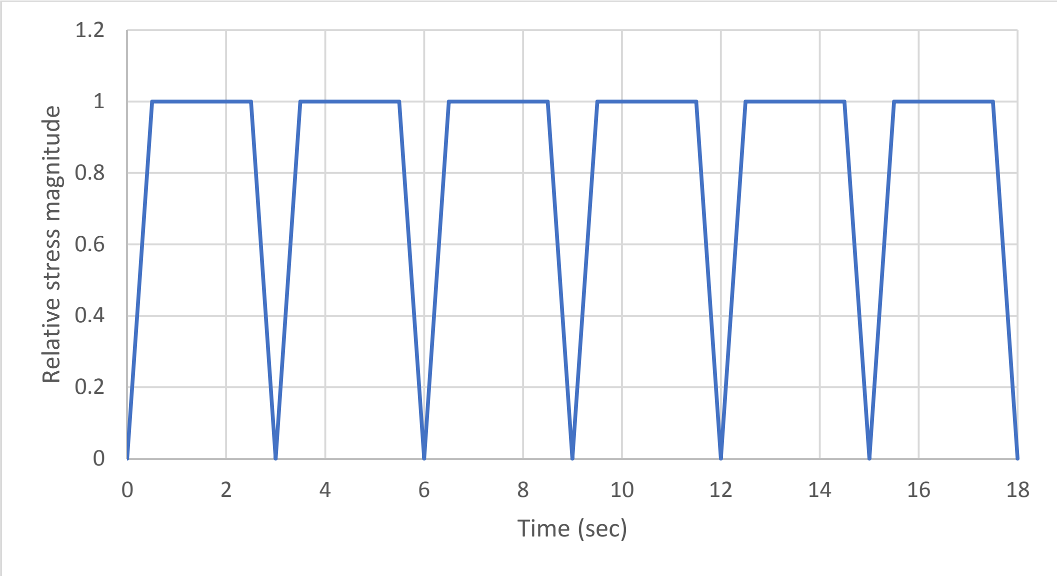


Fig. 9 Load cycles without rest periods

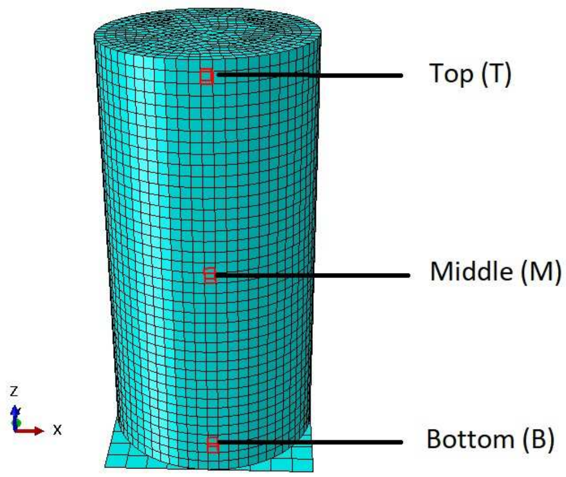


Fig. 10 Finite element mesh and selected three elements

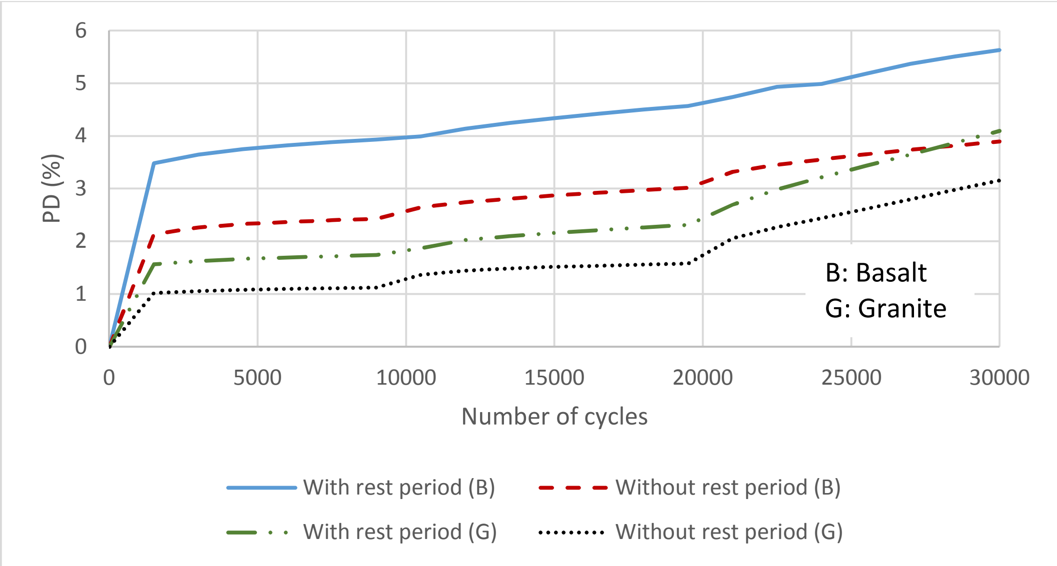


Fig. 11 Permanent deformation of basalt and granite rocks

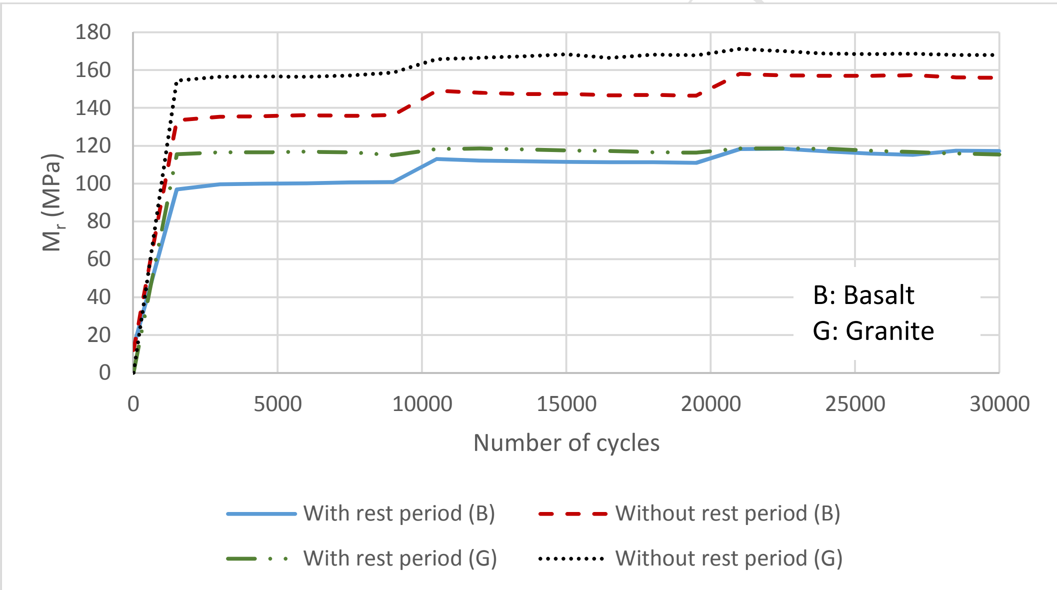
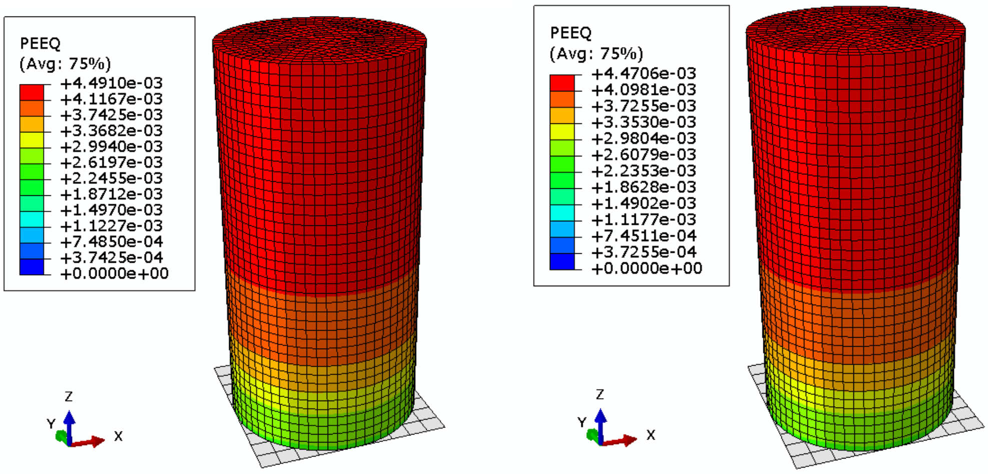
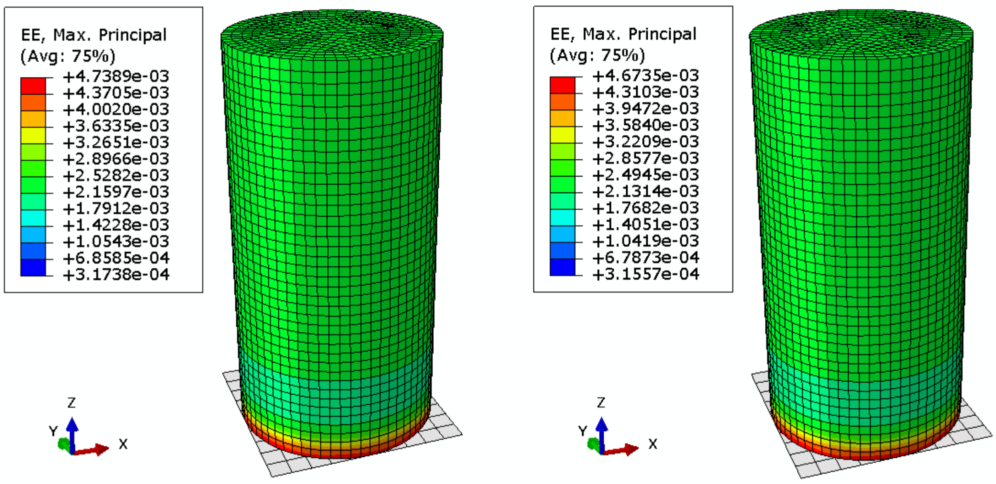


Fig. 12 Resilient modulus of basalt and granite rocks



(a) (b)

Fig. 13 Permanent deformation (a) with rest period (b) without rest period



(a) (b)

Fig. 14 Elastic strain (a) with rest period (b) without rest period

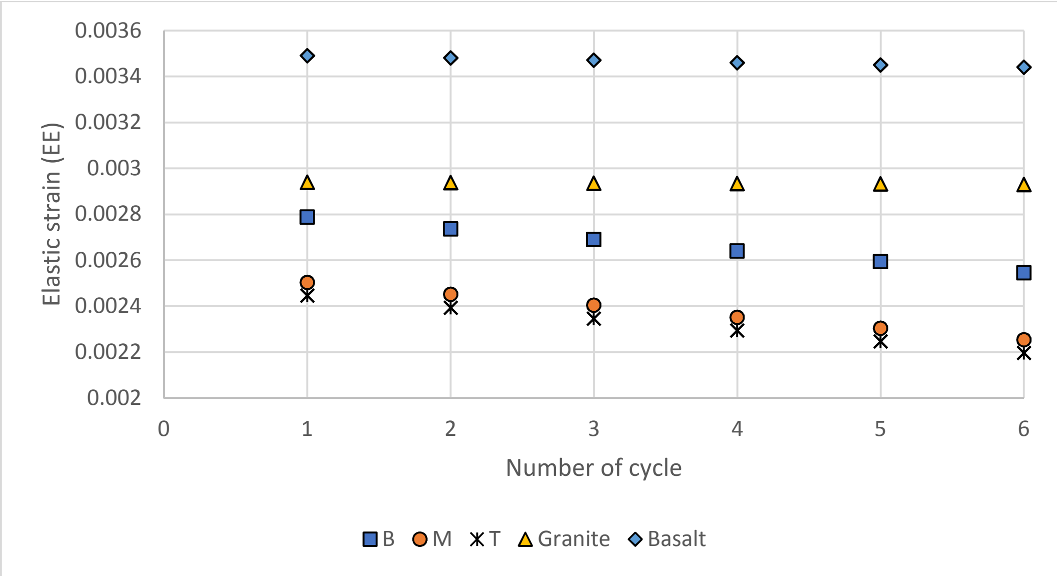


Fig. 15 Elastic strains of experimental and FEM investigations with rest period

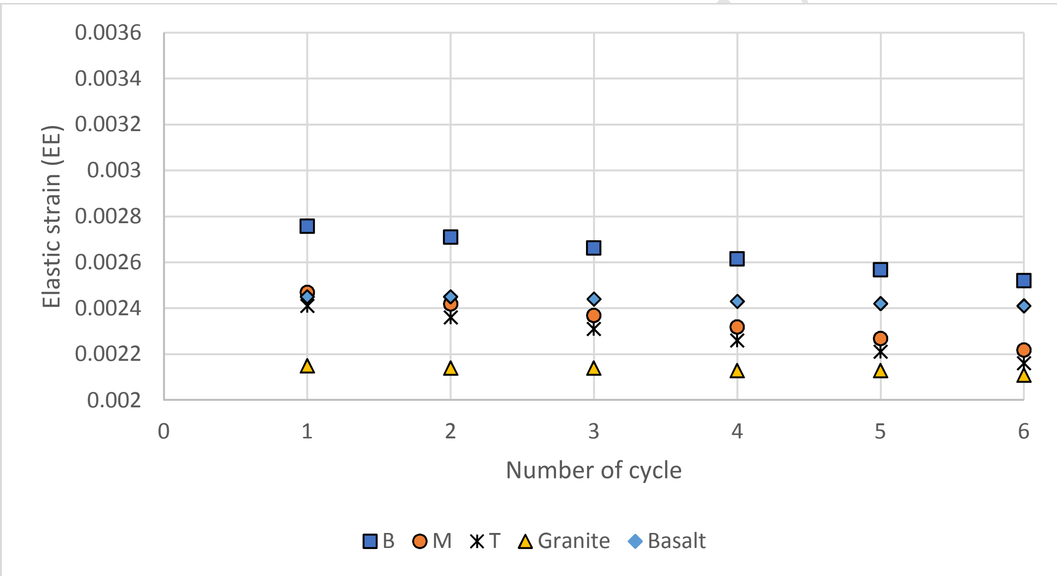


Fig. 16 Elastic strains of experimental and FEM investigations without rest period

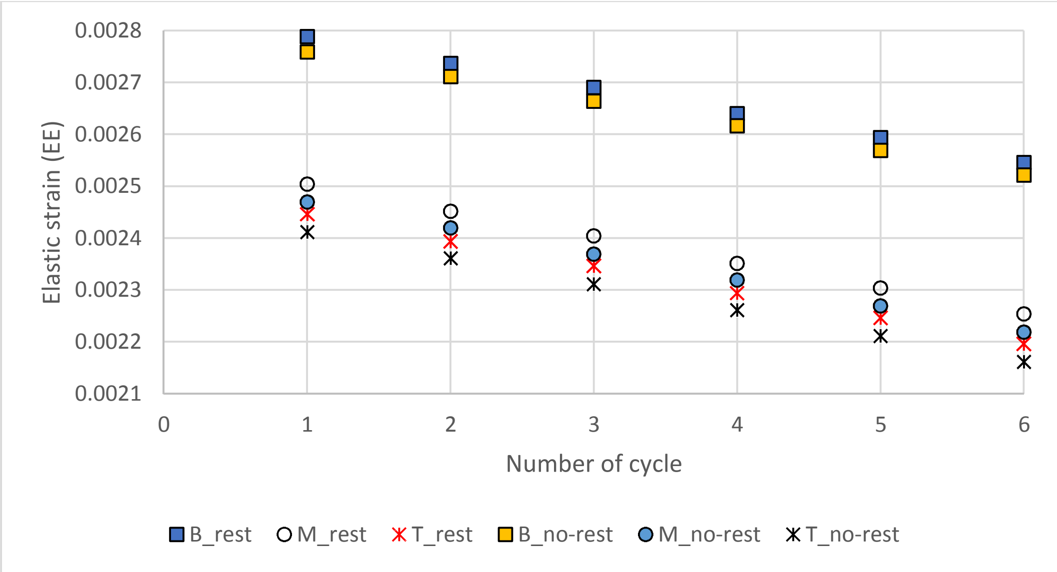
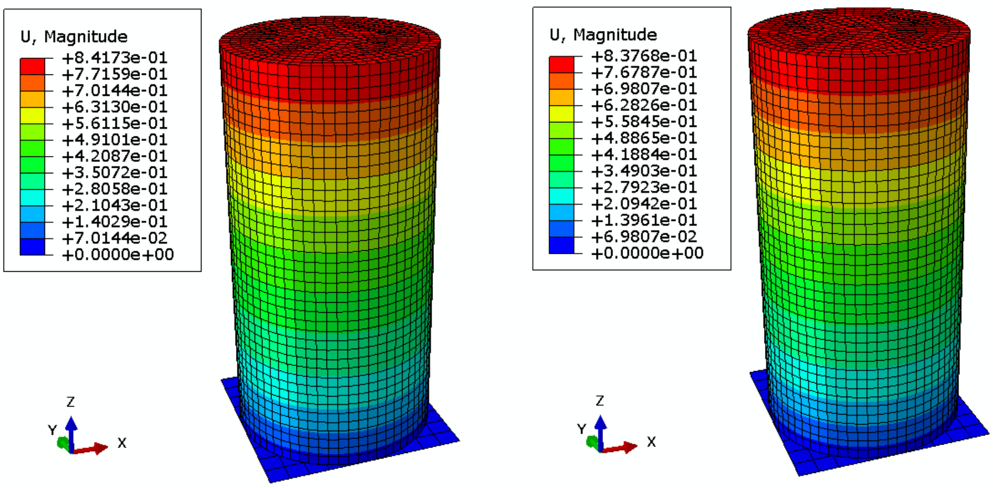


Fig. 17 EE of the FEM investigation with and without period



(a) (b)

Fig. 18 Displacements (a) with rest period (b) without rest period

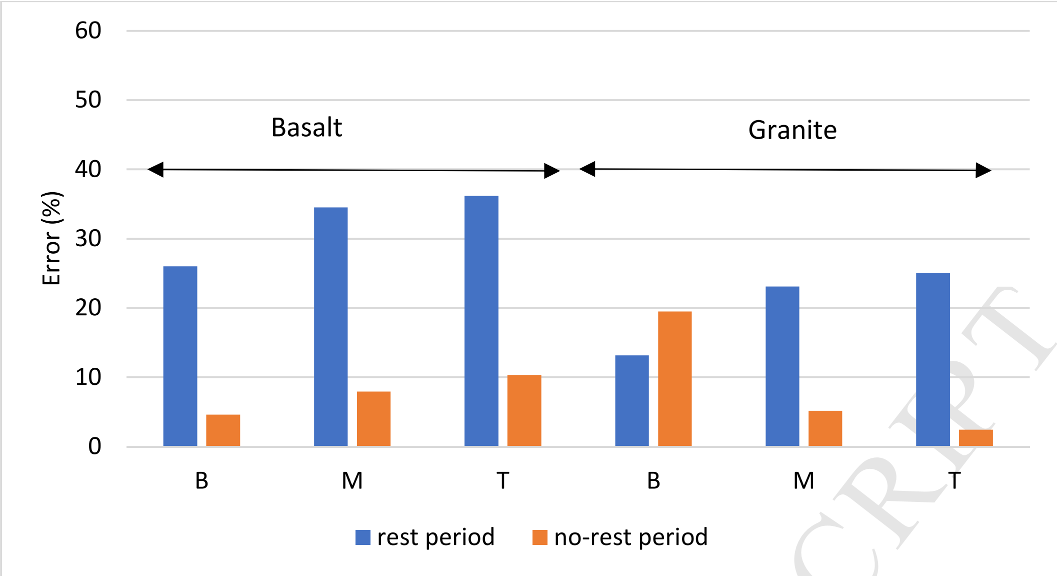


Fig. 19 Errors between experimental and FEM results