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Cover Photograph: The 190-m-high concrete-faced rockfill dam (CFRD) of Nam Ngum 2 Hydropower Project in Lao PDR, at its completion during the first impoundment. Construction of the project involved a variety of challenging geotechnical works that were executed under constraints of environment (Courtesy of Ch. Karnchang (Lao), Co., Ltd.)

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CONTENTS

Main Papers:

Estimation of Permanent Deformations of Tehri Dam Due to 7.0 And 8.5 Magnitude Earthquakes
by A. Sengupta and A. Saikia 209

Environmental Impact Evaluation on Construction of Vertical Cutoff Walls In Landfill Sites
by S. Inazumi and M. Kimura 217

Characterization of Cement-Modified Base Course Materials for Western Australia Roads
by P. Jitsangiam, H. R. Nikraz and K.Siripun 225

Evaluation of A Stabilized Sand Residue for Use As Roadway Materials
by P. Jitsangiam, H. R. Nikraz, and K.Siripun 231

Reliability Based Study on Seismic Stability of Soil Nail Walls
by G. L. S. Babu and V. P. Singh 237

Performance of T-Shape Barrette Pile Against Lateral Force In Bangkok Subsoils
by C. Submaneewong and W. Teparaksa 247

GEOTECHNICAL ENGINEERING

EDITORIAL PANEL

NOTES FOR GUIDANCE TO AUTHORS

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2. The length of titles must not exceed 70 characters and spaces.
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RAMASAMY, N. (1992). Soft ground tunneling in Bangkok subsoils, M. Eng. Thesis, Asian Institute of Technology, Bangkok, Thailand.

TATSUOKA, F. and KOHATA, Y. (1994). Stiffness of hard soils and soft rocks in engineering applications. *Proceedings of the 1st International Conference on Prefailure Behaviour of Geomaterials*, Balkema, Rotterdam, The Netherlands, Vol. 2, pp. 947-1063.

CHARACTERIZATION OF CEMENT-MODIFIED BASE COURSE MATERIALS FOR WESTERN AUSTRALIA ROADS

P. Jitsangiam, [1] H. R. Nikraz[2], K.Siripun[3]

ABSTRACT: The cement-modified soil (CMS) is described as a soil that has been treated with a relatively small amount of cement in order to improve its engineering properties so that it is suitable for construction. This soil stabilization technique is employed for the typical base course material in Western Australia named "*Hydrated Cement Treated Crushed Rock Base (HCTCRB)*". In present, the mechanistic approach of pavement design and analysis become more important and widely used internationally but HCTCRB has been created from the empirical approach empirical approach point of view. In order to be able to use this material effectively relating to the new pavement design method, its shear strength, resilient modulus, and permanent deformation characteristics need to be more investigated and deeply understood. This study aimed to perform the results of the laboratory testing which was carried out to assess the mechanical characteristics of HCTCRB. Our findings show that HCTCRB can be characterized as a relevant cohesive granular material with significant shear strength parameters. Based on the laboratory results, the suitable models of the resilient modulus characteristics and the permanent deformation characteristics were determined and introduced

Keywords: Cement-Modified Soil (CMS), Cement modified base course material, Pavement, Repeated Loading Triaxial (RLT) test, Resilient modulus, Permanent deformation

INTRODUCTION

The cement-modified materials as a base course aggregate for Western Australia roads is crushed rock with the addition of 2% cement, described as Hydrated Cemented Treated Crushed Rock Base (HCTCRB).The main function of the base course is to reduce the vertical compressive stress induced by traffic, in the subbase and the subgrade, to a stress level at which no unacceptable deformation will take place in these layers. Knowledge of HCTCRB shear strength, resilient modulus, and permanent deformation characteristics is important because if these characteristics are well understood, pavement analysis and design can be more reliable than in the past where design was empirically based.

Currently most road and highway agencies rely on the California Bearing Ratio (CBR) to characterize pavement materials for design of pavements. CBR, however, is a static parameter which has been corrected empirically with response of the pavement materials under dynamic loads of moving vehicles. The permanent deformation of pavement materials is manifested as rutting and shoving, the visible damage on the road coming from excess deformation of the pavement. This is caused by the pavement material having insufficient stability to cope with the prevailing loading and environmental conditions. Consequently, clearly understanding shear strength, resilient modulus and permanent deformation characteristics of HCTCRB is important for improved reliability in design.

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This study reports results of tests for shear strength parameters, the resilient modulus, and the permanent deformation of HCTCRB and to report on its characteristics so that a better understanding of the beneficial uses of the material can be gained

MATERIALS

Hydrated Cemented Treated Crushed Rock Base (HCTCRB)

Hydrated cemented treated crushed rock base (HCTCRB) is manufactured by blending 2 % GP or Portland cement, which shall be the General Purpose (GP) or Portland cement (Australian Standard AS 3972-1997 1997), with standard crushed rock base (MAIN ROADS Western Australia 2003). HCTCRB is mixed and stockpiled in the range of -1.0% to +2.0% of the optimum moisture content of the untreated crushed rock base as obtained by WA 133.2(MAIN ROADS Western Australia 1997).

Crushed rock

The crushed rock, used in this study, was obtained from a local Gosnells Quarry. Crushed rock samples were collected randomly from a stockpile area and kept in sealed plastic containers. Samples were re-checked, at the Department of Civil Engineering, Curtin University of Technology, in the laboratory as to their important properties in accordance with the Crushed Rock Base (CRB) specification (MAIN ROADS Western Australia 2003).

Figure1 shows the particle size distribution of the crushed rock of this study corresponded to the average particle size of the base course specifications. Comparisons of important properties and specifications were made as shown in Table 1.

Cement

The cement used in this study was the bagged type GP cement product of Cockburn Cement(COCKBURN CEMENT 2006) complying with Australian Standard(Australian Standard 1997).

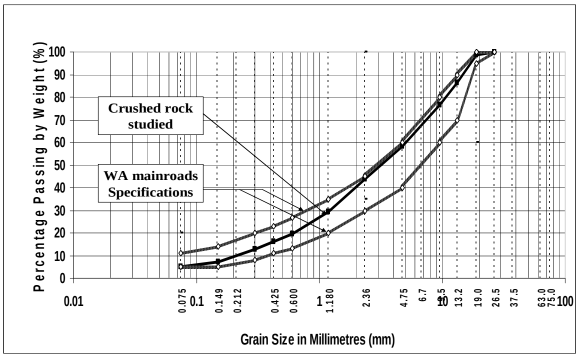


Fig.1 The particle size distribution of crushed rock studied comparing with MRWA's specifications.

Table 1 The important properties of crushed rock studied (before the addition of cement).

Test Methods*	Tests	Results	Specification
WA 120.2	Liquid Limit, LL	22.40 %	<25
WA 121.1	Plastic Limit, PL	17.60 %	N/A
WA 122.1	Plastic Index, PI	4.80 %	N/A
WA 123.1	Linear Shrinkage, LS	1.50 %	0.4-2.0
WA 216.1	Flakiness Index, FI	22.50 %	<30
WA 140.1	Max. Dry Compressive Strength, MDCS	3528 kPa	> 1700 kPa
WA 220.1	California Bearing Ratio, CBR	180	80

*test methods in accordance with MRWA Test Method (MAIN ROADS Western Australia 2006)

LABORATORY PROGRAM AND TESTING

The crushed rock was initially tested in terms of the compaction test in accordance with Main Roads Test Method WA 133.2(MAIN ROADS Western Australia 2006) to establish the Modified compaction curve for determining its optimum moisture content (OMC) and maximum dry density (MDD). This resulted in an average MDD of the crushed rock base studied of 2.27tonnes/m^3 at OMC of 5.5%. HCTCRB samples for triaxial tests then were made at 100% OMC of the crushed rock.

The test program consisted of both static and repeated loading triaxial tests. The static tests were carried out to establish cohesion (c) and internal friction angle (ϕ) of parameters HCTCRB. The repeated loading tests were performed to establish the relationships between the applied stress conditions, resilient modulus values, and the permanent deformation behavior of HCTCRB.

Specimen preparation

All HCTCRB samples were prepared based upon 100% OMC of the crushed rock. The mixing procedure consisted of adding 2% GP cement (by dry masses) to the crushed rock at the 100% OMC condition and mixing then all mixtures in the mixing machine at least 10 minutes or until the mixture being uniform in color and texture. The mixture then was kept at room temperature in sealed plastic bags for a 7-day period. After that, the mixture was then re-mixed in the same mixing machine at least for 10 minutes. Compaction was then carried out in a mould 100mm in diameter and 200mm in height, using 25 blows of a 4.9 kg rammer at 450mm drop height in 8 layers. This is equivalent to 100% Modified energy in terms of total energy per unit volume compared to conventional Modified mould. After compacting, the specimen was carefully removed from the mould. Immediately, after the specimen was removed from the mould, it was reweighed and wrapped with the plastic to prevent loss of moisture and then, the wrapped specimen was left overnight before it was transferred to the bottom platen of the triaxial cell.

Static triaxial tests

The drained triaxial compression tests were conducted to determine Mohr-Coulomb shear strength parameters (c and ϕ) of HCTCRB. The specimens were tested under the unsaturated condition (at the compaction condition) and suctions were not measured during triaxial testing. In these tests, the specimen response was measured at three different constant confining pressures: 50kPa, 100kPa, and 150kPa. These tests were carried out by using the same triaxial equipment and system used for the measurement of resilient modulus and permanent deformation.

Resilient modulus tests

The standard method of Austroads APRG 00/33-2000 (Voung and Brimble 2000) for Repeated Load Triaxial Test Method was followed for the resilient modulus tests and the permanent deformation tests. The UTM-14P digital servo control testing machine which has an ability to conduct resilient modulus tests and permanent deformation tests was used in the Geomechanics Laboratory, Department of Civil Engineering, Curtin University of Technology. Fig.2 shows the apparatus performed in the testing process.

The specimens were placed within the triaxial cell and positioned between the base plate and crosshead of the testing machine. The dynamic axial stress came from a feedback-controlled high pressure air actuator capable of accurately applying a stress pulse following the acting stress of the standard. A confining pressure was generated by a closed loop controlled actuator to simulate the lateral pressure acting on the surrounding materials, as would occur in a road. The confining pressure was applied by air pressure. The machine conveyed a vertical dynamic force of rectangular waveform with a period of 3 secs and a load pulse of 1sec duration, in accordance with the standard requirements and is demonstrated in Fig.3.

The load cell, the confining pressure, and the externally linear variable differential transducer (LVDT) on the top of the triaxial cell, which was used to measure deformations over the entire length of the specimen, were measured by the control of a control and data acquisition system (CDAS) which provided the control signals, signal conditioning, data acquisition. The CDAS was communicated with the computer, which provided the interfacing with the testing software and stored the raw test data. These enabled the resultant stress and strain in the sample to be determined.

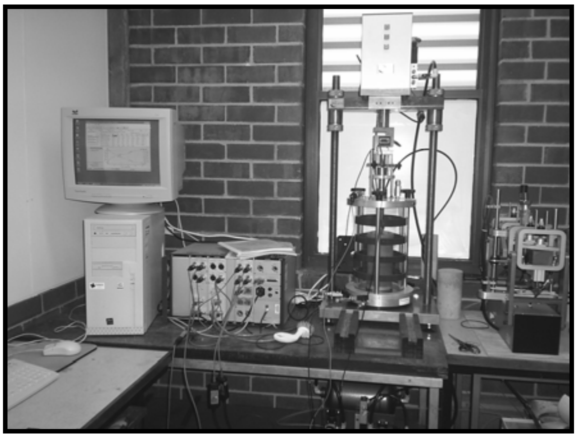


Fig. 2 Triaxial test machine used in this study.

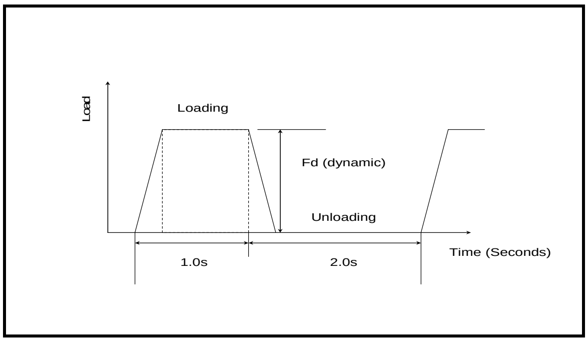


Fig. 3 Illustration of the vertical force waveform.

In accordance with this standard, the specimens were applied sequentially by the difference of the 65 stress stages to check the elastic condition of each specimen throughout the multiple loading stress stages as shown in Fig.4. This process simulates the complicated traffic loading acting on pavement. Before performing the resilient modulus process, a pre-conditioning stage was carried out to allow the end caps to bed into the specimen and allow the applied stresses and resilient strains to stabilise under the imposed stress condition. For these reasons, 1000 loading cycles of pre-conditioning were used and for each stress stage after pre-conditioning, 200 loading cycles were applied to the specimens.

Permanent deformation tests

New specimens were prepared following the same method as the resilient modulus specimens, described in item 3.1. Permanent deformation testing was calculated in accordance with Austroads – APRG 00/33 standard (Voung and Brimble 2000). In this testing, the specimens were loaded with three stress stages, each involving 10,000 cycles at a stress condition of specific dynamic deviator stress and static confining pressure as shown in Table 2.

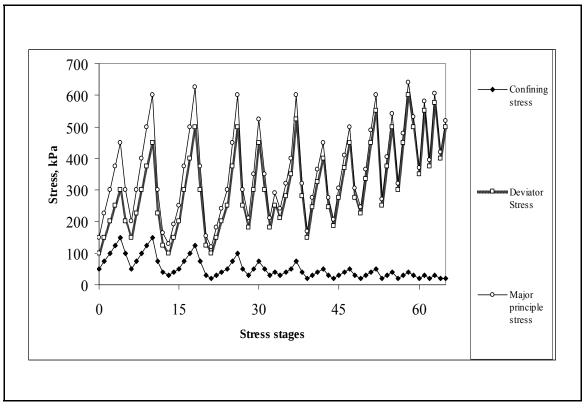


Fig. 4 Applied stresses and its stress stages of the resilient modulus tests.

Table 2 Stress levels for permanent deformation of base materials following Austroad-APRG 00/33 standard

Permanent Deformation Stress Levels		
Stress Stage Number	Base	
	Confining pressure,σ_3 (kPa)	Dynamic deviator stresses,σ_d (kPa)
1	50	350
2	50	450
3	50	550

RESULTS AND DISCUSSION

Static triaxial tests

Static triaxial tests by means of the drained triaxial compression tests were perform to obtain information on the cohesion, c, and the internal friction angle, ϕ, of HCTCRB. These tests also established the failure line of HCTCRB to determine the maximum stress level which could be applied on this material, so that the limited uses of HCTCRB would be known. The confining pressures of 50kPa, 100kPa, and 150kPa were applied on the tested specimens in each test. The characteristics of each test are summarized in Table 3. This should be noticed that the dry unit weight and the water content of HCTCRB were slightly less than the fresh crushed rock values (MDD= 2.27ton/m^3 at OMC=5.5%) after the 7-day hydration period.

Table 3 Characteristics of the static triaxial tests on HCTCRB

Test	Confining pressure (kPa)	Wet unit weight (ton/m^3)	Dry unit weight (ton/m^3)	Water content* (%)
1	50	2.22	2.12	4.52
2	100	2.19	2.09	4.64
3	150	2.19	2.10	4.48

* Water content of the sample after the hydration period of 7 days.

Figure.5(a) depicts the relationship of the deviator stress and the axial strain at the three selected confining pressure. It also can be observed that the static deviator stress initially increases with increasing the axial strain until it reaches the peak strength. For a higher confining pressure, apparently, the peak strength becomes higher and strain corresponding to the peak strength becomes higher, as well. All three curves in Fig.5(a) exhibit that after the peak strength taken place, the postpeak regime, during which the stress reduces with increasing strain. This characteristic is similar to that of dense granular materials and is normally described as strain softening. The strain-softening process is concomitant with the generation of large deformations, which caused geometrically non-linear effects to become important.(Suiker, Selig et al. 2005).

The peak strength of HCTCRB in these tests was interpreted by means of a Mohr-Coulomb failure law that the cohesion, c, and the internal friction angle, ϕ, are considered in a failure relationship, a straight line fitted to a Mohr envelope (Lamb and Whitman 1979).

Figure.5(b) shows the static triaxial test results of HCTCRB on the p-q diagram. On this diagram, the Mohr-Coulomb failure was defined in terms of principle stresses (principle stresses have been written as σ_1= the major principle stress and $\sigma_2=\sigma_3$ = the intermediate or minor principle stress). The deviator stress, q= (σ_1- σ_3), was plotted against the mean applied stress, p = ($\sigma_1+2\sigma_3$)/3. The results shown in Fig.6 indicate that the Mohr-Coulomb failure envelope (corresponding to the peak stresses) is linear for the stress range tested and has the characteristic in p-q stress space: M_p=q/p=1.723 with a deviator stress intercept, q_c = 239kPa. In the conventional Mohr-Coulomb stress space, thus the properties failure correspond to an internal friction angle (ϕ) at peak strength of 42° and apparent cohesion (c) of 177kPa.

The results of the static triaxial test of HCTCRB show that it performs the cohesive granular material behaviors. HCTCRB is not the non-cohesive granular material like the general non-cohesive granular materials such as sands and gravels. The behaviors of HCTCRB strongly depend upon both degrees of cohesion and internal friction angle.

Resilient modulus tests

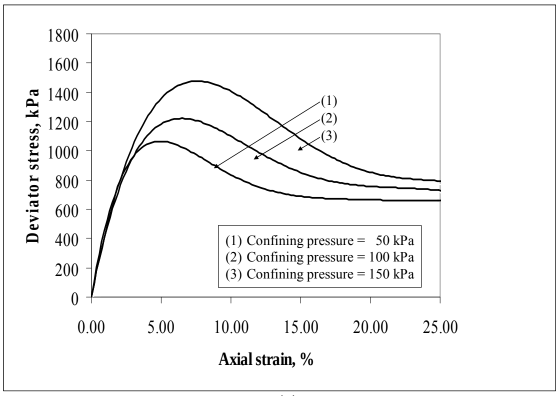
The resilient modulus determined from the RLT test is defined as the ratio of the repeated axial deviator stress to the recoverable or resilient axial strain as shown in Fig.6 and equation (1):

$$M_r = \frac{\sigma_d}{\varepsilon_r} \tag{1}$$

Where M_r is the resilient modulus, σ_d is the repeated deviator stress (cyclic stress in excess of confining pressure), and ε_r is the resilient (recoverable) strain in the vertical direction.

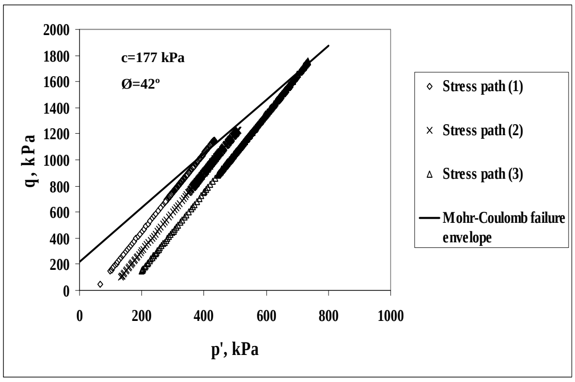
Figure.7 shows the results of the resilient modulus which are plotted against with the bulk stress ($\sigma_1+\sigma_2+\sigma_3$). Generally, the resilient modulus is non-linear with respect to the magnitude of applied stresses. Fig.7 also shows the results of resilient modulus of HCTCRB can be modeled reasonably by using The K-Theta (K-θ) model(Hick and Monismith 1971).

The representative K-θ model of HCTCRB is exhibited in equation (2).



(a)

Fig. 5(a) The static triaxial test results



(b)

Fig. 5(b) The static triaxial test results

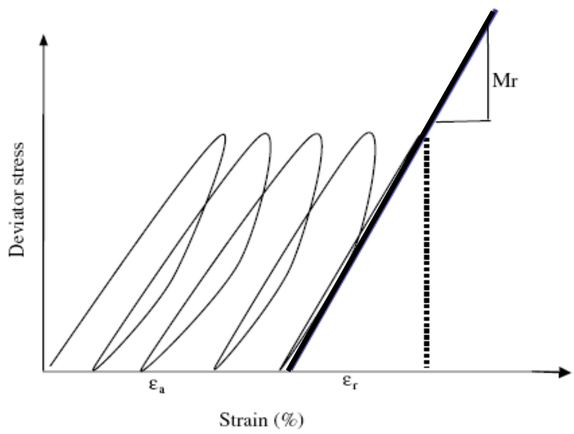


Fig. 6 Resilient Modulus determination from test results (Kim and Kim 2006)

$$M_r = k_1\theta^{k_2} = 7.684\theta^{0.591} \tag{2}$$

Where: M_r is Resilient modulus in MPa; θ is bulk Stress ($\sigma_1+\sigma_2+\sigma_3$) where ($\sigma_1=\sigma_3$); σ_1 is major principal stress (axial stress); σ_3 is minor principal stress (confining stress); k_1= 7.684 and k_2= 0.591 are regression coefficients.

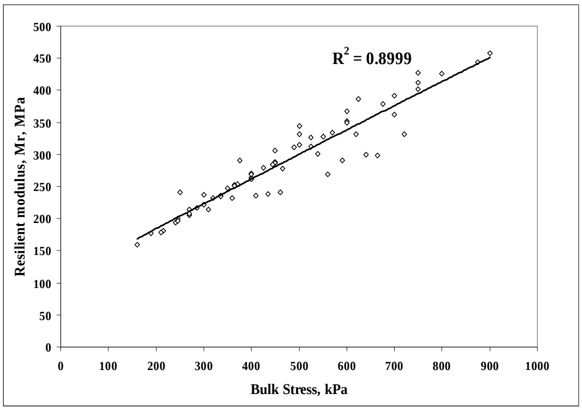


Fig.7 The resilient modulus results.

Permanent deformation tests

Figure.8 (a) and (b) shows the typical results of the permanent deformation test in terms of relationship between permanent deformation and loading cycles for HCTCRB. The various test values could be extracted from Fig.8(a) for uses in assessing the potential for permanent deformation. Furthermore, from Fig.8(a), it can be noted that the permanent deformation of HCTCRB is not dominated by the applied load in the testing range because when the applied loads increase from loading stage 1 to loading stage 3, the permanent deformation of HCTCRB did not increase dramatically. In contrast, the number of loading cycles seemed to be more influential to the permanent deformation values. Fig.8(b) exhibits the comparison of the measured permanent deformation values and the predicted values for a proposed permanent deformation model of HCTCRB. Fig.8(b) indicates that the permanent deformation can be modeled quite reasonably for HCTCRB by using the model suggested by Sweere, G.T.H from SAMARIS(SAMARIS 2004). The proposed permanent deformation model of HCTCRB is shown in equation (3).

$$\varepsilon^{p} = A * N^{B} = 573.223 * N^{0.074} \qquad (3)$$

Where: ε^p is permanent deformation in Micrometers; A=573.223 and B=0.074 are regression constants; and N is the number of loading cycles

CONCLUSIONS

The mechanical behavior of Hydrated Cement Treated Crushed Rock Base (HCTCRB) which is normally used for a base course material in Western Australia were investigated by means of static and repeated loading triaxial tests. The repeated loading triaxial tests were carried out in terms of the resilient modulus test and the permanent deformation test to provide insight into the resilient and permanent deformation characteristics of this material under the real conditions of traffic loading simulated in these tests.

It has been shown that HCTCRB can be characterized as an apparently cohesive granular material which has the cohesion (c) of 177kPa and the internal friction angle (ϕ) of 42°over the stress range significant for pavement behavior. Based on the Austroads – APRG 00/33 test standard, the resilient modulus characteristics could be modeled using the K-θ model. The permanent deformation characteristics could be modeled by using the Sweere' s model.

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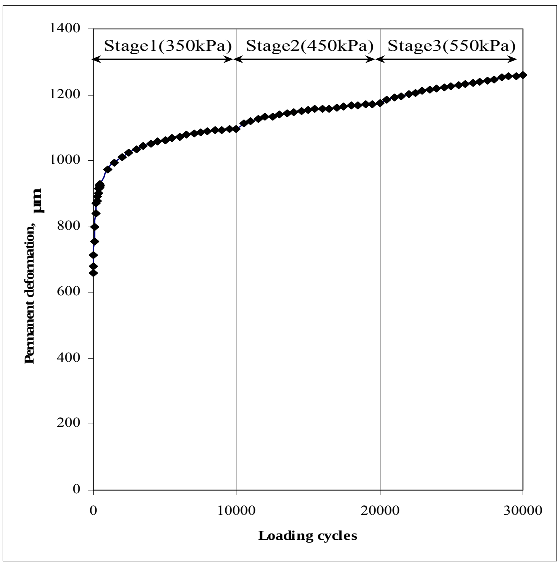
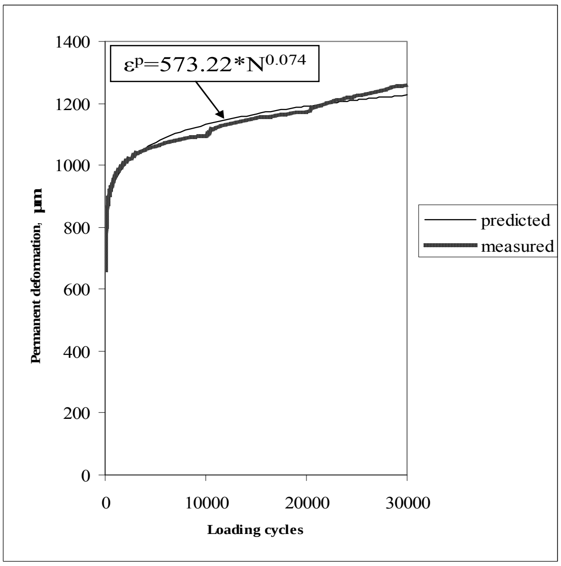


(a)



(b)

Fig. 8 Permanent deformation results and its model

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