Determination of resilient behavior of crushed waste rock using cyclic load CBR test

Shengpeng Hao & Thomas Pabst
Department of Civil, Geological, and Mining Engineering, Polytechnique Montreal, Research Institute on Mines and Environment (RIME), Montréal, QC H3C 3A7, Canada

ABSTRACT
Open-pit mining operations can generate large volumes of waste rocks, which are usually disposed of in piles that can be difficult to manage and reclaim. Crushed waste rock (CWR) is commonly used for the construction of mine haul roads because of the low cost and high strength. Resilient modulus is the primary parameter for flexible roads design, and it can be measured by repeated load triaxial (RLT) test which is complex and time-consuming. Cyclic load CBR (CLCBR) test is an economical alternative and a practical method to estimate resilient behavior of CWR. However, some limitations and shortcomings of cyclic load parameters applied limit the practicability and popularization of CLCBR tests. In this study, CLCBR test was optimized to better simulate realistic haul truck loads. The effect of cyclic load frequency, waveforms, and contact stress on the resilient behavior of CWR was studied.

RÉSUMÉ
Les opérations minières à ciel ouvert peuvent générer d'importants volumes de stériles, qui sont généralement entreposés dans des haldes de grandes dimensions, dont la gestion et la restauration peuvent s'avérer complexes. Les stériles concassés (CWR) sont couramment utilisés pour la construction de routes minières en raison de leur faible coût et de leur résistance élevée. Le module de résilience est un paramètre clef pour la conception de ces routes, et peut être mesuré par essai triaxial cyclique ; cet essai demeure néanmoins long et complexe. L'essai CBR cyclique (CLCBR) est une alternative économique et pratique pour estimer le comportement élastique des CWR. Cependant, certaines contraintes expérimentales limitent l'application et la popularisation de cette approche. Dans cette étude, l'essai CLCBR a donc été optimisé afin de simuler de manière plus réaliste les contraintes induites par les véhicules miniers. L'effet de la fréquence, des formes d'onde et des contraintes sur le comportement élastique des roches stériles concassées a été étudié.

1 INTRODUCTION

Waste rock is typically produced in large quantities, especially in open pit mines, and often stored on the surface, in piles, close to production sites (Figure 1). Management and reclamation of waste rock piles can be challenging because of the large size and the geochemical and geotechnical stability (Blowes 1997; Aubertin 2013). The reuse (or valorization) of waste rock for roads construction is an attractive alternative in terms of economic and environment impact (Figure 1) (Thompson 2011).

Waste rock is characterized by nonlinear behaviors under external loading, and is highly pressure sensitive (Araya 2011). However, most mining haul roads are designed empirically or using linearized elastic theory (Thompson 2011). For instance, characterization of crushed waste rock (CWR) road layers is typically carried out using empirical methods such as California Bearing Ratio (CBR), which limit the performance of pavements, application of waste rock, and increase maintenance costs.

Resilient modulus represents the non-linear stress-strain characteristics of pavement materials, and can be measured by repeated load triaxial (RLT) test (AASHTO T307-99 2017). RLT test is complex and time consuming, especially considering the short-service-life of mine haul roads. Some correlations between CBR and resilient modulus were proposed for natural coarse soils (Lekarp et al. 2000), but their applicability to CWR remains unclear. Therefore, it is desirable to develop alternative economical and practical methods to estimate the resilient properties of pavement materials.

Cyclic load CBR (CLCBR) test, based on the standard CBR test setup, have recently been proposed in some research works (Sas and Gluchowski 2013; Sparsha et al. 2016; Haghighi et al. 2018). The principle of CLCBR test is similar to the standard CBR test but cyclic loads are applied, and this test has the potential for road industry to estimate resilient modulus (Araya et al. 2010). However, the research for CLCBR test is relatively limited, and there are some limitations and shortcomings for conventional CLCBR test method:

- There is only one load sequence applied. So, it is impossible to study the stress-dependent behavior of pavement materials, and to fit into an appropriate modulus model.
- The cyclic load applied in CLCBR tests lacks a strong theoretical background. The cyclic stresses applied to samples should consider the actual vehicle loads.
- There is no clear regulation for the cyclic load frequency, contact stress and waveforms.

In this paper, the conventional CLCBR test was modified and optimized. The resilient modulus of CWR was evaluated by modified CLCBR test, and the effect of cyclic load frequency, duration, contact load, and waveforms on resilient modulus were also studied.

Figure 1. (a) Waste rock pile and (b) mining haul roads made of crushed waste rock at Canadian Malartic mine site, Quebec, Canada

2 MATERIAL AND METHODOLOGY

2.1 Test Material

The testing CWR material was obtained from Canadian Malartic Mine, an open-pit gold mine located in the Abitibi region, in western Quebec, Canada. The particles larger than 19 mm were removed (sieved) because of the limitation of sample size in the CBR mold. Waste rock particles were characterized in terms of angular spherical shape and rough surface texture (Figure 2(a)).

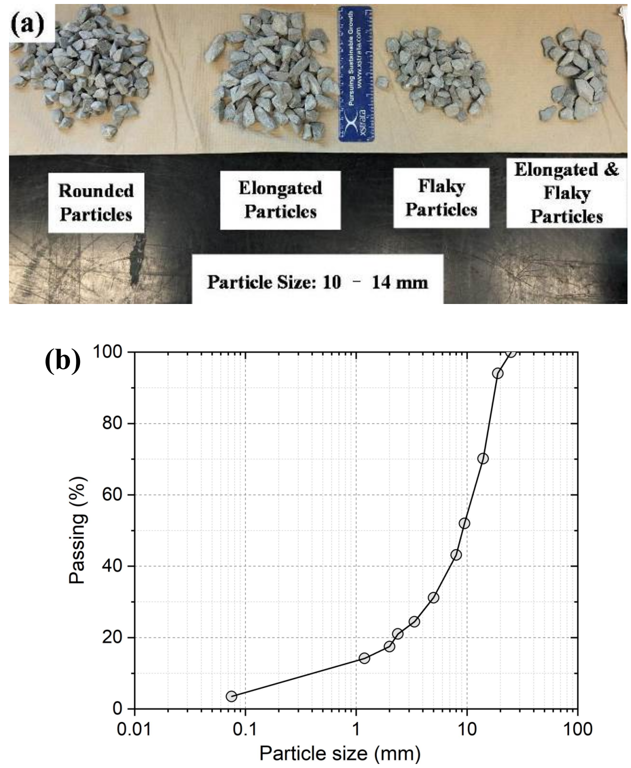

Figure 2. (a) Crushed waste rock particles (fraction 10-14 mm) from Canadian Malartic mine site, and (b) particle size distribution

The particle size distribution (PSD), the specific gravity of particles under and over 4.75 mm, and water absorption of CWR were measured in the laboratory (ASTM C127-15 2015, C136/C136M-19 2019). The PSD of CWR is presented in Figure 2(b), and the material has very small amount (around 3.5%) of fines (particles smaller than 75 microns). X-ray diffraction (XRD) tests were conducted on CWR materials to analyze mineralogy. The shape index was measured in the laboratory using length gauge and thickness gauge (IS 2386 1963). Detailed results of CWR property tests are presented in Table 1.

Table 1. Properties of crushed waste rock used for CLCBR tests

Mineralogy	Proportion	Properties	Results
Quartz	26.08%	Specific gravity (< 4.75 mm)	2.75
Albite	38.74%	Specific gravity (>4.75 mm)	2.71
Muscovite	10.87%	Water absorption (>4.75 mm)	0.41%
Chlorite	7.12%	Elongation index	38.56±1.62%
Others	17.2%	Flakiness index	34.95±2.08%

2.2 Cyclic Load CBR Test

Considering the limitations and shortcomings mentioned above, the conventional CLCBR test technique was modified and optimized in this study. The CBR apparatus was used to conduct modified CLCBR test (Figure 3(a)). The elastic deformation during CLCBR test was measured as the vertical displacement of the plunger during loading and unloading by an external linear variable displacement transducer (LVDT), and the axial vertical load was measured by using a 50 kN capacity external load cell (Figure 3(a)). The CWR samples for CLCBR tests were prepared according to ASTM D1883-16 (2016). The resilient modulus of CWR samples was evaluated from the slope of the unloading curve for the last five cycles for each load sequence.

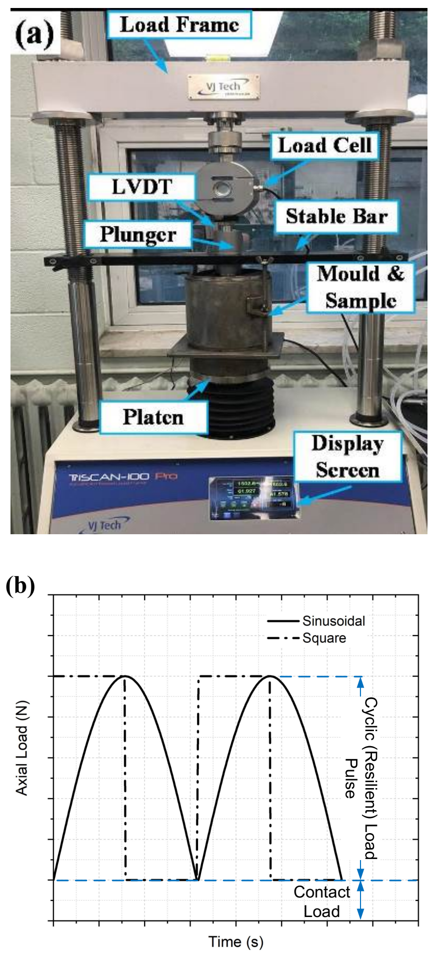

Figure 3. (a) Cyclic load CBR test apparatus at RIME (Polytechnique Montreal) and (b) cyclic load waveforms applied to crushed waste rock samples

The magnitude and sequences of cyclic loads for CLCBR test were modified and optimized based on typical stress conditions observed on mine haul roads caused by mining vehicles. The tire pressure of mining vehicles applied on mining pavements can usually range from 100 kPa to 1000 kPa (Figure 4). Detailed stress sequences applied for CWR samples in CLCBR tests are shown in Table 2. The cyclic load is equal to cyclic stress times cross sectional area of CBR plunger that the diameter is 49.63 mm. The number of load applications for each cyclic load sequence is 100.

The following expression was used to calculate resilient modulus (AASHTO T307-99 2017):

$$M_r = S_{cyclic}/\epsilon_r \quad [1]$$

Where M_r is resilient modulus (kPa), S_{cyclic} is cyclic (resilient) applied axial stress (kPa), ϵ_r is the resilient (recovered) axial strain due to S_{cyclic}.

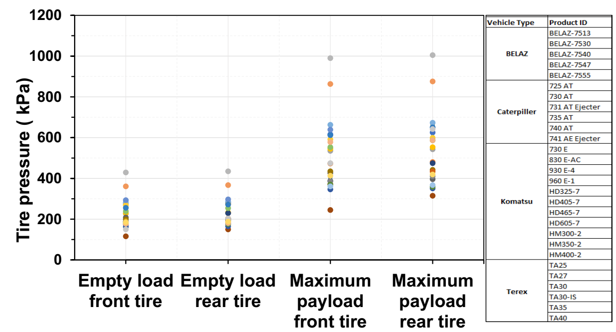

Figure 4. Tire pressure on mining haul roads caused by different types of mining vehicles

Table 1. Testing sequence for crushed waste rock in cyclic load CBR test

Sequence No.	Cyclic stress (kPa)	Cyclic load (N)	Applications
1	100	193.4	100
2	300	580.1	100
3	500	966.8	100
4	700	1353.5	100
5	900	1740.2	100
6	1100	2126.9	100
7	1300	2513.6	100
8	1500	2900.3	100

Sinusoidal and square load waveforms are usually used to simulate the contact stress between truck tires and pavements in numerical simulations and laboratory tests (Figure 4) (Siddharthan et al. 1998; Kim et al. 1999; Kim et al. 2010; Abdo 2017). Therefore, the effect of these two load waveforms on resilient behavior of CWR materials was studied using CLCBR tests. Maximum vertical stress applied to the CWR samples included the contact and cyclic (resilient) stress (Figure 3(b)). Contact stress (i.e. constant stress) was vertical stress imposed on top of the sample to maintain a positive contact between the sample cap and sample. The effect of contact stress on resilient modulus was studied by applying different contact stress values (i.e., 2%, 5%, and 15%) during CLCBR tests. Also, different cyclic load frequencies (i.e. 0.1, 0.3, 0.5, 0.7, and 0.8 Hz) were applied to investigate the effect of cyclic load frequency.

3 RESULTS

3.1 Effect of Cyclic Load Frequency and Duration

Results from CLCBR tests as a function of vertical stress and displacement of plunger are presented in Figure 5. Each CWR sample underwent eight cyclic load sequences, from 100 kPa to 1500 kPa at an interval of 200 kPa. CWR materials were not truly elastic but experienced some non-recoverable displacement after each load application. The increment of non-recoverable displacement was much smaller compared to the resilient displacement after the first few load applications in each load sequence, Figure 5.

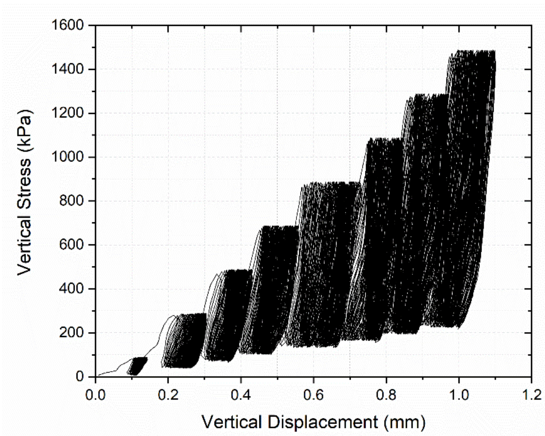

Figure 1. Cyclic load sequences applied for CLCBR tests

0.1, 0.3, 0.5, 0.7, and 0.8 Hz were applied in CLCBR tests to investigate the effect of loading duration and frequency on the resilient modulus, and sinusoidal waveform and 15% of contact stress were applied. Basically, resilient modulus with different load frequencies showed a similar trend, i.e., the resilient modulus increased from around 400 MPa to 2400 MPa as the vertical stress increased from 100 kPa to 1500 kPa. However, the resilient modulus decreased in the cases the vertical stress was higher than 1100 kPa and frequencies were 0.3 and 0.5 Hz (Figure 6). This apparent drop did not occur when the frequencies were 0.7 and 0.8 Hz.

The resilient modulus with different load frequencies presented irregular fluctuations. When the vertical stress was smaller than 1300 kPa, the maximum variation of resilient modulus was around 550 MPa, but the variation between 0.1 Hz and 0.8 Hz was only about 250 MPa. The increase of load frequency (i.e. the decrease of load duration) did not lead to a regular trend of the variations of resilient modulus (Figure 6).

Many factors can affect the resilient modulus of CWR samples, such as confining stress, water contents, density, particle size distribution, and particle shape (Lekarp et al. 2000). Although the testing CWR samples were prepared following the same procedure (i.e. modified Proctor compaction), it was difficult to ensure all the samples were exactly the same in terms of particle size distribution, particle shape, and compaction of each layer in different CWR samples. This variability could result in differences (i.e. ± 26.8%) of the resilient modulus measurement (Figure 7).

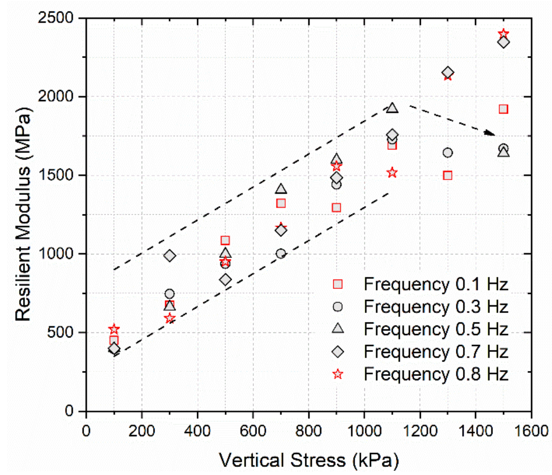

Figure 2. Effect of cyclic load frequency on resilient modulus of CWR materials, and the water contents was 4%, cyclic load frequency was 0.3 Hz, and contact stress was 15% of total vertical stress

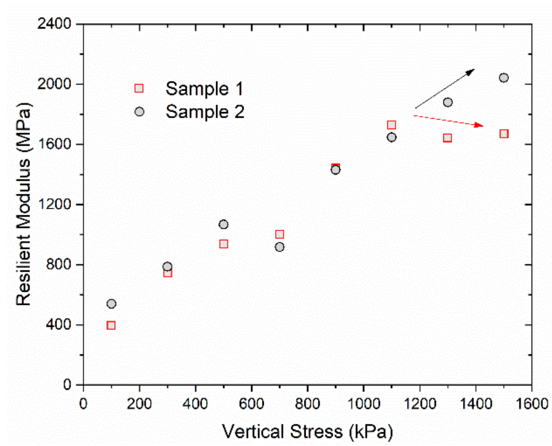

Figure 3. Fluctuations of resilient modulus because of the randomness and dissimilitude of different CWR samples, the water content was 4%, cyclic load frequency was 0.3 Hz, contact stress was 15% of total vertical stress

Two CWR samples with identical test conditions (i.e., same particle size distribution, 4% of water content, 0.3 Hz of load frequency and 15% of contact stress) were prepared for CLCBR tests to evaluate the impact of the randomness and dissimilitude generated during CWR samples preparation (Figure 6). When the vertical stress was lower than 1300 kPa, the resilient modulus of these two samples showed a similar trend: the resilient modulus increased from about 400 MPa to 2100 MPa with the increase of vertical stress, but the measured magnitude was not exactly the same with a difference of about 145 MPa (Figure 7).

The fluctuations in Figure 6 were higher than that in Figure 7, probably because high load frequencies could cause more pronounced but irregular fluctuations. Additional CLCBR tests should be carried out in the future to investigate the impact of load frequency on the evaluation of the resilient modulus.

3.2 Effect of Contact Stress

The resilient modulus of three CWR samples under different contact stresses (i.e., 2%, 5%, and 15% of total vertical stress of plunger) is shown in Figure 8. Resilient modulus of CWR samples showed a similar trend as the vertical stress increase under different contact stresses. When the vertical stress was 100 kPa, the resilient modulus with different contact stresses was almost the same, i.e., about 450 MPa. The difference of resilient modulus between 2% and 15% of contact stresses was increasing with the increase of vertical stress, and it reached to 900 MPa when the vertical stress was 1500 kPa. When the contact stress was 5% of the total vertical stress, the resilient modulus increased from 450 MPa to 1400 MPa. This seems to indicate that higher contact stress leads to a higher resilient modulus result.

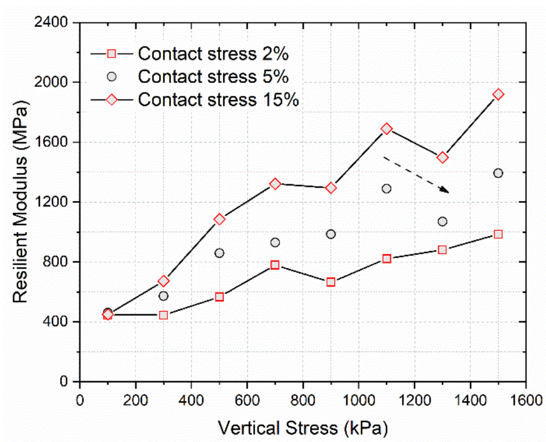

Figure 4. Effect of contact stress on resilient modulus of CWR materials, the load frequency was 0.1 Hz, and water content was 4%

3.3 Effect of Cyclic Load Waveforms

Sinusoidal and square waveforms with 2% and 15% of contact stress and 0.1 and 0.3 Hz of load frequency were used to evaluate the influence of cyclic load waveform on CLCBR tests. When the load frequency was 0.1 Hz, and contact stress 2% of total vertical stress, variations of resilient modulus with different waveforms were very small (i.e., mostly < 150 MPa). When the load frequency was 0.3 Hz and contact stress was 15%, the difference between resilient modulus using sinusoidal and square waveforms became a bit more marked than with lower frequency and contact stress, especially when the vertical stress was 700 kPa (Figure 8). However, the average difference of resilient modulus under different contact stresses was always smaller than 200 MPa.

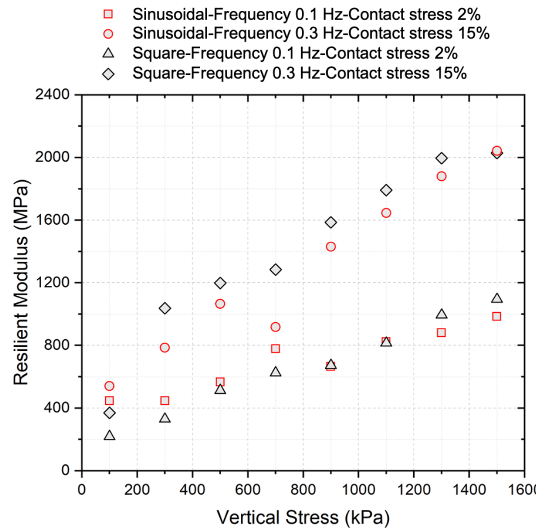

Figure 5. Effect of cyclic load waveforms on resilient modulus of CWR materials, and water content was 4%

4 DISCUSSION

Basically, resilient modulus of CWR materials increased significantly (i.e. 200 MPa – 2400 MPa) when vertical stress increased, although sometimes resilient modulus dropped distinctly when the vertical stress of plunger was higher than 1100 kPa (Figures 6, 7, and 8).

Although the CWR samples for CLCBR tests were prepared using the same protocol (i.e. modified Proctor compaction), it was still difficult to make sure all the samples were exactly the same, such as the particle size distribution, particle shape, and compaction of each layer in CWR samples. The differences observed during CWR samples preparation could cause resilient modulus variations smaller than 150 MPa (Figure 7), which also indicate that CLCBR test results are relatively repeatable.

There was no apparent trend between resilient modulus variations and loading frequency. However, the variations observed for different frequencies were about 550 MPa which was much greater than that caused by the differences during CWR samples preparation (Figures 6 and 7). Therefore, more CLCBR tests should be conducted to investigate the impact of load frequency and durations.

High vertical stress of plunger can crush waste rock particles in the samples, especially the flaky and elongated particles are easy to be broken, which can lead to resilient modulus decreases suddenly. Crush of CWR particles and decrease of resilient modulus usually occurred when vertical stress exceeded 1300 kPa, but the decrease of resilient modulus was rather uncertain (Figures 6, 7, and 8).

When the contact stress was 15% of the total vertical stress, the resilient modulus was much higher than that with 2% contact stress, and the difference of resilient modulus between 2% and 15% contact stress increases with the increase of vertical stress (Figure 8). Higher contact stress therefore seems to increase resilient modulus of CWR samples and should be taken into account when conduct CLCBR tests.

Sinusoidal and square loading waveforms were applied for CLCBR tests to investigate the impact of cyclic load waveforms. Results showed that when the loading frequency and contact stress was low (i.e., frequency < 0.1 Hz contact stress < 2% of total stress), the impact of waveforms on resilient modulus was negligible. When the frequency is 0.3 Hz and contact stress was 15%, the average variation of resilient modulus with different waveforms was smaller than 200 MPa. Therefore, the impact of cyclic load waveforms is deemed insignificant in this study.

However, the resilient modulus obtained from CLCBR tests in this study should be compared and validated using RLT tests results.

5 CONCLUSIONS

CLCBR tests were conducted to investigate the resilient behavior of CWR materials from Canadian Malartic mine site. The cyclic load sequences applied for the CLCBR tests were modified and optimized based on the realistic traffic loading. The effect of cyclic load frequency, load duration, contact stress, and waveforms on the resilient modulus of CWR materials was studied by using CLCBR tests. Preliminary results indicate that the impact of cyclic load frequency, duration and waveforms (i.e., sinusoidal and square) on the resilient modulus is insignificant, but the resilient modulus increases as contact stress (i.e., constant stress) increases. Therefore, contact stress should be taken into account while doing CLCBR tests. Basically, resilient modulus of CWR materials increases with the increase of vertical stress. In addition, the difference generated during CWR samples preparation can cause resilient modulus fluctuations.

However, more CLCBR tests should be conducted to investigate the impact of load frequency. Further study is needed to improve CLCBR test and enhance its practical application. Also, the resilient modulus obtained by CLCBR test and RLT test should be correlated, and the equivalent model should be developed.

REFERENCES

AASHTO T307-99 2017. Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials, Washington, DC.

Abdo, A.M.A. 2017. Effects of Dual Versus Super Single Truck Tire on Flexible Pavement Performance; A Mechanisticapproach, *ARPN Journal of Engineering and Applied Sciences*, 12(13): 4136-4141.

Araya, AA. 2011. Characterization of Unbound Granular Materials for Pavements.

Araya, A.A., Molenaar, A.A. and Houben, L.J. 2010. Characterization of Unbound Granular Materials Using Repeated Load CBR and Triaxial Testing, *Paving Materials and Pavement Analysis*.

ASTM D1883-16 2016. Standard Test Method for California Bearing Ratio (CBR) of Laboratory-Compacted Soils, ASTM International, West Conshohocken, PA.

ASTM C127-15 2015. Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate, ASTM International, West Conshohocken, PA.

ASTM C136/C136M-19 2019. Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, ASTM International, West Conshohocken, PA.

Aubertin, M. 2013. Waste Rock Disposal to Improve the Geotechnical and Geochemical Stability of Piles, *Proceedings of the world mining congress*, Montreal, Canada.

Blowes, D.W. 1997. The Environmental Effects of Mine Wastes, *Proceedings of exploration*.

Haghighi, H., Arulrajah, A., Mohammadinia, A. and Horpibulsuk, S. 2018. A New Approach for Determining Resilient Moduli of Marginal Pavement Base Materials Using the Staged Repeated Load CBR Test Method, *Road Materials and Pavement Design*, 19(8): 1848-1867.

IS 2386 1963. Methods of Test for Aggregates for Concrete, Part I: Particle Size and Shape.

Kim, S.M., Roesset, J.M. and Stokoe II, K.H. 1999. Numerical Simulation of Rolling Dynamic Deflectometer Tests, *Journal of transportation engineering*, 125(2): 85-92.

Kim, Y.R., Ban, H. and Im, S. 2010. Impact of Truck Loading on Design and Analysis of Asphaltic Pavement Structures.

Lekarp, F., Isacsson, U. and Dawson, A. 2000. State of the Art. I: Resilient Response of Unbound Aggregates, *Journal of Transportation Engineering*, 126(1): 66-75.

Sas, W. and Gluchowski, A. 2013. Application of Cyclic CBR Test to Approximation of Subgrade Displacement in Road Pavement, *Acta Scientiarum Polonorum. Architectura*, 12(1).

Siddharthan, R.V., Yao, J. and Sebaaly, P.E. 1998. Pavement Strain from Moving Dynamic 3D Load Distribution, *Journal of Transportation Engineering*, 124(6): 557-566.

Sparsha, N., Robinson, R. and Murali, J. 2016. Use of Repeated Load CBR Test to Characterize Pavement Granular Materials, *Functional Pavement Design*, 965-974.

Thompson, R.J. 2011. Mine Haul Road Design Construction and Maintenance Management, Curtin University, Australia.

ACKNOWLEDGEMENTS

This work was carried out with the financial support from FRQNT and the industrial partners of Research Institute on Mines and the Environment (http://irme.ca/). The equipment used in this study was acquired with a CFI grant.