2018

Dynamic Properties of Mixtures of Waste Materials

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Abstract

The stockpiling of waste mining by-products, i.e. steel furnace slag (SFS) and coal wash (CW) has brought significant environmental hazard and attracted research attention to reuse them in a more innovative way. In recent years, SFS+CW mixtures have been successfully applied in geotechnical projects, while the inclusion of rubber crumb (RC, from waste tyres) will extend them into dynamic projects. Thus the investigation of the geotechnical properties of SFS+CW+RC mixtures under dynamic loading is in urgent need. In this paper, the dynamic properties (i.e. shear modulus and damping ratio) have been explored based on extensive drained cyclic triaxial tests. The influences of number of loading cycles, RC contents, shear strain level, and the effective confining pressure have been presented. The dynamic properties of SFS+CW +RC mixtures presented in this paper will be essential for the application of the mixtures in the seismic isolation projects or railway foundation.

Disciplines

Engineering | Science and Technology Studies

Publication Details

Qi, Y., Indraratna, B. & Vinod, J. S. (2018). Dynamic Properties of Mixtures of Waste Materials. In T. Qiu, B. Tiwari & Z. Zhang (Eds.), Proceedings of GeoShanghai 2018 International Conference: Advances in Soil Dynamics and Foundation Engineering (pp. 308-317). Singapore: Springer.

Dynamic Properties of Mixtures of Waste Materials

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Abstract. The stockpiling of waste mining by-products, i.e. steel furnace slag (SFS) and coal wash (CW) has brought significant environmental hazard and attracted research attention to reuse them in a more innovative way. In recent years, SFS+CW mixtures have been successfully applied in geotechnical projects, while the inclusion of rubber crumb (RC, from waste tyres) will extend them into dynamic projects. Thus the investigation of the geotechnical properties of SFS+CW+RC mixtures under dynamic loading is in urgent need. In this paper, the dynamic properties (i.e. shear modulus and damping ratio) have been explored based on extensive drained cyclic triaxial tests. The influences of number of loading cycles, RC contents, shear strain level, and the effective confining pressure have been presented. The dynamic properties of SFS+CW+RC mixtures presented in this paper will be essential for the application of the mixtures in the seismic isolation projects or railway foundation.

Keywords: Waste materials, Dynamic loading, Shear modulus, Damping ratio.

1 Introduction

Steel furnace slag (SFS) and coal wash (CW) are by-products from steel making and coal mining industries, respectively. They are very common waste materials in Australia, and in the Wollongong region (Australia) alone, the production of SFS and CW could be several million tons per year [1]. Rubber crumbs (RC) are granulated materials from waste tires. The stockpiles of waste tires can lead to serious environmental hazards and have caused great public concern to reuse them. One of the best ways to deal with this problem is to reuse these waste materials into civil engineering projects.

As the detrimental properties of these waste materials (i.e. the swelling potential of SFS, the particle breakage of CW, and the low shear strength and high deformation of RC), they are usually blended with other materials when used in civil engineering. For instance, SFS are usually mixed with fly ash or cement to be served as landfill or used in unbound pavements [2, 3], and the SFS+CW mixtures have been successfully used in practical engineering applications such as port reclamation [1, 4] and landfill projects [5, 6]. With the high damping property, RC is usually blended with sand or other soils applied in seismic conditions or as an integral part of vibration damping systems for machine foundations and railroads [7, 8]. Moreover, Indraratna et al. [9] developed an energy absorbing layer for subballast by adding RC into SFS+CW mixtures.

Since subballast is subjected to cyclic loading, it is of great importance to understand the cyclic loading behavior of SFS+CW+RC mixtures, especially the shear modulus and damping ratio. The aim of this paper is to investigate the influence of RC contents $R_b(\%)$, the loading cycles, the shear strain level, and the effective confining pressure on the shear modulus and damping ratio of SFS+CW+RC mixtures based on drained cyclic loading triaxial tests.

2 Laboratory investigations

2.1 Materials

The SFS and CW used in this study were provided by Illawarra Coal and Australia Steel Milling Services, respectively. RC was from waste tires and three different sizes (0-2.3mm, 0.3-3mm, and 1-7 mm) were used. The particle size distribution (PSD) of SFS, CW, and RC are shown in Fig.1. According to the unified soil classification system, SFS and CW can be classified as well-graded gravel with silty-sand (GW-GM), and well-graded sand with gravel (SW), respectively, while RC can be referred to as granulated rubber.

2.2 Specimen preparation and testing program

To exclude the influence of gradation, all the mixtures tested in this study were mixed to the same gradation (the target PSD), also shown in Fig.1. Please note that the waste materials (i.e. SFS, CW, and RC) were blended by weight, and the content rate of SFS and CW was set to be SFS:CW=7:3 as with this rate the waste mixtures can maintain higher shear strength and less particle breakage [9], then 0%, 10%, 20%, 30%, and 40% RC were added to the SFS+CW mixtures. All the specimens were prepared at the optimum moisture content and compacted to achieve an initial dry unit weight equivalent to 95% of their maximum dry density to simulate typical field conditions of subballast.

A series of stress-controlled drained cyclic triaxial tests were carried out for the SFS+CW+RC mixtures following the procedure suggested by ASTM D5311/D5311M [10]. The specimens were compacted in three layers and had 50 mm in diameter by 100 mm high. In this study, an appropriate range of effective confining pressure (i.e. σ'_3 = 10, 40, and 70 kPa) was used to simulate the field conditions of railway subballast depending on the typical axle loads (heavy haul) and heights of track embankments in the state of NSW [11, 12]. Moreover, to simulate the good drainage condition and the long term permanent settlement response of the subballast layer, the cyclic loading tests were conducted under drained condition, which was in agreement with Suiker et al. [15].

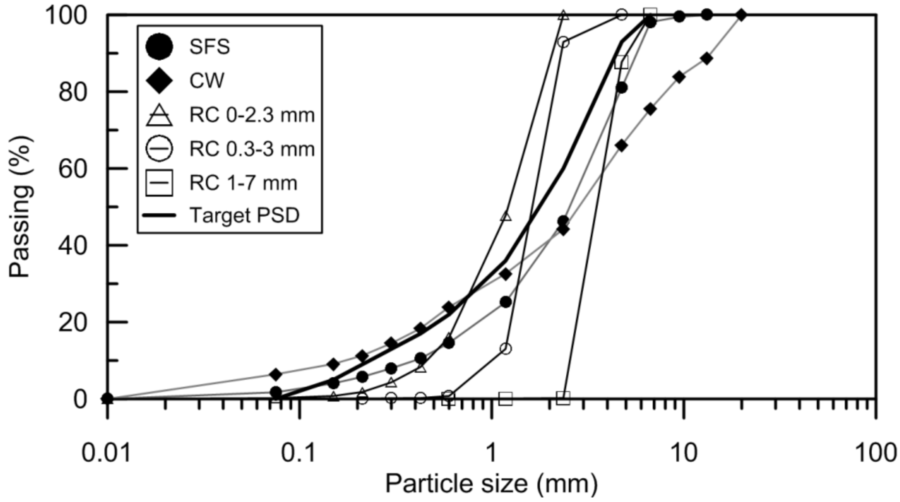

Fig.1 PSD of SFS, CW, RC, and the target PSD for SFS+CW+RC mixtures

Cyclic loading tests were conducted following three stages, i.e. saturation, consolidation, and cyclic loading. During the saturation stage, the specimens were flooded with de-aired water and then the back pressure was applied at an increasing rate of 1 kPa/minute until 500 kPa was reached. This stage was completed when the Skempton's B-value exceeded 0.98, and then isotropic consolidation was carried out under the desired effective confining pressure of 10, 40 or 70 kPa. After consolidation, the cyclic loading stage was conducted at CSR=0.8 (cyclic stress ratio, Equation 1), using a loading frequency of $f = 5\ Hz$. The deviator stress used in this study is governed by σ'_3 and cyclic stress ratio, CSR. For CSR=0.8, the confining pressures of $\sigma'_3 = 10, 40,$ and $70\ kPa$ correspond to deviator stresses of 16, 64, and 112 kPa, respectively. These values are in line with the observed stress conditions generated in typical freight tracks [12]. All the cyclic loading tests were continued for 50000 cycles.

$$CSR = \frac{\sigma_a}{2\sigma'_3} \quad (1)$$

Where, CSR is the cyclic stress ratio; σ_a is the peak cyclic axial stress; and σ'_3 is the effective confining pressure.

3 Test results

The shear modulus G and the damping ratio D are the two key parameters needed to estimate the stiffness and energy absorbing capacity of soil. Damping is the loss of energy within a vibrating or a cyclically loaded system which is usually dissipated in the form of heat or breakage for granular materials; it is commonly used to measure the damping capacity for energy dissipation during dynamic or cyclic loading. The definition of the shear modulus and damping ratio is presented in Fig.2; where the area of the hysteretic loop A_2 in the shear stress-shear strain plain represents the energy dissipated during a loading cycle, while four times the area of the triangle A_1 is the maximum elastic energy absorbed during the cycle [13].

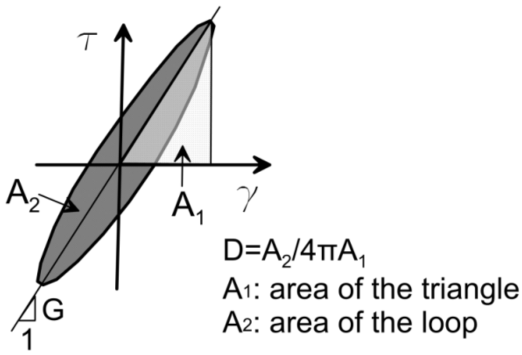

Fig. 2 Definition of shear modulus and damping ratio (after Kokusho [13])

3.1 The effects of $R_b(\%)$ and the effective confining pressure

Fig.3 shows the shear modulus and damping ratio of SFS+CW+RC mixtures with different $R_b(\%)$ versus loading cycles in logarithm. It can be noted that the addition of RC has a significant influence on the shear modulus and damping ratio of SFS+CW+RC mixtures. As with previous studies of rubber-sand mixtures (e.g. [7, 8, 14]), the shear modulus decreases with increasing $R_b(\%)$ because of the low stiffness of rubber materials. Unlike shear modulus, the damping ratio of SFS+CW+RC mixtures increases with $R_b(\%)$ indicating the high damping properties of rubber materials. However, the SFS+CW+RC mixtures with $R_b \geq 10\%$ tend to achieve a similar damping ratio after 10000 cycles (Fig.3a). This is because the inclusion of RC increases the area of the hysteretic loop, but as R_b increase the hysteretic loop becomes more inclined, which then causes a rapid increase in the area of the triangle A_1, and this also suggests that the damping capacity of the waste mixtures with $R_b \geq 10\%$ is similar at high loading cycles, while for the waste mixtures without rubber the value of the damping ratio is stable albeit a little fluctuation after 10 cycles.

The shear modulus calculated from the test result of traditional subballast (well-graded sand with gravel) tested by Suiker et al. [15] is also shown in Fig.3(b). The test conditions were the same with this study except the deviator stresses applied were different. Here only the result of $q = 175\ and\ 91\ kPa$ are presented. It can be seen that the shear modulus increases as the deviator stress increases, and thus it can be estimated that when $q = 112\ kPa$ at $\sigma'_3 = 70\ kPa$ (same with this study), the value of the shear modulus of subballast would be similar with SFS+CW+RC mixtures having 0% RC. Therefore, only the waste mixtures with $R_b \leq 10\%$ have acceptable stiffness comparing with traditional subballast.

The influence of effective confining pressure σ'_3 on the shear modulus and damping ratio of SFS+CW+RC mixtures is presented in Fig.4 (a) and (b), respectively. It is clear that with the same $R_b(\%)$, as σ'_3 increases the shear modulus of the waste mixtures increases while the damping ratio decreases.

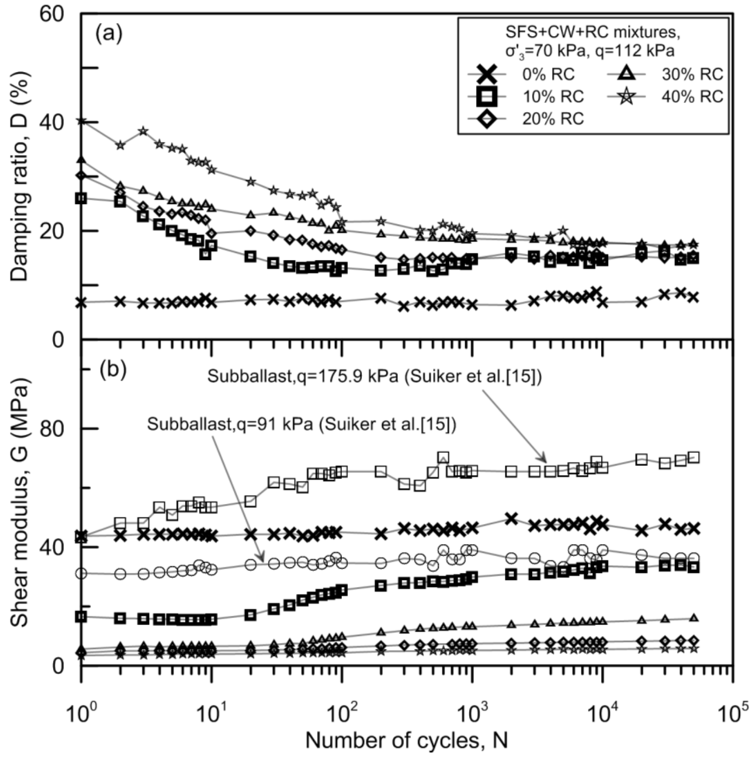

Fig.3 Cyclic loading results of traditional subballast and SFS+CW+RC mixtures with different $R_b(\%)$: (a) damping ratio, and (b) shear modulus

Fig.5 shows the evolution of the shear modulus and damping ratio at 1000 and 10000 cycles varying with $R_b(\%)$ and σ'_3. It is evident from Fig.5 that of the variation of shear modulus and damping ratio with R_b at 1000 cycles is similar to that at 10000 cycles. Note that the effect of confining pressures on shear modulus weakened as R_b increases, which in line with past studies such as Nakhaee & Marandi [16]. This is because as more RC included, the waste mixes tend to behave more elastic, and the influence of the confining pressure become insignificant [7]. Obviously, the behaviour of shear modulus and the damping ratio is governed mainly by R_b. When $R_b < 20\%$, the shear modulus decreases and the damping ratio increases as R_b increase. However, when $R_b > 20\%$ both the shear modulus and the damping ratio only change a little indicating that the rubber crumbs has formed the skeleton of the specimen and the specimen behaves rubber-like. It is worthy to note that when R_b increases in the range of $10\% \leq R_b \leq 20\%$, only a minor increase happens to the damping ratio, suggesting that 10% RC is sufficient for the purpose of energy absorbing.

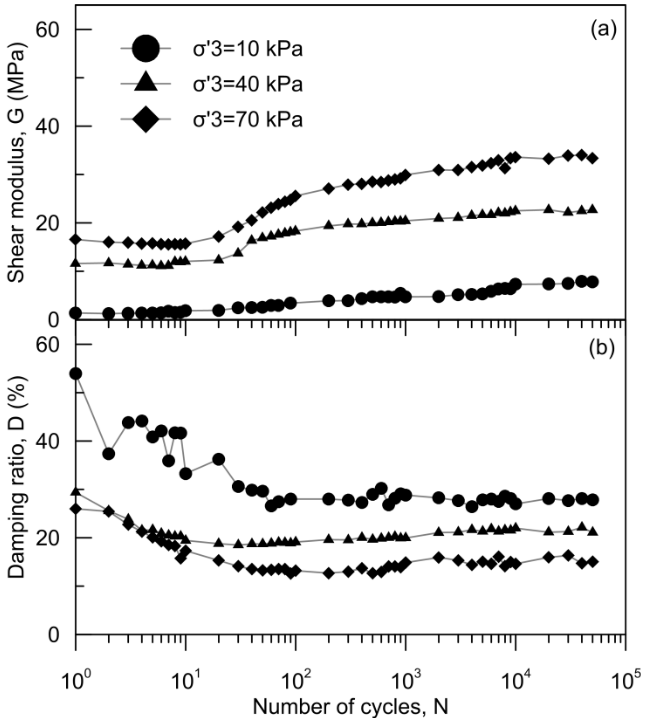

Fig.4 Cyclic loading results of SFS+CW+RC mixtures with R_b=10% under different confining pressures: (a) shear modulus, and (b) damping ratio

3.2 The effects of cyclic loading cycles

The effect of cyclic loading cycles on the shear modulus and damping ratio of SFS+CW+RC mixtures can be observed in Fig.3-4. It can be seen that at $\sigma'_3 = 70\ kPa$ the shear modulus of the waste mixtures with $R_b \geq 10\%$ stays stable during the first 10 cycles and increases at a reducing rate after 10 cycles suggesting that the stiffness of these waste mixtures increases with the contraction of the specimen. For the waste mixtures with $R_b = 0\%$ the shear modulus fluctuates marginally after 10 cycles indicating a stable stiffness of the waste mixtures with no rubber. In Fig.3 (a) and Fig.4 (b), note that the damping ratio of SFS+CW+RC mixtures with $R_b \geq 10\%$ decreases as the loading cycles increase albeit at a reducing rate, while the damping ratio of the waste mixture without rubber keep stable as the cyclic test continuing. It is worthy to note that both the shear modulus and the damping ratio of SFS+CW+RC mixtures stabilized after 10000 cycles.

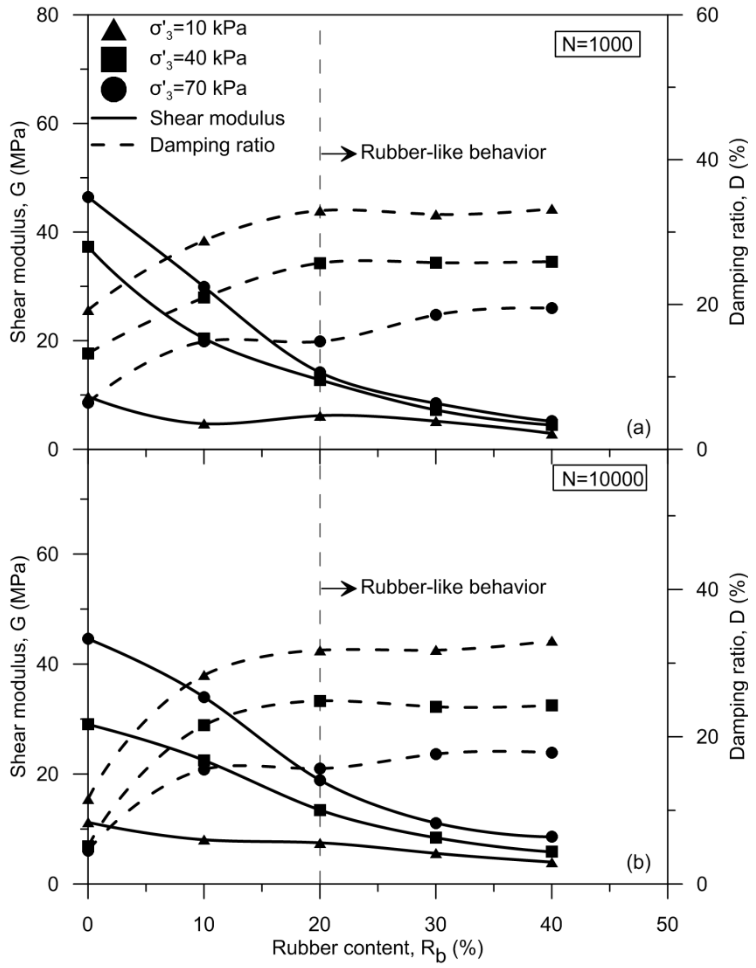

Fig.5 Shear modulus and damping ratio of waste mixtures (SFS:CW=7:3) changing with R_b at (a) N=1000 cycles, and (b) N=10000 cycles

3.3 The effects of shear strain level

Fig.6 (a and b) shows the effect of shear strain level on the shear modulus and damping ratio of the waste mixtures as well as traditional subballast (after Suiker et al.[15]) and sand-RC mixtures (after Li et al.[8]). It is evident from Fig.6 (a) that G decreases with an increase in the shear strain regardless of the magnitude of RC. The variation of G with shear strain for SFS+CW+RC compares well with the subballast material reported by Suiker et al. (2005). The value of shear modulus for sand-RC mixtures decreases as the RC contents increase and the confining pressure decreases, therefore it can be argued that with $RC \leq 10\%$ and at $\sigma'_3 = 70\ kPa$, the shear modulus of the sand-RC mixtures is much lower than SFS+CW+RC mixtures. Fig.6 (b) shows the damping ratio of SFS+CW mixtures increases with shear strain level and a sharp increase occurs when the shear strain reach a certain level. In addition, the damping ratio at this level of RC (10%) is comparable to that obtained with sand-RC mixtures (Fig.6).

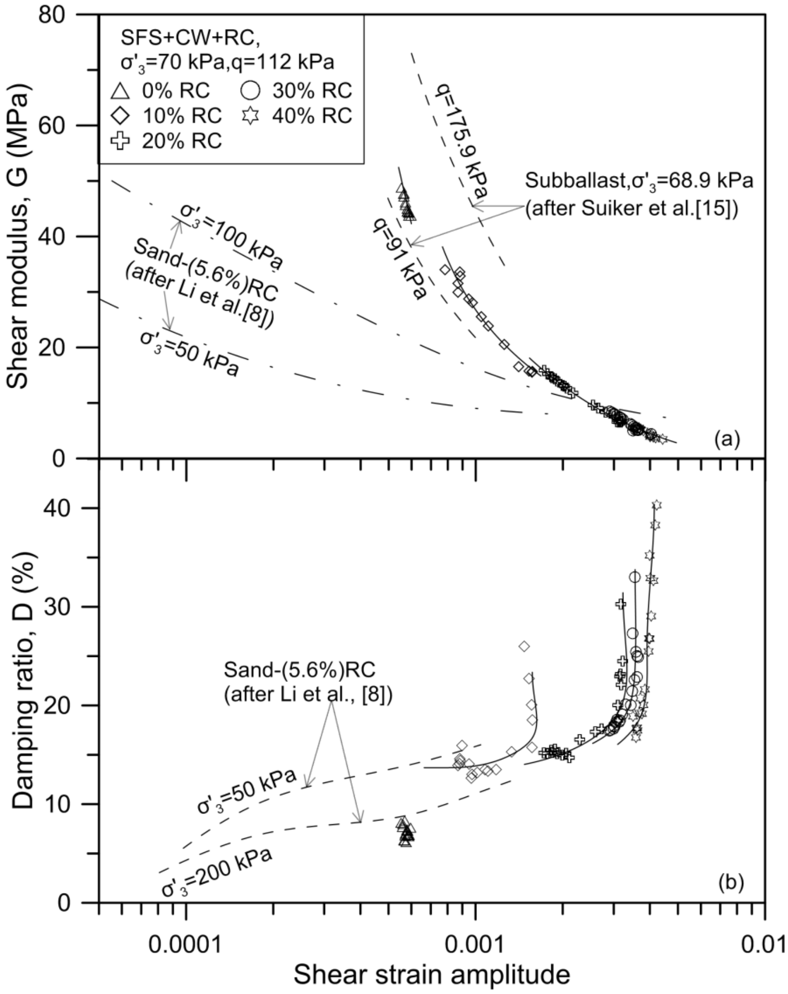

Fig.6 Shear modulus of SFS+CW+RC mixtures changing with shear strain amplitude and comparison with traditional subballast (Suiker et al.[15]) and sand-RC mixtures (Li et al.[8]); (b) Damping ratio of SFS+CW+RC mixtures changing with shear strain amplitude

4 Conclusions

This paper investigates the influence of R_b, σ'_3, and the cyclic loading cycles on the shear modulus and damping ratio of SFS+CW+RC mixtures (SFS:CW=7:3) based on drained cyclic loading triaxial tests. The test result reveals that the addition of RC caused the shear modulus to decrease and the damping ratio to increase indicating that the stiffness of the waste mixtures decreased, while the absorbed energy dissipated to heat or breakage became more efficient. It was also found that the behavior of shear modulus and damping ratio was controlled by the percentage of the waste mixtures inside the mixtures. The particles that form the skeleton of the specimens changed from rigid particles (SFS and CW) to RC gradually as R_b increased, and the transition point was around $R_b = 20\%$. By comparing the shear modulus with traditional subballast, the SFS+CW+RC mixture having 10% RC is a promising structural fill to be used as a subballast layer. Moreover, increasing the confining pressure will cause shear modulus to increase and damping ratio to decrease. The shear modulus decreases with the shear strain level, while the damping ratio increases as the shear strain increases. The shear modulus and damping ratio of all the specimens stabilized after 10000 cycles.

Acknowledgements

The first author would like to acknowledge the financial assistance provided by the China Scholarship Council. The assistance provided by industry (ASMS and South 32) in relation to the procurement of material used in this study is gratefully acknowledged. The assistance in the laboratory from Mr. Richard Berndt and the occasional technical feedback from Dr. Ana Heitor are appreciated.

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