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Investigation on environmental and mechanical properties of reinforced construction and demolition materials with used tires

Etude expérimental sur les propriétés environnementales et mécaniques des matériaux de construction et de démolition renforcés avec des pneus usagés

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ABSTRACT: Enormous construction wastes and used tires have been produced and resulted in significant environmental problems over the world. To reduce the amount of construction wastes and used tires, this study attempts to use construction wastes and used tires as filling materials in geotechnical engineering (i.e. reinforced construction and demolition materials (C&DM) with used tires). The leachability of heavy metals for natural soil and C&DM were assessed by the leaching test. The permanent deformation of the reinforced C&DM with used tires was evaluated by using large-scale dynamic triaxial tests. The pull-out tests were performed on C&DM with used tires to obtain mechanical properties, such as the relationship between pull-out loading and displacement and further to understand the reinforcement mechanism. It was found that the leaching concentration values of six heavy metal elements for C&DM were lower than standard concentration values. The results of dynamic triaxial tests showed that the C&DM reinforced with tires had better capability to resist permanent deformation than that with geogrids. The results of pull-out tests showed that with the increasing amount of transverse ribs, the pull-out load peak point increases under high normal stress, and the strength of C&DM-reinforcement interfaces increased.

RÉSUMÉ : Les déchets de construction et pneus usagés ont été produits et ont entraîné des problèmes environnementaux importants dans le monde entier. Cette étude tente d'utiliser les déchets de construction et les pneus usagés comme matériaux de remplissage en géotechnique (c'est-à-dire des matériaux de construction et de démolition renforcés (C&DM) avec des pneus usagés). La lixiviabilité des métaux lourds pour le sol naturel et C&DM a été évaluée par le test de lixiviation. La déformation permanente du C&DM renforcé avec des pneus usagés a été évaluée en utilisant des essais triaxiaux dynamiques à grande échelle. Les tests d'arrachement ont été effectués sur C&DM avec des pneus usagés pour obtenir des propriétés mécaniques, telles que la relation entre la charge d'arrachement et le déplacement et mieux comprendre le mécanisme de renforcement. Il a été constaté que la concentration de lixiviation de six éléments de métaux lourds pour le C&DM était inférieure à la concentration standard. Les résultats des tests triaxiaux dynamiques ont montré que le C&DM renforcé avec des pneus avait une meilleure capacité à résister à la déformation permanente que celui avec des géogrilles. Les résultats des tests d'arrachement ont montré qu'avec l'augmentation du nombre de nervures transversales, le point de pic de charge d'arrachement augmente sous une contrainte normale élevée et la résistance des interfaces de renforcement C&DM augmente.

KEYWORDS: Construction and demolition materials, used tires, leachability, permanent deformation, Pull-out test.

1 INTRODUCTION.

Enormous construction wastes and used tires have been produced and resulted in significant environmental problems. Construction wastes accounting for 30-40% of the total urban waste in china (Zhao et al. 2010). More than 15 million tons of waste tires are produced annually over the world (Gourav & Ravi 2018). It is predicted that the amount of waste tires will increase by approximately 20% in 2030 (Zhang et al. 2020). Hence, disposing and recycling solid wastes (e.g. construction wastes and used tires) has become one of hot topics in environmental area. In recent years, construction wastes and used tires have been discussed in more and more research projects related to the application in geotechnical engineering (Herrador et al. 2011; Leite et al. 2011; Agrela et al. 2012; Arulrajah et al 2013a; Arulrajah et al 2014; Vieira & Pereira 2015; Vieira et al 2016). In these projects, construction wastes are made into construction and demolition materials (C&DM) through washing, crushing, sieving, and etc.

The application of C&DM and used tires in geotechnical engineering mainly focused on road base, sub-base, embankment, and retaining wall (Herrador et al. 2011; Leite et al. 2011; Agrela et al. 2012; Arulrajah et al 2013; Vieira & Pereira 2015; Edincliler et al. 2010; Kim et al. 2011; Reddy et al. 2017). Through the CBR test, Leite et al. (2011) found that the CBR values of C&DM are very close to those of natural aggregate, which can be used as a filling material in subgrade structures. Lima et al. (1999) first proposed that C&DM can be used as a filling material in retaining wall structures. Arulrajah et al. (2013b) believes that C&DM mixed with high-quality aggregates can be used as a filling material in pavement base and subbase. Compared with natural soil, the rubber can exhibit a greater capacity for energy absorbency than soil under loading. Moreover, rubber has a capability to prevent the stress transferred to the ground when it is used in the ground, embankment, and retaining wall (Edincliler et al. 2010; Kim et al. 2011; Reddy et al. 2017; Li et al. 2018).

Undoubtedly, if reinforced C&DM with used tires can be successfully used in geotechnical engineering, significant environment benefits will be released. For examples, land space can be saved from being used to accommodate these wastes, and conventional good-quality construction materials can be replaced with waste materials to prevent the over-exploitation of good-quality materials. To verify the feasibility of using C&DM in geotechnical engineering, the environmental and mechanical properties of reinforced C&DM with used tires need to be investigated in advance.

This study aims to assess the feasibility of C&DM and used tires in geotechnical engineering, and explore the environmental and mechanical properties of reinforced C&DM with used tires. Therefore, the leachability of C&DM was investigated in this study by the leaching test, and the mechanical property of reinforced C&DM was assessed by dynamic triaxial tests and laboratory pull-out tests.

2 MATERIALS AND METHOD

2.1 *Materials*

2.1.1 *Soil*

Construction wastes were taken from a demolition site of an abandoned dormitory building in Wuhan. The construction wastes were air-dried, and then some wastes, such as glass, steel, and plastic were removed by hands. Bricks and concrete blocks were crushed by machine, respectively, to enable all particles to pass the 20 mm sieve. The obtained bricks and concrete particles were mixed at a mass ratio of 1:2 to form C&DM. The particle size distribution, the maximum dry density and optimum moisture content of C&DM are shown in Figure 1.

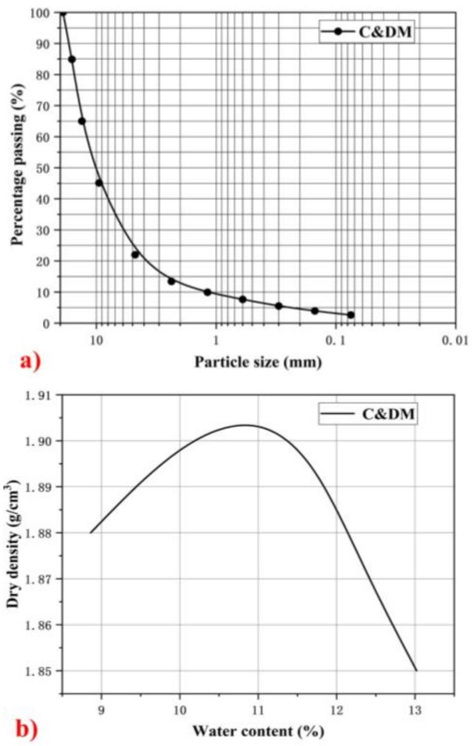


Figure 1. (a) Particle size distribution curve of C&DM and (b) Compaction curve of C&DM.

Physical properties of C&DM are provided in Table 1. The chemical compositions of C&DM are determined using X-ray fluorescence spectrometry (XRF), as listed in Table 2.

Table 1. Physical properties of C&DM

Parameters	*Value*
Uniformity coefficient C_u	10.2
Coefficient of curvature C_c	2.54
Optimum moisture content /%	10.8
Maximum dry density/$g \cdot cm^{-3}$	1.90
Minimum dry density/$g \cdot cm^{-3}$	1.85

Table 2. Chemical composition of C&DM (by mass, %)

Compositions	*Value*
Na_2O	0.92
MgO	2.52
Al_2O_3	13.94
SiO_2	50.01
P_2O_5	0.13
SO_3	0.72
Cl	0.04
K_2O	1.76
CaO	23.62
TiO_2	0.86
MnO	0.13
Fe_2O_3	5.19

2.1.2 *Reinforcements*

The reinforcements used in this study were mini tires, automobile waste tires (discarded after the car travels 80,000 km), and biaxial geogrid. Ultimate tensile strength per meter of mini tires, automobile waste tires, and biaxial geogrid were 54.6 kN/m, 234.7 kN/m, and 25.1 kN/m, respectively.

2.1.3 *Experimental apparatus*

In this study, the leaching test was conducted to obtain leachabilities of heavy metals contained in C&DM. Dynamic tests, and pull-out tests were carried out to investigate reinforced C&DM mechanic properties. Experimental apparatus used in this study can be seen in Figure 2.

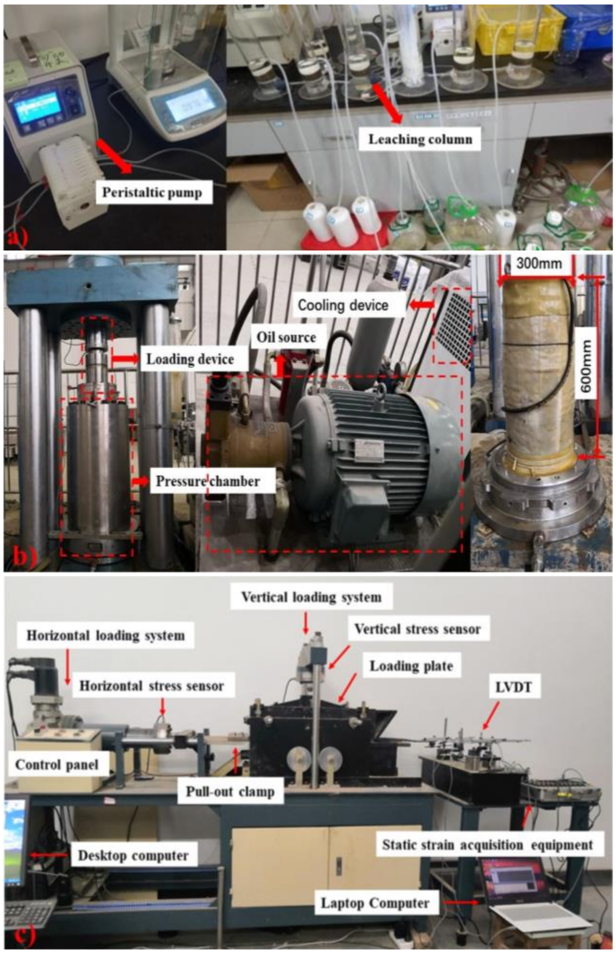


Figure 2. (a) Leaching peristaltic pump, (b) dynamic triaxial apparatus and (c) laboratory pull-out apparatus.

2.2 *Specimen preparation*

The C&DM was mixed with water (water content of 10.8%), then the wet C&DM were placed in a closed tub for 24 h to achieve moisture uniformity within the sample.

The sample was put in a cylindrical mold (diameter 300mm and height 600mm) surrounded with a rubber membrane, and then compacted in four layers, to obtain a specimen corresponding to 94% of the maximum dry density.

2.3 *Leaching test*

A column leaching peristaltic pump was used to perform leaching tests, as shown in Figure 2(a).

2.4 *Dynamic triaxial test*

Consolidated-undrained (CU) dynamic triaxial tests were performed, for the reinforced C&DM with used tires, under a constant confining pressure of 80 kPa, as shown in Figure 2(b). A sinusoidal axial cyclic stress was applied to cylindrical specimens. The number of cycles N was set to 10000 times, and the loading frequency was 1 Hz. The axial loading, confining pressure, back-pressure, pore pressure, deformation, and volume change values were recorded from the monitor.

The tests were stopped when the number of cycles reaches 10000 times or the permanent deformation of specimens reaches 5% of its initial height.

2.5 *Pull-out test*

The pull-out test was conducted to study the interface behaviour between reinforcement and C&DM, as shown in Figure 2(c). Linear variable differential transformers (LVDT) were used to measure the strain of reinforcements. The high-strength steel wire was connected to the magnetic base through a 2-mm steel pipe, and the strain of the reinforcements was measured by a static strain measurement. The software was used to record the pull-out load, displacement, and the normal stress. All tests were carried out under normal stresses of 25, 50, and 75 kPa. Normal stress was applied at a rate of 30 kPa/min. A preload of 0.2 kN was applied for 3 min, after which the horizontal displacement was zeroed. During the test, a pull-out load of 1 mm/min was applied.

The test was stopped when the pull-out load reached the peak value or the displacement reached 80 mm.

3 RESULTS AND DISCUSSION

3.1 *Leaching property*

Six heavy metals, including chromium (Cr), copper (Cu), nickel (Ni), cadmium (Cd), zinc (Zn), and lead (Pb) were investigated for C&DM and the natural soil. The leachability of each element for C&DM and the natural soil is shown in Figure 3. The third-level soil quality standard values according to the Environment al Quality Standard for Soil (GB, 1995) are listed in Table 3.

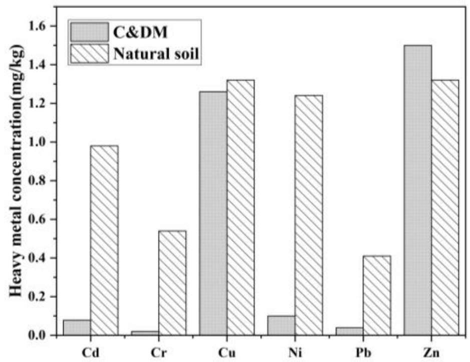


Figure 3. The leachability of six heavy metals contained in C&DM and natural soil.

Table 3. The third-level soil quality standard values (mg/kg)

Elements	*Value*
Cd	1.00
Cr	400
Cu	400
Ni	200
Pb	500
Zn	500

Figure 3 shows that the leached concentration of Cd, Cr, Cu, Ni, and Pb in C&DM are less than that of the natural soil. Additionally, the leached concentration of Zn is slightly higher than that of the natural soil, but lower than that of standard value. Therefore, C&DM will not pose a threat to groundwater in the leaching of heavy metals.

3.2 *Permanent deformation*

In field conditions, road subgrade undertakes cyclic loading, which results in permanent deformation and settlement (Rahman et al. 2014). Therefore, it is very important to investigate permanent deformation under cyclic loading to clarify the long-term stability of the road before the material is used in field applications.

Figure 4 shows that when the failure criterion is reached, the number of cycles N increases significantly for reinforced C&DM with used tires compared to the unreinforced C&DM, which indicates that the tire reinforcement can improve the capability of C&DM to resist permanent deformation. However, the biaxial geogrid seems to be unable to improve this capability as the number of cycles N for biaxial geogrid reinforced C&DM is lower than that of tires-reinforced and unreinforced C&DM. This can be attributed to that although biaxial geogrid can increase interfacial friction resistance, the paving surface is small, which damages the interaction effect between coarse particles.

It's noted that cyclo-hoop effect and friction resistance provided by tires can enhance the particles-tire-particles interaction, which can facilitate the reduction of cracks, and hence improve the capability to resist permanent deformation. A comparison in the place of tire reinforcement illustrates that the higher place where tires are embedded induced better performance in resisting permanent deformation as the cycle number N of the top reinforcement for achieving the failure criterion is fewer than that of the middle and bottom reinforcement.

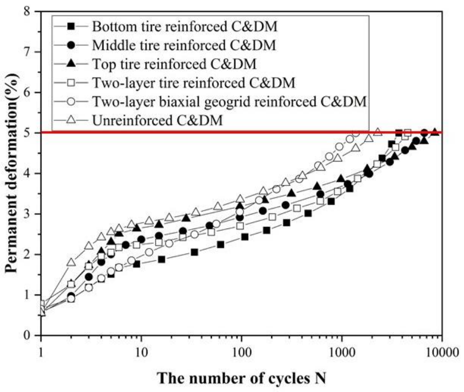
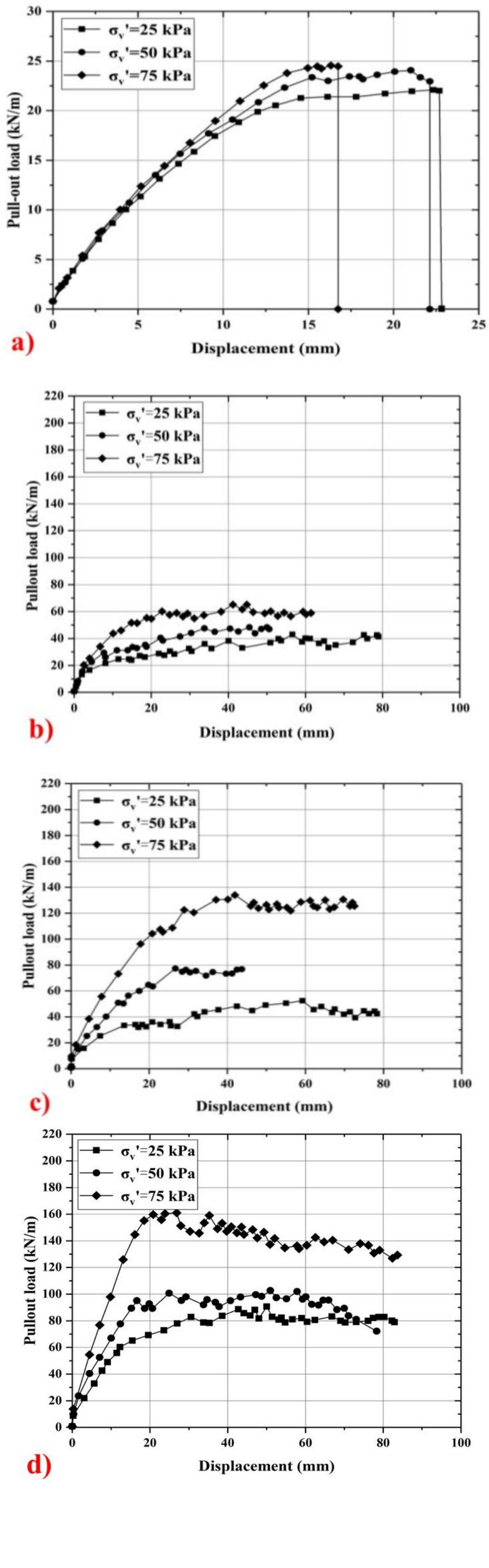


Figure 4. Permanent deformation curve of reinforced C&DM.

3.2 *Pull-out behaviour*

Figure 5 presents pull-out load-displacement curves of reinforced C&DM. The number of transverse ribs of tire strips with steel wires was studied because the pull-out behaviour mainly depends on the transverse ribs of tire strip. No rib, a single rib, three ribs, and four ribs are defined as NR, SR, TR, and FR, respectively.



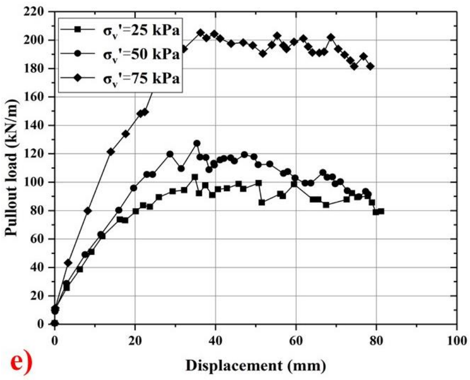


Figure 5. Relationship between pull-out load and displacement of TS under various normal stresses: (a) biaxial geogrid, (b) NR, (c) SR, (d) TR, (e) FR.

Figure 5 shows the normal stresses have insignificant effect on the pull-out load of biaxial geogrid. The maximum difference of the peak pull-out load is only 2.52 kN/m. Nevertheless, the maximum difference in the ultimate displacement is 6.07 mm. This can be due to that the range of the paving surface is large, which is different from the result of dynamic triaxial test. Therefore, the coarse particles of C&DM can interlock with biaxial geogrid, which leads to fractures that occur at a small displacement. It can be concluded that biaxial geogrid has a good effect on the pull-out behaviour when C&DM is used as a filler.

The reinforced C&DM with tire strips have higher strength and lower toughness than those with biaxial geogrid. It can also be found that as the displacement increases, the pull-out load of tire strips rapidly increases to the peak point, then decreases slightly. This is because granular particles are easier to rearrange when the pull-out load and displacement increase to a certain value. Therefore, the curve has a great fluctuation. Moreover, as the number of transverse ribs increases, the more obvious the fluctuation is. However, NR was not significantly affected by normal stress.

It's noted that when the number of transverse ribs is 1, with the increase of the normal stress, the amplitude of the pull-out load increases. When the number of transverse ribs is 3 and 4, and the normal stress is 25 and 50 kPa, the increase in the pull-out load is not significant. When the normal stress is 75 kPa, the pull-out load increases significantly. It can be concluded that tire strips with steel wires can well reinforce C&DM under a high normal stress.

4 CONCLUSIONS

This study investigated environmental and mechanical properties of reinforced C&DM with used tires using leaching test, dynamic triaxial test, and laboratory pull-out test. The main findings are obtained as follows:

- The leached concentration of six heavy metals for C&DM are lower than standard concentration values. C&DM has no threat on groundwater in the leaching of heavy metals.
- Tires can enhance the particles-tire-particles interaction, which facilitates the reduction of cracks and improve the capability to resist permanent deformation. The higher place where tire strips are embedded induced better performance in resisting permanent deformation.
- With an increase in the number of transverse ribs, the pull-out peak value increases and then decrease slightly under high normal stress. It can be concluded that tire strips with steel wires can well reinforce C&DM under a high normal stress.

5 ACKNOWLEDGEMENTS

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