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Evaluation of gravel-tire chips mixtures for their use in marine landfill leachate collection systems

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ABSTRACT: In marine landfill sites, alluvial clay layer is primarily used as an impermeable layer at the bottom of the landfill site. The protection of alluvial clay layer and improving drainage performance during the waste deposition and consolidation are significant issues in marine landfill sites. In this research, as a new and low-cost construction method, a marine landfill site with recycled tire chips reinforcement layer placed between input waste and alluvial clay layer to protect the alluvial clay and improve the drainage performance. However, because of high compressibility of the tire chips alone, gravel can be regarded as a suitable material for the mixture. This study examines the permeability of gravel-tire chips mixture (GTCM) using a new developed large-scale triaxial apparatus during axial compression with lateral pressure of 150kN/m^2. The specimens are produced in a large mold with an inner diameter of 153mm and a height of 300mm. The results concluded that GTCM appeared to be quite promising as a drainage and cushioning material for marine landfill sites.

RÉSUMÉ : Dans les décharges marines, la couche d'argile alluviale est principalement utilisée comme couche imperméable au fond de la décharge. La protection de la couche d'argile alluviale et l'amélioration des performances de drainage pendant le dépôt et la consolidation des déchets sont des questions importantes dans les décharges marines. Dans cette recherche, en tant que nouvelle méthode de construction à faible coût, un site d'enfouissement marin avec une couche de renforcement en copeaux de pneus recyclés placée entre les déchets d'entrée et la couche d'argile alluviale pour protéger l'argile alluviale et améliorer la performance de drainage. Cependant, en raison de la haute compressibilité des copeaux de pneus seuls, le gravier peut être considéré comme un matériau approprié pour le mélange. Cette étude examine la perméabilité du mélange gravier/copeaux de pneus (GTCM) en utilisant un nouvel appareil triaxial à grande échelle développé pendant la compression axiale avec une pression latérale de 150kN/m^2. Les spécimens sont produits dans un moule à grande échelle avec un diamètre intérieur de 153 mm et une hauteur de 300 mm. Les résultats ont conclu que le GTCM semble être assez prometteur en tant que matériau de drainage et d'amortissement pour les sites d'enfouissement marins.

KEYWORDS: Marine landfill, GTCM, triaxial compression, [ermeability, non-darcy.

1 INTRODUCTION

In recent years, the world has seen large-scale earthquake-induced hazards or climate change-related hazards. Especially in Japan, such natural hazards are too frequent in recent years. The Great East Japan Earthquake, which occurred on 11 March 2011, was the largest earthquake in recent Japanese history and approximately 28 million tons of disaster wastes were generated in the three prefectures of Iwate, Miyagi, and Fukushima (Murasawa et al. 2014, Ide 2016). After natural hazards, how to deal with the enormous amount of waste is a long-standing issue in Japan.

In the past few years, the number of marine landfill sites has increased in Japan due to non-availability and shortage of suitable land onshore. As compared to the land disposal sites, marine landfill sites also have a huge waste capacity. According to the investigation of general waste marine landfills in 2013, there are 34 locations in Japan, the total area is 653 hectares, and the total capacity is 128million m^3 (Endo 2016). It is expected to be a viable alternative for land disposal sites in the future.

In marine landfill sites, the alluvial clay layer is primarily used as an impermeable layer at the bottom of the site to prevent the leakage of harmful leachate into the sea. The protection of the alluvial clay layer and improving drainage performance (leachate collection) inside during the waste deposition and consolidation are significant issues in the feasibility of a marine landfill site. However, there is no low-cost construction method developed yet to solve these problems.

In recent decades, research related to the utilization of waste tires in construction projects has been gaining popularity due to its beneficial physical and mechanical properties. Figure 1 shows the recycling status of waste tires in Japan from 2014 to 2019. According to the recycling status of waste tires in Japan in the last 6 years, over 60% of waste tires are burnt to produce energy (JATMA 2019). Thermal recycling is harmful to the environment because it releases more CO_2 to the atmosphere. Therefore, reusing scrap tires into geomaterials such as tire chips leads to a significant reduction of global warming. Besides low-carbon-release characteristics, the other helpful material characteristics of tire-derived geomaterials are as follows: lightweight, excellent vibration absorption capacity, and high permeability (Hazarika 2013, Hazarika et al. 2018, Hazarika et al. 2020, Pasha et al. 2020). Recent studies have reported suitability of tire chips as landfill leachate drainage material in terms of their high permeability (Grayson et al. 2013, Kaushik et al. 2015, Kaushik et al. 2017). However, due to the high compressibility of tire chips, gravel can be regarded as a suitable material for the mixture. In order to evaluate the permeability of gravel-tire chips mixture (GTCM), the non-Darcy flow characteristic of GTCM was proposed in this experimental study.

Darcy's law states that a fluid flow velocity is directly proportional to the pressure gradient, is shown to be accurate only at low flow velocity. As the flow velocity increases in a porous medium like GTCM, the inertial forces become more significant and the relation between the velocity and the potential gradient may become non-linear (Zeng et al. 2006). To account for non-Darcy flow phenomena, Forchheimer (1901) proposed an empirical equation to correct the non-linearity of Darcy's law. The Forchheimer's law has been proved to provide an excellent description for this flow behavior in porous media. The Forchheimer's equation can be expressed as:

$$\frac{dp}{dx} = \frac{\mu}{K} v + \beta \rho v^2 \qquad (1)$$

Where p is the hydraulic pressure, x is the direction of fluid flow, μ is the fluid viscosity, v is the velocity of flow, K is the permeability of flow media, β is the non-Darcy coefficient, ρ is the fluid density. Both β and k are regarded as material constants of the Forchheimer's equation in the range of its validity.

As shown in Figure 2, in this new construction method, GTCM as a leachate drainage layer material is placed between the waste and alluvial clay layer. To evaluate the drainage behaviour of GTCM under different pressure, a new testing system for large-scale triaxial compression and permeability tests was designed and constructed. The purpose of this study is to evaluate the superlative combination of GTCM as leachate drainage layer material for obtaining better permeability in long terms.

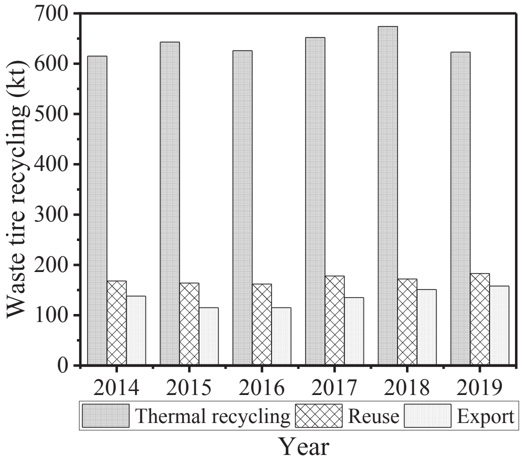


Figure 1. The recycling status of waste tires in Japan (2014-2019) (JATMA 2019).

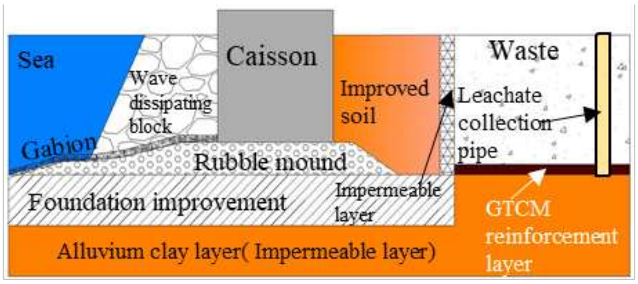


Figure 2. Marine landfill site with a tire chip drainage layer.

2 MATERIALS AND METHODS

2.1 *Testing materials and physical properties*

Pictures of tire chips and gravel samples used in this study are presented in Fig 3. The grain size distribution of GTCM was determined by JGS-0131-2009 is shown in Fig 4. The grain size of tire chips is in the range of 9.5mm to 19mm and for gravel it is 9.5mm to 15mm. The specific gravity (Gs) of GTCM was determined according to JGS-0111-2009. As shown in Figure 5, the specific gravities (Gs) of GTCM decrease with an increase in mass proportion of tire chips from 0 to 100 %, and specific gravity of gravel is 2.64. Pure tire chips have specific gravity of 1.14. A series of minimum and maximum densities tests were conducted according to JGS-0162-2009. As shown in Figure 6, $\rho_{max} - \rho_{min} \approx 0.2 g/cm^3$.

Tire chip (9.5-19mm) Gravel (9.5-15mm)

Figure 3. Tire chips (left) and gravel (right) used in the experimental study.

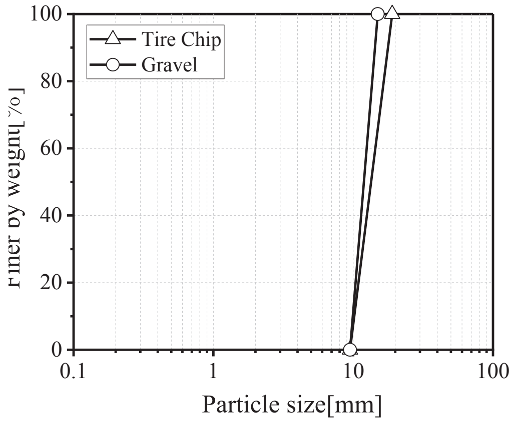


Figure 4. Grain size distribution of GTCM.

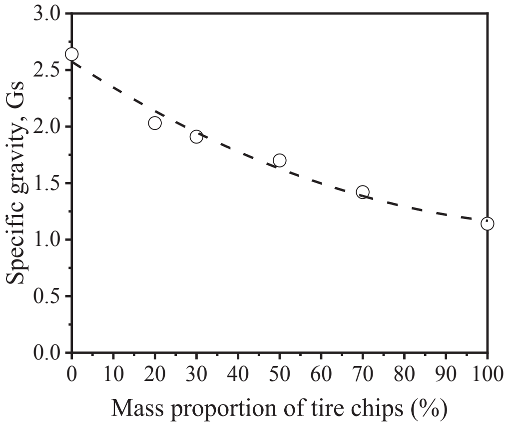


Figure 5. Variation of specific gravity of GTCM.

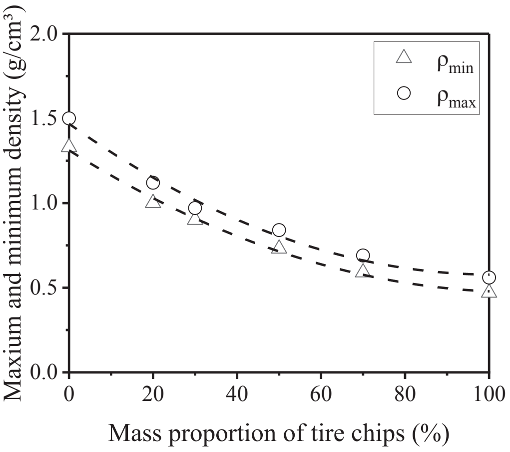


Figure 6. Maximum and minimum densities of GTCM.

2.2 *Large-scale triaxial compression and permeability testing system and test steps*

The new developed testing system for the triaxial compression and permeability test of GTCM includes air cylinder ($Fmax = 20kN$), pressure gage ($Fmax = 50kN$), triaxial cell, hydraulic jack ($Fmax = 50kN$), constant hydrostatic head device and measuring cylinder. The overall setup of the system is shown in Fig 7. The GTCM specimens are prepared in a large mold with an inner diameter of 153mm and a height of 300mm. The specimens are held in shape and isolated from the triaxial cell water by a rubber membrane (with thickness of 1.5mm).

During triaxial compression and permeability testing, the main experimental steps are as follow:

1. Specimen's installation and saturation.

In this study, tire chips contents of 0, 20%, 30%, 50%, 70% and 100% by weight are selected. The mixture is hand-mixed till uniform. In specimen preparation process, gravel and tire chips contents were prepared with a relative density of 70% for all specimens. Before starting the saturation process, CO_2 gas was seeped through the specimen with a slow rate from bottom of specimen to flush out any air trapped inside. Thereafter, the specimens were saturated with water from bottom. The saturation was tested by closing the drainage system, by applying a small increase $\Delta\sigma_r$ in confining pressure, and by measuring the resulting change in pore water pressure Δu. The coefficient B is calculated from Eq. (2). Full saturation was assumed to be achieved when coefficient B was bigger than 0.95.

$$B = \Delta u / \Delta\sigma_r \tag{2}$$

Where $\Delta\sigma_r$ is increase in isometric stress and Δu is increase in pore water pressure due to $\Delta\sigma_r$.

2. Isotropic consolidation and axial compression.

The isotropic stress was increased to 150 kN/m^2, the readings of axial displacement and volume change of the specimen were recorded. After completion of the isotropic consolidation stage, axial load was increased at the rate of 100 kN/m^2 /h. The permeability test is carried out when vertical deformation is significant. The valve of volume change measuring burette was closed, and the water inlet valve, the water collection valve and the drainage valve connected to the constant hydrostatic head device were opened.

3. Forming steady seepage and change of head difference.

In order to form a steady flow, before starting the permeability test, water is drained with a slow rate from bottom of the specimen for 20 minutes. The head difference is calculated from Eq. (3). Herein, the hydraulic gradient i is 0.2 to 1, because when height of the specimen changes significantly after compression, corresponding head difference will be small, which cannot be adjusted by this constant hydrostatic head device. The flow of water is started into the cylinder, and a cylinder with graduated markings is used to obtain the runoff volume Q between two times, t_1 and t_2. This measurement is repeated three times.

$$i = \frac{h_1 - h_2}{L} \tag{3}$$

Where i is hydraulic gradient, $h_1 - h_2$ is difference in water level, L is length of the specimen.

Seepage velocity is calculated from the equation as follows:

$$A = \frac{V}{L} \tag{4}$$

$$v = \frac{Q}{A(t_2 - t_1)} \tag{5}$$

Where A is cross-sectional area of the specimen, V is the volume of specimen (Calculated from volume change), Q is the total volume of outflow water, $t_2 - t_1$ is the seepage time.

At low Reynolds number R_e, viscous dissipation is caused by the viscous force. At higher R_e, the viscous dissipation will rise because of strong inertial forces, following by a change in apparent permeability of the media (Whitaker 1996). Some of the researches have described that the Forchheimer's equation can probably be used over the entire range of Re, as it effectively reduces to Darcy's law at low values of R_e (Huang et al. 2006).

In this research, according to the permeability of experimental data, the non-Darcy flow phenomenon of GTCM is analyzed by Forchheimer's equation.

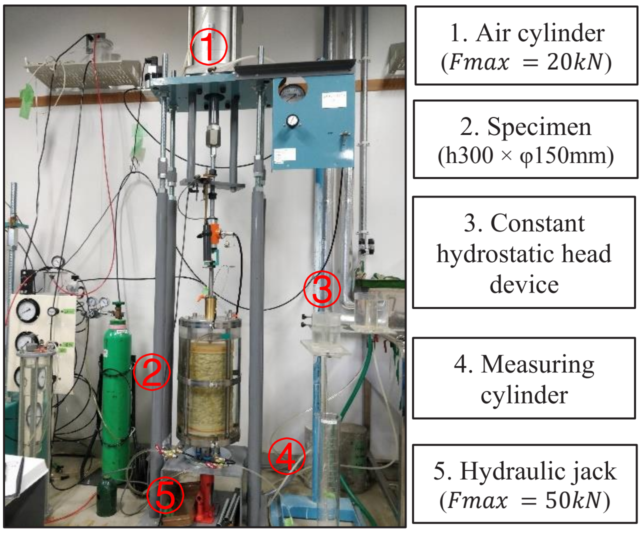


Figure 7. Large-scale triaxial compression and permeability testing apparatus.

3 RESULTS AND DISCUSSION

The relationship between the axial strain and deviatoric stress with different tire chips contents is plotted in Fig 8. Different from the stress path of gravel, due to the low stiffness of tire chip particles, GTCM (MPTC=20% ~ 100%) samples exhibit nearly linear stress-strain behavior for the confining pressures considered in this study. In addition, samples of MPTC=20% and MPTC=30% have similar deviatoric stress-axial strain behavior.

The relationship between the discharge velocity and hydraulic gradient with different tire chips percentage during compression process is shown in Fig 9. Herein, the tire chips percentage is denoted as MPTC, which corresponds to the mass proportion of tire chips in the mixture. The discharge velocity increased with the increase of hydraulic gradient, and it can be obviously seen that the relationship between the discharge velocity and hydraulic gradient is nonlinear. The permeability law of GTCM does not comply with Darcy's law. Instead, the nonlinear Forchheimer's law well fits the experimental data, with the coefficient of determination R^2 of all percentage mixtures around 0.999. Compared to other tire chip contents, there is a more significant change in discharge velocity-hydraulic gradient behavior of GTCM under compression when MPTC=30%, and this change is not obvious when MPTC=50%.

The results of permeability coefficient calculated from Forchheimer's equation are shown in Fig 10. According to Fig 10, GTCM with different tire contents and pressure states has a permeability coefficient on the order of 0.03 ~ 0.07 cm/s. It was found that the permeability coefficient date of GTCM samples did not change significantly at different pressure states. Based on this experimental result, it can be concluded that, similar to permeability of the traditional gravel material, the GTCM has excellent permeability, even after triaxial compression.

In the Forchheimer's equation, the coefficients k and β correspond to the properties of the porous medium and are usually determined by permeability tests (Zeng et al. 2006). Here, the Forchheimer's coefficients k and β were determined by curve fitting Forchheimer's equation (See Fig 9). The non-Darcy coefficient β describes the inertial effect. Ni et al. (2016) proposed that there is a potential relationship between permeability k and non-Darcy coefficient β in sand sandstone, a kind of porous medium. The relationship between permeability k and non-Darcy coefficient β is shown in Fig 11. This relationship did not show the possibility to have obvious relations among the permeability parameters in GTCM under this experimental pressure condition.

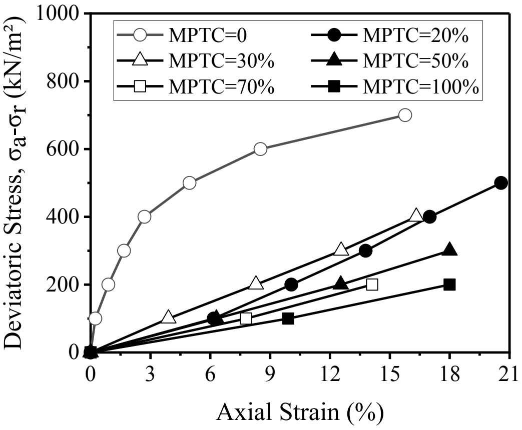
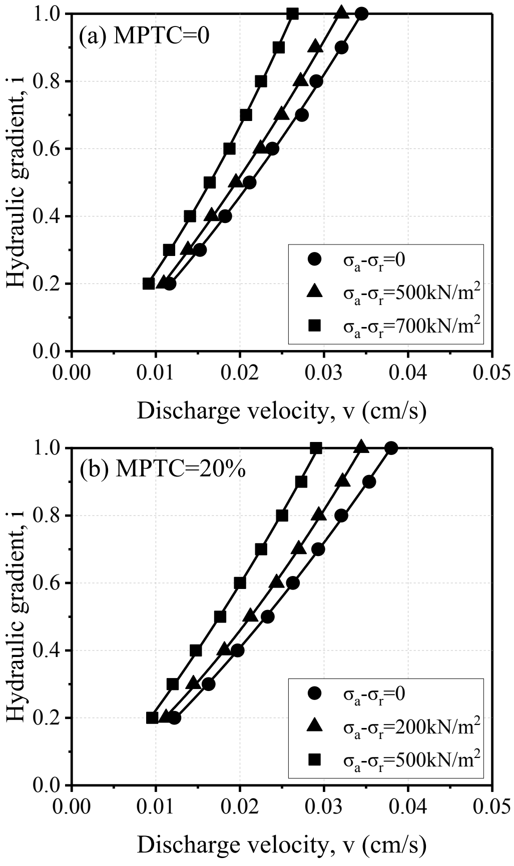


Figure 8. Deviatoric stress-axial strain behavior of GTCM with different tire chips contents.



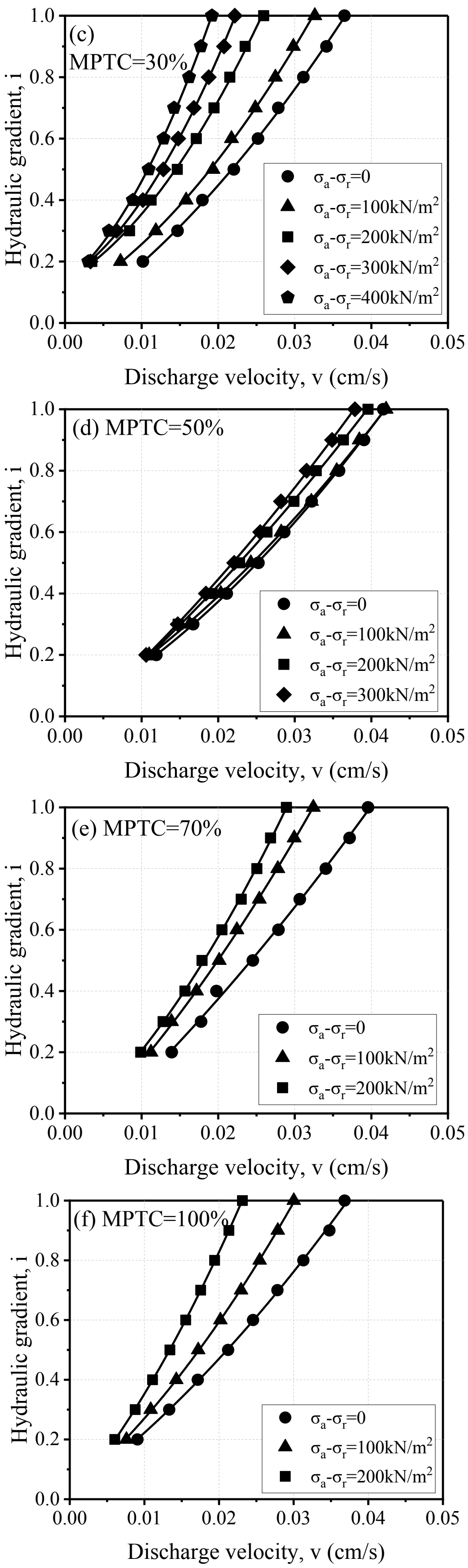


Figure 9. Relationship between the discharge velocity and hydraulic gradient (MPTC: mass proportion of tire chips).

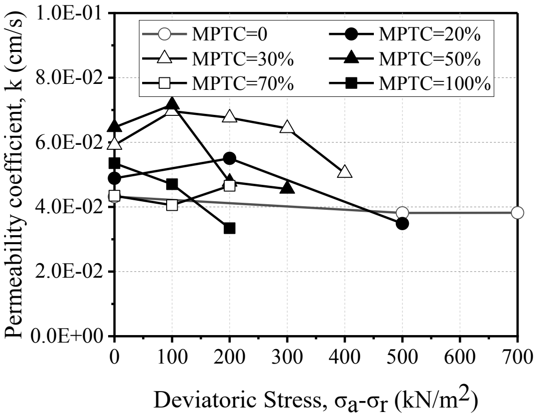


Figure 10. Variation of permeability coefficients during axial compression.

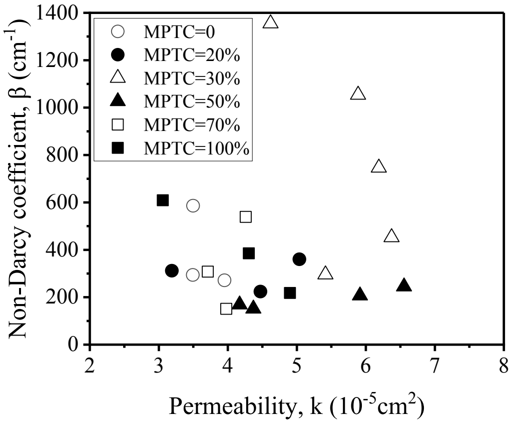


Figure 11. Relationship between permeability k and non-Darcy coefficient β.

4 CONCLUSIONS

This paper provides the initial findings regarding the drainage improvement of the marine landfill site using gravel-tire chips mixture (GTCM). In this study, the permeability of GTCM samples was measured using a new designed large-scale triaxial compression and permeability testing apparatus. The main conclusions from this study are as follows:

1. The stiffness of tire chips will be increased slightly when mixed with gravel, and GTCM shows nearly linear stress-strain behavior in this pressure state.
2. The relationship between the discharge velocity and hydraulic gradient is not linear. The flow behavior for the GTCM has turned out to be non-Darcy. GTCM has high permeability coefficients in a range of 0.03 ~ 0.07 cm/s. This new mixed material has been found to be excellent material as a drainage material for marine landfills.
3. Based on Forchheimer's equation, no obvious relationship between the permeability k and non-Darcy coefficient β was found under this experimental condition.

The application of recycled tire materials is expected to contribute toward significantly reducing CO_2 emission. Using tire chips as a drainage material is an effective way of reusing waste tire and protection of environment. In future studies, a series of triaxial compression and permeability tests will be conducted with different experimental conditions (particle size, relative density, lateral stress etc.). These experimental findings could be extremely helpful for the long-term performance of GTCM reinforcement in marine landfill sites.

6 REFERENCES

Endo K. 2016. Structure, management and role of the marine landfill sites. *Proceedings of the 27th Annual Conference of Japan Society of Material Cycles and Waste Management*, 17-20 (in Japanese).

Forchheimer P. 1901. Wasserbewegung durch boden. *Zeit. Ver. Deutsch. Ing* 45, 1781-1788.

Grayson J. M., Asce S. M., Khan A. A., Asce F. and Karanfil T. 2013. Permeability of uniform and mixed-size tire chips under different loading conditions. *Journal of Irrigation and Drainage Engineering* 139 (11), 939-946.

Hazarika H. 2013. Paradigm shift in earthquake induced geohazards mitigation—Emergence of nondilatant geomaterials. *Proceedings of the Annual Conference of Indian Geotechnical Society,* India, CD-ROM.

Hazarika H., Pasha S. M. K., Ishibashi I., Yoshimoto N., Kinoshita T., Endo S., Karmokar A. K. and Hitosugi T. 2020. Tire-chip reinforced foundation as liquefaction countermeasure for residential buildings. *Soils and Foundations* 22 (11), 315-326.

Hazarika H., Yokota H., Endo S. and Kinoshita, T. 2018. Cascaded recycle of waste tires - some novel approaches towards sustainable geo construction and climate change adaptation-. *Geotechnics for Natural and Engineered Sustainable Technologies*, Singapore, 63-81.

Huang H. and Ayoub J. 2006. Applicability of the Forchheimer equation for Non-Darcy flow in porous media. *SPE Annual Technical Conference and Exhibition,* U.S.A., 1-14.

Ide K. 2016. Treatment of disaster waste generated by the Great East Japan Earthquake -Treatment of disaster waste by member corporations of the Japan Federation of Construction Contractors-. *Japanese Geotechnical Society Special Publication* 2 (2), 135-142.

JATMA. 2019. *<Japan Automobile Tyre Manufacturers Association https://www.jatma.or.jp/environment/report01.html >.*

Kaushik M. K., Kumar A. and Bansal A. 2015. Performance assessment of gravel–tire chips mixes as drainage layer materials using real active MSW landfill leachate. *Geotechnical and Geological Engineering* 33, 1081-1098.

Kaushik M. K., Kumar A. and Bansal A. 2017. Performance of tire chips–gravel combinations with nonwoven geotextile and encapsulated tire chips layers used as filter/separator under incremental stress levels. *European Journal of Environmental and Civil Engineering* 22 (11), 1291-1324.

Murasawa N., Koseki H., Iwata Y. and Sakamoto T. 2014. Great East Japan Earthquake disaster waste and the occurrence of fires. *Procedia Engineering* 84, 472-484.

Ni X. Y., Kulatilake P. H. S. W., Chen Z. C., Gong P and Kong H. 2016. Experimental investigation of Non-Darcy flow in sandstone. *Geotechnical and Geological Engineering* 34, 1835-1846.

Pasha S. M. K., Hazarika H. and Yoshimoto N. 2020. Estimating Dynamic Characteristics of Gravel-Tire Chips Mixtures Using Artificial Intelligence Techniques. *Journal of the Society of Materials Science, Japan* 69 (1), 1-8.

Whitaker S. 1996. The Forchheimer equation: A theoretical development. *Transport in Porous Media* 25, 27-61.

Zeng Z. and Grigg R. 2006. A criterion for Non-Darcy flow in porous media. *Transport in Porous Media* 63, 57-69.