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Reinforcement Effect and Permeability Assessment of Gravel-Tire Chips Mixture (GTCM) for Use in Marine Landfill

Chunrui Hao[1], Hemanta Hazarika[2], Yusaku Isobe[3]

[1]Department of Civil and Structural Engineering, Kyushu University, Fukuoka, Japan
[2]Department of Interdisciplinary Science and Innovation, Kyushu University, Fukuoka, Japan
[3]IMAGEi Consultant Corporation, Tokyo, Japan
Email: haochunrui1992@gmail.com

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Abstract

The number of marine landfills in Japan has increased over the past decade due to the lack of suitable land. For marine landfills, protection of the alluvium clay layer and improvement of the drainage performance in waste inflow are important aspects. In this paper, an economical construction method for these problems is proposed using gravel-tire chips mixture (GTCM) as the horizontal reinforcement and drainage medium beneath the waste. The content and particle size of tire chips mixed with gravel are essential factors that affect the bearing capacity and permeability of the reinforcement layer. Therefore, a series of permeability tests are conducted using newly developed large-scale triaxial compression and permeability test apparatus to investigate the effect of tire chips particle size, the mass proportion of tire chips (MPTC), and triaxial stress on the permeability of GTCM. In addition, the effectiveness of this technique is evaluated by numerical simulations. The experimental results confirm that the shear strength of GTCM is influenced by tire chips content. Furthermore, permeability coefficient of GTCM is on the order of 0.02 cm/s to 0.08 cm/s, which is higher than the tolerable level of permeability of drainage layer in landfills. GTCM sample shows excellent permeability even on higher compression. Moreover, the Non-Darcy flow properties of GTCM (non-linear) are introduced in this study, and an approximate power function relationship between the permeability coefficient and the non-Darcy flow coefficient is developed. The numerical results confirm that GTCM performs better than the sand, a traditional reinforcement material.

Keywords

Compressibility, Gravel-Tire Chips Mixture, Marine Landfill, Permeability, Settlement

1. Introduction

Recently, disasters caused by large earthquakes have been accumulating in Japan. The earthquakes cause widespread damage while creating massive waste. For example, on March 11, 2011, Great East Japan Earthquake, one of the largest earthquakes in Japan's history, caused destructive damage to the eastern coastal areas due to the strong shaking along with the succeeding tsunami. The destruction from the Great East Japan Earthquake and tsunami led to the generation of about 28 million tons of debris in the prefectures of Fukushima, Iwate and Miyagi [1]. Furthermore, during the 2018 Hokkaido Iburi Eastern Earthquake, 148 thousand tons of disaster debris was generated in several cities in the region [2]. Given the rapid economic development and recurring natural hazards, proper waste management has become a necessary strategy for Japan in the long run.

The number of marine landfills in Japan has doubled in the last decade due to the lack of suitable land for coastal metropolis landfills and the important role after a huge disaster. Marine landfills have a larger capacity as compared to land-based landfills. After the Great Hanshin-Awaji Earthquake, marine landfills were used to dispose of a large amount of concrete waste [3]. Endo [3] conducted a nationwide survey of marine landfills for general waste (incinerated ash, construction waste, etc.) and recorded 34 sites across Japan with a total capacity of 128 million·m^3. In the construction of marine waste landfills, the alluvium clay layer generally serves as an impermeable layer at the bottom of the landfill. To prevent polluted leachate from seeping into the ocean, it is essential to protect this impermeable layer during long-term waste placement and consolidation. In addition, to prevent internal seawater overflow after waste input, drainage equipment is generally placed at the height of sea level in marine landfills (see **Figure 1**). The harmful substances deposited at the bottom are difficult to be purified by this design. These problems have attracted considerable interest in the geotechnical field, but to our knowledge, only a few studies have demonstrated an economical method of construction. To improve leachate collection and protection of the natural impermeable layer during waste input, a new low-cost and environmentally friendly technique has been developed and proposed in this study. In this study, coarse-grained tire-derived geomaterial (hereafter referred to as TDGM) is utilized as the horizontal reinforcement and cushioning layer beneath the waste material. The TDGM layer will enhance the bearing capacity of the underlying alluvium clay layer while also acting as a cushion against the waste as well as increasing drainage capacity of the landfill.

The status of recycling of scrap tires in Japan from the year 2014 to 2020 is shown in **Figure 2** [4]. Compared with reuse and export, more than 60% of

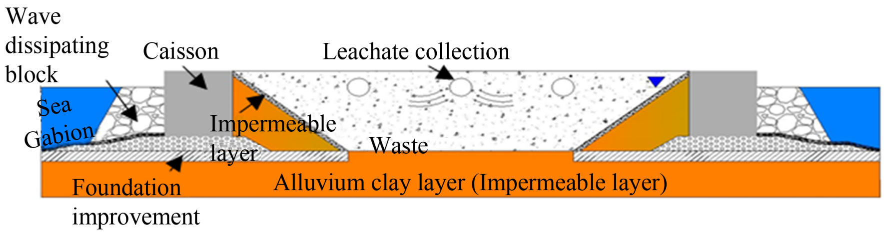


Figure 1. Marine landfill drainage system.

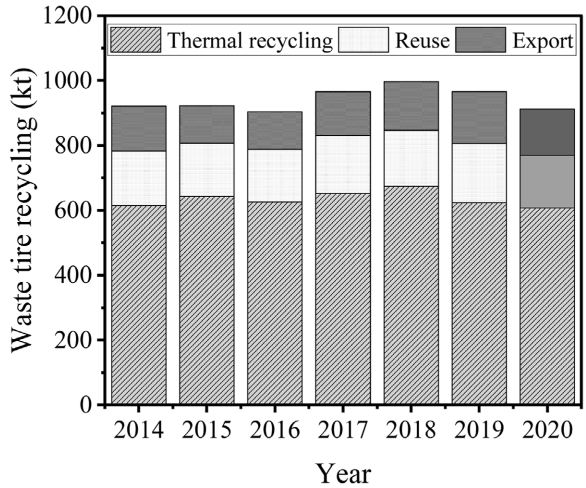


Figure 2. Status of recycling of used tires in Japan from the year 2014 to 2020 (JATMA 2020).

waste tires in Japan are used for thermal energy. Not only in Japan, but also worldwide, the situation of waste tire disposal is basically similar. Compared to other recycling methods, thermal recycling releases more CO_2 into the atmosphere. Therefore, it can be considered that the use of scrap tires for building materials helps to mitigate the greenhouse effect. In recent decades, the use of scrap tires in construction has gradually increased due to their excellent physical and mechanical properties (e.g., high elastic deformability, light weight, high water conductivity) [5] [6] [7] [8] [9]. Furthermore, scrap tires have been found to be a safe material since the long-term impact of leachate from tires on drinking water quality of the groundwater has been found to be under the permissible limit [10]. It should be noted that rubber changes significantly overtime only when exposed to heat, light, oxygen, or ozone. Therefore, it is recommended that this material be used underground or underwater [5].

Since the early 1990s, TDGM (such as tire shreds and tire chips) has been used in construction, especially in the United States and Canada. In the last two decades, the application of tire-derived geomaterials has been extensively studied by many researchers around the world. Hazarika *et al.* [11] conducted a series of 1g shaking tables using a large three-dimensional underwater shaking table to investigate earthquake resistance of caisson structures reinforced with a cushion of tire chips. The experimental results showed that the seismic loading and residual displacement of the caisson decreased during earthquakes due to the elasticity and the drainage of tire chips. Hazarika *et al.* [6] conducted a series of one-dimensional compression and permeability tests using tire shreds and gravel. The results lead to the fact that tire shreds and gravel have similar permeability coefficients after initial consolidation. However, due to the high compressibility of tire chips, it has been recommended to mix tire chips with conventional geomaterials such as sand or gravel to increase the stiffness of the layer and to adjust the particle size distribution and ratio of the tire chips according to the actual project requirements [12]. Recently, one of the most popular ideas in the utilization of tire chips is the application of sand-rubber mixture as a reinforcing material under the building foundation to promote the liquefaction resistance [13]. A difficult problem that arises with this technology is the decrease in the bearing capacity of the foundation. As a countermeasure, it is proposed to use gravel-tire chips mixture (hereafter referred to as GTCM) as a substitute material to improve the overall shear strength [14]. Such a measure can improve the bearing capacity of foundation soil. Pasha *et al.* [15] performed a series of cyclic undrained triaxial tests on GTCM under lateral pressure of 50 kN/m^2 and 100 kN/m^2. It was observed that the liquefaction resistance of GTCM is close to 1 due to the reduction of contact between gravel particles above a threshold tire chips fraction and excellent damping performance of material. Another reason for the increased liquefaction resistance might be excess pore water pressure is suppressed because of higher permeability of GTCM.

As shown in **Figure 3**, the use of gravel-tire chips mixture (GTCM) as a drainage medium and reinforcing material between the waste and the alluvium clay

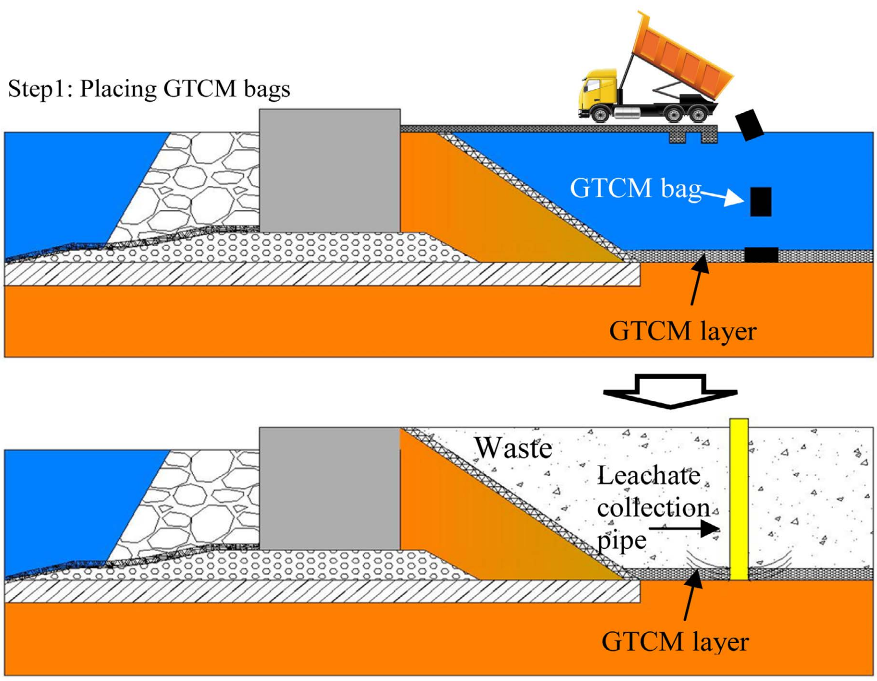


Figure 3. Marine landfill with a GTCM reinforcement layer.

layer to protect the impermeable barrier of the landfill base while improving leachate collection is a new economical and environmentally friendly construction method for marine landfills (gravel is about three times the price of tire chips for the same weight). With regard to this new method, previous research has thoroughly investigated the strong anti-aging property of rubber in seawater [16], the installation method of GTCM [17], and the mitigation of the impact force of waste on alluvium clay layers [18] [19] [20]. The present results firstly confirm that GTCM protects the impermeable layer (alluvium clay). Some other important practical problems we face are the effectiveness of GTCM in reducing the settlement of alluvium clay layer during the placement of waste and the long-term consolidation process (as the landfill base consists of a natural impermeable layer, its significant settlement and damage may lead to the leakage of leachate material in the surrounding ecosystem) and the change in the permeability of GTCM under different loads.

Because GTCM is both drainage and reinforcement materials, the purpose of this study is to investigate the effect of tire chip particle size and mass ratio on the compressibility and permeability of GTCM under different triaxial stress. It also aims to investigate the effect of GTCM on the settlement of alluvium clay. However, because of a limitation in the sizes of standard testing apparatus, there is a lack of data on GTCM with large particle sizes. With respect to the compressibility and permeability of GTCM, a new large-scale triaxial compression and permeability test apparatus is developed as part of this research. A series of compression and permeability tests are performed on GTCM with different tire chip particle size (2 - 4.75 mm, 9.5 - 19 mm) and different mass proportion of tire chips (MPTC) under effective confining pressure of 100 kN/m^2, 150 kN/m^2 and 200 kN/m^2. In addition, a marine landfill with a GTCM reinforcement layer between the waste and the alluvium clay layer (see **Figure 3**) is modelled in a finite element software, PLAXIS 2D. The results of the compression and permeability tests serve as an important source of the material parameters in the numerical study. According to the dual function of drainage and impermeable layer protector, the objectives of this study are twofold: 1) to examine the permeability characteristics of GTCM when subjected to static loading using a large-scale triaxial compression and permeability test apparatus; 2) to evaluate the performance of GTCM in reducing the settlement of alluvium clay by using the numerical PLAXIS software.

2. Theoretical and Experimental Investigation of Seepage in Porous Media

2.1. Reynolds Number and Non-Darcy Flow

Reynolds number is frequently used to indicate the flow pattern in different flow situations (laminar and turbulent). It can be expressed as:

$$Re = \frac{\rho v D}{\mu} = \frac{\text{inertial force}}{\text{viscous force}}. \tag{1}$$

here, Re is the Reynolds number, ρ is the fluid density, v is the flow velocity, D is the columnar sample diameter, μ is the dynamic fluid viscosity.

Darcy's law has been widely used for describing fluid flow through a porous medium. As stated below in Equation (2), the fluid velocity is proportional to the hydraulic gradient at low fluid velocity only. In general, laminar flow in clay or sand can be expressed by Darcy's law.

$$i = \frac{\mathrm{d}p}{\mathrm{d}x} = \frac{1}{k} v . \tag{2}$$

here, p is the hydraulic head in the x direction of flow, i is the hydraulic gradient, k is the permeability coefficient, v is the flow velocity.

As the flow velocity increases in porous media of large size (such as: gravel, tire chips and tire shreds), the inertial effects in fluids become more significant. The relationship between the hydraulic gradient and flow velocity may become non-linear in such situation. In past several works have highlighted that this problem can be overcome by adding a binomial formula and corrected the Darcy's law into Forchheimer's law [21] [22] [23] [24]. Both Darcy (binomial is 0) and non-Darcy phenomena can be explained effectively by the Forchheimer's law. GTCM is classified as a pervious granular media because it contains coarse particles. Hence, using nonlinear formula can better consider the relationship between the hydraulic gradient and flow velocity. The Forchheimer equation [24] can be expressed as:

$$i = \frac{\mathrm{d}p}{\mathrm{d}x} = \frac{\mu}{K} v + \beta \rho v^2 . \tag{3}$$

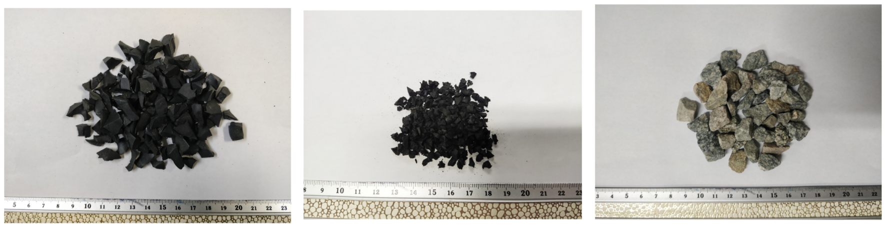
$$k = \frac{K \rho g}{\eta} . \tag{4}$$

here, μ is the fluid dynamic viscosity (Pa·s) (Dynamic viscosity of water at 25˚C is utilized in this study), K is the permeability of flow media, β is the non-Darcy flow coefficient, ρ is the fluid density (g/cm^3), g is the gravity acceleration (m/s^2), η is the coefficient of dynamic viscosity.

Darcy's law is assumed to be valid for laminar flow ($0 < Re < 10$). For transitional flow (nonlinear), Re is in a range of 10 - 1000 and for turbulent, flow Re ≥1000 [25]. In previous studies, researchers have reported the asymptotic process in flow can be accurately predicted by the Forchheimer equation for different ranges of flow Reynolds numbers, both in the nonlinear state and in the turbulent state [26] [27]. In the next section, the permeability of GTCM particles is investigated by Forchheimer equation based on Reynolds number.

2.2. Test Materials

Figures 4-6 represent the material and the physical properties of the GTCM used in this study. Tire chips and gravel samples used in this study are shown in **Figure 4**. The grain size distribution tests for tire chips and gravel are performed as per JGS 0131-2009. Tire chips used in this study are of two gradations, TC1



TC1: Tire chip (9.5 - 19 mm) TC2: Tire chip (2 - 4.75 mm) G: Gravel (9.5 - 15 mm)

Figure 4. Tire chips and gravel used in the preparation of GTCM sample.

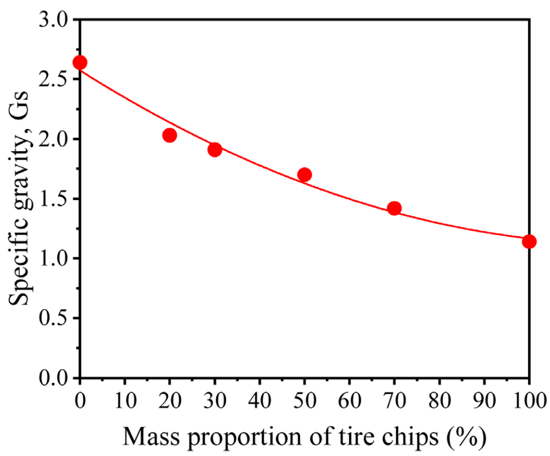


Figure 5. Specific gravity of GTCM particles.

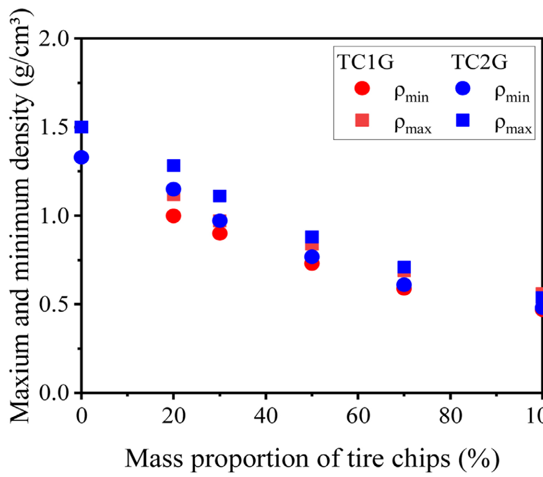


Figure 6. Maximum and minimum densities of GTCM particles.

(passing through 19 mm and retaining on 9.5 mm aperture sieve) and TC2 (passing through 4.75 mm and retaining on 2 mm aperture sieve). Gravel is of particle size varying from 9.5 mm to 15 mm. The specific gravity of GTCM particles is depicted in **Figure 5**. The specific gravity (Gs) of GTCM is determined as per JGS-0111-2009. The specific gravities (Gs) of the tire chips and gravel are 1.14 and 2.64 respectively. As seen in **Figure 5**, the specific gravities (Gs) of

GTCM decrease with increasing tire chips mass fraction from 0 to 100%.

To evaluate the effect of tire chips on the pore filling of GTCM particles, a series of minimum and maximum densities tests were carried out (See **Figure 6**) according to JGS-0162-2009. It is observed that both minimum and maximum densities of GTCM particles decrease with increase in the mass proportion of tire chips (MPTC). Due to smaller particle size in TC2, the maximum and minimum densities are higher than TC1.

2.3. Experimental Setup and Procedure

To evaluate the mechanical properties and permeability of the large particle size GTCM material, a new large-scale experimental apparatus was developed based on a traditional triaxial machine (See **Figure 6**). As shown in **Figure 7**, the new large-scale triaxial compression and permeability testing system mainly include: air cylinder (maximum load capacity 20 kN), pressure gage, hydraulic jack (load range 50 kN), axial and lateral pressure controlling cell, volume change burette, constant hydrostatic head device, measuring cylinder and CO_2 gas for saturation. It is capable of testing specimens with coarse particles that cannot be tested with traditional testing apparatus. And the compressibility and permeability of larger particle materials can be measured simultaneously under various lateral pressure and axial pressure conditions using this large-scale testing apparatus, which is an extension of a conventional triaxial testing machine. Rubber membrane of thickness 1.5 mm is used for making cylindrical samples. Samples are prepared in a large PVC mold with an inner diameter of 153 mm and height of 300 mm. The test procedure followed for the experimental tests is as following.

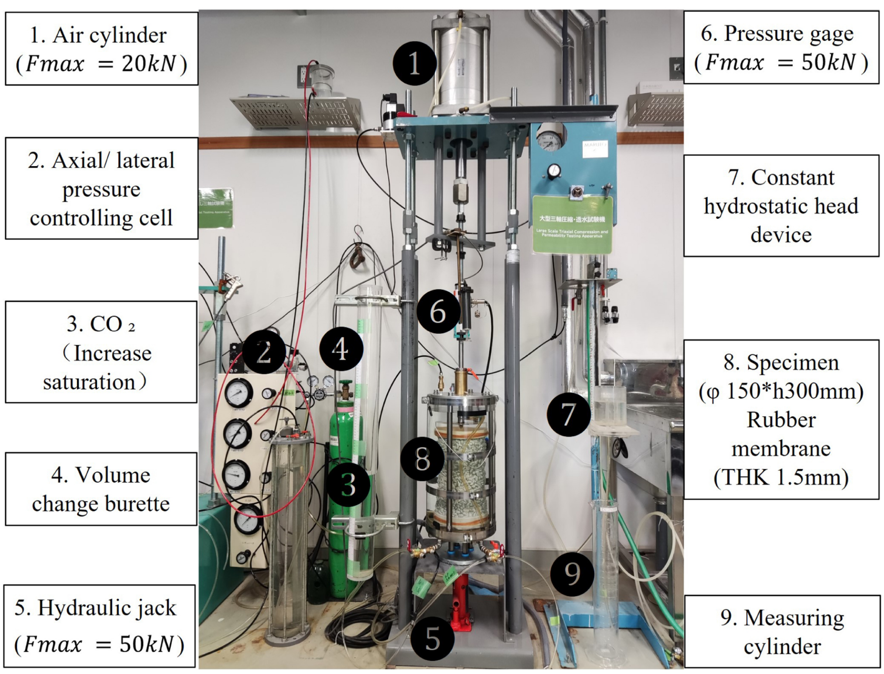


Figure 7. Large-scale triaxial compression and permeability testing system.

1) Sample preparation

The mass proportion of tire chips of 0, 20%, 30%, 50%, 70% and 100% are determined and the tire chips and gravel are mixed by hand until a uniform mixture is achieved. The sample is then prepared by placing the mixture in the PVC mould maintaining a relative density of 70% (dense state).

2) Sample saturation

Before beginning the saturation procedure, CO_2 gas is slowly passed through the sample from the bottom to flush out any trapped air. Following this the GTCM sample is then saturated with water slowly from the inlet valve in the bottom. Until water flows from the water collection valve (See ⑨ in **Figure 7**), at this point the sample saturation is completed and the water is kept flowing through the sample for 10 more minutes.

3) Consolidation and axial compression

After the saturation, the water inlet valve and the water collection valve are closed, and the valve connected to the volume change measuring burette is opened. The isotropic stress is increased to 100 kN/m^2, 150 kN/m^2, 200 kN/m^2, respectively in stages and the readings of the final axial displacement and volume change of the sample are recorded. In axial compression process, the sample is compressed with a rate of 100 kN/m^2/h (For simultaneous permeability tests, increase 100 kPa and hold for one hour afterwards), and compression is terminated when an axial strain of 15% is achieved. The axial displacement and volume change are measured during the axial compression process.

4) Forming steady flow and change of head difference

After completion of the isotropic compression stage, the valve of volume change measuring burette is closed, and the water inlet valve, the water collection valve, and the valve connected to the constant hydrostatic head device are opened. To form a steady flow, firstly, water is drained through the sample for 20 minutes. The head difference is determined by Equation (5). As rising water level due to rainfall is a major concern for the drainage design for actual site condition, a wide range of tests have been carried out on the GTCM specimens with different hydraulic head conditions. Furthermore, it should be noted that, the hydraulic head (i) below 0.1 cannot be adjusted by the current equipment therefore, the range of i for this research has been kept in the range of 0.2 to 1. The flow of water is initiated into the water collection cylinder, and the water flow rate Q is measured using a cylinder with graduated markings between two times, t_1 and t_2. To obtain accurate flow rates, this testing is carried out three times in total with the same head of water. The same procedure is used in the axial pressure increase process.

$$i = \frac{h_1 - h_2}{L}. \quad (5)$$

$$A = \frac{V}{L}. \quad (6)$$

$$v = \frac{Q}{A(t_1 - t_2)}. \quad (7)$$

In Equations (5), (6) and (7), i is hydraulic gradient, h_1 - h_2 is head difference (cm), L is height of the sample (cm), A is the cross-sectional area of sample (cm^2), V is the volume of sample (Calculated from volume change) (cm^3), v is the flow velocity (cm/s), t_1 - t_2 is the seepage time (s), Q is the flow rate (cm^3) between t_1 and t_2.

3. Experimental Results and Discussion

To demonstrate the feasibility of the proposed drainage and reinforcement technique, a detailed evaluation of the compressibility and permeability of GTCM under various pressure conditions is prerequisite and is discussed in this section. Unlike many previous one-dimensional pressure and permeability tests conducted with a metal cylinder [6] [28], this permeability test is conducted in a triaxial cell apparatus under triaxial pressure. And since the samples are encased by a rubber membrane, the cross-sectional area may change with appropriate pressure. In addition, due to the large size of GTCM particles, penetration of the membrane on the sample surface usually occurs during the loading process. Due to this potentially complex constraint, the cross-sectional area calculated from the volume and height of the sample is assumed to be effective in this experimental study.

The effect of MPTC (mass proportion of tire chips) on deviatoric stress-axial strain is shown in **Figure 8**. It must be pointed out that different from the general triaxial test, this experiment is not a continuous pressurization. Axial load is increased by 100 kPa per transient. As expected, a higher percentage of tire chips in GTCM contributes to lower values of shear strength. It can be observed that the tire chips sample (MPTC = 100%) is significantly different from the gravel-only sample (MPTC = 0). This implies that compared with gravel samples, pure tire chips have insufficient bearing capacity. For the gravel-only sample, the deviatoric stress can converge to a constant value. In contrast, a nearly linear stress-strain relationship is observed for the GTCM samples when MPTC is in the range of 50% - 100% with no significant deviatoric peak stress. The linear increase in deviatoric stress can confirm that the mixed tire chips promote better stress transfer compared to the gravel particles. For the GTCM samples with MPTC = 20% - 30%, there may be a trend of convergence as the stress is mainly transferred between the gravel particles, the effect of gravel is more considerable. Hence, it can be recognized that a smaller MPTC is preferred because the reinforcing effect can be sufficiently mobilized. In **Figure 8(b)** and **Figure 8(c)**, a similar stress-strain relationship of GTCM (MPTC > 0) is observed when the lateral pressure is increased from 150 kN/m^2 to 200 kN/m^2. This behavior can be attributed to the sufficient consolidation of the samples. The stress-strain relationship of TC1G and TC2G with different sizes of mixed tire chip particles is similar. Previous studies came to the similar conclusion regarding material

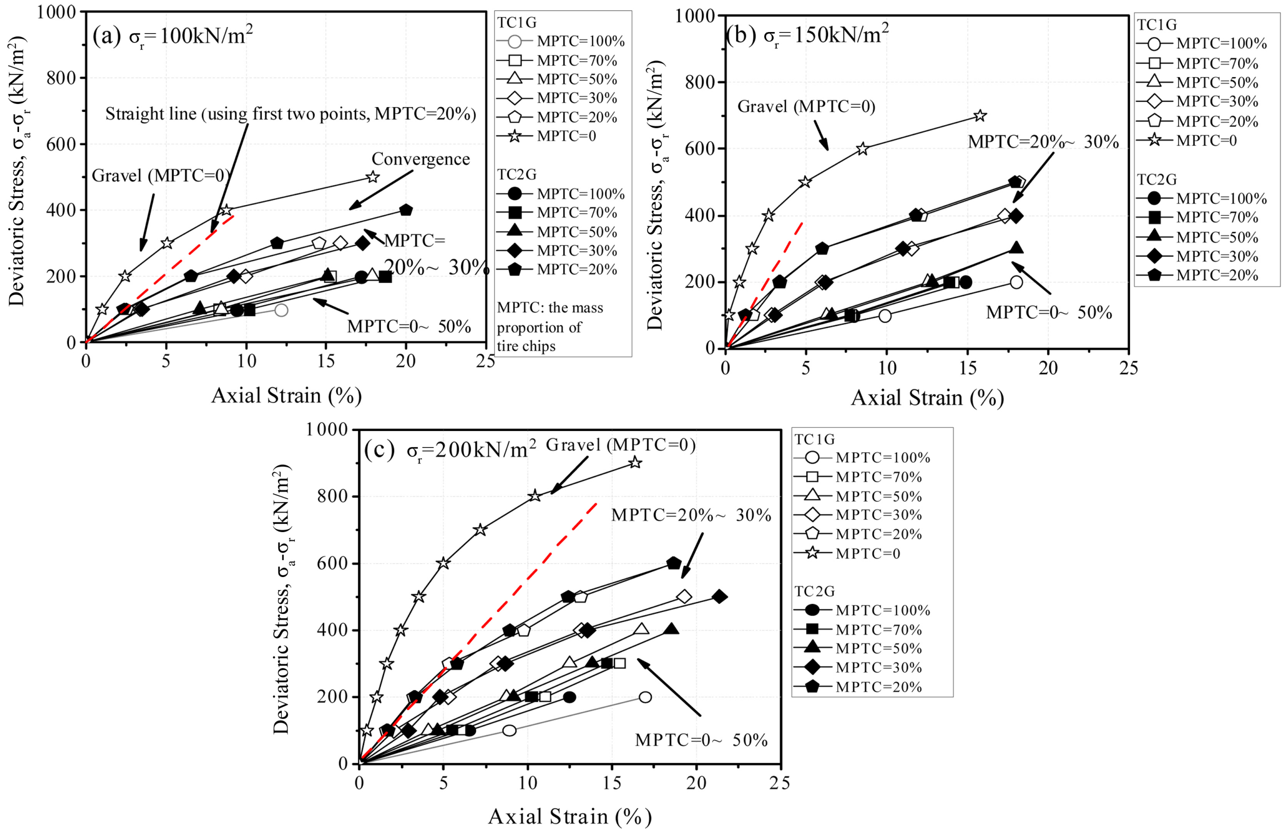


Figure 8. Effect of MPTC (mass proportion of tire chips) on deviatoric stress-axial strain. (a) σ_r = 100 kN/m^2; (b) σ_r = 150 kN/m^2; (c) σ_r = 200 kN/m^2.

stiffness and the effect of tire chip size on the shear strength of GTCM [9].

The relationship between the hydraulic gradient and Reynolds number in axial compression is shown in **Figure 9**. **Figure 9** shows the Reynolds number of G, TC1, and TC2 (MPTC = 0 and 1) according to Equation (1) at the test maximum lateral pressure condition. The Reynolds number increases linearly with an increasing hydraulic gradient. Due to the high compressibility and smaller size of TC2, TC2 has lower values of Reynolds number. The increase in axial pressure and the narrowness of the channel lead to an increase in water resistance. Overall, pure gravel and pure tire chips have a Reynolds number on the order of 10 - 60 in the axial compression process. It can be pointed out that in GTCM, a kind of composite porous medium, there is still a nonlinear flow behavior (transitional flow, $10 < Re < 1000$) under higher pressure [25]. As described, the permeability test results will be in better agreement with Forchheimer's law (nonlinear relationship) compared with Darcy's law (linear relationship). In the research work conducted by Koohmishi and Azarhoosh, the nonlinear relationship between flow velocity and hydraulic gradient was observed for the permeability of crumb rubber [29].

Figure 10 illustrates the change in porosity during axial compression. As the MPTC is increased, the porosity continues to decrease. It can be observed that

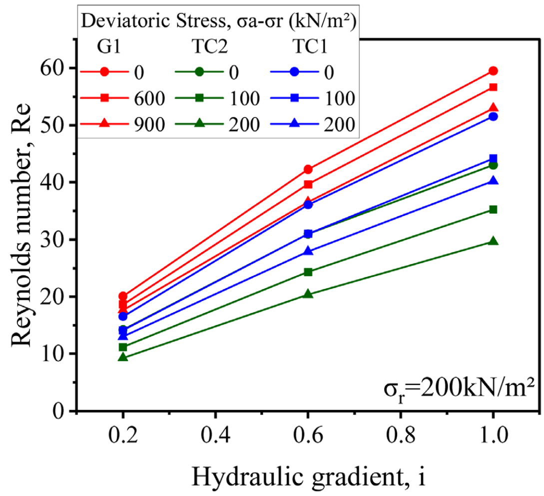


Figure 9. Relationship between hydraulic gradient and Reynolds number in axial compression process.

increasing the lateral pressure has no significant effect on the change in porosity. The porosity values in **Figure 10** range from 0.2 to 0.4. Overall, the particle size of the tire chips has almost no significant effect on the change in porosity of GTCM in the compacted state.

The relationship between porosity and permeability coefficient is shown in **Figure 11**. From **Figure 11**, it can be seen that the permeability coefficient increases slowly with increasing porosity. According to Forchheimer's law, the values of permeability coefficient of TC1G range from 0.04 cm/s to 0.08 cm/s. The value of permeability coefficient of TC2G ranges from 0.02 cm/s to 0.08 cm/s. Even the permeability of GTCM in some combinations is higher than that of gravel under triaxial pressure, which was used as traditional drainage material. The values of GTCM permeability coefficient in previous studies range from 0.02 cm/s to 0.6 cm/s, which is a higher value than that reported here [30]. It should be noted that higher compression indicates lower permeability of GTCM. Material was not sufficiently compressed in the prior study. The permeability coefficient of 0.01 cm/s is usually considered as an acceptable value for drainage layers in landfills [31]. Thus, based on the above results, it can be concluded that the replacement of gravel with tire chips did not affect the overall permeability, even under great pressure. On the contrary, this makes it possible to use tire-derived geomaterials such as tire chips, an environmentally friendly and inexpensive material, in a landfill drainage system.

In the Forchheimer equation, the non-Darcy flow coefficient (inertial effect) is related to the properties of porous media, such as permeability, tortuosity, and pore size, which must be determined by permeability tests. However, the effect of non-Darcy flow is rarely considered in the study of seepage in porous media [24] [32]. Due to the difficulty of measuring the tortuosity of the material in practice, especially in mixed materials such as GTCM, one way to overcome this problem is to find the relationship between the permeability coefficient and the

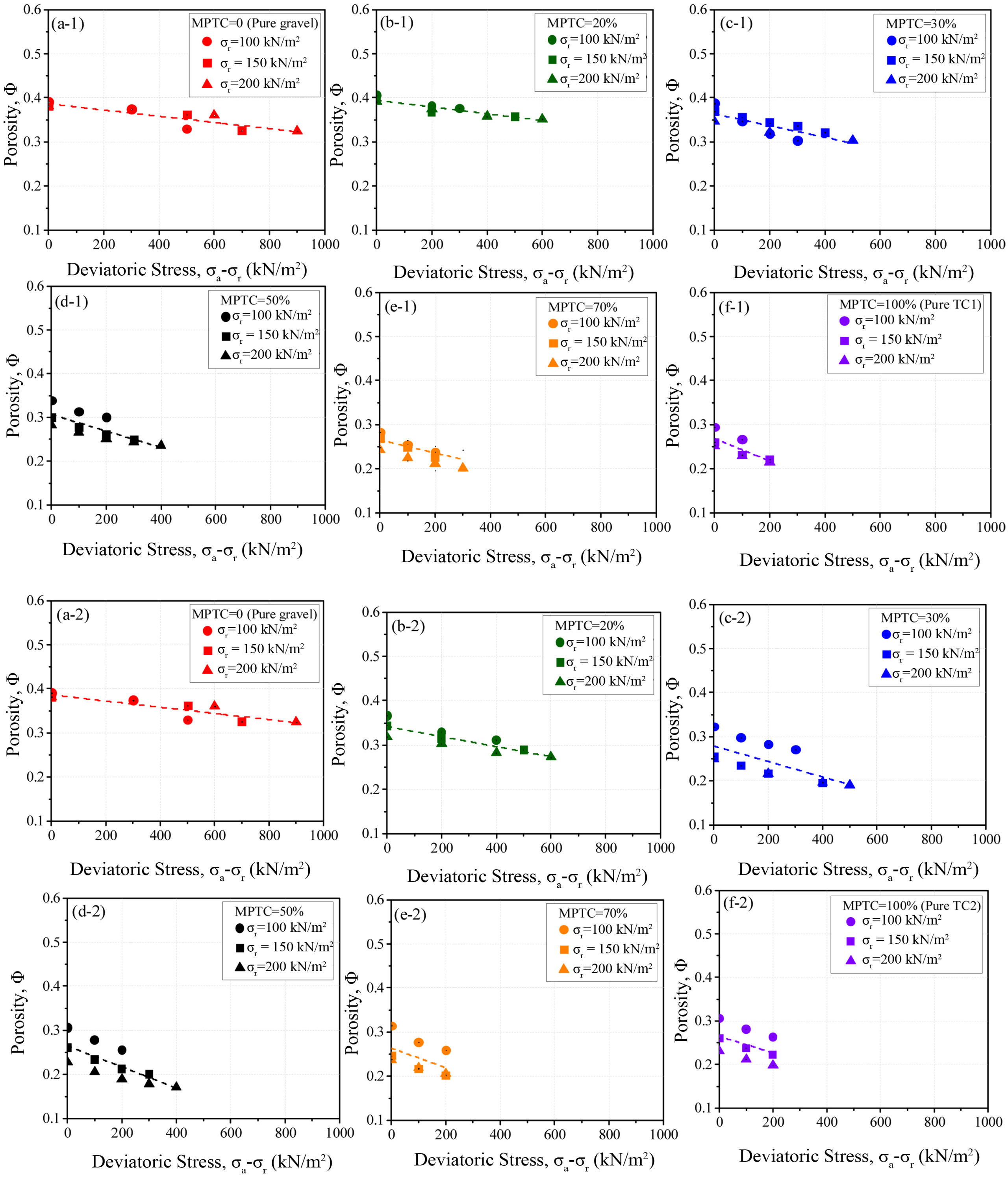


Figure 10. Variation of porosity during axial compression. TC1G: (a-1) MPTC = 0; (b-1) MPTC = 20%; (c-1) MPTC = 30%; (d-1) MPTC = 50%; (e-1) MPTC = 70%; (f-1) MPTC = 100%. TC2G: (a-2) MPTC = 0; (b-2) MPTC = 20%; (c-2) MPTC = 30%; (d-2) MPTC = 50%; (e-2) MPTC = 70%; (f-2) MPTC = 100%. TC1: 9.5 - 19 mm; TC2: 2 - 4.75 mm; G: 9.5 - 15 mm.

non-Darcy flow coefficient. A number of researchers have found through experimental and theoretical studies that there is an approximate power function

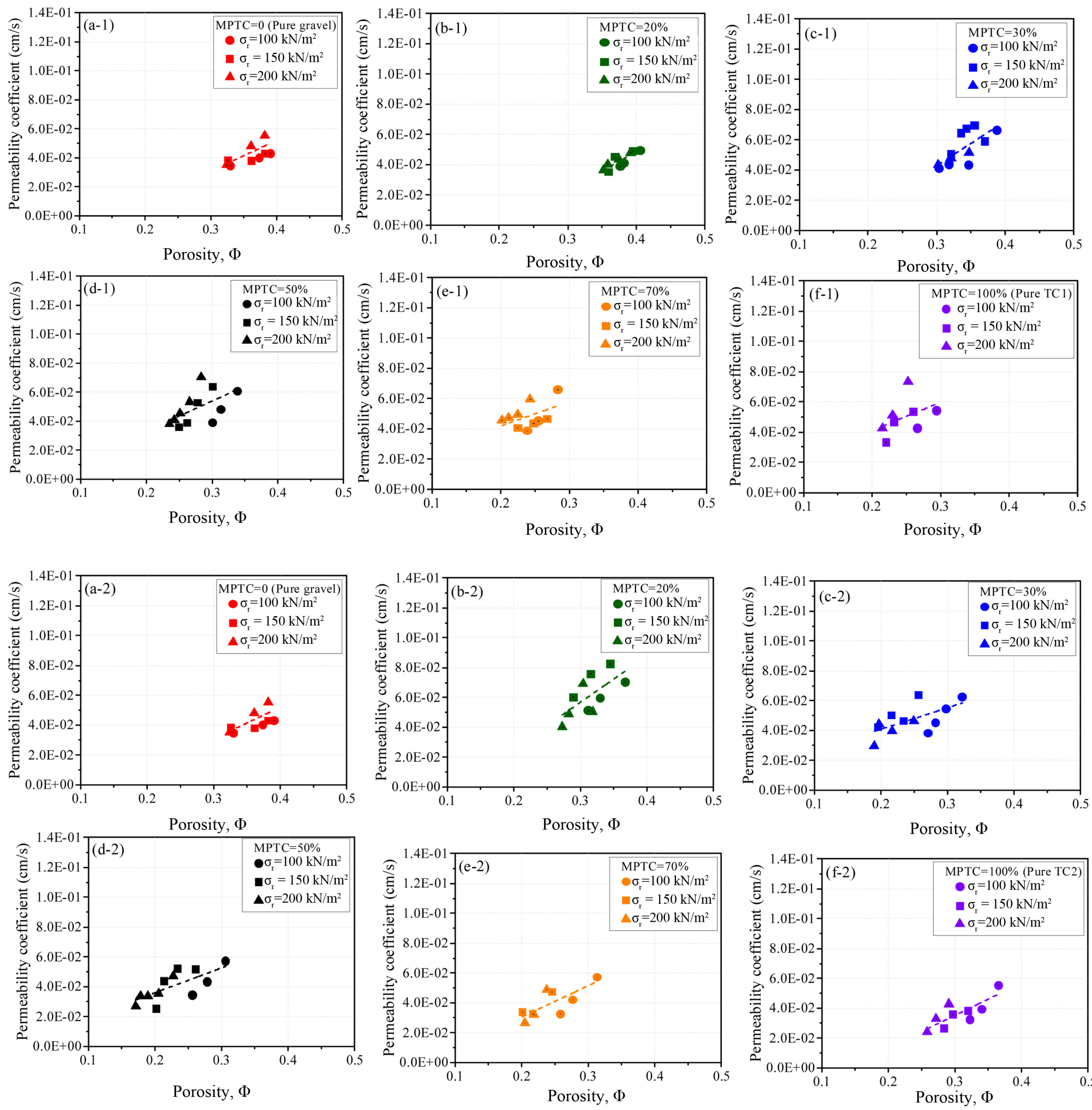


Figure 11. Relationship between porosity Φ and permeability coefficient k. TC1G: (a-1) MPTC = 0; (b-1) MPTC = 20%; (c-1) MPTC = 30%; (d-1) MPTC = 50%; (e-1) MPTC = 70%; (f-1) MPTC = 100%. TC2G: (a-2) MPTC = 0; (b-2) MPTC = 20%; (c-2) MPTC = 30%; (d-2) MPTC = 50%; (e-2) MPTC = 70%; (f-2) MPTC = 100%.

between the non-Darcy flow coefficient and the permeability coefficient in the seepage of the porous medium [33] [34] [35]. **Figure 12** shows the relationship between the permeability coefficient and the non-Darcy coefficient. As reported by Liu *et al.* [36], the non-Darcy coefficient decreases with the increasing permeability coefficient in porous media. In other words, the complex paths in porous media are one of the causes of non-Darcy flow. Therefore, TC2G has a higher value of the non-Darcy coefficient compared to TC1G, which is due to

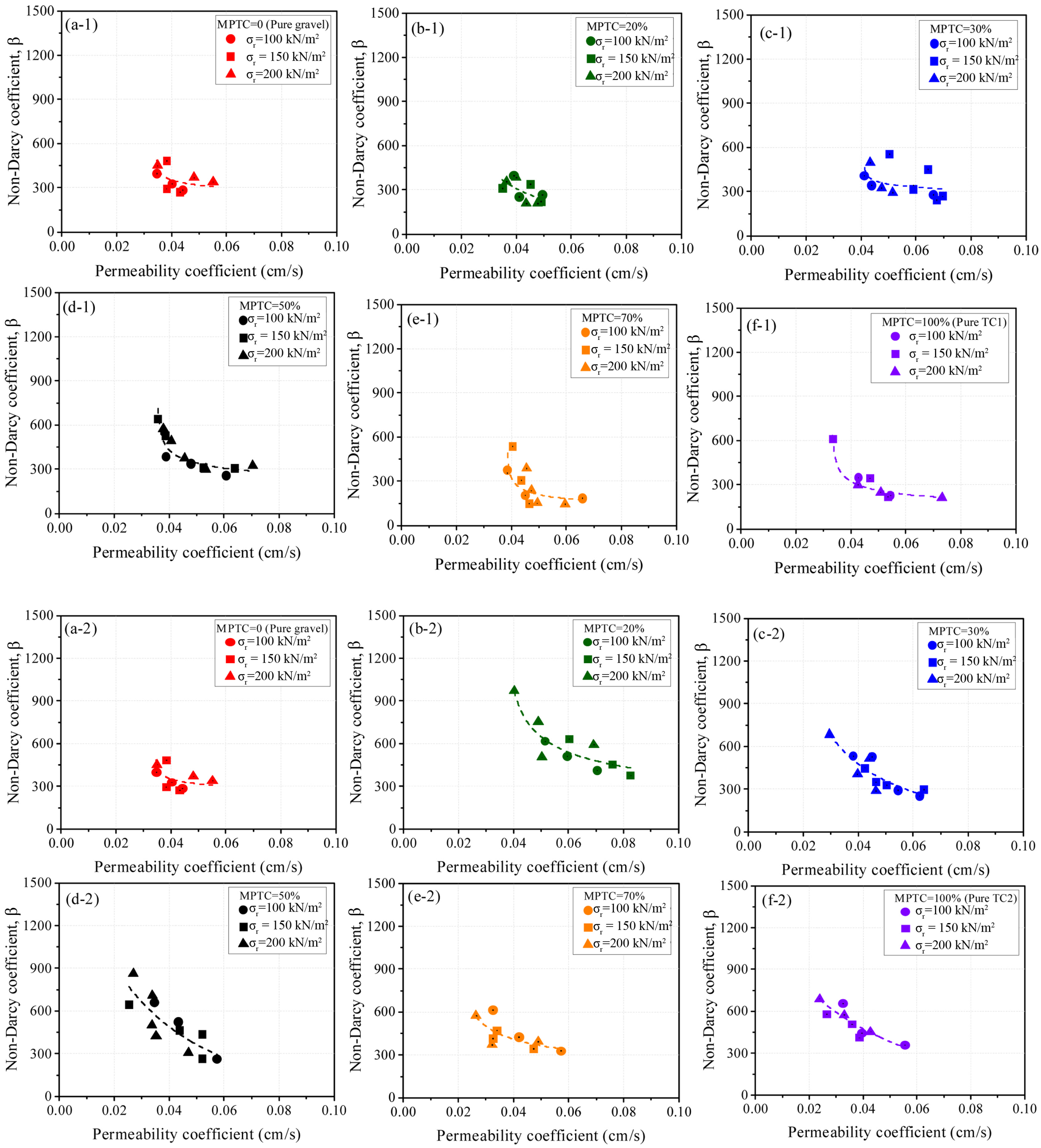


Figure 12. Relationship between permeability coefficient k and non-Darcy coefficient β. TC1G: (a-1) MPTC = 0; (b-1) MPTC = 20%; (c-1) MPTC = 30%; (d-1) MPTC = 50%; (e-1) MPTC = 70%; (f-1) MPTC = 100%. TC2G: (a-2) MPTC = 0; (b-2) MPTC = 20%; (c-2) MPTC = 30%; (d-2) MPTC = 50%; (e-2) MPTC = 70%; (f-2) MPTC = 100%.

the smaller particle size and more tortuous path. In Figure 12, a functional form that was used to fit non-Darcy coefficient at various permeability coefficients is presented. As can be seen in Figure 12, this relationship for GTCM indicates the possibility of establishing relationships between permeability parameters. Therefore, it can be concluded that the non-Darcy coefficient and the permeability coefficient have a power function as an approximation. And the T1G and TC2G materials have similar experimental behavior.

In summary, particle size (2 - 19 mm) and tire chip content have a slight effect on the permeability of GTCM, gravel-tire chips mixture in these experimental conditions. Therefore, the shear strength of GTCM needs to be considered more in the actual design. The strength of the mixture can be increased by upgrading the percentage of gravel. Meanwhile, tire chips with relatively large particle sizes are projected to be used in practice from a cost standpoint. In addition to improving the efficiency of leachate collection (permeability) during the waste consolidation process, another major purpose of the GTCM setting is to protect impermeable layers. In the next section, the reinforcement effect of GTCM is presented.

4. Numerical Investigations

4.1. Numerical Model

As stated before, reinforcement is also one of the major roles of GTCM. Abdullah *et al.* [37] studied the settlement mechanism in a shallow foundation reinforced with a vertical and horizontal layer of tire chips under seismic motion using hardening soil model. To evaluate the effectiveness of GTCM, this numerical study uses the Sekiguchi-Ohta model (Viscid model) to model soil elements for the alluvium clay layer, and the Hardening soil model is used for model the GTCM reinforcement layer and the sand layer (comparative study). As reported in previous studies by Abdullah *et al.* [37] and Murakami *et al.* [38], these models and clay parameters are selected to capture the settlement behavior of the alluvium clay under waste loading. The input elastic modulus property of the GTCM with MPTC = 20% and σ_r = 150 kN/m^2 is used from the observed values of the triaxial compression tests.

As a reference model, the numerical model considered for the reinforced case in the analyses is shown in **Figure 13**. Standard fixities were applied in the horizontal direction on both sides of the model, while at the bottom of the model, the movement was restricted in both the horizontal and vertical directions. The numerical studies aim to evaluate the reinforcing performance of GTCM under the waste. Therefore, the simulations on unimproved and improved conditions were investigated. **Table 1** shows nine numerical simulation cases, including reinforced cases and unreinforced cases. It should be noted that the model case E-1 with sand layer is shown as reference case for GTCM. Using the above two numerical models, a numerical analysis is performed by varying the width and thickness of the alluvium clay layers and the saturated unit weight of the waste. In this study, a parametric case study is performed for models considering a 50 m wide alluvium clay layer with different thicknesses. For a GTCM reinforcement layer of 0 m thickness the cases A-1, B-1, and C-1 represent alluvium clay layer thicknesses of 5 m, 10 m, and 15 m. Similarly, for a GTCM reinforcement

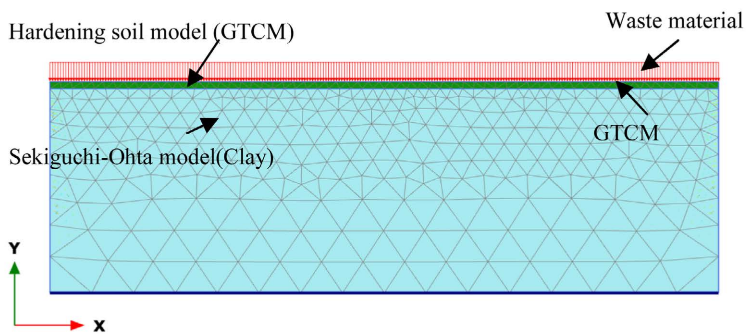


Figure 13. Finite element model of the reinforced case.

Table 1. Numerical simulation cases.

Case	Saturated unit weight of waste (kN/m³)	The thickness of reinforcement (m)	The thickness of alluvium clay (m)	The width of alluvium clay (m)
	14	0	5	50
	17	0	5	50
Case A-1	20	0	5	50
	14	0.5	5	50
	17	0.5	5	50
Case A-2	20	0.5	5	50
	14	0	10	50
	17	0	10	50
Case B-1	20	0	10	50
	14	0.5	10	50
	17	0.5	10	50
Case B-2	20	0.5	10	50
	14	0	15	50
	17	0	15	50
Case C-1	20	0	15	50
	14	0.5	15	50
	17	0.5	15	50
Case C-2	20	0.5	15	50
	14	0	10	200
	17	0	10	200
Case D-1	20	0	10	200
	14	0.5	10	200
	17	0.5	10	200
Case D-2	20	0.5	10	200
	14	0.5	10	200
	17	0.5	10	200
Case E-1 (Sand)	20	0.5	10	200

layer of 0.5 m thickness the cases A-2, B-2, and C-2 represent alluvium clay layer thicknesses of 5 m, 10 m, and 15 m. Additionally, cases D-1 and D-2 represent the model for 200 m alluvium clay width and 10 m alluvium clay thickness, with 0 m and 0.5 m GTCM reinforcement layer thickness, respectively. While Case E-1 represents the model with 200 m wide and 10 m thick alluvium clay layer with 0.5 m thick sand layer as reinforcement material instead of GTCM.

In this study, the simulation of the consolidation of the alluvium clay layer as a function of the life of the landfill is divided into two phases. The first phase assumes a vertical increase in waste dump height at a rate of 1 m per year for the first 15 years, while the second phase applies to the next 15 years, assuming only settlement due to consolidation. Waste above the GTCM reinforcement layer is simulated by varying the vertical stress from the top. The parameters used in simulation are shown in **Table 2**.

4.2. Numerical Result

Figure 14 depict the maximum settlement of the alluvium clay layer over a period of 30 years. It can be observed that the maximum settlements in the unreinforced cases are larger as compared to the cases with GTCM reinforcement, and that the maximum settlements in the reinforced cases are almost identical. In the cases with GTCM reinforcement, the maximum settlement of the alluvium clay layer is about 0.05 m in 30 years. In the unreinforced case, the maximum settlements range from 0.07 m to 0.15 m due to the difference in the saturation weight of the waste. In **Figure 14(a)**, for the unreinforced case, the maximum settlement decreases as the clay thickness increases. On the contrary, from **Figure 14(b)**, the maximum settlement increases as the clay width increases. Abdullah [39] observed the similar settlement variation to Case D-2 by placing GTCM reinforcement beneath the shallow foundation (See **Figure 14(c)**). It indicates that the horizontal GTCM reinforcing technique can help to restrict the settlement of alluvium clay layer (natural impermeable layer) and to provide

Table 2. Parameters used in simulation [37] [38].

	Hardening soil model	Sekiguchi-Ohta model
Parameter	GTCM	Clay
Saturated unit weight (kN/m^3)	15	16
Secant Modulus (kN/m^2)	3300	-
Reference stress for stiffnesses (kN/m^2)	100	-
Adhesive force (kN/m^2)	5	12.2
Compression index	-	0.5
Recompression index	-	0.02
Poisson's ratio	0.2	0.5

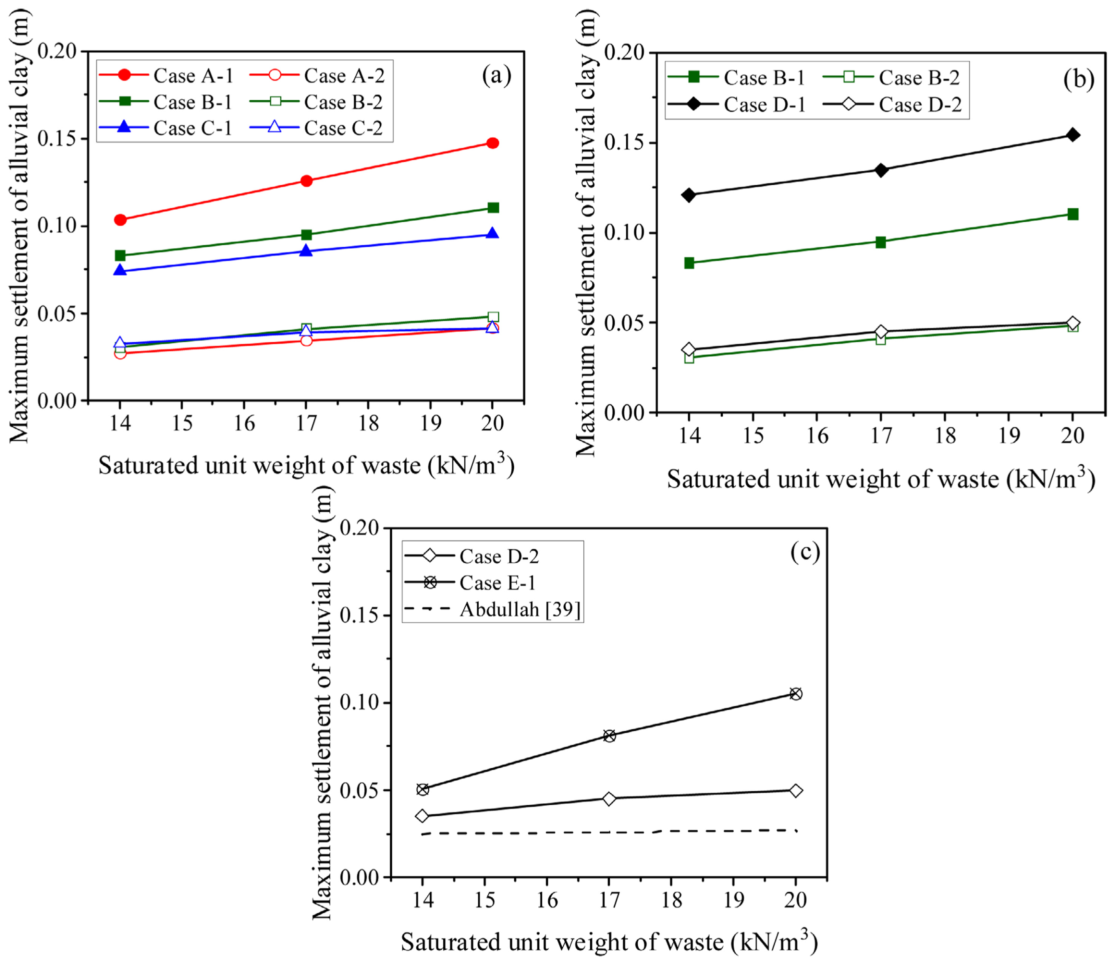


Figure 14. Maximum settlement of alluvium clay with different (a) clay thicknesses (b) clay widths (c) materials.

bearing support to the vertical load imposed by waste. The maximum settlement of the case reinforced with GTCM is lower than that of the case with the sand reinforcement layer, as shown in **Figure 14(c)**. Considering the above results, it is clear that GTCM is more effective than sand, a traditional reinforcement material in landfills [40]. Overall, based on the settlement value of clay, GTCM has no significant effect on the settlement of alluvium clay. As a reinforcement and drainage material, the drainage effect of the material is more acute and obvious than the reinforcement effect. In conclusion, the experimental and numerical results confirmed that the marine landfill site with horizontal GTCM reinforced method is effective in clay settlement control and offers favorable contribution in drainage performance. Future investigation should consider the effects of material particle size on permeability more carefully.

5. Conclusions

The use of recycled tire materials is expected to result in a significant reduction in CO_2 emissions. Using tire chips as a drainage material is an efficient way to recycle scrap tires. Through this paper, the compressibility and permeability of

GTCM are investigated using a newly designed large-scale triaxial apparatus. In addition, the reinforcement effect of GTCM is evaluated using the finite element software, PLAXIS 2D. The obtained results lead to the following main conclusions:

1) The nearly linear stress-strain relationship is observed for GTCM when MPTC is in the range of 50% - 100%. For the GTCM samples with MPTC = 20% - 30%, the stress-strain relationship shows an approximate converging trend. This may be related to the stress transfer mainly through gravel to gravel, the effect of gravel is more considerable. Therefore, lower tire chips content is preferred, as it effectively increases the stiffness of the GTCM reinforcement layer.

2) According to Reynolds number, it is be noted that there are inertial forces in the seepage of GTCM. It appears that nonlinear flow behavior is more acceptable. However, the calculated permeability coefficient of GTCM (TC1G and TC2G) from the Forchheimer equation is on the order of 0.02 cm/s to 0.08 cm/s. Therefore, GTCM is an excellent drainage material for landfill drainage layers based on the acceptable level of permeability coefficient. Collectively, tire chips mass fraction and particle size have limited influence on the permeability of GTCM under triaxial pressure in this experimental research. From the point of view of cost, it is recommended to use relatively large grains of tire chips for the mixture.

3) TC2G has a higher non-Darcy coefficient. It may be due to the tortuous inter-granular path. With an increasing permeability coefficient, the non-Darcy coefficient decreases. In addition, an approximate power function relation between the permeability coefficient and non-Darcy coefficient. This relationship for GTCM indicates the possibility of establishing relationships between permeability parameters.

4) The GTCM reinforcement can help to restrict the settlement of alluvium clay. In reducing the settlement of alluvium clay, GTCM is preferable to sand, the traditional reinforcing material in landfills. However, numerical simulation results show that GTCM reinforcement has a limited effect on the alluvium clay settlement in 30 years, indicating that the drainage role will be more prominent.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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