Water retention properties of sands mixed with Ca-Mg composites as attenuation layer

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ABSTRACT

One strategy currently being explored in the development of a technically simple and practical countermeasure when utilising geogenic contaminated soils as fill materials in an embankment involves the installation of a compacted soil layer with attenuation capacity underlain the contaminated geomaterials. Water retention property, which is one of the important soil hydraulic properties in the simulation of water flow, needs to be better understood for selecting a suitable composite of base material and stabilizing agent as the attenuation layer. In this study, the water retention characteristics of six composites with different sandy soils and calcium-magnesium composite sizes were investigated. It was found out that mixing the sandy soil with the mineral-based agent improves its water retention characteristics, especially when the soil is a well-graded type. The highest residual saturation ($S_r$) was found for the decomposed granite sand mixed with the powder agent of under 2 mm, which reached 87%. Poorly-graded sandy soils like the silica sand were found not to be suitable base material for the attenuation layer, because they drastically become impermeable, where $k$ reaches nearly $1 \times 10^{-14}$ m/s from very small changes in negative pressures.

Keywords: attenuation layer, base material, Ca-Mg composite, geogenic contaminated soil, water retention property

1 INTRODUCTION

Over the past decades, the concept of sustainable reuse for surplus soil, generated from projects for road, rail, and other infrastructure-related developments, has attracted a lot of interests from the regulatory authorities, construction industry, and scientific community, among others (Magnusson et al., 2015; Katsumi et al., 2019). By segregating surplus soil based on the soil type, water content, and their strength characteristics, such materials can be reused in various earthworks in Japan (Katsumi et al., 2004). Good quality soils, such as sand or gravel, have been utilised for road base or fill materials for shallow geostuctures. In some situations, by employing chemical or mineral-based stabilizing agents, soils characterised by poor geotechnical features can be changed into valuable construction materials (Ota et al., 2018). Recently, however, various cases of different kinds of geogenic heavy metals in the excavated soils were reported in many areas, for example, in Italy (Cremisini and Armiento, 2016), Hong Kong (Li et al., 2017b), and Japan (Katsumi et al., 2004; Li et al., 2017a). In Japan, because of public consciousness and conservative environmental laws/regulations against contaminants, it is a serious challenge to handle such materials which would be reused for the other purposes of construction.

Moderate regulations and their interpretations are necessary to realise the compatibility between the reuse of geogenic contaminated soils and contaminant control. According to various technical reports, such soils exhibit leaching concentrations only 2-3 times higher (or just slightly higher in some cases) than the regulatory limits (Katsumi et al., 2019). Also, a practical but secure way of reusing such marginally contaminated soils needs to be defined in such way as to be flexible enough for many site applications, while ensuring an acceptable level of protection for the environment and public health (Birle et al., 2010; Katsumi et al., 2019).

Among the various countermeasures for such soils containing geogenic heavy metals, the attenuation layer method, shown in Fig.1, is gaining its importance in recent days due to its technically simple and easy application. This method requires low investment to execute and offers better mechanical stability and constructability with sufficient compaction, unlike the layered system using geomembranes (Nozaki et al., 2013).

Fig. 1. Schematic diagram of the attenuation layer method.
With this method contamination of the surrounding environment can be prevented by the attenuation capacity of the permeable soil layer installed beneath embankment, even when the contaminated soils are used without any other barrier system (Tatsuoka et al., 2015; Tangviroon et al., 2017). One of the common recommendations to construct the attenuation layer is to mix a base material of sandy soil with stabilizing agent, and laying the composite with proper compaction to achieve a layer with a hydraulic conductivity \( k \) of about \( 1 \times 10^{-5} \) m/s (Nozaki et al., 2013).

As a material for the attenuation layer, calcium-magnesium (Ca-Mg) composite has various merits due to its high attenuation function for several heavy metals and pH buffering capabilities. According to Mo et al. (2018) and Gathuka et al. (2019), the three available sizes of the material can improve the attenuation function of a base material. But, considering the actual site conditions, the agent of coarse type of 2-9.5 mm might be better, due to cost savings following from reduced production processes. The agent size offers better handling and can be homogeneously distributed in the base material. Also, less, but long-term reactivity is expected when employing this agent size.

Hydraulic performance and attenuation capacity are important aspects commonly considered when assessing the performance of materials for the attenuation layer (Tabelin et al., 2014; Mo et al., 2015b; Gathuka et al., 2019). However, the characteristics of water flow in the layer can have a significant influence on its permeability and attenuation function (Ghasemzadeh, 2008; Francisca et al., 2012). Water retention property, which is one of the important soil hydraulic properties in the simulation of flow conditions, needs to be better understood so as to select a suitable base material and agent.

The water retention characteristics of six composites with different agent sizes and base materials were investigated, to acquire detailed quantitative information pertaining to the effect of base material and sizes of the Ca-Mg composite on the hydraulic properties of the attenuation layer. This is valuable in terms of recognising the limitations of suitable construction materials for the attenuation layer.

2 MATERIALS AND METHODS

2.1 Materials

Two base materials of decomposed granite soil of under 2 mm and silica sand, were employed. Particle size distribution of the soils is shown in Fig. 2 and was determined according to the Japanese Geotechnical Society Standards, JGS 0131. According to JGS 0051, the decomposed granite soil was classified as a well-graded sand with fine fraction (S-F) and silica sand as a poorly-graded sand (S).

Ca-Mg composite of different sizes was supplied by Sumitomo Osaka Cement Co., Ltd. It is produced by blending calcined dolomite-like natural minerals with special additives. The main constituent of the material is calcium (as CaCO₃) and its content is about 35.6%. Magnesium (as MgCO₃ and MgO) content is only about 19.4%. It also contains trace amounts of iron (as FeSO₄).

The agent of powder type of under 0.075 mm and coarse type of 2-9.5 mm was used as a stabilizing agent. Particle size distribution of the coarse agent is shown in Fig. 2. The specific surface area (SSA) value of the two agent sizes was estimated via the Brunauer-Emmet-Teller (BET) N₂ method. Table 1 summarizes the properties of the material.

As summarized in Table 2, six composites with different base materials and agent sizes were prepared. The agent was added to the dry soil, at 0 or 5% (or 50g/kg-soil) by dry weight of the mixture and mixed in the dry state first. And then admixed with the required amount of distilled water that depends on their optimum moisture content which ranged between10 and 12%. All mixing was done with a mechanical mixer, and proper care was taken to prepare a homogeneous mixture at each stage of mixing.

![Fig. 2. Particle size distribution curves of the decomposed granite soil of under 2 mm, silica sand, and Ca-Mg composite of coarse type of 2-9.5 mm.](image)

Table 1. Chemical composition and physical property of the stabilizing agent.

| Chemical composition or property | Value |
|---------------------------------|-------|
| Chemical composition* (wt. %)   |       |
| CaO                             | 35.6  |
| MgO                             | 19.4  |
| SO₃                             | 3.98  |
| Fe₂O₃                           | 3.73  |
| SiO₂                            | 1.52  |
| Al₂O₃                           | 0.07  |
| P₂O₅                            | 0.04  |
| Loss on ignition                | 33.5  |

| Physical property               | Value |
|---------------------------------|-------|
| Specific surface area (m²/g)    | 9.85  (Powder)** |
|                                 | 3.6 (Coarse)    |

* Source: Data from The Society of Materials Science (2014). Analysis was conducted according to JIS R 9011 °Chemical.
** Source: Data from Itaya et al. (2013).
2.2 Water retention characteristics tests

As summarised in Table 2, the water retention characteristics of six composites with different base materials and agent sizes were investigated.

As shown in Fig. 3, the Tempe cell was employed to obtain the water retention curves of composites with base material of decomposed granite soil (Case 1-3). The mixture (in wet state) was compacted in three equal layers (1 cm each) in a 5.4-cm inner diameter and 3-cm high brass cylinder and then confined by a base plate and top cap. After this, the specimen was saturated for 24 hours in a vacuum deaerator. The amount of mass for each layer was standardised based on the results of the A-a method of the standard Proctor compaction test (JGS 0711) and considering a compaction degree of 95%.

Drainage tests were carried out at several air entry pressures ($u_a$) for all 3 cases. Air entry pressure was supplied through the inlet tube at the top cap and water allowed to drain out from the bottom outlet, which was open to the atmosphere (0 kPa). Change in weight of the system with time was recorded for the corresponding entry air pressure. Entry air pressure was incrementally adjusted after equilibrium was achieved. In sandy soil, residual saturation ($S_{fr}$) tends to remain constant for $u_a$>10 kPa (Fredlund and Xing, 1994), so $u_a$ ranging from 0-10 kPa was applied.

Because it was difficult to properly control the air entry pressure in the low ranges of $u_a$<2 kPa, due to the low water retention capacity inherent by the poorly graded soil (silica sand), the soil column method was used instead to obtain the water retention curves of composites with base material of silica sand (Case 4-6).

For soil column method, a polyvinyl-chloride pipe of 2.5 cm in inner diameter was first cut into 12 fractions (each of 5 cm in height), and then attached together by curing tape and supported by a pole. The column was then partially submerged in water, by placing it inside a tank containing distilled water. Mixture (in wet state) was poured in the column and compacted in several equal layers, in water-submerged condition, so as to prepare a fully saturated soil column. By determining the dry mass of the soil after the test, a compaction degree between 92 and 95% was verified. More water was then poured to the soil column from the top until the water level was above the soil layer, to ensure that the soil was fully saturated before starting the drainage test. With the top part of the column open to the atmosphere, water was allowed to drain from the soil for 24 hours. After the drainage test, the soil column was divided into 5-cm high fractions and soil in each fraction carefully extracted for water content and dry mass measurements.

Saturation ($S_r$) was determined using equation (1), by considering the particle density ($\rho_s$), void ratio ($e$), and water content ($w$) of the sandy soil porous medium. The water content of the sandy soil was determined according to JGS 0121. Suction ($\psi$) was calculated from the difference between the air-entry pressure ($u_a$) and water pressure ($u_w$), i.e. $\psi = u_a - u_w$.

$$S_r = \frac{w}{100} \cdot \frac{\rho_s}{\rho_w}$$

The equation (2) proposed by van Genuchten (1980) was applied to obtain the best fitting curve to the experimental data of the drainage process. Under the conditions of available measured data of the soil water content and suction, the parameters of the van Genuchten (VG) model were estimated by the least square method, and the corresponding water retention curves acquired.

$$S_r(\psi) = S_{fr} + \frac{1-S_{fr}}{\left[1+(\alpha \psi)^{1-\frac{n}}\right]^n}$$

where $S_{fr}$ is the residual saturation, and $\alpha$, which is related to the point of curvature and $n$, which is related to the pore size distribution, are VG model parameters.

3 RESULTS AND DISCUSSIONS

3.1 Water retention characteristics of sandy soils mixed with different agent sizes

The water retention curves for the six composites (Case 1-6) are shown in Fig. 4 and 5. In the figures, the symbols represent measured data and the fitting curves, obtained using the soil hydraulic parameters given in Table 3, are shown by solid lines. Inspection of the curves shows a good agreement between the measured and predicted degree of saturation using the S-shape curve fitting equation proposed by van Genuchten (1980).
Table 3. Soil hydraulic parameters.

| Case | 1   | 2   | 3   | 4   | 5   | 6   |
|------|-----|-----|-----|-----|-----|-----|
|       | $k_{sat}$ (m/s) |    |    |    |    |    |
|       | $\phi$ |    |    |    |    |    |
|       | $S_{s}$ (%) |    |    |    |    |    |
|       | $\psi$ (kPa) |    |    |    |    |    |

*Note: Values of $k_{sat}$ are generic and were based on several technical reports.*

Fig. 4. Effect of different agent sizes on the water retention property of a well-graded sandy soil (Case 1-3).

Fig. 5. Effect of different agent sizes on the water retention property of a poorly-graded sandy soil (Case 4-6).

Notice that the sandy soil loses its water relatively quickly, while the sand-agent composites and especially composites with the agent of powder type lose their water much more gradually. The residual saturation of the sandy soil was lower when compared to that mixed with the agent. The highest residual saturation was found for the decomposed granite soil mixed with the powder agent, which reached 87%. This suggests that the Ca-Mg composite not only improves the attenuation function of a base material (Mo et al., 2015a; Gathuka et al., 2019) but also improves its water retention property, which is particularly noticeable for a well-graded soil.

Fig. 6. Water retention properties of sandy soils mixed with the coarse agent (Case 3 and 6).

The majority of pores in the silica sand-agent composites drain at relatively small negative pressures as compared to those of the decomposed granite soil-agent composites, which do not drain much until very relatively large negative pressures are applied, as is expected for well-graded soils. As shown in Fig. 6, when the decomposed granite mixed with coarse agent (Case 3) is employed in the site, $S_{e}$ of about 63% is expected under high negative pressures, which is much higher than for the composites with silica sand and coarse agent (Case 6), where it reaches about 4%.

3.2 Permeability function of sandy soils mixed with different agent sizes

The unsaturated hydraulic conductivity ($k$) of the porous medium was calculated using the van Genuchten-Mualem equation (3).

$$k(\theta) = k_{sat} \times S_{e}^{\frac{1}{m}} \left[1 - \left(1 - S_{e}^{\frac{1}{m}}\right)^{n}\right]^{2}$$

$$S_{e} = \frac{\theta - \theta_{e}}{\theta_{r} - \theta_{e}}$$

$$m = 1 - \frac{1}{n}$$

where $S_{e}$ is the effective degree of saturation, $\theta$ is the volumetric water content, $\theta_{e}$ is the residual volumetric water content, and $\theta_{r}$ is the residual saturation.
water content, $\theta_s$ is saturated volumetric water content, $k_r$ is relative hydraulic conductivity, $\gamma$ is a constant and typically considered as 0.5, $n$ and $m$ are VG model parameters, $k$ is the unsaturated hydraulic conductivity, and $k_{sat}$ is the saturated hydraulic conductivity of the porous medium.

As shown in Fig.7, $k$ decreases with an increase in negative pressures (which force pore water out) and tends to remain constant at relatively high pressures. Although the silica sand mixed coarse agent (Case 6) was permeable ($k=1\times10^{-4}$ m/s) at relatively small negative pressures, which is ascribed to the initial $k_{sat}$ value, its permeability function drastically dropped by several orders until the soil became impermeable ($k=1\times10^{-14}$ m/s), because at the boundary of the soil layer, even if the water content becomes discontinues, the pore water pressure keeps the continuity, which is much noticeable in a poorly-graded soil. Comparing the residual hydraulic conductivity of the composites of the two different soils and coarse agent, $k$ in Case 6 was relatively low as compared to in Case 3, where it tends to remain constant at $1\times10^{-11}$ m/s.

By adding the agent to decomposed granite soil, sharp decrements of $k$ were suppressed with increased negative pressures. Also, relatively small changes in $k$ were observed when the agent was employed. Although decomposed granite soil mixed with powder agent had the highest $S_r$, which reached 87%, the residual hydraulic conductivity is expected to be the same as that of decomposed granite soil mixed with the coarse agent.

As shown in Fig.7, $k$ decreased exponentially with reducing saturation as pore water was forced out, which was drastic for the composites of silica sand. Poorly graded soils typically have large voids, therefore when small negative pressure is applied, pore water is forced out easily, for it cannot stay in the large voids. In unsaturated conditions, the infiltrate water flows in the consecutive fluid phase and it circumvents the relatively large gaps. From this view, as the soil becomes unsaturated, the permeability function decreases, since the seepage water flow is deterred.

One of the principal objectives of the attenuation layer design is to provide for proper drainage of water inside the embankment, which is important to reduce pore pressures that tend to reduce the stability of an embankment. Therefore, poorly-graded sandy soils like the silica sand are not suitable base material for the attenuation layer, because they drastically become impermeable, where $k$ reaches nearly $1\times10^{-14}$ m/s, from very small changes in negative pressures. This is valuable information in terms of recognising the limitations of suitable base materials.

The hydraulic conductivity of the layer affects the leachate residence time ($t_c$) which refers to the duration the leachate is in contact with the solid materials and is given by equation (4). Mo et al. (2018) found out that the attenuation function is improved with longer time.

$$t_c = \frac{L \times \phi}{k \times i}$$  

Fig. 7. Permeability function of sandy soils mixed with different agent sizes.

Considering a simplified condition of a saturated 30-cm thick attenuation layer with a porosity ($\phi$) of 0.28 and seepage under a hydraulic gradient ($i=h_w/L$, where $h_w$ is the leachate head, and $L$ thickness of layer) which in the field is generally close to 1 (Sharma and Lewis, 1994), the time, $t_c$ was estimated to be 25 hours for Case 3. Under this condition, a high sorption performance is expected, and as the time increases due to a decrease in $k$, the attenuation function of the layer will improve.

4 CONCLUSIONS

This study focused on the characterization of water retention properties of several composites with different agent sizes of Ca-Mg composite and base materials, with the aim of better understanding and recognising the limitations of base material of sandy soil for construction of attenuation layer. From this study, it was concluded that:

1. The water retention curves showed a good agreement between the measured and predicted degree of saturation using the S-shape curve fitting equation proposed by van Genuchten (1980) which shows that the van Genuchten model is reliable for predicting the
water retention characteristics of sandy soils.

2. Employing agent improves the water retention characteristics of a sandy soil, and especially for a well-graded soil. The highest residual saturation was found in the decomposed granite soil-powder agent composite, which reached 87%.

3. Poorly graded sandy soils like silica sand are not recommended to use as a base material for the attenuation layer, because they drastically become impermeable, where \( k \) reaches about \( 1 \times 10^{-14} \text{ m/s} \) from very small changes in negative pressures.

4. By adding the Ca-Mg composite to decomposed granite soil, sharp decrements of \( k \) were suppressed with increased negative pressures. Also, relatively small changes in \( k \) were observed when the agent was employed. Although decomposed granite soil mixed with powder agent had the highest \( S_f \) which reached 87\%, the residual hydraulic conductivity is expected to be the same as that of decomposed granite soil mixed with the coarse agent, which was estimated to be nearly constant at \( 1 \times 10^{-13} \text{ m/s} \).

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