



# Effect of freeze–thaw cycles on the strength and physical properties of cement-stabilised soil containing recycled bassanite and coal ash



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## ABSTRACT

Earth materials deteriorate physically under freeze–thaw cycling. It is thus important to determine how freeze–thaw cycling affects their properties of new man-made materials in areas experiencing seasonal frost. The effect of variable freeze–thaw cycling on the durability of cement-stabilised soils containing bassanite and coal ash was quantified to promote the use of bassanite in earthwork project in seasonal frost areas. For this purpose, very soft clay was stabilised with 5% cement content by weight of dry soil, and bassanite and coal ash were mixed with it in differing proportions. These stabilised soil samples were subjected to differing numbers of freeze–thaw cycles (up to five cycles), after curing for 28 days. Unconfined compressive strength and several physical properties were investigated after freeze–thaw cycling. The results show that the addition of both bassanite and coal ash improves the strength and durability of stabilised soils significantly, whereas the addition of coal ash alone has a negative effect on strength improvement. Unconfined compressive strength increases with increased bassanite and coal ash contents. With respect to freezing and thawing durability, the first or second cycles of freeze–thaw action markedly decrease the unconfined compressive strength of both treated and untreated cement-stabilised soils, but further cycles have little additional influence. The use of both additives improves durability, and retains 65–85% strength compared to corresponding non-frozen stabilised soils; if either additive is used, the strength is 55–65%; and if no additives are used, about 50%. The effects of freeze–thaw cycling on water content and dry density are negligible compared to those of additive contents. Volume after freezing increased slightly with increase in the number of freeze–thaw cycles, although volume after thawing fell slightly and reached minimum at the first thawing process.

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## 1. Introduction

Freeze–thaw action affects earthworks in cold regions. Soils expand during freezing due to the formation of ice crystals, thus increasing the volume compared to the liquid state, whereas they contract during thawing process. Soil structures deteriorate when such freeze–thaw action is repeated (Ghazavi and Roustaei, 2010; Konrad, 1989). As well as the intensity of freezing, the type of materials used in construction also influences the degradation of stabilised soils caused by such environmental factors. Durability of stabilised soils under repeated freeze–thaw action varies, depending on the type and proportion of stabilising agents used (Khoury and Zaman, 2007; Olgun, 2013).

Chemical stabilization of ground is frequently employed, due to a shortage of soil materials suitable for earthworks. Bassanite produced from the recycling of waste gypsum plasterboard has recently been identified as being a highly effective material for ground improvement.

The management of waste gypsum has become an issue in recent years, and the effective use of recycled bassanite is thus an environmental bonus. The addition of recycled bassanite to cement-stabilised soils increases the compressive strength with increase in its content, and consequently waste gypsum shows promise as a ground improver (Kamei and Shuku, 2007). Durability of these materials under varying environmental conditions has been investigated. These include behaviour in wet and dry conditions (Kamei et al., 2011) and during freeze–thaw (Kamei et al., 2012b). Bassanite recycled from gypsum waste materials was first used in Japan as a stabiliser material in ground improvement projects (Ahmed et al., 2011a).

Electricity demand is expected to grow in future because of long-run economic growth and improvement in life quality. Coal-fuelled generation accounts for 40% of electricity supply in the world. Coal ash is produced as a by-product by coal-fired power plants, and it is problematic that the annual discharge of ash will continue to increase. To deal with the large amount of coal ash produced, coal ash has begun to be used effectively as a ground improver. The addition of both coal ash and bassanite to cement-stabilised soils increases their compressive strength (Kamei et al., 2010b, 2012a), reduces dissolution of fluorine and boron, both of which are hazardous elements (Kamei et al.,

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2010a), and improves durability under cyclical wetting and drying (Kamei et al., 2013).

From late winter to early spring a subarctic zone experiences drastic diurnal changes in temperature that swing across freezing point. The design and construction of earth structures in such an environment requires prior knowledge of how freeze–thaw action affects the mechanical properties of construction materials. Some studies reported that unconfined compressive strength of clay soils under freeze–thaw actions generally increased using fibre (Ghazavi and Roustaei, 2010; Zaimoglu, 2010), and synthetic fluid (Gullu and Hazirbaba, 2010). Moreover, the optimum additive contents in lime-stabilised clay soils were calculated as concerns rice husk ash and fibre (Olgun, 2013). On the other hand, some authors have investigated the freeze–thaw durability of soil stabilised with recycled and waste materials. The use of waste materials in the modification of stabilised granular soils improves the freezing and thawing durability. The waste materials used include cement–kiln dust (Zaman et al., 1999); silica fume, fly ash, and red mud (Yarbasi et al., 2007); bassanite (Ahmed and Ugai, 2011; Kamei et al., 2012b); and tyre cord (Jafari and Esnaashari, 2012).

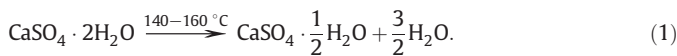
The objective of this study was to investigate how the combination of recycled bassanite and coal ash affects compressive strength, physical properties, and freeze–thaw durability of cement-stabilised soils, for different contents of bassanite and coal ash, and for variable numbers of the freeze and thaw cycles.

## 2. Materials and methods

### 2.1. Materials

Clay soil, bassanite, coal ash, and blast furnace cement type-B were used as materials in this study. The artificial clay soil, generally called kaolinite soil, was in a dry state, and mixing it with sufficient water made it representative of tested soil, which is very soft clay (Table 1). According to the unified soil classification system (USCS), the tested soil can be classified as clay with high plasticity.

Bassanite (hemihydrate calcium sulphate,  $\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$ ) used in this study was produced in a construction company (Table 2). The process of producing recycled bassanite from gypsum waste plasterboards (dehydrate calcium sulphate,  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) was presented in detail in previous studies (Ahmed et al., 2011b; Kamei and Shuku, 2007). The air-dried gypsum waste plasterboard was crushed and screened to remove any solid or contaminated materials, such as paper, wood, fibres, paints, and stones. The crushed gypsum waste was heated for a certain time under temperature ranging between 140 °C and 160 °C to remove three quarters of the water molecules, and then recycled bassanite was produced according to



When mixed with water, bassanite absorbs water, then returns quickly to dihydrate form, and hardens simultaneously.

Coal ash used in this study was a by-product from a coal-fired power plant, but particle size was regulated by a supplier (Table 3).  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$  are the main chemical components present in the coal ash, collectively accounting for 93.58% of the bulk composition; LOI is 2.2%, and the percentage retained in sieve # 325 is 18.9%. According to ASTM C 618-78, the type of coal ash used in this research is categorised

as class F fly ash because the total amount ( $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{Fe}_2\text{O}_3$ ) is found to be more than 70%, LOI is less than 6%, and the percentage retained in sieve # 325 is less than 34%. The self-hardening property of the coal ash is limited because it contains only 1.96% CaO.

Blast furnace slag cement type-B was used in this study in small amounts to prevent heavy metals from being released from the test soils because of the water-solubility of gypsum (Tables 4 and 5). These data were provided by the supplier.

### 2.2. Specimen preparation and freeze–thaw process

The test soil was made with a W/S ratio of 140%, where W = weight of water, and S = weight of dry soil. The clay soils found in some locations in Japan are very soft, and are described as marine clays. These have approximately the same water content as the test soil prepared here. This type of very soft clay soil is widespread, especially around the Haneda airport area in Tokyo. Water contents of 140% have been reported several *in situ* seabed clays in Japan (Nakase and Kamei, 1984).

Differing soil mixtures were prepared in the present study. These had B/S ratios of 0, 5, 10, and 20%, where B = weight of bassanite, and A/S 0, 10, and 20%, where A = weight of coal ash. Cement content (C/S) was 5%, where C = weight of cement. In the preparation of all types of specimens, the required amounts of cement and coal ash were first measured and mixed with the tested soil in the dry state. The required amount of water was then added to the dry coal ash–cement–soil mixture, and homogenised using an automatic mixer. The mixing continued for 4 min, until a uniform colour was obtained. Preliminary experiment showed that moist mixtures stiffened rapidly when bassanite was added; moreover, the addition of more than 20% bassanite prevented us from mixing the mixture. Consequently, the required amount of bassanite was added to the liquefied mixture and mixed only 60 s, immediately before the mixture was placed in the mould.

The mixtures were placed in cylindrical moulds with internal dimensions of 50 mm in diameter and 100 mm in height. A thin flexible sheet of cellulose acetate greased on both sides was mounted on the inner surface of the mould to prevent friction between the sample and mould during sample extraction. The moulds were filled with five equal layers of the mixture, with each successive layer tapped with a rubber hammer to remove any bubbles within the soil matrix. The loaded moulds were placed in polyethylene bags to prevent loss of moisture, and then left to rest at a controlled temperature of 20 °C for 24 h. The samples were then carefully extracted from the moulds. The extracted samples were wrapped with thin polyvinylidene chloride films and held at 20 °C in a temperature-controlled room until they aged for 28 days. To ensure reliability, three identical samples were prepared for each case.

The 28 day-cured samples were subsequently subjected to differing numbers of freeze–thaw cycles under closed condition, following a standard method defined by the Japanese Highway Society (JHS, 2001). After curing was completed, the wrapped samples were subjected to freezing for 24 h at  $-10\text{ }^\circ\text{C}$  in a freezer, and then thawed at room temperature for another 24 h, to represent a single freeze–thaw cycle. The samples were subjected to the required number of freeze–thaw cycles (up to 5 cycles) because ultimate stresses of treated samples under lower confining pressure do not almost change in the freeze–thaw cycle more than 3 (Kamei et al., 2012b; Wang et al., 2007). They were then tested to evaluate how freeze–thaw cycles affect the durability of very

**Table 1**  
Physical properties and chemical compositions of kaolin soil used in this study.

Physical properties				Physical compositions (%)			Chemical compositions (%)							
$\rho_s$ (g/cm <sup>3</sup> )	$w_L$ (%)	$w_p$ (%)	PI	Sand	Silt	Clay	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>	CaO	MgO	K <sub>2</sub> O	Na <sub>2</sub> O
2.679	73.1	36.7	36.4	0.0	35.3	64.7	68.1	24.8	0.14	0.15	0.02	0.02	1.54	0.56

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