Construction and Building Materials 38 (2013) 224–235

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

The use of recycled bassanite and coal ash to enhance the strength of very soft clay in dry and wet environmental conditions

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HIGHLIGHTS

- ▶ Recycled bassanite and coal ash used as stabilizer materials for very soft clay.
- ▶ Recycled bassanite is produced from gypsum waste plasterboard.
- ▶ Strength and durability improved with the increase of bassanite and coal ash ratios.
- ▶ Wet–dry cycles has insignificant effect on mechanical properties and volume changes.
- ▶ Samples stabilized with bassanite and coal ash are durable against wet environment.

ARTICLE INFO

Article history:
Received 8 December 2011
Received in revised form 25 July 2012
Accepted 11 August 2012
Available online 28 September 2012

Keywords:
Recycled bassanite
Coal ash
Soil improvement
Compressive strength
Durability
Wet environment

ABSTRACT

This study investigates the use of recycled bassanite, produced from gypsum waste, in conjunction with coal ash as a stabiliser material to improve the strength of very soft clay soil as well as to improve its durability in a wet environment. Additionally, this study investigated the effect of wet–dry cycles, referred in this study as a wet environment, on durability, strength and mechanical properties of very soft clay soil stabilised with recycled bassanite and coal ash. Four different combinations of the bassanite–soil ratios ranging between 0% and 20% as well as three different combinations of the coal ash–soil ratios ranging between 0% and 20% were used. The results showed that the use of recycled bassanite and coal ash significantly increase strength and improve durability. Both strength and durability improved with an increase of bassanite and coal ash content in the soil mixture. The use of coal ash alone is not recommended because it has a slightly negative effect on soil strength. The increase in the bassanite and coal ash contents is associated with the decrease in moisture content and the increase in dry unit weight. Curing time has a significant effect on the improvement of strength in the early days compared to the later days. The durability of the stabilised soil specimens decreased with an increase in the wet–dry cycles up to the third cycle, and then the effect of the wet–dry cycles decreased. Coal ash has a significant effect on the improvement of durability, especially for samples stabilised with a small amount of bassanite. The influence of the wet–dry cycles on mechanical properties, such as water content, dry unit weight and volume changes, is not significant. Generally, samples stabilised with bassanite and coal ash within the investigated limits in this study are durable against the effects of the wet–dry cycles. It is shown that the incorporation of recycled bassanite and coal ash to improve the strength and durability of very soft clay soil achieves an acceptable performance in both wet and dry environmental conditions. In addition, the effective use of waste gypsum and coal ash contributes to developing a sustainable society by reducing the huge quantities of solid wastes, producing useful material from waste material, and establishing a sound environment.

1. Introduction

The use of waste and recycled materials in earthwork projects has many economic and environmental benefits for our society. It helps to reduce the cost of disposal in landfill sites, the cost of earthwork projects and to maintain a sound environment. Consequently, extensive research has been conducted to investigate

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0950-0618/$ - see front matter
http://dx.doi.org/10.1016/j.conbuildmat.2012.08.028

the use of different types of waste and recycled materials as alternative materials in ground improvement projects. Examples of such waste and recycled materials include recycled gypsum, coal and fly ashes, cement kiln dust, blast furnace slag, incinerated sewage ash, stone dust, rice husk ash and industrial lime waste [1–15]. Gypsum waste plasterboards and coal ash are two examples of waste materials produced in Japan. More than 1.6 million tons of gypsum waste plasterboards are produced in Japan during the stages of production, construction and demolition [1–3]. The disposal of gypsum materials in traditional landfill sites is prohibited in Japan, and such waste must be disposed of in controlled landfill sites [3]. The emission of hydrogen sulphide occurs when gypsum waste is exposed to water [16,17]. Additionally, fluorine is released, which may be higher than the permitted limits in Japan and result in contaminated soil [16,18]. The cost of disposal in controlled landfill sites is high; hence, the recycling of gypsum waste was recently initiated in Japan to avoid the high cost of disposal and to maintain a sound environment. The use of recycled bassanite, which is derived from gypsum waste plasterboard in ground improvement projects, is one of the appropriate applications because bassanite has the potential to develop binding between soil particles [1–3,14]. The application of recycled bassanite as a soil stabiliser is a good solution to reduce the huge quantities of gypsum waste, but its use is associated with many challenges because bassanite is soluble in water [6,19,20]. The addition of a solidification agent to reduce the solubility of bassanite is essential for avoiding the occurrence of any mechanical and environmental hazards in the future. Most of the previous studies that dealt with the application of recycled bassanite in ground improvement projects used cement as a solidification agent without the addition of other types of waste or recycled materials [1–3,16]. The coal ash has a great record of use in soil stabilisation for fine grained and soft clay soils because it has self-cementing properties and pozzolanic reactions [21]. To coal ash was added to the stabilised cement/lime soils because it promotes the activity of pozzolanic reactions between the cementation materials and soil, and improves the strength [21–24]. There are large quantities of coal ash produced annually in Japan, approximately 7.1 million tons. Approximately 1.5 million tons of coal ash was sent to landfill sites, as reported in 2000 [25]. Consequently, the incorporation of coal ash as an agent material in soil stabilised with recycled bassanite will be more economical to improve the durability of the stabilised soil and prevent the solubility of bassanite, which will reduce the quantity of cement needed. Therefore, the main goal of this study is to investigate and evaluate the feasibility of using recycled bassanite in conjunction with coal ash as a soil stabiliser to improve the strength and durability of very soft clay soil. Specifically, the objectives are to study the factors affecting the performance and strength of stabilised soil, such as bassanite–soil ratio, coal ash–soil ratio and curing time. In addition, this study will investigate the effect of wet–dry cycles, referred in this study as a wet environment, on the durability of soil stabilised with recycled bassanite and coal ash.

2. Materials and methods

The three stabilising agents used in this research are recycled bassanite, which is derived from gypsum waste plasterboard, coal ash, and blast furnace slag cement type-B. The soil used is artificial Kaoline clay soil type, and it is known as MC clay in the Japanese market. The tested soil was brought from an industrial clay company in Japan. The physical properties and the chemical compositions of the tested soil are presented in Tables 1 and 2, respectively. The grain size distribution curves for the tested soil, coal ash and recycled bassanite are shown in Fig. 1. According to the unified soil classification system (USCS), the tested soil can be classified as clay with high plasticity. To achieve a very soft state for the tested soil, the oven-dry soil was mixed with water with a content of 140% based on dry soil mass; consequently, the tested soil achieved a very soft state. The soil with 140% water content was created to represent the soft clay soil types, which are spread throughout locations in Japan and have approximately the same water content. In fact, this type of soil exists around Haneda Airport in Tokyo, and the average water content was found to be approximately 140%, which was recorded in several cases as presented in the previous study [26]. The soil was mixed with water by an automatic mixer, and the mixing process was prolonged for an adequate time to achieve a homogeneous state for the tested soil.

The recycled bassanite used in this study was derived from gypsum waste plasterboard. The process of producing recycled bassanite from gypsum waste plasterboards was presented in detail in previous studies [1–3]. In brief, the air-dried gypsum waste was crushed and then screened to remove any solid or contaminated materials, such as paper, wood, fibres, paints, and stones. The crushed gypsum waste was heated under temperatures ranging between 140 and 160 °C for a certain time to remove three quarters of the water molecules, and then recycled bassanite was produced as presented in the following equation.

$$CaSO_4 \cdot 2H_2O \xrightarrow{140-160\,^{\circ}C} CaSO_4 \cdot 1/2H_2O + CaSO_4 \cdot 3/2H_2O$$

The physical properties and chemical compositions of the recycled bassanite used in this study are presented in Table 3. There are four different mixtures of the bassanite–soil ratios (B/S) of 0%, 5%, 10% and 20% that were used to study the influence of recycled bassanite content on strength, durability and mechanical properties of the tested soil.

The coal ash used in this study was brought from Energia Eco Material Co., Ltd. in Japan. Originally, this type of coal ash was produced from an electrical power plant in the south of Japan. In fact, fly ash characteristics are different from site to site because the properties of fly ash depend on the type of fuel/coal used and the additives used during the combustion process. There are two types of fly ash, namely C and F. Type C is derived from sub-bituminous coals and consists primarily of calcium alumina-sulphate glass, tri calcium aluminates, and free lime. Additionally, type C is referred to as the high calcium fly ash because it has 20–30% calcium compounds; consequently, type C has a self-cementing property [21,22]. Type F is

Table 2
Chemical compositions of the tested soil.

Chemical element	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	K_2O	Na_2O
Value (%)	68.1	24.8	0.14	0.15	0.02	0.02	1.54	0.56

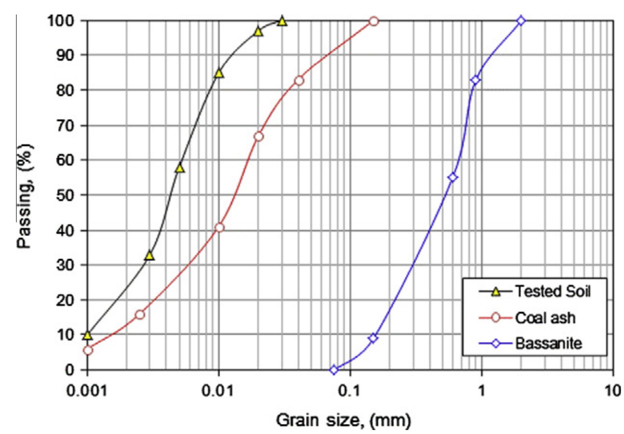

Fig. 1. Grain size distributions for tested soil, coal ash and recycled bassanite.

Table 1
Physical properties of the tested soil.

Engineering property	Dry density, ρ_s (gm/cm^3)	Liquid limit, LL (%)	Plastic limit, PL (%)	Plasticity index, I_P (%)	Compositions		
					Sand (%)	Silt (%)	Clay (%)
Value	2.679	73.1	36.7	36.4	0.0	35.3	64.7