



## Technical Note

# On the compressive strength and geo-environmental properties of MC-clay soil treated with recycled bassanite

M. Kobayashi<sup>1</sup>, U. H. Issa<sup>2</sup>, A. Ahmed<sup>3,\*</sup>

Received: June 2013, Revised: September 2014, Accepted: February 2015

### Abstract

The use of recycled bassanite, produced from gypsum wastes, in ground improvement projects is initiated recently in Japan to eliminate the huge quantities of gypsum wastes. Meanwhile the use of recycled bassanite has a positive effect on the environment and economy, it has many challenges. These challenges are related to the release of fluorine more than the standard limits results in contaminated fluorine soil. This research investigates the effect of the amount of bassanite, and water content on the release of fluorine from MC-clay soil stabilized with bassanite, taking in consideration their effect on the compressive strength. Recycled bassanite was mixed with furnace cement with a ratio of 1:1 to prevent the solubility of bassanite. Different amounts of this admixture were mixed with the tested soil at different water contents. Unconfined compression test was used to determine the compressive strength while the solubility of fluorine was used to represent the geo-environmental properties in term of the release of fluorine. Scan electron microscopic (SEM) test was done to identify the development of cementation compounds in the matrix of treated-bassanite soil. Test results showed that, the addition of bassanite had a significant effect on the improvement of compressive strength by increasing the amount of bassanite. Curing time had a significant effect on the increase of compressive strength, the strength increases with the increase of curing time, especially in the later curing time. The release of fluorine increases with increasing the amount of bassanite in soil mixture. The increase of water content had an indirect effect on the release of fluorine while it had a negative effect on the improvement of strength and consuming the amount of admixture. The increase of strength is associated with the decrease of the release of fluorine. Recycled bassanite, produced from gypsum wastes, had a potential to be used as a stabilizer material for MC-clay soil and meet the standards of environment.

**Keywords:** Recycled bassanite, Soil stabilization, Geo-environment, Compressive strength, MC-clay soil.

## 1. Introduction

Although the application of recycled bassanite produced from gypsum wastes, as a stabilizer material in earthwork projects, has many economic benefits, it has many challenges related to the environment. The release of fluorine more than the permitted standards is considered one of the most critical issues constrains the incorporation of recycled bassanite in ground improvement projects [1-4]. Increasing the solubility of fluorine in soil or in drinking water more than the standards reported by World Health Organization (WHO) has a negative effect on human health [5].

As the environmental regulations in Japan are very restricted compared to those in other countries, dealing with recycled and waste materials in Japan has many restrictions.

For example, the allowable value for fluorine in drinking water according to WHO was found 1.4 to 1.8 mg/l depending on the areas and weathering conditions [6]. While the standard for fluorine solubility in Japan was found to be 0.8 mg/l according to environmental guidelines issued by Ministry of Environment, Japan [7].

The application of recycled bassanite as a stabilizing material in earthwork projects is considered one of the appropriate ways to eliminate the huge quantities of gypsum wastes with minimum cost and to meet the standards of the environment. For example in Japan, up to the author's knowledge, recycled bassanite was used as a stabilizer material in five construction projects including unpaved and paved roads, embankments, and slope stability [3-4, 8-9]. The executed projects based on recycled bassanite as a stabilizer material included two embankments in Ota city, unpaved road in Tomioka,

\* Corresponding author: aly\_76@hotmail.com

<sup>1</sup> Manager, Environmental Business Department, DC Cement CO, Ltd, Tokyo, Japan

<sup>2</sup> Assistant Professor, Civil Engineering Department, Faculty of Engineering, El-Minia University, El-Minia, Egypt

<sup>3</sup> Professor, Civil Engineering Department, Beni-Suef University, Beni-Suef, Egypt

rehabilitation of paved road in Kiryu city, and slope stability for pond projects in Nakahara and Tukiyou cities, in Gunma Prefecture, Japan. Types of the investigated soils in these projects were silty clay, clayey soil, soft clay, very soft clay and organic clay soil. For each project, different amounts of recycled bassanite were used depending on type of the tested soil, the required strength, and project purpose. Hence, it is difficult to obtain clear understanding from these studies for the parameters controlling and influencing the geotechnical and environmental properties of treated-bassanite soil due to the change of soil type from project to another. The major parameters control, both geotechnical and environmental properties of treated-bassanite soil, are the amount of bassanite, and moisture content. Besides, there are other secondary parameters controlling the performance of treated-bassanite soil. These parameters include type and content of solidification agent, mixing method, and weathering conditions. These parameters were investigated previously with soils varying from one study to another [3-4, 10-13]. Generally, the change of soil type does not have a significant effect on the secondary parameters that control the geotechnical and environmental properties of treated-bassanite soil.

It is essential to understand the influence of moisture content and amount of bassanite on the properties of treated-bassanite soil, to meet the standards of the environment when recycled bassanite is incorporated in ground improvement projects. Increasing the amount of bassanite in soil mixture is expected to have an influence on the environmental properties of stabilized soil in term of the release of fluorine. Besides, the amount of bassanite in soil mixture plays an important role for the improvement of strength as well having an effect on the

mechanical properties of treated soil. Moisture content of the tested soil is expected to influence the solubility of fluorine since the formation of cementation compounds such as ettringite, which constrains the release of fluorine, controlled by the availability of water in soil mixture. In addition, the degree of moisture for the tested soil may be expected to influence both strength and mechanical properties of treated-bassanite soil. Consequently, this study investigates the effect of bassanite-amount, moisture content and curing time on geo-environmental and geo-mechanical properties of treated-bassanite soil. The release of fluorine refers to geo-environmental properties while strength, moisture content and curing time refer to geo-mechanical properties. For that purpose, recycled bassanite was mixed with furnace cement type-B with a ratio of 1:1 and different amounts of this admixture were mixed with the tested soil at different moisture contents. The amount of admixture was determined based on the results available in previous works that investigated the incorporation of recycled bassanite as a stabilizing material in some ground improvement projects in Japan.

## 2. Materials Used

Three different types of materials, artificial kaolin clay, recycled bassanite and furnace cement type-B, were used in this research. Artificial kaolin clay named as MC-clay soil was brought from some industrial clay company in Japan. Tables 1 and 2 present the mechanical properties and chemical compositions of the used MC-clay soil. According to the Unified Soil Classification System (USCS), the MC-clay soil can be classified as clay with high plasticity (MC).

**Table 1** Physical properties of MC-clay soil

Mechanical Property	$\rho_s$ (g/cm <sup>3</sup> )	$w_L$ (%)	$w_P$ (%)	$PI$	Mechanical compositions		
					Sand (%)	Silt (%)	Clay (%)
Value	2.68	73.10	36.70	36.40	0.00	35.30	64.70

**Table 2** Chemical compositions of MC-clay soil

Chemical Element	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
Amount, (%)	68.10	24.80	0.14	0.15	0.02	0.02	1.54	0.56

Recycled bassanite was produced by heating gypsum waste plasterboards. The process of production of recycled bassanite from gypsum wastes were presented in details in the previous works [14-15]. The chemical name of bassanite is calcium sulfate hemi-hydrate (CaSO<sub>4</sub>.0.5H<sub>2</sub>O). Based on the results of XRD the produced recycled bassanite included calcium sulfate hemi-hydrate (CaSO<sub>4</sub>.0.5H<sub>2</sub>O) with a content of 92.6%, while the contents of calcium sulfate hydrate (CaSO<sub>4</sub>.H<sub>2</sub>O) and calcium sulfate (CaSO<sub>4</sub>) were found 2.10% and 5.30%, respectively.

The type of cement used in this research is furnace cement type-B and it was brought from DC Cement

Company, Tokyo, Japan. This type of cement comprises 30 to 60 % furnace slag in its composition and it is produced from by-product of Portland cement. Table 3 represents the mechanical and chemical properties of furnace cement type-B used in this research. The main goal of adding cement to recycled bassanite is to prevent the solubility of bassanite since bassanite is a soluble material in water. The mixing ratio for bassanite to cement in this study was selected 1:1. This selection was based on the results presented in previous work, which indicated that the mixing ratio of 1:1 meet the standards of both geo-mechanical and geo-environmental properties [9, 16].

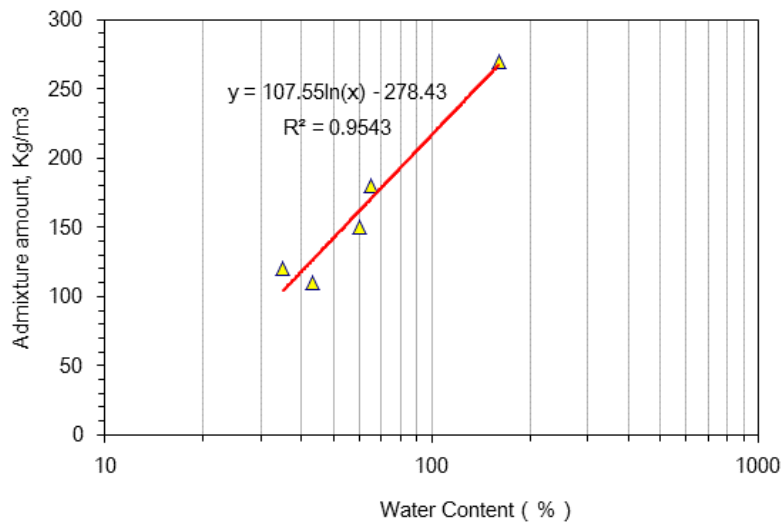
**Table 3** Mechanical and chemical properties of Furnace cement type-B (Supplied from company)

Specific surface area (cm <sup>2</sup> /g)	Mechanical Properties						Chemical Properties				
	Setting		Stability	Compressive strength			MgO (%)	SO <sub>3</sub> (%)	Ig. Loss (%)	Total alkali (%)	Cl- (%)
	Initial (min)	Final (h)		1d	7d	28d					
≥ 3000	≥ 60	≤ 10	Good	≥ 10.0	≥ 17.5	≥ 42.5	≤ 6.0	≤ 4.0	≤ 3.0	—	—

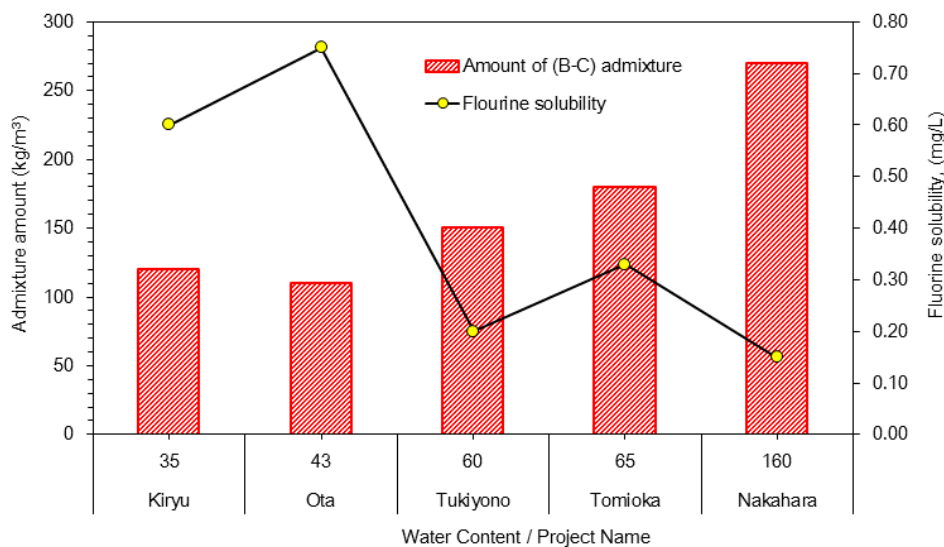
### 3. Testing Procedures and Results

Five different percentages of water contents and admixture amounts of bassanite-cement were investigated. The relation between admixture amount and water content was obtained based on the data available in previous projects which used such admixture, with the same ratio approximately, as a stabilizing material for different types of soils as presented in Fig. 1. Five different water

contents of 45, 55, 65, 80, and 100% were used and then the required amount of admixture was obtained based on the equation developed from the relationship between water content and admixture amount for previous cases as presented in Fig. 1. Fig. 2 shows the relationships between fluorine solubility, admixture amount and water content for different previous projects where bassanite was used as a stabilizer material in Japan.



**Fig. 1** Relationship between admixture amount and water content based on previous projects in Japan.



**Fig. 2** Relationship between admixture amount and Fluorine solubility based on previous projects in Japan

The tested soil was mixed with different contents of water and admixture amounts according to the values obtained from the developed equation presented in Fig. 1. The 28 days-cured samples were tested for fluorine solubility using the standard leaching method for measuring the fluorine from the soil, which was reported in Japanese Soil Measurement manual issued by Ministry of Land, Infrastructure, Transport and Tourism of Japan [17]. The procedures of measuring the solubility of fluorine by using the standard Japanese leaching method was presented in details in the previous works [1,3]. In brief, the tested soil was dried prior to crush and then the crushed soil sample was mixed with distilled water with a ratio of 1:10 then shaken for a certain amount of time using a shaker prior to measuring the solubility of fluorine. The solubility of fluorine was measured for samples cured for 28 days and this is based on the results presented in previous work which indicated that the 28 days curing is recommended to measure the solubility of fluorine since no more change can take place in the solubility value of fluorine after the 28-days curing time [3]. Fig. 3 shows the

relationship between fluorine solubility and ultimate strength at different water contents and Fig. 5 shows the relationship between admixture amount and fluorine solubility at different water contents.

SEM test was done on un/treated-bassanite MC-clay soil samples to identify the formation of ettringite in soil matrix. A JEOL JSM 6580 scanning electron microscope machine operating at 15kV was used to run SEM tests. For that, two tiny pieces of the dried tested soil sample were mounted on a copper specimen holder and then coated with a thin layer of gold to provide surface conductivity. A special technique was used to run the process of installation using a certain vacuum with specified electrical current. It is important to note that the two tiny pieces of the tested soil were assumed to represent the whole soil sample as well as to represent the chemical reactions induced between soil particles and stabilizer. Fig. 4 shows SEM images for different samples of MC-clay soil stabilized with different ratios of water content/admixture content (W/A).

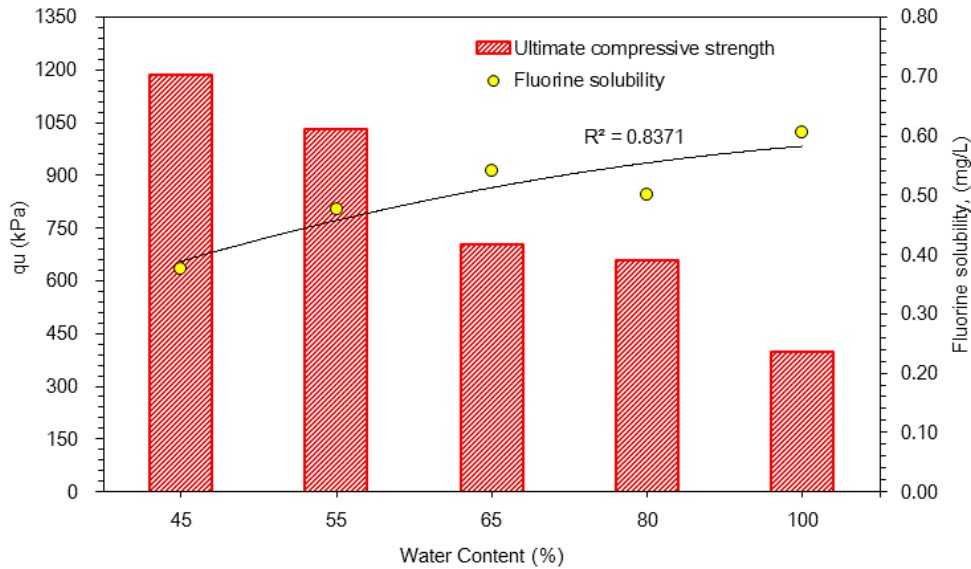
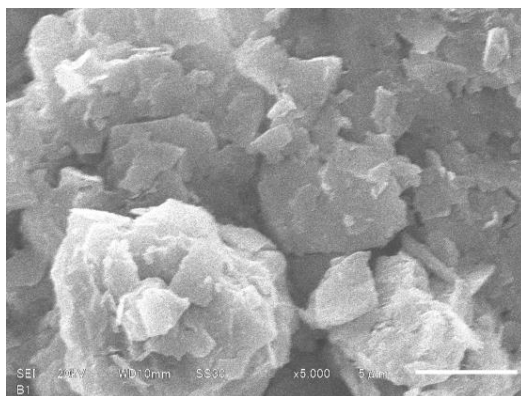
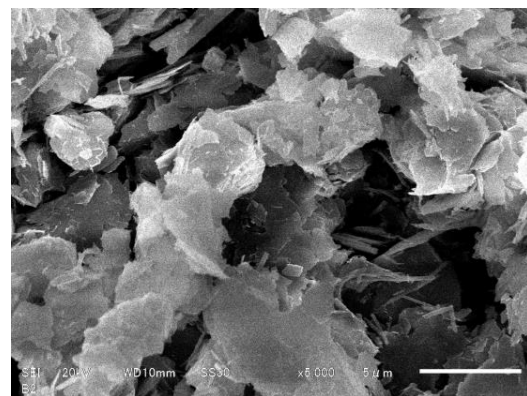


Fig. 3 Effects of ultimate strength on the solubility of fluorine for stabilized MC-clay soil at different water contents

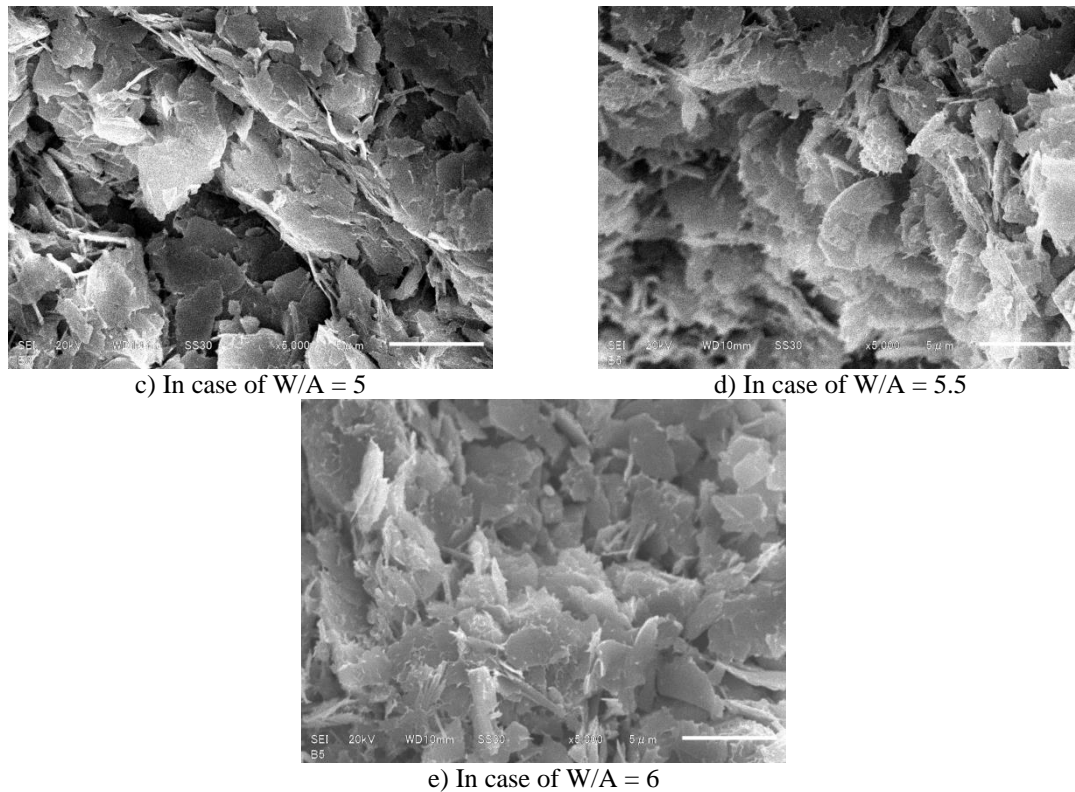


a) In case of W/A = 4.5

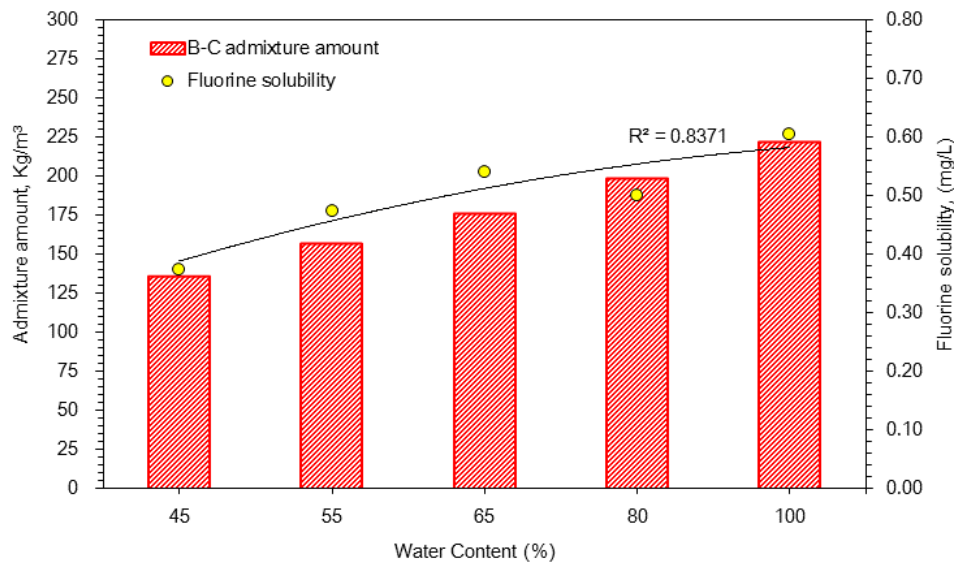


b) In case of W/A = 4.8





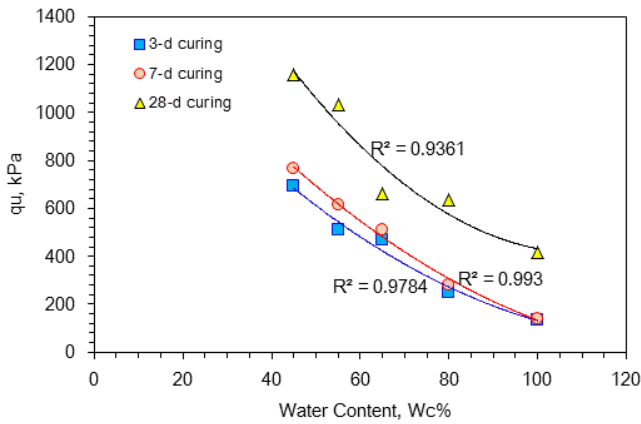
**Fig. 4** SEM images for MC-clay soil stabilized with different ratios of water content/admixture content (W/A).



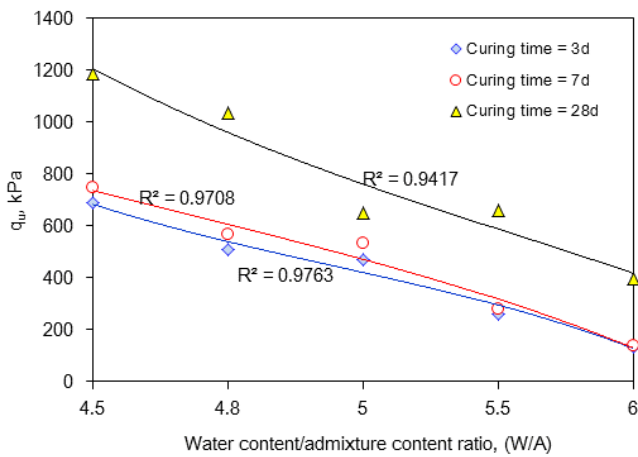
**Fig. 5** Effect of admixture amount on the solubility of Fluorine for Stabilized MC clay at different water contents

To determine the compressive strength for treated-bassanite soil, cylindrical stabilized soil samples were prepared. The procedures of sample preparation were presented briefly herein. Firstly, the tested soil was mixed with the required different contents of water and amounts of the admixture of bassanite-cement according to the testing program. Subsequently, the soil mixture was placed in cylindrical plastic molds and then compacted statically. The procedures of sample preparation for unconfined compression test were presented in details in previous works [14, 18]. The casted samples were cured for different lengths of time 3, 7, and 28 days respectively,

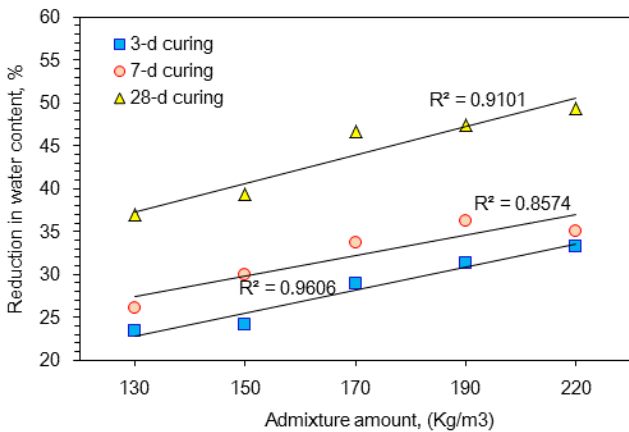
before testing for unconfined compression strength. The casted samples were cured in the controlled room at constant humidity and temperature. Samples were tested for unconfined compression strength in accordance with the standard test method ASTM D2166-06 [19]. The relationships between water content and (W/A) ratio against ultimate strength at different curing times are shown in Figs. 6 and 7, respectively. Fig. 8 shows the effect of admixture amount on the reduction of water content at different curing times.



**Fig. 6** Relationship between ultimate strength and water content for stabilized MC clay soil at different curing time



**Fig. 7** Effect of the ratio of water content/admixture content on the ultimate strength at different curing times



**Fig. 8** Effects of admixture amount on the reduction of water content for stabilized MC clay soil at different curing times

#### 4. Discussion of Results

Fig. 1 shows the relation between admixture amount and water content for different previous projects used bassanite-cement admixture as a stabilizer material. It is clear from this figure that increasing water content is associated with increasing the required amount of

admixture. This result is related to the fact that the increase of water content of soil, the decrease of strength and the required amount of admixture increased to achieve acceptable strength. Besides, the increase of water content needs more quantity of admixture to reduce water content for the tested soil. Based on this relation, equation described the relationship between admixture amount and water content was developed as presented in Fig. 1. This equation was used to determine the required amount of admixture for the tested soil at the different investigated water contents used and this equation is limited only for this study.

Fig. 2 shows the relationships between the amount of admixture and the solubility of fluorine against water contents for different previous projects, while bassanite-cement admixture was used as a stabilizer material. It is obvious from this figure that the required amount of admixture increases with the increase of water content while there is no clear trend for the solubility of fluorine. The unclear trend for the solubility of fluorine against the amount of admixture and water content is probably related to the change of soil type from project to another. Consequently, the parameter of soil type should be fixed to obtain clear understanding for the effect of admixture amount on the solubility of fluorine.

Fig. 3 shows the relationship between ultimate strength and fluorine solubility at different water contents used for Mc-clay soil stabilized with bassanite-cement admixture. This figure indicates that ultimate strength decreases with the increase of water content. This result is probably related to the fact that increasing water content is associated with the increase the number of voids in soil matrix and the ability of soil particles to sustain more loads decreases leading to a decrease in strength. As result the decrease of strength the solubility of fluorine increases as indicated in this figure. The increase of fluorine solubility in this case is probably related to the shortage of the developed solidification between soil particles and then the release of fluorine cannot be constrained completely. It is well known that the improvement in strength for soil stabilized with bassanite-cement admixture is related to dewatering, carbonation, reduction in plasticity and the development of cementation compounds in soil matrix. The development of cementation compounds is the major factor controlling the permanent improvement in strength. Decreasing the improvement in strength is probably related to the shortage in the development of cementation compounds in soil matrix. The major cementation compound which is capable to capture the fluorine on the surface of its crystals is ettringite [1, 20-21]. The formation of ettringite for different MC-clay soil samples treated with bassanite-cement admixture is not detected as proved by Scan Electron Microscope (SEM) images as indicated in Fig. 4. It can be concluded that strength of stabilized soil control the solubility of fluorine for soil samples treated with bassanite-cement admixture, the solubility of fluorine increases with the decrease of strength. Besides, the compressive strength decreases with the increase of water content.

Fig. 5 shows the relationship between the amount of

admixture and fluorine solubility at different water contents used. It is obvious from this figure that increasing the amount of admixture is associated with the increase of fluorine solubility. This result is probably related to increasing the content of bassanite in soil mixture, increasing the chance for the release of fluorine due to the availability of bassanite in soil mixture that helps for the release of fluorine. We can conclude that the amount of bassanite in soil mixture has a significant effect on the release of fluorine. Also, this figure indicates that the increase of water content is associated with increasing the required amount of admixture. This result is in agreement with the results of previous studies presented in Figs 1 and 2. Consequently, we can say that water content has indirect significant effect on the solubility of fluorine since both strength and amount of admixture are influenced directly by the moisture content of the tested soil.

Fig. 6 shows the effect of curing time on the ultimate compressive strength. As expected before, the compressive strength was enhanced with the increase of curing time. This result is related to the fact that increasing curing time gave the chance for stabilized soil samples to complete the chemical reactions induced between soil particles and admixture. Besides increasing curing time has a significant effect on the reduction of moisture content and strength improves with the increase of curing time because water is consumed during the induced chemical reactions. It is obvious from this figure that there is no much difference between the measured values of strength in the case of curing times of 3 and 7 days compared to the case of 28 days curing. This result is probably related to the chemical reactions between clay particles and admixture which may have needed more time, probably more than 7 days, to be significant. Also, this figure indicates that strength decreases with the increase of water content for different curing times used.

Fig. 7 shows the influence of the ratio of water content/admixture content (W/A) on the ultimate compressive strength at different curing times. As observed from this figure the ultimate strength decreases with the increase of the ratio of W/A. This result is related to the reason mentioned above which is, water content of the tested soil is considered the major parameter control the improvement of strength. Also, this result confirms the indirect effect of water content on the solubility of fluorine, since water content controlled both strength and admixture amount. Consequently, it is a vital to investigate the appropriate ratio of W/A to meet the required mechanical and environmental properties for soil stabilized with bassanite. To meet the standards of environmental and mechanical properties for treated-bassanite soil, it is recommended to deal with the ratio of W/A while it's not recommended to deal with admixture amount and water content individually.

Fig. 8 shows the influence of admixture amount on the reduction of water content. This figure indicates that increasing admixture amount has a significant effect on the increase of the reduction of water content for different curing times used. This result is probably related to the potential of bassanite ( $\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$ ) to absorb the water

from the moist soil to recover the three quarter of water molecules that are already missed during production process by heating to change for calcium sulfate hydrate ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ). Consequently, increasing the availability of bassanite amount in soil mixture increases the chance for absorbing more water from the tested soil.

## 5. Conclusions

This study investigated the major factors controlling the release of fluorine from MC-clay soil treated with recycled bassanite and the compressive strength of treated-bassanite soil. Based on test results, the following conclusions can be drawn as below:

1. Bassanite-cement admixture had a potential to be used as a stabilizer material for MC-clay soil and the suggested admixture contents used in this research meet the standards of environment and achieved acceptable strength.
2. The major direct factors controlling the release of fluorine from treated-bassanite soil are the amount of admixture and strength. While water content of the tested soil had a significant effect on the strength, it had an indirect significant effect on the release of fluorine.
3. The ultimate compressive strength increased with the increase of curing time. The effect of early curing times is not significant on the improvement of strength compared to the later curing time.
4. The reduction in water content increased with the increase the amount of admixture in soil mixture. The ratio of water content to admixture content (W/A) had a significant effect on the improvement of strength, strength decreases with the increase the ratio of (W/A).

It is recommended for site engineers who deal with treated-bassanite soil, to use the ratio of (W/A) in their design and not to deal with the amount of admixture and water content individually to meet the required strength and standards of environment.

**Acknowledgments:** Funding of this study is provided through a grant from Japan Society for the Promotion of Science, JSPS, to Dr. Aly Ahmed with ID No: P10137. The authors appreciate the financial support from this organization. Special thanks extend to the staff of Profa Environmental Company, Ltd., Maebashi, Japan for their help during environmental works. Also, authors would like to thank the staff of DC Cement Company, Ltd., Tokyo, Japan for their help for conducting Scanning Electron Microscopic tests in its laboratories.

## References

- [1] Kamei T, Horai H. Development of solidification technology for fluorine contaminated Bassanite using Portland blast-furnace (B) cement, Japanese Geotechnical Journal, 2008, No. 1, Vol. 4, pp. 91-98. (In Japanese).
- [2] Ahmed A, Ugai K, Kamei T. Environmental evaluation for clayey soil stabilized with gypsum waste plasterboard in Japan, In the Proceeding of the International Geo-Hunan 2011 Conference, June 9-11, Hunan, China, Geotechnical Special Publication, ASCE, 2011, Vol. 217, pp. 9-17.

- [3] Ahmed A, Ugai K, Kamei T. Laboratory and field evaluations of recycled gypsum as a stabilizer agent in embankment construction, *Journal of Soils and Foundations*, 2011, No. 6, Vol. 51, pp. 975-990.
- [4] Ahmed A, Ugai K, Kamei T. Assessment of recycled gypsum for organic soft clay soil improvement, In the Proceedings of the 2012 Geo-Congress, March 25-29<sup>th</sup>, Oakland, California, USA, Geotechnical Special Publication, ASCE, 2012, Vol. 225, pp. 1026-1035.
- [5] World Health Organization (WHO). Fluoride in drinking-water. Background document for development of WHO Guidelines for Drinking-water Quality, 2004, 17 p.
- [6] World Health Organization (WHO). Fluorine and Fluorides-Environmental health Criteria, Geneva, 1984, No. 36.
- [7] Ministry of the Environment Government of Japan (MOE). Soil Contamination Countermeasures. Soil Environment Management Division, Environmental Management Bureau Ministry of the Environment, Government of Japan, 2012.
- [8] SATA Construction Company Ltd. Technical Report: Construction of road projects in Kiryu and Tomioka sites, SATA Const, CO. Ltd., Maebashi city, Gunma, Japan, 2011, 26 p.
- [9] Ahmed A, Ugai K, Taira J. Soaking effect on strength and performance of fine grained soil stabilized with recycled gypsum, In the Proceedings of the First International Conference on Geotechnique, Construction Materials and Environment, GEOMAT, Nov. 21-23, Tsu City, Mie, Japan, 2011, No. 84, Vol. 1, pp. 343-348.
- [10] Ahmed A., Ugai K. 2011. Environmental effects on durability of soil stabilized with recycled gypsum. *Journal of Cold Regions Science and Technology* 2011; 66(2-3): 84-92.
- [11] Kamei T, Ahmed A, Shibi T. Effect of freeze-thaw cycles on durability and strength of very soft clay soil stabilised with recycled bassanite, *Journal of Cold Regions Science and Technology*, 2012, Vol. 82, pp. 124-129.
- [12] Kamei T, Ahmed A, Shibi T. The use of recycled bassanite and coal ash to enhance the strength of very soft clay, *Journal of Construction and Building Materials*, 2013, No. 1, Vol. 38, pp. 224-235.
- [13] Kamei T, Ahmed A, Ugai K. Durability of soft clay soil stabilized with recycled bassanite and furnace cement mixture, *Journal of Soils and Foundations*, 2013, No. 1, Vol. 53, pp. 155-165.
- [14] Ahmed A, Ugai K, Kamei T. Investigation of recycled gypsum in conjunction with waste plastic trays for ground improvement, *Journal of Construction and Building Materials*, 2011, No. 1, Vol. 25, pp. 208-217.
- [15] Kamei T, Kato T, Shuku T. Effective use for bassanite as soil improvement materials -Recycling of waste plasterboard, *Japanese Geotechnical Society Electronic Journal*, 2007, No. 3, Vol. 2, pp. 245-252 (In Japanese).
- [16] Ahmed A, Kobayashi M, Ugai K. Performance assessment of clay soil stabilized with recycled gypsum based on SEM and XRD, In the Proceeding of the 2<sup>nd</sup> International Conference on Advances in Transportation Geotechnics II, -IS-Hokkaido 2012, 9-12<sup>th</sup> September, Sapporo, University of Hokkaido, Japan, No. 37, pp. 272-280.
- [17] Ministry of Land, Infrastructure, Transport and Tourism of Japan, (MLIT). Environmental Testing Measurements: Tank Leaching Test Method for fluorine, 2001 (In Japanese).
- [18] Kamei T, Shuku T. Unconfined compressive strength of cement-stabilized soils containing Bassanite produced from waste plasterboard, *Japanese Geotechnical Society Electronic Journal*, 2007, No. 3, Vol. 2, pp. 237-244. (In Japanese)
- [19] ASTM 2166-66. Unconfined compression testing. Annual Book of American Society for Testing and Materials Standards, ASTM, USA, 2007.
- [20] Solem-Tishmack JK, McCarthy GJ. High-calcium coal combustion by-products: engineering properties, ettringite formation and potential in solidification and stabilization of selenium and boron, *Cement and Concrete Research*, 1995, No. 3, Vol. 25, pp. 658-670.
- [21] Chrysochoou M, Dermatas D. Evaluation of ettringite and hydrocalumite formation for heavy metal immobilization: Literature review and experimental study, *Journal of Hazardous Materials*, 2006, No. 1, Vol. 136, pp. 20-33.