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# The Suitability of Gypsum as a Ground Improvement Agent

## L'adaptation du Gypse Comme Agent D'amélioration du Sol

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**ABSTRACT:** The addition of cement to soil has become an increasingly popular method for ground improvement, but there are environmental concerns in the production and use of cement and it is also relatively expensive. Gypsum is an alternative to cement that has been investigated in laboratory studies and in field studies using recycled bassanite, a common waste product. As a ground improvement agent, gypsum is of interest as it easily mixed and quickly forms a hard paste upon hydration with the resulting mass experiencing relatively little change in volume, but its use is currently limited due to concerns relating to gypsum's solubility of 2-6g/l. Despite the large quantity of literature on the behaviour of gypsum in natural deposits, most of these papers are from the perspective of soil science and have primarily focused on the chemistry of gypsiferous soils. This paper aims to i) summarise relevant literature found in soil science, and, ii) discuss the suitability of gypsum as a cementing agent in ground improvement.

**RÉSUMÉ:** L'ajout de ciment au sol est devenu une méthode de plus en plus populaire pour l'amélioration du sol, mais il y a des préoccupations environnementales dans la production et l'utilisation du ciment et son utilisation est également relativement coûteuse. Le gypse est une alternative au ciment qui a fait l'objet d'études de laboratoire et d'études sur le terrain utilisant de la bassanite recyclée, un produit de déchet commun. En tant qu'agent améliorant le sol, le gypse présente un intérêt car il se mélange facilement et forme rapidement une pâte dure lors de l'hydratation, la masse résultante subissant relativement peu de changement de volume, mais son utilisation est actuellement limitée en raison de la solubilité du gypse de 2-6 g / L. Malgré la grande quantité de publications sur le comportement du gypse dans les dépôts naturels, la plupart de ces documents concernent la science du sol et ont principalement porté sur la chimie des sols gypsifères. Cet article a pour but i) de résumer la littérature pertinente relative à la science du sol, et, ii) discuter de la pertinence du gypse comme agent de cimentation.

**KEYWORDS:** Gypsum, Ground Improvement, Cementation

### 1 INTRODUCTION

In order to control the movement of an excavation or road embankment on soft soil, ground improvement techniques are often needed to rapidly increase the strength and stiffness of the soil. These methods of ground improvement include partial or complete replacement; preloading with or without vertical drains; sand, stone, lime or cement columns and deep soil mixing (e.g. Leroueil et al., 1990; Lin & Wong, 1999; Mitchell, 1990; Mitchell, 1981). Due to its relatively short programme time, especially when compared to more traditional techniques such as preloading with wick drains, soil mixing has become increasingly popular as a ground treatment technique in soft soils.

In the case of cement-treated soils, the increase in strength of soft clay arising from the introduction of cement has been well established (Kamruzzaman et al., 2009; Mitchell, 1981; O'Rourke et al., 1998; Tan et al., 2002). While it is still unclear as to the type of microstructure that is induced into the soil-cement mix by the reaction, the improvement of engineering properties has largely been attributed to the formation of primary and secondary cementitious materials in the soil matrix (Kamruzzaman et al., 2009). In sandy soils cement bonds the particles together and creates stiff and strong cement-treated soils.

Gypsum (calcium sulphate dihydrate) is another additive that can be mixed with soil to improve soil properties and has been used in New South Wales, Australia, in some infrastructure projects by introducing small quantities (~5%) of gypsum to stabilize the soil. Also bassanite (calcium sulphate hemihydrate) has been investigated for use in ground improvement because of the significant increase in the production and demolition of plasterboards in the construction industry (Ahmed, 2013; Ahmed, 2015; Ahmed & Issa, 2014; Ganjian et al., 2008; Kamei et al., 2013). The main argument for the introduction of recycled bassanite as a ground improvement agent has been the environmental benefit associated with the reduction in the quantity of both waste plasterboards sent to landfills and the

amount of cement used. This field of research has been of particular interest in Japan where recent amendments in the specifications have allowed for increased percentages of gypsum/bassanite to be mixed in construction soils (Kuttah & Sato, 2015).

There is limited knowledge regarding the use of gypsum as an additive in ground improvement. To address this limitation the literature on the physiochemical and mechanical properties of gypsum is summarized and the paper then discusses the potential of using gypsum as an alternative or supplementary agent for ground improvement.

### 2 PHYSIOCHEMICAL PROPERTIES

#### 2.1 Mineralogy and formation

In arid and sub-humid regions where sulphur-rich minerals such as pyrite are present, weathering and oxidisation can often lead to the formation of large horizontal gypsiferous deposits (FAO, 1990). These formations occur in one of two ways, i) by the evaporation of mineralised ground water and ii) by the precipitation of gypsum within the groundwater itself. In the case of pedogenic gypsum, precipitation results in large interlocking euhedral to subhedral spindle shaped crystals (Nettleton et al., 1982).

The leaching of saline soils has also been known to be a source of gypsum in the subsurface horizon. In these cases, leaching in soils containing sulphate and calcium can lead to precipitation and accumulation of gypsum (Nettleton et al., 1982). With most gypsiferous soils being located in dry, low annual rainfall areas, the presence of gypsum reflects the characteristic (lack of) wetness and often intensive evaporation that was present at the time of formation, or an indication of a brackish water-table (Nettleton et al., 1982).

The main point of interest in relation to the handling and understanding of gypsum is the variation in products of its dehydration. The three principal phases that occur in the system of calcium sulphate-water are:  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  (calcium sulphate

dihydrate otherwise known as gypsum),  $\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$  (calcium sulphate hemihydrate), and  $\text{CaSO}_4$  (calcium sulphate anhydrite or simply anhydrite) (Derr, 1966).

The structure of gypsum consists of parallel layers of  $(\text{SO}_4)^{2-}$  groups strongly bonded to  $(\text{Ca})^{2+}$ . These layers are separated by weak hydrogen bonds between water molecules and neighbouring Ca-O polyhedrons (Derr, 1966). The specific gravity of gypsum has been reported to between 2.3 and 2.5 (Al-Dabbas et al., 2012; Horta & De, 1989; Kuttah & Sato, 2015).

### 2.2 Hydration and solubility

As noted in the previous section, calcium sulphate occurs in three distinct phases and despite their chemical likeness, the absence of hydration in the anhydrite minerals leads to a marked difference in behaviour, due mainly to the difference in attraction and absorption to water molecules and the resulting disturbance to its crystalline structure (Lewry & Williamson, 1994; Solis & Zhang, 2008). As both hemihydrate and dihydrate are both soluble in water, 0.65 g/100 ml and 0.24 g/100 ml respectively (Lewry & Williamson, 1994), dissolution of gypsiferous minerals from geological formations can cause significant subsidence. This is especially problematic in areas where there is active circulation of groundwater that is undersaturated in calcium sulphate, where it is common to encounter underground voids and caverns (Yılmaz, 2001; Yılmaz et al., 2011).

In closed systems, issues related to dissolution can become problematic as saturation is achieved relatively quickly and hence both dissolution and precipitation are possible (Yılmaz, 2001). Areas that experience frequent temperature fluctuations are additionally susceptible to heaving due to the hydration and dehydration of gypsiferous compounds (Yılmaz, 2001). The volume change due to hydration of anhydrite is -9% for a closed system, whereas the dehydration of gypsum results in a +9.9% volume change for a closed system. The volume change can be significantly greater in an open system, where water is allowed to enter and exit the system. For an open system, the volume change due to hydration of anhydrite is +62.6%, whereas the dehydration of gypsum results in a -38.5% volume change (Zanbak & Arthur, 1986).

## 3 MECHANICAL PROPERTIES

### 3.1 Microstructure

The microstructural features developed during the hydration of the gypsum crystals are widely recognised to be a critical factor in determining the strength of the material (e.g. Ludwig & Singh, 1978; Singh & Middendorf, 2007; Yu & Brouwers, 2011). Lewry and Williamson (1994) describe how the strength of the hardened gypsum compound depends on i) the size and shape of the component crystals, ii) the strength of the bond between the crystals, iii) impurities which may form part of the crystals, and iv) the amount of voids in the set mass.

By testing samples of gypsum formed by mixing plaster (hemihydrate) with water in a three-point bending rig, Lewry and Williamson (1994) were able to describe the setting of the paste as a three-stage process, namely; i) a rapid build-up of strength due to the development of an interlocking matrix of dihydrate needles; ii) a drop in strength to approximately 80% of the initial maximum due to the relief of internal stress as needles advance against each other; and iii) a further increase in strength over 15-20 hours reaching a limiting value approximately twice that of stage one. These phases during the setting of gypsum can be interpreted from Figure 1. Lewry and Williamson (1994) explain that the further increase in strength of the gypsum plaster in stage three is due to the loss of lubricating solution between the dihydrate crystals as the specimen dries out, leading to the remaining dihydrate

precipitating from solution between the needles, cementing the crystals together and further increasing the strength of the material.

Interestingly, Lewry and Williamson (1994) concluded that excess water played a critical role in the strength of gypsum after comparing the results of the dry strength tests, samples allowed to dry after casting, with that observed in “wet” test specimens, samples kept under polyethylene film to prevent moisture loss. As shown in Figure 1b, for the wet specimens there is a clear absence of the third phase of setting seen in the “dry” specimens. Yu and Brouwers (2011) also add that the hydration process requires excess water to facilitate the transportation of ions to nucleation sites. At the completion of hydration, excess water occupies space that contributes to voids in the hardened gypsum paste.

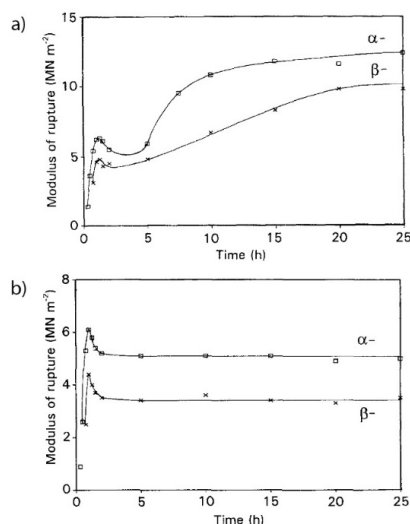


Figure 1. The development of a) “dry” strength and b) “wet” strength of two different gypsum products as the paste hardens (Lewry & Williamson, 1994)

### 3.2 Strength and Stiffness

From the description of the microstructural features, it is evident that the strength and stiffness of a gypsiferous material is derived from the formation of the interlocking crystals and the bonds between them. Since the work of Schiller (1957) on the setting of gypsum plaster, it has been understood that the strength of gypsum paste is related to the amount of water used in the hydration of hemihydrate. Lewry and Williamson (1994) have also noted the strength decreases with increasing porosity and suggested this is a result of porosity produced by the evaporation of the excess water, and that higher strength is associated with the interconnectedness of dihydrate needles.

Many researchers have established that the compressive strength of gypsum varies from the 10 MPa to 100 MPa (e.g. Schiller, 1957; Singh & Middendorf, 2007; Yılmaz, 2010; Yılmaz & Sendir, 2002; Yu & Brouwers, 2011). The variability in the recorded strength of gypsum can be partly explained by understanding the hydration process and resulting microstructural matrix of the hardened paste, and also by the amounts of the various phases in the plaster.

While there has been significant research into the strength of gypsum, testing has been mainly limited to unconfined compressive strength (UCS) tests (e.g. Al-Dabbas et al., 2012; Azam & Abduljawwad, 2000; Yılmaz, 2001; Yılmaz, 2010). Additionally, despite the literature on the physical and mechanical properties, especially those considering the microscopic scale, there does not currently exist any significant research on the partially saturated or fully saturated strength of gypsiferous soils (Yılmaz, 2010).

3.2.1 The effect of water content and wetting-drying cycles on strength parameters

To investigate the variation of UCS for gypsiferous soils with saturation, Al-Dabbas et al. (2012) performed a number of tests on undisturbed soil specimens taken from block samples. In the tests, samples were tested both in dry and soaked states. Different soaking periods were used, varying from a few minutes to a number of days. The average maximum UCS value, in dry conditions was reported to be 11.4 MN/m<sup>2</sup>, while the UCS reduced down to as low as 0 MN/m<sup>2</sup> for samples that had disintegrated as a result of soaking.

Aldaood et al. (2014b) have also reported similar trends in an overall reduction of UCS values with wetting-drying cycles for lime-stabilized gypseous soils. For both the wet and dry states, increasing the number of cycles decreases strength of the material. This is to be expected as there are significant volume changes, and thus structural damage to the sample.

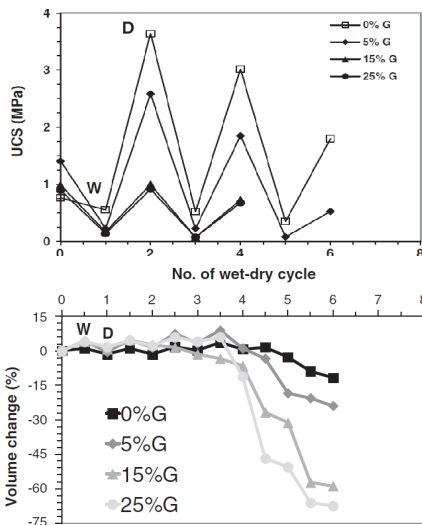


Figure 2. Variation of a) unconfined compressive strength and b) volume with number of wetting-drying cycles for various percentages of gypsum content (Aldaood et al., 2014b)

For gypsiferous rocks, Yılmaz (2010) found that while there was a decrease in UCS values with time for submerged cores, the strength approached a limiting value with 65% strength loss or 35% of the original strength.

3.2.2 Gypsum as an artificial cementing agent

Due to the increasing popularity of cement stabilized soils, there has been a growing interest in the behavior of both naturally and artificially cemented samples. As there are considerable costs and technical difficulties associated with the extraction and storage of high-quality naturally structured soils, researchers have been testing artificially cemented samples (e.g. Ismail et al., 2002). Gypsum plaster is an attractive cementing agent because of its rapid setting and ease of use. Its use to create artificially cemented sands and soft rocks has been widely reported (Huang and Airey, 1998, Ismail et al, 2002). Gypsum cemented sands behave similarly to other artificially cemented sands, however, they have been found to demonstrate higher creep rates than other natural and artificial weak rocks. When plaster is mixed with clays structured samples with significant strength and stiffness are created (Le, 2017).

4 DISCUSSION

It appears contradictory that despite the extensive literature on reducing the negative impact of natural gypsiferous soils, researchers are now investigating the potential use of gypsum in ground stabilization. The focus of these studies has been on the

use of recycled bassanite, a product derived from gypsum waste plasterboard, in ground improvement as a means to eliminate gypsum waste materials, reduce the cost of ground improvement and better meet environmental sustainability requirements.

For more standard cementing agents, such as lime and cement, the engineering behaviour of stabilized soils is well understood to be a result of the formation of primary and secondary cementitious clusters in the soil matrix. The hydration and crystallization process is also clear in gypsiferous samples, but the complex interactions with environmental factors greatly contribute to uncertainties surrounding the strength and durability when using bassanite in ground improvement. The following sections summarize the literature available on these uncertainties.

**Strength:** For admixtures of bassanite and cement/lime, Ahmed (2015) reports that there was a significant increase in compressive strength with increasing amounts of the admixture and curing time. The improvement in strength when bassanite was added was mainly attributed to the potential of bassanite to absorb water from the soil and the strength increase associated with standard cement-mixed soils (Ahmed, 2015). As shown in Table 1, while an increasing ratio of admixture has a significant negative effect on the compressive strength of bassanite-cement stabilized soil, there is actually a slight improvement in strength for admixtures of bassanite-lime which increases with the ratio of bassanite to lime.

Table 1 Effect of the content and ratio of admixture on the UCS of stabilized soil with different curing times (Ahmed, 2015)

| Admixture type | Curing time | Values of unconfined compressive strength, kPa |      |       |                          |      |      |
|----------------|-------------|--|------|-------|--------------------------|------|------|
|                |             | Admixture content, (B-C/L)%                    |      |       | Admixture ratio, (B:C/L) |      |      |
|                |             | 7.5%   | 15%  | 22.5% | 1:1                      | 2:1  | 3:1  |
| B-C            | 3d          | 6  | 322  | 897   | 897                      | 313  | 109  |
|                | 7d          | 12   | 360  | 1260  | 1260                     | 380  | 140  |
|                | 28d         | 20   | 570  | 2018  | 2018                     | 570  | 220  |
| B-L            | 3d          | 53   | 92   | 118   | 118                      | 122  | 124  |
|                | 7d          | 107  | 329  | 364   | 364                      | 370  | 398  |
|                | 28d         | 150  | 1312 | 1900  | 1900                     | 1940 | 1995 |

Similar results were found by Ahmed (2013) whereby there was a significant increase in UCS values with increasing percentage of a 1:1 ratio of bassanite to furnace slag cement admixture. The resulting stabilized soil was also found to have an increased stiffness and a lower strain at failure.

Where there are expansive clays, dehydrated calcium sulphate has been observed to reduce the swell pressures in the ground. This is a result of the clay-anhydrite mixture having a lower water content and higher dry unit weight when compared to clay-gypsum mixtures (Azam & Abduljawad, 2000). Yılmaz and Civelekoglu (2009) determined that by adding up to 5% gypsum to an expansive clay soil, significant improvements can be obtained. Above this amount, improvements are much less significant when compared to costs.

**Durability:** In order to investigate the durability of gypsum cemented soils, samples of soft to very soft clay with an admixture of recycled bassanite and cement or lime were subjected to wetting-drying and freeze-thaw cycles. Soils stabilized with only recycled bassanite were observed to completely lose their strength with cycles of wet-dry and freeze-thaw actions (Ahmed & Ugai, 2011).

For samples of both treated and untreated soil, it was found that there was a decrease of about 10-15% in soil strength with the number of wetting-drying cycles (Kamei et al., 2013). For bassanite-furnace cement mixtures, it was found that while there were decreases in the strength and durability of the samples with wetting-drying cycles, this effect diminished after the third cycle (Kamei et al., 2013). It was also found that the

wetting-drying cycles had no significant effect on the water content, the dry unit weight or the volume change for the bassanite-furnace cement mixture.

Samples of lime stabilized gypsiferous soils subjected to freezing and thawing experienced significant loss in strength with the number cycles. Aldaood et al. (2014a) observed that by the 5th cycle, almost all of the strength had been lost due to volume change and increasing porosity.

In conditions where samples of bassanite-cement and bassanite-lime were continuously submerged, Ahmed and Issa (2014) observed that the amount of admixture had a significant effect on the durability of cement treated samples in comparison with lime treated samples. For samples with increasing amounts of bassanite, durability was observed to decrease. Ahmed and Issa (2014) also reported that samples were significantly affected by soaking during the early stages but had stabilized after 15 days. These results largely agree with those presented by Yilmaz (2010) on gypsiferous rock.

## 5 CONCLUSION

The hydration of gypsum plaster (hemihydrate) when mixed with a range of soils produces well cemented materials with significant strength and stiffness. However, due to its solubility and chemical reactivity the long term durability of gypsum cannot be assured. Thus, while gypsum has potential for use in ground improvement further site specific studies are recommended to ensure it will produce the intended benefit.

There is some evidence to suggest that recycled gypsum in combination with lime can provide effective ground improvement.

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