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Review

# Soil stabilization with gypsum: A review

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ABSTRACT

The demand for sustainable ground improvement methods is rising as urban development expands into areas with challenging soil conditions. Traditional approaches, mostly reliant on cement and lime, contribute significantly to anthropogenic greenhouse gas emissions. Researchers, therefore, are constantly searching for new environmentally friendly stabilization methods to improve the engineering properties of soils. One alternative material used for this purpose is gypsum in its hydrated and dehydrated (hemihydrate/anhydrate) states. Not only can natural gypsum be used for ground improvement but also industrial waste and by-products (e.g. used or waste plasterboard, phosphogypsum, flue gas desulfurization gypsum, titanium dioxide production gypsum by-product) can be recycled, and used. Successful application of these materials could lower the carbon footprint of the construction industries (by reducing the consumption of cement and lime) as well as other industries (by recycling their waste and by-products). However, using gypsum presents challenges due to its moderate water solubility, the formation of swelling clay minerals under certain conditions, and the tendency of dehydrated gypsum to swell upon exposure to water, to name a few. Furthermore, the mechanisms leading to the improved behavior of the gypsum-treated soils are complicated, which has resulted in some seemingly contradictory results reported in the literature. This study presents a systematic and extensive review of the observed behavior of gypsum-treated soils and the different mechanisms causing the observed behavior. The research gaps and the required future steps to address these gaps have been identified and reported. A summary of the effect of gypsum treatment on the mechanical and engineering properties of soils, including unconfined compressive strength (UCS), California Bearing Ratio (CBR), swell potential, Atterberg limits, optimum moisture content (OMC), maximum dry density (MDD), durability, and environmental effects has also been presented.

## 1. Introduction

As the world's population continues to grow, and with the limited space in urban areas, civil infrastructures are expanding into areas with less-than-desirable ground conditions. Consequently, the demand for ground improvement projects to accommodate these civil infrastructure expansions is simultaneously increasing. Ground improvement could have different objectives, and depending on the project, usually one or more of these objectives are sought. Typical objectives of ground improvement methods include increasing shear strength and bearing resistance, increasing density, decreasing permeability, minimizing deformations (settlement, heave, distortions), increasing drainage, accelerating consolidation, decreasing imposed loads, providing lateral stability, increasing liquefaction resistance, and transferring embankment loads to more competent subsurface layers (FHWA, 2017). For instance, soils and soft geomaterials have low fracture toughness values and are prone to cracking. This low inherent fracture resistance of soils and soft rocks coupled with complex field loading conditions leads to cracking failures in geotechnical structures such as pavements, dams, and slopes (Hamidi et al., 2017; Aliha et al., 2022; Cheng et al., 2022). Ground improvement methods can be used to enhance the fracture resistance of soils and soft geomaterials by increasing the fracture-filling ratio (which reduces the interconnected fracture voids and relative surface occupied by fluid) or increasing their tensile strength by cementation (Mohammad Aliha et al., 2021). Many of these objectives, particularly increasing the shear and tensile strength, bearing resistance, controlling deformations, and increasing liquefaction

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resistance, are traditionally achieved by adding grouts and other types of cement/lime-based binders (Afrin, 2017; FHWA, 2017; Amhadi and Assaf, 2019). Cement and lime manufacturing is responsible for more than 4% of total anthropogenic $CO_2$ emissions in the world and, which is considered as one of the construction industry's primary contributors to greenhouse gas (GHG) emissions (Spaulding et al., 2008). To reduce the GHG emissions of the construction industry, researchers are continuously searching for alternative sustainable ground improvement methods. For instance, the potential for microbially induced calcite precipitation, geopolymers, industrial waste, recycled material, and natural substances to be used as cementing materials is being extensively studied. One of the substances that could be used to reduce the amount of cement and lime used in ground improvement methods but has received relatively less attention in recent years is gypsum ($CaSO_4.2H_2O$) and its associated (dehydrated) minerals hemihydrate ($CaSO_4.1/2H_2O$), also known as bassanite or simply plaster) and anhydrite ($CaSO_4$). Typically, natural deposits predominantly consist of one of these minerals while containing some amounts of other associated minerals as well. In this paper, for simplicity, the term gypsum is used to generally represent a mix of gypsum-hemihydrate-anhydrite unless otherwise specified.

Gypsum in its natural state (gypsum mineral), as recycled and industrial waste (e.g. used or waste plasterboards), or as phosphate industry and thermal power plants by-product (e.g. phosphogypsum, flue gas desulfurization gypsum) has the potential to be used as a cementing/adhesive material instead of cement for ground improvement. Hence, using gypsum as a binder not only reduces the amount of cement and lime used in ground improvement methods but also helps reduce and recycle the waste and byproducts of other industries.

On the other hand, gypsum is moderately water-soluble, and anhydrite, its associated anhydrous mineral, changes volume and swells when exposed to water (Yılmaz, 2001). Strength loss due to dissolution along with swelling due to wetting should be considered in the strength limit and service limit designs of soils treated with gypsum/anhydrite as well as gypseous soils, i.e. soils that naturally contain gypsum/anhydrite. These challenges are probably one of the reasons that ground improvement using gypsum/hemihydrate/anhydrite, as a cementing material has not received much attention recently. Considering their effectiveness in improving the mechanical properties of soils (Kuttah and Sato, 2015), and their broad sustainability advantages, it seems necessary to fully understand the benefits and shortcomings of this method and to identify the future research needs to fully take advantage of this approach. To achieve this goal, a systematic review of the use of gypsum as a cementing material in ground improvement methods and the behavior of gypsum-stabilized soils is presented here. Applicability, advantages, and disadvantages of using gypsum as a cementing material in ground improvement methods, and future research steps are identified.

## 2. Basic mechanisms leading to improved engineering/mechanical properties of chemically stabilized soils

Adding cementitious and pozzolanic material to the soil modifies soil behavior through four mechanisms, i.e. cation exchange, particle restructuring (flocculation and agglomeration), cementitious hydration, and pozzolanic reactions.

In the cation exchange mechanism, monovalent cations on clay particles (e.g. sodium and potassium) are replaced by higher valence cations such as calcium. This exchange leads to a thinner diffused layer around clay particles, which in turn reduces the plasticity of clayey soils. Eq. (1) (Mitchell and Soga, 2005) shows the relationship between the thickness of the double layer ($x$ in the equation is considered to be a measure of the double layer thickness) and different parameters of the soil and pore water, including the cation valence, $\nu$:

$$x = \left(\frac{\varepsilon_0 DkT}{2n_0 e^2 \nu^2}\right)^{1/2} \tag{1}$$

where $\varepsilon_0$ is the permittivity of vacuum, $D$ is the dielectric constant of the medium, $k$ is Boltzmann constant (the gas constant per molecule) ($1.38 \times 10^{-23}$ J K$^{-1}$), $T$ is the temperature (K), $n_0$ is electrolyte concentration and e is the electronic charge ($1.602 \times 10^{-19}$ C) . Eq. (1) clearly shows that the thickness of the double layer is inversely proportional to the cation valence and replacing the monovalent cation on the clay particles with a higher valence decreases the thickness of the diffused layer.

The shrunk diffused layer also allows for flocculation and agglomeration, which results in clot-like masses and larger aggregate-like particles, improving the texture of the particles. This process leads to a decrease in the amount of fine particles present and, as a result, reduces the specific surface area (Ijaz et al., 2022).

Cementitious hydration and pozzolanic reaction products bind soil particles together (Adaska and Taylor, 2020). Hydration is a rapid chemical reaction between water and cementitious contents like calcium oxides (Eq. (2)). Dissolution of the binder particles leads to the precipitation of C—S—H and C-A-H gels that act as a binder in the soil matrix. The heat released during the reaction dries the soil while the increased calcium ion concentration raises pH, enabling pozzolanic reactions:

$$CaO + H_2O \rightarrow Ca(OH)_2 + \text{Heat} \tag{2}$$

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2(OH)^- \tag{3}$$

The pozzolanic reaction is a long-term reaction that occurs between calcium hydroxide and silicates or aluminates. When calcium hydroxide, which is produced when cement or lime hydrates react with dissolved silica ($SiO_2$) and alumina ($Al_2O_3$), forms additional calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) cementitious gels that bind soil particles:

$$\left.\begin{array}{l} Ca^{2+} + 2(OH) + SiO_2 \rightarrow C{-}S{-}H \\ Ca^{2+} + 2(OH) + Al_2O_3 \rightarrow C{-}A{-}H \end{array}\right\} \tag{4}$$

Through the pozzolanic reactions and hydration, a hardened cementitious soil composite is formed. The initial stage of hydration provides a strong foundation for pozzolanic reactions. These chemical processes enhance problematic soils by bonding particles, reducing compressibility and permeability, and increasing shear strength and durability (Bergado et al., 1996; Sargent, 2015).

Similar to traditional chemical stabilizers such as lime and cement, adding gypsum modifies the soil properties through cation exchange and particle restructuring, as well as bonding soil particles together. The formation of cementitious hydration products, i.e. calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH), has also been reported in the gypsum-treated clays (Latifi et al., 2018). The mechanical behavior of gypsum-treated soils also depends on many other factors including, the treated soil type, grain size distribution, moisture content, and plasticity of the fine particles. The effects of adding gypsum to different soils on their mechanical behavior are summarized in the following sections.

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## 3. Unconfined compressive strength (UCS)

### *3.1. UCS of soils treated with gypsum of soils treated with gypsum*

Several studies have investigated the effects of gypsum as an additive on the UCS of different soils (Yilmaz and Civelekoglu, 2009; Ahmed et al., 2011; Kamei et al., 2013; Kobayashi et al., 2013; Sivapullaiah and Jha, 2014; Jha and Sivapullaiah, 2016; Kiliç et al., 2016; Latifi et al., 2018; Al-Adili et al., 2019; Hastuty, 2019; Khan, 2019; Subramanian et al., 2019; Al-Adhamii et al., 2020; Ma et al., 2020; Al-Alawi et al., 2020, 2023; Rizki Abdila et al., 2020; Aldaood et al., 2021; Maichin et al., 2021; Mustapa et al., 2021; Zha et al., 2021; Dutta and Yadav, 2022; Ebailila et al., 2022; Wu et al., 2022; Shivanshi and Akhtar, 2023).

Some study results that reported the effects of adding different amounts of gypsum on the UCS of fine-grained soils (mostly clayey soils) after 7 d and 28 d of curing time are summarized in Figs. 1 and 2, respectively. Two different trends are observed in each figure. One trend shows the UCS of the treated clayey soils increases continuously as more gypsum is added to the soil, while the other trend indicates an optimum gypsum content, after which the UCS of the treated clayey soil either remains the same or decreases. This optimum gypsum content for different clayey soils seems to range from around 7%–15% of gypsum by weight. The improved UCS of gypsum-treated clays has been mostly attributed to the cation exchange capacity of clays (Yilmaz and Civelekoglu, 2009; Ahmed et al., 2011; Jha and Sivapullaiah, 2016; Khan, 2019; Zha et al., 2021). The cation exchange seems to be the main contributing factor in improving the UCS of clays, which means that the optimum gypsum content can be considered as the amount of gypsum required to satisfy the cation exchange capacity of the clay particles. Since different clay minerals have different cation exchange capacities, ranging from 1 meq/100 g in Dickite up to 150 meq/100 g in Vermiculite and Nontronite (Mitchell and Soga, 2005), the optimum gypsum content depends on the types and the percentage of clay minerals in the soil. It can therefore be expected that, in general, the higher the plasticity of the clayey soils, the higher the optimum gypsum content required to achieve the highest UCS. The results of the published experimental studies seem to be in good agreement with this hypothesis. Taking a closer look at the results of the studies that showed a continuous increase in the UCS of the treated clayey soils without an optimum, it can be seen that the soils treated in these studies were very high plasticity expansive soils (e.g. bentonite). It could be argued that these studies possibly did not continue their experiments to reach the cation exchange capacity of their soils and, therefore, did not find an optimum gypsum content. It is also worth mentioning that the cation exchange capacity of soils changes with temperature, pressure, soil-solution composition, and soil-solution ratio (Sposito, 2016). If solid waste gypsum is used instead of natural gypsum, certain properties of the gypsum waste could change the cation exchange capacity of clays and affect the stabilization results. For example, Zha et al. (2021), showed that the solid waste gypsum produced as a byproduct of titanium dioxide production is a weakly alkaline residue. Adding these solid wastes to clayey soils in the presence of water creates a slightly alkaline environment, which increases the cation exchange rate and the cation exchange capacity of the clay particles. Their results are included in Figs. 1 and 2. As can be seen in these figures, their results do not reveal any optimum gypsum content, which is probably due to the high cation exchange capacity of the expansive clays used in their experiments. The expansive clays naturally have a high cation exchange capacity, and the alkaline environment produced by the solid waste gypsum used in their experiments probably increased the capacity even further.

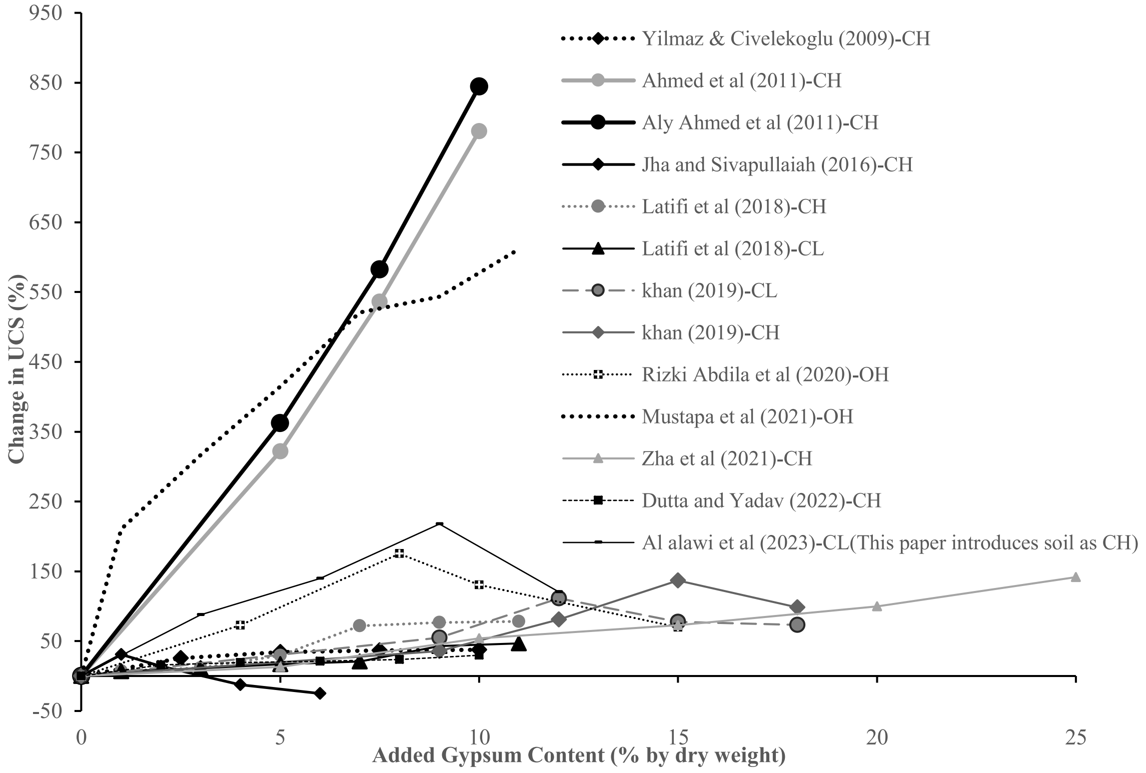

**Fig. 1.** Effects of adding gypsum on the UCS of fine-grained soils (mostly clayey soils) after 7 days of curing period.

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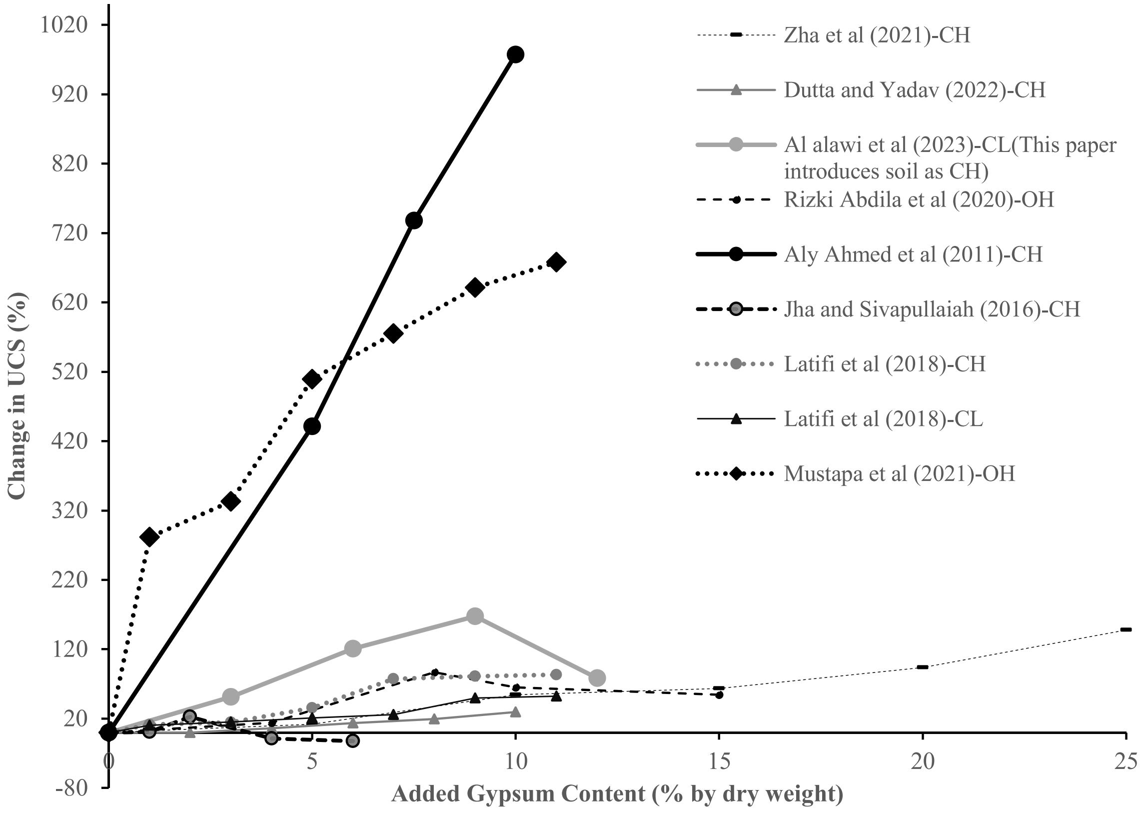

**Fig. 2.** Effects of adding gypsum on the UCS of fine-grained soils (mostly clayey soils) after 28 d of curing period.

Therefore, an optimum gypsum content was not achieved even after adding up to 25% by weight of gypsum.

In addition to the cation exchange, the formation of cementitious hydration products such as (CSH) and (CAH) has also been reported in gypsum-treated clays (Latifi et al., 2018; Zha et al., 2021). The CSH and CAH can be produced through the pozzolanic reaction if the calcium from gypsum reacts with soluble alumina and silica from clay in the presence of water. The produced calcium silicate and calcium aluminate hydrates could increase the UCS of the treated clays. Latifi et al. (2018), for example, conducted a series of experiments where they added varying amounts of gypsum to kaolinite (low-plasticity clay) and bentonite (high-plasticity clay) soils to study the stabilization effects of gypsum. Their results confirmed the formation of these cementitious hydration products in their gypsum-treated samples. The formation of cementitious hydration products after the cation exchange capacity is reached could be another reason that the UCS of some gypsum-treated clays continues to increase without an optimum. Latifi et al. (2018), results also showed that gypsum treatment changed the soil's structure from a dispersed structure in the untreated state to a flocculated structure after the treatment. As explained before, the cation exchange mechanism is responsible for this change in the structure of the soil. It is not clear, however, whether the two mechanisms, i.e., formation of cementitious hydration products and cation exchange, are working concurrently. It is possible that one mechanism is dominant at some stages and the other mechanism becomes more dominant at later stages. For example, it is possible that the cation exchange is the dominant mechanism at first until the cation exchange capacity is reached, after which the formation of cementitious hydration products becomes the main stabilizing mechanism. If the formation of cementitious hydration products is inhibited for any reason, the increase in the UCS of the treated clays stops after reaching the cation exchange capacity (as seen in some experimental results). Further investigation is required to understand these mechanisms and determine the possible inhibitory conditions preventing the formation of cementitious hydration products.

Previous discussion offered some explanation about the existence of an optimum gypsum content in some soils. It is unclear, however, why in some cases the UCS of the treated soil does not stay constant and starts to decrease after reaching the optimum gypsum content. Although the mechanisms causing the decrease in the UCS after reaching the optimum gypsum content are not fully understood currently, it could be due to a combination of a few factors. Gypsum particles are soft (hardness of 2 Mohs Hardness Scale) and inert (as compared to plat-like clay particles where electrical forces between the particles significantly influence their behavior (Helle et al., 2016)). When increasing the gypsum content in a clay-gypsum mixture, the excess cations in the solution, after cation exchange capacity is reached, recrystallize to form gypsum particles during the curing period. These soft particles are coarse grain (>75 μm), and the surface forces that previously held fine-grained clay minerals together are not effective anymore. Furthermore, gypsum particles formed by recrystallization are more regular in shape compared to the natural soil particles (Zha et al., 2021) leading to looser packing, larger pore sizes, and weaker structure. The crushing of these low-hardness gypsum particles also contributes to the reduced strength. Therefore, the UCS of the clay-

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gypsum mixture decreases (compared to the UCS of samples treated with the optimum gypsum content) after the cation exchange capacity of the clay minerals is reached. It is worth mentioning that gypsum in lower concentrations could also act as a cementing agent, bonding the soil particles together and filling the pores, which increases the UCS of the soil. However, as the concentration of gypsum increases to a point where the gypsum particles are not cementing and filling agents anymore, they start to become the controlling constituent of the soil skeleton. The soil skeleton with gypsum particles as its primary constituent is weaker than that of a soil skeleton with clay particles as its primary constituent and gypsum as a bonding and filling agent. Therefore, the UCS of gypsum-treated soil starts to decrease after the optimum gypsum content is reached, but it will still be higher than that of untreated soil. It should be noted that these possible mechanisms are not well studied and further investigations are needed to better understand the micro and macro behavior of gypsum-treated clay soils, especially after the optimum gypsum content is reached.

Very few studies have investigated the effects of adding gypsum on the UCS of sandy soils. This is probably because of the relatively high solubility of gypsum in water. Unlike fine-grained material, where cation exchange is the main mechanism for improved behavior of the treated soil, the stabilizing effect of gypsum in coarse-grained soils is primarily through the bonding of soil particles together by gypsum similar to cement. Long-term exposure to water level changes, e.g. wetting-drying cycles, may dissolve the bonding gypsum in the treated soil, leading to loss of strength. Nevertheless, gypsum can still be used for the stabilization of coarse-grained soils when dissolution is not a concern, e.g. in some arid areas. Al-Alawi et al. (2020), for example, investigated the change in the UCS of Sabkha soil, which is a poorly graded (SP) from the arid area of Oman. They mixed 3%, 6%, 9%, and 12% by weight of gypsum with the soil and concluded that the 28 d UCS of the soil increased by about 33% after adding up to 6% by weight of gypsum. Adding gypsum above 6% by weight reduced the UCS of the treated gypsum compared to the optimum 6% gypsum, but it was still 12% higher than the untreated soil (Al-Alawi et al., 2020). In coarse-grained soils, the optimum gypsum content can probably be related to the maximum amount of gypsum that can be added to the soil before the gypsum particles become the primary constituent governing the behavior of the treated soil. As explained before, gypsum particles being the primary constituent leads to lower UCS (compared to the soil treated with the optimum gypsum content) due to particle crushing and weaker soil skeleton. In addition, it is known that changing the gypsum content changes the optimum moisture content (OMC) of the soil-gypsum mixture (see Fig. 3). Therefore, if the OMC is not measured for each gypsum content tested and all the UCS samples were prepared at the same OMC calculated from one test (OMC of untreated soil or soil treated with a specific gypsum content), the UCS of samples with different gypsum contents cannot be compared. Some of the cited studies did not measure the OMC of the treated soils for every gypsum content, and that could be another reason for the observed decrease in the UCS of the treated soil after optimum gypsum content was reached. This concept can be explained using an example shown in Fig. 3. Imagine the OMC is only measured for soil with 10% added gypsum, presented by the black curve in the figure. When the next increment of gypsum is added (say 12% gypsum), the OMC of the treated soil could be less than that of the soil with the 10% added gypsum, as shown in the figure. Now, if the soil with 12% gypsum (gray) is compacted according to the OMC of the soil with 10% gypsum (black), it is actually compacted on the wet-side of its own OMC. Soils compacted on the wet-side have significantly lower strengths (UCS) compared to the soils compacted at OMC or on the dry-side. Therefore, the UCS of the gray soil (higher gypsum content) could appear less than that of the black soil (lower gypsum content) because it was compacted on the wet-side while the black soil was compacted at optimum. Therefore, this reduced strength at higher gypsum content is erroneous and is caused by compacting on the soil on the wet-side of the compaction curve. If both soils were compacted at their respective OMCs, the results could have been different.

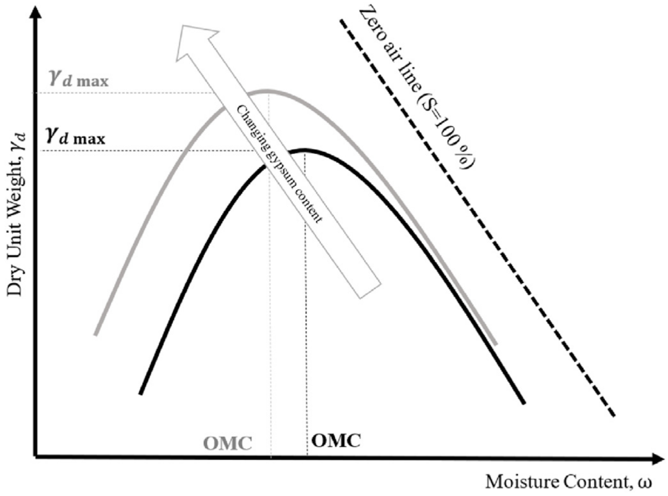

**Fig. 3.** Compaction plot of two hypothetical soils treated with different gypsum contents.

### 3.2. UCS of soils treated with gypsum and other additives

Gypsum has been used not only as the sole stabilizing agent but also as a complementary additive along with cement, lime, and other stabilizers (Ahmed et al., 2011; Kamei et al., 2013; Sivapullaiah and Jha, 2014; Kiliç et al., 2016; Al-Homidy et al., 2017; Maichin et al., 2021; Aldaood et al., 2021; Ebailila et al., 2022; Wu et al., 2022; Shivanshi and Akhtar, 2023). Their results generally indicate that the UCS of soils treated with gypsum plus cement and lime is somewhere between the UCS of soils treated with gypsum alone and the soils treated with cement and/or lime alone. Figs. 4 and 5 summarize the observed effects of adding different amounts of gypsum on the UCS of fine-grained soils mixed with other additives after 7 d and 28 d of curing, respectively. The trends observed in these plots are similar to those observed in the stabilization efforts using gypsum as the only additive shown in Figs. 1 and 2. Whether the gypsum is used as the sole stabilizer or as a complimentary additive, the observed increase in the UCS of the treated samples is more pronounced in high plasticity and expansive clays compared to low plasticity soils. UCS increases of up to around 950% are reported for high plasticity soils, whereas the increase in low plasticity soils is typically around 50% to around 200%.

One unique and very interesting behavior was reported by Kiliç et al. (2016) as shown in Figs. 4 and 5. They reported that adding 1.5% by dry weight of gypsum and 1.5% by dry weight of lime (a total of 3% additives) to the high plasticity clay samples tested in their study decreased the 28-d UCS of the treated soil by about 50% compared to the untreated soil. However, after adding 3% by dry weight of gypsum and 3% by dry weight of lime (a total of 6% additives), the 28-d UCS of the treated soil increased by about 50% compared to the untreated soil. Kiliç et al. (2016) did not offer any

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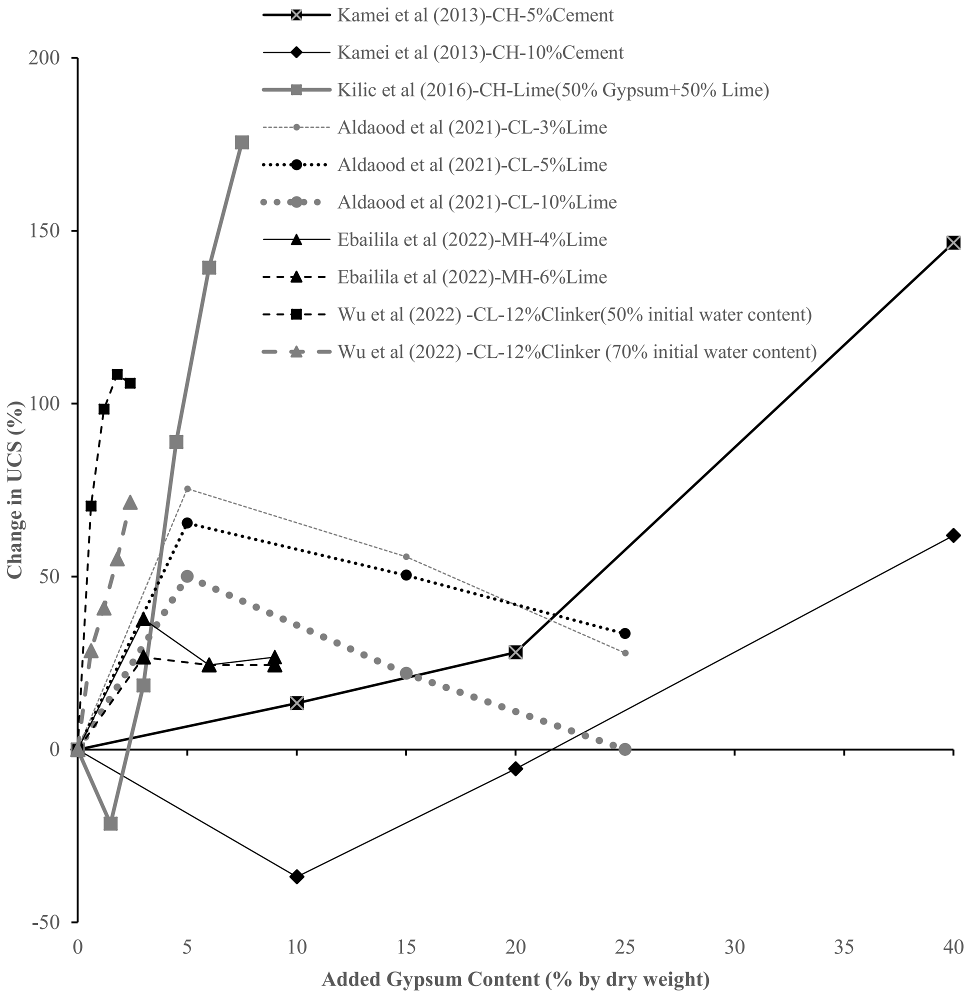

**Fig. 4.** Effects of adding gypsum along with other additives on the UCS of fine-grained soils (mostly clayey soils) after 7 d of curing period.

explanations for the initial decrease in the UCS of the treated soil, and to the best of the authors' knowledge, such behavior has not been reported by other researchers. This could be an important factor in the design of soil improvement projects and needs to be further investigated.

## 4. California Bearing Ratio (CBR)

### 4.1. CBR of soils treated with gypsum

Several studies have investigated the effects of adding gypsum to soil on their CBR (Razouki and Al-Azawi, 2003; Razouki and Kuttah, 2006; 2008; Ismail and Hilo, 2008; Bhardwaj and Kumar, 2019; Kurniawan et al., 2020; Al-Alawi et al., 2020, 2023; Edora and Adajar, 2021; Maichin et al., 2021; Eisa et al., 2022). The observed effects of adding different amounts of gypsum on the CBR of soils after curing under soaked and unsoaked conditions are summarized in Fig. 6.

As shown in Fig. 6, the change in the CBR of the treated soils follows a similar trend to the observed change in the UCS of treated samples. The data presented in Fig. 6 also indicates that adding gypsum has a more noticeable effect on the soaked CBR of the treated soils compared to the unsoaked CBR. In other words, the increase observed in the CBR of the gypsum-treated soils under soaked conditions is higher than the increase observed in the CBR of the gypsum-treated soils under unsoaked conditions. This should not be confused with the relationship between the unsoaked CBR and soaked CBR of gypsum-treated (or gypsiferous) soils. The soaked CBR of gypsiferous soils is generally lower than their unsoaked CBR. The data in Fig. 6, however, shows that adding gypsum improves the soaked CBR of the treated soils more than it improves their unsoaked CBR. The absolute values of the soaked CBR of the treated soils were still lower than their unsoaked CBR values, as reported in the original papers used to develop the plot in Fig. 6.

Some researchers have studied the relationship between the unsoaked CBR and soaked CBR of gypsum-treated soils and gypsiferous soils found in semiarid areas such as the Middle East, Spain, North Africa, Southern Central Australia, and the Western USA (e.g. (Fekpe, 1989; Razouki and Kuttah, 2006)). Fekpe (1989), developed an equation to predict the soaked CBR of the gypsum-treated and gypsiferous soils from their unsoaked CBR values. Their equation did not account for the surcharge load effects and was only applicable to coarse-grained soils. Building on this equation, Razouki and Kuttah (2006) developed a more general equation applicable to both fine-grained and coarse-grained soils, taking into account the effects of the surcharge loads used in the CBR tests:

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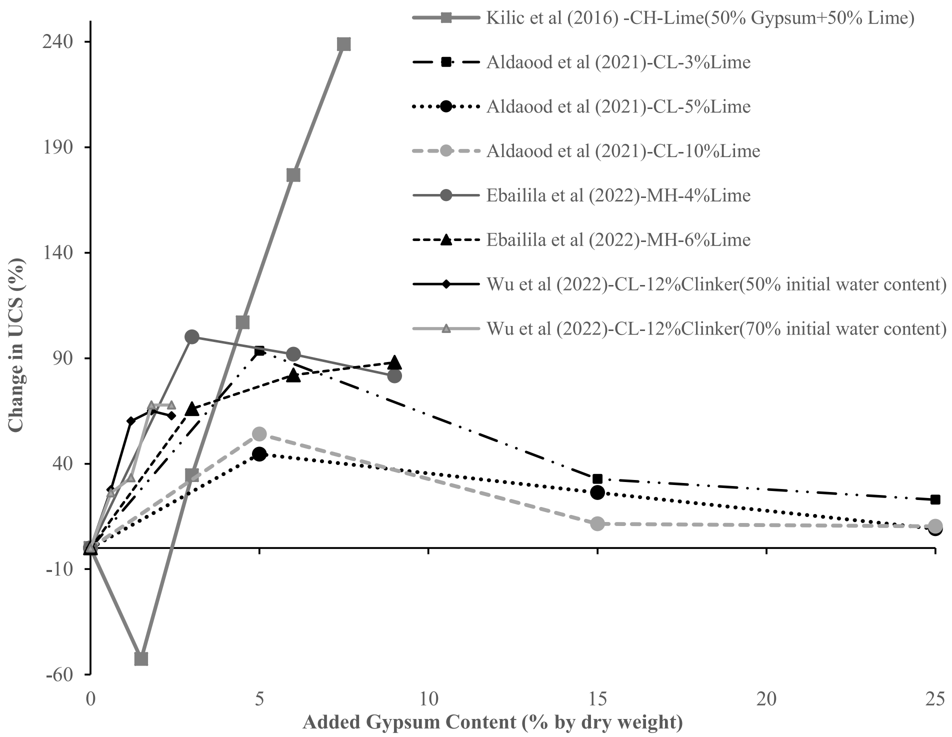

**Fig. 5.** Effects of adding gypsum along with other additives on the UCS of fine-grained soils (mostly clayey soils) after 28 d of curing period.

$$\mathrm{CBR_s}/\mathrm{CBR_u}=\left[\frac{7200(T+4)}{(T+1)(T+180)}+0.02\mathrm{L}+\left(\frac{95}{L}\right)^4\right]\times\left(\frac{65}{P+G}\right)(\mathrm{For}\,T\geq4) \tag{5}$$

where $L$ is the applied surcharge load (N), $T$ is the soaking period (days), $P$ is the fine fraction of the soil (%), i.e. the percent passing sieve No. 200., and $G$ is the initial gypsum content (%).

### 4.2. CBR of soils treated with gypsum and other additives

Several researchers have investigated the effects of adding gypsum along with other additives on the CBR of soils (Bhardwaj and Kumar, 2019; Yuvan et al., 2019; Edora and Adajar, 2021; Maichin et al., 2021). The results of their investigations have been summarized in Fig. 7. As can be seen in the figure, unlike other results discussed so far, no optimum gypsum content has been reported when gypsum is used as a complementary additive along with other stabilizers. It should be noted, however, that lower percentages of gypsum (up to 5 % with only one case where 15% gypsum was added) have been used in these studies. The optimum gypsum contents observed in previous plots are typically between 5% and 10%, with some even as high as 15%. As discussed before, even higher optimum gypsum contents are possible, especially in highly plastic and expansive clays. It is, therefore, necessary to continue such experiments to higher gypsum percentages to determine if an optimum gypsum content exists when gypsum is used as a complementary additive along with other stabilizers. Furthermore, very interesting results have been reported by Yuvan et al. (2019), as can be seen in Fig. 7. They used gypsum as a complementary additive along with waste plastic to improve the CBR of black cotton soil. Their results showed that adding gypsum and plastic slightly increases the unsoaked CBR of the treated soils but decreases the soaked CBR of the treated soil. No explanation was offered by the authors for this observed behavior. Further investigation is recommended to understand the mechanisms causing this behavior.

## 5. The swell potential

### 5.1. The swell potential of soils treated with gypsum

Several studies have investigated the effects of adding gypsum to soil on their swell potential (Azam and Abduljauwad, 2000; Razouki and Al-Azawi, 2003; Ameta et al., 2007; Kousa; Jaksa, 2010; Kiliç et al., 2016; Bhardwaj & Kumar, 2019; Khadka et al., 2020; Kurniawan et al., 2020; Al-Hokabi et al., 2021; Toksöz Hozatlıoğlu and Yılmaz, 2021; Zha et al., 2021 Ebailila et al., 2022; Eisa et al., 2022). Fig. 8 summarizes the results of a few studies that reported the observed changes in the swell potential of clayey soils after adding gypsum. As can be seen in the figure, adding gypsum reduces the swell potential of expansive clays by up to 70%. The swelling properties of soils are strongly related to their cation exchange capacity. Adding gypsum to clays results in the replacement of the monovalent cations on clay particles by calcium, which in turn reduces the swell potential of these expansive soils. The maximum reduction in the swell potential is achieved when the required amount of gypsum to satisfy the cation exchange capacity of the clays is added to the soil. Contrary to the UCS and CBR of gypsum-treated soils that decreased when more than optimum gypsum content was added (as discussed before, possibly due to particle crushing and weaker soil skeleton), adding gypsum above the optimum content does not change the swell potential of the soil and the swell potential stays constant. This is because particle

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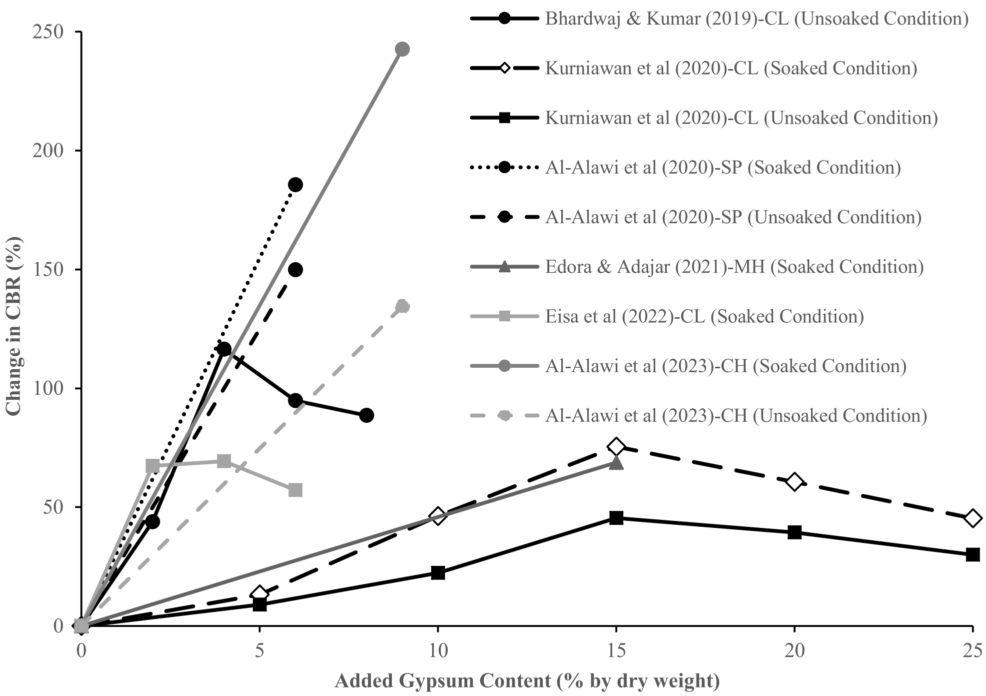

**Fig. 6.** Effects of adding gypsum on the CBR of soils under soaked and unsoaked conditions.

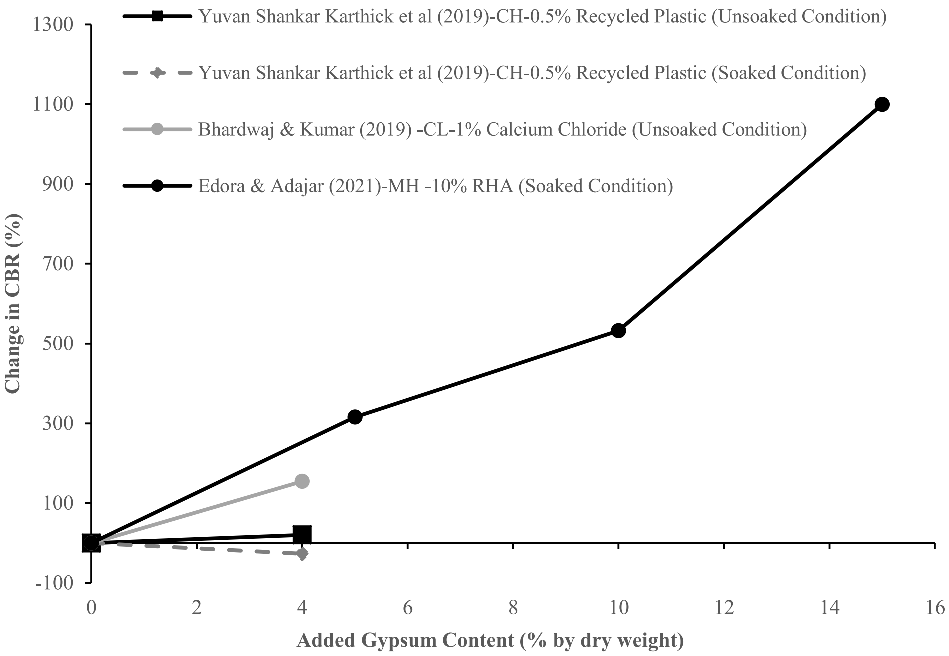

**Fig. 7.** Effects of adding gypsum along with other additives on the CBR of soils under soaked and unsoaked conditions.

crushing is not a concern in the swelling process, and soil's macrostructure (skeleton) does not significantly contribute to the swelling behavior of soils, i.e. soil composition, type of clays, and their cation exchange capacities govern the swell potential of soils. Unlike other data presented in Fig. 8, the results of experiments conducted by Zha et al. (2021) show a slower rate of swell potential reduction at lower added gypsum concentrations (up to 10% added gypsum), but the swell potential reduction rate increased significantly after 10% added gypsum. Their results also do not appear to show an optimum gypsum content. The change in the rate could be because of the fact that Zha et al. (2021) used solid waste gypsum (titanium gypsum, which is a by-product of titanium oxide production) instead of pure gypsum. As explained before, the specific

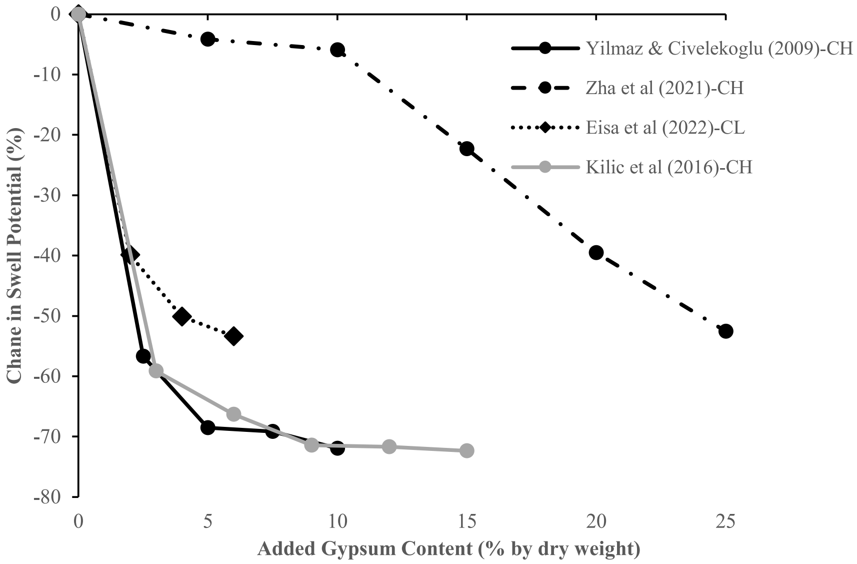

**Fig. 8.** Effects of adding gypsum on the swell potential of soils.

properties of the gypsum waste could change the cation exchange capacity of clays and affect the stabilization results.

### 5.2. The swell potential of soils treated with gypsum and other additives

The effect of gypsum as an additive along with other soil stabilizers on the swell potential of soil has also been studied by multiple researchers (Ameta et al., 2007; Kiliç et al., 2016; Bhardwaj and Kumar, 2019; Khadka et al., 2020; Al-Hokabi et al., 2021; Ebailila et al., 2022). A summary of some of these studies is shown in Fig. 9. While some of the results are similar to the behavior of soils treated with gypsum as the sole stabilizer, some interesting observations are noticed in this plot. First, adding 1% calcium chloride along with the gypsum causes the swell potential of the treated soil to increase after the optimum gypsum content is reached. Second, the addition of gypsum and lime together seems to increase the swell potential of expansive soils under soaked conditions. These observations can be related to the excessive calcium ions introduced to the soil-solution mix by simultaneously adding gypsum and lime or gypsum and calcium chloride to the soil. The gypsum dissolution releases sulfate ions, which then react with alumina from the clay and the excess calcium in the solution to form ettringite (Ebailila et al., 2022). This phenomenon has also been reported in the stabilization of high sulfate-bearing soils (Adeleke et al., 2022). The newly formed ettringite is a needle-shaped expansive crystalline mineral with a high specific surface area and unsatisfied charges. This newly formed expansive mineral

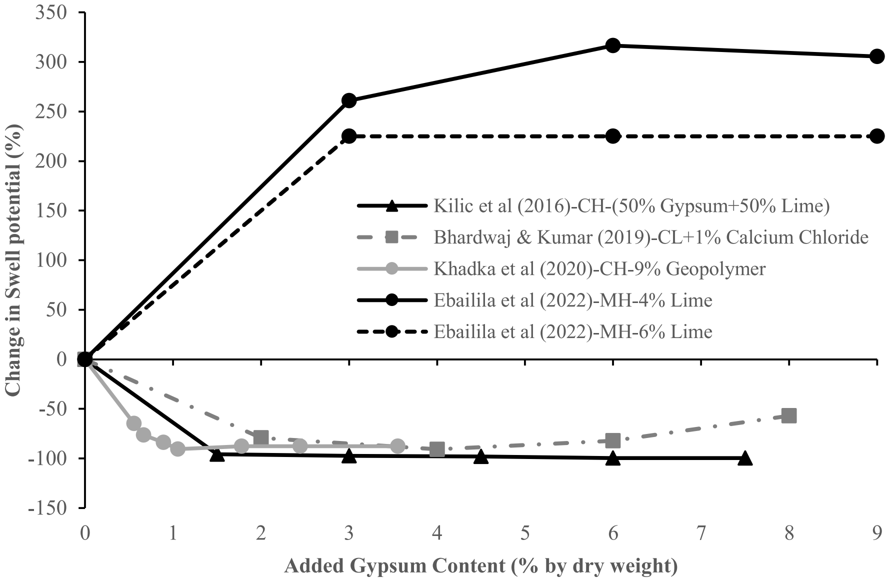

**Fig. 9.** Effects of adding gypsum along with other additives on the swell potential of soils.

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then absorbs water and expands, causing an increase in the swell potential of the treated soils (Ebailila et al., 2022). However, the same additives, i.e. gypsum and lime, under unsoaked conditions improve (decrease) the swell potential of the treated soils as shown by the results of Kiliç et al. (2016) shown in Fig. 9. This is because, without the soaking condition and unavailability of enough water, the formation of ettringite is limited, and the moderate amount of newly formed ettringite minerals mostly fills the pores of the soil. Therefore, under unsoaked conditions, ettringite formation not only does not increase the swell potential of the soils but also helps increase the strength properties, such as the UCS of the treated soil, by filling the pores and increasing the interlocking of soil particles.

## 6. Compaction properties

### 6.1. Compaction properties of soils treated with gypsum

Several studies have investigated the effects of adding gypsum to soil on their compaction (moisture-density) properties, i.e. Maximum dry density (MDD), and Optimum moisture content (OMC) (Razouki et al., 2008; Ahmed et al., 2011; Kobayashi et al., 2013; Kamei et al., 2013; Aldaood et al., 2014, 2021; Sivapullaiah and Jha and Sivapullaiah, 2016; Latifi et al., 2018; Al-Adili et al., 2019; Bhardwaj and Kumar, 2019; Hastuty, 2019; Khan, 2019; Al-Adhamii et al., 2020; Al-Alawi et al., 2020; Zha et al., 2021; Maichin et al., 2021; Dutta and Yadav, 2022; Eisa et al., 2022; Wu et al., 2022; Shivanshi and Akhtar, 2023). Figs. 10 and 11 summarize the results of some of these studies investigating the effects of adding gypsum to soils on their OMC and MDD, respectively. As can be seen from the data presented in these figures, adding gypsum can increase or decrease both MDD and OMC of the treated soils. As discussed before and shown by Eq. (1) (Mitchell and Soga, 2005), adding gypsum to clayey soils leads to cation exchange and increased electrolyte concentration in the pore water, which in turn suppresses the thickness of the double diffuse layer. The suppressed diffuse layer results in the reduction of interparticle repulsion forces, which allows the particles to flocculate. The pore volume of the flocculated structure is higher than the pore volume of the untreated soil (which has a more dispersed structure). Therefore, the flocculated structure has a larger pore volume and a lower density. The OMC and the MDD are inversely correlated, and therefore, when the dry density decreases, typically, the OMC increases possibly due to the larger void volumes that can be filled with water (Kamei et al., 2013). On the other hand, when non-plastic (and sometimes even low-plasticity) soils, such as in the case reported by Hastuty (2019), or sand and clay mixtures, such as in the case reported by Eisa et al. (2022), are treated with gypsum, the finer gypsum particles fill the pores of the treated sample increasing the density of the treated soils. Overall, the dominant trend appears to be that adding gypsum decreases the MDD and increases the OMC of high-plasticity soils, while the opposite effect is dominant in the low-plasticity soils, i.e. adding gypsum decreases the MDD and increases the OMC of low-plasticity soils. However, various factors appear to affect these trends, resulting in the exact opposite results that have been reported as shown in these figures. Factors affecting these results include the type of added gypsum (for example when hemihydrate calcium sulfate, i.e. bassanite, is used instead of gypsum, or when solid waste byproducts such as titanium gypsum, phosphorous gypsum, and desulfurization gypsum are used instead of pure gypsum), the type and percentage of fine portion of the soil (especially the type of clay minerals), whether or not cementitious hydration products due to pozzolanic reactions are formed, and finally whether or not ettringite mineral is formed and in what amount. It should also be noted that the

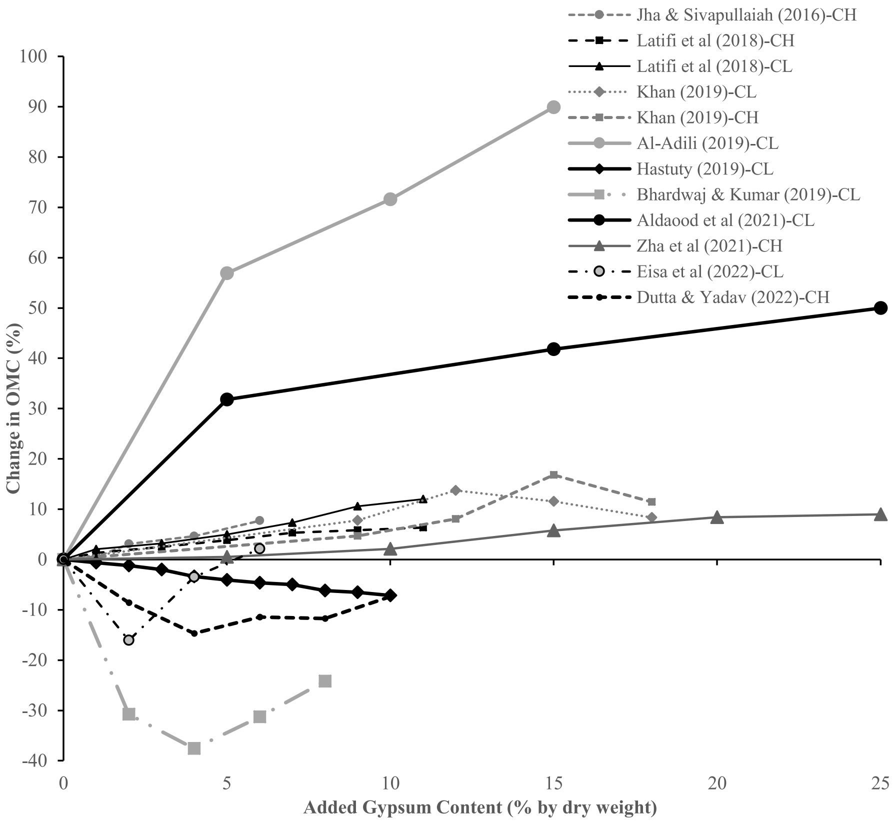

**Fig. 10.** Effects of adding gypsum to soil on their OMC.

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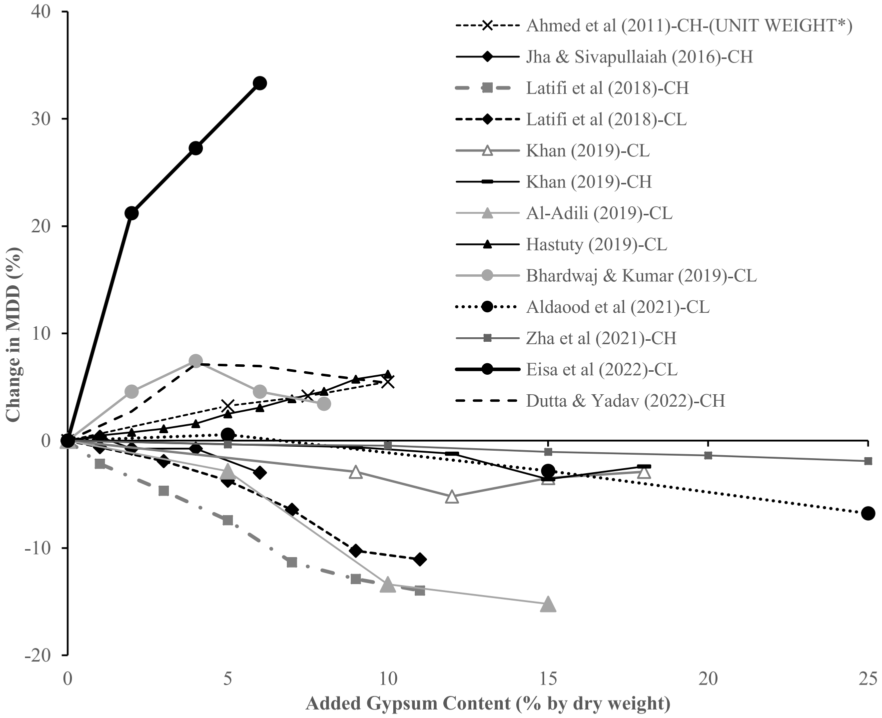

**Fig. 11.** Effects of adding gypsum to soil on their MDD.

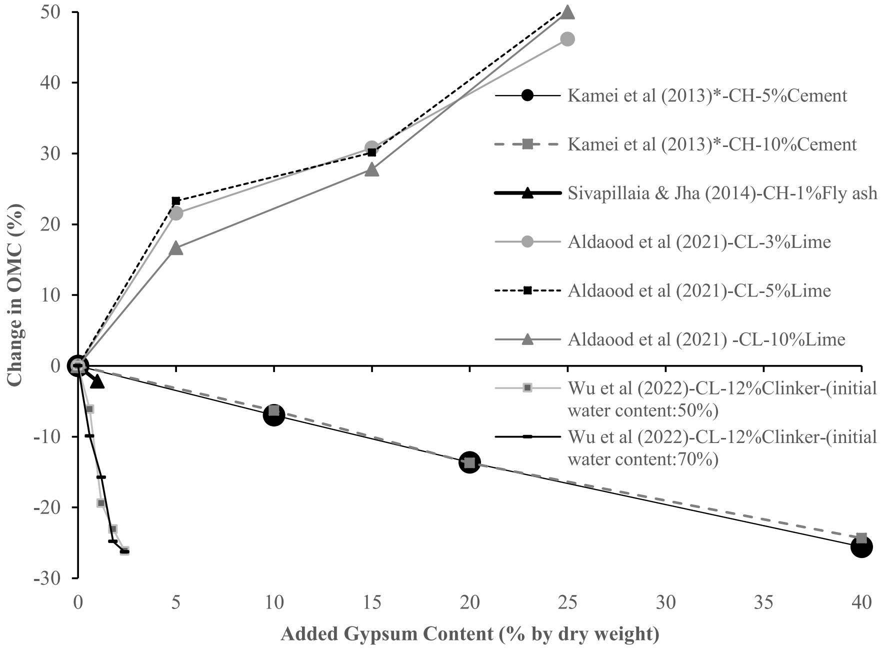

**Fig. 12.** Effects of adding gypsum along with other stabilizers to soil on their OMC. * Is describing change in Water Content NOT OMC.

specific gravity of gypsum (around 2.3) is lower than that of most soils (around 2.6 for quartz and up to 2.8 for some clays). This could also affect the MDD of the treated soils compared to the untreated soil. Unfortunately, a comprehensive understanding of these factors and their exact effects on the compaction behavior of gypsum-treated soils is currently not available. Compaction properties are very important, especially in transportation-related geotechnical designs, and therefore, the effects of gypsum stabilization need to be systematically studied to better understand the effects of each one of these factors. Until such an understanding is obtained through further research, the gypsum stabilization projects should be designed on a case-by-case basis using experiments conducted on the project site's soils with the intended gypsum to be used as the stabilizer.

### *6.2. Compaction properties of soil treated with gypsum and other additives*

Many researchers have also investigated the effects of adding gypsum along with other additives on the MDD and OMC of soils (Ahmed et al., 2011, 2012; Kamei et al., 2013; Aldaood et al., 2014, 2021; Sivapullaiah and Jha, 2014; Latifi et al., 2018; Bhardwaj and Kumar, 2019; Al-Adhamii et al., 2020; Maichin et al., 2021; Wu et al., 2022; Shivanshi and Akhtar, 2023). A summary of some of their results is presented in Figs. 12 and 13. As can be seen from these figures, reported trends are similar to the trends observed in soils treated with gypsum alone. Some of the results, however, show an increase in the MDD with the addition of gypsum up to a certain content, after which the MDD starts to decrease. The soils tested in these studies were mostly low-plasticity fine-grained soils with sand. The increase in MDD was stipulated to be the result of added gypsum filling the voids of the coarser-grained soil particles up to a certain gypsum content, after which the lower specific gravity of the gypsum compared to the soil, caused the MDD to decrease. Similar to the case where gypsum without other additives was used to stabilize the soils, further research is required to better understand the compaction behavior of soils treated with gypsum along with other additives.

## 7. Atterberg limits of soils treated with gypsum

Several studies have investigated the effects of adding gypsum to soil on their Atterberg limits (Azam and Abduljauwad, 2000; Ameta et al., 2007; Yilmaz and Civelekoglu, 2009; Kousa; Jaksa, 2010; Sivapullaiah and Jha, 2014; Latifi et al., 2018; Al-Adili et al., 2019; Hastuty, 2019; Yuvan et al., 2019; Al-Adhamii et al., 2020; Zha et al., 2021). A summary of the changes in the liquid limit (LL), plastic limit (PL), and plasticity index (PI) of soils treated with gypsum are shown in Figs. 14–16, respectively. The results show that the LL is generally decreased after adding gypsum to high-plasticity soils, which is caused by the cation exchange mechanism. In low-plasticity soils, especially when recycled or solid waste gypsum from other industries such as titanium dioxide production is used, the LL decreases initially but starts to increase after a certain amount of additives, i.e. waste gypsum is added. This is attributed to the absorbance of water by these additives. When increasing amounts of such additives are added, they start to absorb more water, which could affect the engineering properties of the treated soils, especially in areas prone to wetting-drying or freeze-thaw cycles (Zha et al., 2021). Adding gypsum to high-plasticity soils and the subsequent cation exchange typically decreases the PL and the PI of the soil as well. Again, treating low-plasticity soils with gypsum, especially non-pure gypsum, could increase the PL and PI of the treated soils, as shown in the figures.

## 8. Other properties of soils after gypsum treatment with and without other additives

The effects of gypsum stabilization on other soil properties have also been studied occasionally. Al-Adili et al. (2019), for example, studied the effects of adding bassanite (0–15%) to soft clay on the compression index (*Cc*) of the soil. Their results showed that Cc of treated soil increased by adding up to 5% of recycled gypsum

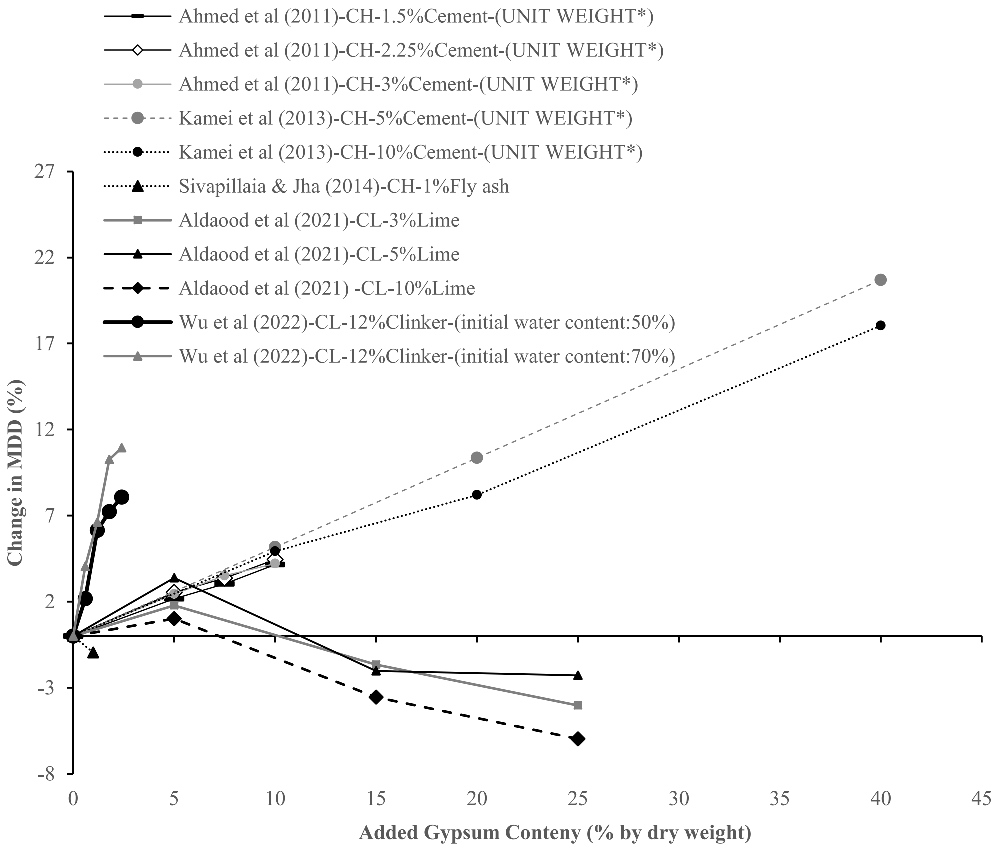

**Fig. 13.** Effects of adding gypsum along with other stabilizers to soil on their MDD. * Is describing change in Unit Weight NOT MMD.

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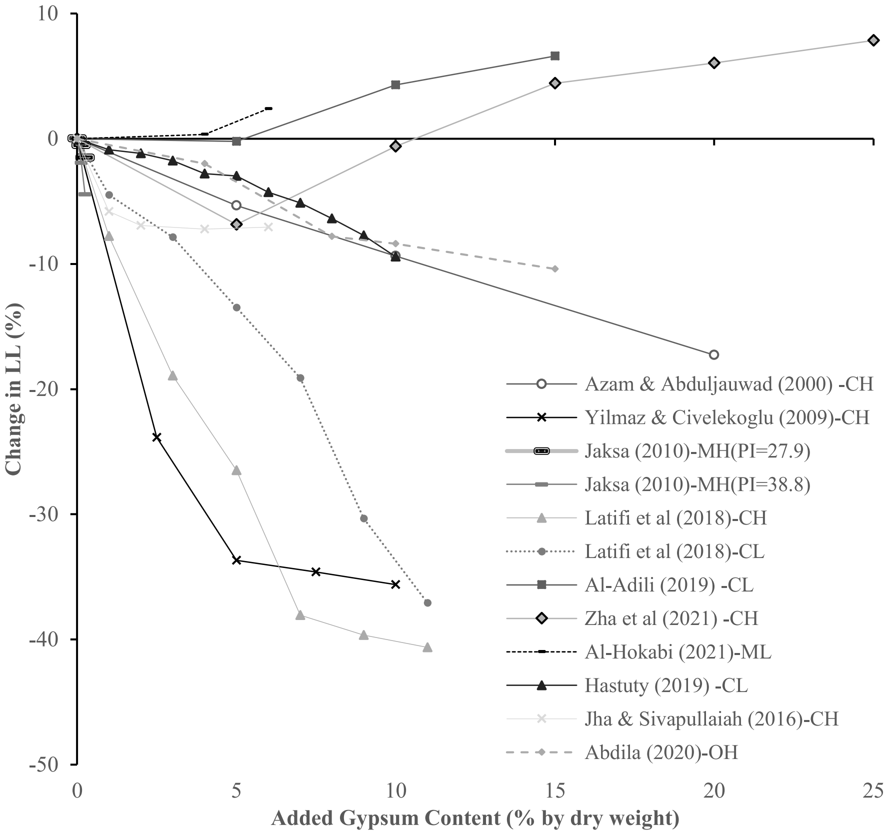

**Fig. 14.** Change in the LL of soils treated with gypsum.

additive, after which (beyond 5% gypsum additive) Cc started to decrease (Al-Adili et al., 2019). Mustapa et al. (2021) demonstrated that gypsum can be used to reduce the compression index of organic soils (Mustapa et al., 2021). Using direct shear tests, Apriyanti et al. (2019) showed that both cohesion and the friction angle of clay increase when gypsum and tin tailings are added to clayey soils. Using unconsolidated undrained triaxial tests, Razouki et al. (2007) showed that the increase in friction angle of clayey soils treated with 33% gypsum is more pronounced under soaked conditions compared to unsoaked conditions. They further showed that there is a noticeable decrease in the cohesion and friction angle of treated soils compacted at OMC as the soaking period increases (Razouki et al., 2007). Using unconsolidated undrained triaxial tests again, Razouki and Kuttah (2020) showed that both the cohesion and friction angle of gypsum-rich soils decreased with long-term soaking. Based on the observed decrease in the cohesion and friction angle, they demonstrated that the ultimate bearing capacity of a strip footing (width of 1 m) in soaked conditions is 37.68% of the same footing in unsoaked conditions. This indicates that long-term soaked conditions must be considered in design (Razouki and Kuttah, 2020). Ahmed and Ugai (2011) showed that sandy soils stabilized with gypsum alone without a cementing agent such as cement or lime are not durable in wetting-drying and/or freeze-thaw environments (Ahmed and Ugai, 2011). Edora and Adajar (2021) studied the effects of adding gypsum and rice husk ash (RHA) on the permeability of expansive clays and concluded that the optimum mixture to improve the permeability contains 15% gypsum 10% RHA (Edora and Adajar, 2021). Razouki and Kuttah (2004) showed that the resilient modulus and shear-wave velocity of the compacted clayey soil treated with 33% gypsum significantly decreases with increasing soaking time. Ahmed et al. (2012) showed that soft clay treated with recycled gypsum exhibits higher cone penetration resistance (Ahmed et al., 2012). Maqsood et al. (2020) evaluated the effect of aging (9 months) on gypsum mixed sand (GMS) and reported a normalized peak strength reduction of about 20% after the first month. After this initial term, the soil's mechanical behavior was independent of aging (Maqsood et al., 2020). Kobayashi et al. (2013) studied the effects of recycled bassanite on the Splitting tensile strength of sandy and silty soils. Their results indicated that splitting tensile strength increased as recycled bassanite content increased (Kobayashi et al., 2013). Al-Adhamii et al. (2020) studied the effects of crude oil on the shear strength and collapsibility of gypseous (gypsum content = 34%) silty sand (SM). They showed that adding 9% crude oil could increase the cohesion, decrease the friction angle, obliterate the adverse effects of soaking on gypseous soils, and reduce their collapsibility (Al-Adhamii et al., 2020). Abdulrahman and Ihsan (2020) showed that using 16% eggshell powder can enhance the collapse index (measured from odometer tests) of gypseous sandy soil (SW-SM) (Abdulrahman and Ihsan, 2020).

Poch et al. (1998) studied the physical behavior of gypsiferous soils with 0–90% gypsum content. Their results indicated that gypseous soil (nearly 90%) could retain higher water content near saturation conditions in comparison with non-gypseous soils (Poch et al., 1998). Moret-Fernández and Herrero (2015) investigated the impact of gypsum content on water retention of soils. Their results indicated that the content of gypsum has a substantial effect on the water retention curve of soils and higher retention occurred near saturation conditions and exhibited steeper slopes. Also, the

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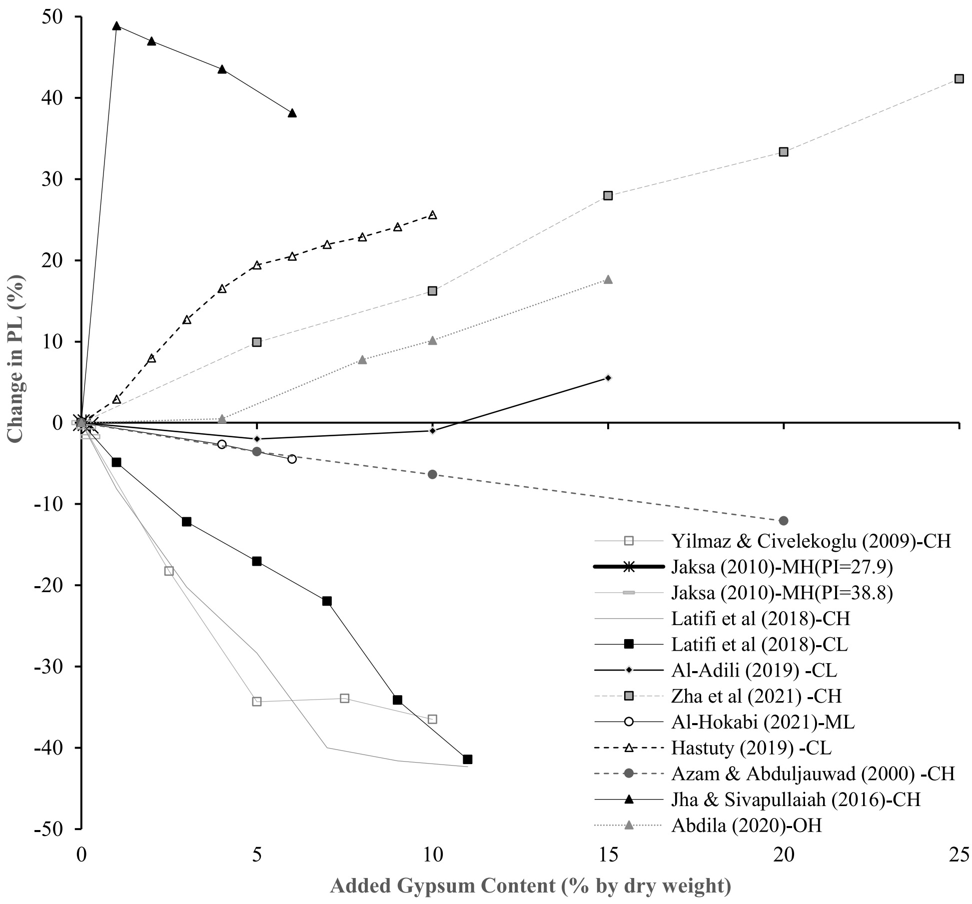

**Fig. 15.** Change in the PL of soils treated with gypsum.

threshold equivalent gypsum content to make a significant influence on WRC was about 40 % (Moret-Fernández and Herrero, 2015). Aldaood et al. (2014) studied the effects of gypsum and lime on the water retention curve of natural fine-grained soils. Their results indicated that gypsum content has an important influence on the water retention curve of the soil and its effect is higher than curing time or temperature. In addition, this study revealed that using lower compaction effort could lead to a decrease in the risk of gypsum dissolution by preserving lower water retention for a fixed (Aldaood et al., 2014).

## 9. Durability of soils treated with gypsum

One of the main concerns regarding gypsum-treated soil is loss of strength due to dissolution of gypsum in water. Several studies investigated the durability of gypsum-stabilized soils using freeze-thaw and wetting-drying experiments (Ahmed and Ugai, 2011; Kamei et al., 2013; Hafshejani and Amin, 2015; Kuttah and Sato, 2015; Salih et al., 2020; Mirabi et al., 2021; Pu et al., 2021; Zeng et al., 2023). The results of some of these studies are summarized in Figs. 17 and 18. These results show that both freeze-thaw and wetting-drying cycles lead to a significant loss in the strength of treated samples but the effects of freeze-thaw cycles are more pronounced. This is a typical behavior expected in chemically stabilized soils including the soils treated with cement and lime (Ahmed and Ugai, 2011). However, the strength loss of gypsum-treated soils is much higher (or fewer cycles are required to reduce the strength) compared to that of cement/lime-treated soils. This is attributed to the high solubility of gypsum in water.

Using cement and lime combined with gypsum could significantly improve the durability of treated soils compared to soils stabilized by gypsum alone (Kamei et al., 2013; Pu et al., 2021). This significant improvement is due to the hydration products of cement/lime that are less water-soluble. Interestingly, some studies even show an initial increase in the strength of soils stabilized with gypsum and cement during the first few wetting-drying cycles. This behavior is mainly correlated with the additional curing that occurs due to late pozzolanic reactions during the wetting phases. These new bonds strengthen the treated soil in the early cycles of wetting-drying cycles but they start to degrade in later cycles leading to reduced strength (Ahmed and Ugai, 2011; Kamei et al., 2013).

Furthermore, the results demonstrate that cement-gypsum stabilization typically provides better durability compared to lime-gypsum stabilization. However, the percentage of admixture used can change this behavior. For example, Ahmed and Issa (2014) investigated the impact of soaking in wet conditions on clayey soil treated with recycled gypsum and lime/cement. They showed that increasing gypsum-cement content increases the durability of the treated soil while increasing gypsum-lime content does not change the durability of the treated soil. More importantly, they showed that at lower percentages of admixtures, the gypsum-lime combination is more durable than the gypsum-cement admixture. Based on durability criteria, they concluded that a gypsum-cement

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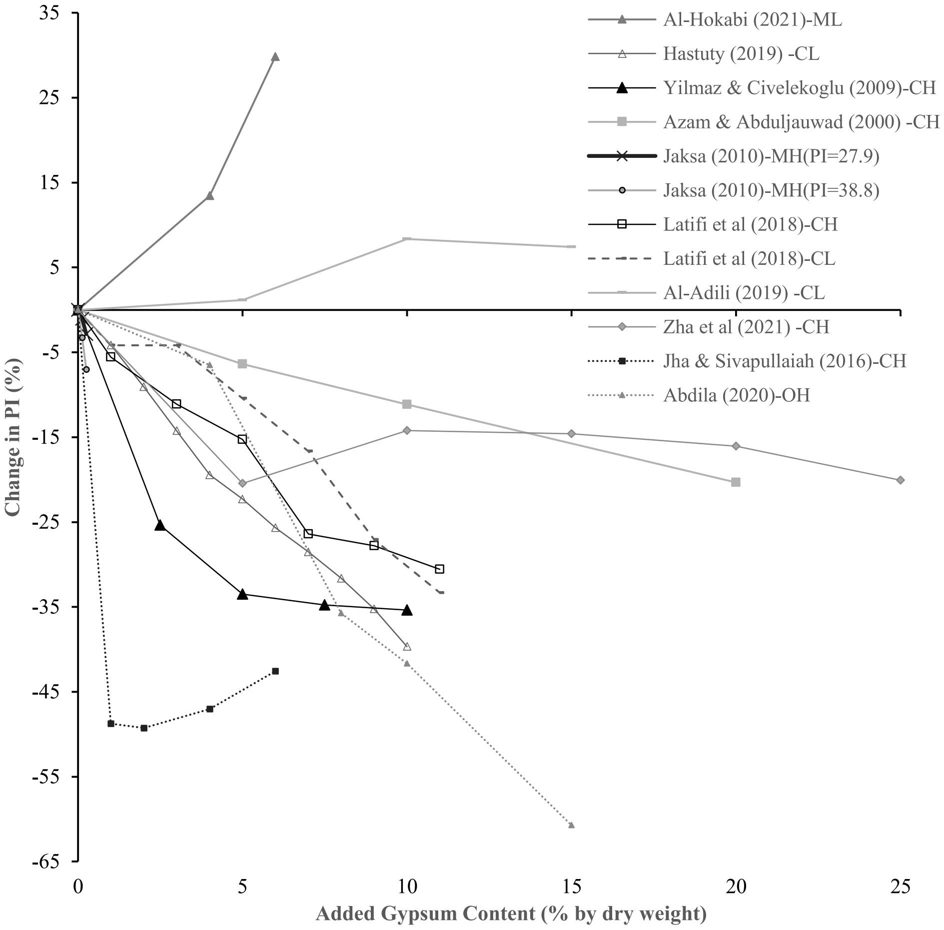

**Fig. 16.** Change in the PI of soils treated with gypsum.

admixture comprising 22.5% by weight, with ratios between 1:1 to 2:1, provides the highest durability.

Based on these findings, it can be concluded that gypsum stabilization in areas with wet-dry or freeze-thaw seasons should be used with caution, and a combination of gypsum with other additives could be a better choice in these areas.

## 10. Environmental impacts of using gypsum to stabilize soils

Several researchers studied the environmental effect of adding gypsum to the soils (Yu et al., 2003; Tayibi et al., 2009; Lee et al., 2010; Truman et al., 2010; Dubrovina et al., 2021; Popp et al., 2021; Pu et al., 2021). These studies show that adding gypsum has positive and negative environmental results. Applying gypsum to agricultural soils, for example, increases water infiltration and retention and decreases runoff by preserving soil porosity, limiting clay dispersion, and surface sealing (Truman et al., 2010). Increasing infiltration and reducing runoff, as well as enhancing deposition of eroded particles lead to decreased erosion in treated soils (Yu et al., 2003). Furthermore, Lee et al. (2010) revealed that the cation exchange caused by adding gypsum to clayey soils leads to the flocculation of clay particles and the formation of larger aggregates (lumps). The flocculation and formation of larger aggregates lead to increased porosity and reduced crusting of the soil surface (soil crusting could inhibit plant growth).

Moreover, manufacturing gypsum binders and products requires less energy and results in lower $CO_2$ emissions compared to materials like cement and lime. Reusing scrap gypsum from manufacturing, recycled gypsum from products like wallboards, or using flue gas desulfurization (FGD) gypsum as a synthetic gypsum can further lower the environmental impacts of ground improvement projects.

On the other hand, there are some environmental concerns associated with using some gypsum products for soil stabilization. For example, adding phosphogypsum to soils can lead to contamination with radioactivity (Phosphogypsum contains elevated levels of naturally occurring radioactive materials (NORM) such as radium, uranium, and lead), heavy metals (phosphogypsum can contain high levels of heavy metals like cadmium, chromium, zinc, lead, arsenic, and mercury), fluoride, and other pollutants (phosphogypsum may contain residual acids, metalloids like selenium, sulfate salts, and organic compounds) that are concentrated in the waste gypsum and can leach to the soil (Tayibi et al., 2009). Popp et al. (2021) revealed that mixing gypsum with additives like lime and cement could reduce the leaching of impurities from gypsum in the soil to safe levels through immobilization and pH increase. Despite these findings, there are still concerns about radon emissions, groundwater leaching of contaminants, and bioaccumulation of toxic elements in the food chain when using phosphogypsum as a soil stabilizer even at recommended application rates (Tayibi et al., 2009).

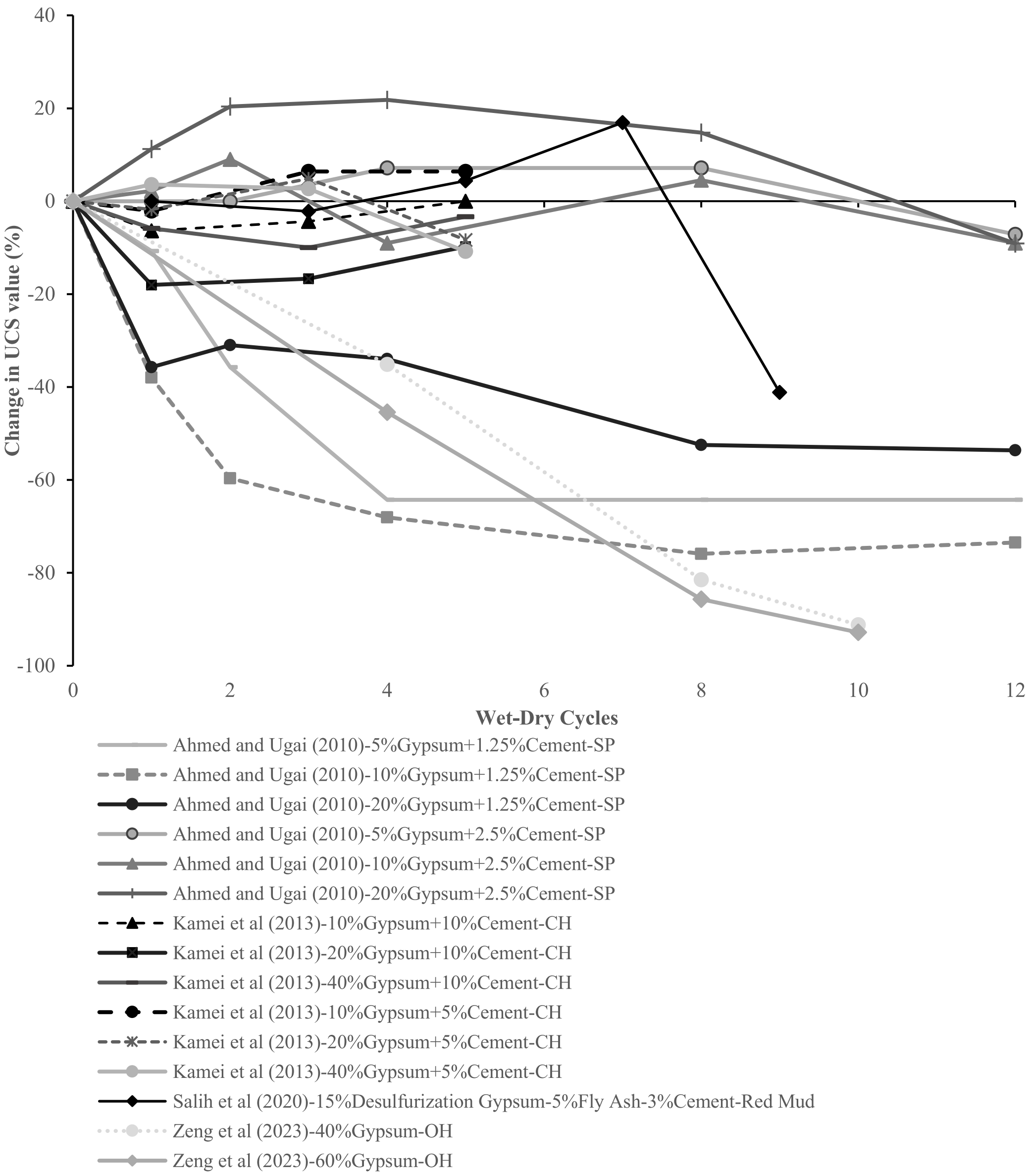

**Fig. 17.** Change in UCS value of soils treated with gypsum after different number of wet-dry cycles.

Another concern related to gypsum stabilization has been reported by Dubrovina et al. (2021). They studied the effect of applying gypsum to metal-contaminated soils on plant growth and metal bioavailability. It was revealed that gypsum did not alleviate copper smelter pollution impacts on plants grown in contaminated soils. Instead, gypsum increased soluble metal concentrations and increased the phytotoxicity effects on biomass and cover. Dubrovina et al. (2021) on the other hand, showed that gypsum could reduce metal toxicity of soils artificially enriched with metals. However, they concluded that gypsum treatment could trigger “delayed geochemical hazards” and emphasized the importance of testing remediation strategies on soils collected directly from the field (instead of artificially enriched soils). Overall, utilizing gypsum in soil could have different environmental effects, and investigating its long-term application and effects in different environments needs to be studied and considered in the design of ground improvement projects.

## 11. Concluding remarks

The effect of adding gypsum to soil properties is a complex and multifaceted subject with implications for a wide range of geotechnical applications. This comprehensive review has delved into the various aspects of how gypsum affects soil behavior, including its influence on the UCS, CBR, swell potential, compaction properties, and Atterberg limits. The systematic review conducted in this study highlights several key findings.

(1) Gypsum can significantly enhance the UCS and CBR of soils, particularly high-plasticity and expansive clays. The increase in strength is primarily attributed to the cation exchange capacity and formation of cementitious hydration products. It is possible that the cation exchange is the dominant mechanism until the cation exchange capacity is reached, after which the formation of cementitious hydration

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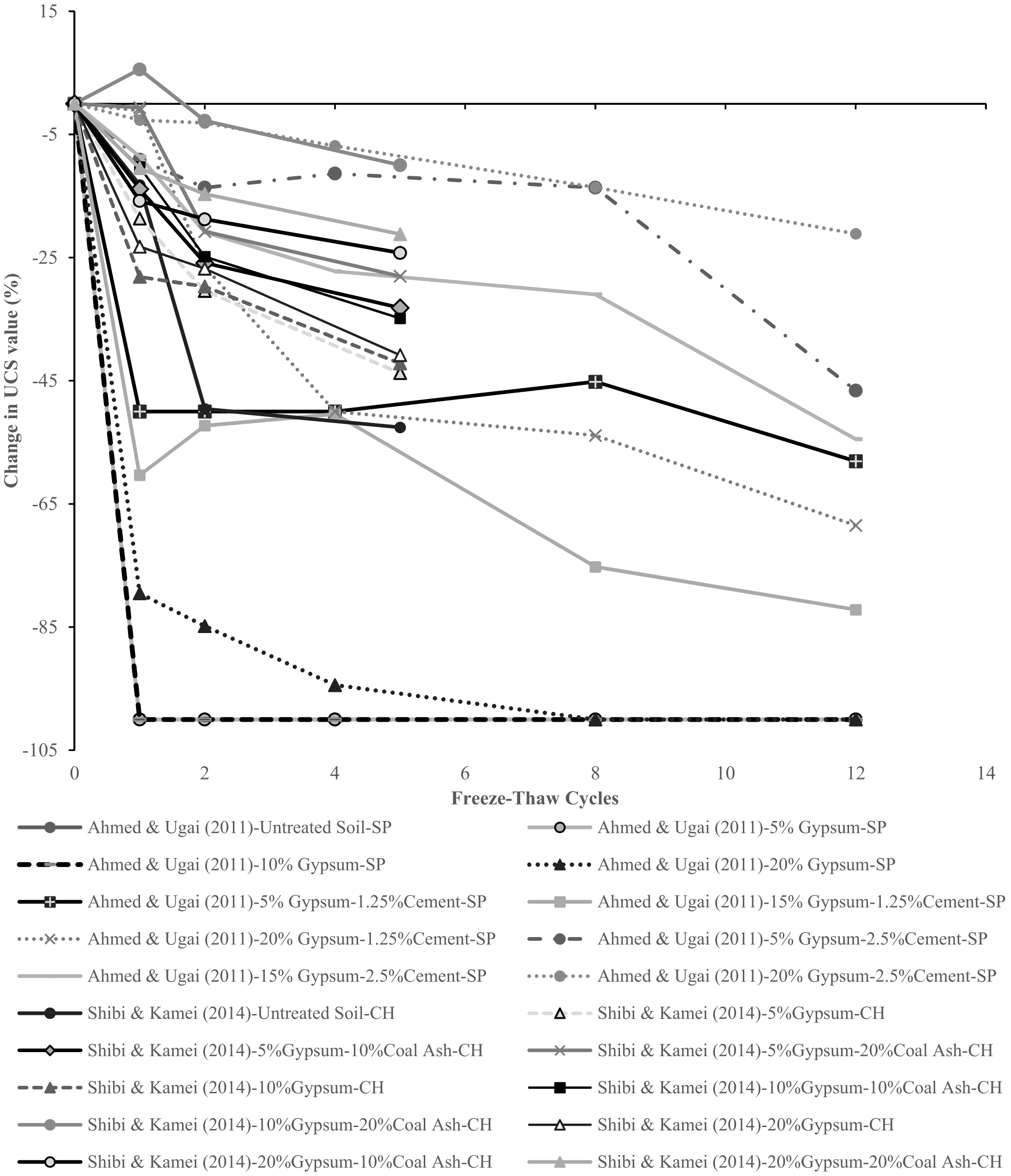

**Fig. 18.** Figure Change in UCS value of soils treated with gypsum after different numbers of freeze-thaw.

products becomes the main stabilizing mechanism. If the formation of cementitious hydration products is inhibited for any reason, the increase in the UCS of the treated clays stops after reaching the cation exchange capacity (as seen in some experimental results). Further investigation is required to understand these mechanisms and determine the possible inhibitory conditions preventing the formation of cementitious hydration products.

(2) There appears to be an optimum gypsum content, after which the strength parameters stay constant or decrease compared to the strength of the soil treated at optimum gypsum content.

(3) The mechanisms causing the decrease in the strength of treated soil after reaching the optimum gypsum content are not currently fully understood. Although an attempt was made here by the authors to hypothesize several possible explanations for this behavior, further investigations are needed to better understand the micro and macro behavior of gypsum-treated clay soils, especially after the optimum gypsum content is reached.

(4) When studying the effects of adding gypsum to soils on their mechanical behavior, it is important to measure the OMC of the soil at each gypsum content, compact each treated soil at its own OMC, and then compare the results. If the soil is compacted at the same moisture content for all added gypsum contents, the results cannot be compared.

(5) The addition of gypsum typically reduces the swell potential of highly plastic clays by replacing monovalent cations with calcium ions. However, the formation of ettringite minerals after adding gypsum may reverse this behavior in some cases and increase the swell potential of treated soils. This is another area that warrants future research to identify and predict the possibility of the formation and the amount of the

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ettringite minerals and their effects on the treated soil's behavior.

(6) High-plasticity soils typically experience a decrease in MDD and an increase in OMC with gypsum addition. Conversely, low-plasticity soils may exhibit the opposite trend, with MDD increasing due to gypsum filling voids until a certain content, beyond which MDD decreases. However, the impact of gypsum on compaction properties is influenced by several factors, including soil type, gypsum source, and gypsum content. Unfortunately, a comprehensive understanding of these factors and their exact effects on the compaction behavior of gypsum-treated soils is currently not available. Compaction properties are very important, especially in transportation-related geotechnical designs and therefore, the effects of gypsum stabilization need to be systematically studied to better understand the effects of each one of these factors. Until such an understanding is obtained through further research, the gypsum stabilization projects should be designed on a case-by-case basis using experiments conducted on the project site's soils with the intended gypsum to be used as the stabilizer.

(7) Adding gypsum generally reduces the LL, PL, and PI of high-plasticity soils through the cation exchange mechanism. In contrast, the effects on low-plasticity and sandy soils can vary, with initial decreases followed by increases in LL, PL, and PI, particularly when using non-pure gypsum or solid waste gypsum.

(8) When gypsum is combined with other additives such as lime or cement, the excess calcium ions can lead to the formation of ettringite minerals, affecting LL and PL. The effects on engineering behavior can vary depending on the concentration of additives.

(9) Although many studies are available on the UCS of gypsum-treated soils, the effects of adding gypsum on shear strength parameters and deformation properties such as the modulus of elasticity are not well studied. As these properties are important in designing effective ground improvement methods, additional studies are required to investigate the effects of adding gypsum on these properties of soils.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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