# Effect of Saturation and Cementation on the Stiffness of Gypsiferous Soils

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**Abstract.** Gypsiferous soils are found in several arid regions of the world and are known to cause structural hazards due to their collapsible nature. The collapsibility of gypsiferous soils is dependent on a number of soil parameters and gypsum content is one of the key factors. Gypsum acts as a weak cementing agent in the soils. In terms of macro-scale procedures for site suitability investigations, the non-destructive testing methods, using shear-wave velocity measurements are valuable to quickly characterize the stiffness properties of the sites and subsurface soil conditions. In this study, free-free resonant column testing was used to study the shear-wave velocity patterns of reconstituted specimens of sand and gypsum under different degrees of saturation. An overall increase in stiffness was observed with decrease in degree of saturation. The rise is stiffness was attributed to a combination of cementation and matric suction processes. Cementation was observed in specimens containing gypsum. For soils with less than 30% gypsum content, matric suction was a dominant factor in increasing the stiffness of the soil and cementation effect was not very strong. For soils with gypsum content of 30% or more, an appreciable amount of cementation was observed and matric suction showed little impact. The peaks in shear wave velocity caused by matric suction were replaced by a plateauing feature. Using the Soil water characteristic curve approach, regression relationships were developed to determine the contributions of matric suction and cementation towards the change in stiffness of the soils. The results from this study can be used to predict the stiffness behavior and gypsum content of gypsiferous soils in the field.

**Keywords:** Gypsum, matric suction, cementation

# 1 Introduction

Gypsum rich soils are often found in arid and semi-arid regions of the world along with calcite and dolomite in the form of evaporites. The mineral Gypsum ($CaSO4.2H_2 O$), is soft, light and moderately soluble in water. Soils in arid and semi-arid regions containing gypsum, calcium carbonate and other such salts often exhibit a appreciable degree of cementation and suction. These properties have a considerable influence on the engineering behavior of these soils. Gypsum acts as a weak cementing agent and the introduction of water into gypsum soils leads to collapse settlement due to dissolution of gypsum and re-arrangement of soil particles. Collapsibility is a major geotechnical concern for gypsum rich soils and has been widely documented. Structures like irrigation canals and dams have been reported to show major deformations and failures. Many such instances have been reported in Iraq. The deformation of irrigation canals in Ebro Valley, Spain, constructed on gypsiferous loess soils is another prominent example [1]. Fourteen dam sites in the United States have been affected by dissolution of gypsum karst as of 1998 [2].

There is a need to develop non-destructive and non-intrusive tests for rapid assessment of sites with gypsum rich soils. Geophysical testing methods such as seismic tests are attractive candidates for such tests. Parameters such as P-wave and S-wave velocities obtained from these tests can be correlated to a number of engineering parameters of the soils. On a laboratory scale, Conventionally, fixed–free resonant column testing or the bender element testing methods have been in use for performing low-strain tests on soils. For this study, the free-free resonant column testing (FFRC) method was used, which is a simpler alternative to the conventional fixed-free resonant column test [3]. Tests were conducted on specimens of sand with varying amounts of gypsum and moisture contents. The changes in soil stiffness were measured in terms of their shear-wave velocity ($v_s$) and small-strain shear modulus ($G_{max}$). By studying the variations in stiffness profiles, judgements can be made about gypsum content and the physical state of the soil.

The engineering behavior of collapsible and partially cemented soils such as gypsiferous soils has been studied by numerous researchers. Fattah et al. (2008) [4] studied the effect of gypsum content on the collapse potential of of gypsum soils in Iraq using. They found that collapse potential of the soils increased with gypsum content. Al-Marsoumi et al. (2008) [5] studied the influence of gypsum content on the shear strength parameters of six different gypsiferous soil samples collected near Basrah, Iraq. They performed triaxial compression and unconfined compressive strength tests and found that the angle of internal friction and cohesion of the soil samples increased with gypsum conetnt up to 20% and decreased thereatfter. Haeri et al. (2005) [6] studied the effect of cementation on the stiffness of artificially cemented sands.

The impact of cementation and matric suction on the stiffness of sandy soils has been studied by several researchers. Khosravi et al . (2009) [7], studied the impact of effective stress on the dynamic shear modulus of unsaturated sand. They used a fixed-free resonant column device with a capacity to apply upto 10 kPa of matric suction to test the effect of normal stress and matric suction on the stiffness of unsaturated sands. Qian et al. (1991) [8] used resonant column testing to study the effect of saturation, grain size, confining pressure and void ratio on the dynamic properties of sand. Sawangasuriya et al. (2009) [9] investigated the nature of small-strain shear modulus of fine-grained compacted subgrade soils. They utilized bender element testing and developed relationships between shear modulus and the net effective confining stress and matric suction using the soil water characteristic curve (SWCC). Rinaldi and Santamarina (2008) [10] reported the cementation behavior of unsaturated soil deposits and its contribution towards the increase in small-strain stiffness.

## 2 Description of this study

The term ‘gypsiferous’ is broadly used to describe soils containing at least 2% gypsum [1]. Gypsum is usually found in arid regions, where soils generally have substantial coarse-grained fractions. The natural gypsum content in these soils varies from around less than 10% in the surface layers to as high as 35-70% in the subsoil layers. Considering these aspects, mixtures of poorly graded fine sand and ground commercial gypsum (Allied Custom Gypsum) were reconstituted in the laboratory with different percentages of gypsum by weight. Fig. 1 shows the gradation curves of the sand and gypsum used. Five specimens were tested with gypsum contents ranging from 0% to 40%. Cylindrical specimens were prepared by air pluviation method by tamping. The void ratio of the all specimens was kept close to 0.55.

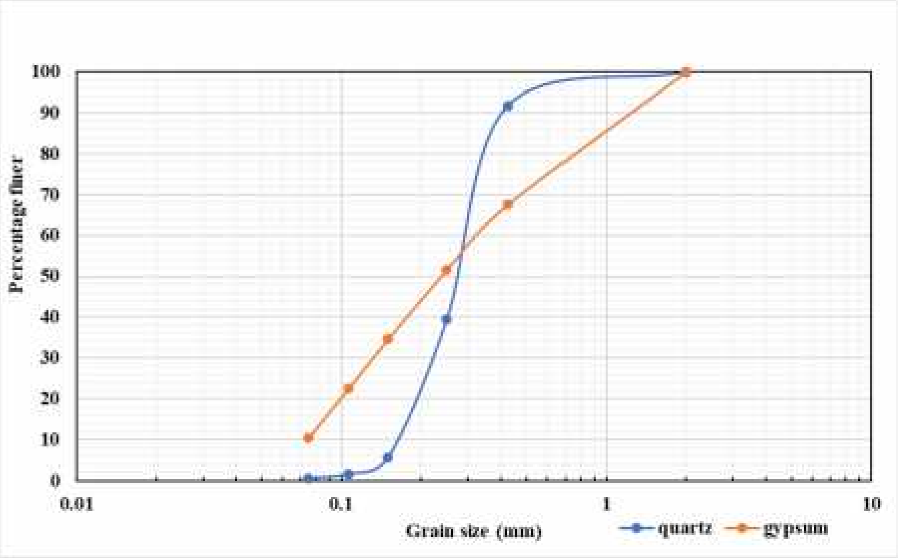

**Fig. 1.** Grain size distribution of the sand and gypsum used

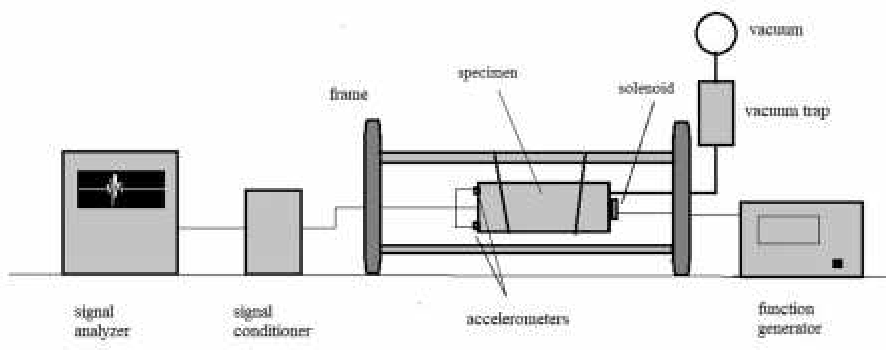

**Fig. 2.** Free-Free Resonant Column Testing arrangement

The mixtures were constructed as cylindrical specimens with a 2:1 (length: diameter) aspect ratio using a latex membrane and two plastic end caps. A Ledex 500 rotary solenoid was attached to one endcap and a pair of PCB 353B16 accelerometers was attached to the other endcap across the diameter (Figure 2). The solenoid, which is driven by a function generator, excites the specimen in the torsional mode by imparting a transient pulse. The time-domain torsional excitation of the specimen measured by the accelerometers and the response was converted into the frequency domain. The resonant frequency of the specimen ($f_n$) was identified as the frequency which produces the maximum torsional acceleration (Kalinski & Thummaluru, 2005). For this test configuration, $v_s$ is calculated using the relation:

$$v_s = 2 f_n l \tag{1}$$

Where $l$ is the length of the specimen in meters, and $f_n$ is in Hz.

The small-strain shear modulus ($G_{max}$) for the specimens was calculated using the expression:

$$G_{max} = \rho v_s^2 \tag{2}$$

where $\rho$ is the bulk density of the material (in kg/m$^3$)

Vacuum of 17” Hg (58 kPa) was applied to one end of the specimen to provide confinement. The specimen was then mounted in a free-free configuration on an assembly of two end plates and supporting rods (Fig. 2). Shear-wave velocity measurements were initially taken on the dry specimen and then the specimens were saturated by passing water through it, until no further increase in specimen weight was observed. A vacuum trap was attached to the assembly so that no water would escape into the vacuum source. The moisture in the specimens was continually reduced using a combination of vacuum and low pressure air. Low pressure air (5-10 kPa) was required at lower degrees of saturation to dry the specimen. Measurements of resonant frequency ($f_n$) were taken at varying degrees of saturation and the corresponding $v_s$ and $G_{max}$ values were calculated. Five soils were tested with gypsum contents ranging from 0% to 40%.

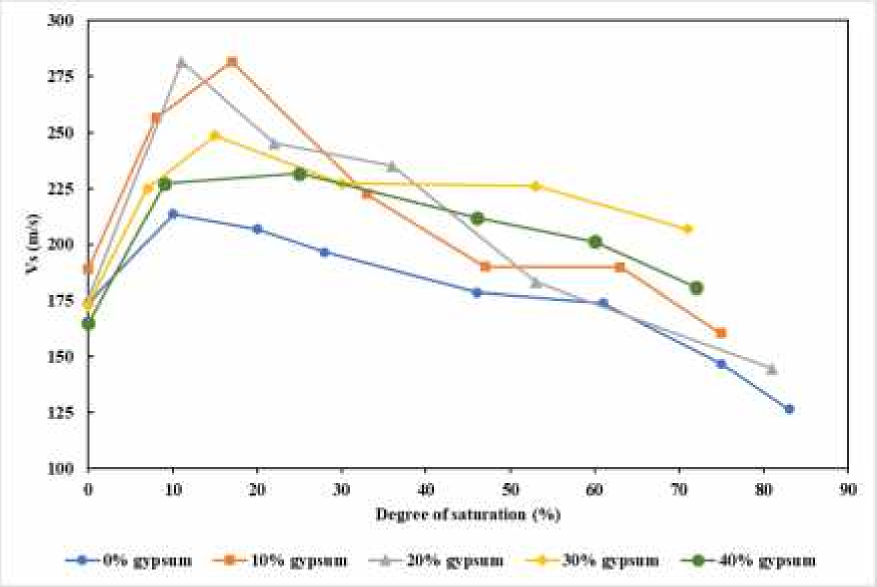

**Fig. 3.** Measured Vs values from Free-Free Resonant Column testing

## 3 Results

The tests on the 5 speciemns showed that $v_s$ increased with decreasing degree of saturation (S%). This trend continued up to the residual degree of saturation for the soils which was about 10-20%. Shear wave velocity was lowest at moisture levels close to saturation. For all the specimens, stifnness increased sharply at saturations of around 10%-20%. The increase was very pronounced for the 10% and 20% gypsum mixtures. With further increase in gypsum content, these peaks reduced and were gradually replaced by a plateauing feature. The plots of $v_s$ versus S% for the 5 tested speciemns are shown in Fig. 3. Using the bulk densities of the specimens, the small-strain shear modulus ($G_{max}$) was calculated. Fig. 4, shows the plotos $G_{max}$ versus S% for the specimens. The trends are in agreement with the findings of Qian et al. (1991), who observed an increase in $G_{max}$ for sands with decreasing saturation, using resonant column testing. They found that, for different confining pressures, the maximum stiffness occurred around residual degrees of saturation which was close to 10%.

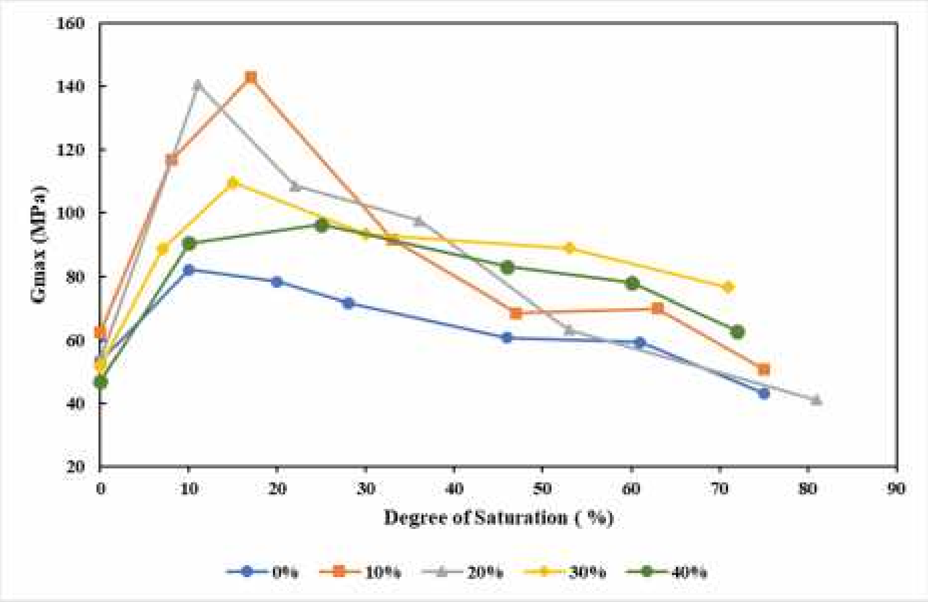

**Fig. 4.** Calculated $G_{max}$ values from Free-Free Resonant Column testing

It was also observed that at low degrees of saturations, the 10% and 20% gypsum mixtures exhibited the highest $v_s$. Shear wave velocities as high as 280 m/s were measured at these specific moisture and gypsum combinations. The corresponding $G_{max}$ values for these specimens were as high as 140 MPa, which were around 1.75 times higher than the corresponding $G_{max}$ value for 0% gypsum specimen.

Matric suction is the well established mechanism which contributes to the increase in stiffness of the soils at low moisture contents. Additionally,cementation between the gyspum and sand particles also enabled the increase in stiffness of the speciemens. The contributions of both these factors vary for different gypsum percentages. Matric suction appeared to be the dominating factor at low gypsum contents as infered by the distinct peaks in the curve. As the gypsum content was increased, cementation effect was more prominent and the specimens show a tendency to form crusts, causing the peaks to become smaller and less distinct. The cementing effect can also be seen from the fact that the 30 and 40% gypsum specimens possess relatively higher $G_{max}$ values at higher S%.

## 4 Interpretation

It is necessary to evaluate the relative contributions of matric suction and cementation towards increase in stiffness had to be estimated for different gypsum percentages. In order to accomplish this, the soil water characterisitic curve (SWCC) had to be developed for the sand. The relationship between soil moisture content and the matric suction (ψ) is represented using the SWCC. For this study, an SWCC was constructed for the sand using the Fredlund and Ching (1994) model [11]. Using this model, the relationship between volumeric moisture content (θ) and matric suction (ψ) is defined as:

$$\theta = [\, 1 - \ln (1+\psi/\psi_r)/\ln(1 +1{,}000{,}000/\psi_r)]\ [\theta_s / \{\ln [\exp (1) +(\psi/a)^n])^m\}] \qquad (3)$$

where a, m and $\psi_r$ are empirical parameters, dependent on the $D_{60}$ of the soil and n = 7.5 , for non-plastic soils [12].

The model parameters were chosen from the test data and gradation curve (Figure 5). It has been shown by researchers that the small-strain shear modulus of soils increases with increase in matric suction [13]. Since matric suction increases with lowering in moisture content, it follows that stiffness also increases with decrease in moisture. The increase in stiffness is however limited till residual moisture content.

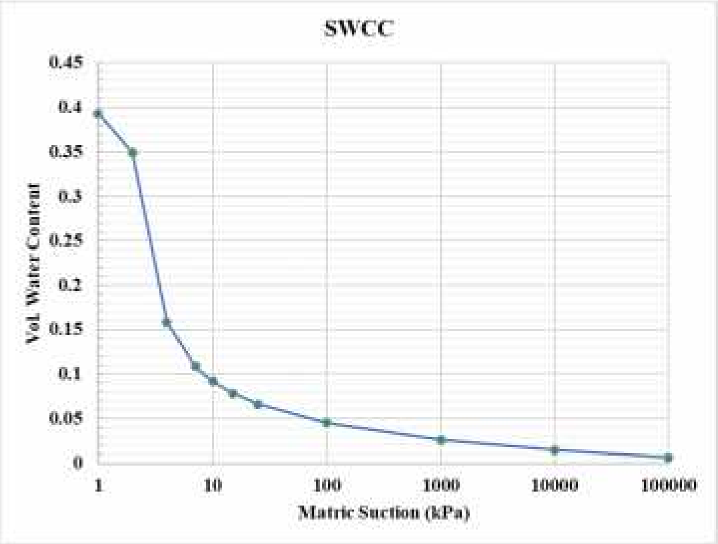

**Fig. 5.** Soil-Water Characteristic Curve for the test sand

The gradation curve (Fig.1) showed that the $D_{60}$ value was almost the same for both sand and gypsum. As such, the SWCC constructed above was assumed to be valid for gypsum sands as well. The $G_{max}$ values for soils with 0%, 10% and 30%

gypsum were plotted against matric suction and simple regression analyses were performed (Figure 6) to model the stiffness increase. Since stiffness increase only took place between transition zone moistutre and residual moisture, only those data points were chosen for the regression. In other words, ψ values corresponding a saturation range of 10% to 80% were considered for the model. Relationship between Gmax and ψ were developed in the form of:

$$G_{max} = a\ ln(\ \psi) + b \tag{4}$$

Where ‘a’ explained the weight of the matric suction term and ‘b’ represented the contribution of the cementation effect induced by gypsum content. It is seen from Fig. 6 that the paramater ‘a’ is the highest for the 10% gypsum soil. The parameter ‘b’ is the highest for the 30% gypsum soil. This quantifies the contribution of matric suction and cementation features towards incrase in stiffness at different gypsum concentrations.

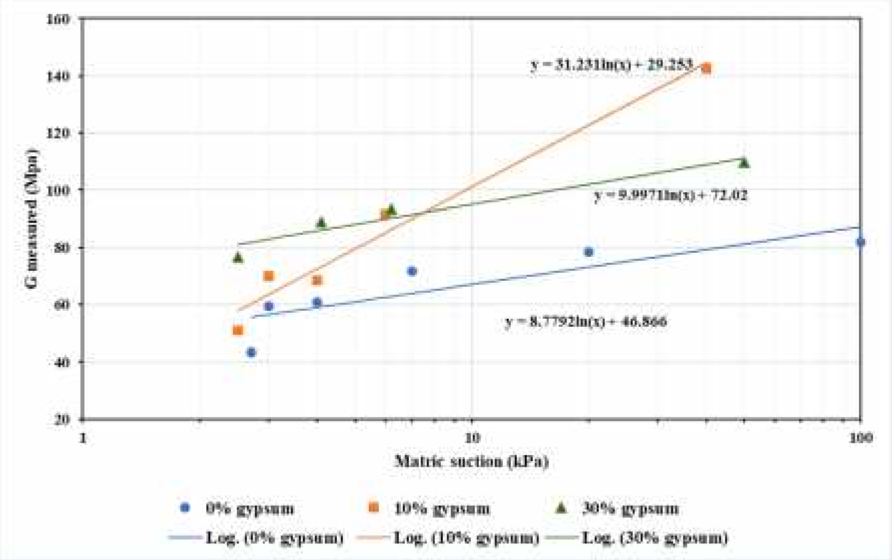

**Fig. 6.** Regression model for $G_{max}$ versus matric suction for three gypsum percentages

At around 10%-20% gypsum, the gypsum particles tend to fill the void spaces between the sand particles and the soil matrix becomes stiffer [14]. At greater than 30%, gypsum acts as a dispersing agent and also the cementing action becomes more predominant. With further increase in gypsum concentration, the bulk density of the soil matrix decerases. This is because of the lower specific gravity of gypsum (2.33) in comparison to sand (2.65). As the bulk density gets lowered, it follows from Eq. 2 that the stiffness also decreases with further increase in gypsum.

The matric suction has much pronounced influenceon the $G_{max}$ value at 10% gypsum soil in comparison to 30% gypsum soil as revealed by the steeper slope for the 10% gypsum relationship in Fig.6. It is also clear that at low matric suction conditions the effect of cementation resulted in higher $G_{max}$ value. The slope of the 30% curve is nearly same when compared to the 0% gypsum situation. This indicates that by 30% gypsum, the matric suction is just about as good as that for sand alone and whatever increase is obtained in the $G_{max}$ is on account of cementation effect.

## 5 Conclusion

The stiffness of reconstituted gypsum sand mixtures was measured at varying degrees of saturation in terms of shear wave velocity ($v_s$). The small strain shear modulus was in-turn calculated from the shear wave velocities. The moisture content of the sample and the presence of gypsum showed a marked effect on the stiffness of the sand. The following conclusions could be drawn from the study:

- Stiffness increased with decrease in moisture, up to the residual moisture (10%-20%) content because of the effect of matric suction.
- The presence of gypsum and water brought about a cementing effect, also leading to a rise in stiffness of the soil.
- At lower gypsum concentrations, of 20 % or less, the stiffness of the sand increased steeply with decrease in moisture due to matric suction effect.
- At higher gypsum concentrations (30% or more), the effect of cementation between sand and gypsum particles increases. This is countered by the dispersing action of gypsum and the decreasing unit weight of the soil, leading to a reduction in stiffness.
- The stiffness of gypsiferous sands were in general higher than that of sand without gypsum.

Results of this nature could be used as a basis for conducting non-destructive surface geophysical tests such Multi-Channel Analysis of Surface Waves (MASW), to measure the in-situ $v_s$ of soils in places where the engineering properties of gypsiferous soils are of concern. From the observed variations $v_s$ trends, a judgement can be made about the gypsum content of the soil. The measurements can also be co-related with geotechnical parameters of soils such as SPT-N value, friction angle, unit weight, shear strength etc. at places where adequate data or measurements are not available.

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