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Influence of Recycled Aggregate on the Settlement Behaviour of Circular Footing Resting on Gypseous Soil

Shahlaa Natiq Ezzat[1], Naser Abed Hasen[2]
[1,2] Department of Civil Engineering/ Engineering College/Tikrit University /Tikrit, Iraq

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ABSTRACT

This study examines the settlement behavior of circular footings on gypseous soils with different gypsum contents under dry and saturated conditions. Three types of soils have been considered: S1, S2 and S3 with gypsum contents of about 30%, 47% and 69% respectively. The soils were improved with recycled concrete (RC) at dry weight proportions of 5%, 10%, 15%, 20% & 25% and the effect of treatment depth (0.5D, 1D & 1.5D where D is the diameter of footing) was investigated through the model tests in the laboratory. The results show that RC addition significantly ameliorates the settlement and increases the load-carrying capacity of the soil -footing system. Under dry conditions, the reduction of settlement was about 28-58%, 8-54%, and 7-53% for S1, S2, and S3 respectively depending on RC contents and treatment depths. The improvement was greatest at higher RC contents of 20 to 25% and greater treatment depths (1D-1.5D). Under saturated conditions, the improvement was still obvious but was of a comparatively lower value due to gypsum dissolution and collapse behavior. The settlement reduction was noted for about 21% to 68%, 10% to 45% and 10% to 50% for S1, S2 and S3, respectively. The effectiveness of RC reduced with an increase in gypsum contents with saturation effect since the loss of natural cementation decreased the overall stiffness of the soil. The results further show that by increasing the treatment depth the performance is significantly improved, i.e. more of the stress influence zone is incorporated within the treated layer, thereby improving the distribution of the loads and reducing deformation. The improvement mechanisms are principally attributed to void filling, improved particle interlocking, increased stiffness of soil matrix and the potential self-cementing effect of residual cementitious materials in recycled concrete. In conclusion, recycled concrete is a great and sustainable material to enhance the engineering behavior of gypseous soils. Optimal performance was obtained under dry conditions at 25% RC and a treatment depth of 1.5D while the unfavorable condition was obtained under saturation in highly gypseous soil (S3). These results point out the importance of the gypsum content and the moisture conditions in design and stability of foundations built on gypseous soils.

Corresponding Author:

Naser Abed Hasen
Department of Civil Engineering/ Engineering College/Tikrit University /Tikrit, Iraq
Email: Naser.a.hassan@tu.edu.iq

1. INTRODUCTION

Gypsum soils are widely distributed in arid and semi-arid regions, particularly in Iraq. It are regarded as problematic foundation soils because their engineering behavior is strongly controlled by gypsum content and moisture conditions. Under dry conditions, gypsum acts as a natural cementing agent between soil particles, providing relatively high apparent strength and stiffness. However, this cementation is metastable and may deteriorate rapidly when the soil is exposed to water. Gypsum dissolution weakens interparticle bonds, increases compressibility, reduces shear strength, and may lead to severe collapse and excessive settlement, creating significant challenges for foundation design and long-term structural performance [1], [2].

The behavior of shallow foundations on gypseous soils is therefore highly dependent on the interaction between soil structure, gypsum content, loading conditions, and moisture variation. Circular footings are commonly used to support tanks, silos, columns, and industrial structures because of their symmetrical geometry and efficient load distribution. However, when such footings rest on collapsible gypseous soils, their bearing capacity and settlement response may deteriorate considerably, particularly after wetting. Previous investigations have shown that confinement and reinforcement can improve footing performance by reducing lateral deformation and enhancing load transfer within the supporting soil [3], [4].

Several stabilization techniques have been proposed to improve the engineering properties of gypseous soils. Conventional additives such as lime and cement can enhance strength by forming cementitious products, although their effectiveness may vary with gypsum content, curing conditions, and moisture exposure [1], [5]. Geosynthetic reinforcement has also been reported to improve bearing capacity and reduce settlement by providing tensile resistance and restraining lateral soil deformation [10]. More recently, increasing attention has been paid to sustainable stabilization methods using recycled and waste materials to improve soil performance while reducing environmental impact.

Among these materials, recycled concrete aggregate (RCA) has shown considerable potential as a sustainable soil-improvement material. Previous studies have reported that crushed concrete waste can increase bearing capacity, reduce compressibility and collapsibility, and improve shear strength through void filling, particle interlocking, and densification of the soil matrix [6]–[8]. Recycled concrete layers beneath shallow foundations have also been shown to improve load distribution and reduce settlement by increasing the stiffness of the supporting layer [9]. In addition, residual cementitious compounds associated with recycled concrete may provide supplementary bonding within the treated soil matrix.

Despite these encouraging findings, relatively limited information is available regarding the combined influence of recycled concrete content, treatment depth, gypsum content, and moisture condition on the load-settlement behavior of circular footings resting on gypseous soils. This issue is particularly important because the effectiveness of stabilization under dry conditions may differ substantially from that under saturated conditions due to gypsum dissolution and loss of natural cementation [11].

Accordingly, the present study investigates the performance of circular footings resting on gypseous soils treated with different percentages of recycled concrete and different treatment depths. Three soils with varying gypsum contents are examined under both dry and saturated conditions to evaluate the influence of recycled concrete on settlement behavior and load-carrying performance. The study aims to identify effective treatment combinations and assess the applicability of recycled concrete as a sustainable and economical material for improving the performance of shallow foundations constructed on problematic gypseous soils.

2. MATERIALS AND LABORATORY MODEL TESTS

2.1. Materials

Materials used in this study are described, which contain two main materials: Gypseous soils and the added material is Recycled Concrete (RC) debris from demolished buildings.

2.1.1 Gypseous Soils

The mechanical properties of gypseous soils are highly water-sensitive, with water infiltration leading to gypsum dissolution, loss of cementation bonds, decreased strength and stiffness, increased compressibility, and increased collapse potential [12]–[15]. Stabilizing materials have been of great interest in recent years for reducing these effects. Recycled concrete waste is highly effective at improving bearing capacity and reducing compressibility through void filling and enhanced particle interlocking [16]–[18]. Other additives, such as nano-silica and industrial by-products, also enhanced durability and mechanical properties, especially under soaked conditions [19]–[21].

The disturbed gypseous soil samples were retrieved from 0.5 to 4 m from three different sites in Salah Al-Din Governorate in Iraq, namely Al-Sultan Compound in Tikrit (S1) (with 69% gypsum), Al-Deum (S2) (with 30% gypsum), and Al-Door (S3) (with 48% gypsum). The amount of gypsum was determined by chemical analysis and verified by the Al-Mufty and Nashat methods. A summary of the main physical and engineering properties of the studied soils is presented in Table 1.

Table 1. Properties of Soil Used in the Study.

Properties	Specification	S1	S2	S3
Gypsum content %	Al-Mufty and Nashat	30%	47%	69%
Moisture content, ω%	ASTM D2216-02	9%	8%	6%
Specific gravity, Gs	ASTM D-854	2.64	2.61	2.58
Coefficient of uniformity Cu	ASTM D-421	17.2	7.6	4.6
Coefficient of curvature Cc	ASTM D-421	0.75	0.40	0.84
Unified Soil Classification System	Sieve analysis	SP	SP	SP
Min. dry unit weight ($\gamma d(min)$) kN/m^3	ASTM D4254-00	9.2	8.9	8.2
Max. dry unit weight ($\gamma d(max)$) kN/m^3	ASTM D1557-12	12.8	12.2	11.7
Failed dry unit weight ($\gamma d(field)$) kN/m^3	ASTM D1557-00	11.9	11.4	10.7
c (kPa)	ASTM D-3080	3.2	5.7	8.5
Ø (degree)	ASTM D-3080	25.6	29.4	34.7

2.1.2 Recycle concrete

Gypseous soil was improved with recycled concrete from blasting and demolition waste, encouraging sustainable practices and environmental conservation. The recycled concrete was prepared by crushing concrete cubes produced in the Concrete Laboratory of Tikrit University by the Los Angeles abrasion machine and then sieving through 4.75 mm sieve to get uniformly graduated particle. This method improves the properties of soil by promoting particle interlocking and reducing the voids of soil matrix [16].

2.2. Laboratory Model Tests

2.2.1. The Footing Models

This research used circular footing models with a diameter of 100 mm. The thickness is 30mm, including two layers of plastic glass, each 15mm thick, used for the construction of these footing models. A 1mm deep circular groove is formed at the center of one face of the footing to house the metallic ball. A rough surface was implemented on the opposite side of the footing to enhance friction between the foundation and the underlying soil during load application.

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2.2.2. The Test Box

900 mm and 550 mm high, as shown in Figure 2. The container was made of 6 mm thick steel plates for the base and side walls and was additionally stiffened with four steel channels running 150 mm from the base to provide structural stability and prevent deformation during the loading. To minimize the effects of boundaries, and hence minimize the amount of friction between the soil and the walls of the container, the internal surfaces of the box were coated with a low-friction material. Such treatment is unavoidable in tests in the laboratory model to simulate realistic stress conditions and prevent overestimation of the soil resistance from side friction. During sample preparation, reference marker lines were drawn along the inner walls of the box to control the thickness of the placement of each soil layer. This procedure ensured a uniform compaction, and accurate achievement of the target relative density throughout the soil bed. Controlled placement of the layer and compaction techniques are commonly implemented in physical modeling studies to ensure repeatability and reliability of the experimental results [22], [9].

2.2.3. The Loading Framework

The test box was positioned on a sturdy steel framework measuring 1100 × 1100 mm and 80 mm in thickness. This base was connected to a locally manufactured, robust loading frame, as depicted in Figure 1. The structure comprises two steel channel columns, each 1520 mm high, internally connected to a loading platform. The platform navigates the columns and can be secured at any height using slotting spindles and holes positioned at consistent intervals. Four short steel angles connect the two columns to the frame's lower plate, providing stability.

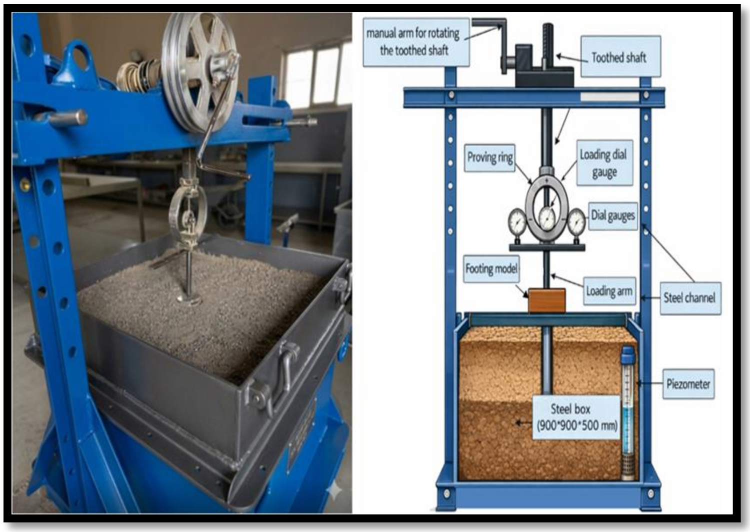

Figure 1. Explains the details of the test box.

2.2.4. The Loading System

The experimental work is conducted in the Geotechnical Laboratory of the Civil Engineering Department at Tikrit University. The laboratory model was produced locally. The load was applied via the mechanical arrangement used during testing. The proving ring is secured to a cylindrical shaft with a 550 mm diameter and a 40 mm height, facilitating load transfer to the footing and allowing the ring to be repositioned at any desired location before or after the test. A steel plate was fabricated for each footing, which was secured to the end of the proving ring and employed to transmit the force as an evenly distributed line load. Three dial gauges were affixed to the footing for measurement purposes. The initial gauge was positioned within the proving ring to quantify the load; the subsequent gauge was affixed to the internal surface of the testing box via a steel arm to assess vertical settlement; and the third gauge was secured to the testing box with an additional steel arm to evaluate horizontal displacement. The employed dial gauges possessed an accuracy of 0.01 mm and a range of 25 mm.

2.3. Preparation of Untreated soil Model

A representative gypseous soil sample was collected from previously determined places and the samples were taken to the Soil Laboratory in Tikrit University for testing and preparation. The collected soil passes through a sieve of 4.75 mm sieve so that uniform particle size distribution and removing the coarse fraction. The untreated soil sample (0% recycled concrete) was firstly prepared and tested for a reference condition. The soil bed was built up by adding soil in successive layers of 10 centimeters each, until the desired height was reached. Each layer was compacted with great care in order to reach the desired relative density of 70 %. The same preparation procedure was always used for all test samples to insure uniformity and repeatability of results.

2.4. Preparation of Treated Soil Model

All of the tests were carried out according to a uniform and standardized preparation procedure. After soil preparation recycled cement concrete debris was added to the gypseous soil with predetermined proportions of 5%, 10%, 15%, 20% and 25% dry weight of soil. The mixing procedure took place outside the test box also; strength was used to mix well until the uniformity of the mixture is achieved. The choice of the mixing ratios was taken from the frequently adopted values in previous studies where recycled concrete contents between 5-25% were found to give a significant enhancement in soil strength and compressibility characteristics while ensuring workability [6], [8]. The prepared soil - concrete mixture was then positioned in the test box in layers of 100 mm each. Each layer was carefully compacted in order to reach the target relative density of 70% ensuring uniformity throughout the soil bed. This process was repeated until it reached the required height. Following placement, the surface of the soil was levelled so that there would be minimum disturbance and the desired kind of contact conditions. Finally, the model footing was placed in the center of the prepared soil surface after finishing the compaction process, so that the load transfer during the test could be accurate when the load was tested.

2.5. The Model preparation for soaking

The soaked soil bed was left to dry by adding water slowly in the test box until water level was at the same level as the surface of soil. A transparent plastic tube was then placed on the side of the container and the water level was carefully controlled and maintained up to the point of complete saturation of the soil specimen. The soaking

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process was sustained at 24 hours' time to ensure that enough time was taken to enable the water to penetrate and stabilize the soil structure.

After the soaking time, dial gauges were used to measure the settlement. The first samples were measured after two hours of loading to obtain the initial stage of deformation of the soil when the soil was saturated. This process allows assessing the short-term and long-term settlement properties.

Figure 2 is depicted the experimental arrangement in the soaking and loading processes with the soil container being connected to the water inside the container by the inlet and outlet of water, the transparent tube to control the water level and the loading system with proving ring placed above the dirt surface. The model guarantees correct modeling of submerged environment and regulated observation of settlement reaction.

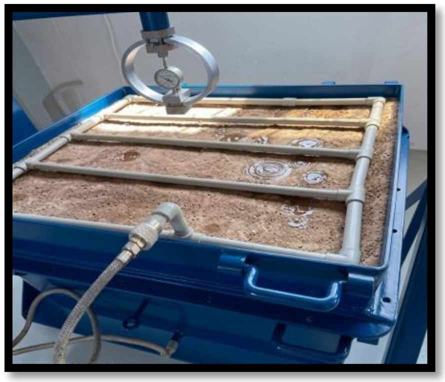

Figure 2. Immersion stages.

2.6. Experimental Program

The settlement behavior of circular footings over treated gypseous soil was also tested in controlled model tests in the laboratory under centrally applied loading conditions. In every test, the preparation of the soil bed was done in the center of the footing, and the loading was done progressively through a mechanical loading system.

The measurements were taken in terms of settlement by dial gauges which were placed symmetrical in the surrounding of the footing to guarantee the precision and consistency of the settlement readings. The first reading was taken even before loading and readings were then taken at every increment of loading. Other time-varying readings were also taken to observe instantaneous and consolidation settlement actions especially when soaked.

These tests were conducted at various improvement depths (0.5D, 1D and 1.5D) where D is the footing diameter. The depth of improvement was found to have an effect on settlement behavior when the load-settlement response of each case was compared at a constant relative density of 70%.

3. RESULTS AND DISCUSSION

Figure 3 (a, b and c) show that recycled concrete (RC) markedly improves the settlement response of dry gypseous soil (S1). With increasing RC content, settlement decreased, while the load-carrying capacity for a given settlement increased. The footing performance was further improved by increasing the treatment depth from 0.5D to 1.0D and 1.5D.

This type of soil (S1) has about 30% gypsum and is partially cemented; hence, it is moderately stable under dry conditions. The improvement achieved by RC is primarily attributed to void filling, increased particle interlocking, matrix strengthening, and possibly residual cementitious activity.

The amount of reduction in settlement was 28–58%, 28–60%, and 23–68% for treatment depths of 0.5D, 1.0D, and 1.5D, respectively, at an applied stress of approximately 300 kPa. Settlement was most effectively reduced at 25% RC and a treatment depth of 1.5D, to ~4.1 mm. This superior response is correlated to the larger treated zone within the footing stress influence zone, thus providing better load transfer and decreasing compressibility.

In general, the depth of treatment and RC content had a significant influence on settlement reduction, and the trends obtained are consistent with previous studies showing that soils stabilized with recycled concrete materials have improved bearing performance [6, 9]. The outcomes thus support the possibility of using RC as a sustainable material to enhance the performance of gypseous soils under dry conditions.

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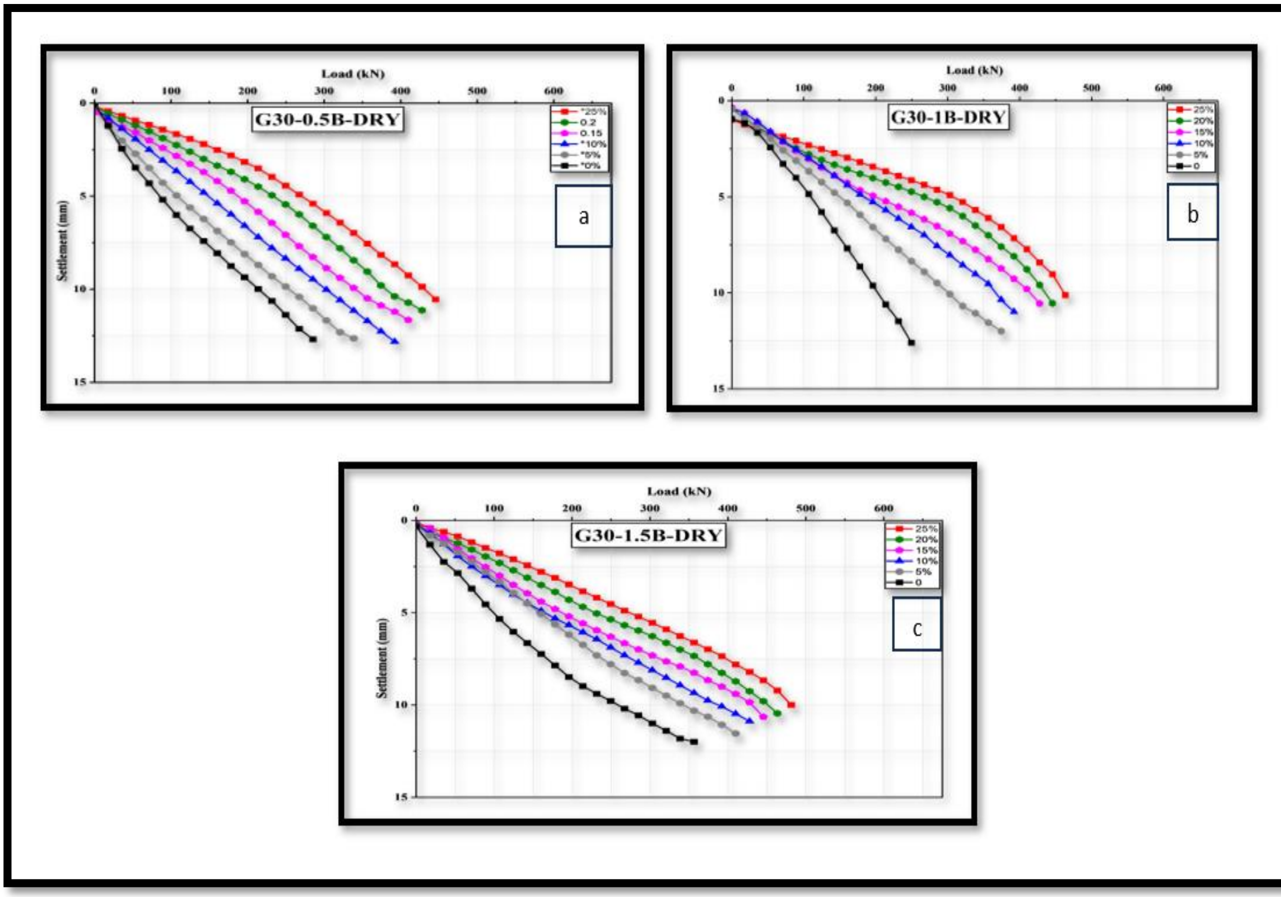

Figure 3. Shows the effect of adding RC at different concentrations into the dry gypsum soil (S1) to a depth of: a) 0.5D, b) 1D and c) 1.5D.

As shown in Figure 4 (a, b and c), saturation causes a significant increase in the settlement of gypseous soil (S1) due to the dissolution of gypsum and the consequent loss of interparticle cementation. However, consistently increasing the use of recycled concrete (RC) reduced settlement, and this improvement increased with the percentage of RC in the concrete and/or the treatment depth.

Settlement reduced by approximately 21–50% when the RC content was increased from 5 to 25%, from 12 mm for untreated soil to 9.5–6.0 mm for a treatment depth of 0.5D at an applied stress of about 150 kPa. Settlement reduced from about 13 mm to 10.5–6.3 mm at 1.0D and about 200 kPa, with the reductions being 19- 52%. The most significant reduction was observed at 1.5D, where settlement decreased from ~13.5 mm to 11.0- 6.0 mm, representing a reduction of 18- 56%.

The better response is due to void filling, improved particle interlocking, greater matrix stiffness, and/or the remaining cementitious activity of the recycled concrete. A greater depth of treatment will also place a larger fraction of the footing stress influence zone within the improved zone, thereby further distributing loads and reducing deformations.

In general, there is a significant improvement in the settlement performance of saturated gypseous soil as RC increases with treatment depth, with the optimum result achieved at 25% RC and 1.5D. However, settlement remains higher than under dry conditions, indicating that gypsum dissolution under wet conditions has a predominant negative effect on soil stability.

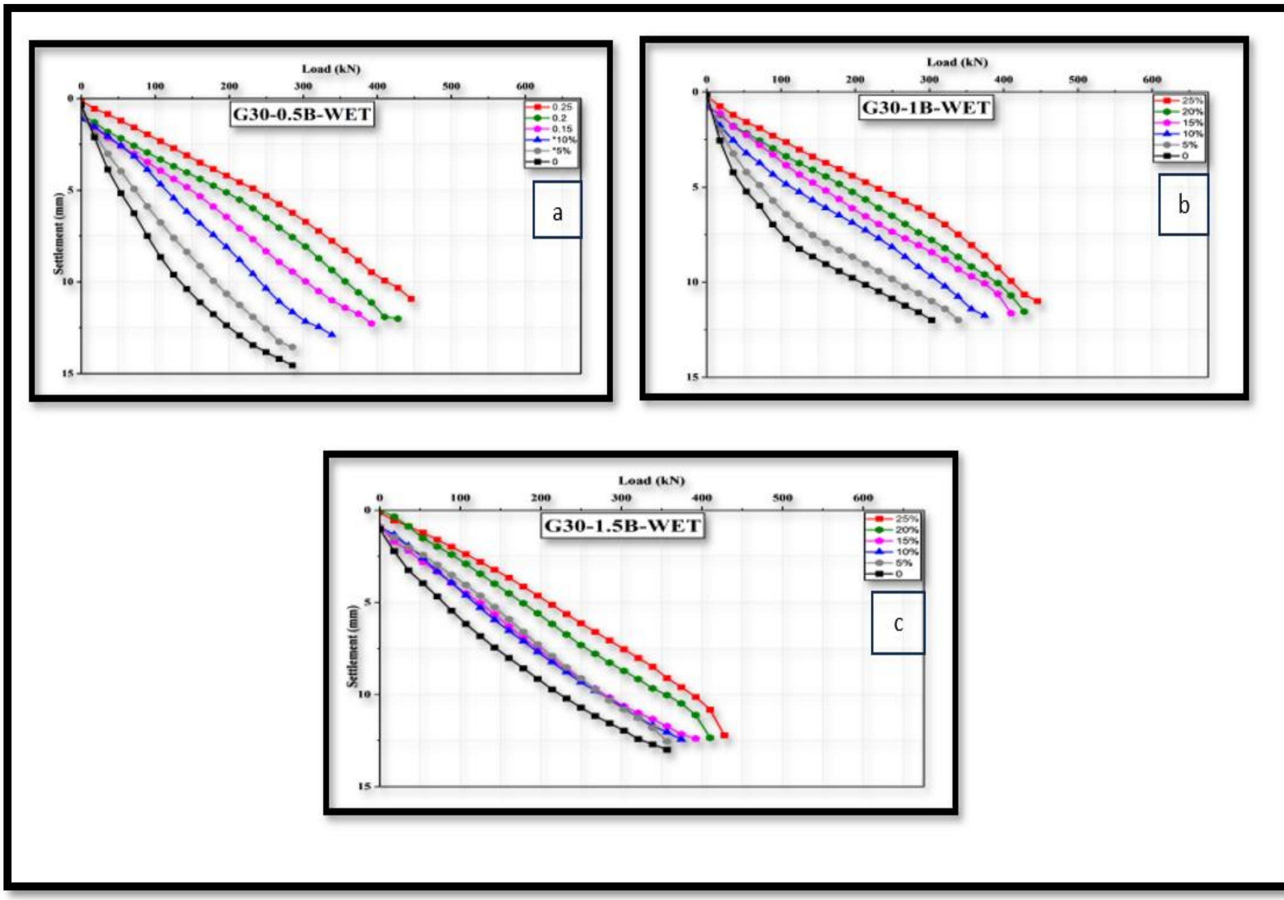

Figure 4. Shows the effect of adding RC at different concentrations into the saturated gypsum soil (S1) to a depth of: a) 0.5D, b) 1D and c) 1.5D.

The results presented in Figure 5 (a, b and c) indicate that the settlement response of the circular footing on dry gypseous soil S2 (approximately 47% gypseous) is significantly improved when it is placed on recycled concrete (RC). The load-carrying capacity increased with increasing RC content, and the improvement was also affected by the depth of treatment. The greater the RC content, the greater the decrease in settlement and the greater the load-bearing capacity of the foundation.

At a depth of 0.5D and an applied stress of ~300 kPa, the settlements for untreated soil were estimated at ~12.5 mm, while they ranged from 11.5–5.8 mm for RCs of 5–25%, representing a reduction of ~8–54%. Settlement reduced from approximately 12.8 mm at 1.0D to 9.8–6.2 mm, which is a reduction of 23–52%. The settlement at 1.5D decreased from ~12.0 mm to 9.5–6.2 mm, representing a decrease of around 21–48%.

Void filling, particle interlocking, strengthening of the soil-RC matrix, and the potential for residual cementitious activity in recycled concrete are the factors primarily responsible for the improvement. Generally, improvements were observed with increasing treatment depth; however, the results suggest that 1.5D did not significantly outperform 1.0D, indicating that treatment efficiency is a function not only of depth but also of compaction quality and the uniform distribution of RC in the treated zone.

Best performance was achieved with 25% RC, with 1.0D as the optimum treatment depth under dry conditions for S2. The results of this study are consistent with the suitability of recycled concrete as a sustainable stabilizing material to reduce settlement and improve the stiffness and bearing response of highly gypseous soils.

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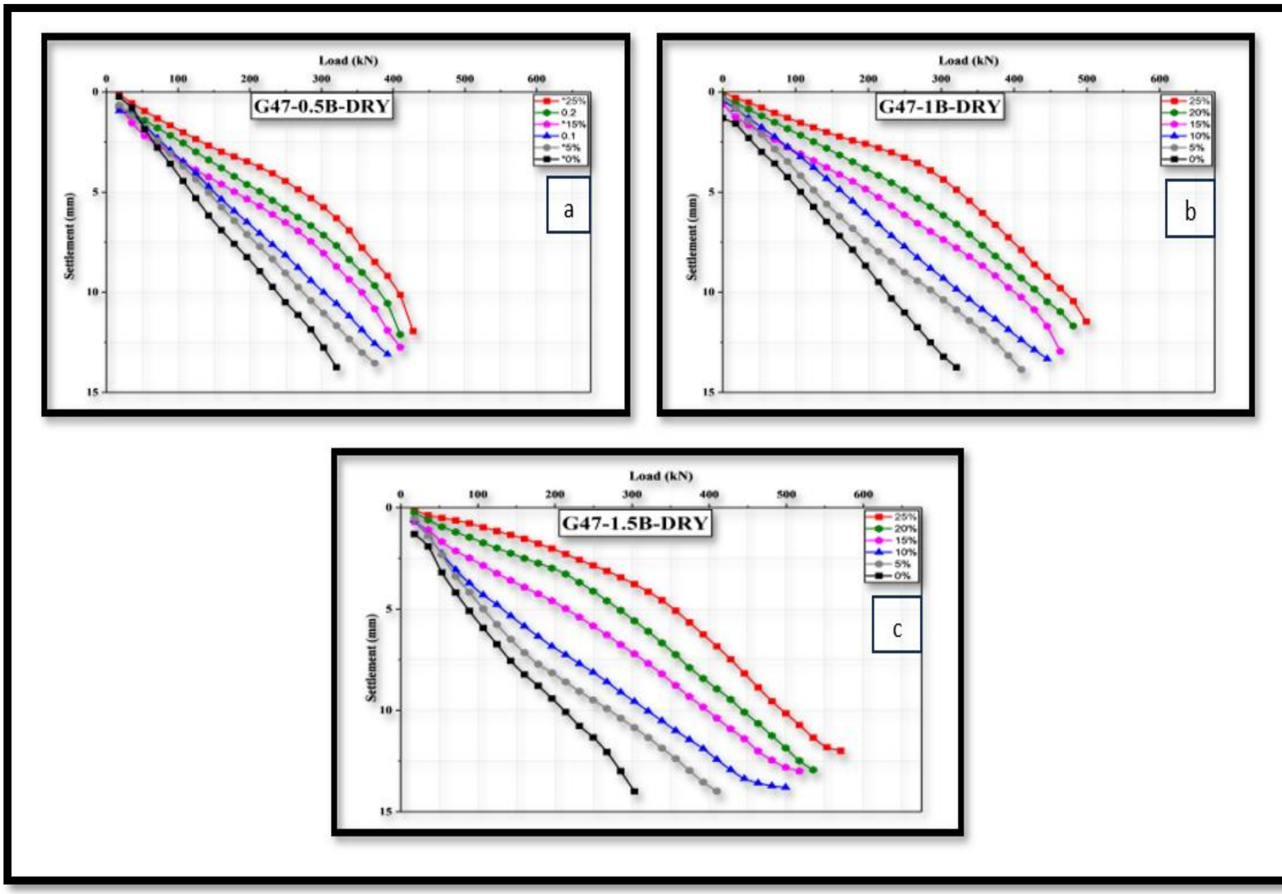

Figure 5. Shows the effect of adding RC at different concentrations into the dry gypsum soil (S2) to a depth of: a) 0.5D, b) 1D and c) 1.5D.

The gypsum dissolution and the resulting reduction in interparticle cementation clearly increase the settlement of gypseous soil S2, as seen in Figure 6 (a, b and c). However, most findings indicated that the footing response was generally improved by using recycled concrete (RC), with reductions evidenced by increased deformation. The extent of improvement was dependent on the proportion of RC and the depth of treatment.

Settlement also decreased with the incorporation of RCs into the soil, from about 14.5 mm (untreated soil) to 13.0–8.0 mm (5–25% RC content), representing a reduction of approximately 10–45 mm at a treatment depth of 0.5D and an applied stress of approximately 300 kPa. At 1.0D, there was a decrease in settlement of 10–43%, from approximately 12.0 mm to 10.8–6.8 mm. The improvement at 1.0D was the most consistent, as a greater portion of the footing stress influence zone was extended into the treated layer, resulting in better confinement and stress distribution.

The response was not as consistent at 1.5D. At 5, 10, and 15% RC, the settlement reduced from about 11.5 mm in untreated soil to 10.8 mm, 10.0 mm, and 8.0 mm, respectively, but 20 and 25% RC did not yield further improvement. This behavior may indicate that, under saturated conditions, continuous improvement may not always be achievable as treatment depth and RC content (or both) increase, possibly due to poorer compaction efficiency, segregation, or poor matrix continuity at higher RC contents.

Overall, RC improved the settlement behavior of saturated S2; however, its effectiveness was lower than under dry conditions due to gypsum dissolution. Optimum performance was achieved at a treatment depth of 1.0D, especially at higher RC contents (up to 25%), with the best performance at RC of ~15% at 1.5D. The results indicate that RC content and treatment depth should be optimized to stabilize highly gypseous soils under saturated conditions.

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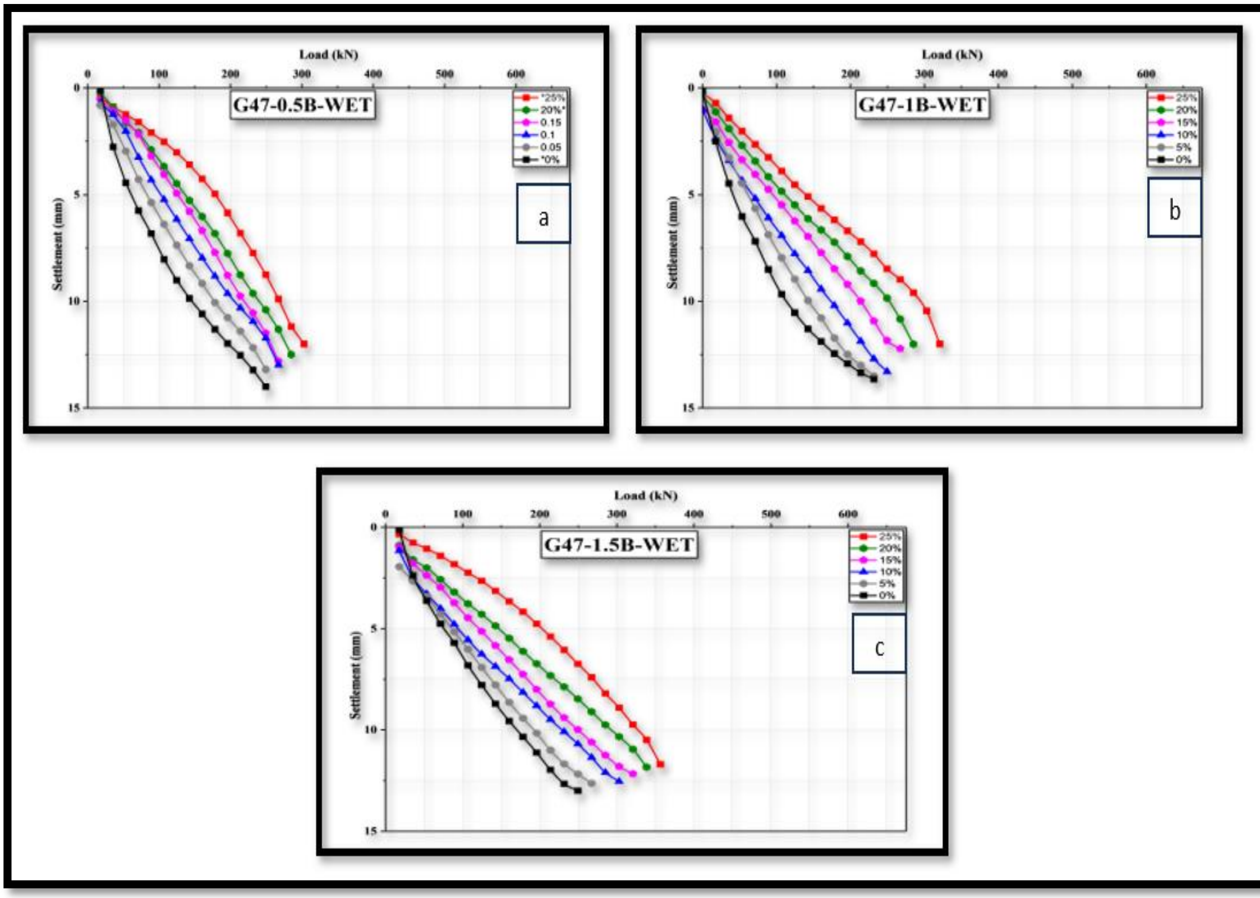

Figure 6. Shows the effect of adding RC at different concentrations into the Saturated gypsum soil (S2) to a depth of: a) 0.5D, b) 1D and c) 1.5D.

As shown in Figure 7 (a, b and c), the settlement characteristics of circular footings made of recycled concrete (RC) are significantly improved when used on dry gypseous soil S3, which contains about 69% gypsum. The high gypsum content offers good cementation and initial stiffness under dry conditions, but the soil is brittle, and its deformation increases with increasing stress. RC content was consistently increased, with a consistent decrease in settlement and an increase in load-carrying capacity.

After a treatment depth of 300 kPa, the settlement reduction ranged from 7-37%, 12-46%, and 15-53% at applied stress levels of 0.5D, 1.0D, and 1.5D, respectively. As RC content increased to 25%, the corresponding settlement decreased as follows: from about 13.5 to 8.5 mm at 0.5D, from about 14.5 to 7.8 mm at 1.0D, and from about 14.8 to 7.0 mm at 1.5D.

It is thought that this improvement is due to void filling, better interlock between the particles, higher stiffness of the matrix, and potential cementitious activity of the cementing materials (residual). The deeper the treatment, the more of the influence zone of footing stresses will be inside the improved zone; the less compressible it will be and the better the load distribution will be.

In general, RC content and treatment depth were significant in reducing settlement; the optimal results were obtained with 25% RC content and a treatment depth of 1.5D. The results of this study validate the viability of using recycled concrete as a sustainable material for stabilizing highly gypseous soil under dry conditions.

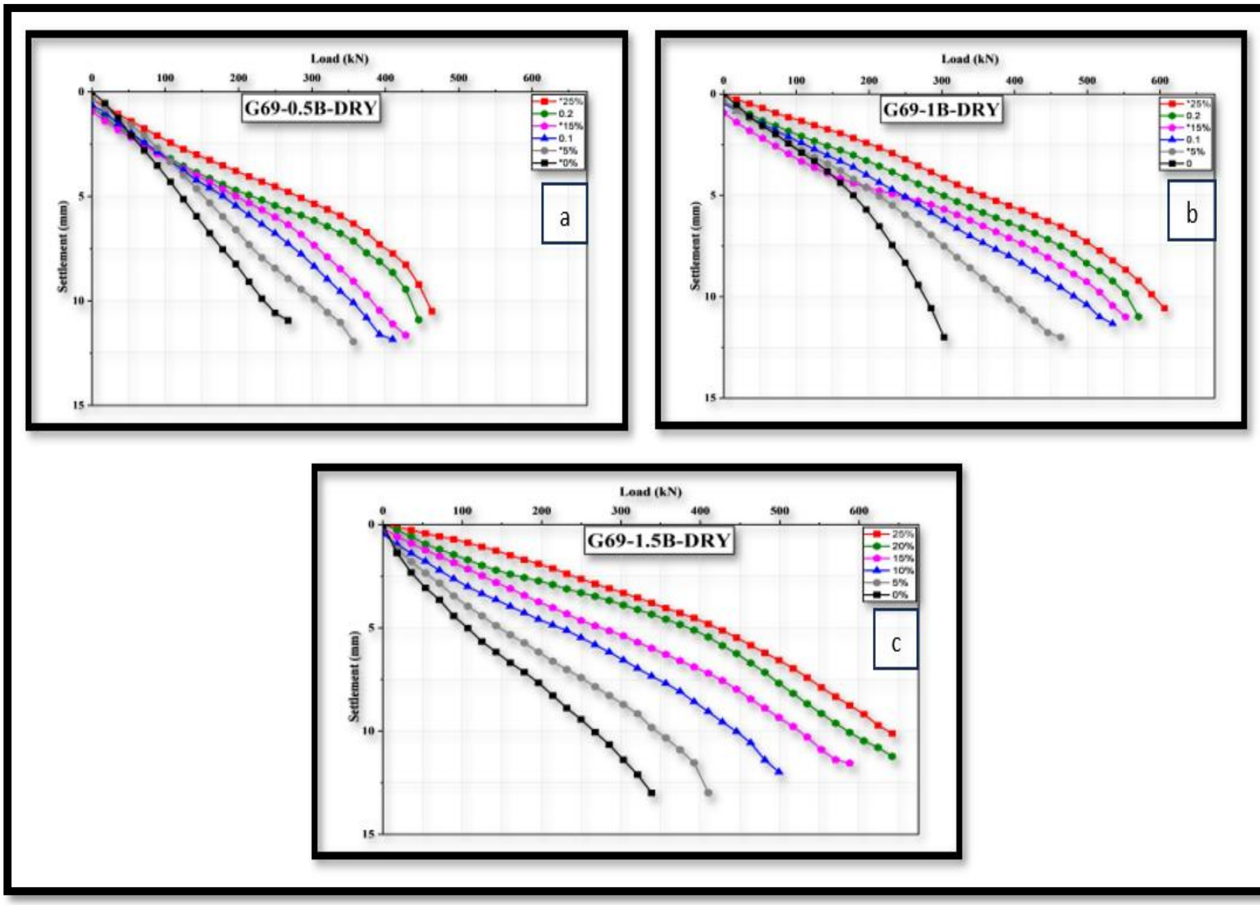

Figure 7. Shows the effect of adding RC at different concentrations into the dry gypsum soil (S3) to a depth of: a) 0.5D, b) 1D and c) 1.5D.

As can be seen from Figure 8 (a, b and c), recycled concrete (RC) is highly effective in controlling the settlement response of the circular footing design constructed in the saturated gypseous soil S3, which contains about 69% gypsum. In water-saturated soils, gypsum dissolution renders the natural cementation bonds ineffective, making the untreated soils more prone to deformation and collapse. However, the higher the RC content, the better the load-bearing capacity and the lower the settlement.

The reductions in settlement were approximately 10–40% at a treatment depth of 0.5D, 9–45% at 1.0D, and 8–50% at 1.5D, at an applied stress of approximately 250 kPa. As RC content rose to 25%, the settlement dropped from approximately 12.5 mm to 7.5 mm at 0.5D, from 13.2 mm to 7.2 mm at 1.0D, and from 13.0 mm to 6.5 mm at 1.5D.

The improvement is likely due to the void filling, particle interlocking, increased matrix stiffness, and the continued cementitious activity of the recycled concrete. To further enhance performance, the treatment depth was increased by incorporating more of the footing stress influence area into the stabilized zone, thereby decreasing compressibility and improving load distribution.

Overall, the settlement reduction was significant for both RC content and treatment depth, with 25% RC and 1.5D showing the best performance. The results showed that the improvement under saturated conditions remained lower than under dry conditions due to high gypsum dissolution. Still, it confirmed that RC is an effective, sustainable cementitious material for highly gypseous soils under soaking conditions.

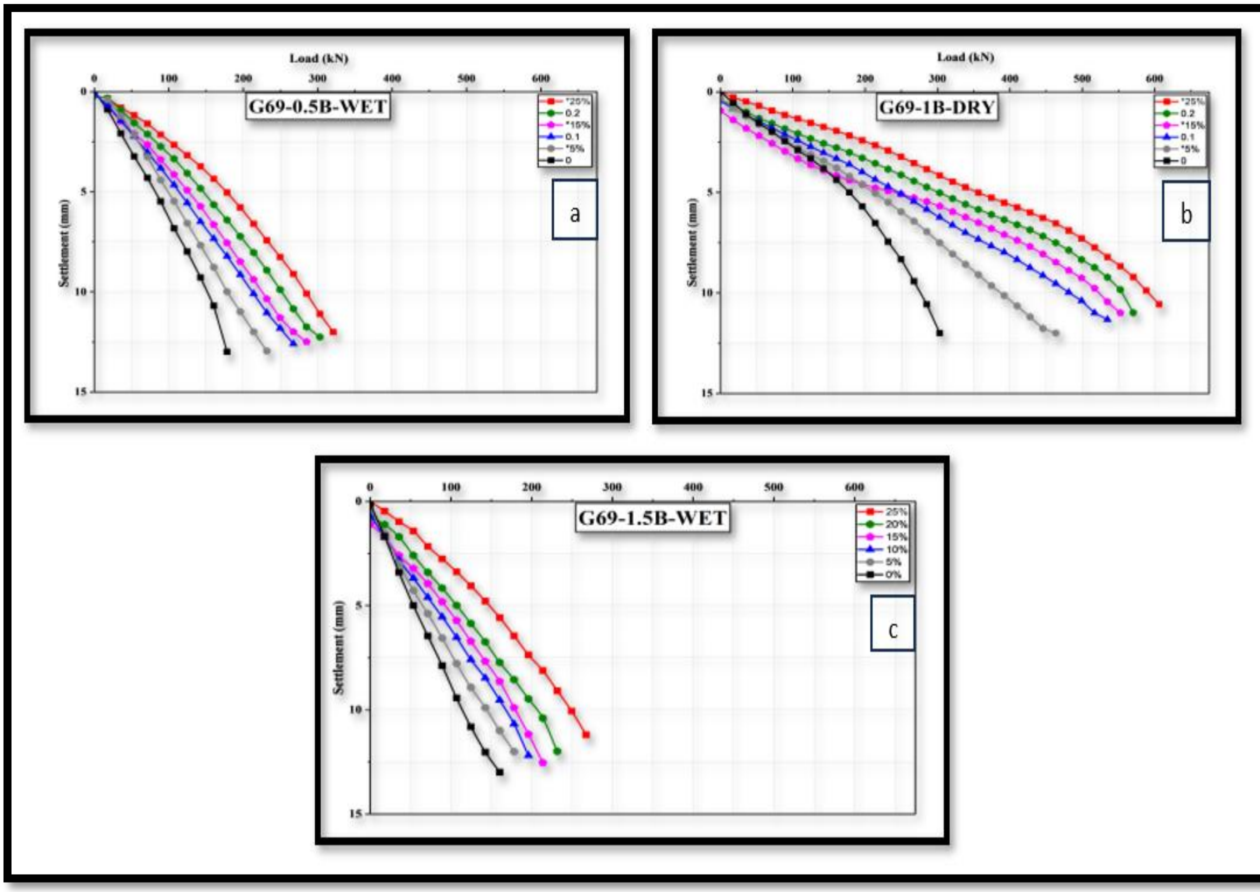

Figure 8. Shows the effect of adding RC at different concentrations into the saturated gypsum soil (S3) to a depth of: a) 0.5D, b) 1D and c) 1.5D.

A comparative evaluation of the load - settlement behavior for soils S1, S2 and S3 shows that gypsum content and moisture condition have a decisive influence on the foundation performance. Under dry conditions all soils showed improvement in the behavior due to the cementation effect of gypsum with an increase in the gypsum content providing greater initial stiffness. Accordingly, soil S3 (69% gypsum) showed the highest resistance to deformation for low to moderate stress levels, followed by S2 (47%) and then S1 (30%). However, even though the stiffness of S3 was higher, its response was relatively brittle at higher loads.

In contrast, under saturating conditions, an entirely different trend was found. The dissolution of gypsum reduced significantly the strength and stiffness of soil and hence caused more settlement. The severity of this effect was directly proportional to gypsum content and as a result S3 showed the highest settlement and collapse potential, followed by S2, whereas S1 showed the most stable behavior due to its lower gypsum content.

The effectiveness of recycled concrete (RC) in settlement reduction was apparent in all soils, but the performance of RC varied depending on gypsum content and moisture conditions. Under dry conditions the gain was more significant in S1 and S2, while S3 showed a rather gradual increase because of the high cementation already in place. Under saturated conditions, RC substantially reduced settlement in all cases, but efficiency declined with addition of gypsum because of the overriding effect of dissolution.

In terms of the depth of treatment, increases in depth from 0.5D to 1D and 1.5D consistently resulted in improvement in performance across all soils. The optimum depth range was found generally to be 1D to 1.5D where a greater proportion of the stress influence zone was incorporated within the treated layer that resulted in a better load distribution and lower deformation. Overall, the highest performance was found in dry S3 in high RC content and deeper treatment depth owing to its high stiffness, while S1 showed the most stable and reliable behavior under all the conditions, especially under saturation. Contrarily, the least favorable condition was saturated S3 with a combination of high gypsum content with water caused severe loss of strength and maximum settlement.

4. CONCLUSION

The settlement performance of circular footings in gypseous soils with varying gypsum content under both dry and saturated conditions was evaluated, and the effects of recycled concrete (RC) content and treatment depth were investigated. The key findings are summarized below:

1. The use of recycled concrete generally enhanced the performance of footings, particularly in terms of settlement and load-carrying capacity, with the greatest improvement achieved at RC contents of 20–25%.
2. Further increasing the treatment depth from 0.5D to 1.0D and 1.5D, the 1.0D–1.5D range was the most effective.
3. It was found that the higher the gypsum content, the higher the apparent stiffness in dry conditions due to natural cementation, and the lower the apparent stiffness in saturated conditions due to gypsum dissolution, which led to a significant loss of bonding and, therefore, settlement. With increasing gypsum content, the severity of this effect increased, as S3 was most susceptible to collapse.
4. The improvements provided by RC have been primarily attributed to void filling, improved particle interlocking, increased matrix stiffness, and residual cementitious activity. However, it was less effective under saturated conditions due to gypsum dissolution.
5. The optimal condition was dry, with 25% RC at a depth of 1.5D, whereas saturated S3 was the worst due to moisture and high gypsum content, leading to degradation.

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BIOGRAPHIES OF AUTHORS

	Shahla Natiq Izzat is a master's student at Tikrit University/College of Engineering/Civil Engineering, currently employed at the Ministry of Education, School Buildings Department. Her research interests include sustainability, waste recycling, improving gypsum soils in the region in general, auditing and scheduling building and project plans, cost and time studies, and sustainability in construction projects. Her can be contacted at email: SNEpeng12@st.tu.edu.iq
	Naser Abed Hassan was born in Iraq in October 1985. I obtained a Master's degree in Civil Engineering with a specialization in Soil Mechanics and Foundation Engineering from the University of Tikrit, Iraq, and a Ph.D. in the same field from the University of Tikrit. My primary area of specialization is Soil Mechanics and Foundation Engineering. I am currently working at the Ministry of Higher Education and Scientific Research, University of Tikrit, College of Engineering, Department of Civil Engineering. My interests include various applications of engineering principles in the fields of education, sustainability, and pollution. My current research focuses on soil treatment and improvement of its properties using additives, as well as soil dynamics and soil stabilization under dynamic loading conditions. I am also committed to supporting academic and technical advancement in my field, university, and college. He can be contacted at email: Naser.a.hassan@tu.edu.iq