



COMPARITIVE EVALUATION OF RECYCLED BENTONITE, FLY ASH AND CUTBACK ASPHALT FOR MITIGATING COLLAPSE POTENTIAL OF IRAQI GYPSEOUS SOILS

*Ahmed M. Ali¹, Zainab H. Shakir², Arkan Obaid³, Mohammed A. Al-Neami⁴ and Huda K. Kareem⁵

^{1,2,3, and 4}College of Civil Engineering, University of Technology, Baghdad, Iraq; ⁵University of Education, Iraq

*Corresponding Author, Received: 20 June 2026, Revised: 24 July 2026, Accepted: 28 July 2026

ABSTRACT: In arid and semi-arid regions of Iraq, and due to increasing urbanization, gypseous soils may dissolve upon wetting, resulting in much volumetric collapse and serious structural damage. An experimental analysis using a one-dimensional oedometer test was conducted using recycled materials, namely pile-drilling-induced bentonite, fly ash and cutback asphalt, to improve and mitigate the collapse resistance of gypsum-rich soils. The study aims to assess the effects of these additives on the settlement properties and their collapse potential. A total of twenty-one model collapsibility tests were performed at an inundation stress of 200 kPa on untreated (9.2, 21.5, 33% of gypsum percent) and treated soil samples with varying contents of additives, at 5, 10, and 15%. The current study shows that the water-holding capacity of soil is enhanced by the presence of bentonite, while fly ash promotes pozzolanic bonding and particle interlocking. The results also revealed the soil with 33% of gypsum content can be classified as problematic, while non- problematic case was found for the case of 9.2% based on the severity indication. Although each material plays a crucial role in improving the performance of gypseous soil upon wetting, fly ash has the edge over the rest; the collapse potential drops to 0.91% with 15% fly ash added for 21.5% gypsum. In brief, the recycled material has been confirmed as a sustainable stabilizer for gypseous soil, offering a viable alternative in problematic soils.

Keywords: Gypsum soil, Collapse potential, Recycled materials, Cutback asphalt, Pozzolanic bonding

1. INTRODUCTION

Collapsible soil, a type of gypsum soil, can be one of the major problematic soils in Iraq. Despite being known for its challenging characteristics, such as low shear strength, low density, weak bonding material. It is widely distributed and covers large areas of the ground surface layers, reaching up to 30% of Iraq, especially in the western and southern parts. It undergoes a considerable volume contraction upon wetting, and pose substantial risks to construction and transportation infrastructure, leading to costly damage and maintenance challenges [1]. The terminology gypseous soil differs to the collapsible soil, where the latter behavior is controlled by its gypsum content and salt dissolution potential rather than the mechanical response to wetting. The urbanization increasing in such a rich soil area has recently forced engineers to enhance and select alternatives for deep foundation and other costly ground improvement techniques. In response, the use of cost-effective recycled materials can be a promising strategy in the field of collapsible soil stabilization without substantial environmental concerns [2].

The functional importance of mitigating soil

collapse is underscored by the systematic occurrence of pavement settlements and multi-story building-supported footings, underscoring the need for effective stabilization methods to assess geotechnical implications and optimize eco-friendly strategies [3]. Historically, soil improvement techniques have advanced from mechanical and chemical methods developed in the mid-20th century to more sustainable and cost-effective admixture-based methods [4]. The use of recycled materials, such as bentonite slurry induced during bored-pile construction or fly ash produced by coal combustion, can be of vital significance, as it reduces waste disposal issues and supports the ninth goal of sustainable development regarding industry, innovation, and infrastructure. It promotes the use of recycling in soil remediation and converts waste into practical, ready-to-use alternatives. Despite numerous studies on specific additives, a comprehensive comparison is lacking on geotechnical performance and environmental considerations [5]. Controversies exist regarding the optimal stabilizer; for instance, fly ash, with its pozzolanic activity, offers environmental benefits but may be less effective than conventional substances such as bentonite or asphalt components.

Additionally, the influence of treatment on key parameters, such as the coefficient of consolidation and collapse potential, is reported inconsistently [6].

The pozzolanic nature of the fly ash, especially when it is in contact with calcium-rich soil, tends to increase soil density through cementitious bonds if it is blended with small quantities of cement. Baloochi and Sakr used the fly ash with CKD with percentages of 5, 10, and 15% to stabilize two cases of collapsible soils, natural and artificial soil prepared with kaolin [7,8]. The fly ash additive was able to minimize the collapse potential of the both soils from 15 to 4.4%, Fly ash significantly improves shear strength parameters and effectively reduces collapse potential by reducing infiltration pathway, with optimal performance typically observed at dosages between 12% and 20% [9,10]. Bentonite decreases both the compression and recompression indices and reduces the coefficient of consolidation by filling soil voids and decreasing permeability, The collapse has shown a substantial reduction of 70-82% when adding kaolin and bentonite in sequence. The highly gypsum soil needed 10% of the bentonite to minimize the severity classification from moderate to non-risk [11,12]. Albusoda investigated the effect of mixing varying amounts of bentonite on the settlement characteristics and collapse potential of 25% gypsum soil [13]. The results indicated a remarkable reduction in the compression C_c and rebound C_r indices, with a 47% reduction when the bentonite content is 3%. Along the same lines, the collapse behavior shifted from moderate severity to a no-problem case, the smaller bentonite plates readily fill the voids between gypsum crystals and sand grains, resulting in a lower initial void ratio and greater capacity to hold water. Kadhim investigated the effect of cutback asphalt (MC-30) on the shear strength and collapse potential of 34% gypsum soil from the Tikrit district, Al-Qadisiya city [14]. The results indicated that the optimal binder content is 6-8% to reduce collapse potential and achieve the maximum soaked CBR test value. Gypsum-rich soil, according to [15], can undergo significant deterioration due to salt dissolution and the loss of interparticle bridges, the asphaltic component may delay the initiation of collapse. Despite its vital contribution, this area has received minimal scholarly attention to date.

Eventually, there is a research gap in the holistic topic of gypseous soil, and few studies have captured the complex soil-additive interactions across varying gypsum contents and optimal material content. besides, the novelty focuses on investigating the combined effect of these additives for improving the collapse properties of gypseous soil by adopting essential laboratory tests under 200 kPa inundation

loading level, and well identifying the mechanism by which the cut asphalt reduces time-dependent salt dissolution. Unlike previous studies that relied on the material-based additives. Integrating the mechanical effect of these recycled materials remains lacking and challenging, and offer new insight into growing sustainable treatment methods. The content of the subsequent sections of the article is described

2. RESEARCH SIGNIFICANCE

Recent breakthroughs reveal that recycled materials used to mitigate collapsible soil offer cost-effective, applicable alternatives, and high sustainability. Urbanization in such soils incorporating infiltration patterns and drainage systems integrated into a remediation plan, along with the constraint of accessibility in some urban areas, makes shifting towards additive stabilization practical. Geotechnically, specific materials such as fly ash and bentonite have distinct properties with water barrier and pozzolanic activity tailored to reduce the sudden dissolution of gypsum upon wetting. Thus, the research aims to evaluate the effectiveness of fly ash, bentonite, and cutback asphalt in reducing the collapse potential and settlement characteristics of gypseous soil with two problematic gypsum contents, 21.5 and 33%, tailored specifically, for shallow foundations and pavement subgrade applications.

3. MATERIALS USED AND SAMPLING PROCESS

3.1 Natural Gypseous Soils

The soil samples were brought from Tikrit District, Salahaddin governorate, 140 Km northeast of the capital Baghdad, and taken from a depth of 0.75-1m below ground level at different locations of the area of interest, as shown in Figure 1.



Fig. 1 Sampling locations of the collapsible soil

Three categories of soil have been collected and experimentally tested to quantify their gypsum content and other physical and chemical properties. The gypsum content is calculated from the SO_3 proportion specified in [16]). Deeper soil sampling is done to prevent organic matter from interfering with the targeted soil.

The specimens selected for the tests were placed in an oven at 45 C° to maintain the water of crystallization in the salt grain and alleviate the mineralogical transformation of the $CaSO_4 \cdot 2H_2O$ [17]; in the same context, diluted kerosene is used as a pore fluid instead of the distilled water used in the pycnometer to prevent the gypsum dissolution in the specific gravity test ASTM D854. The results for the physical and chemical properties of gypseous soils are listed in Table 1 and Figure 2.

Table 1. Physical and mechanical properties of soils

Property index	Soil1	Soil2	Soil3
Specific gravity G_s	2.57	2.50	2.47
Max dry unit weight γ KN/m ³	18.0	17.2	16.3
Optimum moisture content %	15.6	16.8	18.65
Initial void ratio e	0.51	0.47	0.45
Plasticity index $P. I\%$	22	NP	NP
sand, silt and clay %	2.3, and 97.7	5.3, and 94.7	5.8, and 94.2
Soil classification (USCS)	CL	CL	CH

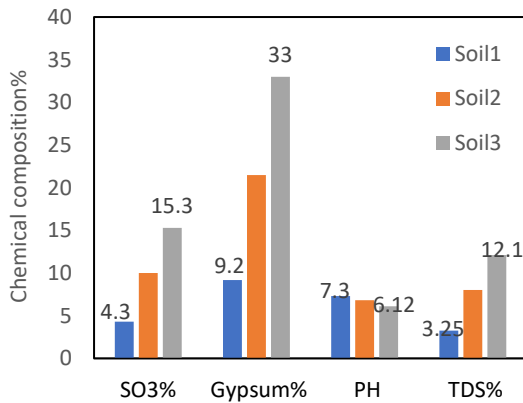


Fig.2 Chemical composition of the gypseous soils

3.2 Recycled Bentonite

This material was obtained from a site in Abu-Ghraib city, where bored piles are installed. It is an absorptive aluminum phyllosilicate clay, generally composed of montmorillonite. Its distinct colloidal properties, such as a higher water-holding capacity where the specific surface area is 732 m²/g, make the material-based slurry practical for soil stabilization

and excavation support in piling construction [18]. Once spent, turn out to be polluted with other soil particles, considerably altering the physical and chemical characteristics. The other characteristics involve a plasticity index of 119.2, a free swelling index of 11.6 ml/2g, and a pH value of around 9, beside the lose of ignition range of 10-12. Thus, recycled materials may exhibit increased density and viscosity, as well as decreased plasticity index and thixotropy, compared to the original bentonite [19].

3.3 Fly Ash

Class F commercial fly ash, with a fine, grey, powdery nature, was used due to its pozzolanic reaction, availability, and low cost. Some physical properties were tested, 2.24 is a specific gravity of the material, and an average value of the finesses less than 18.5%. As shown in Table 2, the major elemental composition of the material shows the presence of silicate, Alumina, and Hematite, each exceeding 70%, which supports the ASTM C618 requirement to classify the material as class F. The microstructural illustrations from SEM tests of bentonite and fly ash are shown in Figures 3 and 4.

Table 2. Chemical composition of the fly ash material

Symbol	Proportion%
SiO ₂	54.2
Al ₂ O ₃	20.1
Fe ₂ O ₃	8.41
MgO	2.46
CaO	1.86
K ₂ O	1.20

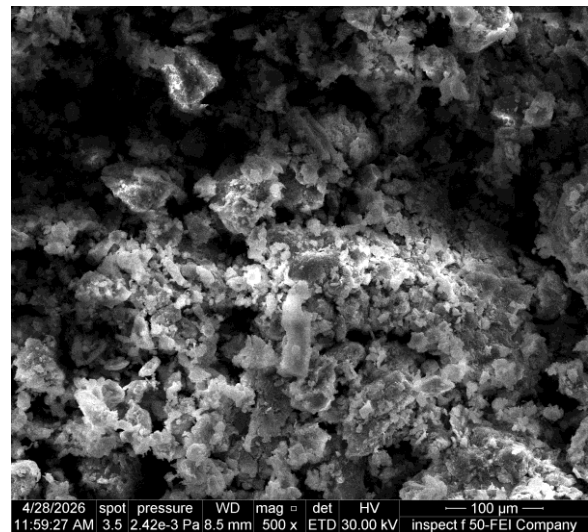


Fig.3 SEM Microstructural Analysis of recycled bentonite

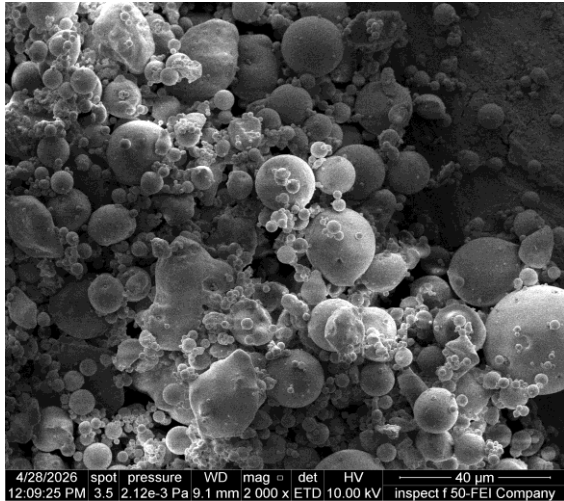


Fig.4 SEM Microstructural Analysis of fly ash

3.4 Cutback Asphalt MC-30

The type of asphalt used in this study is Medium Curing Cut-Back (MC-30) Liquid asphalt produced by Al-Dora Refinery in Baghdad Governorate. This type is manufactured at Al-Dora Refinery by mixing (90.6%) asphalt cement and (9.4%) Kerosene. More details are shown in Table 3.

Table 3. Properties of cutback asphalt (MC-30)

Property index	Value
Cold patch mix-medium curing	MC-30
Penetration on Residue @ 25 °C (100 g, 5 s)	200
Residue by distillation %	≥70
Kinematic viscosity at 60 °C (mm ² /s)	30-60
Solubility in CCL4	≥99%

3.5 Preparation of Soil Samples and Testing Method

The three soil specimens were air-dried, pulverized, and thoroughly mixed to achieve homogeneity prior to testing. For this study, samples were prepared at a dry unit weight of rounds 16 to 18 kN/m³, corresponding to a field relative compaction of 72%. Distilled water was utilized during the experimental procedures. The soil was placed in the consolidation cell ring, which has a diameter of 75mm and 19mm thick in layers and compacted statically, as illustrated in Figure 5 and tested according to ASTM D5333.

4. MODEL TESTING PROGRAM FOR STABILIZED GYPSEOUS SOIL

The model tests are divided into two parts. First, a series of tests was conducted on untreated natural soil with varying gypsum contents (9.2%, 21.5%, and

33% by weight) to assess soil collapsibility. Second, soil stabilization was investigated using three materials—recycled bentonite, fly ash, and cutback asphalt—to improve the properties of gypsum soils, as shown in Figure 6. These additives were incorporated at 5%, 10%, and 15% of the soil weight.



Fig.5 Soil preparation steps in single collapse test

The selected percentages were based on economic considerations and findings from previous studies in this field, reporting that the selected range provides the balance between the practical performance and the feasible applicability. Beyond the 15% of the additive, they noticeably increase the overall compressibility of the soil, and reduce the feasibility for a full-scale treatment. In this study, the treatment process was applied only to soils with gypsum contents of 21.5% and 33%. The collapse potential at 9.2% gypsum content was approximately 1%, classifying the soil as non-problematic. Thus, additives were not used at this percentage, as will be discussed in the next section.



Fig.6 Soil samples stabilized with fly ash (left), bentonite (middle), and cutback asphalt (right) used in collapse tests

5. EXPERIMENTAL TEST RESULTS

5.1 Influence of Gypsum Content of natural Soil

In this section, three models of natural soil at gypsum content (GC) of (9.2, 21.5, and 33%) were examined in this analysis. The soil at these percentages is classified as having slight, moderate, and high gypsum content, respectively. While gypsum was found to increase the strength of the tested clays, especially in the dry state due to bonding between particles, these bonds are broken down upon wetting of the soil. Thus, to evaluate the severity of gypseous soil when subjected to water, collapse potential values were obtained for each soil case and extracted from Figure 7 and Eq.1.

$$CP (\%) = \left[\frac{\Delta e}{(1 + e_b)} \right] \times 100 \quad (1)$$

The symbols of Δe and e_b are the change of void ratio before and after inundation at 200 kPa, and void ratio before wetting, respectively. From above, it can be noted that the collapse potential (C_p) increases with increasing gypsum content. So, the collapse deformation values were 1.0, 3.89, and 6.05%, corresponding to gypsum contents of 9.2, 21.5, and 33%, respectively. As mentioned before and according to [20], soil states are classified as no problem ($C_p = 0$ to 1), moderate problem ($C_p = 1$ to 5), and problem ($C_p = 5$ to 10) for gypsum contents of 9.2%, 21.5%, and 33%, respectively.

It is observed that a higher gypsum content is associated with a higher collapsibility potential, and this is attributed to the fact that the amount of gypsum in the soil skeleton is affected upon wetting or saturation.

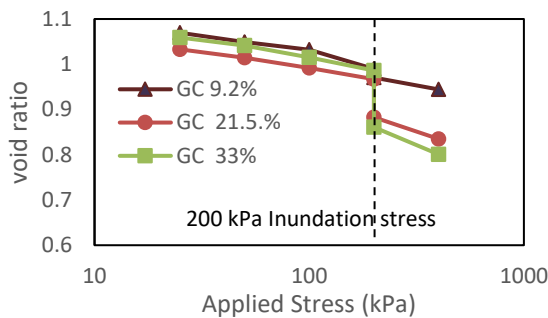


Fig.7 Collapse test results for untreated soils

This leads to the significant dissolution of the salts, as the gypsum content in the soil is higher. Accordingly, at the highly gypseous soil, the voids left in the soil body will be more than in cases where small amounts of gypsum are used. Thereafter, after dissolving the salt to saturation, the volume of soil particles that have vanished will increase the volume of voids; consequently, the density will decrease, and the collapse will primarily occur [21].

5.2 Stabilization Process Using Recycled Materials

5.2.1 Effect of recycled bentonite on soil collapse

The effectiveness of bentonite in reducing collapse potential is primarily determined by hydration rather than cementitious curing [22]. Accordingly, treated specimens require adequate moistening to ensure uniform hydration and a reduction in hydraulic conductivity within 24 hours [23]. The measured gypsum content of the soil is 9.2%, which falls within acceptable limits and is not expected to adversely affect soil particle packing upon wetting. Consequently, no specific gypsum-related soil improvement is required in the next analysis.

To investigate the enhanced behavior of gypseous soil, recycled bentonite was applied to reduce the soil's collapsibility. Six oedometer tests were performed on two soil samples containing 21.5% and 33% gypsum, with three tests conducted for each condition. The influence of the bentonite-gypsum soil mixture on collapse behavior is illustrated in Figures 8 and 9. The test results demonstrate that adding bentonite to gypseous soil substantially affects the collapse potential. It was found that the collapsibility potential is decreased from 6.05% without an additive (33% gypsum content) to certain values of (3.85, 2.95 and 1.9%) at different bentonite contents equal to (5, 10 and 15%). While for the case of (21.5% gypsum content), the value of C_p is reduced from 3.89% to (3.2, 2.65 and 0.85%) at the same percentages of additive.

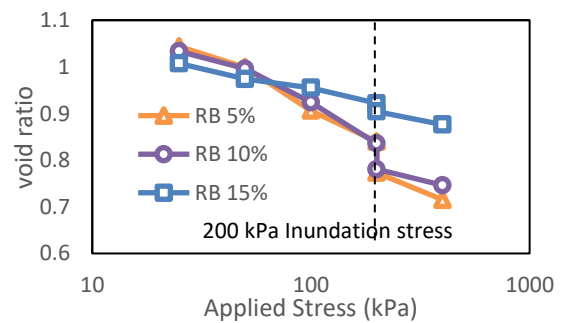


Fig.8 Collapse test for treated soil with gypsum content of 21.5% using bentonite

The reason for this reduction in collapse potential is that bentonite can retain large amounts of water due to its tendency to swell upon wetting. Hence, when the bentonite surrounds the gypsum particle, the water that moves in the voids will be forced and absorbed by the bentonite. However, the ability of water to reach the gypsum particles will be minimized, and as a result, the collapse potential will also decrease. Moreover, the effect of bentonite in

reducing the collapse potential is more pronounced at 20% gypsum content. The collapse potential is reduced by 0.85% at an additive content of 15%; at this level, the soil classification has been converted from problematic to no problem. On the other hand, for 30% gypsum content, a remarkable reduction in collapse potential was observed even at 15% additive content. The value of C_p has decreased dramatically to 1.9%, and the soil can be classified as a moderate problem.

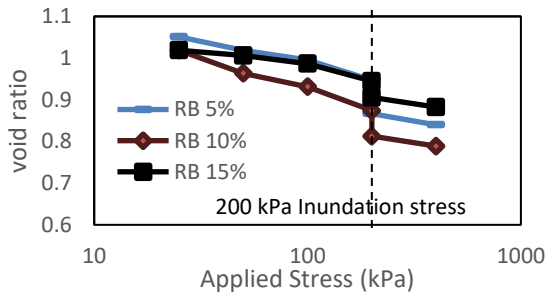


Fig.9 Collapse test for treated soil with gypsum content of 33% using bentonite

5.2.2 Effect of cutback asphalt on soil collapse

The treatment mechanism of liquid asphalt products involves increasing cohesive strength and reducing water penetration due to the physical presence of asphalt. Figures 10 and 11 present the results of six oedometer tests stabilized with CBA.

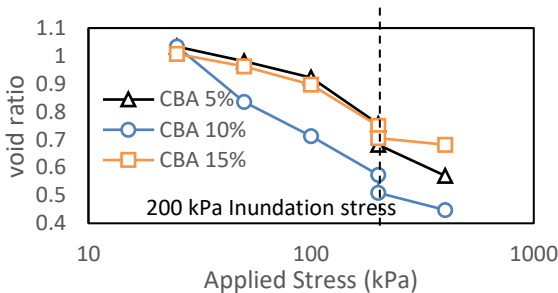


Fig.10 Collapse test for treated soil with gypsum content of 21.5% using cutback asphalt

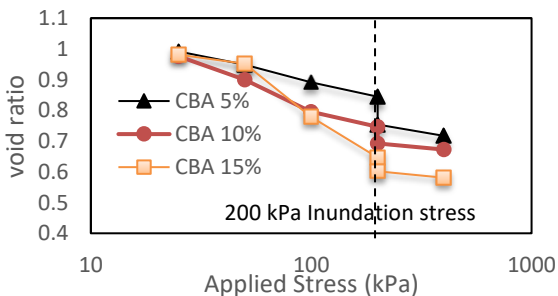


Fig.11 Collapse test for treated soil with gypsum content of 33% using cutback asphalt

The selection of cutback asphalt (CBA) content is determined by the desired degree of soil improvement. In this study, gypseous soils containing 21.5% and 33% gypsum were separately stabilized using varying amounts of cutback asphalt (5%, 10%, and 15%).

At 21.5% gypsum content, collapsibility potential decreased from 3.89% in untreated samples to 3.6%, 3.1%, and 2.05% with 5, 10, and 15% cutback asphalt, respectively. For samples with 33% gypsum, the collapse potential was reduced from 6.05% to 4.35%, 2.6%, and 2.15% at the same additive levels.

Tests on soil mixed with cutback asphalt demonstrate a significant reduction in collapse potential when liquid asphalt is incorporated. A lower binder content offers less effectiveness against filtration, while collapse potential values declined with increasing additive amount. Optimum stabilization of the collapse potential was observed at 15% cutback asphalt. This should be incorporated with an environmental assessment and cost analysis, especially for large-scale improvement. The reduction in collapse potential was 47% and 64% for soils containing 21.5% and 33% gypsum, respectively. In both cases, the soil classification shifted to the lower limit of moderate problematic (C_p 1-5%), particularly in the case with 33% gypsum content. The mechanism of gypseous soil treatment by cutback asphalt relies on three primary aspects. The waterproofing theory states that liquid asphalt within soil voids creates a hydrophobic barrier. Coating individual soil particles protects gypsum particles, prevents water infiltration, and enhances bonding after the asphalt component evaporates, thereby reducing salt dissolution and, in turn, decreasing soil collapsibility. This coincides with the outcomes reported by [24,25].

5.2.3 Effect of fly ash on soil collapse

The results of the collapsibility tests obtained with the treatment of some gypseous soils and presented in Table 3 suggest that fly ash type F can be used for this purpose. Based on collapse potential, the reductions were estimated in the range of (3.9–0.91) % for gypsum 21.5% and (6.05–1.76%) for 33%.

Table 4. Collapse results for fly ash-treated soil

Index Property	value		
Fly ash percent %	5	10	15
Collapse potential % for Gc 21.5%	3.42	2.44	0.91
Collapse potential % for Gc 33%	3.02	2.04	1.76

The improvement was also more noticeable as the fly ash content increased, demonstrating a gradual modification of soil structure [26]. The

maximum collapse reduction for both gypseous soils was two- to threefold at salt contents of 21.5% and 33%, respectively. It is due to the formation of cementitious products that strengthen interparticle contacts, rather than to the pore-filling ability of fly ash, which is limited by alumina and silica components that make them difficult to rearrange during wetting. Specimens with higher gypsum content would have a greater residual collapse potential due to the dominance of weaker gypsum bonds that are susceptible to dissolution when saturated.

5.3 Optimizing the Recycled Materials effectiveness in Reducing Collapsible Soil

The degree of improvement of gypseous soil primarily depends on the amount of treatment material and the nature of the interaction between the two substances. In the current study, both additives (cutback asphalt and bentonite) have proven highly effective in the treatment of gypseous soil. Hence, to determine the most suitable material for stabilizing collapsible soil, the degree of improvement for each material was evaluated. Figures 12 and 13 show the relationship between the collapse potential and additive content.

Bentonite-stabilized soil exhibited only minor improvement at 33% gypsum content. At 21.5% gypsum, bentonite demonstrated superior performance compared to cutback asphalt.

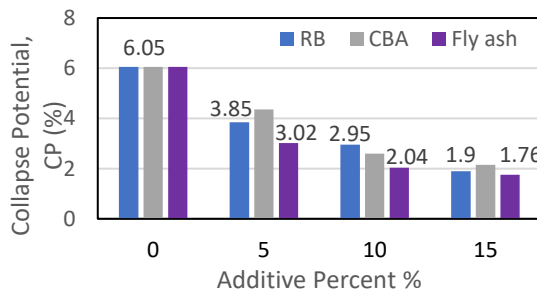


Fig.12 Effect of type and additive content on the collapse potential for a gypseous soil with 33%

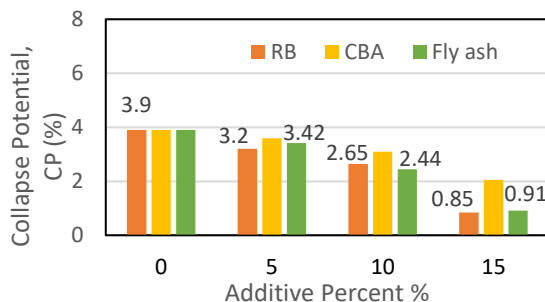


Fig.13 Effect of type and additive content on the

collapse potential for a gypseous soil with 21.5%

Particularly, with a 15% additive which improved soil conditions from moderate concern to no observable issues. Fly ash consistently yielded the most favorable results, especially at higher dosages. The collapse severity was reduced to a level significantly below 1, compared with that of the untreated soil.

5.4 Influence of Additive Content on the Coefficient of Salt Dissolution

The coefficient of consolidation (C_v) quantifies the rate at which saturated clay or other soils undergo consolidation, or compaction, in response to increased pressure. Earlier, recycled materials were added to gypseous soil to reduce the collapse potential, and the resulting soil was then compared with established criteria to assess severity. The coefficient of consolidation represents the apparent rate of deformation and might serve as a quantitative index for evaluating collapse potential, and is estimated using the traditional Taylor method. Additional details are provided in Figures 14 and 15.

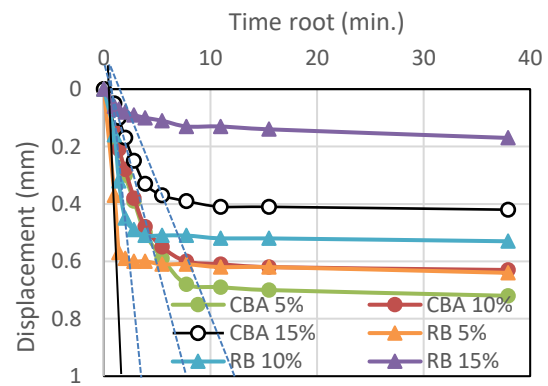


Fig.14 Effect of additive content on the coefficient of consolidation at a gypsum content of 21.5%

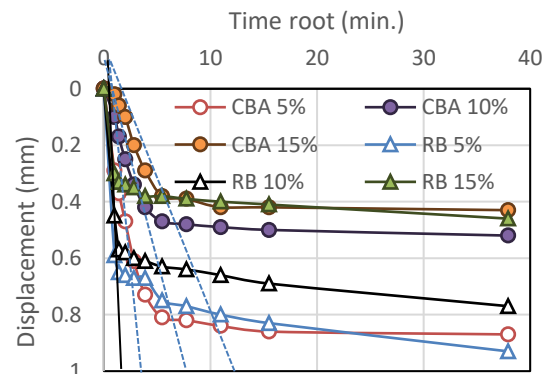


Fig.15 Effect of additive content on the coefficient of

consolidation at a gypsum content of 33%

The value of C_v depends on the degree of consolidation (U_z), sample thickness (H), and t_{90} , the time required to reach 90% consolidation. The value of t_{90} is graphically estimated, by plotting an initial tangent to the displacement-time curve, followed by a second line with a slope of 15% greater than the initial line. The point at which this line intersects to the curve represent the time of 90% consolidation. Treatment materials were incorporated into the soil to demonstrate their ability to delay the consolidation rate.

The data indicate that the time required to reach 90% consolidation increases with the amount of additive, regardless of whether cutback asphalt or bentonite is used. Fly ash does not possess intrinsic waterproof properties. Class F fly ash relies mainly on the pozzolanic reaction rather than on pore filling. Its effectiveness in reducing soil collapse and enhancing bonding is greater than its ability to isolate salt particles from water especially when compared to other materials. This effect can be attributed to the coating, bonding and pore-filling mechanisms. The treatment materials reduce water's ability to contact the surfaces of gypsum particles. Moreover, the additives form a thin layer around soil particles, which slows the interaction between water and gypsum. As a result, salt dissolution requires a longer testing period to achieve measurable settlement. The values of the coefficient of consolidation (C_v) for different additive contents are presented in Table 5.

Table 5. Consolidation rate parameters for additive-treated gypseous soils

Index Property	value		
Cutback asphalt %	5	10	15
C_v for Gc 21.5% in m^2/day	0.011	0.007	0.0051
C_v for Gc 33% in m^2/day	0.016	0.0068	0.0042
Recycled Bentonite %	5	10	15
C_v for Gc 21.5% in m^2/day	0.05	0.034	0.028
C_v for Gc 33% in m^2/day	0.085	0.054	0.048

The results demonstrate that the displacement rate under a 200 kPa stress decreases as the additive content increases. This trend is evident from the time values recorded throughout the test. The values of C_v for cutback asphalt-stabilized soils are generally found to be fourfold lower than their corresponding values using 5% recycled bentonite. This influence becomes more pronounced at 15%, where the cutback material shows a high, surpassing range of 4-11 times across all gypsum contents. The coating property is more effective at reducing the dissolution rate than the holding capacity of

bentonite. For soil containing 21.5% gypsum, 90% consolidation is achieved in 4.41 minutes with 15% RB and in 24.0 minutes with 15% CBA. Alongside, for soil with 33% gypsum, t_{90} values are 30.25 minutes for cutback asphalt and 2.54 minutes for bentonite at the same additive content.

The test results indicate that cutback asphalt is effective in reducing the rate of collapse during soil saturation. This efficiency may be attributed to the physical properties of liquid asphalt, which is considered a viable alternative material in soil testing, particularly for soils containing high concentrations of water-soluble salts. Also, these materials may increase particle cohesion due to absorption between the soil and the liquid material.

Overall, the results of this study demonstrate a significant reduction in collapse deformation and salt dissolution rate when recycled materials such as fly ash, bentonite, and liquid asphalt MC-30 are utilized. At a 5% additive content, fly ash and recycled bentonite exhibit 5-11% lower residual collapse potential than other materials when stabilizing untreated soil with a gypsum content of 21.5%. The effects of fly ash and recycled bentonite are comparable, reducing collapse by 56-59% relative to CBA at a 15% additive content. In soils with 33% gypsum content, fly ash outperforms other additives, reducing collapsibility by 18 to 31% more than CBA at 15% and 5% respectively. Fly ash is also more effective than recycled bentonite, mitigating collapse potential by 7% and 21% at additive contents of 15% and 5%, respectively. Regarding salt dissolution rate, the coating effect of CBA surpasses that of bentonite at 10% with t_{90} values approximately 78-87% higher than those recorded for recycled bentonite-treated soil at gypsum contents of 21.5% and 33% respectively.

The current findings are consistent with previous relevant studies [9,11], which reported that the critical gypsum content is about 10-20%, and that the collapse potential can be reduced by 13-83% when using the stabilizing materials mentioned above, depending on the dosage and additive type. The difference from some related studies that concluded the optimal dosage of CBA is 4-5%, and around 20% fly ash as stabilizers [6]. This can be attributed to differences in gypsum content, curing time, and chemical composition of the materials used. However, although fly ash shows superiority over RB and CBA in mitigating collapse potential, especially for highly gypsum-content soils due to its significant pozzolanic interaction that stiffens the salt-atom-connected bridges, it still reveals insufficient properties for time-dependent gypseous soil characteristics. Thus, the optimal materials should account for both trends in the stabilized collapsible

soil and environmental concerns, as well as their contribution to sustainable development.

6. CONCLUSIONS

The influence of recycled bentonite, cutback asphalt, and fly ash was investigated through a series of laboratory tests to assess their dosages and gypsum content on the collapse deformation and time-dependent properties of collapsible soil. All the materials demonstrated a reasonable contribution to mitigating collapsibility, and the fly ash surpassed the other additives, reducing the collapse potential by 70% compared to the untreated case of 33% gypsum using 15% of fly ash. Using 10% of the additive content is sufficient to reduce the severity of gypseous soil from severe to moderate for any material type based on the thresholds suggested by [20]. Cutback asphalt has proved to be a viable material for lowering the rate of deformation, with a Cv. value 10 times lower than that of bentonite at 15%, where the values of Cv. are 0.048 and 0.0042m²/day for RB and CBA, respectively. The fly ash and bentonite demonstrated their effectiveness in reducing collapse and, to a lesser extent, in slowing the rate of salt deformation; on the other hand, the liquid asphalt showed a completely contrasting trend in the wetting-induced soils. In sum, there is no single optimal dosage capable of governing and mitigating all the essential issues of collapsible soil; each material is tailored to treat a specific condition.

7. REFERENCES

1. Turan C., Javadi A. A., Vinai R., and Beig Z. R. Geotechnical Characteristics of Fine-Grained Soils Stabilized with Fly Ash, a Review. *Sustainability Journal*, 14(24), 2022, pp. 1-31.
2. Shaker Z. H., Ali A. M., Abdulrasool, A. S., and Hasan H. M. A Parametric Study on the Use of Construction Wastes in Stone Columns Placed in Peaty Soil. *The 5th International Conference on Buildings, Construction, and Environmental Engineering: Bcee5, AIP Conference Proceeding. Amman, 19 November, 2024: 020016*. pp. 1-9.
3. Daraei A., Sherwani A. F. H., Faraj R. H., Mohammad, S., Kurdo, S., Zare, S., and Mahmoodzadeh A. Stabilization of Problematic Soil by Utilizing Cementitious Materials. *Journal of Innovative Infrastructure Solutions*, 4(33), 2019, pp. 1-11.
4. Ray P. and Roy S. An Analytical Review on Comparative Analysis of Ground Improvement Using Various Admixtures. *Journal of Mines, Metals and Fuels*, 71(11), 2024, pp. 1939–1953.
5. Bahmyari H., Ajdari M., Vakili A. The Role of the Cement, Lime, and Natural Pozzolan Stabilizations on the Mechanical Response of a Collapsible Soil. *Transportation Infrastructure Geotechnology Journal*. 8, 2021, pp. 452–472.
6. Ahmad. F., Beenish., Khalil U. R., Ahmad. A., and Siffat A. M. Effect of Bentonite on the Coefficient of Consolidation of Soil, *International Journal of Emerging Trends in Engineering Research*, 9 (9), 2021, pp. 1230-1234.
7. Baloochi H., Aponte D. and Barra M. Soil Stabilization Using Waste Paper Fly Ash: Precautions for Its Correct Use. *Applied Sciences*, 10(23), 2020, 8750, pp. 1-15.
8. Sakr M., Ahmed M.A. N. and Asal, D. Behavior of Collapsible Soils Improved by Fly Ash and Cement Kiln Dust. *Journal of Engineering Research*. 4, 2020, pp. 20-25.
9. Jassam M. G., Hussein I. S., and Ameen A. N. Enhancing the Engineering Properties of Gypseous Soil Utilizing Fly Ash. *Engineering, Technology & Applied Science Research*, 15(4), 2025, pp. 25922–25927.
10. Mahmood T. E., Hamed M. H., and Ibrahim A. K. Geotechnical Behaviour of Gypseous Soil Treated by Geopolymer Additives, *Diyala Journal of Engineering Sciences*, 16(4), 2023, pp. 110-119.
11. Karim H. H., Schanz T., and Nasif M.H. Improving collapsibility and Compressibility of Gypseous Sandy Soil Using Bentonite and Kaolinite. *Engineering and Technology Journal*, (30)18, 2012, pp. 3141-3153.
12. Liu Z., Bolton M., Oh E., Liu Y. and Ong D. E.L. Effect Of Cement and Bentonite Mixture on the Consolidation Behavior of Soft Estuarine Soils. *GEOMATE Journal*, 18(65), 2020, pp. 49-54.
13. Al-Busoda B. S. Z. Treatment of Collapsibility of Gypseous Soil. *Journal of Engineering*, 14(3), 2008, pp. 444–457.
14. Kadhim A. J. Stabilization of Gypseous Soil by Cutback Asphalt for Roads Construction, *Journal of Engineering and Development*, 18(1), 2014, pp.46-67.
15. Barazanji A. F. Gypsiferous Soils of Iraq, PH.D. Thesis, 1973, State University of Ghent, Belgium.
16. British Standards Institution. BS 1377: London, Methods of test for soils for civil engineering purposes, 1993, Part 5, pp. 8-22.
17. Head, K. H. 1992. *Manual of Soil Laboratory Testing*. Volume 1: 1992, Soil Classification and Compaction Tests. 2nd ed. New York: Halsted Press, pp. 22-26.
18. Akhtar M. S. Bentonite and Polymeric Support Fluids Used for Stabilization in Excavations.

- Turkish Journal of Engineering, 7 (4), 2023, pp.338-348.
19. Jiao C., Diao Y., Zheng G., Liu Y., Huang J., Zhang Y., Zhao L. Reuse of Drilling Waste Slurry as the Grouting Material for the Real-Time Capsule Grouting Technique. *Materials*, 16(4), 2023, 1540, pp. 1-18.
 20. Clemence S. P. and Finbarr A. O. Design considerations for collapsible soils. *Journal of the Geotechnical Engineering Division*, 107(GT3), 1981, pp.305–317.
 21. Chen X., OK Y., and Wu J. Effects of Different Organic Materials Application on Soil Physicochemical Properties in a Primary Saline-Alkali Soil, *Eurasian Soil Science*, 53, 2020, pp.798–808.
 22. Soumia B., Khelifa A., and Ouassila B. Treatment of a collapsible soil using a bentonite–cement mixture. *Studia Geotechnica et Mechanica Journal*, 40(4), 2018, pp. 233–243.
 23. Wang Q., Cui Y. J., Tang A. M., Barnichon J. D., Saba S. and Ye W. M. Hydraulic conductivity and microstructure changes of compacted bentonite/sand mixture during hydration. *Journal of Engineering Geology*, 164, 2013, pp. 67–76.
 24. Hacheem A., Al-Khyat Z., Saeed, S. K. A., and Fartosy S. H. L. Stability of gypseous soils slopes stabilized with cutback asphalt and lime using the finite element method. *Magazine of Civil Engineering*, 17(8),2024, 13207, pp.1-12.
 25. Shakir Z. H. Improvement of gypseous soil using cutback asphalt. *Journal of Engineering*, 23(10), 2017, pp. 44–61.
 26. Alsafi S., Farzadnia N., Asadi A., and Huat B. K. Collapsibility potential of gypseous soil stabilized with fly ash geopolymer: Characterization and assessment. *Construction and Building Materials Journal*, 137, 2017, pp.390–409.

Copyright © Int. J. of GEOMATE All rights reserved, including making copies, unless permission is obtained from the copyright proprietors.
