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Evaluation of Cement By-Pass Dust-Treated Desert Sand as Low-Permeability Barrier Material in Landfill Facilities

Yahya Hamza Karagoly[1], Alyaa Ali Ameri[2], Wathiq Jasim Al-Jabban[3], and Jinan Jawad Alwash[4]

[1] Lecturer, Civil Engineering Dept., Faculty of Engineering, Univ. of Babylon, P.O. Box 4, Al Hillah 51002, Babil, Iraq, E-mail: eng.yahya.karagoly@uobabylon.edu.iq (corresponding author).

[2] Lecturer, Civil Engineering Dept., Faculty of Engineering, Univ. of Babylon, P.O. Box 4, Al Hillah 51002, Babil, Iraq, E-mail: eng.alyaaa.ali@uobabylon.edu.iq

[3] Lecturer, Environmental Engineering Dept., Faculty of Engineering, Univ. of Babylon, P.O. Box 4, Al Hillah 51002, Babil, Iraq, E-mail: wathiq.aljabban@uobabylon.edu.iq

[4] Assistant Professor, Civil Engineering Dept., Faculty of Engineering, Univ. of Babylon, P.O. Box 4, Al Hillah 51002, Babil, Iraq, E-mail: eng.jinan.jawad@uobabylon.edu.iq

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Abstract: The use of desert sand in its natural state as barrier material in engineered landfill systems is not possible due to its high hydraulic conductivity and low strength. Therefore, improvement of this type of soil is essential. The current study includes treatment of sand with different Cement By-Pass Dust (CBPD) percentages: 4%, 8%, 12%, 16%, 20%, 24%, 28%, and 36% by dry weight of mixture. The prepared mixtures were assessed in terms of their compaction, hydraulic conductivity, and unconfined compressive strength properties. The results indicated that adding CBPD initially reduced the optimum moisture content and then a continuous increase was observed, while the maximum dry unit weight showed an upward trend and peaked at 20% CBPD and then decreased. The hydraulic conductivity decreased with increasing CBPD amount and with time. For CBPD contents equal to or greater than 20%, the hydraulic conductivity dropped to less than 10^{-9}m/s. The values of unconfined compressive strength of the cured mixtures at various periods exhibited an increasing trend with increasing CBPD percentages and were found to be greater than 200kN/m^2. The desert sand treated with 20% CBPD is a promising material that meets the practical requirements for hydraulic conductivity and unconfined compressive strength for the development of engineered landfill barrier systems.

Keywords: Desert Sand, cement by-pass dust, barrier system/material, hydraulic conductivity, unconfined compressive strength.

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1. Introduction

In many parts of the world, some locally available soils are considered problematic and pose significant challenges for construction and infrastructure development. These challenges may be encountered in different applications due to one or more of the material’s key characteristics, such as permeability, strength, and volumetric changes (Baghdadi et al., 1995; Rezaei et al., 2012), or because the material does not meet the performance requirements of a specific application. For instance, desert sand is considered problematic soil (Al-Refeai and Al-Karni, 1999) and cannot be used directly in some geotechnical and geoenvironmental applications.

1.1. Desert Sand

Large quantities of desert sand are found in numerous regions across the globe, especially within arid and semi-arid climates. In Iraq, desert sand covers vast areas, accounting for more than 30% of the total land area (Altameemi et al., 2023). In general, the desert sands are not suitable for use in many construction applications, such as waste containment systems, engineered landfill facilities, dams, roads, and structures, due to their loose structure, difficulty in compaction, low strength, and high permeability (Al-Aghbari and Dutta, 2005; Al-Aghbari et al., 2009; Al-Homidy et al., 2024). On the other hand, because desert sands have low water retention, they exhibit low shrinkage during desiccation (Daniel and Wu, 1993).

In desert areas, sandy soil is sometimes the only option and can be expensive to replace. Thus, this type of soil needs to be treated and improved before use in various applications. One method for modifying and stabilising sandy soils is the addition of various materials, such as cement, lime, fly ash, lime kiln dust, Cement By-Pass Dust (CBPD), bitumen emulsions, bentonite, and polymer emulsions (Elipe and López-Querol, 2014; Elbaz et al., 2019). Cement By-Pass Dust as a waste material can be considered a cost-effective alternative to other materials (Ismail and Belal, 2016). Thus, mixtures of desert sand and cement by-pass dust can be investigated and assessed as a potential alternative barrier material for use in engineered waste landfills.

1.2. The use of CBPD

Previous investigations have revealed that the CBPD is one of the important chemical additives and has recently been approved or suggested for use in various applications such as stabilization and modification process of soils, concrete and cement industry, agriculture field, construction of barrier systems for landfills, operations of mine reclamation, filler material in asphalt concrete mixes, and waste treatment (EPA, 1993; Adaska and Taubert, 2008; Rahman et al., 2011; Elbaz et al., 2019; Al-Asi and Asi, 2021). The CBPD is a waste material generated in significant amounts throughout the production of Ordinary Portland cement, and also known as Cement Kiln Dust (CKD) (Sharkawi, 2015; Barnat-Hunek et al., 2018). Globally, cement is produced at a rate of approximately 4 billion tonnes annually (Hegde, 2024), and the amount of CBPD annually is about 10-14 percent of the produced cement (Karagoly et al., 2025). In Iraq, about 350,000 tonnes are generated annually as an industrial by-product resulting from Portland cement production processes (Mosa et al., 2017).

It is a fine powder, ranging in color from off-white to light brown and consists of micron-sized particles. These fine dust particles are released with the gases emitted during the calcination process of feed materials and are collected in the rotary kiln using a particulate emission control device (e.g. electrostatic precipitators) throughout the clinker production phase (Kunal et al., 2012). The CBPD is composed mainly of lime, alumina, and silica, and is considered a pozzolanic material (Mohamed, 2002; Naik et al., 2003). The pozzolanic reactions are affected by chemical composition of the CBPD (Bhatty et al., 1994; Miller and Zaman, 2000; Pranshoo Solanki et al., 2007), which can vary widely based on several factors such as raw materials, combustion fuel, kiln design and equipment configuration (Kunal et al., 2012). The CBPD is generally considered a non-hazardous material due to its relatively low potential for heavy metal leaching (Rahman et al., 2011; Sharma, 2017). However, it poses major challenges in terms of storage and environmental pollution (Baghdadi et al., 1995; Siddique and Rajor, 2014). Its reuse across various applications offers cost-effective, sustainable solutions (Elbaz et al., 2019).

When CBPD comes into contact with water, a hydration process occurs in which lime is the main reactive component, and considerable initial heat is emitted (Czapik et al., 2020). Hydration of CaO results in calcium hydroxide ($CaOH_2$) and Friedl's salt (aluminum-calcium chloride salts) (Liyanage and Gamage, 2021).

1.3. Engineered Landfills

A landfill is a hydraulic barrier system and a waste containment facility designed to dispose of solid waste and isolate it from the surrounding environment, consequently protecting the environment from pollutants. The engineered landfill consists of two main components, the liner system, and the cover system. The liner system is the most important part of a landfill, used for waste disposal and to prevent the migration of leachate and gas into the surrounding soil, groundwater, and environment. It includes a bottom liner and side wall barriers. The cover system should protect the environment by reducing waste exposure, minimizing the leachate generation (by preventing water infiltration and accidental intrusion), controlling gas emissions, and protecting people and wildlife from exposure to pollutants.

The effectiveness of a landfill depends primarily on the performance of the low permeable barriers incorporated into the liner and cover systems. These barriers typically consist of natural or treated soil, geosynthetic materials, bituminous materials and industrial by-products. Avery and Crooks (1987) and the United States Environmental Protection Agency (USEPA, 1998) specify that the hydraulic conductivity of the compacted barrier layer in liner and cover systems must be very low, i.e., equal to or less than 10^{-9}m/sec. In addition, to ensure long-term structural stability and durability, an unconfined compressive strength of at least 200kPa is recommended as a practical standard (Daniel and Wu, 1993; Ryan and Day, 2002).

1.4. Previous Studies

In numerous regions worldwide, diverse materials have been used to enhance the properties of sandy soil and to explore the possible applications of the produced mixtures. Examples of the most common materials used in treatment of the sandy soils are cement (Bell, 1993 and Aiban, 1994), cement kiln dust (Baghdadi and Rahman, 1990; Freer Hewish et al., 1999), bentonite (O'Sadnick et al., 1995; Mollins et al., 1996), asphalt and cement/asphalt and lime (Wahhab and Asi, 1997), fly ash/ fly ash and lime (Taha and Pradeep, 1997; Consoli et al., 2001), cement, fly ash and fiber reinforcement (Kaniraj and Havanagi, 2001), polyethylene terephthalate fiber and cement (Consoli et al., 2002).

In this section, the focus will be on reviewing the literature on the treatment of sandy soils using the CBPD. Many researchers (e.g., McCoy and Kriner, 1971; Baghdadi and Rahman, 1990; Miller and Azad, 2000; Parsons et al., 2004; Sreekrishnavilasam et al., 2007; Peethamparan et al., 2008; Moses and Afolayan, 2013) have referred to the fact that the fresh CBPD is viable in the treatment of different types of soils and other civil/environmental engineering uses, due to its reactive lime component. Other researchers reported that the CBPD can be effectively used to treat geotechnically challenging soils (Sayah, 1993; Miller et al., 1997; Parsons et al., 2004; Keerthi et al., 2013; Nasr, 2015). The Behavior of sand-CBPD mixtures in terms of various engineering properties has also been studied by several researchers. Napeierala (1983) treated sandy soil with a CBPD for pavement subgrade works. Compressive strength increased with increasing cement dust, reaching 250kPa at 15% CBPD. Similarly, Baghdadi and Rahman (1990), Freer-Hewish et al. (1990), Baghdadi et al. (1995), and Al-Aghbari and Dutta (2005) studied and evaluated the properties of mixtures of desert sand CBPD for use in road construction. These studies reported that the stabilized sand showed significant improvement in California bearing ratio, unconfined compressive strength, and durability, and could be used as a base or sub-base material. Another study presented by Al-Refeai and Al-Karni (1999) assessed the impact of CBPD addition on the characteristics of dune sand. As CBPD increased, the study found that the permeability of treated dune sand decreased and the unconfined compressive strength increased. Al-Aghbari et al. (2009) mixed the desert sand with ordinary Portland cement and its industrial byproduct (cement kiln dust) to explore the possibility of using this type of soil as a foundation-bearing soil. The maximum dry density, shear strength parameters (C and Ø), and unconfined compressive strength were significantly improved. The collapsibility and compressibility properties of dune sand treated with different contents of CBPD, ranging between 4% and 20%, were also studied by Altameemi et al. (2023). These properties were reduced, and the compaction characteristics improved with the increase of CBPD. In addition, the study referred to the possibility of using the treated sand in different civil works.

Previous studies have mainly focused on evaluating the suitability of CBPD-treated sandy soils for use in road construction works and foundation bearing layers. On the other hand, research on the use of CBPD and desert sands mixtures in other applications, such as engineered waste landfills, is still limited. The current study addresses a critical geo-environmental challenge: providing suitable material for waste containment in resource-scarce regions. Our study focuses on two problematic materials: an industrial by-product of CBPD that must be disposed of and desert sands, which are unsuitable for construction. This research accurately assesses whether the combination of the two meets the necessary hydraulic and mechanical standards required for landfill liner and cover applications in arid/semi-arid regions (where importing suitable clay soil is economically and environmentally costly).

2. Materials and Method

2.1. Materials

2.1.1. Sand

The desert sand used in the current investigation was sourced from the desert region in the southwestern part of Iraq, Al-Najaf Province. The particle-size analysis of sand was performed according to ASTM D 422, and particle-size distribution is presented in Fig. 1. The tested sand was found to be Poorly Graded Sand (SP) following ASTM D2487 of the Unified Soil Classification System (USCS) and has effective Diameter (D10) = 0.14mm, mean Diameter (D50) = 0.35mm, Coefficient Of Uniformity (Cu) = 3.2, Coefficient of Curvature (Cc) = 0.84, and Specific Gravity (Gs) = 2.67. More detailed information is shown in Table 1. Based on the standard proctor method, the peak dry unit weight was 16.87kN/m^3, achieved at an optimum water content of 13.6%.

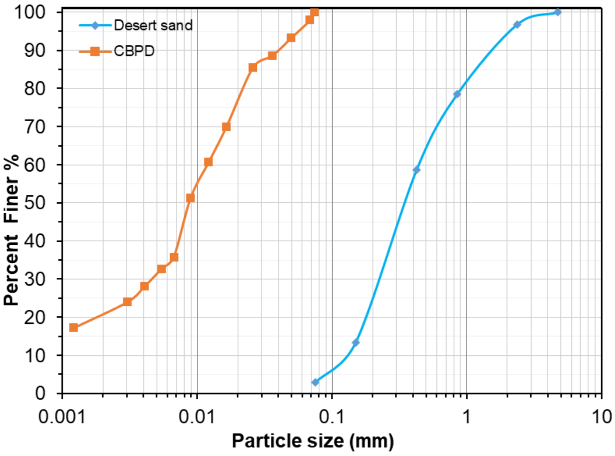


Fig. 1. Grain size distribution curves of desert sand and cement by-pass dust

2.1.2. CBPD

The CBPD was sourced from recent waste piles at the Al Kufa cement production plant situated in Al Kufa district, Al-Najaf Province, Iraq. The collected dust was stored in sealed containers prior to use. The CBPD is characterized by its brown color and a measured specific gravity value of 2.83. Particle size analysis was conducted according to ASTM D 422, and the particle size distribution curve is shown in Fig. 1.

The CBPD primarily consists of silt-sized particles and is classified as Silt of Low Plasticity (ML) under the USCS, as determined by its particle-size distribution (Fig. 1) and plasticity properties (Table 1). The chemical test results given in Table 2 showed that CBPD material contains a large amount of Calcium Oxide (CaO) that gives it good pozzolanic characteristics. Maximum compaction was achieved at a dry unit weight of 14.91kN/m^2 and a corresponding moisture content of 26%. In addition, the Hydration Modulus (HM) proposed by Kamon and Nontananandh (1991) was found to be 2.2, indicating that the CBPD is a reactive material, according to the HM values of about 1.7 and 2.4 for the alite and belite components, respectively. These components are considered as references and represent the common cementitious phases found in the Portland cement (Sreekrishnavilasam and Santagata, 2006).

Table 1. Properties of the CBPD and desert sand used in this study.

	CBPD	Desert Sand
Specific gravity, G_s	2.83	2.67
Atterberg limits		
Liquid limit, LL (%)	33	….
Plastic limit, PL (%)	29	….
Plasticity index, PI (%)	04	…..
Particle size distribution		
Sand (%)	….	97.1
Silt-size (%)	79	2.9
Clay-size (%)	21	….
Classification (USCS)	ML	SP
Compaction characteristics		
Optimum water content (%)	26	13.6
Maximum dry unit weight (kN/m^3)	14.91	16.87
Blaine fineness (cm^2/g)	0.36	….

Table 2. Chemical composition/properties of the CBPD under investigation

Oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	Na_2O	MgO	SO_3	Cl	LOI	pH	Free lime	HM[1]
%	14.82	4.2	2.4	47.21	1.1	0.63	2.3	9.27	…	15.76	12.2	3.52	**2.2**

[1]HM= $CaO/(Al_2O_3 + SiO_2 + Fe_2O_3)$

2.2. Method

2.2.1. Compaction tests

The standard proctor method (ASTM D 698) was followed to obtain compaction curves and relevant parameters for the desert sand, CBPD, and desert CBPD sand mixtures. The desert sand soil with various percentages of CBPD (4, 8, 12, 16, 20, 24, 28, and 36% by dry weight of the mixture) was carefully blended until a homogeneous color was achieved, and then the required water was added to aid mixing and compaction.

2.2.2. Hydraulic conductivity

Measurements of hydraulic conductivity were conducted utilizing the falling-head method in a rigid-wall permeameter for the desert sand CBPD mixtures, following the standard method ASTM D5856, and the constant head method for untreated desert sand soil in accordance with the standard method ASTM D2434. Specimens were prepared at various CBPD contents (0%, 4%, 8%, 12%, 16%, 20%, 24%, and 28%) by dry weight of the mixture and compacted in the mold at the corresponding standard proctor parameters. The specimens were immersed in tap water for at least 24 hours, and vacuum pressure was also applied to enhance saturation. The specimens were then connected to the tap water as a permeant liquid and tested under a hydraulic gradient ranging between 5 and 17. The hydraulic conductivity was measured during and after the saturation process and exhibited a decreasing trend over time. Tests were terminated when the change in the hydraulic conductivity became slight or negligible.

2.2.3. Unconfined compressive strength

Following the standard method ASTM D2166, Unconfined Compressive Strength (UCS) was assessed via a series of tests on cylindrical specimens of desert sand CBPD mixtures prepared with different densities and water contents corresponding to the maximum dry density and optimum water content for each added percentage of CBPD (8, 12, 16, 20, 24, & 28%). The test specimens were prepared by carefully mixing a specified amount of the dry CBPD sand mixture with water. The resulting mixture was placed in layers inside a split mold (38mm internal diameter and 76mm height), and a tamping rod was utilized to compact each layer until the mold was completely filled and the required density was achieved. Following the compaction, the cylindrical specimens were extracted from their mold, wrapped with a thin plastic film, sealed in plastic bags to prevent moisture evaporation and then kept inside a desiccator for periods of 7, 14, and 28 days for homogeneous moisture distribution and curing under controlled laboratory conditions: a temperature of 25±2ºC and a relative humidity of 50±3%. Triplicate tests were carried out for each combination of curing period and additive percentage. After curing, the specimens were loaded axially at a strain rate of 1.25%min (ASTM D2166). In addition, uncured compacted specimens were tested directly after preparing them. The mixtures containing 0% and 4% CBPD were not considered in the unconfined compression tests due to the difficulty of obtaining sound cylindrical specimens.

3. Results and Discussion

3.1. Compaction characteristics

Figs. 2, 3, and 4 present the compaction test results for desert sand CBPD mixtures containing various CBPD proportions: 4%, 8%, 12%, 16%, 20%, 24%, 28%, and 36% by dry weight of the mixture. Test results of sand and CBPD are also included in Fig. 2.

It is clear from Fig. 3 that as the percentage of CBPD increases, the optimum moisture content decreases, and the minimum value is reached at 8% of the additive. This reduction can be attributed to the CBPD partially filling the air voids in the sand matrix, thereby reducing the water required to lubricate the sand particles. For percentages of CBPD greater than 8%, a different trend is observed, and the optimum water content increases with further addition of CBPD. This behaviour can be attributed to the fact that increasing the cement by-pass dust added to the sand requires more water for hydration, and consequently, the water-holding capacity increases.

Fig. 4 states that adding different percentages of CBPD up to 20% increases the maximum dry unit weight, and the peak is reached. This trend can be attributed to the fact that the additive, having a specific gravity greater than sand, occupies the pore space, leading to an increase in the unit weight of mixtures. At higher CBPD levels, the maximum dry unit weight decreases. The reason behind this trend is that increasing the amount of additive makes the mixtures finer and has more pore space, resulting in increasing the imbibition of water and thus increasing the optimum water content of the CBPD sand mixtures. Since the water has a specific gravity lower than that of the sand and CBPD particles, the imbibed water reduces the maximum dry unit weight of the mixtures.

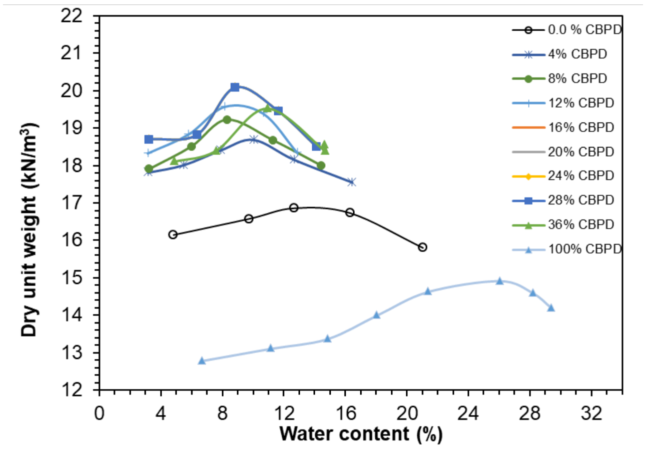


Fig. 2. Compaction curves for desert sand, CBPD, and desert CBPD sand mixtures

3.2. Hydraulic Conductivity

Fig. 5(a) shows the variation in hydraulic conductivity of the compacted mixtures against time at different percentages of cement by-pass dust added to the desert sand. Mixtures containing 0% and 4% of CBPD, with almost constant values of hydraulic conductivity, were recorded after saturation and up to the end of the considered test time. For mixtures containing 8% to 28% CBPD, the hydraulic conductivity exhibited a decreasing trend with time, particularly at high percentages of CBPD. In addition, with increasing additive amount, a longer time is required to reach steady hydraulic conductivity readings. This behaviour can be attributed to the hydration process of calcium oxide (CaO) occurring during exposure of cement by-pass dust to water. Ramachandran et al. (1964) and Liyanage and Gamage (2021) reported that the hydration process of the CaO leads to the formation and growth of Calcium Hydroxide ($Ca(OH)_2$) crystals. This process increases crystal size, thereby reducing pore size.Fig. 5(b) also reveals that increasing the amount of additive leads to a significant decrease in hydraulic conductivity. In addition to the effect of hydration products of calcium oxide, this reduction can also be attributed to the fact that the additive is very fine and helps to fill the voids and develop a new structure with smaller pore spaces that affect the flow paths available for water movement.

The experimental hydraulic conductivity data were analyzed using descriptive statistics in Microsoft Excel. The experimental data and analysis results are presented in Table 1 (Appendix) and show a rapid decrease in the hydraulic coefficient (k) with increasing CBPD% during both the saturation and steady-state phases. The coefficients of variation of 2.053 during saturation and 2.34 at steady state indicate higher variability and sensitivity of Coefficient of Permeability (k) to CBPD content, revealing that CBPD is a controlling factor causing hydraulic behavior and is effective in reducing permeability.

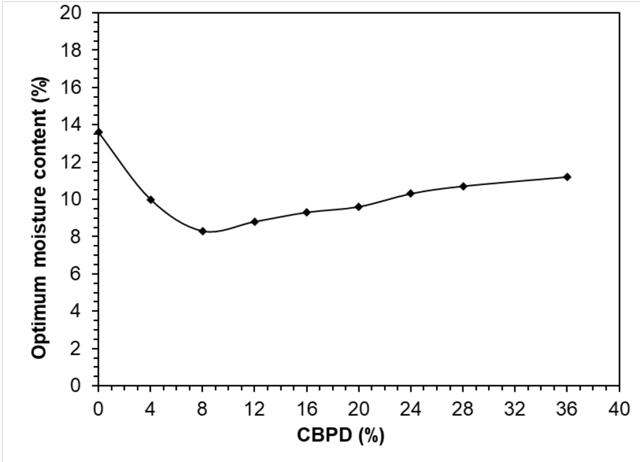


Fig. 3. Variation of optimum water content with percentages of CBPD

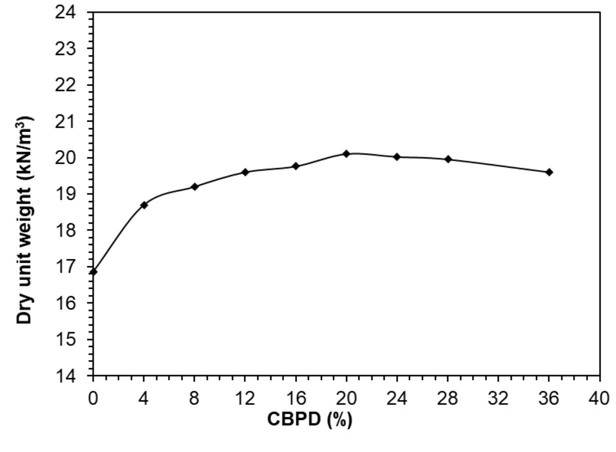


Fig. 4. Variation of dry unit weight with percentages of CBPD

Table 3. Compaction test results

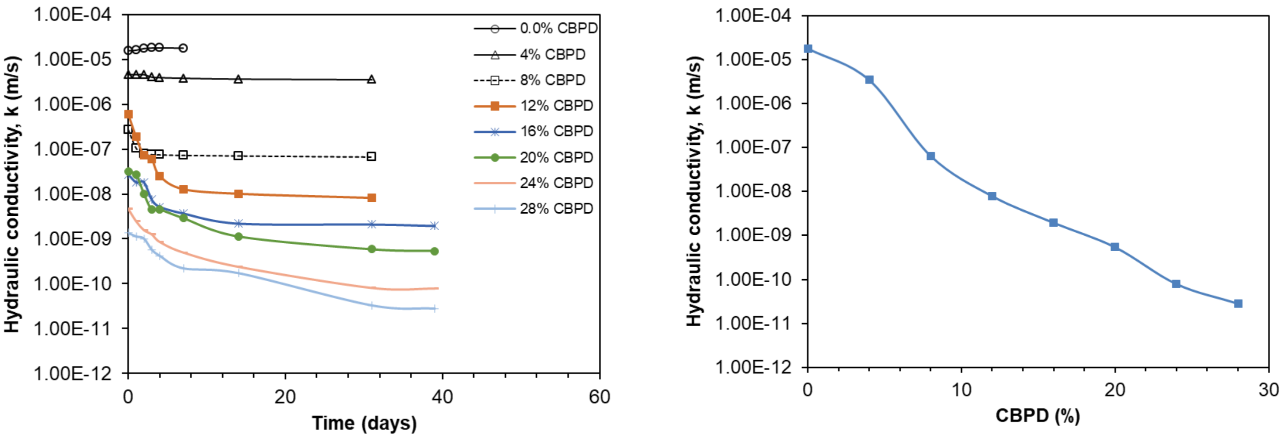
CBPD (%)	0	4	8	12	16	20	24	28	36	100
Max. Dry uint weight (kN/m^3)	16.87	18.7	19.2	19.6	19.76	20.1	20.02	19.95	19.6	14.91
O.M.C (%)	13.6	10	8.3	8.8	9.3	9.6	10.3	10.7	11.2	26

The final hydraulic conductivity values range from 1.77 * 10^{-5} to 2.81 * 10^{-11}m/s. At 20% CBPD and above, the values were found to be less than 10^{-9}m/s required for most barrier systems.

3.3. Unconfined Compression Strength (UCS)

The effect of curing time and additive amount on the unconfined compressive strength of mixtures was also investigated in this study. Figs. 7(a), (b), (c), (d), (e) and (f) illustrate the variation of UCS versus axial strain for several mixtures treated with various contents of CBPD: 8%, 12%, 16%, 20%, 24%, & 28%, respectively and cured at 0 days, 7 days, 14 days and 28 days. In general, all specimens cured under 7, 14, and 28 days clearly exhibited that the UCS increases with increasing strain and peaks at a certain value of strain, and then sharply reduces, giving a brittle failure mode, whereas in the uncured specimens, it increases and then gradually decreases, resulting in a ductile failure behavior.

Figs. 8 and 9 indicate the variation of UCS with curing time and cement by-pass dust added with different contents. From Fig. 8, it can be noticed that as the curing time increases, the unconfined compressive strength for almost all of the mixtures considerably increases, except for that treated with 8% CBPD, where an insignificant increase in the UCS is observed. The increase in the UCS can be attributed to cement by-pass dust hydration products that reduce the void space, enhance the interlocking between the sand grains and develop cohesive strength. Also, it can be seen from Fig. 9 that the unconfined compressive strength of specimens cured under different curing times (7, 14, and 28 days) significantly increases with an increase in additive content, while a slight increase in the UCS is observed for the untreated specimens.



(a) Variation of hydraulic conductivity with time

(b) Variation with percentages of CBPD

Fig. 5. Variation of hydraulic conductivity

From the results of descriptive statistical analysis shown in Table 2 (Appendix), it is obvious that the UCS is controlled by both CBPD% and curing time, with the curing time governing early development of strength. The maximum increase occurs during the first seven days, due to the rapid formation of hydration products. While increasing CBPD% mainly raises the final strength, it increases with longer curing times, revealing its long-term role in enhancing and supporting the cohesive soil matrix. High coefficients of variation also indicate a strong relationship between strength and curing time.

The unconfined compressive strength of uncured mixtures ranged between 15.4kN/m^2 and 195.8kN/m^2, depending on the added CBPD amount. While the mixtures cured at different periods showed high values of UCS, the minimum value was found to be 505.9kN/m2, which is higher than the practical strength requirements (200kN/m^2) recommended for most applications.

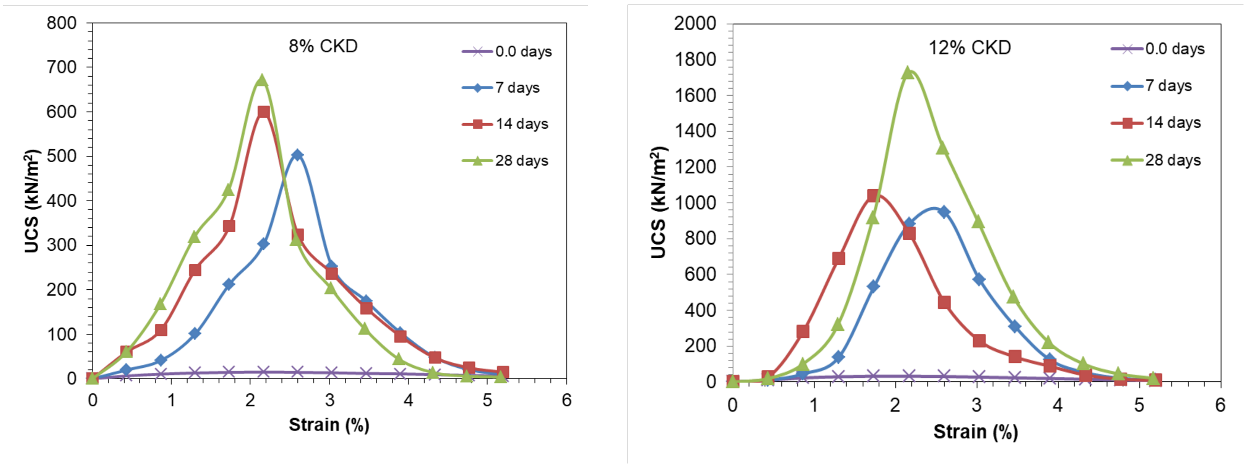
4. Conclusion

The present study was performed to explore the impact of CBPD addition on the behavior of desert sand in terms of compaction parameters, hydraulic conductivity, and unconfined compressive strength, as well as to evaluate the possibility of using the sand-CBPD mixture as a potential barrier material in engineered landfill facilities. The following conclusions were drawn from the experiments conducted in this study.

- Compaction parameters of mixtures were found to be significantly affected by adding cement by-pass dust (CBPD). Optimum moisture content dropped and then increased, while the maximum unit weight rose and then decreased.
- The hydraulic conductivity of mixtures was found to decrease with the addition of the CBPD and time. At 20% CBPD and above, the hydraulic conductivity was found to be lower than the specified standard value (10-9m/s) for barrier systems.
- At low content of CBPD, insignificant change in hydraulic conductivity was noted, and this can be attributed to the fact that the content is insufficient to fill the void spaces between the sand particles and produce appreciable hydration products.
- The unconfined compressive strength of mixtures was observed to increase when increasing the CBPD content and curing time, and at any increase, the cured USC value was greater than 200 kN/m2.
- The mixture containing 20% CBPD can be considered as a promising material for use in barrier layers as it meets the practical requirements in terms of hydraulic conductivity and unconfined compressive strength.

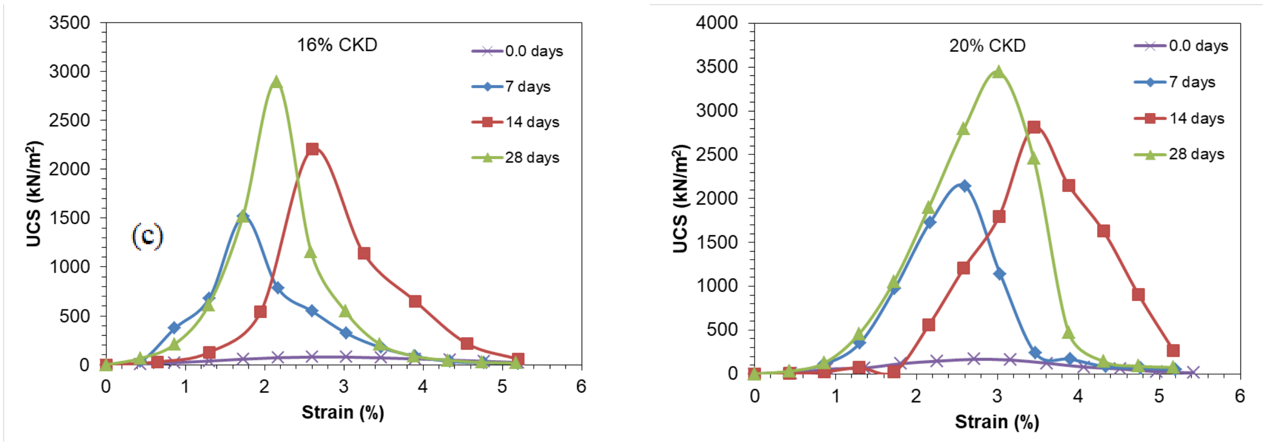
Although short-term laboratory results (up to 28 days) are promising, several critical aspects of practical application remain unverified and must be explicitly acknowledged. These include durability in severe environments, resistance to salts, heavy metals, and leaching behavior, and the influence of variations in the physical and chemical properties of the CBPD material (from various plants or production batches) on the reaction. The conclusions presented here are limited to the early-age performance of a single, specific material under controlled conditions. Therefore, it is recommended that future work concentrate on:

- Evaluating the long-term durability under cyclical environmental stresses.
- Investigating the effect of source variability on performance.
- Performing a quantitative analysis of leaching behavior for safety verification.
- Conducting pilot-scale experimental studies for developing a methodology for mixing, placement, and compaction.



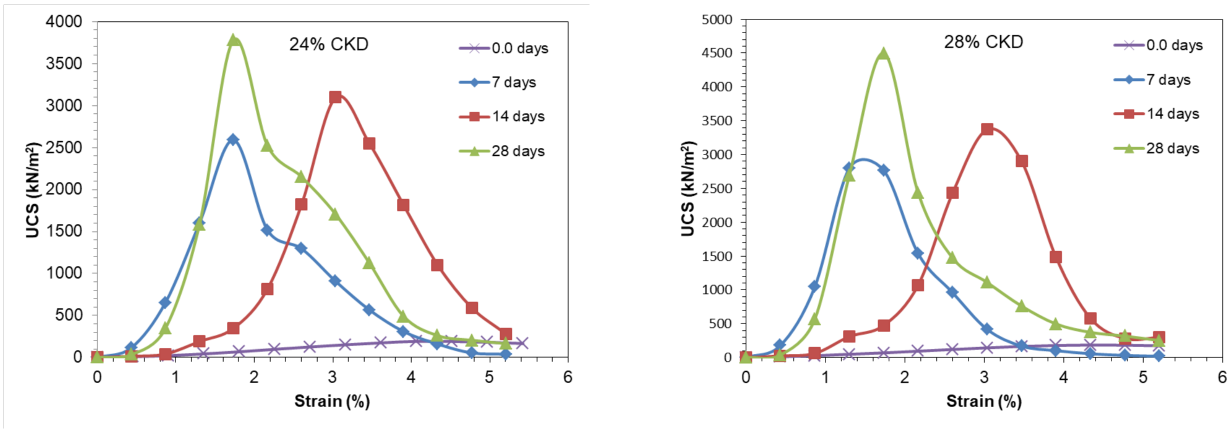
(a) 8%

(b) 12%



(c) 16%

(d) 20%



(e) 24%

(f) 28%

Fig. 7. Variation of UCS with axial strain at different percentages of CBPD

Author Contributions

Yahya Hamza Karagoly conceived and designed the study, conducted the experiments and collected the data, contributed to data interpretation, wrote the initial draft, and revised the manuscript. Alyaa Ali Ameri contributed to the study's conceptualization, data collection and interpretation, and drafting and editing the manuscript. Wathiq Jasim Al-Jabban assisted in drafting and revising the manuscript. Jinan Jawad Alwash supported the drafting and editing process of the manuscript. All authors critically reviewed and approved the final version of the manuscript, taking accountability for all aspects of the work.

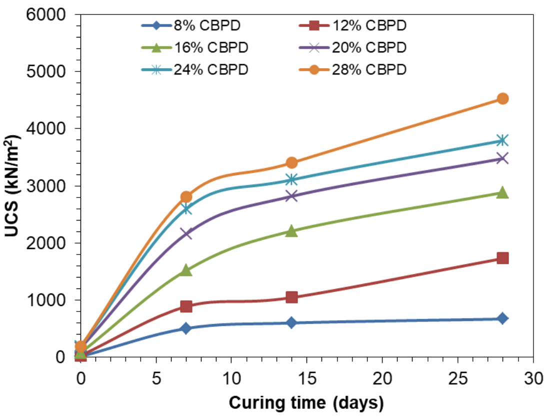


Fig. 8. Variation of UCS with curing time

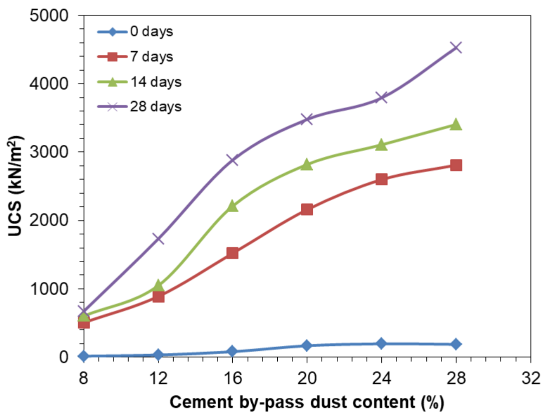


Fig. 9. Variation of UCS with CBPD

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Institutional Review Board Statement

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Declaration of Artificial Intelligence (AI) Tools

The authors confirm that no AI tools were used in the preparation of this manuscript.

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Yahya Karagoly holds a Ph.D. in Geoenvironmental Engineering (2020) from Cardiff University, UK, a master's of science in Geotechnical Engineering (2000) from Technology University, Iraq, and a Bachelor of Science in Civil Engineering (1997) from Babylon University, Iraq. He currently serves as a lecturer in the Department of Civil Engineering at Babylon University's Faculty of Engineering. His research interests focus on unsaturated soils, sustainable materials, reuse of by-products and problematic soils.

Alyaa Ali Ameri holds a master's in Geotechnical Engineering (2003) from Technology University, Iraq, and a Bachelor of Science in Civil Engineering (1999) from Babylon University/Iraq. She is currently a lecturer in the Department of Civil Engineering at Babylon University. Her research interests focus on gypsum soil remedies and the reuse of by-product additives as stabilizers for unstable soils.

Wathiq Jasim Al-Jabban holds a Ph.D. in Geotechnical Engineering (2019) from Lulea University of Technology -Sweden, a master's in Geotechnical Engineering (2001) from University of Technology, Iraq, and a B.Sc. in Civil Engineering (1998) from Babylon University, Iraq. He is currently a lecturer in the Department of Environmental Engineering at Babylon University's Faculty of Engineering. His research interests focus on soil stabilization and improvement techniques, chemical stabilizations, and the reuse of by-products in soil treatment.

Jinan Jawad Alwash is an Assistant Professor in the Department of Civil Engineering, Faculty of Engineering, Babylon University. Educational background is: bachelor's in Civil Engineering from the University of Technology in Baghdad /Iraq, in 1987. She earned a master's in Construction Materials from the University of Babylon in 2006. She has several publications in international journals, including Civil Engineering and Technology and the Journal of Mechanical and Production Engineering Research and Development. She has participated in several national conferences. Her main areas of interest are the durability of concrete, improving the properties of construction products by using fibers and additives, self-compacting concrete, and self-compacting lightweight concrete.

Appendix: Results of descriptive statistical analysis of hydraulic conductivity and unconfined compressive strength data

Table 1. Descriptive statistical measures for the coefficient of hydraulic conductivity for desert CBPD sand mixtures.

CBPD (%)	During saturation	After reaching steady readings
0	1.50E-05	1.77E-05
4	4.56E-06	3.41E-06
8	2.71E-07	6.38E-08
12	5.99E-07	7.81E-09
16	2.74E-08	1.94E-09
20	3.12E-08	5.39E-10
24	4.67E-09	7.82E-11
28	1.35E-09	2.81E-11
Minimum	1.35E-09	2.81E-11
Maximum	1.50E-05	1.77E-05
Mean	2.56E-06	2.65E-06
Standard Deviation	5.26069E-06	6.19707E-06
Coefficient of Variance	2.053	2.34

Table 2. Descriptive statistical measures for unconfined compressive strength (UCS) in (kPa) for different contents (CBPD%) and curing periods (days).

CBPD, **Curing , (day)**	**8%**	**12%**	**16%**	**20%**	**24%**	**28%**
0 days	15.4	32.5	80.7	167.8	195.8	187.5
7 days	505.9	889.3	1520.5	2159.2	2597.8	2809.4
14 days	602.9	1047.6	2210.9	2819.4	3107.6	3404.7
28 days	672.5	1731.2	2884.5	3478.8	3793.9	4525.9
Minimum UCS (kPa)	15.4	32.5	80.7	167.8	195.8	187.5
Maximum UCS (kPa)	672.5	1731.2	2884.5	3478.8	3793.9	4525.9
Mean UCS (kPa)	449.175	925.15	1674.15	2156.3	2423.775	2731.875
Standard Deviation (kPa)	297.144	698.288	1199.408	1430.949	1564.078	1839.481
Coefficient of Variance %	66.153	75.478	71.643	66.361	64.531	67.334