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The Influence of Cement Stabilization on Marl-Gravel Mixtures for Application in Road Pavement Layer Construction

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ABSTRACT: Marl is recognized as a problematic soil type in geotechnical engineering, particularly in the construction of flexible pavement structures, due to its sensitivity to environmental conditions. Upon moisture infiltration, marl exhibits significant swelling and volumetric expansion. Conversely, exposure to elevated ambient temperatures induces shrinkage, volume reduction, and deterioration of mechanical strength, primarily resulting from pore development within the marly layers. The present study aims to evaluate the effectiveness of cement stabilization on argillaceous marl–gravel mixtures sourced from Tabriz, to enhance their suitability for use in road pavement layer construction. In the experimental program, marl was mixed with gravel at proportions of 10% and 30%, followed by the addition of cement in the amounts of 4%, 6%, and 10% by weight. The prepared specimens were cured under standard conditions for a period of 28 days. To assess the performance of the stabilized mixtures, a comprehensive suite of laboratory tests was conducted, including evaluations of plasticity, dry density, California Bearing Ratio (CBR) under both dry and saturated conditions, unconfined compressive strength, indirect tensile strength, and permeability. The findings revealed that the optimum mixture consisted of marl with 30% gravel and 10% cement. This formulation demonstrated a 15.2 times enhancement in unconfined compressive strength, a 1.38times increase in CBR, and a 15.2% reduction in swelling. These results underscore the potential of the optimized mixture for effective application in road pavement construction, particularly in cold and moisture-prone environments.

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1- Problem statement

Marly soils are considered among the most problematic and sensitive soil types in civil engineering projects, particularly in road pavement systems [1]. These calcareous–clayey sedimentary materials consist of varying proportions of calcium carbonate, clay minerals, and silt or sand. Based on their dominant constituents, marls are generally classified into three main types: calcareous marl, rich in $CaCO_3$ and exhibiting low plasticity; argillaceous marl, dominated by clay minerals with higher plasticity and swelling potential; and silty or sandy marl, which contains a greater proportion of coarse particles and demonstrates higher permeability and strength. The geotechnical behavior of marl, such as its compressibility, workability, and response to stabilization, strongly depends on the relative proportions of carbonate and clay minerals.

Due to their variable composition and moisture sensitivity, marl soils can cause considerable damage to engineering and geotechnical structures. When subjected to wetting and drying cycles, they undergo volumetric changes, including swelling, shrinkage, and strength loss, which can lead to foundation settlement, cracking, and slope instability. The presence of soluble salts and gypsum in some marls may further accelerate deterioration through chemical reactions and softening of the soil matrix.

Since most pavement layers in urban areas are flexible, the selection of appropriate materials for their construction is of critical importance. Marly soils tend to swell and expand upon water absorption, while exposure to high ambient temperatures causes shrinkage and volume reduction due to moisture loss and pore development within the soil matrix. These volumetric variations impair the soil's ability to distribute loads uniformly, resulting in differential settlement, deformation, and cracking of the pavement structure. Consequently, this leads to significant damage to both the pavement body and the asphalt surface. Therefore, identifying technically and economically feasible stabilization methods to improve the bearing capacity of marly soils and mitigate associated damages is essential. The main objective of the present study is to investigate the performance of argillaceous marl–gravel–cement mixtures for use in pavement layers, utilizing materials sourced from the Tabriz region. The detailed results and analyses are presented in the subsequent sections

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2- Study area

Marly soils are characterized by their heterogeneous composition, consisting of clay minerals, calcium carbonate, and silt-sized particles [2]. The presence of clay minerals contributes to their plasticity and shrink–swell behavior, while the calcium carbonate content influences their strength and compressibility. The specific proportions of these components significantly impact the overall geotechnical properties of the soil. The interaction between clay and calcium carbonate renders marly clay highly sensitive to moisture variations. The clay fraction expands upon wetting and contracts upon drying, whereas calcium carbonate contributes to natural cementation but also increases susceptibility to weathering. In general, marl soil is described in various studies as a hard-to-very hard marine carbonate soil, often green in color. It has also been defined as a deposit composed of silt and clay containing gray or green calcite [3]. Marl is a soft, clay-rich limestone used to describe rocks with 35 to 65 percent carbonate content. In engineering geology and geotechnical engineering, terms such as “colored soils,” “carbonate soils,” and “marl” are used to refer to fine soil compositions containing carbonate minerals [4, 5]. The Tabriz city, located in the northwest of Iran, is characterized by a variety of fine cohesive soils, including clay, silt, and marl. It is worth noting that numerous studies have been conducted on the properties of the cohesive clay and silt soils in Tabriz by various researchers. Several investigations have also examined the mechanical and physical properties of Tabriz’s clay marl soils [6]. The strength, deformation characteristics, and stress–strain behavior of these soils have been evaluated through both laboratory and field tests. Three distinct types of marl soils have been identified in Tabriz, commonly observed in yellow, green, and gray colors. Table 1 summarizes the physical and plasticity properties of marl samples from the Tabriz region. As previously mentioned, a significant portion of the soil in the city of Tabriz, located in the northwest of Iran, consists of marly soils (carbonate clays). Outcrops of these soils are visible in many parts of the city, particularly in the northern and northeastern regions, as illustrated in Figure 1.

According to studies, marly clay soil formations may be found in Tabriz’s Kuye Fereshteh and Marzdaran districts [7, 8]. These locations, located in the northeastern section of the city, have silty clay strata that are exposed to groundwater drainage paths from Tabriz’s northern highlands. These soils have an important propensity for consolidation and settlement. As a result of these conditions, many residential buildings built in recent years in these locations have sustained considerable structural damage. Additionally, existing pavement layers have seen significant settling and deformation as a result of water absorption [7-11].

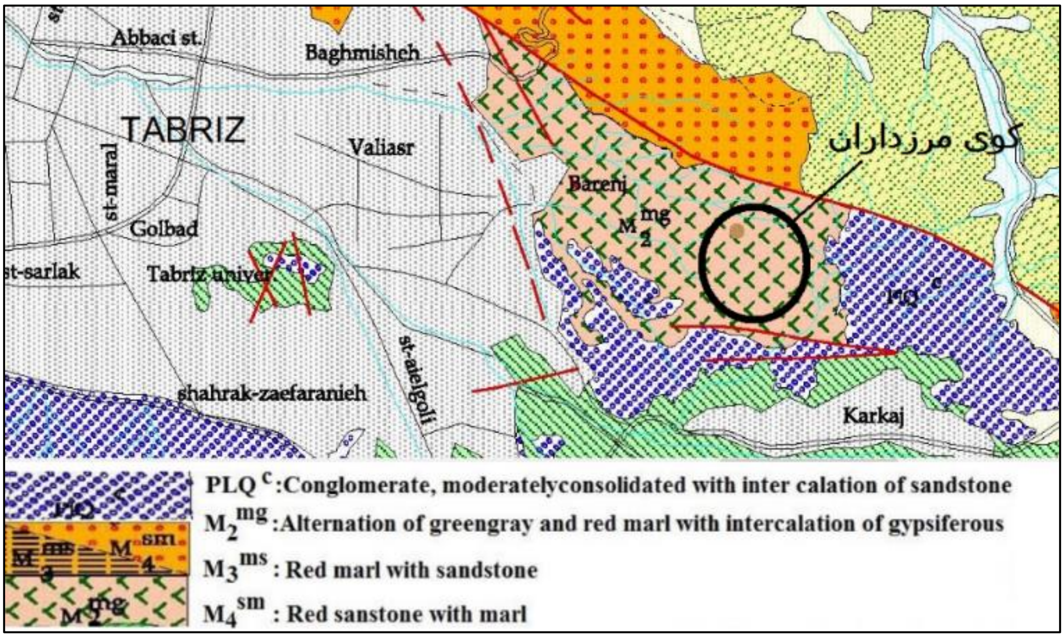

Fig. 1. Location of marl strata in Tabriz city, including the research area.

Table 1. Physical and plastic properties of Tabriz marl [6].

Soil type	Soil category	LL (%)	PI (%)
Yellow marl	CL-CH	55-75	30-35
Green marl	CL-CH	50-65	20-25
Gray marl	CL-CH, MH	40-60	15-20

3- Literature review

As previously stated, marly soils, which are widespread in civil engineering and road construction projects, present substantial issues due to their sensitivity to volumetric changes under different moisture and temperature conditions. These soils are often made up of a combination of clay and calcareous minerals [12]. There are several methods available for stabilizing and improving the geotechnical qualities of problematic soils. These include mechanical approaches (for example, roller compaction), chemical methods (including chemical reactions through the addition of materials such as nanomaterials, cement, lime, and bitumen), and, more recently, the use of geosynthetic materials to improve the performance of weak soils. Cement, as an adhesive, helps to stabilize soils by increasing their strength and stiffness [13]. During the hydration process, cement forms calcium silicate hydrate (C-S-H) gel, which binds soil particles together, resulting in a stronger and more cohesive mass [14]. The addition of cement also reduces soil flexibility and the potential for shrinkage and swelling, increasing resistance to volumetric changes. The amount of cement required for efficient stabilization is determined by the soil's unique qualities and desired level of improvement. Several studies have explored the stabilization of clayey soils with cement, confirming its effectiveness for improving geotechnical performance. Numerous studies have explored the application of cement and various additives to mitigate clay swelling and enhance soil performance for road construction purposes. One such study examined the comparative effects of cement, lime, and CBR PLUS nanopolymer on clay, with a focus on swelling reduction. The findings revealed that cement exhibited superior performance in minimizing swelling relative to both lime and nanopolymer treatments [15]. Another investigation assessed the use of cement in combination with bagasse ash to stabilize soft clay. The study reported that incorporating 20% bagasse ash by weight into the cement mixture substantially improved the clay's bearing capacity [16]. Similarly, cement kiln dust has been utilized to treat highly expansive clay. It was observed that adding 30% cement kiln dust and allowing a 28-day curing period resulted in a 7.8-fold increase in unconfined compressive strength [17]. The synergistic effect of lime and cement was also studied in the context of glycerol-contaminated clay. The results indicated that the addition of 9% cement and 10% lime by weight notably enhanced the mechanical strength of the contaminated soil [18]. In a separate study focusing on coastal clay from the Marshland region of Nigeria, the application of 20% cement or 11% lime significantly improved the soil's bearing capacity [19]. Additionally, cement stabilization was implemented for road construction over clayey soils in Bali, Indonesia. Observations from this project confirmed that cement addition effectively improved the geotechnical characteristics of the treated clay [20]. Also, several studiess have focused on stabilizing and enhancing the geotechnical characteristics of soil layers within the study area. In particular, materials such as glass fiber-reinforced plastic (GFRP), polypropylene fibers, and glass fibers have been employed to improve the marl soils of the Kuye Fereshteh region in Tabriz. Results show that incorporating 0.8% glass fibers into clay leads to notable improvements in both geotechnical performance and bearing capacity. Moreover, polypropylene fibers have exhibited a more significant effect than glass fibers in increasing the bearing strength of clay soils [21–22]. The combined use of nanoclay and limestone powder has also been explored for improving the geotechnical properties of clay in Nasr town. According to the results, a mixture containing 5% nanoclay and 10% limestone powder, with a curing period of 7 days, increased the shear strength of the stabilized soil by 33% [23]. In another study, the effect of Tabrizi tree sawdust ash on the stabilization of marl soil in the Marzdaran area of Tabriz was evaluated. The findings indicated that the addition of 3% sawdust ash, followed by 14 days of curing, resulted in a 65% increase in uniaxial compressive strength and a 53% increase in shear strength compared to the untreated soil [24]. Conversely, the incorporation of sand into marly soil enhances its drainage properties and reduces its vulnerability to volumetric changes [14]. Gravel acts as a structural framework within the soil matrix, thereby increasing the internal friction angle and shear strength. Improved drainage prevents the accumulation of excess moisture, which is a primary factor contributing to soil swelling and instability. The size and gradation of sand particles are crucial elements that determine their effectiveness in stabilizing the soil. Recently, a study was conducted on the use of marble waste powder in the manufacture of self-compacting concrete. The results showed the use of waste marble powder (WMP) as partial cement replacement and waste marble aggregates (WMA) as fine aggregate replacement in self-compacting concrete (SCC). Experimental tests assessed compressive strength, durability, and replacement levels (5–20% WMP;

20–40% WMA), supported by life cycle assessment and eco-cost optimization. Results showed 5% WMP and all WMA mixes improved strength, while marble-based mixes enhanced acid resistance and reduced environmental impacts. The 10% WMP mix was identified as the most sustainable, offering balanced mechanical, environmental, and economic performance [25].

A review of the existing literature indicates that the application of cement in the stabilization of marly soils has been relatively limited, particularly in the study area. Moreover, the potential role of gravel in mitigating the environmental impacts of cement has not been sufficiently explored.

Considering that Tabriz is characterized by a cold climate with frequent frost events, and that argillaceous marl soil is identified as one of the most problematic soil types in the region, the stabilization of this soil using a gravel–cement mixture to enhance its mechanical and geotechnical properties represents a key innovation of the present study. Therefore, this research aims to assess the efficiency of cement–gravel mixtures in stabilizing argillaceous marly soils, to improve both the short-term performance and the long-term durability of road pavement layers. Addressing this research gap underscores the importance of developing sustainable and effective stabilization techniques tailored to the specific geotechnical challenges of the region.

4- Objectives

This study primarily aims to evaluate the potential of argillaceous marl–gravel–cement mixtures to improve their mechanical and geotechnical characteristics for use in road pavement construction., The study aims to:

Evaluate the effect of different cement contents (4%, 6%, and 10%) on the strength and deformation behavior of marly soils.

Assess the influence of gravel addition at varying percentages (10%, 20%, and 30%) on the compressibility, swelling, and permeability of the stabilized soil.

Identify the optimum gravel–cement mixture that enhances short-term stability and durability of argillaceous marl for use in road pavement construction.

To achieve these objectives, a series of laboratory tests was conducted, including uniaxial compressive strength (UCS), California Bearing Ratio (CBR), indirect tensile strength, and permeability tests, on marl samples stabilized with different proportions of cement and gravel.

5- Materials and methods

5- 1- Materials

As previously stated, this study aims to evaluate the influence of cement stabilization on a gravel–marl mixture to enhance its geotechnical characteristics. The tested soil is classified as argillaceous marl, sampled from the Marzdaran Town district located in Tabriz, Iran. Argillaceous marl dominates at the surface, followed by olive green marl at intermediate levels and gray to dark marl at further depths. To stabilize the studied argillaceous marl soil, a gravel and cement mixture was applied. The gravel used in this study was obtained from the Tal Maseh sand Washing Plant in Tabriz and is a mix of crushed and natural particles. The grain size distribution curves of the studied marl and gravel were determined in accordance with ASTM D421-85 [26] and ASTM D422-63 [27] standards, as shown in Figure 2. According to the Unified Soil Classification System (USCS), the studied argillaceous marl is classified as CL–CH, while the tested angular gravel is categorized as GP. The plasticity characteristics of the marl were determined in accordance with ASTM D4318-95a [28], and the specific gravity of the materials was measured following ASTM D854-02 [29]. The results are presented in Table 2. The cement used in this study is Type II Portland cement, obtained from the Simian Sofian factory in Tabriz. The chemical composition of the marl and cement, as determined by XRD analysis in the Central Laboratory of Tabriz University was conducted, is presented in Table 3, and images of the tested materials are shown in Figure 3. According to Table 3., based on the oxide composition, the soil exhibits high contents of silica (SiO_2 = 48.55%), alumina (Al_2O_3 = 12.85%), and iron oxide (Fe_2O_3= 5.67%), along with relatively low amounts of calcium (CaO = 7.22%) and magnesium (MgO = 4.34%). The high ratio of silicate to carbonate components (approximately 6:1) indicates that the material is classified as argillaceous marl. This type of marl typically shows medium to high plasticity, high compressibility, and good reactivity with cement due to the presence of active silica and alumina phases. The minor sulfate content (SO_2 = 2.8%) suggests the possible presence of gypsum, which may play a secondary role in the soil stabilization process.

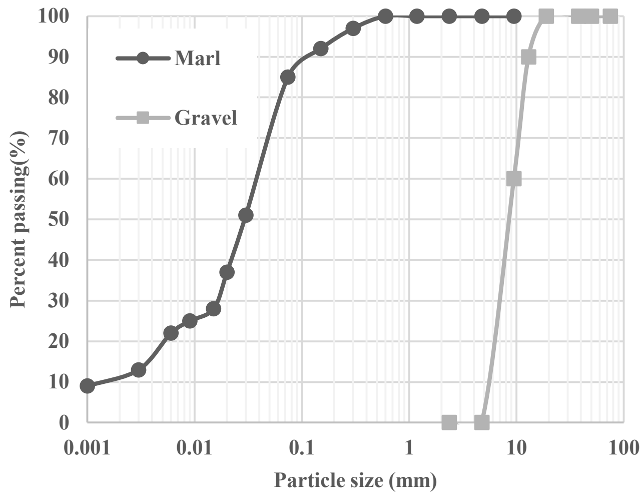

Fig. 2. Grain size distribution curves of the studied marl and gravel.

5- 2- Experimental program

According to ASTM C618-22 [30], pozzolanic or

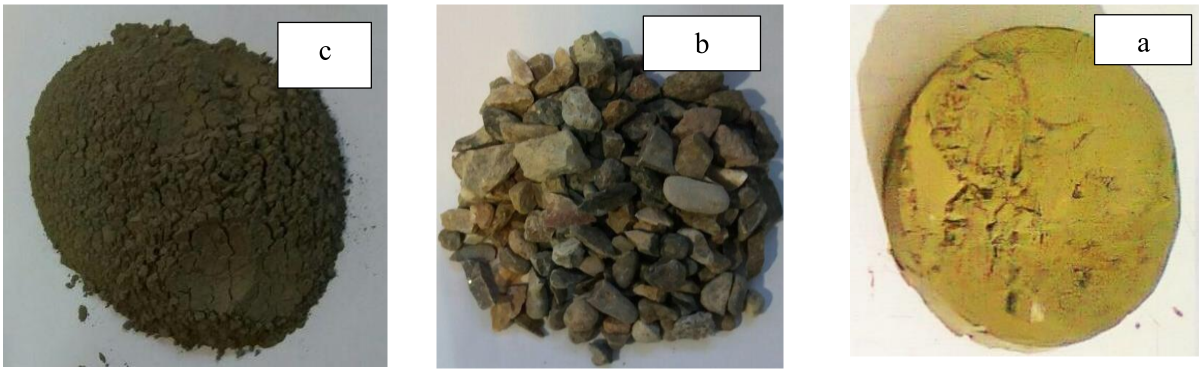

Fig. 3. Images of the materials studied, a- marl, b- sand, c- Portland cement type 2.

Table 2. Geotechnical properties of studied materials.

Soil properties	Marl	Gravel
Specific gravity (Gs)	2.88	2.63
Percent of clay particle (C)	96 %	--
Liquid limit (LL)-(%)	74 %	--
Plasticity index (PI)-(%)	34 %	--

cementitious behavior is observed when the combined content of SiO_2, Al_2O_3, and Fe_2O_3 in the mixture approaches 70%. As detailed in Table 3, the argillaceous marl soil exhibits a composition close to 70%, confirming the presence of these pozzolanic conditions. Additionally, the CaO, SiO_2, and Al_2O_3 components in cement facilitate the formation of C-S-H and C-A-S-H gels upon hydration. This cementation process contributes to a reduction in soil settlement and deformation resulting from water absorption. Furthermore, it enhances the connection of fine soil particles, promoting the formation of larger aggregates [31].

In the present study, based on a review of previous research, gravel was initially incorporated into the argillaceous marl soil at 10% and 30% by weight. This was followed by the addition of cement at 4%, 6%, and 10% to the marl-gravel mixture to enhance its geotechnical properties. Uniform and homogeneous samples for geotechnical parameter evaluation were prepared in accordance with ASTM C305-14 [32]. In this process, the marl and gravel mixtures were first mixed with water (according to the optimum moisture content which was obtained using a compact test) in a mixer to achieve proper cohesion between the materials. Cement was then added to the mixture. According to the standard ASTM C305-14, the mixing process was paused for 30 seconds to allow the materials to absorb moisture along with the cement. Next, the mixing continued for 30 seconds at a slow speed, followed by 15 seconds at a cleaning speed, and 60 seconds at a medium speed. The mixer used in the present study is the epicyclic/planetary type and is branded Humboldt (5-L), Hobart (Planetary Laboratory Mixers), which matches the ASTM C305-14 standard.

Table 3. Chemical Elements in Studied Marl and Type II Portland cement.

Elements	Portland cement Type II (%)	Marl (%)
SiO_2	20.1	48.55
Al_2O_3	4.50	12.85
Fe_2O_3	3.7	5.67
TiO_2	-	0.57
CaO	60.50	7.22
MgO	3.12	4.34
Na_2O	0.45	0.61
K_2O	0.50	2.37
SO_3	-	2.8
MnO	-	0.07
P_2O_5	-	0.1
other	7.13	14.85
C_3S	48.67	-
C_2S	20.91	-
C_3A	5.66	-
C_4AF	11.26	-

Once the mixing process was complete, the samples were stored in a sealed plastic container at ambient temperature (23°C) for 28 days to complete the curing process. To fulfill the objectives of this study and to maintain consistency in specimen dimensions, samples were initially fabricated in the

Table 4. Test program conducted on the samples studied in the present study.

Test program		Material			Tests					
No	Sample name	Soil Matrix	Gravel (%)	Cement (%)	PI	Compaction	Uniaxial strength	CBR (dry and saturate)	Splitting Tensile Strength	Permeability
1	M-0G-0C	Marl	0	-	*	*	*	*	*	*
2	M-10G-0C	Marl	10	-	-	*	*	*	*	*
3	M-30G-0C	Marl	30	-	-	*	*	*	*	*
4	M-0G-4C	Marl	0	4	*	*	*	*	*	*
5	M-0G-6C	Marl	0	6	*	*	*	*	*	*
6	M-0G-10C	Marl	0	10	*	*	*	*	*	*
7	M-10G-4C	Marl	10	4	-	*	*	*	*	*
8	M-10G-6C	Marl	10	6	-	*	*	*	*	*
9	M-10G-10C	Marl	10	10	-	*	*	*	*	*
10	M-30G-4C	Marl	30	4	-	*	*	*	*	*
11	M-30G-6C	Marl	30	6	-	*	*	*	*	*
12	M-30G-10C	Marl	30	10	-	*	*	*	*	*

form of California Bearing Ratio (CBR) molds. A standard Proctor compaction test was then performed in accordance with ASTM D698-2000 [33] to determine the optimum moisture content and maximum dry density. To evaluate the geotechnical behavior of the stabilized mixtures, a series of laboratory tests were conducted, including unconfined compressive strength (UCS) testing (ASTM D2166-16) [34], splitting tensile strength (STS) testing (ASTM C496) [35], falling head permeability testing (ASTM D5084) [36], and CBR testing under both dry and saturated conditions (ASTM D1883) [37]. The test program conducted on the studied samples is presented in Table 4. It is worth noting that 25% of the tests were repeated to verify the results.

6- Results

6- 1- Atterberg limit test

The Atterberg limits (liquid limit and plastic limit) were determined on the fine fraction of the mixture, i.e., the material passing the No. 40 (0.425 mm) sieve. Since the combination of Portland cement and argillaceous marl forms a continuous matrix between the coarse particles, the plasticity index (PI) was reported as a representative property of this matrix. Particles larger than 12.5 mm were excluded from the test, and only the passing fraction was used to determine the plasticity characteristics.

The Atterberg limit test results for marl with varying cement contents after 28 days of curing are presented in Figure 4. The findings show a clear reduction in the plasticity index (PI) of the marl matrix as the cement content increases. Specifically, at a cement content of 10%, the PI decreases

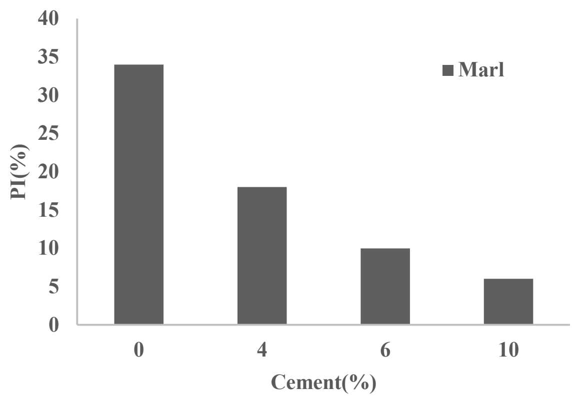

Fig. 4. Effect of Cement on the Plasticity Index of the argillaceous Marl.

by approximately 18% compared to the untreated soil. This reduction can be attributed to the chemical composition of marl, which typically contains calcium carbonate ($CaCO_3$) and clay minerals. When cement is added, hydration reactions produce calcium hydroxide ($Ca(OH)_2$), which subsequently reacts with the calcium carbonate and clay minerals present in the soil matrix. These pozzolanic and ion-exchange reactions lead to the formation of stable cementitious products such as calcium silicate hydrates (C–S–H) and calcium aluminate hydrates (C–A–H).

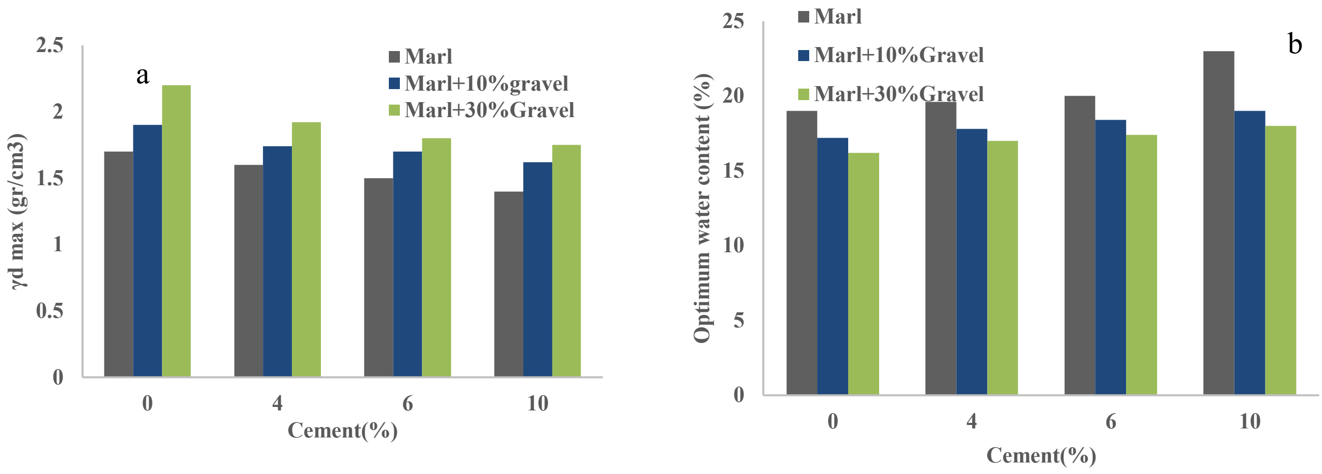

Fig. 5. The effect of cement on the results of the compaction test for the studied Marl and Gravel mixture: a) Maximum dry unit weight, b) Optimum moisture content.

Based on the obtained results, it can be concluded that the addition of 10% cement to argillaceous marl soil significantly decreases its swelling potential and water absorption capacity, while enhancing its resistance to freeze–thaw cycles. These improvements make the stabilized material suitable for use in the construction of pavement layers in cold and frost-prone regions.

6- 2- Compaction test

Figures 5(a, b), illustrate the results of the Standard Proctor compaction tests performed on the improved soil samples before curing. As evident from Figure 5(a), as the cement content in argillaceous marl soil increases, the maximum dry unit weight (γ_{dmax}) decreases. In particular, when the cement content reaches 10%, the γ_{dmax} decreases by 82%. The decrease in maximum dry density with increasing cement content in marl soil is attributed to the rise in porosity and the lower effective particle density caused by cement addition. As the cement content increases, hydration reactions form C–S–H phases that create a more porous and rigid structure, reducing the soil's compactability. At higher cement contents (e.g., 10%), the cementitious bonds dominate the packing behavior, leading to a pronounced reduction in the maximum dry density.

Furthermore, incorporating gravel into argillaceous marl increases the maximum dry unit weight (γ_{dmax}) of the soil mixture. When the gravel content reaches 30%, the γ_{dmax} value rises by approximately 29%. As shown in Figure 5(a), the addition of gravel also enhances the γ_{dmax} of the marl–gravel–cement mixtures. In particular, the combination of 30% gravel and 10% cement yields about a 3% increase in the maximum dry unit weight compared to the unstabilized marl. This improvement can be attributed to the presence of coarse gravel particles and the newly formed aggregates produced by the cementation reactions between marl and cement, which collectively transform the soil matrix from fine-grained to coarser-textured. However, by analyzing the overall results, it is evident that increasing the cement content alone tends to slightly reduce the γ_{dmax} due to the development of a more porous structure induced by hydration products.

As shown in Figure 5(b), increasing the cement content to 10% in marl soil results in an increasing of the optimum water content (OWC) to 21%. The increase in optimum water content is due to the higher water demand for hydration reactions and the greater specific surface area of the cement-improved particles. These factors require more moisture to achieve proper lubrication and compaction during the Proctor test. Furthermore, the addition of 10% cement to a marl–gravel mixture containing 30% gravel increases the optimum water content by 11% to the unstabilized state (marl+30%gravel without cement). In general, the trends illustrated in Figure 5(b) indicate that the optimum water content (OWC) increased with higher cement content in all mixtures. This behavior can be attributed to the consumption of part of the mixing water during cement hydration and the greater water demand required to achieve the target compaction density. In contrast, the inclusion of sand led to a reduction in OWC, as coarser particles possess a lower specific surface area and therefore require less water for lubrication and particle rearrangement. The combined effect of cement and sand results in an increase in OWC caused by cement being partially offset by the reduction induced by sand. Consequently, in the mixture containing 10% cement and 30% gravel, a balance between these opposing effects was established, resulting in an intermediate and stable optimum water content. As a result, this stabilization process allows for the use of these materials in the construction of road pavement layers and in enhancing the geotechnical properties of the soil.

6- 3- California bearing ratio test (CBR)

To assess the influence of cement stabilization on the load-bearing capacity of a marl–gravel mixture after 28 days of curing, considering its potential use in road pavement layers, the California Bearing Ratio (CBR) test was carried out under both dry and saturated conditions. Specimens were compacted using a standard Proctor energy of 56 blows per layer, and CBR values were recorded at a piston penetration of 2.5 cm. The test results are presented in Figures 6(a) and 6(b). As shown in Figure 6(a), under dry loading conditions and in the absence of cement stabilization, increasing the gravel content in the marl–gravel mixture to 30% results in an approximately 12 times increase in the bearing capacity. According to Code No. 234 [38], such an improvement indicates that the material satisfies the standards for usage in subgrade and subbase layers in pavement construction. Moreover, incorporating cement into the marl–gravel mixture and curing the specimens for 28 days results in a noticeable improvement in bearing capacity, with a positive correlation observed as the cement content increases up to 10%. The bearing capacity of unimproved marl increases by approximately 2.5 times upon stabilization, while the mixture containing 30% gravel and 10% cement exhibits a 1.34 times increase compared to the marl–gravel blend without cement. In accordance with Code No. 234, these enhancements qualify cement-stabilized marl for use in sub-base layer construction, whereas the mixture with 30% gravel and 10% cement satisfies the performance criteria for both subbase and base layers. Figure 6(b) illustrates the results of the CBR tests performed on the specimens under saturated conditions. As shown, unstabilized marl exhibits very low bearing capacity. The addition of up to 30% gravel significantly enhances its performance, resulting in a 14.5 times increase in bearing capacity, thereby rendering the mixture suitable for subbase layer applications. Moreover, when cement is incorporated into the marl–gravel mixture and the specimens are cured for 28 days, the mechanical strength improves considerably compared to the unstabilized condition. Similar to the behavior under dry conditions, the inclusion of 10% cement in pure marl and in marl containing 10% and 30% gravel mixture increases the bearing capacity by factors of 15.6, 2.59, and 1.38, respectively. According to Code No. 234, cement-stabilized marl satisfies the requirements for subbase construction, while the combined use of cement and gravel produces a stabilized material suitable for base layer construction.

The California Bearing Ratio (CBR) test conducted under saturated conditions also assessed the influence of cement on the swelling behavior of the marl–gravel mixture, as illustrated in Figure 7. The results demonstrate that cement addition markedly decreases the swelling potential of the mixture. Specifically, increasing the gravel content to 30% reduces swelling by approximately 65% compared to unimproved marl. Moreover, incorporating 10% cement into the marl–gravel mixture with 30% gravel yields a further reduction of about 15.2% in swelling. The observed trend is nonlinear, and a regression analysis has been applied to better highlight the influence of increasing cement content on swelling. It is important to distinguish the roles of the two materials: cement acts primarily as a binder, reducing expansion through particle cohesion, whereas gravel facilitates drainage, thereby indirectly contributing to the reduction of swelling. This differentiation clarifies the mechanisms by which each additive affects soil behavior. Based on the CBR test findings under both dry and saturated conditions, a mixture comprising 30% gravel and 10% cement exhibits favorable performance and is deemed suitable for use in pavement layer construction. Also, it should be noted

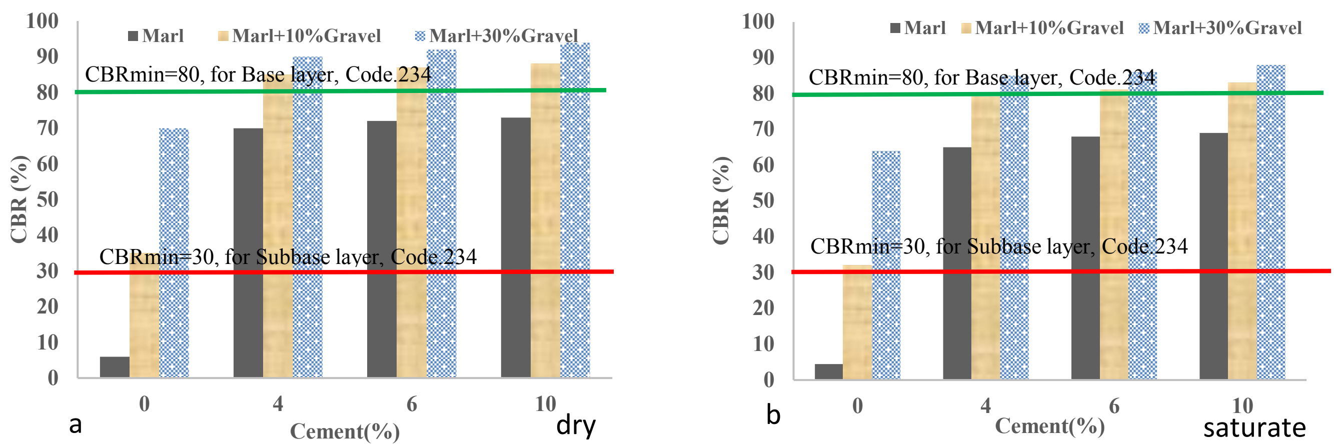

Fig. 6. Influence of cement stabilization on the California Bearing Ratio (CBR) performance of Marl–Gravel mixtures after 28 days of curing under: (a) dry loading conditions, and (b) saturated loading conditions.

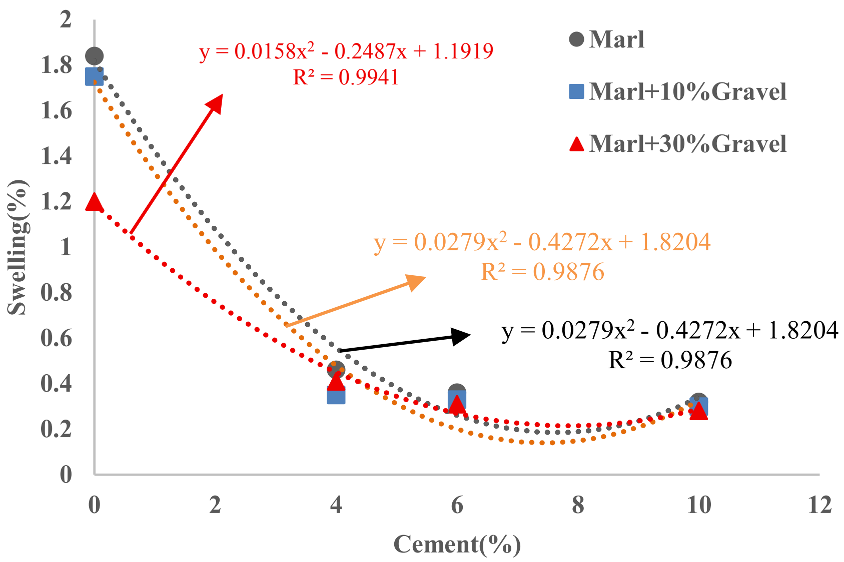

Fig. 7. The influence of cement on the swelling rate of the Marl and Gravel mixture after 28 days of curing.

6- 4- Permeability test

In the construction of road pavement structures, particularly the subbase layer, the permeability and drainage characteristics of the materials used are of critical importance. These properties play a vital role in cold climate regions, where frost penetration can adversely affect frost-susceptible soils such as marl, potentially leading to swelling, loss of strength, and structural failure of the pavement. Falling head permeability tests were performed to analyze the hydraulic behavior of the selected soil combinations, adapted to the specific properties of the soils under study. The results of this study are illustrated in Figure 8(a, b). As shown in Figure 8(a), permeability increases with the incorporation of gravel into marl soil. This can be attributed to the fine nature of marl, which has a low void ratio. The addition of gravel, a coarse aggregate, increases the interparticle voids, thereby modifying the soil structure from a predominantly fine matrix to a more coarse-grained framework, which facilitates greater fluid flow. This procedure increases the void ratio, which allows water to flow more easily through soil particles. Despite the high cohesiveness of marl soil, the addition of gravel reduces its cohesion, allowing for greater particle separation. This, in turn, increases the soil's permeability. Figure 8(b) illustrates the effect of cement on the permeability of a marl–gravel mixture. As shown, the addition of cement to marl reduces permeability. This reduction occurs primarily because the cement fills the voids between soil particles during the initial stages of hydration, leading to a denser and more compact soil structure. Upon completion of the curing period and the hydration process, the formation of cementitious products, primarily calcium silicate hydrate (C–S–H) results in the establishment of strong interparticle connections within the soil matrix. This microstructural densification leads to a reduction in void ratio and a corresponding decrease in permeability. Additionally, when 10% gravel is added to the marl–cement mixture, the permeability after 28 days of curing is found to be higher than that of the marl–cement blend without gravel, likely due to increased macro-voids introduced by the coarse particles. However, with an increase in cement content to 10%, the permeability trend reverses and decreases, reflecting enhanced particle connecting and pore-filling effects. The observed behavior can be attributed to the combined influence of gravel particles and cement within the marl matrix. Gravel contributes to increased permeability due to its low water absorption capacity, which alters the soil structure and particle arrangement. However, with increasing cement content in the marl–gravel mixture, a reduction in permeability is observed. This is primarily due to the hydration reactions between cement particles and the marl, which lead to the formation of cementitious cohesions, filling void spaces, and reducing the overall porosity. Finally, the addition of cement to the marl mixture containing 30% gravel results in an increase in the permeability of the stabilized sample. However, this increase is relatively small compared to the permeability of gravel alone in marl soil. This behavior can be attributed to the fact that cement reacts with water to form compounds such as calcium silicate hydrate (C–S–H) and calcium hydroxide (CH). These compounds effectively fill the soil pores, thereby reducing the void spaces between particles. Furthermore, cement serves as an adhesive, encouraging the formation of a denser soil structure by increasing the aggregation of marl-gravel particles. Water flow through the soil matrix is restricted by the development of cementitious compounds, which lowers the mixture's void ratio. Permeability decreases as a result of these smaller pore spaces. Therefore, it can be inferred from the experimental data that although adding gravel to marl improves its permeability and drainage, the permeability can

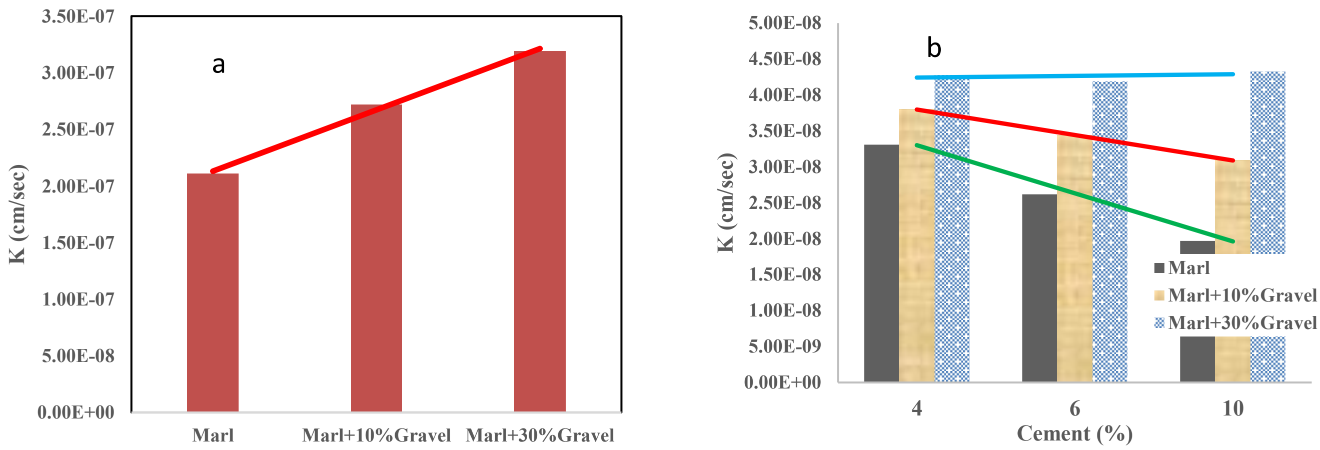

Fig. 8. Variations in permeability of the studied samples: (a) Effect of Gravel on the permeability of Marl; (b) Effect of Cement on the permeability of the Marl–Gravel mixture after 28 days of curing.

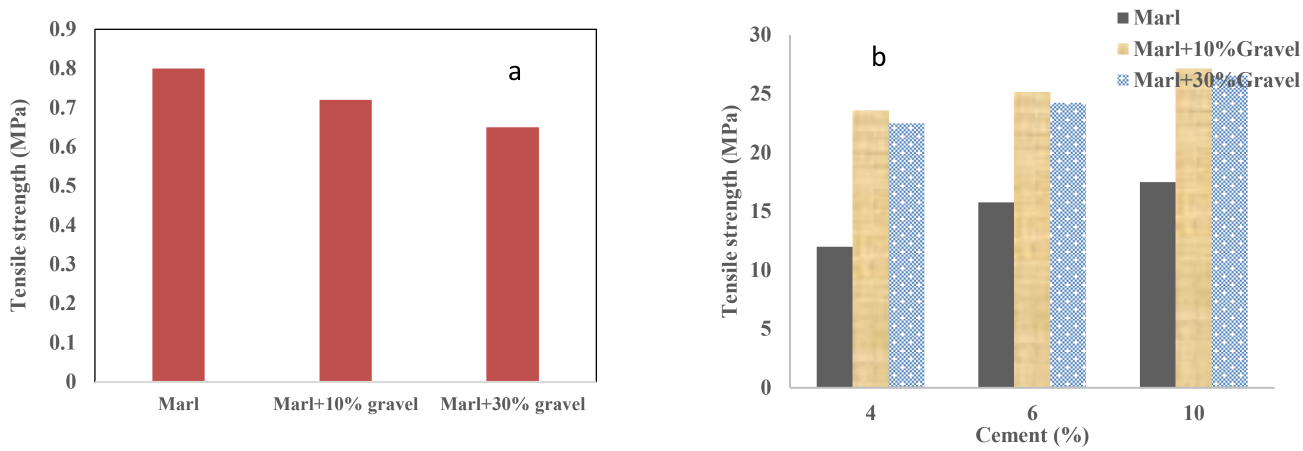

Fig. 9. Variations in Indirect Tensile Strength of Studied Samples: (A) Effect of Gravel on Marl Indirect Tensile Strength, (B) Effect of Cement on Indirect Tensile Strength of Marl and Gravel Mixture after 28 Days of Curing.

be further maximized by adding more cement to the marl–gravel mixture.

6- 5- Splitting tensile strength test

One of the primary geotechnical challenges in the construction of pavement layers is the inherently low tensile strength of materials, which may result in excessive settlement and structural deformation of the pavement system. To investigate the influence of cement stabilization on the tensile load-bearing capacity of marl–gravel mixtures, indirect tensile strength (Brazilian) tests were conducted in accordance with ASTM C496, employing a constant loading rate of 0.05 MPa/s. The splitting tensile strength of the samples after 28 days of curing was calculated using Equation (1), where σ_t, represents the tensile strength, P is the applied load, D is the diameter, and L is the length of the cylindrical specimen.

$$\sigma_t = \frac{2P}{\pi . L . D} \qquad (1)$$

The results of the indirect tensile strength tests are illustrated in Figure 9(a, b). As depicted, the tensile strength of marl decreases progressively with an increase in gravel content. Marl, being a fine-grained soil with considerable cohesive properties, tends to form strong interparticle connections. However, the inclusion of gravel, which is characterized by its coarse aggregates and non-cohesive nature, disrupts the soil matrix and weakens the interparticle skeleton. This reduction in matrix cohesion and continuity leads to a noticeable decline in tensile strength. Although the diagram in Figure 5-a shows that increasing the sand content in marl leads to a higher maximum dry unit weight, the resulting soil structure may become somewhat heterogeneous. This heterogeneity can lead to stress concentrations at localized points, ultimately resulting in a reduction in overall tensile strength. As shown in the graphs in Figure 9-b, the indirect tensile strength of all samples exhibits an increasing trend with higher cement content after 28 days of curing. Thus, when the cement content reaches 10%, the increase in bearing capacity relative to the unimproved state is 22 times for marl, 38 times for the marl with 10% gravel mixture, and 41 times for the marl with 30% gravel mixture. This behavior can be attributed to the fact that, in the marl with 10% gravel, the gravel particles are present in lower proportions, which facilitates better connectivity between the finer marl and cement particles. This improved combination leads to stronger connections between particles, consequently increasing tensile strength. In contrast, a mixture containing 30% gravel has a higher proportion of coarse particles, which can create voids and weaken the cohesion between particles.

6- 6- Uniaxial compressive strength test

As mentioned, in the present study, the samples to be evaluated were prepared to fit the size of the California Bearing Ratio (CBR) test mold. To conduct the uniaxial compressive strength test, as shown in Figure 10, two metal plates were placed at the top and bottom of the sample to evenly distribute the applied load across its surface.

The test results are illustrated in Figures 11(a), (b), and (c). As shown in Figure 11(a), the uniaxial compressive strength of marl significantly increases with the addition of gravel, reaching up to 14.5 times that of unimproved marl. This improvement can be attributed to the enhanced particle interlocking and frictional resistance provided by the coarse gravel particles. The gravel acts as a structural skeleton within the soil matrix, reducing void ratio and increasing dry unit weight. These changes lead to a denser, more stable soil fabric, which in turn enhances the compressive strength of the mixture.

Fig. 10. Procedure for conducting uniaxial compressive strength tests on the studied samples.

The presence of coarser gravel particles facilitates a more uniform distribution of stresses throughout the sample volume, thereby reducing the potential for localized stress concentrations. Moreover, when 10% cement is added to the marl–gravel mixtures and cured for 28 days, a significant enhancement in uniaxial compressive strength is observed. Specifically, the strength increases by factors of 23.4 for pure marl, 37.5 for marl with 10% gravel, and 4.9 for marl with 30% gravel, relative to their corresponding unstabilized conditions. These conditions also suggest that the cement hydration process leads to the formation of cementitious compounds, such as calcium silicate hydrate (C–S–H) gel and calcium hydroxide [$Ca(OH)_2$], through the reaction of cement with water. The C–S–H gel functions as a natural binder that effectively bonds marl and sand particles together, thereby enhancing the overall strength of the mixture. Furthermore, certain silicate and aluminate minerals present in the marl participate in pozzolanic reactions with the calcium hydroxide [$Ca(OH)_2$] released during cement hydration. These secondary reactions result in the formation of additional cementitious compounds, contributing to a denser, more durable soil matrix. As a result, the strength of the stabilized soil continues to increase over time, particularly beyond the conventional 28-day curing period.

Also, in Table 6. summarizes the statistical analysis of uniaxial compressive strength (UCS) results can be seen. For each condition, three replicates were tested (n = 3). The results are reported as mean, standard deviation (SD), coefficient of variation (COV), and 95% confidence intervals (CI). The improved samples showed significant strength enhancements, with low COV values (< 8%), indicating high repeatability of the results. It should be noted that due to time and laboratory limitations, the number of test repetitions was set to 3.

To assess the influence of cement stabilization on the deformability of marl–gravel mixtures, the secant modulus of deformation (E_{50}) was evaluated from the stress–strain curves obtained in the uniaxial compressive strength tests, as shown in Figure 11(b). In line with the trends observed for compressive strength at failure, the results demonstrate that increasing the gravel content up to 30% leads to a 4.5times increase in E_{50}. This suggests that the inclusion of gravel enhances the stiffness of the mixture by improving particle interlocking and reducing overall compressibility. Additionally, after 28 days of curing, the marl mixture containing 30% gravel and 10% cement shows the greatest rise in secant modulus following the addition of cement. In particular, the secant modulus is 5.25 times higher than in the

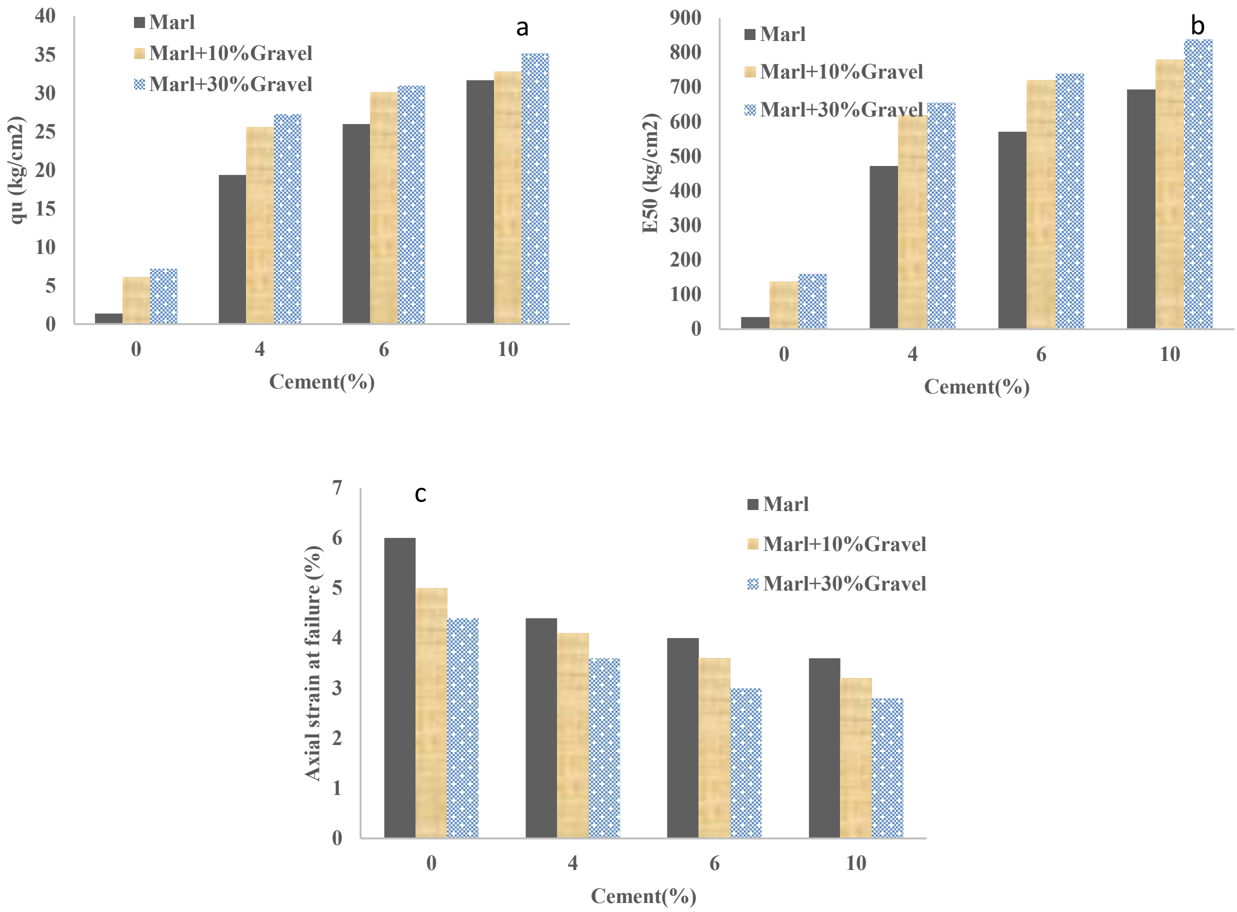

Fig. 11. Influence of Cement on Uniaxial Compressive Strength Test Results of Marl and Gravel Mixtures After 28 Days of Curing: a) Uniaxial Compressive Strength at Failure, b) Secant Modulus (E_{50}), c) Axial Strain at Failure.

Table 5. Statistical analysis of uniaxial compressive strength (UCS).

Soil mix	Cement (%)	n	Mean UCS (MPa)	SD (MPa)	COV (%)	CI (MPa) 95%	Strength gain
Clay	0	3	1.4	0.015	1.07	1.42	1
Clay	4	3	19.4	0.25	1.3	19.8	13.8
Clay	6	3	26	0.98	3.8	27.5	18.5
Clay	10	3	31.7	0.651	2.05	32.7	30.3
Clay+10%gravel	0	3	6.1	0.353	5.8	6.66	1
Clay+10%gravel	4	3	25.6	0.7	2.73	26.7	4.19
Clay+10%gravel	6	3	30.1	0.95	3.15	31.6	4.9
Clay+10%gravel	10	3	32.8	0.707	2.15	33.9	5.37
Clay+30%gravel	0	3	7.2	0.45	6.25	7.92	1
Clay+30%gravel	4	3	27.3	0.452	1.65	28	3.79
Clay+30%gravel	6	3	31	1.51	4.87	33.4	4.3
Clay+30%gravel	10	3	35.2	0.4	1.13	35.8	4.88

Table 6. Qualitative and economic comparison of materials similar to cement in stabilizing the studied soil.

Criteria	Portland cement (OPC)	Lime (with pozzolan)	Fly ash	Ground Granulated Blast-Furnace Slag (GGBS)	Geopolymer (Fly ash + GGBS + activator)
Effectiveness in 28 days	Good and fast	Moderate to good (depending on soil type)	Slower, competitive at higher doses	Good (with activator)	Very good and competitive or better
Sensitivity to sulfate/carbonate	Average	Risk in the presence of sulfate	Depends on fly ash type	Better than cement in some cases	Typically good and stable
Requirement to control percentage/formula	Low	Needs to be combined with pozzolan for optimum	Higher amount or additive required	Needs precise ratio	Requires activator and chemical control
Environmental impact (CO_2)	High	Less than cement	Low (industrial recycling)	Low	Low (although activator is effective)
Availability and initial cost	Usually available	Available (price as a function of energy)	Variable	Variable	Less available, higher initial cost

unstabilized state. The stiffness and resistance to deformation of the material under load can be measured by the secant modulus. According to the observed results, the mixture gets more rigid as a result of cement hydration, and its behavior changes from being flexible and ductile to being more brittle. This indicates that less deformation takes place for a given stress level, which raises the secant modulus. Furthermore, loading causes permanent deformation (plastic stresses) in uncemented marl. But when cement is added, the mixture behaves more elastically and the plastic strains are decreased. This change in mechanical behavior leads to a steeper slope in the stress–strain curve, indicating an increase in stiffness and consequently a higher secant modulus. The variation in axial strain at failure for the studied specimens is shown in Figure 11(c). The findings show that axial strain at failure decreases when the amount of gravel in marl soil increases. Gravel, with its coarser grain size, improves particle interlocking and compaction, increasing the mixture's stiffness and decreasing its deformability under load, even if pure marl has a very high degree of plasticity.

When gravel is added to marl, the combination changes from a soft, highly flexible substance to a composite that is stiffer and more structurally stable. Because of this increase in stiffness, the specimen fails at lower deformation levels because the axial strain at failure is reduced. When cement is added to marl-garvel mixes, a similar pattern is seen. All samples show a consistent drop in axial strain at failure as the cement percentage rises to 10%, suggesting a shift toward more brittle behavior brought on by cementation and matrix densification. This behavior can be attributed to the increased cement content and the progression of cement hydration, which result in a denser and more rigid soil matrix. As stiffness increases, the material's ability to undergo deformation before failure diminishes, leading to reduced strain capacity. Consequently, the failure mechanism shifts from gradual, ductile deformation to a more sudden and brittle fracture.

The findings of this study indicate that the investigated marl soil, stabilized with a mixture of 30% gravel and 10% cement, exhibited satisfactory geotechnical performance after 28 days of curing. Nevertheless, it is essential to further assess the feasibility of employing alternative stabilizing agents from both technical and economic perspectives. Potential substitutes such as lime, fly ash, blast furnace slag, and geopolymer-based binders possess distinct mechanical, environmental, and cost-related characteristics. A qualitative comparison suggests that the optimal choice of stabilizer is influenced by multiple factors, including soil type, prevailing chemical conditions, and long-term durability requirements. Furthermore, economic considerations reveal that both the initial investment and the life-cycle costs of each material may play a decisive role in determining their suitability for practical applications (Table 6).

7- Conclusion

Marly soils are considered problematic and sensitive soils in civil engineering projects, particularly in road pavement construction. These soils exhibit swelling and volume increase upon water absorption, and conversely, they undergo shrinkage and volume reduction, along with a decrease in bearing capacity, due to moisture loss and the formation of voids within the marly soil layers when ambient temperatures rise. These conditions can lead to settlement, deformation, and failure of the pavement structure built upon these layers, resulting in significant damage to the pavement body and the asphalt surface. This study aims to evaluate the effect of cement stabilization on a marl–gravel mixture sourced from the Tabriz region, with a view toward its potential use in road pavement layers. Since argillaceous marl is abundantly distributed throughout the study area, this type of marl was selected as the representative soil for the present investigation.

The experimental findings demonstrate that a mixture comprising marl with 30% gravel and 10% cement, after a 28-day curing period, exhibits optimum geotechnical performance for use in the subbase and base layers of pavements, particularly in cold climate conditions. This composition enhances the maximum dry unit weight of the soil by approximately 103 times compared to the unimproved marl, reduces water absorption by 5.26 %, improves load-bearing capacity as measured by the California Bearing Ratio (CBR) test by a factor of 1.34, and lowers the swelling potential by 15.2%. Furthermore, permeability testing revealed that this specific mixture facilitates adequate drainage and prevents the formation of ice lenses in cold regions. The uniaxial compressive strength test demonstrated that the optimum mixture, through the cement hydration process and the formation of cementitious materials, involves the reaction of cement with water to produce compounds such as C-S-H (calcium silicate hydrate) gel and $Ca(OH)_2$(calcium hydroxide). The C-S-H gel acts as a natural binder, bonding the marl and gravel particles together. Additionally, some of the silicates and aluminates present in the marl undergo pozzolanic reactions with the calcium hydroxide ($Ca(OH)_2$) produced from the cement, leading to the development of a hard and durable structure and increasing the bearing capacity by a factor of 4.9. These results indicate that, according to Code No. 234, this optimum mixture is acceptable for the construction of road pavements. Also, the results of this study demonstrated that the short-term (28 days curing) effectiveness of cement stabilization under laboratory conditions. However, the long-term behavior and actual performance under field conditions, particularly in cold regions, require further investigation and extended testing. Therefore, the present findings only reflect the short-term performance of cement stabilization, and any generalization to longer-term behavior or different environmental conditions should be made with caution.

In addition to the technical improvements achieved through the use of Portland cement, it should be noted that cement production has considerable environmental drawbacks. The manufacture of Portland cement is responsible for significant CO_2 emissions, with approximately one tonne of CO_2 released for every tonne of cement produced. This environmental burden highlights the necessity of balancing geotechnical performance enhancements with sustainability concerns. Therefore, while the results of this study demonstrate the effectiveness of cement in improving the geomechanical behavior of saline-sodic soils, the potential environmental costs must also be acknowledged.

8- Future research

Future research should prioritize the development and application of sustainable alternatives to Portland cement for soil stabilization. Promising options include supplementary cementitious materials such as micronized slag, fly ash, natural pozzolans, or geopolymer-based binders, which can substantially reduce the carbon footprint of soil improvement practices. Comprehensive investigations of the mechanical, chemical, and durability performance of these eco-friendly materials, in comparison with conventional Portland cement, would provide valuable insights. Additionally, life-cycle assessment (LCA) studies are recommended to evaluate the long-term environmental impacts and overall sustainability of various stabilization strategies. Future studies should also consider the effects of freeze-thaw cycles and sulfate attack on these alternative stabilizers.

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