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The effect of phosphogypsum on stabilizing clay soil and improving its properties for use as foundation soil

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Abstract

Expansive soil covers large areas in a variety of regions in Jordan which is insufficient to meet the engineering specifications in construction. Phosphogypsum is considered to be the main by-product material which comes from phosphate rock deposits that is available in Jordan. The main purpose of this research is to study the effects of stabilization by phosphogypsum on expansive soil properties. Three Jordanian regions were chosen to represent the expansive soils, Irbid, Madaba, and Abu-Nusire city. Soils were mixed with phosphogypsum at different percentages by dry weight of soil. Some of the representative laboratory tests for swell properties were conducted: grain size distribution, plasticity limits, standard compaction test, swell pressure and others. Laboratory results showed a positive response in the engineering soil properties which were confirmed by the Jordanian specifications for the sub-grade soils which may be used in road and building constructions. A 20% to 30% of phosphogypsum by weight of dry soil was found suitable to improve the engineering soil properties, such as the decrease in clay content and changed in classification from A-7 and A-6 soils to A-6 and A-4 soils, respectively. Field tests on short sections of roadways treated with phosphogypsum under a low to medium sustained traffic are recommended.

1. Introduction

Soil is one of the basic elements of the highway structure. It has a major influence on the design and construction of roadway pavements. Many studies and researches proved that highways constructed over plastic soil suffered from a high degree of distresses on the pavement [1,2]. Expansive soil is widely spread in Jordan and also all over the world. The use of such soil in roadway structure causes distresses, and that is attributed to the repetition of swelling and shrinkage of the expansive soil [3]. These soils are mainly affected when they come in contact with water that causes swelling and shrinking once it is removed and evaporated. The effects of all climatic situations on expansive soils must be considered during design analyses and may very well need to be overcome by stabilization methods in areas where seasonal moisture variations occur [4]. Therefore, improvement of this type of soil is essential. Soil improvement techniques can be classified in various ways according to the nature of the process involved, the material added, etc. [5]. Stabilization technique [6] can be used to improve the poor properties of expansive soil by reducing the high degree of plasticity and increasing the strength of subgrade and that leads to support the pavement under a load of traffic at all climate conditions, cut down on required pavement thickness, and prolong pavement life. Over long-term period, the strength that is provided by it is much higher than that for cement stabilized granular materials [7]. There are different methods of stabilization and these are mechanical, thermal, chemical, and electrical, and the selection of the stabilization method depends on many factors such as soil type and type of construction work [5,6]. In mechanical stabilization, the grading of a soil is changed by mixing it with other types of soils of different grades. By doing so, a compacted soil mass can be achieved. On the other hand, chemical stabilization is associated with the modification of soil properties by the addition of chemically active materials. In soil stabilization, it is very important to understand the material properties involved in the mixture and the outcome after mixing [8]. Stabilization agents are selected according to the type of soil, stability problem, and the economics of their use versus other solutions, such as bypassing or removing and replacing bad soil or redesigning of the pavement structure [9]. Phosphogypsum is a by-product waste material from the phosphate industry in Jordan which exists in large quantities. Hamawi [10] proved that phosphogypsum has binding properties and it can be used as a stabilizing agent to improve different soil properties such as strength, shrinkage, swelling pressure, water absorption, and permeability with a subsequent positive effect on roadway structure [9]. Phosphogypsum can strongly enhance the long-term strengths [6].

The standard cross-section for most of the constructed highway pavements consists of a relatively thin wearing surface built over a base course and a sub-base course material resting upon a compacted sub-grade. Highway deterioration is attributed to different types of failure or a break down in one or more of the pavement components of such magnitude that may render the pavement incapable of sustaining the loads imposed upon its surface. These failures may result from a structural weakness of the pavement constructed over unsuitable

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sub-grade materials, such as expansive soils. Expansive soils are usually stated in terms of its property such as unexpected expansion and contraction, prolonged water retains capacity, low rate of permeability, poor load transfer mechanism, and high compressibility. Due to these properties, the rate of failure mechanisms such as excessive settlement and sub-grade failures attain at a very fast rate, and the expansive soils are declared as more vulnerable than other types of soils. Hence, it becomes difficult for a civil engineer to make the construction using this type of soils. In Modern standard of life, the growth of Industrialization leads to increase the uncontrollable rate of effluence and generation of solid waste and the clearance of waste become a huge challenge to all the countries. The construction material production industries are showing major interest for utilizing this waste and the researchers tried to prepare a new kind of material for construction activities in large scales. In this paper, an effort is taken to investigate the variety of solid wastes that have been utilized in soil stabilization as a strengthening agent with or without lime and cement, in order to find the possible ways of utilizing the solid waste in huge practice for geotechnical applications. The problems of foundations built on expansive soil include heaving, cracking, and a break-up of pavement [11]. Also, building foundation slabs grade members, channels' reservoirs lining and streets may also pose such problems, due to swelling and shrinkage phenomena in the soil [12]. Many processes were used to avoid the potential soil problems and those are, first, by removing the undesirable soil and replacing it with a suitable one having good engineering properties, and second, by improving the soil with an artificial method to create a better one to meet the requirements of the roadway structural design and construction. The second approach may be the more feasible and attractive one and that includes the treatment of poor soils by stabilizing them with a suitable stabilizing agent. The quantity of the stabilizer is determined by several laboratory tests depending on the field, weather conditions, and other durability processes [5]. Previous researchers studied the effect of stabilization on soil properties, by using different additives, such as cement, lime, white cement kiln dust (WCKD), and phosphogypsum.

- **Cement stabilization:** Generally, cement stabilization is used for cohesionless soil with the best results are obtained with well-graded soils with a fine content of less than 50% and a plasticity index less than 20%. Cement could improve the properties of clayey soils with the addition of 5% by dry weight of soil that results in a drastic reduction in swelling potential [13,14].

- **Lime stabilization:** Lime stabilization has been used in construction for more than 5,000 years. Generally, lime stabilization is used for cohesive soils, where a quantity of 2% to 6% of lime by dry weight of soil is needed for stabilization. Lime stabilization is more effective with highly plastic and wet clayey soils [14]. This is of great importance as the addition of phosphogypsum has no effect on plasticity of the soil [15]. There are two types of chemical reactions for lime soil stabilization: one of them is the lime-soil modification reaction, which occurs immediately within a few minutes to an hour, causing a reduction in plasticity, volume change, and increase in soil workability [1,2,9,14,15].

- **Clay soil properties:** Clay is defined as a fine-grained soil with particle sizes less than 0.002 mm in diameter. Clay particles mainly consist of three types of minerals which are: kaolinite, montmorillonite, and illite. These minerals are responsible for the large volume change in expansive soils. They consist of plates with flat shapes, which are strongly attracted together to form lumps. The clay lumps have a strong affinity to water absorption in dry soil and have the ability to hold a film of water adsorbed on the surface of a flat plate that causes swelling in clay soil and removing this water will cause the soil to shrink [14]. Phosphate content in the original phosphogypsum varied over a wide range [16].

- **Phosphogypsum:** The word phosphogypsum indicates the industrial origin (phospho) and the predominate composition (-gypsum) [17]. Phosphogypsum is a byproduct material of wet acid production of phosphoric acid, produced from the fertilizer's industry in huge quantities. This by-product (- gypsum) precipitates during the reaction of sulfuric acid with phosphate rock [18]. For each ton of phosphoric acid, 5 tons of phosphogypsum are produced [9,10], approximately 110 million tons are expected to be produced all over the world [9]. A mixture of expandable aggregates. Clay, granulating slag with gypsonate binder, is used in making a light concrete, strong and thermally insulated, that could greatly lower the percentage of cement additions without reducing the mechanical strength. Gypsum has been used in making the fire protection cover of internal and external pieces of wood in the buildings. This application was first used in London on August 16th, 1667 [9]. Hamawi [5] has added phosphor-gypsum to three types of soil. Brown clay, green clay, and sand, and some of the engineering properties were improved, such as plasticity and strength [5]. Nurhayat [16] found that the most resistance of the adobe samples against softening in water was obtained with 25% PG addition. Al-Louzi [9] has studied the possibility of improving the properties of Asphalt mixtures by adding several types of phosphate as fillers. Phosphogypsum material is one of these fillers which has been found ineffective to improve Asphalt mixture stability [9].

The residual dissolved phosphate (RDP) could be further stabilized/ solidified (S/S) in the backfill via the hydration process [9]. There are three processes of phosphoric acid production: di- hydrate, himi-hydrate and hemi-di-hydrate combination. Di-Hydrate process (DH) is the most widely used in the world for producing the acid. DH process designed to produce 28% to 30% P205 acid, with high rate of filtration, uranium has to be extracted out. It yields 4.9 tons of dry phosphogypsum per each ton of P205 produce. Hemi-Hydrate process (HH) This process is relatively widely used in the worid, next to the di-hydrate process. It produces 40% to 52% P205 acid, with a high capital cost for filtration. It yields 4.3 tons of dry phosphogypsum per each ton of P205 acid [9,10]. Hemi- Di- Hydrate process (HDH) This process combines the advantages of the two di-hydrate and hemi-hydrate processes. It has been developed to produce 40% to 52% acid and its yield in dry phosphogypsum is about 4.9 ton/ton P205 produced [9,10]. It could be considered an economical process which produces a very clean phosphogypsum, but its production and maintenance cost is relatively higher than di-hydrated process. The annual production of phosphogypsum in the world is 140 million tons per year to 180 million tons per year, and only 15% of them have been utilized. Large quantities of phosphogypsum are available all over the world. Therefore, many research activities are directed towards processing of phosphogypsum, such as the production of building materials and as an additive for cement industries.

- **Volume change:** Volume change could be defined as the movement of solid volume due to changes in soil moisture content.

The amount of volume change depends on different factors such as the change in soil moisture content, the composition of the soil, weather, climate, and environment conditions. There are many processes that could be used to prevent volume change in the soil, and that is to control its water content such as proper compaction of the soil. Compaction of soils is one of the methods of soil stabilization. Through compaction, the stiffness and strength properties of the soil are improved and the permeability reduced [19]. Compaction at moisture content near or slightly in excess of the optimum moisture content, pre-soaking with water (the soil flooded prior to construction of the pavement, causes the sub-grade to lose some of its swelling characteristics), and appropriate chemical or physical treatment, such as lime stabilization [1,2,5,14,20,21].

- **Swell pressure and shrinkage characteristics:** Cohesive soil particles have tiny lumps covered by a water film. These particles are strongly tightened together by the inter-particle attractive forces. When these small lumps have desiccated, a reduction in the thickness of the adsorbed water film at the point of contact and an increase in the inter-particle stresses occur. Then these particles get closer to each other, and the volume of the soil decreases. This phenomenon is known as soil shrinkage. Al-Akhras [12] brought many samples of different types of Irbid soils and tested them in three orientations: vertical, horizontal, and inclined at 45°. It was noted that the greatest swell potential and swell pressure occurred in vertical soil samples. In soil lime treatment, the addition of lime up to 3% by dry weight of soil decreases the swell in soil, and it may approach zero-swell after 28 days curing period [5,21]. Swell percent and swell pressure increase in soil with the increase in dry density at a condition of no volume change and low water content and decrease with the increase in the moisture content of the compaction and at constant dry density.

- **Consistency limits of cohesive soils:** There are three states of consistency: liquid, plastic, and solid State. Liquid limit (LL) is the moisture content at which soil-mixture changes its consistency from liquid to plastic. Plastic limit (PL) is the moisture content at which the mixture changes from a plastic state to a non-plastic state (brittle). The plasticity index (PI) represents the range of moisture content over which the soil remains in plastic condition [21]. The difference between the liquid limit and plastic limit is equal to the plasticity index, and it may be used to establish the degree of plasticity, as shown in Table 1 [14]. The degree of expansiveness can be approximately determined by knowing the PI value and the percentage of clay in the soil [9,14,21]. Plasticity decreases by WCKD-soil treatment, and the rate of decrease slows after the addition of 10% of WCKD to Na'ymeh and Al-Jiza soils [22]. Plasticity can be reduced by the addition of phosphogypsum to clay soil [10]. Lime is a soil modifier, so when stabilizing soil with lime its plasticity index decreases. The decrease in plasticity slows down beyond the addition of 3% lime [12].

Table 1. The results of natural water content tests of natural soils and phosphogypsum.

Soil sample	(N.W.C) %Natural water content
Irbid soil	17.45
Madaba soil	16.25
Abu Nusire soil	12.82
Phosphogypsum	18-20

- **Permeability:** The permeability is defined as the capacity of the soil to allow water to pass through it through a network of channels formed by its pores [21]. Permeability in the soil depends mainly on particle size distribution, porosity, mineralogical composition of solids, the type of adsorbed cation, and temperature of water [21,23].

In this research paper, we will study the effect of phosphogypsum treatment on expansive soil properties through several experiments on soil samples from Jordan. A demographic representation for the expansive soil samples was deployed to increase the research validity. The optimal percentage of phosphogypsum by weight of dry soil was realized to improve the engineering soil properties. We investigate whether this improvement promotes soils as engineering materials in roadway structures that sustain low to medium traffic loads. As well, we validate if the use of phosphogypsum in expansive soil treatment is structurally, economically and environmentally feasible, especially since expansive soils are widely spread in Jordan.

2. Experimental methods

2.1 Soil samples

Sufficient quantities of expansive clay soil were brought from different areas in Jordan. These types of soils do not meet the specifications required for roadway construction [24]. The disturbed soil samples were obtained from three selected sites and taken from a depth of 0.5 m to 0.8 m underground surface. These selected sites are Irbid at 2 km southwest of Jordan University of Science and Technology, a site 15 km North of Madaba, and a site in the west of Abu-Nusire town, as shown in Figure 1. Sufficient quantity of a by-product phosphogypsum was brought from phosphate mining company in Amman.

Figure 1. Three selected sites of Jordan expansive soil. From https://commons.wikimedia.org/wiki/File:Jordan_location_map.svg by NordNordWest, License: CC-BY-SA 3.0

2.2 Laboratory tests and results

The samples of expansive soils were tested in the laboratories of the University of Jordan, Ministry of Public Works and Housing and Natural Resources Authority. All the required tests were carried out according to (AASHTO), (B.S) Standards, and (ASTM) specifications.

The following tests were done for soil-phosphogypsum mixture with different percentages (0% to 30%) of phosphogypsum by dry weight of soil. A quantity of clay was weighed, and the amount of gypsum to be added was directly decided in function of the weight of the clay. Batches of mixture were prepared at each gypsum content which enabled tests to be performed: Natural moisture content, specific gravity, grain size analysis (sieve analysis and hydrometer analysis), atterberg limits (liquid limit test, plastic limit test, and plasticity index), compaction test, swell pressure test, permeability and percent absorption.

2.3 Natural moisture content

This test is essential to determine the amount of water present in the soil in terms of dry weight (AASHTO, ASTM, B.S Standards). The soil samples were brought from the three sites immediately to the laboratory after being covered with foil papers and packed in a plastic bag to maintain their humidity without any loss. Three samples of soil for each of the three sites were prepared by placing each specimen in a weighted can and determining the wet weight. Then these specimens were placed in an oven to dry at a temperature of 110° ± 5%, to obtain the weight of the dry soil sample. Compute the water content percent from this equation:

$$W_{\%} = \left(\frac{W_w}{W_s}\right) * 100 \qquad (1)$$

$$W_w = W_{wet} - W_s \qquad (2)$$

Where W_{wet} = wet weight of soil, W_s = dry weight of soil, W_w = weight of water

2.4 Specific gravity (g]Gs)

The specific gravity value of the soil is necessary to compute the void ratio of the soil that will be used in the hydrometer analysis. G_s is equal to the ratio of the weight of a substance to the weight of water as long as equal volumes are involved.

$$G_s = \frac{\frac{W_s}{v}}{\frac{W_w}{v}} = \frac{W_s}{W_w} \qquad (3)$$

The specific gravity values of the three soil types before adding phosphogypsum and after adding 25% phosphogypsum (this percent was investigated later in chapter four) by weight of soil were obtained according to (AASHTO and ASTM) specifications, and the results are shown in Table 2. The specific gravity of the phosphogypsum was found to be 2.38, which is an average of three samples that have been tested.

2.5 Grain size analysis

The grain size analysis is an attempt to determine the relative proportions of different sizes which make up a given soil mass.

Sieve analysis: A 0.5 kg of an oven-dry soil for each type of soil was washed individually by water on the No. 200 sieve, the residual grains were poured by back washing into a large weighed dish. The dish and the remaining soil-water suspension were placed in an oven for drying and then, a sieve analysis test was accomplished by obtaining the quantity of materials passing through a given sieve opening. The results are shown in the Table 3 for Irbid, Madaba and Abu-Nusire soils respectively.

Hydrometer test: A quantity of 50g of an oven-dry well pulverized soil passing the No. 200 sieve were mixed with 125 mL of 4% $NaPO_3$ solution to form a 1000 cm^3 quantity of solution. When the dispersing agent is added, it neutralizes the charges on the smaller soil grains that have been close to each other and creates larger particles, so they settle faster through the fluid than the smaller particles, according to Stoke's law. Distribution of soil particles from the No. 200 sieve (0.075 mm) to around 0.001mm was obtained. The principal value of hydrometer analysis is the determination of the percent clay (percent finer than 0.002 mm), which is the most important fraction that influences the behavior of cohesive soils. The results are shown in Table 4 for the three natural soils and Table 5 for 28 days cured soils after being treated with 25% phosphogypsum.

Table 2. Specific gravity of soils before treatment and after treatment with 25% of phosphogypsum.

Soil sample	**G_s specific gravity**	
	At 0% phos.	**At 25% phos.**
Irbid	2.62	2.576
Madaba	2.58	2.547
Abu-Nusire	2.68	2.638

Table 3. Result of sieve analysis of Irbid, Madaba and Abu-Nusire soil before treatment and after treated with 25% of phosphogypsum.

Sieve no.	**Before treatment with PG**			**After treatment with 25% PG**		
	Irbid	**Madaba**	**Abu-Nusire**	**Irbid**	**Madaba**	**Abu-Nusire**
4	100	100	100	100	100	100
10	100	99	96.9	94	95.62	93.4
40	97	94.9	89.6	90	91.83	82.9
200	92	91.5	81.56	86	83	73

Table 4. Hydrometer analysis for natural soils.

Soil type	%sand	%clay	%silt
Irbid	7.60	45	42.9
Madaba	8.50	35	56.5
Abu-Nusire	18.44	35	46.6

Table 5. Hydrometer analysis for treated soils with 0% and 25% phosphogypsum and 28-days curing time.

% Phospogypsum	Treated with 0% PG			Treated with 25% PG		
Soil type	**%sand**	**%clay**	**%silt**	**%sand**	**%clay**	**%silt**
Irbid	7.60	45	42.9	14	27	59
Madaba	8.50	35	56.5	17	25	58
Abu-Nusire	18.44	35	46.6	27	20	53

Table 6. Effect of phosphogypsum content on consistency limit for Irbid, Madaba and Abu-Nusire soils.

% Phospogypsum		0%	10%	15%	20%	25%	30%
Irbid soil	Liquid limit (%)	47.4	44.3	41.6	39.8	38.60	37.80
	Plastic limit (%)	22.4	23.9	24.6	24.1	24.54	24.98
	Plasticity index (%)	24.9	20.4	17.0	15.0	14.06	12.82
Madaba soil	Liquid limit (%)	43.0	35.2	34.5	33.8	32.03	31.40
	Plastic limit (%)	28.0	24.2	24.1	24.1	22.60	22.07
	Plasticity index (%)	15.4	11.0	10.4	9.74	9.43	9.33
Abu-Nusire soil	Liquid limit (%)	40.0	39.2	37.5	36.3	34.66	34.20
	Plastic limit (%)	22.0	22.6	22.8	25.1	24.91	24.37
	Plasticity index (%)	18.0	16.4	14.7	11.1	9.75	9.83

2.6 Atterberg limits

Liquid limit: Enough number of samples were prepared and tested according to (AASHTO T89) specification. All samples were made by passing a pulverized portion of oven-dry soil through a No.40 sieve, and an amount of 50 g from each soil was mixed with water. This part of the soil was placed in a brass cup, cut with standard groove, and then dropped from a height of 1 cm. The liquid limit was determined as the percent of water content that caused the groove to close 12.7 mm on the 25 blows of cu against the base of the apparatus. The results are summarized in Tabe 6.

Percentage was determined, and that was equal to the plastic limit value. The results are summarized in Table 6 for Irbid, Madaba, and Abu-Nusire soils.

Plasticity index (PI): PI-values were determined by computing the difference between liquid limit and plastic limit values, and the results are shown in Table 6 for Irbid, Madaba, and Abu-Nusire soils.

2.7 Compaction test

Standard compaction tests are essential for determining the optimum moisture contents which are required for preparing samples for performing swelling pressure and permeability tests. Each proctor specimen required 3.0 kg of oven-dried soil, which was pulverized sufficiently and sieved through the No.4 sieve. The amounts of phosphogypsum added were (0% to 30%) by dry weight of soil, and each soil-phosphogypsum mixture was mixed with different quantities of water, then standard proctor test was carried out according to (AASHTO T99). Moisture-density relationships are illustrated in Figures 2 and Figures 3 for phosphogypsum and the three types of soils. Maximum dry density and corresponding optimum moisture content values are summarized in Table 7 for Irbid, Madaba, and Abu-Nusire soils.

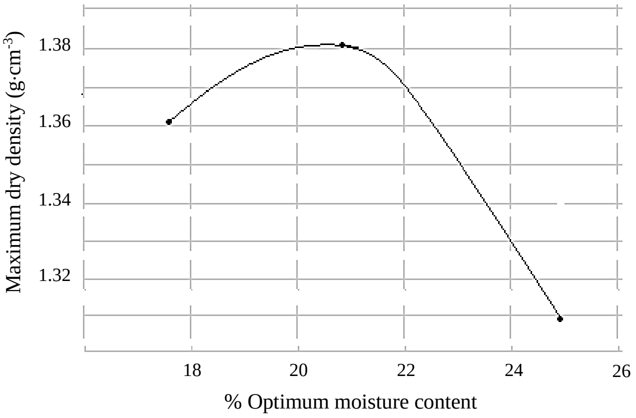

Figure 2. Moisture-density relationship for phosphogypsum.

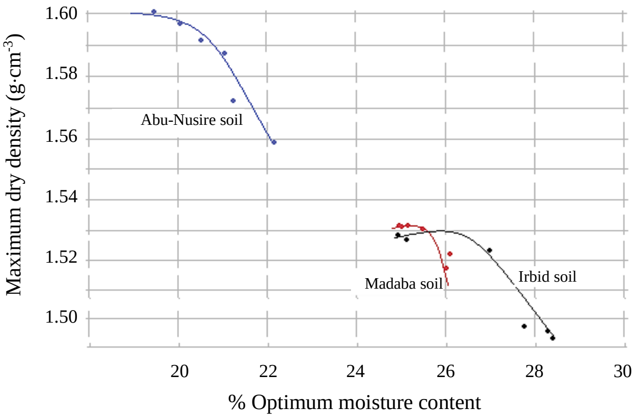

Figure 3. Moisture-density relationship for Irbid, Madaba and Abu-Nusire soils treated with various phosphogypsum content.

Table 7. Maximum dry density and corresponding optimum moisture content of Irbid, Madaba Abu-Nusire soil with various phosphogypsum contents.

% Phospogypsum		**0%**	**10%**	**15%**	**20%**	**25%**	**30%**
Irbid soil	Maximum dry density (g·cm^{-3})	1.53	1.53	1.52	1.49	1.465	1.44
	Optimum moisture content (O.M.C) (%)	24.9	25.4	26.8	27.6	28.21	28.28
Madaba soil	Maximum dry density (g·cm^{-3})	1.53	1.53	1.53	1.52	1.511	1.496
	Optimum moisture content (O.M.C) (%)	25	25.1	25.2	25.5	26.42	25.95
Abu-Nusire soil	Maximum dry density (g·cm^{-3})	1.61	1.6	1.59	1.59	1.572	1.558
	Optimum moisture content (O.M.C) (%)	19.7	20.2	20.5	21.1	21.52	22.04

Table 8. Effect of phosphogypsum content on permeability coefficient of each soil.

% Phosphogypsum	**0%**	**10%**	**15%**	**20%**	**25%**	**30%**
K-value for Irbid soil $*10^{-7}$	0.02	0.9	3.573	8.95	14.255	14.53
K-value for Madaba soil $*10^{-7}$	0.34	1.67	3.45	6.07	7.60	7.57
K-value for Abu-Nusire soil $*10^{-7}$	2.4	5.511	12.35	18.1	24.62	25.6

Table 9. X-ray diffraction analysis and natural soils and phosphogypsum.

Soil sample	**Major**	**Minor**	**Trace**
Irbid	Quartz	Calcite	Kalonite and feldspar
Madaba	Quartz	Calcite and feldspar	kalonite
Abu-Nusire	Calcite	Quartz	kalonite
Phosphogypsum	Gypsum	-	Quartz

Table 10. Results of chemical composition tests of natural soils and phosphogypsum

Soil sample	**Na_2O (%)**	**MgO (%)**	**Al_2O_3 (%)**	**SiO_2 (%)**	**P_2O_5 (%)**	**K_2O (%)**	**CaO (%)**	**TiO_2 (%)**	**MnO (%)**	**FeO_3 (%)**
Irbid	0.00	3.39	12.53	49.65	0.13	1.31	10.12	1.10	0.1	7.47
Madaba	0.17	2.48	12.22	56.82	0.21	1.74	9.05	1.17	0.1	6.66
Abu-Nusire	0.01	2.41	8.91	40.34	0.14	1.29	23.66	0.87	0.09	5.13
Phosphogypsum	0.00	1.28	0.38	3.06	1.17	0.06	35.10	0.02	0.3	0.2

2.8 Swell pressure test

The samples for swell pressure test were made by compacting the soil-phosphogypsum mixtures at their O.M.C. according to standard AASHTO compacting test and left for curing in the compaction cylinder. Enough number of samples were prepared after being stabilized with 0% to 30% of phosphogypsum by dry weight of soils and they were cured for 0, 7, 14, 21 days, then carefully trimmed to fill the consolidation floating ring, mounted in the Oedometer devices and soaked with water. The sum of surcharge weights which were applied to prevent swell divided by area of floating ring, were considered as the swell pressure values in kg·cm^{-2}.

2.9 Permeability

The coefficient of permeability of cohesive soils was determined according to (AASHTOT215) falling head method. The soil phosphorgypsum mixtures were performed by compacting them [25,26]. Values of effect of Phosphogypsum content on permeability coefficient of each soil are summarized in Table 8 for Irbid, Madaba, and Abu-Nusire soils.

2.10 Chemical test

Chemical analysis tests were carried out by the natural resource authority. Two types of tests were done: X-ray diffraction test (XRD) (Table 9) and chemical composition test (Table 10). These tests were performed on the three soil types of soil before and after treatment with 25% phosphogypsum by weight of soil and cured for 28 days. The extent of existence of a mineral in the soil is expressed as "major", "minor" and "trace" based on relative XRD height peak data.

3. Results and discussion

3.1 Grain size analysis

Figure 4 shows the grain size distribution for natural phosphogypsum material. Figure 5 shows the grain size distribution for the three soils namely Irbid, Madaba, and Abu-Nusire, respectively. Untreated soil and soil mixed with 25% phosphogypsum by weight of soil and cured for 28 days are shown. The figure for the three soils shows that percent of sand increases and percent of clay decreases due to the presence of phosphogypsum, which is an increase in grain size of the soil after being treated with phosphogypsum. This means that agglomeration, coarsening, and flocculation of the soil particles have occurred, possibly due to either cation exchange or crowding of additional cations into the clay minerals, both processes help change the electric-charge density around the clay particles, then these particles become electrically attracted to one another [5,10,22]. The effect of phosphogypsum treatment on grain size distribution is similar to that for soil treated with lime [5].

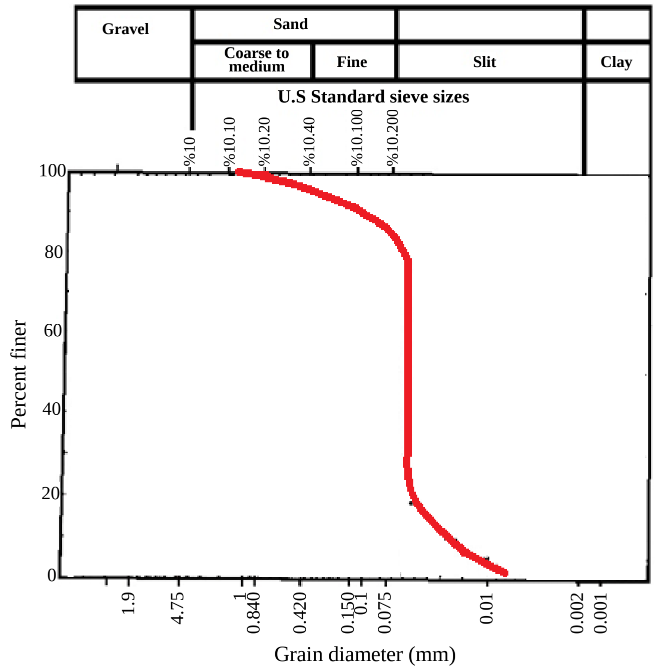

Figure 4. Grain size distribution of phosphogypsum.

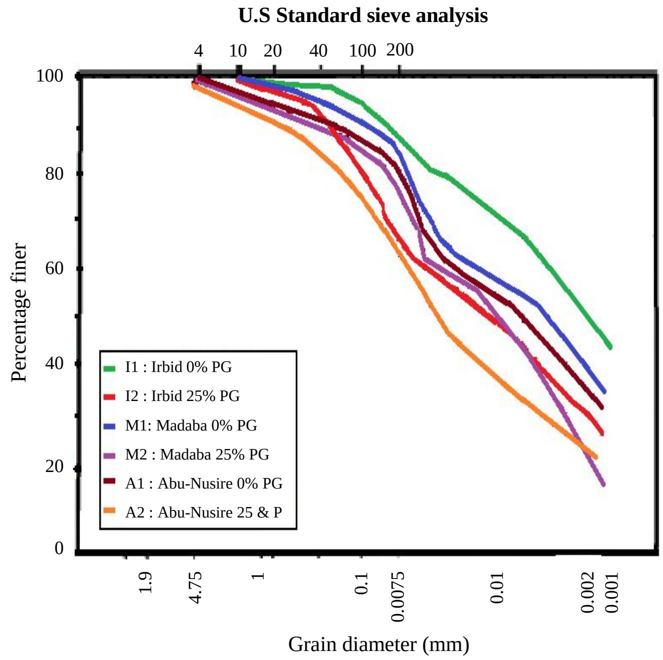

Figure 5. Grain size distribution of Irbid, Madaba and Abu-Nusire soils: at natural condition 0% of phosphogypsum (I1, M1, A1 blue curves), after treatment with 25% of phosphogypsum and 28-days curing time (I2, M2, A2 red curves).

3.2 Atterberg limits

Figures 6 to Fugures 8 represent the Atterberg limits relationship with percent of phosphogypsum in the soil mixture for Irbid, Madaba, and Abu-Nusire soils. These figures show that as the percent of phosphogypsum increases, liquid limit and plasticity index decrease for the three soils. Plastic limit increases for Irbid and Abu-Nusire soils, but it decreases in Madaba soil. Figure 9 shows the relationship between phosphogypsum and plasticity index for Irbid, Madaba, and Abu-Nusire soils. It is seen that the plasticity index decreases as phosphogypsum content increases for the three soils, which are mainly due to a reduction in liquid limit.

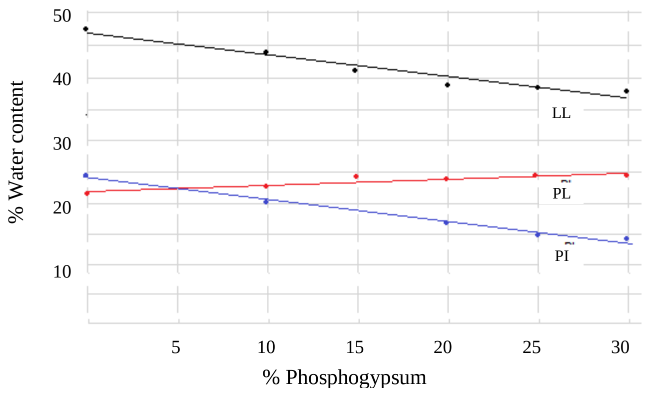

Figure 6. Effect of phosphogypsum content on consistency limits of Irbid soil.

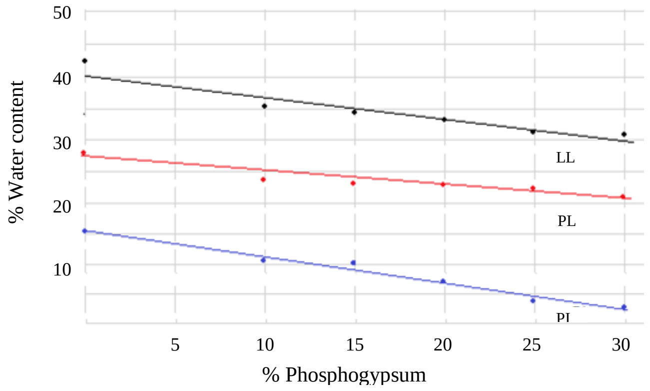

Figure 7. Effect of phosphogypsum content on consistency limits of Madaba soil.

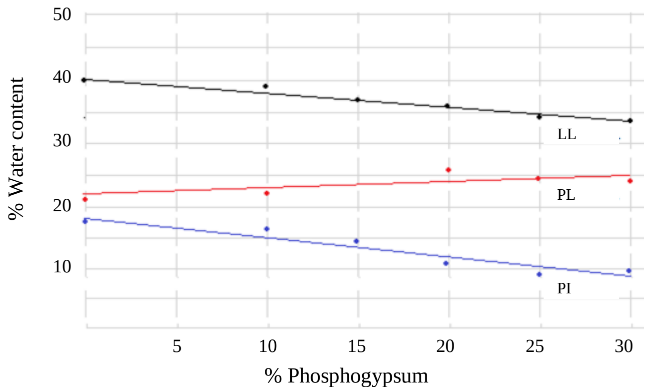

Figure 8. Effect of phosphogypsum content on consistency limits of Abu-Nusire soil.

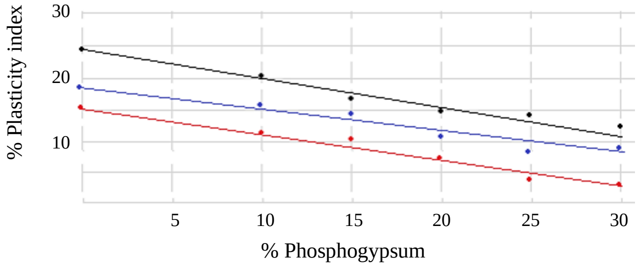

Figure 9. Effect of phosphogypsum treatment on Plasticity index.

Previous studies on lime and cement treatment have shown similar effects on consistency limits of the treated soils as seen in Figure 9 taken from reference [1] and [2], which shows the effect of lime treatment on consistency limits of 13 clay soils, the effect of Portland cement treatment on Consistency limits of A-7-6 soil taken from Illinois State. It could be seen from these two figures that the liquid limit decreases, the plastic limit increases, and the plasticity index sharply decreases. The decrease in liquid limit with phosphogypsum treatment in the soil is attributed to two processes that might have occurred during the agglomeration of soil particles. Cation valence and ion exchange where calcium ions of phosphogypsum replaced the weaker ions. Chemical hardening in some of the attracted ions which decreases the film of water surrounding the particles and consequently leads to a decrease in the liquid limit [5,10,14]. Yoder [2] investigated the changes in the Atterberg limits of lime treated soils, which were caused by the ion exchange. Since calcium ions in lime are divalent and serve to bind the soil particles together, then a more open and granular structure is produced and that leads to reduce the plasticity in treated soils [1,2]. The plastic limit increase is due to an increase in the optimum moisture content of the soil-phosphogypsum mixture as shown in Table 6. There is a sufficient attractive water film surrounding the mixture particles that allowing the particles to change the position and re-flocculate under the rolling process during the plastic limit test, which provides deforming forces without creating a continuous air-water interface between a group of particles, thus some of the phosphogypsum treated soils behave plastically.

In Madaba soil treated by phosphogypsum, on the other hand, plastic limit decreased because of the soil grain composition. A very slight increase in the optimum moisture content is noticed as shown in Table 6, so there is no sufficient water surrounding the soil particles and that decreases the movement of particles to change their position under the rolling process in the plastic limit test [1,2,14].

3.3 Classification

Treatment of the soil with phosphogypsum changes the classification group of the soil, as shown in Table 11.

In Irbid, soil which was treated with phosphogypsum, the classification changed from A-7-5 clay soil to A-6 silty-clay soil at 20-30 percent of phosphogypsum. In Madaba, soil treatment with phosphogypsum was very effective as it changed the classification from A-7-6 clay soil to A-6 silty clay soil after the addition of 10% phosphogypsum and changed it to A4 sand-silt clay soil after the addition of 20-30% of phosphogypsum to the soil.

Phosphogypsum treatment of Abu-Nusire soil improved classification from A-6 before treatment to A-4 after the addition of 25% to 30% phosphogypsum. These improvements in soil classification will enable the soils to meet the Jordanian specifications for road construction. The properties of treated soils are superior to those of the soils having the same classification designation [27].

3.4 Compaction

Figure 10 shows the relationship between maximum dry density and phosphogypsum content respectively for Irbid, Madaba, and Abu-Nusire soils while Figure 11 shows the relationship between optimum moisture content and phosphogypsum content respectively for Irbid, Madaba, and Abu-Nusire soils. It could be seen that the treatment of all types of soils with phosphogypsum decreased the maximum dry density with a corresponding increase in optimum moisture content. That is attributed to the replacement of soil particles by phosphogypsum particles, which have lower specific gravity and lower dry unit weight than the soil. The agglomeration of the particles and the increase in the soil particle size cause an increase in the average pore size. Consequently, more amount of water is required to fill these pores, and this leads to a decrease in the maximum dry density and an increase in optimum moisture content. Each soil has a different density and a different mineral composition, but all soils have clay minerals with different percentages. Therefore, the effect of phosphogypsum content on each soil would differ, but the overall behaviors are similar.

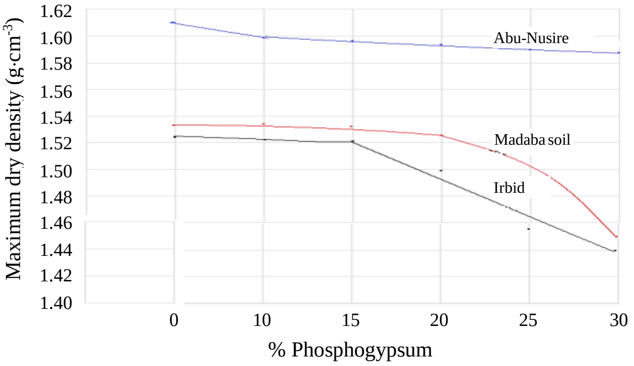

Figure 10. Effect of phosphogypsum on Max. dry density of Irbid Soil, Mababa soil and Abo-Nusire soil.

Table 11. Classification of natural soils and treated soils with phosphogypsum according to (AASHTO) soils classification system.

% Phosphogypsum	Irbid	Madaba	Abu-Nusire
0	A-7-5	A-7-6	A-6
10	A-7-5	A-6	A-6
15	A-7-5	A-6	A-6
20	A-6	A-4	A-6
25	A-6	A-4	A-4
30	A-6	A-4	A-4

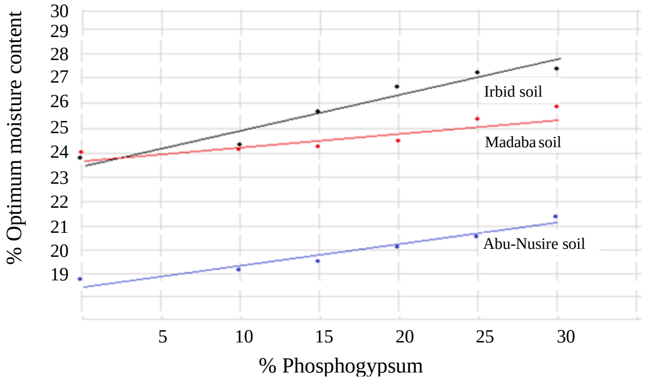

Figure 11. Effect of phosphogypsum on optimum moisture content of Irbid Soil, Madaba Soil, Abu-Nusire soils.

3.5 Degree of expansiveness

The degree of the expansiveness of the three types of soils decreased with phosphogypsum treatment due to the decrease in their plasticity index and the amount of clay. The results are shown in Table 12, which are determined similar findings established for South African expansive clay [14,21]. As illustrated in Table 12, the degree of expansiveness was decreased one degree and that was from high to medium in Irbid soil and from medium to low in Madaba soil, but it was decreased in Abu-Nusire soil two degrees and that was from high to low, which means that the effect of phosphogypsum treatment on Abu-Nusire soil is more than the effect on the other two soils of Irbid and Madaba.

3.6 Swell pressure

Figures 12 and Figrure 13 show the relationship between percent phosphogypsum and swell pressure for Irbid. Madaba and Abu-Nusire soils, respectively, for different curing periods. It is seen that swell pressure decreases with the increase of phosphogypsum content in the three soil types. The decrease in swell pressure curves was rapid for 0% to 10% of phosphogypsum. After that, the rate of reduction became less rapid for 10% to 20% of phosphogypsum, then it slowed down after 20% of phosphogypsum. The reduction in swell pressure with phosphogypsum treatment is attributed to the soil structure factor, which has a dominating influence on the swelling characteristics of expansive soils. The results of grain size analysis and mineralogical analysis indicated that there is a decrease in the amount of clay and loss in some clay minerals such as, kaolinite and feldspar, that lead to a decrease in the affinity for water in the mixture saturated particles, an increase in the inter particles attractive force which attracts the particles to each other and in decreasing the separation distance between them, and all these factors increase the resistance to expansion [5,14]. Figure 14 shows the relationship between swell pressure and curing time for Irbid, Madaba, and Abu-Nusire soils, respectively. On each figure, different percentages of phosphogypsum are shown. This figure shows a decrease in swell pressure of the three types of soil.

Curing time has more effect on swell pressure with low percent (10%, 45%) of phosphogypsum in the mixtures of Irbid, Madaba, and Abu-Nusire soils. After 21-days curing period for soils containing 20% to 30% of phosphogypsum, swell pressure approaches very little values, about 0.122 kg·cm^{-1} to 0.065 kg·cm^{-1} in Irbid soil, 0.02 kg·cm^{-1} to 0.015 kg·cm^{-1} in Madaba soil and 0.026 kg·cm^{-1} to 0.022 kg·cm^{-1} in Abu-Nusire soil. The effect of curing time on swell pressure after phosphogypsum treatment is similar to the effect of lime treatment on the swell, as seen in the effect of lime on Irbid clay soil that was used by Alawneh [5]. Effectively, Alawneh [5] has shown the effect of lime treatment on swell percent and swell pressure respectively for Irbid clay soil at zero- and 28-days curing period. It is seen that swell percent and swell pressure decrease with the lime treatment of the soil and they reached zero after the addition of 9% lime with zero curing time. The reduction rate, however, increases with curing time since swell percent and swell pressure reached zero after the addition of 3% lime when curing was 28 days. Reduction in swell percent and swell pressure in soils treated with phosphogypsum or/and lime may be attributed to the formation of cementing products that increase the bond between soil particles as a result of the long-term hardening cementitious reaction [5,13].

Table 12. Degree of expansiveness of natural soils and soils treated with 25% of phosphogypsum according to chart in Figure (12).

Soil sample	**Degree of expansiveness**	
	At 0% phos.	**At 25% phos.**
Irbid	High	Medium
Madaba	Medium	Low
Abu-Nusire	High	Low

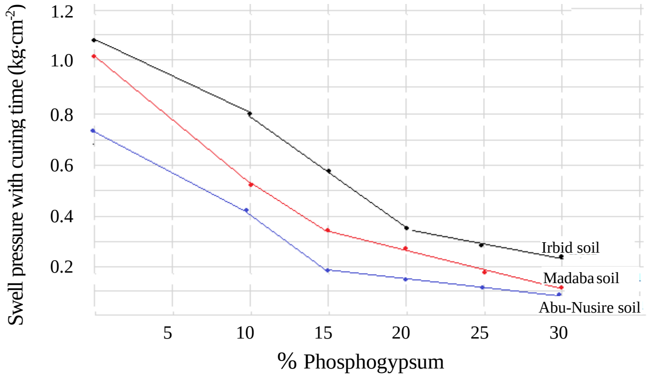

Figure 12. Swell pressure vs percent admixture of phosphogypsum at zero day curing time for Irbid, Madaba and Abu-Nusire soils.

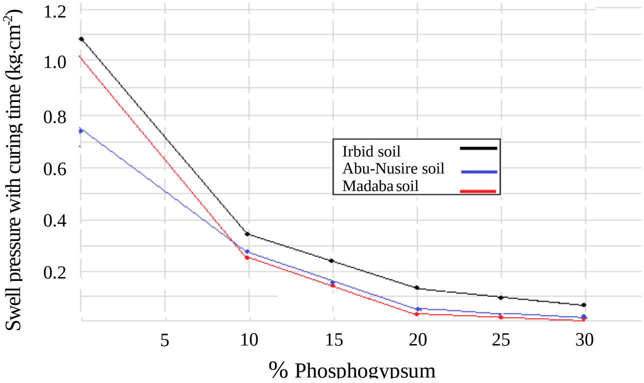

Figure 13. Swell pressure vs. percent admixture of phosphogypsum at 21 days curing time for Irbid, Madaba and Abu-Nusire soils

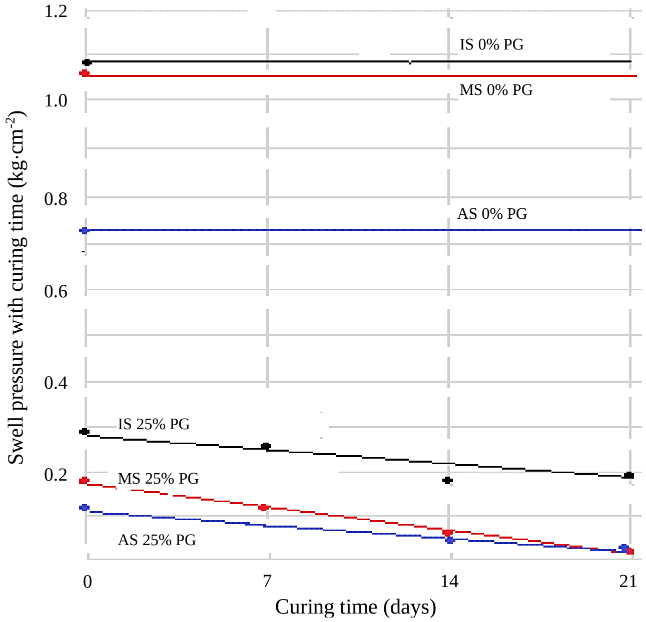

Figure 14. Variation of swell pressure with curing time for untreated and treated Irbid, Madaba and Abu-Nusire soils with different phosphogypsum contents.

3.7 Permeability and percent absorption characteristics

The effect of phosphogypsum contents on the coefficient of permeability is shown in Figures 15 and Fiugure 16 for Irbid, Madaba, and Abu-Nusire soils, respectively. As illustrated in the figures, the coefficient of permeability (k-value) increases with the increase in phosphogypsum percent. This increase is gentle till 10% of phosphogypsum, then it started to increase rapidly to 25% of phosphogypsum. After that the increase became slow. The increase in permeability of the soil with phosphogypsum treatment is attributed to agglomeration, granulation, and subsequent increase of the particles size in the mixture, which would increase the pore size and tend to increase the flow of water seepage and permeability in the soil. At a percent below 10% of phosphogypsum, the agglomeration, granulation, and subsequent increase in particles' size were not enough to increase permeability tremendously. The gentle increase in permeability with an increase in percent phosphogypsum more than 25% is attributed to the availability of more binding particles of phosphogypsum which began to fill the voids existing in the soil mixture. Alawneh [5] has found the effect of lime treatment on the coefficient of permeability for Irbid clay soil that the lime treatment increases the permeability of cohesive soils [5] and that is compatible with phosphogypsum treatment.

Figure 16 shows the effect of phosphogypsum treatment on percent absorption for Irbid, Madaba, and Abu-Nusire soil. It could be seen that % absorption decreases with phosphogypsum treatment in the three soils. This reduction in % absorption is attributed to the decrease in clay minerals, which are responsible for the ability of absorption of water in the soil and the ability to maintain the available amount of water adsorbed between their plate matrices [14]. Table 13 shows a reduction in clay content after treating the soil with phosphogypsum and the percent of clay in Irbid soil is more than in Madaba and Abu-Nusire soils, so the % of absorption in Irbid soil is more than in Madaba and Abu-Nusire soils as seen in Figure 16.

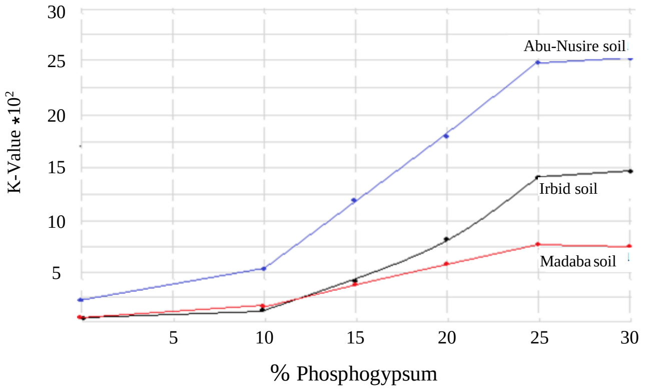

Figure 15. Effect of phosphogypsum content on coefficient of permeability of Irbid, Madaba and Abu-Nusire soils.

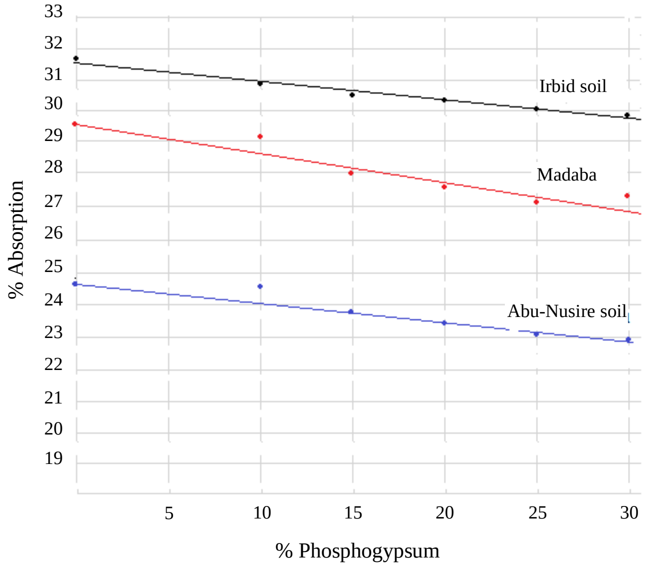

Figure 16. Effect of phosphogypsum treatment on percent absorption.

Table 13. Effect of phosphogypsum content on percent absorption of each soil.

Phosphogypsum	0%	10%	15%	20%	25%	30%
% absorption for Irbid soil	31.789	30.97	30.6	30.4	30.01	29.88
% absorption for Madaba soil	29.51	29.135	28	27.6	27.24	27.4
% absorption for Abu-Nusire soil	24.688	24.65	23.8	23.5	23.07	22.95

4. Conclusions

. In this research paper, we studied the effects of soil stabilization by phosphogypsum on its expansive properties through experiments on samples from Irbid, Madaba, and Abu-Nusire cities in Jordan. We found that stabilization of expansive clay soils with phosphogypsum could improve the engineering soil properties. This improvement upgrades soils for use as engineering materials in roadway structures that sustain low to medium traffic loads. Phosphogypsum treatment decreases the clay content and increases sand and silt contents of soils. It also reduces plasticity index, liquid limit, swell pressure, percentage of water absorption and maximum dry density, enhances permeability and prevents volume changes of soil-phosphogypsum mixtures. Irbid, Madaba and Abu-Nusire cities in Jordan have different weathers and environmental factors. Each soil has a different mineral composition, but all soils have clay minerals with different percentages. Therefore, the effect of phosphogypsum content on each soil would differ. But, the overall behaviors would be similar. The only drawback of such an addition is the pollution that can be caused by the radioactive nanoparticles of phosphogypsum altering plant growth [28] and water quality [29] in the processed land. However, the effect of this significant problem can be limited thanks to the availability of circuits for clean water supply and to applying land detoxification methods.

As a future direction of this research paper, we recommend using phosphogypsum as a by-product waste material in expansive soil treatment is structurally, economically and environmentally feasible since expansive soils are widely spread in Jordan. The recommended percent of phosphigypsum is 20% to 25% by dry weight of soil. We also recommend studying the effect of phosphogypsum treatment on other expansive soils in different regions in Jordan and different soil properties such as frost action and adverse drainage conditions. As well, we advise to study of the effect of phosphogypsum treatment on swelling pressure in the soil during a long period of curing time for (28 days and more) and the effect of stabilization of many types of Jordan soils; brown, green and sandy soils with many types of agents to observe the change in soil characteristics.

Author contributions

Mai Yahya Maaitah conceived this experimental study and performed and validated the analytical methods. Mus'ab Banat contributed to the scholarly publishing of this research paper through the development of the layout and structure of this final output.

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