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Application of phosphogypsum in soil stabilization

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Abstract

This paper describes the application of phosphogypsum with cement and fly ash for soil stabilization. Atterberg limits, standard Proctor compaction and unconfined compressive strength tests were carried out on cement, fly ash and phosphogypsum stabilized soil samples. Treatment with cement, fly ash and phosphogypsum generally reduces the plasticity index. The maximum dry unit weights increase as cement and phosphogypsum contents increase, but decrease as fly ash content increases. Generally optimum moisture contents of the stabilized soil samples decrease with addition of cement, fly ash and phosphogypsum. Unconfined compressive strengths of untreated soils were in all cases lower than that for treated soils. The cement content has a significantly higher influence than the fly ash content. The use of two waste by-products, phosphogypsum and fly ash may provide an inexpensive and advantageous construction product.

Keywords: Soil stabilization; Phosphogypsum; Fly ash; Cement

1. Introduction

Chemical stabilization is the modification of the properties of a locally available soil to improve its engineering performance. The two most commonly used chemical stabilization methods are lime stabilization and cement stabilization. Additives such as fly ash and phosphogypsum can be added to the soil–lime and soil–cement mixtures to further enhance the properties of the stabilized soil. In the present study, an industrial by-product phosphogypsum has been used with cement and fly ash as a chemical stabilization material to improve the engineering properties of selected soils. Phosphogypsum (PG) and fly ash (FA) are industrial by-products generated by phosphoric fertilizer industry and thermal power plants. Approximately 15 million tons of FA and 3 million tons of PG are generated every year in Turkey; these wastes are discarded in landfills, rivers and ponds.

PG is a by-product of the fertilizer industry, specially the production of phosphoric acid from phosphate rock. PG consists primarily of calcium sulfate and contains some impurities such as P_2O_5, F^- and organic substances. The presence of impurities puts restrictions on the use of PG in building materials and soil amendments. Relatively little of this by-product is currently utilized by the cement and gypsum industries as a set retarder for cement and for making gypsum plaster and bricks [1–7]. PG has also been reused with some success in stabilized road bases, unbound road bases, and roller-compacted concrete [8,9].

PG can be stabilized with class C fly ash and cement for potential use in soil stabilization. Cement-stabilized phosphogypsum has been studied over the last decade [10,11]. Studies have been shown that PG alone is not sufficient for road base construction. The addition of Portland cement or fly ash to PG yields slightly higher maximum dry density and optimum moisture content values for stabilized PG mixtures, in comparison with unstabilized PG mixtures. These studies recommended that cement with C_3A content less than 7% can be used with PG. For most soil–cement applications, Type I or Type II Portland cement was used conforming to ASTM C150 [12]. Cement content requirements vary depending on the desired properties of the soil-cement mixture and the soil type. Generally, as the clay

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content of the soil increases the quantity of cement required for stabilization. Some researchers recommend that the range of cement contents can be selected as 5–15% [13,14]. It is also recommended that stabilized base mixtures containing PG should be designed as close as possible to optimum moisture content and maximum dry density conditions, as determined by either the modified or standard Proctor test method [15,16].

FA is a pozzolanic material and has been classified into two classes, F and C, based on the chemical composition. Class F fly ash is produced by burning anthracite and bituminous coal, and class C fly ash is produced by burning lignite and sub-bituminous coal. The major difference between class F and class C fly ash is in the amount of calcium and the silica, alumina, and iron content in the ash. Class C fly ash, in addition to having pozzolanic properties, also has some cementitious properties and it has been successfully used as part of the binder in stabilized base applications [17,18].

The large volumes of unused PG can be re-used by combining FA and Portland cement in the building industry. However, environmental concerns have developed in the last 10 years because of the presence of radionuclides in PG. This material contains naturally occurring radioactivity and ^{226}Ra is major source of radioactivity. PG that exceeds 370 Bq kg^{-1}(10 pCi g^{-1}) of radioactivity has been banned from all uses by the Environmental Protection Agency (EPA) since 1992. The international limit prescribed by European Atomic Commission (EURATOM) is 500 Bq kg^{-1} (13.5 pCi g^{-1}) [19,20].

There is no unanimity on the safe limit for the radioactivity exposure due to PG. In the meanwhile, the phosphate industry has been looking into different ways of reducing the size of stacks. Researchers also seek the application areas for PG because the researches indicate that it would be more environmentally sounds to use by-products rather than dump them.

2. Experimental study

Representative soil samples were collected at 1.5 m depth from two deposits in Balikesir, Turkey. The properties of the soil samples designated as soil I and soil II are shown in Table 1. Soil samples can be classified as an A-7-5 soil in the AASHTO soil classification system. The soil samples are MH and CH-type according to the Unified Soil Classification System.

The cement used was Portland composite cement CEM II/B-M 32.5 R produced according to EN-197. The physical, chemical and strength properties of Portland composite cement (C) are presented in Table 2. The specific gravity and specific surface area of cement was 2.96 and 3633 cm^2 g^{-1}, respectively. The percentage of cement retained on sieve no. 325 (45-μm) was 6.9%.

FA was obtained from Soma Seas Thermal Plant in Manisa, Turkey. The Soma FA was produced from lignite coal and contains significant amount of CaO with a lime content of 15.34%. The chemical composition of Soma FA is given in Table 2. According to ASTM C 618 Soma FA can be classified as class C fly ash due to its chemical composition. This fly ash in addition to having pozzolanic properties also has some cementitous properties. The total amount of SiO_2, Al_2O_3 and Fe_2O_3 is 74.32% which is an amount larger than the value given by ASTM standard for type C class fly ash. Free lime content of FA complies with TSI [21] and EN [22] standards because it is 1.90%. The amount of SO_3 with 0.99% is less than the value given by the standards. Pozzolanic activity index (PAI) of Soma FA is 88% at 28 days and this value satisfies the ASTM C 618 limit (75%). PAI also meets the TSI and EN criteria that are 75% and 85% at 28 days and 90 days, respectively. The retained on 45-μm sieve was 16% which was less than 40%

Table 1
The properties of test soils

Property	Soil I	Soil II
Classification		
AASHTO	A-7-5	A-7-5
USCS	MH	CH
Atterberg limits		
Liquid limit LL (%)	56.41	72.46
Plastic limit PL (%)	35.71	33.33
Plasticity index PI (%)	20.70	39.13
Grain size distribution		
Gravel (>4.75 mm), (%)	1.00	0.00
Sand (0.075–4.75 mm), (%)	18.00	12.00
Clay and silt (<0.075 mm) (%)	81.00	88.00
Proctor test		
Optimum water content w_{opt} (%)	37.70	43.48
Maximum dry weight $\gamma_{d\ max}$ (kN/m^3)	13.64	14.00
Specific gravity	2.44	2.31

Table 2
Properties of materials used

Constituent (%)	Cement	FA	PG
Chemical properties			
SiO_2	31.42	45.98	3.44
Al_2O_3	8.86	23.75	0.88
Fe_2O_3	3.47	4.59	0.32
CaO	44.28	15.34	32.04
MgO	1.57	2.10	—
SO_3	2.45	0.99	44.67
K_2O	1.54	1.19	—
Na_2O	0.55	0.21	0.13
P_2O_5	—	—	0.50
F	—	—	0.79
CaO_{free}	0.85	1.90	0.81
Loss on ignition	5.04	1.62	21.06
Physical properties			
Specific gravity	2.89	2.24	2.96
Blaine (m^2/kg)	363	390	467
Retained on			
♯ 200 (75 μm) sieve (%)	0.1	16.00	20.13
♯ 325 (45 μm) sieve (%)	6.9	31.20	38.00

of requirement of TSI and EN standards. This value also was less than 34% of requirements of ASTM standards.

PG as a by-product of phosphoric acid process was procured from Bagfas fertilizer factory in Bandirma, Turkey. The chemical composition of PG is presented in Table 2. The major constituent in PG is calcium sulfate and, as a result, PG exhibits acidic properties (pH less than 3). The specific gravity of PG is 2.89 and the optimum moisture content is 13% and the maximum dry density is 14.70 kN m^{-3} based on standard Proctor compaction. PG is a damp, powdery material that is predominantly silt sized and has little or no plasticity. The maximum size range is between approximately 0.5 and 1.0 mm. PG can be classified as a silty soil, an A-4 or ML soil, with little or no plasticity. The results of radioactivity analyses of PG determined by Turkish Atomic Energy Association (Cekmece Nuclear Research and Training Center) are ^{226}Ra: 22 Bq kg^{-1}, ^{238}U: 9.0 Bq kg^{-1}, ^{232}Th: 1.0 Bq kg^{-1} and ^{40}K: 11 Bq kg^{-1}. Measures carried out on radioactivity of PG from Bagfas fertilizer plant permit its classification among weakly radioactive materials.

PG is generated as a filter cake in the wet process and is pumped in slurry form to holding ponds. The wet PG may need to be spread out in fairly thin layers for a few days. For this reason, the appropriate amount of PG and soil were air dried. The air dried soil was first passed a No. 40 (425 μm) standard sieve before tests. The required amount of stabilizer measured as a percent of dry soil was added to soil and mixed thoroughly to produce a homogenous soil blends. Then the appropriate amount of water calculated by weight of the soil mass was sprayed on the soil blends. The samples were molded at maximum dry density and optimum moisture content in accordance with TSI procedure [23]. Atterberg limits, standard Proctor compaction and unconfined compressive strength tests were carried out on soil samples prepared with stabilizer addition at variable percentages in order to examine their influence. Compaction characteristics and the description of soil mixtures are given in Tables 3 and 4, respectively. Each soil samples used in the unconfined compressive strength test was statically compacted in the cylindrical mold (38 mm in diameter and 76 mm high) at the optimum moisture content and maximum dry density. For curing, the samples were closely wrapped and placed in laboratory room where the temperature was maintained around 21 °C. The samples cured for 2 days and after curing unconfined compressive strength test was conducted.

3. Results and discussions

The effect of cement stabilization and cement–phosphogypsum stabilization on the consistency limits are shown in Table 3. It can be observed that a reduction in plasticity of stabilized soil as a result of increase in liquid limit values. Treatment with cement and phosphogypsum generally reduces the plasticity of the soils. Plasticity index was not determined for each soil with addition of 10% and 15% of cement. In general, 2.5–5% of cement and 2.5–5% of phosphogypsum show the optimum amount to reduce the plasticity of soils. Fig. 1 shows the effect of the addition of cement and cement–phosphogypsum mixtures on the compaction characteristics of the soils. An increase in dry unit weight and a decrease in optimum moisture content occurred as the cement and phosphogypsum contents increased for all soils. The increase in dry unit weight is generally accepted as an indicator of improvement.

The maximum dry unit weight and optimum moisture content and consistency limits of soils mixed with fly ash and fly ash–phosphogypsum mixtures are reported in Table 4. The addition fly ash generally decreases the plasticity index. Fly ash reduces the plasticity index of high plasticity soils but has little influence on the plasticity index of low plasticity fine soils. This behavior is attributed to smaller particle size, higher specific surface area and less crystallinity that make the clay minerals more susceptible to lime. The effect of fly ash and fly ash–phosphogypsum on maximum dry unit weight and optimum moisture content of stabilized soils are shown in Fig. 2. Maximum dry unit

Table 3
The results of compaction and Atterberg limit test of cement/cement–phosphogypsum stabilized soil

Mixture	w_{opt} (%)	$\gamma_{d\ max}$ (kN/m^3)	LL (%)	PL (%)	PI (%)
Soil I + 0% C	37.70	13.64	56.41	35.71	20.70
Soil I + 5% C	37.80	13.63	52.70	32.70	20.42
Soil I + 10% C	36.75	13.64	59.87	—	—
Soil I + 15% C	36.90	13.95	59.98	—	—
Soil I + (2.5% C + 2.5% PG)	38.40	13.53	58.59	53.13	6.45
Soil I + (5% C + 5% PG)	39.00	13.56	57.63	46.15	11.48
Soil I + (7.5% C + 7.5% PG)	38.35	13.62	64.72	46.67	18.05
Soil II + 0% C	43.58	14.00	72.46	33.33	39.13
Soil II + 5% C	34.50	14.27	58.36	28.79	23.71
Soil II + 10% C	32.83	14.19	63.75	—	—
Soil II + 15% C	32.53	14.17	57.50	—	—
Soil II + (2.5% C + 2.5% PG)	37.70	13.90	58.36	44.44	13.92
Soil II + (5% C + 5% PG)	34.30	13.95	55.22	38.46	16.76
Soil II + (7.5% C + 7.5% PG)	31.70	14.00	73.32	58.58	14.74

Table 4
The results of compaction and Atterberg limit test of fly ash/fly ash–phosphogypsum stabilized soil

Mixture	w_{opt} (%)	$\gamma_{d\ max}$ (kN/m^3)	LL (%)	PL (%)	PI (%)
Soil I + 0% FA	37.70	13.64	56.41	35.71	20.70
Soil I + 5% FA	39.20	12.34	55.22	44.44	10.78
Soil I + 10% FA	34.90	12.60	59.12	36.84	12.28
Soil I + 15% FA	34.60	12.86	53.23	38.46	14.77
Soil I + (2.5% FA + 2.5% PG)	35.30	12.60	47.55	25.00	22.55
Soil I + (5% FA + 5% PG)	37.20	12.50	59.67	33.33	26.34
Soil I + (7.5% FA + 7.5% PG)	37.20	12.50	49.76	35.71	14.05
Soil II + 0% FA	43.58	14.00	72.46	33.33	39.13
Soil II + 5% FA	32.40	13.39	76.20	50.00	26.20
Soil II + 10% FA	32.50	13.51	58.36	33.33	25.03
Soil II + 15% FA	32.50	13.58	58.84	33.33	25.51
Soil II + (2.5% FA + 2.5% PG)	30.50	13.30	84.93	50.00	34.93
Soil II + (5% FA + 5% PG)	30.40	13.30	75.37	33.33	42.04
Soil II + (7.5% FA + 7.5% PG)	32.20	13.40	62.11	25.00	37.11

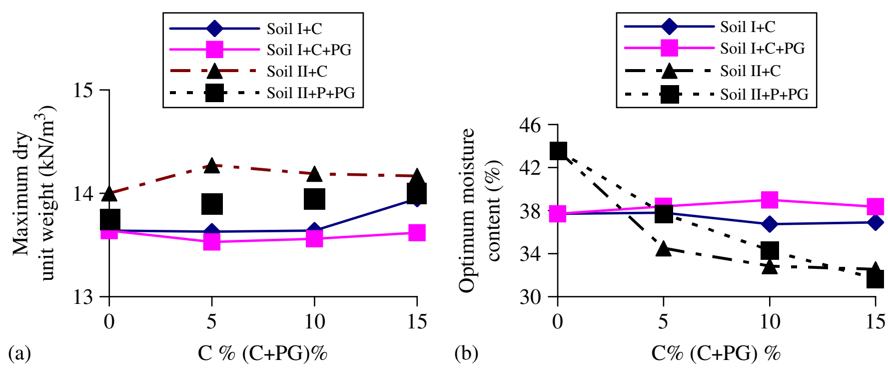

Fig. 1. Variation of compaction characteristics of soils stabilized cement/cement–phosphogypsum: (a) maximum dry density, (b) optimum moisture content.

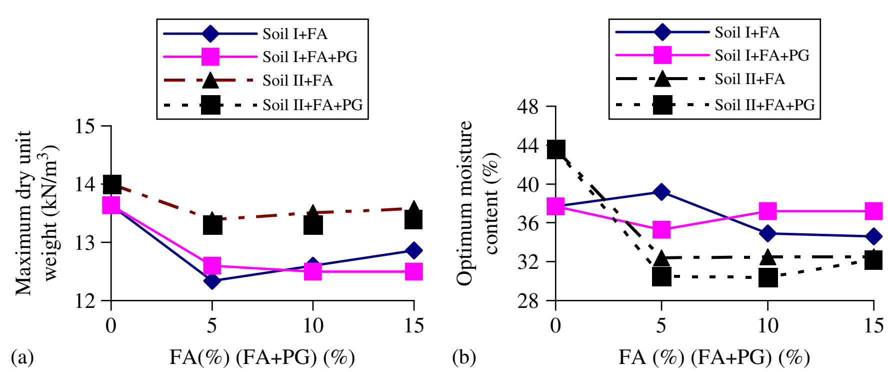

Fig. 2. Variation of compaction characteristics of soils stabilized fly ash/fly ash–phosphogypsum: (a) maximum dry density (b) optimum moisture content.

weight and optimum moisture content decreases with increasing of fly ash and phosphogypsum content. There is a substantial decrease of optimum moisture content at 5% of FA for soil II and after then the value remains relatively constant. However, the addition of 5% of fly ash alone causes the increase in optimum moisture content of soil II. The maximum dry unit weight decreases with increasing fly ash content because of the lower specific surface gravity of the fly ash than that of the soils. Some researchers also indicate that the reduction in dry unit weight occurs because of both particles size and specific gravity of soil and stabilizer [24].

Fig. 3 shows the unconfined compressive strength test results of soils stabilized with cement, fly ash and phosphogypsum. Unconfined compressive strengths of untreated soils were in all cases lower than treated soils.

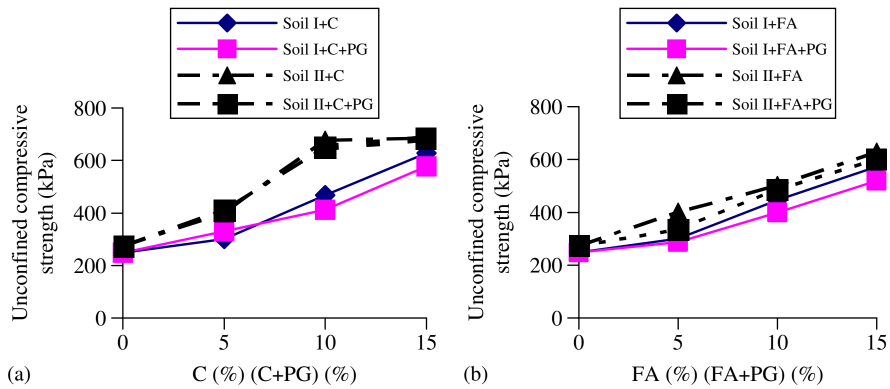

Fig. 3. Unconfined compressive strength of soil stabilized with addition of (a) cement and cement–phosphogypsum, (b) fly ash and fly ash–phosphogypsum.

There is significant gain strength with addition of cement. The gain in unconfined compressive strength is dependent on the cement content. The cement content has significantly higher influence than fly ash content. A high increase in unconfined compressive strength occurred with 15% of cement content for soil II.

4. Conclusions

This study reports the application of phosphogypsum with cement and fly ash as a stabilization agent on two selected soils. In the light of the test results the following conclusions can be made:

1. Treatment with phosphogypsum, fly ash and cement generally reduces the plasticity index. Principally, a reduction in plasticity is an indicator of improvement.
2. The maximum dry unit weight of phosphogypsum-stabilized soils increases with increasing phosphogypsum content. Besides this, fly ash content decreases the maximum dry unit weight.
3. Generally the optimum moisture content decreases with addition of cement, fly ash and phosphogypsum.
4. Unconfined compressive strengths of unstabilized soils were lower than the stabilized soils. The cement content has a significantly higher influence than the fly ash content.

Phosphogypsum, a solid by-product of phosphoric acid manufacturing, can potentially stabilize the expansive or non-expansive soils mixed with cement and class C fly ash. Approximately 3 million tons of phosphogypsum and 10 million tons of fly ash are generated by phosphate fertilizer industry and thermal power plant, for each year in Turkey of which these wastes are discarded in landfills or rivers. Considering the high cost of cement, the utilization of phosphogypsum and fly ash instead of dumping as waste materials both provides a significant contribution for country's economy and solution of the environmental pollution problem.

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