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Shear Strength and Microstructure of a Soil Treated by Magnesium Potassium Phosphate Cement (MKPC)

Ibtehaj Taha Jawad*
Department of Civil Engineering, College of Engineering, University of Babylon.

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ABSTRACT
This paper aimed to use a low pH-cement for treatment of an acidic soil. The soil was obtained from a depth of 70 cm below natural ground level. The cement used is called magnesium potassium phosphate cement (MKPC) which is prepared by a combination of magnesium oxide (MgO) and mono potassium phosphate (KH_2PO_4). Four cement doses ranged (0, 3.0, 5.0, and 7.0 %) were mixed by dry unit weigh of pure soil. The evolution in compressive strength and microstructure of soil-MKPC mixture were studied in this paper. The results show that a considerable growth in soil strength was obtained. The micrographs exhibit formation of MKPC cement and reduction in voids (i.e. densification of treated soil) as well as soil particles were glued together by cement formed.

مقاومة القص والبنية المجهرية للتربة المعالجة بسمنت فوسفات المغنيسيوم البوتاسيوم (MKPC)

الخلاصة
هذا البحث يهدف لاستخدام سمنت ذا رقم هيدروجيني واطئ لمعالجة التربة الحامضية. التربة المستخدمة لهذا الغرض استخرجت من عمق 70 سم تحت مستوى الارض الطبيعية. السمنت المستخدم يسمى فوسفات المغنيسيوم البوتاسيوم (MKPC) والذي يحضر بخلط اوكسيد المغنيسيوم (MgO) مع فوسفات البوتاسيوم الاحادية (KH_2PO_4) مع الماء. اربع نسب مختلفة من السمنت تراوحت بين 0 و 3.0 و5.0 و 7.0 % خلطت كنسب وزنية من التربة الاصلية الجافة. في هذه الورقة تمت دراسة تطور مقاومة التربة للقص والتغير في البنية المجهرية بعد اضافة السمنت ومقارنتها مع بنية التربة الاصلية. لقد اظهرت النتائج ان هناك نموا معتبرا في مقاومة القص للتربة المعالجة. كما ان البنية المجهرية للتربة بينت تكون المادة السمنية بشكل ملحوظ ونقصان في فجوات التربة (كثافة اعلى للتربة المعالجة) بالاضافة الى ترابط الحبيبات مع بعضها البعض بواسطة المادة السمنتية المتكونة.

الكلمات المفتاحية
معالجة التربة، البنية المجهرية للتربة، مقاومة التربة للقص، سمنت فوسفات المغنيسيوم البوتاسيوم

*Corresponding author.
E-mail addresses: eng.ibtehaj.taha@uobabylon.edu.iq
& ibtehaj78@yahoo.com

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Introduction

According to Little & Nair 2009 [1], Portlandite ($Ca(OH)_2$) represents 25 % (by volume) of chemical products of Portland cement (PC) hydration. The high solubility and reactivity of this product make it easy to interact with sulfate which leads up to form high expansive component called ettringite (calcium–aluminum–sulfate). This component induced swelling and strength reduction in Portland cement – treated soil [2, 3, 4, 5]. Moreover, production process of PC causes negative environmental impact and high energy consumption [6, 7, 8]. Therefore, a partially or fully replacement of Portland cement (PC) has became an urgent need Qiao et al. 2010 and Chau et al. 2011 [8, 9] show that the magnesium phosphate cement is the most likely alternative candidate to Portland cement. This cement sets rabidly at room temperature and characterized by high crystalline products, high water resistance, low permeability and good durability, as well as, it possesses a premium bond compared with PC [8, 9, 10, 11, 12]. Argonne National Laboratories of the United States have developed a magnesium phosphate cement depending on the base – acid reaction between magnesium oxide and potassium dihydrogen phosphate with water [13]. Ceramicrete is the name that has been lunched their product and the following chemical equation described the chemical reaction:

$$MgO + KH_2PO_4 + 5H_2O \Longrightarrow MgKPO_4.6H_2O \quad (1)$$

Ceramicrete or magnesium potassium phosphate cement (MKPC) has been found that it has isostructure with struvite [8]. Mattigod et al. 2011 [14] reported that a rare property of binding itself is one of the features that MKPC possesses. Heat evolution which coincides with the chemical reaction induces increasing the rate of the reaction, hence, in the hot environment, a so quickly dissolution for oxide leads to form a non crystallized (bad coordinated network) precipitant [15]. Consequently, to overcome this problem and to increase MKPC workability, boron compounds can be used to slow down the oxide dissolution [8, 12, 16, 17, 18].

The aim of this paper is to investigate the capability of MKPC of increasing soil strength. The microstructure of soil-MKPC mixture by using Field-Emission Scanning Electron Microscope (FESEM) was detected as well.

Materials

1. Soil

Table (1) shows the physical properties of the soil used in this research. The soil was collected from a depth of 70 cm below natural ground surface. Figure 1 and 2 show the grain size distribution and dry density-water content relationship, respectively.

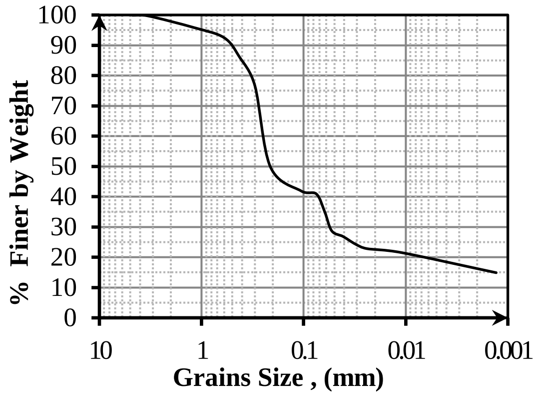


Figure 1: Grain size distribution for the test soil

Table 1 :physical properties of tested soil

Property	Maximum dry density (gm/cm^3)	Optimum water content (%)	Liquid limit (%)	Plasticity Index (%)	% Gravel	% Sand	% Silt	% Clay	pH -Value	UCSC
Values	1.78	16.0	25	12	0	59	25	16	4.6	SC
Specification	BS 1377- 4:1990		BS 1377-2:1990		BS 1377-1:1990				ASTM D 6276	/

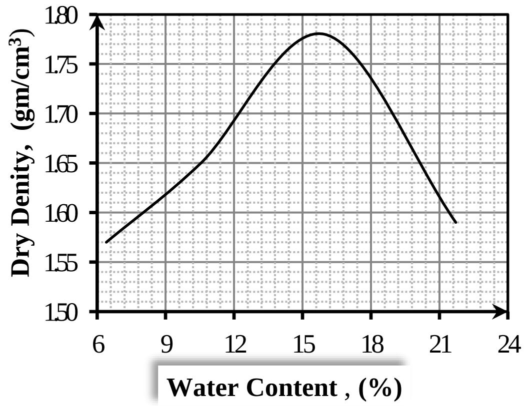


Figure 2 :dry density-water content relationship

2. Magnesium Oxide (Magnesia)

Magnesium oxide (MgO) of purity not less than 99 % was used to prepare the MKPC cement. Based on the supplier (Inframat Advanced Materials Company, USA), MgO possesses the following chemical properties (Table 2):

Table 2: chemical properties magnesium oxide as provided by Manufacturer ((Inframat Advanced Materials Company, USA)

Formula	MgO	Ca	Al	B	Fe	Mn	Na	Ni	Si	Zn
Value %	> 99.5	≤ 0.10	≤ 0.05 each							

3. Mono Potassium Phosphate

Green Life Agriculture Sdn Bhd Company, Malaysia, was the supplier of Mono potassium phosphate (KH2PO4). It is a colorless crystal with purity greater than 99 %. The chemical and physical properties illustrated in Table 3 are provided by the supplier.

Table 3: chemical and physical properties of mono potassium phosphate as provided by manufacturer (Green Life Agriculture Sdn Bhd Company, Malaysia)

Property	Analysis results
Physical Properties	
Purity	99.4 %
Color	Colorless crystal
Density	2.338 g/cm^3
Solubility (water)	33 g/ 100 ml
PH (25 º C)	4.4 – 4.7
Chemical Properties	
Phosphorus (P2O5) % w/w	52 %
Potassium (K2O) % w/w	34.4%
Lead (as Pb)	Not Detected (<0.1)
Arsenic (as As)	Not Detected (<0.1)
Mercury (as Hg)	Not Detected (<0.1)
Cadmium (as Cd)	0.1
Copper (as Cu)	0.1
Cobalt (as Co)	Not Detected (<0.1)
Molybdenum (as Mo)	Not Detected (<0.1)
Nickel (as Ni)	0.4
Selenium (as Se)	Not Detected (<0.1)

4. Disodium Tetraborate Decahydrate (Borax)

($Na_2B_4O_7 \cdot 10H_2O$) is the chemical formula of Borax which supplied from Active Micro Fertilizer (M) Sdn.Bhd Company, Malaysia, under trading name of (ACTIBOR11). The supplied borax has purity of 99.9 % with physical properties presented in Table 4 as provided by manufacture.

Table 4: physical properties of Borax as provided by manufacture (Active Micro Fertilizer (M) Sdn.Bhd Company, Malaysia)

Property	Values/Description
Appearance	White, Odorless, Crystalline Solid
Specific gravity	1.71
Solubility in water	4.70% @ 20°C; 65.64% @ 100°C
pH (20°C)	9.3 (0.1% solution), 9.2 (1.0% solution)

MKPC preparation

Theoretically, reaction of one mole of MgO with one mole of KH2PO4 produces one mole of MKPC as presented in equation 1. Some researchers adopted the theoretical molar ratio in preparation MKPC [19, 20]. While, some others have prepared MKPC with magnesia to phosphate (M/P) molar ratio of more than 1 (ranged from 2 to 10) [8, 12, 17]. The rising of molar ratio of M/P to more than 1 is because of the rapid reaction of reactants provides no enough time for magnesium oxide to fully reaction [8]. A molar ratio of 1:1 was adopted in this research. Borax was used to slow down the reaction rate. Based on the previous study, the percentage of borax ranged 2.5 to more than 10 % by weight of MgO [8, 17].

Methodology

Four cement contents of 0.0, 3.0, 5.0, and 7.0 % were mixed with pure soil. Optimum water content was used to prepare all specimens. Unconfined compression strength test was carried out to evaluate the evolution in soil strength. All specimens were tested after 24 hours since the chemical reaction take place in the early hours of mixing. The microstructure of soil-MKPC mixture was detected using Field-Emission Scanning Electron Microscope (FESEM). Comparison was made between the microstructure of pure soil and mixed soil. The specimens used for this purpose were pulverized and sieved through 100 mesh screen. Three different magnifications were chosen to clarify the microstructure of pure and MKPC-soil mixture, namely 1.00 KX, 5.00 KX and 10.00 KX. The scales corresponding to each magnification are 10.0 μm, 2.0 μm, and 1.0 μm, respectively.

Results and Discussion

1. Results of Unconfined Compression Strength

Figure 3 shown below presented the results obtained from unconfined compression test. Strength gain along the curve shown in figure calls attention. The original soil (0.0 % MKPC cement) has UCS of 151 kN/m^2. The strength has increased progressively by increasing the content of MKPC. Soil strength reaches values of 286 kN/m^2, 534 kN/m^2, and 615 kN/m^2 for 3.0 %, 5.0 %, and 7.0 %, respectively.

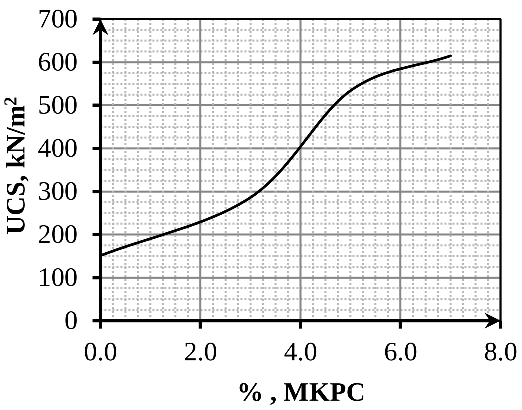


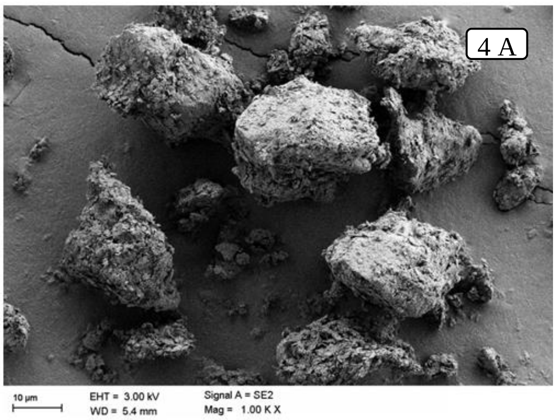
Figure 3: unconfined compressive strength results

2. Results of Microstructure

Micrograph 2A and 2B show the pure soil and MKPC-soil mixture under magnification of 1.00 KX. It can be seen that the grain size of treated soil turned out to be coarser than that of original soil. This is because of the bonding action of MKPC cement which makes the grains stick together.

On the other hand the figure 3A and 3B illustrate the both soils under higher magnification. The pure soil consists of plate-like shape particles. A new compound can be observed in the treated soil compared to original soil. This is may be disclosed the formation of cemented material i.e. MKPC cement.

An extra zooming in can be displayed in figure 4A and 4B. Flocculated platy grains can be viewed in both Figures. Figure 5B shows distinctly cement synthesis. Which appeared as big solid mass compared to original soil grains. It is obviously being seen that soil structure contains voids much more than that in treated soil. This change in soil structure points to develop packing density of the treated soil



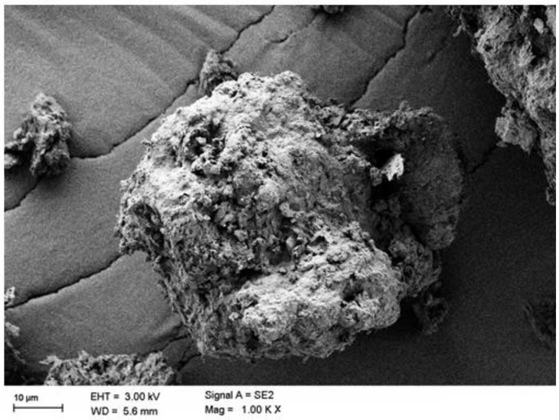
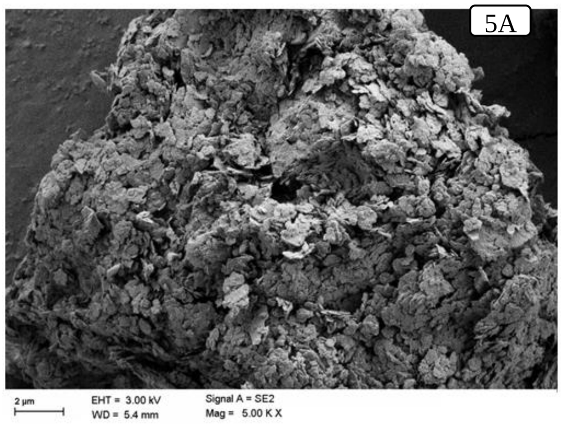


Figure 4:Micrograph of untreated soil (4A) and treated soil (4B) under magnification of 1.00 KX



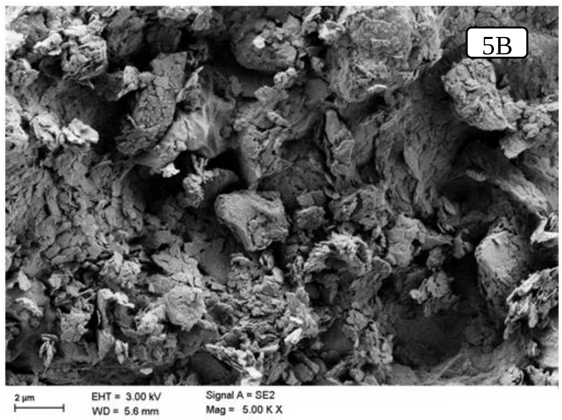


Figure 5 Micrograph of untreated soil (5A) and treated soil (5B) under magnification of 5.00 KX

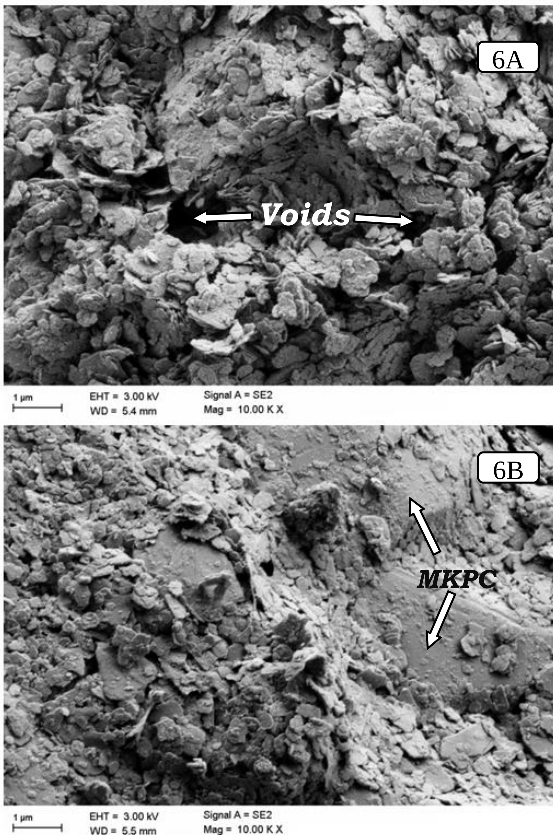


Figure 6: Micrograph of untreated soil (6A) and treated soil (6B) under magnification of 10.00 KX

3. Justification of Soil Strength Gain

Based on the outcomes obtained by the microstructure images, the strength gain can be justified by the following tips:

- Increase the grains size of treated soil makes the particles more tough.
- The formation of MKPC cement as solid mass which characterized binding itself.
- Reduction in voids and densification in soil packing.

Conclusion

Using Magnesium Potassium Phosphate Cement (MKPC) as low pH cemented material in the field of soil treatment gave the following feedbacks:

1. The unconfined compressive strength (UCS) of tested soil has increased noticeably with increase MKPC doses.

2. The FESEM inspection shows a substantial alteration in the structure of treated soil. The following alterations can be explored:

i. The particle size of treated soil seemed coarser than that of virgin soil.
ii. Dissimilar structure of solid mass points to formation of MKPC cement.
iii. Densification in soil mass due to lowering in voids of treated soil.

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