Research Article

Feasibility of Stabilized Zn and Pb Contaminated Soils as Roadway Subgrade Materials

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The authors have developed a new binder, KMP, which is made from oxalic acid-activated phosphate rock, monopotassium phosphate (KH₂PO₄), and reactive magnesia (MgO). This study explores the acid neutralization capacity, strength characteristics, water-soaking durability, resilient modulus, and pore size distribution of KMP stabilized soils with individual Zn, Pb, or coexisting Zn and Pb contaminants. For comparison purpose, Portland cement (PC) is also tested. The results show that KMP stabilized soils have a higher acid buffering capacity than PC stabilized soils, regardless of the soil contamination conditions. The water stability coefficient and resilient modulus of the KMP stabilized soils are found to be higher than PC stabilized soils. The reasons for the differences in these properties between KMP and PC stabilized soils are interpreted based on the stability and dissolubility of the main hydration products of the KMP and PC stabilized soils, the soil pore distribution, and concentration of Mg or Ca leached from the KMP and PC stabilized soils obtained from the acid neutralization capacity tests. Overall, this study demonstrates that the KMP is effective in stabilizing soils that are contaminated with Zn or Pb alone and mixed Zn and Pb contaminants, and the KMP stabilized soils are better suited as roadway subgrade material.

1. Introduction

Large quantities of abandoned industrial sites, which may be contaminated by high concentrations of heavy metals, have been produced, caused by the rapid industrialization and urbanization in China for the last several decades [1]. Heavy metals are risky to environmental and human health and lead to degrading the mechanical properties of soils, restricting the redevelopment of the abandoned industrial sites [2, 3]. Solidification and stabilization (S/S) remediation technology is one of the widely used technologies that involve mixing binders and contaminated soils to reduce the mobility of contaminants and strengthen the mechanical stability of the soils by physical and chemical methods [4, 5].

Portland cement (PC), the high alkali cementitious material, is widely used to immobilize heavy metals, including Pb, Zn, Cu, and Cd contained in waste or soil [6–8]. However, the heavy metal immobilization by PC depends significantly on the degree of cement hydration and alkaline environment. Previous studies have reported that heavy metals in the PC stabilized soils would leach easily when exposed to the long-term external conditions such as acid rain, sulfate attack, freeze-thaw cycling, and carbonation [4, 5]. In addition, the strength and modulus of cement stabilized soils decreased rapidly as Zn concentrations increased [5]. For heavy metals such as Zn and Pb, a tremendous retardant effect on cement hydration has been proved to exist. Du et al. [4] reported that the presence of Pb and Zn in the cement stabilized soils hinders the formation of Ca(OH)₂/CSH and thereby decreases the soil buffering capacity. In this case, the higher the concentration, the more intensive the retardant effect of heavy metals [4, 5]. Therefore, it is necessary to develop alternative binders to stabilize soils that have relatively...
high concentrations of Zn and Pb. Besides, the treated contaminated soils should have environmental safety and mechanical stability so that they can be reused as materials for civil engineering projects such as roadway subgrade course materials.

Recently, the authors developed a new binder, KMP, which is made from oxalic acid-activated phosphate rock, monopotassium phosphate (KH₂PO₄), and reactive magnesia (MgO) [3]. Compared with PC, the KMP binder may be more valuable in the attempt to stabilize soil that is contaminated with Zn or Pb alone and mixed Zn and Pb for the following reasons: (1) the hydration products of KMP with significant strength (e.g., bobierrite (MgKPO₄·6H₂O) and k-struvite (Mg₅(PO₄)₂·8H₂O)) are formed through an acid-base reaction between the MgO and PO₄³⁻ released from the acidified apatite and KH₂PO₄. This reaction process is less affected by the pH solution relative to the cement hydration reaction. Hence, the KMP stabilized soils may provide more reliable strength relative to PC stabilized soils, and (2) the reaction of KMP with Zn and Pb in soils can produce insoluble metal phosphates, such as Zn₁₀(PO₄)₆·4H₂O, Ca₂Zn₇(PO₄)₂·2H₂O, and fluoroxyprymorphomorphtie (Pb₅(PO₄)₆F), which have outstanding chemical and morphologic stability despite the strong acid and alkali circumstances [9]. Therefore, it is reasonable to expect that the KMP stabilized soil would exhibit higher leachability, acid buffer capacity, strength, or water-soaking durability relative to the PC stabilized soils.

The effectiveness of the S/S is usually defined by the strength and leaching resistance of solidified products. The leaching resistance of solidified soils depends on contaminant speciation, which is difficult to characterize. A series of methods, such as toxicity characteristic leaching procedure (TCLP) tests or single batch test (EN 12457-2) [10], are usually used to evaluate the S/S and characterize the solidified soils. However, different leaching tests can lead to different characterization of the same soil and may not represent the leaching level in the real environments due to the different disposal or leaching conditions of the stabilized soils, such as pH, redox potential (Eh), liquid-to-solid ratio, and leachate type [11]. When the stabilized soils are used as the roadway subgrade materials, the acid rain is a major environmental concern. Stegemann and Zhou [12] put forward that leaching metals tend to be a function of pH value of the solidified matrix. When the used binders are high alkali cementitious materials, such as PC, quicklime, and pulverized fly ash, the pore water pH of all S/S soils will be highly alkaline initially, and this alkalinity will be neutralized over time by acidic influences, which will gradually cause the dissolution of the hydration products and metal contaminants. Thus, using acid neutralization capacity (ANC) test [13], which measures leachate pH, can help to characterize chemical immobilization of contaminants, as well as chemical durability of the S/S matrix [12], and can represent the disposal conditions. The unconfined compressive strength test provides basic information of strength on soil stabilization and is used for quality control in pavement design. In addition, the resilient modulus (MR) is also a common measure of the strength of a mixture design in roadways and is often used to decide the structural layer coefficients of the subbase layers for designing pavements. Although plenty of studies have evaluated the strength of stabilized soils, they only refer to the dry environment; few of them focus on the water-soaking durability [3, 5, 6, 14, 15]. Nevertheless, the use of binders in wet environment has more challenges due to the solubility of binders in water [16].

A previous study [3, 17] has discussed the leachability and unconfined compressive strength of Zn, Pb, or Zn/Pb contaminated soils stabilized by KMP. It is found that soils that initially contained relatively high concentrations of both individual and mixed Zn and Pb contaminants displayed low leachability or ecotoxicity and high unconfined compressive strength after stabilization with the KMP, which demonstrates that KMP satisfactorily and effectively stabilized these soils. However, Du et al. [3] did not explore the characteristics of ANC, water-soaking durability, and resilient modulus of KMP stabilized Zn and Pb contaminated soils. The goal of the present study was to evaluate these properties to further investigate the feasibility of KMP stabilized soils for potential reuse as roadway subgrade materials. For comparison purpose, PC is also tested as a control binder. Several series of tests, including ANC tests, mercury intrusion porosimetry (MIP), water-soaking durability tests, and MR tests, are conducted. The effects of the initial Zn and Pb contaminations on the water stability and MR of the soils are discussed. The difference of the above properties for the KMP and PC stabilized soils is assessed based on the results of ANC and MIP tests and stability and dissolubility of the main hydration products of the KMP and PC.

2. Materials and Methods

2.1. Materials. The soil used in this study was collected from Nanjing City, China. Table 1 shows its basic physicochemical properties. The Atterberg limits were measured as per ASTM D4318 [18]. Based on the Unified Soil Classification System [19], the soil is classified as low plasticity clay. The chemical compositions of the apatite, PC, and soil were measured using an X-ray fluorescence spectrometer and their values are shown in Table 2. Commercial apatite cores with diameters of approximately 30 cm were crushed and ground to pass through a sieve with an opening size of 0.075 mm. The chemical analytical reagent, KH₂PO₄, was obtained from Sinopharm Chemical Reagent Co. Ltd., China. For the KMP powder, the proportions of the acidified phosphate rock, KH₂PO₄, and reactive MgO were controlled as 1:1:2 (on powder, the proportions of the acidified phosphate rock, Sinopharm Chemical Reagent Co. Ltd., China. Table 1 shows its basic physicochemical properties. The Atterberg limits were measured as per ASTM D4318 [18]. Based on the Unified Soil Classification System [19], the soil is classified as low plasticity clay. The chemical compositions of the apatite, PC, and soil were measured using an X-ray fluorescence spectrometer and their values are shown in Table 2. Commercial apatite cores with diameters of approximately 30 cm were crushed and ground to pass through a sieve with an opening size of 0.075 mm. The chemical analytical reagent, KH₂PO₄, was obtained from Sinopharm Chemical Reagent Co. Ltd., China. For the KMP powder, the proportions of the acidified phosphate rock, KH₂PO₄, and reactive MgO were controlled as 1:1:2 (on dry weight basis), since this ratio yields relatively low leachability and high unconfined compressive strength for the stabilized soils [3].

2.2. Specimen Preparation. To prepare Zn and Pb or Zn and Pb mixed-contaminated soil specimens, a predetermined volume of selected stock solution was mixed with the air-dried clean soil until its water content reached its optimum water content (27%). The solution-soil mixture was thoroughly mixed using an electronic mixer to create a homogeneous paste that was then sealed in a closed container.
The ANC test was performed as per USEPA Method 1313 [20]. A series of batch extraction tests were conducted on 20 g of crushed, sieved (<100 μm), and stabilized soils cured for 28 d using 200 mL of nitric acid solutions with various concentrations as extraction liquids. After tumbling for 18 h, the pH of the solution filtered with a 0.45 μm membrane filter was measured with a pH meter HORIBA D-54. Measurements were made in triplicate and the average values were recorded. In this study, the ratio of leached Mg or Ca concentration for the stabilized contaminated soils to that of the stabilized clean soil (RLC) is used to quantify the relative stability of KMP hydration products (MgKPO₄·6H₂O and Mg₃(PO₄)₂·8H₂O, mainly) and PC hydration products (CSH and Ca(OH)₂, mainly) in the ANC test at the leachate of which pH = 7. The concentrations of the leached Mg and Ca were measured using an IRIS Advantage Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES). The definition of RLC is expressed by the following equation:

$$RLC = \frac{[M_i]}{[M_o]} \quad (1)$$

where $[M_i]$ and $[M_o]$ are the measured leached Mg or Ca concentration for the stabilized contaminated soil or clean soil, respectively, mg/L.

For the MIP test, the soil sample of approximately 1 cm³ was retrieved from a carefully hand-broken identical specimen after curing for 28 d. The test soil was frozen using liquid nitrogen with a boiling point of −195°C and placed in a freezing unit with a vacuum chamber to be dried by sublimation of the frozen water at a temperature of −80°C. Then, the specimens were analyzed using an Auto Pore IV 9510 mercury intrusion porosimeter. The freeze-drying apparatus used in this study was the XIANOU-18N freeze-drier. In this method, the capillary pressure equation is employed to compute the pore diameter as expressed by Mitchell [21]:

$$d = \frac{4 \pi \cos \theta}{\rho}, \quad (2)$$

where $d$ is the diameter of the pore intruded, $\tau$ is the surface tension of intruding mercury (4.84 × 10⁻⁴ N/mm at 25°C), $\theta$ is the contact angle (135° in this study), and $\rho$ is the applied pressure of mercury intrusion (maximum 413 MPa in this study).

The water-soaking durability test was conducted as per the method recommended by Du et al. [14]. Each identical specimen was immersed under the water table of distilled water with a volume of 1.5 L. The water-soaking period was 1 d and the value of unconfined compression strength ($q'_u$) after soaking was measured by the unconfined compression tests (UCTs) for each identical sample. The UCTs were conducted on the stabilized soils with a strain rate of 1%/min, as per ASTM D 4219-08 [22]. Three identical samples were tested and the average value of $q'_u$ was recorded. The water stability coefficient ($K_s$), which defines the water stability of the soils, was determined using the following equation:

$$K_s = \frac{q'_u}{q_u}, \quad (3)$$

where $q'_u$ is the measured unconfined compression strength after water-soaking test (kPa) and $q_u$ is the measured unconfined compression strength before water-soaking test (kPa), the data based on a previous study [3].
The resilient modulus ($M_R$) of the soil was measured using the plate loading test outlined by the China Test Methods of Soils for Highway Engineering [23]. With the assumption that the stabilized soil layer is homogeneous, isotropic, elastic, and infinite in depth, $M_R$ of the material can be determined using the following equation based on the method of the elasticity theory [24]:

$$M_R = \frac{\pi \sigma_l r^2}{4l} \left(1 - \mu^2\right),$$

where $M_R$ is the resilient modulus of elasticity of the material (MPa), $\sigma_l$ is the pressure applied to the surface of the plate (MPa), $r$ is the radius of the plate (50 mm in this study), $l$ is the deflection of the plate associated with the pressure, and $\mu$ is Poisson’s ratio (0.3 in this study). The stresses and displacements were measured using a hydraulic multifunction material testing system (UTM-25). For each case tested, one identical sample was subjected to the resilient modulus test.

### 3. Results and Discussion

#### 3.1. Acid Neutralization Capacity

Figures 1(a) and 1(b) present the titration curves obtained from the ANC tests for the stabilized soils with different initial soil contaminant conditions and cured for 28 d. The titration curves were obtained by plotting the amount of acid added and the final equilibrium pH of each leachate and the slope of the titration curve corresponds to the ability to resist a change in the pH of the leachate since the dissolution of hydration products in stabilized soils [25]. The slope of the titration curves for the KMP stabilized soils is noticeably gentler than that of the PC stabilized soils. A significant turning point appears near the 400 cmol/kg nitric acid solution point for both the KMP and PC stabilized soils. When the acid addition is < 400 cmol/kg, the presence of heavy metal causes a rapid drop in pH compared to the stabilized clean soil. With a relatively high amount of acid addition (i.e., ≥400 cmol/kg), the KMP stabilized soils displays a significantly gentler slope relative to the PC stabilized soils.

An index denoted by $\beta$, representing moles of strong acid $C_A$ ($H^+$) added to the soil to cause a unit change in leachate pH, is used to define the acid buffering capacity of the soil and expressed in the following equation [25]:

$$\beta = \frac{dC_A}{dpH}.$$  

Figure 2 illustrates the variations in the values of $\beta$ (acid buffer capacity) as calculated using equation (5) with the amount of acid added. It can be concluded that the KMP stabilized soils display higher values of $\beta$ regardless of the initial soil contamination conditions.

Figures 3(a) and 3(b) show the variations in the leached Mg and Ca concentrations and RLC with the initial soil contamination conditions for the stabilized soils cured for 28 d were obtained from the ANC tests. The pH of the leachate was 7. Generally, the concentrations of Mg and Ca leached from the stabilized contaminated soils are higher than those leached from the stabilized clean soils and they rise with an increase in the initial Zn concentration (Figure 3(a)). The leached Mg and Ca concentrations for the mixed Zn and Pb contaminants (Zn1.5Pb2) are much higher than those for the Zn or Pb contaminant alone. The values of RLC of Mg for the KMP stabilized soils are approximately 46 to 170%, which are notably lower than those of Ca for PC stabilized soils (50 to 440%) (Figure 3(b)).

#### 3.2. Water Stability Coefficient

Figures 4(a) and 4(b) present the variations of $q^*_u$ of the stabilized clean and contaminated soils that experienced the water-soaking tests, with the initial soil contamination conditions. For the uncontaminated condition (Zn0Pb0), the KMP stabilized soils exhibit lower $q^*_u$ than PC stabilized soils for both binder contents of 4% and 6%, when the curing time is 6 d (Figure 4). However, for the cases of Zn or Pb alone and mixed Zn and Pb (Zn1.5Pb2) contaminants, the KMP stabilized soils display notably higher $q^*_u$ values, irrespective of the curing time or binder content.

Figure 5 shows that the $K_r$ values of the KMP stabilized clean soils (Zn0Pb0) are about 10 to 35% lower than those of the PC stabilized clean soils. In contrast, the KMP stabilized contaminated soils (Zn1.5, Zn1.5Pb2, and Pb2) display 3 to 465% higher $K_r$ values than the PC stabilized soils, indicating that the former possess superior water-resistance capacity and this is consistent with the results presented in Figure 4.

Figure 6 presents a comparison of apparent surface characteristics between the KMP and PC stabilized soils which were cured for 27 d and then subsequently soaked for 1 d. It can be seen that the macrocracks occurred at the surfaces of all PC stabilized soils, whereas only a few numbers of cracks developed at the surface of the KMP stabilized soil with mixed Zn concentration of 1.5% and Pb concentration of 2%. The observations further suggest that the KMP stabilized soils have greater water stability as compared to the PC stabilized soils.

#### 3.3. Resilient Modulus

Figure 7 shows the measured resilient modulus ($M_R$) for the clean (Zn0Pb0) and contaminated soils with mixed Zn concentration of 1.5% and Pb concentrations for the mixed Zn and Pb contaminants (Zn1.5Pb2) are much higher than those for the Zn or Pb contaminant alone. The values of RLC of Mg for the KMP stabilized soils are approximately 46 to 170%, which are notably lower than those of Ca for PC stabilized soils (50 to 440%) (Figure 3(b)).

### Table 3: Zn and Pb concentrations and curing times for various tests and analyses of spiked soils.

| Test program | Zn or/and Pb concentration (%) | Binder content (%) | Curing time (d) |
|--------------|-------------------------------|------------------|-----------------|
| ANC          | Zn0Pb0*, Zn1.5, Zn1.5Pb2, and Pb2 | 6                | 28              |
| MIP          | Zn0Pb0*, Zn0.5, Zn1, Zn1.5, Zn1.5Pb2, and Pb2 | 6                | 28              |
| WSD          | Zn0Pb0*, Zn1.5, Zn1.5Pb2, and Pb2 | 4, 6             | 6, 27           |
| RMT*         | Zn0Pb0* and Zn1.5Pb2           | 6                | 28              |

ANC = acid neutralization capacity; MIP = mercury intrusion porosimetry test; WSD = water-soaking durability test; RMT = resilient modulus test.

* Untreated clean soil.
concentration of 2% (Zn1.5Pb2) when stabilized with 6% KMP or PC. The $M_R$ values of the KMP and PC stabilized clean soils are 155% and 238% higher than those of the stabilized contaminated soils, respectively, indicating that the presence of heavy metals has exposed a notable impact on the measured $M_R$. In addition, the corresponding $M_R$ of the KMP stabilized soils is 6% lower than that of the PC stabilized soils for the case of Zn0Pb0, whereas it is 24% higher than that of the PC stabilized soils (Zn1.5Pb2), indicating that the KMP binder is more capable of strengthening $M_R$ of the soils tested in this study.

3.4. Soil Pore Size Distribution. Figure 8 shows the pore size distributions (PSDs) of KMP and PC stabilized clean and contaminated soils. The $y$-axis of PSD curves of the stabilized soils is plotted as $f(D) = \frac{dV}{d\log D}$, where $V$ is the volume of mercury intruded at a given pressure increment that corresponds to the pore having a diameter of $D$ in 1 g of the dry soil [5]. It can be seen that the variation of cumulative pore volume with a pore diameter is of a bimodal type, which is a common modal observed for compacted soils [26] as well as cement stabilized Zn-contaminated soils [5]. The first mode is characterized by pore sizes ranging from 0.003 to

![Figure 1: pH-acid titration curves of the stabilized clean and contaminated soils cured for 28 d: (a) KMP binder; (b) PC binder.](image)

![Figure 2: Buffer capacity ($\beta$) of the stabilized contaminated soils cured for 28 d: (a) KMP binder; (b) PC binder.](image)
0.1 μm; meanwhile, the pore sizes at the second mode span the interval of 0.1 to 2 μm. For the stabilized clean and contaminated soils, the first pore diameter peaks have increased from 0.02 to 0.03 μm and 0.02 to 0.04 μm with increasing Zn concentration, respectively; the second pore diameter peaks exhibit a similar trend of change with increasing Zn concentration. At a given Zn concentration, the two pore diameter peaks of the KMP stabilized soils are lower than those of the PC stabilized soils (Figure 9), indicating that the KMP stabilized soils have a denser structure.

In this study, each peak of the PSDs curves was simulated by a Gaussian distribution function suggested by previous studies [5, 26], as expressed by the following fitting equation:

$$f(D) = \sum_{i=1}^{n} q_i f_i(D) = \sum_{i=1}^{n} q_i \frac{1}{\sqrt{2\pi \sigma_i^2}} e^{-\left[\left(\log(D) - \mu_i\right)^2 / 2\sigma_i^2\right]} ,$$

where $n$ is the number of peaks in PSD curves on a logarithmic scale (2 for the bimodal types), $q_i$ is the pore volume in the 1 g dry soil covered by the fitted curve of $f_i(D)$ (mL/g), $\sigma_i$ is the standard deviation on a logarithmic scale, and $\mu_i$ is...
Figure 5: Variations in the water stability coefficient ($K_r$) with the initial soil contamination conditions for the stabilized soils cured for 6 and 27 d: (a) 4% binder and (b) 6% binder.

Figure 6: Photos showing the cracks developed on the surfaces of the stabilized soils after water-soaking tests (curing time of 27 d and binder content of 6%). (a) KMP Zn0Pb0. (b) KMP Zn1.5. (c) KMP Pb2. (d) KMP Zn1.5Pb2. (e) PC Zn0Pb0. (f) PC Zn1.5. (g) PC Pb2. (h) PC Zn1.5Pb2.
the mean pore diameter in the fitted curve of $f_i(D)$ on a logarithmic scale ($\mu m$) [26].

Table 4 lists the fitting parameters obtained using equation (6). From Table 4, it is found that $a_1$ changes marginally for both KMP and PC stabilized soils when the Zn concentration increases from 0% to 1.5%; on the contrary, $a_2$ increases from 0.028 to 0.044 mL/g and 0.026 to 0.048 mL/g for the KMP and PC stabilized soils, respectively. In addition, there are no differences in the values of $a_1$ and $a_2$ between the KMP and PC stabilized soils. As for $\mu_1$ and $\mu_2$, they both increase with increasing Zn concentration. When Zn concentration increases from 0% to 1.5%, it can be observed that $\mu_1$ of KMP stabilized soils varies from 0.019 to 0.034, which is an 78.9% increase. In contrast, $\mu_1$ of PC stabilized soils varies from 0.021 to 0.04, which is an 90.5% increase. In addition, $\mu_2$ of KMP stabilized soils varies from 0.391 to 0.440, which is an 12.5% increase, and $\mu_2$ of PC stabilized soils varies from 0.411 to 0.485, which is an 18% increase when Zn concentration increases from 0% to 1.5%. According to this, it further demonstrates that the KMP stabilized soils have a denser structure, as suggested by a previous study [5], which may be attributed to the more prominent filling of soil pores by the KMP hydration products (e.g., bohierite (MgKPO$_4$·6H$_2$O) and k-struvite (Mg$_3$(PO$_4$)$_2$·8H$_2$O)) relative to those of PC (e.g., Ca(OH)$_2$, CSH, and CAH).

Figure 9 illustrates the typical bimodal PSD peak fitting result for the KMP stabilized clean soils (Pb0Zn0) and contaminated soils with mixed Zn concentration of 1.5% and Pb concentration of 2% (Zn1.5Pb2). It shows that all the simulated PSD curves have bimodal characteristics ($n = 2$). The dual peaks in the PSD curves represent intra-aggregate and interaggregate pores, respectively, and the formation of intra-aggregate pores is due to the filling of the large pores by hydration products of KMP or cement [5].

### 4. Discussion

The ANC test results show that the KMP stabilized soils display higher acid buffering capacity (Figures 1 and 2). The ratio of leached concentration (RLC) of Mg for the KMP stabilized soil is significantly lower relative to Ca for the PC stabilized soil regardless of the Zn or Pb concentration (Figure 3), indicating that a lower amount of Mg or Ca has been leached from the stabilized soil and the soil would consequently display a slow reduction in strength as a result of the graduation dissolution of the hydration products as suggested by previous studies [27]. These findings can be attributed to two reasons: (1) the main alkaline hydration products of KMP such as MgKPO$_4$·6H$_2$O and Mg$_3$(PO$_4$)$_2$·8H$_2$O are difficult to dissolve under the acidic environment and have significantly stable mineral crystal-line morphologies in a wide range of acidic conditions [3, 9, 28]. In contrast, the cement hydration products such as Ca(OH)$_2$, CSH, and CAH have a relatively higher solubility and are more easy to dissolve under acidic condition [4, 29], and (2) Zn or Pb merely consumes a small amount of PO$_4^{3-}$ and hydroxyl ions (OH$^-$), which results in a marginal impact on the formation of MgKPO$_4$·6H$_2$O and Mg$_3$(PO$_4$)$_2$·8H$_2$O in the KMP stabilized soils [3]. However, for the PC stabilized soils, the presence of Zn would remarkably retard the cement hydration or pozzolanic reaction and lead to a reduction in these cement hydration products such as Ca(OH)$_2$ or CSH, which are primary contributors to the acid buffer capacity [4, 5].

The water-soaking durability test and resilient modulus test results show that KMP stabilized contaminated soils possess higher $q_{sv}$, $K_r$, and $M_R$ relative to the PC stabilized contaminated soils, regardless of the initial soil contamination condition (Figures 4, 5, and 7). The phenomenon can be attributed to three causes: (1) the KMP stabilized
contaminated soils have a denser structure and higher resistance to water adsorption as a consequence, as illustrated by the PSD curves (Figures 8 and 9) as well as PSD simulation results mentioned in the previous section (Table 4); (2) the RLC of Mg for the KMP stabilized soil is lower than the RLC of Ca for the PC stabilized soil (Figure 3(b)); (3) the main KMP hydration products, including MgKPO$_4$·$6$H$_2$O and Mg$_3$(PO$_4$)$_2$·$8$H$_2$O, have higher $q'_u$ values relative to the CSH, the main cement hydration product and primary contributor to $q'_u$. Qiao et al. [30] indicated that magnesium phosphate cement (MPC) pastes, mainly containing potassium dihydrogen phosphate (KH$_2$PO$_4$) and magnesia (MgO), had a remarkable bond strength relative to the PC mortars. Since the hardening mechanisms and hydration products of KMP are similar to those of MPC, it is reasonable to infer that the main hydration products of KMP may provide higher bond strength to the soil presented in this study.

The resilient modulus test results show that the $M_R$ values of the soils decrease with an increase in the Zn concentration particularly for the soils contaminated with Zn1.5Pb2 (Figure 7). And the water-soaking test results also show that the obvious crack developed in KMP/PC stabilized soils with Zn1.5Pb2 (Figure 6). The observation is attributed

![Figure 8: Pore size distribution of the stabilized soils cured for 28 d: (a) KMP and (b) PC.](image)

![Figure 9: Bimodal PSD peak fitting for the KMP stabilized soils cured for 28 d: (a) Zn0Pb0 and (b) Zn1.5Pb2.](image)
to two facts: (1) the soils display a relatively looser structure as the Zn concentration increases, as illustrated by the rise in the values of $\mu_1$ and $\mu_2$ obtained from the PSD simulations (Table 4); (2) the formation of the KMP and PC hydration products is retarded when Zn or Pb is presented in the soils, as suggested by previous studies [3, 5]. Subsequently, the bonding strengths of the soils will decrease as the Zn concentration increases.

5. Conclusions

This study presented a detailed investigation on the acid neutralization capacity, pore size distribution, water stability coefficient, and resilient modulus characteristics of the KMP and PC stabilized soils with Zn or Pb alone and mixed Zn and Pb contaminants. The stabilized soils could be the potential roadway subgrade course materials. Based on the test results, the following conclusions can be drawn:

1. The acid neutralization capacity titration curves of the KMP stabilized soils were flatter relative to the PC stabilized soils and those of the acid buffer capacity index, $\beta$, were higher, which indicates that the KMP stabilized soils possess a higher acid buffering capacity. The values of the ratio of the leached concentration of Mg for the KMP stabilized soils were approximately 46 to 170%, which are notably lower than those of Ca for the PC stabilized soils.

2. The KMP stabilized contaminated soils exhibited higher $q_a$ and $K_r$ values relative to the PC stabilized ones that underwent the water-soaking tests for both binder contents of 4% and 6%, irrespective of the curing time, which indicates that the former possessed a superior water-resistance capacity. At the 6% binder content, the macrocracks occurred on the surfaces of the PC stabilized soils, whereas a few numbers of cracks developed on the surface of the KMP stabilized sample with mixed Zn and Pb contaminants.

3. At 6% binder content, the MR values of the KMP and PC stabilized clean soils were 155% and 238%, respectively, which are higher than those of the stabilized contaminated ones. The MR of the KMP stabilized soil was 24% higher relative to the PC stabilized one with mixed Zn and Pb contaminants.

(4) The PSD curves of the KMP and PC stabilized soils had bimodal characteristics. The $a_2$, $\mu_1$, and $\mu_2$ parameters increased noticeably with the increase in Zn concentration, whereas the $a_1$ change was insignificant. For a given Zn concentration, the KMP stabilized soils displayed lower values of $a_2$ or $\mu_2$, indicating that they had a denser structure relative to the PC stabilized soils.

Overall, this study demonstrates that the KMP provides super efficiency in stabilizing soils that are contaminated with Zn or Pb alone and mixed Zn and Pb contaminants. Additional research is warranted to investigate the leachability, strength, water-soaking durability, and resilient modulus of the stabilized contaminated soils at actual field sites. Further quantitative X-ray diffraction analysis and scanning electron microscope analysis are needed to understand the microscale change in the properties of the stabilized soils.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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