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Study on mechanical properties of phosphate tailings modified clay as subgrade filler

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Abstract. To improve the utilization rate of phosphate tailings (PTs) and widen the sources of subgrade filler, the PTs is employed to modify clay, forming a PTs modified clay, applied in the subgrade. Accordingly, the environmental friendliness of PTs was investigated. Subsequently, an optimal proportion was determined through compaction and California Bearing Ratio (*CBR*) experiments. Afterward, the stability of mixture with the optimal proportion was further evaluated through the water stability and dry-wet stability experiments. Finally, via the gradation and microstructure experiments, the strength mechanism of PTs modified clay was analyzed. The results show that the PTs were classified in the non-hazardous solid wastes, belonging to Class A building materials. With the increase of PTs content and the decrease of clay content, the optimum water content and the swelling degree gradually decrease, while the maximum dry density and *CBR* first increase and then decrease, reaching their peak value at 50% PTs content, which is the optimal proportion. The resilient modulus of PTs modified clay at the optimal proportion reaches 110.2 MPa. The water stability coefficient becomes stable after soaking for 4 days, while the dry-wet stability coefficient decreases with the increase of cycles and tends to be stable after 8 cycles. Under the long-term action, the dry-wet change has a greater adverse impact than continuous soaking. The analysis demonstrates that the better strength mainly comes from the skeleton role of PTs and the cementation of clay. The systematic laboratory test results and economic analysis collectively provide data evidence for the advantages of PTs modified clay as a subgrade filler.

Keywords: clay; economic efficiency; environment-friendly; mechanical property; mechanism; phosphate tailings

1. Introduction

Solid phosphate ore is known as the only kind of phosphorus resource that can be exploited by mankind currently, with the characteristics of irreplaceable and non-renewable, contributing to high demand. The phosphorus resources are the raw materials for industrial products such as fertilizers, detergents, animal food supplements, etc (Csillag *et al*. 2006).

The phosphate ore is abundant in quantity but unsatisfactory in quality in China. Among the proved reserves, 90% of phosphate ore is at low and medium grade (Yang *et al*. 2021), therefore which requires beneficiation to enrich the phosphate concentrate. In all beneficiations, flotation is most used, but it produces substantial amounts of by-products, phosphate tailings (PTs) (Moukannaa *et al*. 2019). By estimation, producing phosphate concentrate in one ton would generate 0.3 to 0.4 tons of PTs (Zheng *et al*. 2015), even reaching 0.44 tons in certain cases (Wei *et al*. 2012, Yang *et al*. 2017). On the contrary to the massive at the waste, it is a the relatively low utilization rate, at only 5% to 7% (Wu *et al*. 2020, Yang *et al*. 2017). Thus, PTs have been piled up year after year, resulting in their current storage beyond imagination.

Taking the Lianyungang Jinping phosphorus mine in China for example, for almost 50 years of beneficiation, it had generated more than 30 million tons of PTs, which were stored in the tailing pond, protected by dams with an area of 3 km^2, the depth of 5 to 20 m. The large accumulation of PTs has occupied a lot of land, causing soil and water pollution, that affects the surrounding ecological environment (Wei *et al*. 2012). It takes loads of money and work to maintain the daily operation of the dams. The dam failure may result in heavy casualties and property losses, which is a hidden danger that people are deeply worried about. Therefore, how to deal with the PTs has become a

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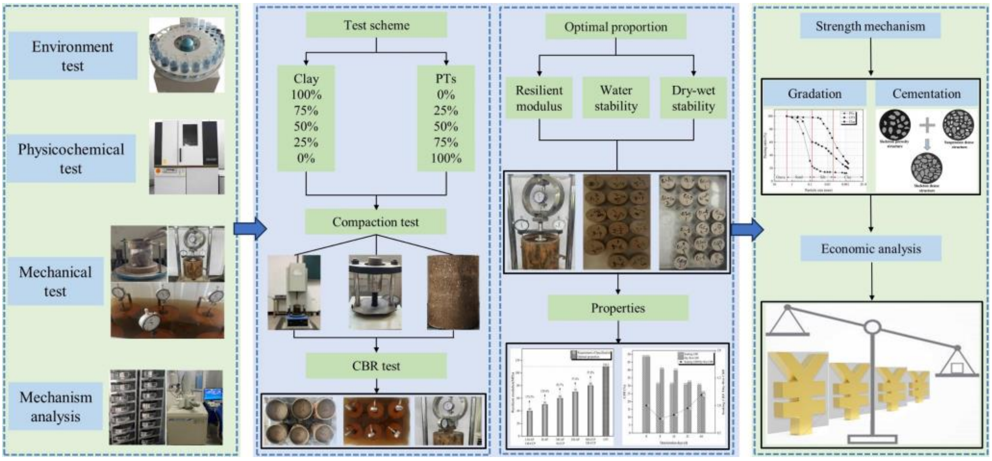


Fig. 1 Experiment procedures and research objective

serious social problem (Dixon-Hardy *et al*. 2007, Rico *et al*. 2008a, b).

The research of PTs applied in civil engineering has made some achievements. PTs can be activated by the heat treatment or alkali-activators, to synthesize the geopolymer and geopolymer mortar (Haddaji *et al*. 2021, Hamdane *et al*. 2020, Moukannaa *et al*. 2018). PTs can be as cement filler (Zheng *et al*. 2015) and also utilized to fill the goaf (Li *et al*. 2017, Zhang *et al*. 2018). PTs can be cemented by binding materials then pressed into unburned bricks (Ru 2010), or mixed with clay or fly ash to prepare sintered bricks (Gu *et al*. 2015, Loutou *et al*. 2019) and ceramsite (Zhang 2023, Yang *et al*. 2017) through high temperature. PTs can be used to make foamed concrete as insulation wall materials (Ding *et al*. 2019, Li *et al*. 2016).

Solid wastes have been increasingly employed in the problematic soils to enhance their geotechnical properties (Bera and Chakraborty 2015, Nasiri *et al*. 2021). Just like those other solid wastes (Yu *et al*. 2016, Zhao *et al*. 2019), alone or with cementitious materials, the PTs can also modify various types of soils, to improve their mechanical properties (Bakhshizadeh *et al*. 2022). Being a filler, that is one of the simple, large consuming, and highly efficient ways for the PTs.

The PTs were stabilized using lime and fly ash, the proportion of lime: fly ash: PTs was 8:22:70, the compaction degree was 97%, the 7d *UCS* (unconfined compressive strength) was 0.81 MPa, the 28d strength was 1.24 MPa (Luo and Yan 2005). PTs were mixed with marine sediment, concluding that the optimum content of PTs was 50%, in this case, the dry density and cohesion were maximum, but the void ratio, compression index, and coefficient of compressibility were minimum (Li *et al*. 2017). The PTs were used with cement to stabilize soft soil with the natural water content of 100% (Zhao *et al*. 2011), the addition of PTs could significantly increase the *UCS* and *CBR* value, and water stability of the mixture (Zhao *et al*. 2012). The expansive soil was stabilized from a highway in Anhui, adding PTs of 0%, 2.5%, 5%, 7.5% and 10%, the free swelling ratio of modified soil decreased by 0%, 14.7%, 14.54%, 13.2%, 2.3%, meanwhile, the appropriate content of PTs could also enhance the compressive strength and shear strength of expansive soil, the effect is best when the content was 7.5% (Zhuang *et al*. 2019).

The incorporation of PTs has a good effect to improve the mechanical properties of clay. The PTs content of 5%, 10%, 15%, and 20% were used to modify the clay, and the compression and triaxial tests of the mixture were conducted (Wang 2017): with the PTs content increased, the shear strength of mixture increased; when the PTs content was 15%, the compression indexes with different dry densities all reached the minimum. The PTs at the content of 10%, 30%, 50%, and 70% were used to improve the clay (Ren and Shao 2018): with the increase of PTs content, the optimum water content of the mixture gradually decreased, while the maximum dry density and *CBR* strength first increased and then decreased, the peak corresponding to the PTs content of 50%.

The goal of this article is to utilize the PTs to modify clay as a subgrade filler, playing the advantages of PTs and clay (particle characteristic of PTs and high plasticity of clay), and complementing the deficiencies of the two materials (looseness of PTs and low strength of clay). The PTs are proved to be environment-friendly, are capable as subgrade materials. Based on it, the mechanical properties, road performance, and stability of PTs modified clay are systematically carried on. The analysis of strength mechanism and the remarkable economic efficiency provides a broader prospect for the application of PTs modified clay as the subgrade filler. The experiment procedures and research objective are shown in Fig. 1.

2. Material and methods

2.1 PTs and clay

The PTs were taken from the tailing pond of Jinping phosphorus mine. The PTs are light brown (Fig. 10(a)), their particles are loose, being like superfine sands. Therefore, it is lack of bonding capacity (Zhao *et al*. 2023a). The clay was sampled from Guanyun county in Lianyungang, and belongs to the marine clay with high liquid limit. The clay is dark brown, whose particles stuck

Table 1 Chemical constituents of PTs and clay

Constituents	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	P_2O_5	MnO	LOI*
PTs (%)	13.2	2.03	1.90	26.3	15.0	0.72	0.17	2.4	0.8	37.48
Clay (%)	56.68	17.22	6.46	7.54	3.06	3.32	1.69	—	—	4.03

*LOI is a loss on ignition. Because the main constituents of PTs are $CaCO_3$ and $MgCO_3$, the lost main constituent on ignition is CO_2

Table 2 Engineering properties of PTs and clay

Project	Natural water content	Specific gravity	Liquid limit	Plastic limit	Plasticity index	Clay* content	Silt* content	Sand* content
PTs/%	5.3	2.96	—	—	—	13.3	9.6	77.1
Clay/%	42.1	2.71	56.44	34.69	21.75	26.5	71.5	2.0

*Clay grain size<0.005 mm. *Silt grain size in 0.005~0.075 mm. *Sand grain size in 0.075~0.25 mm

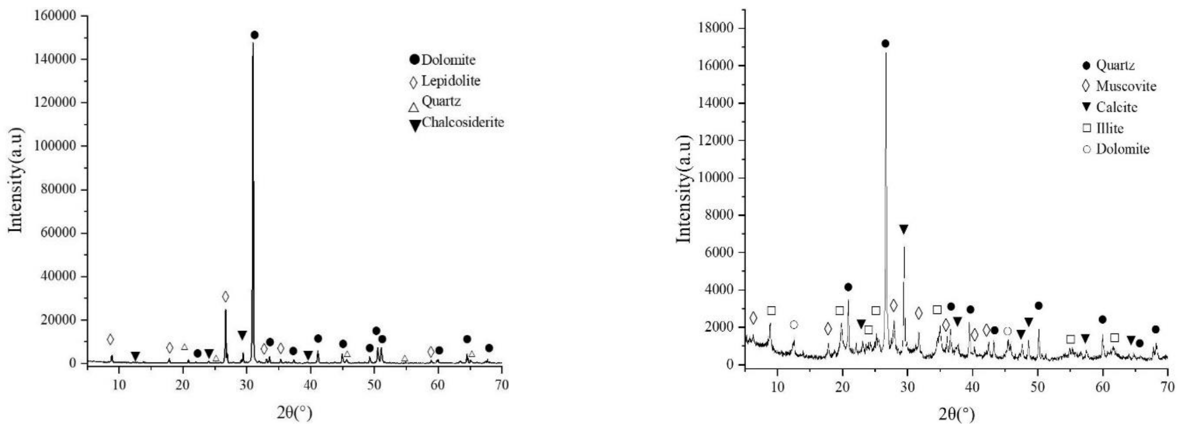


Fig. 2 XRD of materials (left PTs, right clay)

together into lumps because of high viscosity. The clay with high liquid limit is not suitable for direct utilization in the subgrade, especially the subgrade of high-grade road, and needs modification. The chemical constituents of PTs and clay are listed in Table 1. The engineering properties of PTs and clay are summarized in Table 2. The mineral constituents of PTs and clay are shown in Fig. 2.

The PTs have the characteristics of high CaO and MgO (corresponding to minerals dolomite), low SiO_2, Al_2O_3, and Fe_2O_3, lower K_2O and Na_2O. The grain constituents are mainly sand, with less clay and silt particles. The mineral characteristics determine that the PTs are inactive (Gu *et al*. 2015, Zhao *et al*. 2023a). The grain characteristics determine that the PTs have a loose structure and poor cohesion (Zhao *et al*. 2023a), which can be used as a skeleton to modify clay. The clay has the characteristics of high SiO_2, Al_2O_3, and Fe_2O_3 (corresponding to minerals quartz and illite (Zhao *et al*. 2023b). The clay is mainly composed of silt and clay particles, and the content of sand particles is very small. It shows that the clay has the strong absorption and retention capacity to water, and the great compressibility and expansion. The clay can cement and fill the skeleton formed by the PTs.

2.2 Test methods

2.2.1 Environment tests

Leaching toxicity test

The leaching toxicity test was performed according to HJ/T299 (2007). For testing the leaching toxicity of heavy metal and organic matter, 150-200 g samples were added to the leaching agent 1# at the solid-to-liquid ratio of 10:1, were flipped and shaken to get the leaching solution. For testing the leaching toxicity of cyanide and volatile organic compound, 40-50 g samples were added in the prepared extractant 2# at the solid-to-liquid ratio of 10:1, installing Zero-Headspace Extraction Vessel, which was flipped and shaken to collect the leaching solution.

Radioactivity detection

The radioactivity detection was conducted based on GB 6566 (2010). The PTs were prepared more than 3 kg, which were crushed then ground into the grains with a size of less than 0.16 mm. When the decay chain of natural radioactivity in the PTs was almost in equilibrium, the specific activities of radium-226, thorium-232, and potassium-40 were measured with an energy spectrometer.

2.2.2 Mechanical test

Compaction test

The compaction test used the heavy method according to JTG 3430 (2020), to obtain the maximum dry density and the optimum water content. The specimens were loaded into the compaction cylinder in 5 layers, each layer being compacted 27 times.

CBR test

According to JTG E51 (2009), the specimens were made by the heavy method at the specified degree of compaction and the optimum water content. The specimens stood still for 15 min to drain water, after soaking for 4 d (96h). The specimens were tested with the pavement material strength instrument, adding load to make the penetrating rod press at a speed of 1-1.25mm/min into them.

Resilient modulus test

The making method of specimens was the same as the *CBR* test. According to JTG 3430 (2020), the indoor resilient modulus test was carried out by the strength instrument. The predetermined maximum pressure was divided into 4-6 levels for loading, and the loading time for each level was 1 min.

Stability test

The making methods of specimens for water stability and dry-wet stability were the same as the *CBR* test to obtain their *CBR* values. In the test of water stability, the specimens were soaked in the water for different days. The accelerated dry-wet cycle method was used. Soaking specimens for 4 d, then baking them for 4 d at 45°C in a drying oven to simulate natural air drying. 8 days in total were regarded as one dry-wet cycle (Chen 2020).

3. Result and discussion

3.1 Environmental friendliness

Obtained from the analysis of chemical constituents, the PTs have no harmful substances and belong to the inert material (Zhao *et al*. 2023a). The PTs are suitable to modify clay as the subgrade filler, which has the advantages of simplicity, convenience, large consumption and high efficiency. It is greatly significant for saving land and protecting the environment (JTG D30. 2015). However, in the actual application of PTs, people always have some doubts, worrying that the PTs are toxic or radioactive, and have a potential adverse influence on the environment and human health. To dispel people's doubts and make better use of the PTs, the environmental tests were carried out in two aspects: leaching toxicity and radioactivity detection.

3.1.1 Leaching toxicity detection

The leaching toxicity test of PTs was conducted, to simulate the process of the harmful components leaching from the PTs into the surrounding, under the influence of acid rain, in the irregular landfill disposal, storage, and land use after being the harmless treatment of PTs. Based on the Identification Standards for Hazardous Wastes Identification for Extraction Toxicity (GB 5085.3. 2007), the Specifications for Design of Highway Subgrades (JTG D30. 2015), the possible environmental risks of leaching pollutants in the PTs are analyzed. Table 3 lists the concentrations of pollutants in the extraction solutions of PTs and the limits of different standards on the concentrations of pollutants.

Take Pb as an example, its content in the leachate is 0.00333 mg·L^{-1}, while the limits of GB 5085.3 (2007) and JTG D30 (2015) respectively are 1 and 0.50 mg·L^{-1}, Pb content is only 0.333% and 0.666% of the limits. The content of any hazardous components (inorganic elements and compounds) in the PTs leachate does not exceed, even is far below the concentration limits required in GB 5085.3 (2007), therefore the PTs are judged to have no leaching toxicity, belonging to the non-hazardous solid wastes. The conclusion is helpful to broaden the application of PTs. All indicators of PTs leaching solution are far lower than the limits of JTG D30 (2015) on the hazardous substance of industrial wastes used as filling materials, indicating that the PTs can be applied in the subgrade.

Table 3 Leaching toxicity detection of PTs

Project	Leachate (mg·L^{-1})	GB 5085.3 (2007) limits (mg· L^{-1})	JTG D30 (2015) limits (mg· L^{-1})
Cu	0.01	100	75
Zn	0.02	100	75
Cd	0.00333	1	0.50
Pb	0.02516	5	5
Total Cr	ND*	15	12
Cr (Hexavalent)	0.005	5	2.50
Alkyl mercury	ND*	Absence	0.25 (Mercury and its compounds)
Hg	ND*	0.1	0.001(Organic mercury)
Be	ND*	0.02	0.2
Ba	0.146	100	150
Ni	0.02	5	15
Ag	0.01	5	—
As	0.00256	5	2.5
Se	0.00221	1	—
Inorganic fluoride (Not including calcium fluoride)	1.84	100	100
Cyanide	ND*	5	5

*ND: No detected

3.1.2 Radioactivity detection

The tailing pond of Jinping phosphorus mine is similar to a fan shape, distributed at 30°, covering an area of 3 km^2, in a naturally formed ravine. Around the center of the pond and an equal distance of about 100 m, 5 boreholes were deployed, from which sampling was carried out at 12 points with different depth. As shown in Fig. 3.

By the detection of samples taken from 12 measuring points, specific activities of Ra-226, Th-232, and K-40 radionuclides of PTs were measured to calculate internal exposure indexes (IRa) and external exposure indexes (Ir) at each measuring point, shown in Table 4.

The internal exposure indexes of PTs are between 0.08 and 0.12, and the external exposure indexes of PTs are between 0.10 and 0.20, which are both far less than 1.0. The value of 1.0 is the requirement of the Limit of radionuclides in building

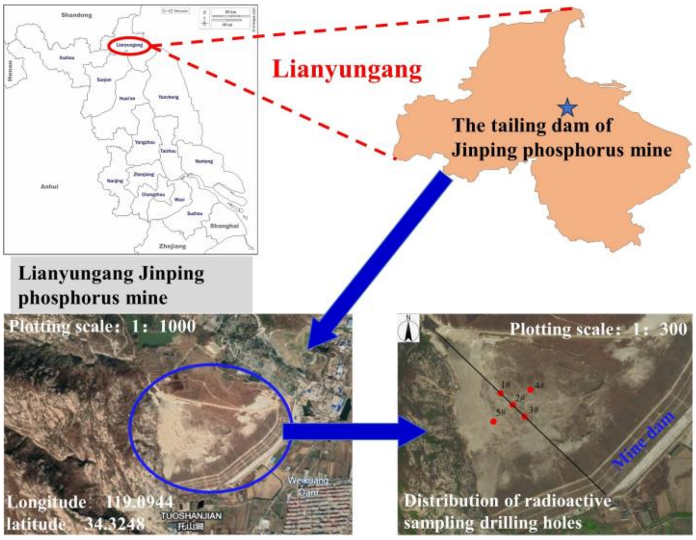


Fig. 3 Distribution of radioactive sampling drilling holes

Table 4 Results of radioactivity detection (Hu *et al*. 2009)

Hole number	Hole depth (m)	Sampling	Specific activity C* (Bq/kg) *Ra-226*	*Th-232*	*K-40*	Internal exposure index $I_{Ra}^* \leq 1.0$	External exposure index $I_r^* \leq 1.0$
1#	-2	The sampling quality is greater than or equal to 2 kg, of each depth, of each hole.	15.8	2.0	200.7	0.08	0.10
	-7		23.5	8.9	281.9	0.12	0.17
	-12		22.7	12.8	362.3	0.11	0.20
	-17		21.4	15.6	304.9	0.11	0.19
2#	-3		18.4	5.9	226.4	0.09	0.13
	-8		23.5	7.8	273.6	0.12	0.16
3#	-4		19.7	6.2	214.7	0.10	0.13
	-9		20.2	10.3	271.3	0.10	0.16
4#	-5		21.8	4.1	250.4	0.11	0.13
	-10		24.6	11.0	300.6	0.12	0.18
5#	-6		22.9	11.2	324.7	0.12	0.18
	-11		24.6	9.6	270.1	0.12	0.17

*I_{Ra}-internal exposure index; *I_r-external exposure index; *C-specific activity

materials (GB 6566. 2010), that shows the PTs belong to class A building material (Hu *et al.* 2009). Therefore, the production, marketing, and use of PTs are not restricted. From the perspective of radioactivity, there is completely no problem in applying the PTs as the subgrade filler.

3.2 Mechanical properties

The *CBR* is an index that characterizes the water stability and the ability to resist local indentation deformation of subgrade materials, through which the optimal proportion can be screened out reasonably. The compaction degree is the construction control index. The excellent resilient modulus of subgrade may be realized through the reasonable selection of filler and effective control of compaction degree. For the PTs modified clay being a subgrade filler, it is necessary to research its *CBR*, resilient modulus, and stability, under the required compaction degree.

3.2.1 Test scheme

By studying the influence of PTs and clay content changing on the compaction performance and *CBR* strength properties, the optimal proportion is selected, to verify road performance. The test scheme is shown in Table 5.

3.2.2 Compaction property

The compaction tests were carried out on each proportion in Table 5. The compaction results are shown in Fig. 4.

With the increase of PTs content and the decrease of clay content, the optimum water content of PTs modified clay gradually decreases, the two presenting a linear relationship. Although for the specific density, the PTs is greater than the clay, with the increase of PTs content and the decrease of clay content, the maximum dry density of the mixture does not increase continuously. Instead, it first increases and then decreases, whose peak corresponding to the proportion of 50% PTs: 50% clay (CP3). For the maximum dry density, CP3 is

Table 5 Test scheme

Specimen No.	Proportion
CP1	100% clay + 0% PTs
CP2	75% clay + 25% PTs
CP3	50% clay + 50% PTs
CP4	25% clay + 75% PTs
CP5	0% clay + 100% PTs

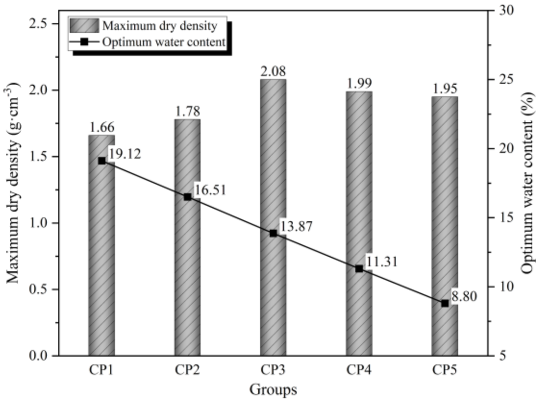


Fig. 4 Compaction property of PTs modified clay

0.42 g·cm^{-3} and 0.13 g·cm^{-3} larger than CP1 and CP5, respectively. The water absorption of PTs is lower than clay, resulting in the optimum water content of the mixture falling down with the increase of PTs content.

The maximum dry density is affected by the specific gravity of PTs and clay, but the interaction between PTs particles and clay particles are more significant. When the PTs content reaches 50%, the coarser particles of PTs form a skeleton, whose pores are filled by the finer clay particles, that presents a skeleton-dense structure. Therefore, the proportion possesses the highest dry density to have the best compaction performance.

3.2.3 CBR property

The minimum compaction degree of embankment and subgrade recommended by AASHTO (1993) are all greater than 95%, except for special soils; the minimum compaction degree of the expressway and first-class roadbed are 96% stipulated by JTG D30 (2015). Therefore, the 96% of the compaction degree is performed in this study.

From Fig. 5, the *CBR* value of the mixture with the increase of PTs content first increases and then decreases, and reaches the peak value at 50% of PTs content, echoing the change in the maximum dry density. As the PTs content increases, the swelling degree keeps decreasing. For CP5, since it is made of pure PTs, no the clay, and the PTs are similar to extra fine sand, therefore its swelling degree is 0.

For the discrimination of expansive soil, the swell-shrink total rate under load pressure is mostly used JTG D30 (2015). In engineering practice, because of easier availability, the swelling degree of soaking *CBR* is also often recommended. The corresponding relationship between the swell-shrink total rate and the swelling degree, as shown in Table 6.

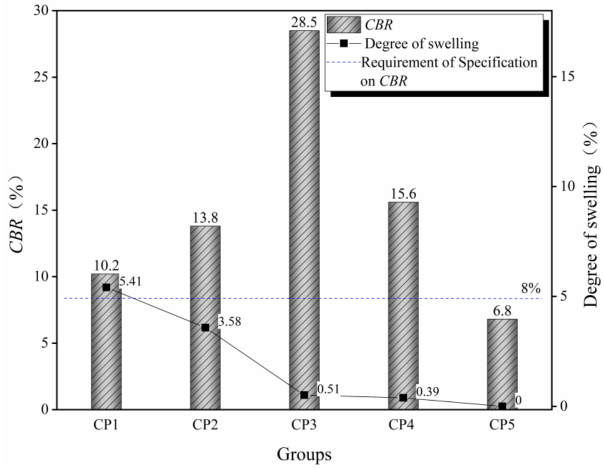
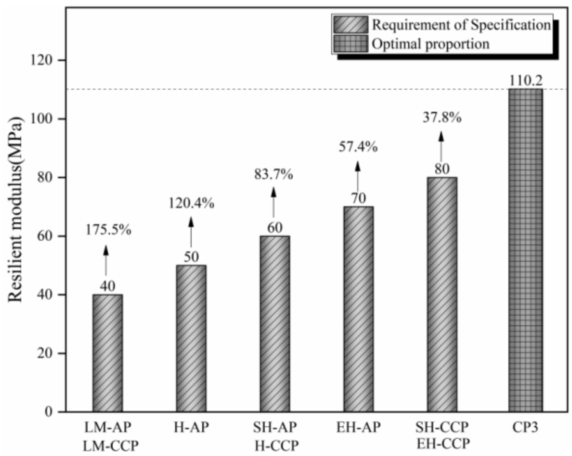


Fig. 5 *CBR* strength and swelling degree of PTs modified clay



LM: light and medium traffic; H: heavy traffic; SH: special heavy traffic; EH: extremely heavy traffic; AP: asphalt pavement specification; CCP: cement concrete pavement specification

Fig. 6 Comparison of resilient modulus of CP3 and requirements of specifications

CP1 is the proportion of no mixing the PTs, made of the pure clay, and its swelling degree is 5.41%, which is between 5-8%. According to the corresponding relationship in Table 6, CP1 belongs to the weak expansive soil, which can be used after treatment in the embankment or roadbed. The swelling degrees of CP2-CP4 are all less than 5%, which is non-expansive soil and can be used directly. Although the swelling degree of CP5 is 0, less than 5%, due to its lack of cementing materials, the overall structure is loose, which should be used after taking the treatment of edging in practical applications.

3.2.4 Optimal proportion and resilient modulus

Considering the PTs content and *CBR* strength comprehensively, the optimal proportion is recommended as 50% PTs: 50% clay, namely CP3. The resilient modulus of CP3 at the compaction degree of 96%, and the requirements on resilient modulus of the top surface of subgrade in specifications (JTG D40. 2011, JTG D50. 2017) are shown in Fig. 6.

Table 6 Corresponding relationship between swell-shrink total rate and swelling degree

Filler grade	Swell-shrink total rate under load pressure (%) (JTG D30. 2015)	Degree of swelling (%) (Fang *et al*. 2005)	Use scope
Non-expansive soil	$e_{ps}<0.7$	$a<5$	It can be used directly.
Weak expansive soil	$0.7\leq e_{ps}<2.5$	$5\leq a<8$	It can be used for the filling of embankment range after taking the physical treatment measures of edging, reinforcement, and setting up the cushion, and it can be used for the filling of the roadbed after treatment with an inorganic binder.
Middle expansive soil	$2.5\leq e_{ps}<5.0$	$8\leq a<13$	It can be used as a subgrade filler after being treated with an inorganic binder.
Strong expansive soil	$e_{ps}\geq 5.0$	$a>13$	It should not be used as a subgrade filler.

1. When the height of the embankment is greater than or equal to 3 m, the expansion rate test under the pressure of 50 kPa shall be used to calculate the swell-shrink total rate.
2. When the height of the embankment is less than 3 m, the expansion rate test under the pressure of 25 kPa shall be used to calculate the swell-shrink total rate.
3. e_{ps} is the swell-shrink total rate, a is the degree of *CBR* swelling, which is the ratio of the height change after soaking to the height of the original specimen (120 mm)

The resilient modulus of CP3 is 110.2 MPa, which is greater than the specification requirements. Compared to the requirements of asphalt pavement, 110.2 MPa is higher 57.4% (extremely heavy traffic), is higher 83.7% (extra heavy traffic), is higher 120.4% (heavy traffic)), and is higher 175.5% (medium, light traffic)). Compared to the requirements of cement concrete pavement, 110.2 MPa is higher 37.8% (extremely heavy and very heavy traffic), is higher 83.7% (heavy traffic)), and is higher 175.5% (medium, light traffic).

3.3 Stability

Lianyungang is a coastal city, on the southern margin of warm temperate zone, with a humid monsoon climate. The rainy season is long and the rainfall is abundant, which mainly concentrates in July, August, and September, accounting for about 66.7% of the annual rainfall. Meanwhile, from July to September, the sunshine is strong, which results in large evaporation, accounting for about 46.0% of the annual evaporation (Chen 2020). In the Lianyungang area, the long-term soaking caused by continuous rainfall, and the dry-wet cycles created by the alternating action of heavy rainfall and strong evaporation, reduce the strength and stability of subgrade. Therefore, the research of PTs modified clay on water soaking stability and dry-wet stability is imperative.

3.3.1 Water stability

After soaking for different days, at the compaction degree of 96%, the *CBR* tests of CP3 were carried out. Its purpose is to simulate the field environment, measuring whether the *CBR* can keep steady, under continuous soaking conditions. The definition of water stability coefficient is proposed, that is, the ratio of soaking *CBR* to non-soaking *CBR*. As shown in Eq. (1).

$$S_{cs}=\frac{CBR_{cs}}{CBR_0} \tag{1}$$

Where :

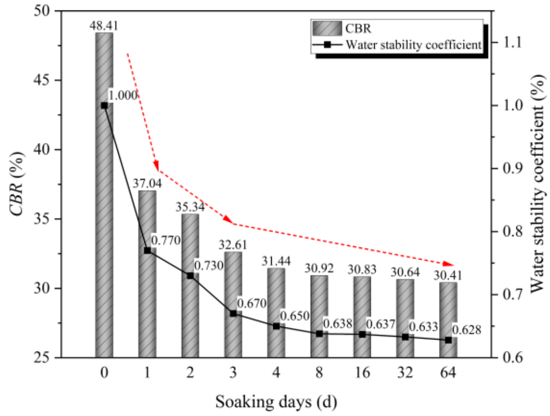


Fig. 7 Water stability

S_{cs} is the water stability coefficient.

CBR_{cs} is the soaking *CBR* value for different days, %.

CBR_0 is the non-soaking *CBR* value, %.

The changes of *CBR* and S_{cs} with the different soaking time are used to evaluate the water stability. As shown in Fig. 7

When CP3 is soaked for 1 d, its *CBR* and S_{cs} decreases rapidly, being 11.37% and 0.23, respectively. After that, the *CBR* and S_{cs} continue to decrease with the prolongation of soaking time, but the decreasing rate turns slower. After soaking for 4 days, the *CBR* and S_{cs} have tended to be stable. Soaking for 8 d, 32 d, and 64 d, the *CBR* and S_{cs} hardly change. The change in water stability can be divided into three stages. The first day is the steep dropping stage, 2-4 d is the slow descent stage, and after 4 d is the stable stage. These results also prove the rationality of the soaking time of 4d in the *CBR* test of JTG D30-2015 from the side (Zhao *et al*. 2023a).

3.3.2 Dry-wet stability

The dry-wet cycle tests were carried out to assess the dry-wet stability of CP3. The wet-dry stability coefficient is used as the measurement index, which is the ratio of *CBR* after *n* dry-wet cycles to *CBR* without dry-wet cycles. As shown in Eq. (2).

$$S_{dw} = \frac{CBR_n}{CBR_0} \tag{2}$$

Where:

S_{dw} is the dry-wet stability coefficient.
CBR_n is the *CBR* after *n* dry-wet cycles, %.
CBR_0 is the *CBR* without wet-dry cycles, %.

As shown in Fig. 8. With the increase of wet-dry cycles, the *CBR* and S_{dw} gradually decrease and slowly tend to be stable. Until 8 cycles (64 d), the *CBR* values all are greater than 8% (JTG D30. 2015), which is the requirement of specification on the upper roadbed of the highway.

The change of dry-wet stability also can be divided into three stages. The 0-8 d is the steep dropping stage, 8-40 d is the slow descent stage, and after 40 d is the stable stage. In the first stage, *CBR* and S_{dw} decrease by 7.87 MPa and 0.16, respectively. In the second stage, *CBR* and S_{dw} decrease by 10.63 MPa and 0.22, respectively. In the third stage, *CBR* and S_{dw} decrease by 4.33 MPa and 0.09, respectively.

3.3.3 Comparison of water stability and dry-wet stability

To determine the effect of deterioration conditions (continuous soaking and dry-wet cycles) on the strength properties, the *CBR* with the same deterioration time is compared in Fig. 9.

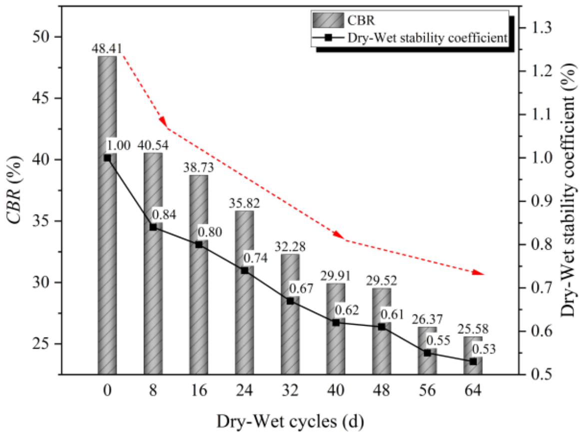


Fig. 8 Dry-wet stability

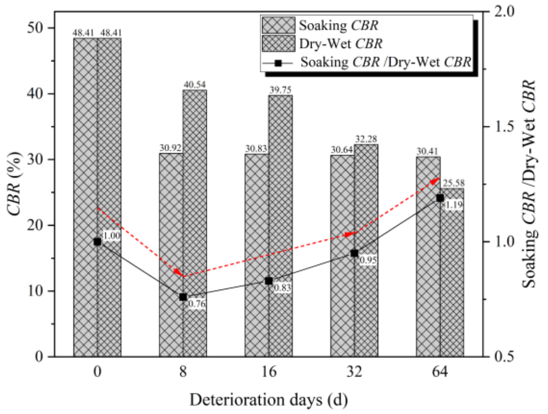


Fig. 9 Comparison of water stability and dry-wet stability

Time has an important influence on the changing trend of the ratio of soaking stability and dry-wet stability. The overall trend change can be divided into three stages. Under the initial condition of the same *CBR*, for 8 d (first stage), the soaking *CBR* is lower than the *CBR* of one dry-wet cycle. With the extension of time (8d-32d, second stage), the soaking *CBR* remains almost stable, while the *CBR* after dry-wet cycles decreases significantly, indicating that its deterioration degree increases greatly. Therefore, CBR_{cs}/CBR_n increases. Entering the third stage (32 d-64 d), the soaking *CBR* barely changes, while the dry-wet *CBR* continues to decrease. Thus, in this stage, CBR_{cs}/CBR_n increases more significantly. It shows that under long-term action, the dry-wet change has a greater adverse impact than the continuous soaking on the strength properties.

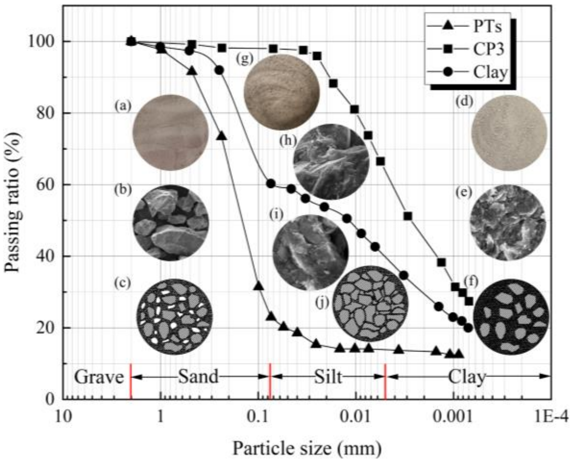
4. Strength mechanism analysis

The strength mechanism of PTs modified clay is explained from the gradation and microstructure. The gradation analysis, the soil structure analysis, the microstructure analysis of PTs, clay, and CP3 are summarized in Fig. 10.

The PTs belong to extra fine sands, their particle size is mainly between 0.075-0.25 mm. The macro-appearance of PTs is fine and smooth (Fig. 10(a)), but their micro-morphology is angular clearly after being magnified by 100 times (Fig. 10(b)). The strength of PTs mainly depends on the friction force of particles. The particle size of clay is mainly between 0.0007-0.01 mm (Fig. 10(d)). Being magnified by 2000 times, the microscopic clay is mainly lumpy, platelike, and has fewer flakes, particles connecting more closely, with smaller pores (Fig. 10(e)). The strength of clay is mainly provided by the cohesion.

The PTs have a larger particle size to provide the supporting role of the skeleton. While the clay with smaller particles is suitable to fill and cement the skeleton formed by the PTs. 50% content of PTs mixes with 50% content of clay to form a CP3 mixture (Fig. 10(g)). The different positions of the mixture were scanned by SEM. Amplifying 2000 times, it finds the surface rough structure of PTs particle (Fig. 10(h)); amplifying 5000 times, it observes the lumpy and platelike structure of clay particles (Fig. 10(i)), but no viewing the appearance of new hydrates. These indicate that there is no chemical reaction between the PTs and the clay, because of the nonreactivity of PTs.

When the PTs content is greater than 50%, the contact is mainly among PTs particles, the clay particles embedded in the PTs particles. The clay particles cannot fully fill the pores between the PTs particles and cement well the PTs particles. The mixture changes into the skeleton-porosity structure (Fig. 10(c)). Lacking the filling and cementation of clay, the structure of the mixture is loose and its integrity is worse, which leads to the drop of *CBR*. When the PTs content is less than 50%, the contact between the PTs particles decreases, the skeleton effect weakens, that leads to the decrease of friction force. The excessive clay wraps and fills the PTs to make them in a suspending state. The mixture is the suspension-dense structure (Fig. 10(f)). Meanwhile, the clay has strong water absorption and retention, that thickens the internal water film,



(a) macro-appearance of PTs, (b) micro-morphology of PTs, (c) skeleton-porosity structure, (d) macro-appearance of clay, (e) micro-morphology of clay, (f) suspension-dense structure, (g) macro-appearance of CP3, (h) micro-morphology of CP3 (2000 times), (i) micro-morphology of CP3 (5000 times) and (j) skeleton-dense structure

Fig. 10 Structure analysis of mixture

and weakens its cementation effect, the swelling degree turning bigger, the compactness turning lower. Eventually, the *CBR* decreases.

The gradation curve of CP3 (50% PTs) is between the PTs and clay, which is continuous and smooth, indicating that the particle size of PTs and clay complements each other (Zhao *et al*. 2023a), the skeleton role forming perfectly, the cementation role playing fully. The mixture belongs to the skeleton-dense structure (Fig.10(j)). Therefore, the friction force is the largest, the cohesion is the largest, and the *CBR* is also the maximum.

5. Economic analysis

The economic efficiency analysis of PTs as subgrade filler is mainly discussed from the following two aspects, one is direct economic efficiency, which refers to the cost saving of materials; the other is indirect economic efficiency, which refers to the price of land occupied by the storage of PTs.

5.1 Direct economy

The direct economy of PTs modified clay is embodied, taking the optimal proportion CP3 as an example, through the comparison of material price with the common subgrade filler, lime stabilized clay (LSC). The price of all materials is obtained from the Liansu expressway subgrade completed in May 2023, in which an 80 m test section of PTs modified clay was built. Excluding the test section, the 5% lime stabilized clay was adopted in the subgrade. The compaction degree adopts the minimum requirements of the highway and the first-class highway roadbed, being 96%.

The price expression of fillers is shown in Eq. (3), its results are calculated in Table 7.

$$m_t = \gamma_{\max} / w_{oc} \times c_d \times \left(p_a \times m_a + p_b \times m_b \right) \tag{3}$$

Table 7 Price of fillers (RMB)

Material price (yuan/t)	PTs	Clay			Lime
	35	26			520
Comparison project	Proportion	$\gamma_{\max}$	w_{oc}	c_d	Filler price (yuan/m^3)
CP3	50% clay + 50% PTs	2.08	13.87	96%	70.17
LSC	5% lime + 100% clay	1.66	16.2		91.13

Table 8 Indirect economy of PTs (RMB)

Project	Land area (m^2)	Unit price (yuan/m^2)	Total price (million yuan)
PTs	3×106	900	270

Where:
m_t is the filler price, yuan/m^3.
$\gamma_{\max}$ is the maximum dry density, g/cm^3.
w_{oc} is the optimum water content, %.
c_d is the compaction degree, %.
p_a is the component content of *a*, %.
p_b is the component content of *b*, %.
m_a is the price of *a*, yuan/t.
m_b is the price of *b*, yuan/t.

The CP3 is 70.17 yuan/m^3, while the LSC is 91.13 yuan/m^3. Compared to the two, the CP3 is 19.96 yuan/m^3 cheaper, being 21.90% of the LSC. The economic efficiency of PTs modified clay is markedly significant.

5.2 Indirect economy

The indirect economic efficiency of PTs is embodied by the price of occupied land, taking the Jinping phosphorus mine for example. As shown in Table 8.

Table 8 only lists the direct land price, while its indirect social value is difficult to estimate. Through the above comparison and analysis, it can be seen that the PTs modified clay as the subgrade filler has obvious economic advantages, especially with the improvement of environmental requirements and the lack of soil resources, the economic advantages of PTs modified clay will become more prominent.

6. Conclusions

The PTs are used to modify the clay as the subgrade filler. The following are the main conclusions:

• The PTs belong to the non-hazardous solid wastes and class A construction materials. The PTs are environment-friendly materials and meet the requirements of the specification, which are suitable for modifying clay as the subgrade filler.

• The optimum water content and swelling degree of PTs modified clay are affected obviously by the content changing content of PTs and clay. The maximum dry density and *CBR* value both have a peak, corresponding to the proportion of 50% PTs: 50% clay, which is determined as the optimal proportion, whose resilient modulus is far beyond the requirements of specifications.

• The *CBR* value and water stability coefficient of specimens drop with the increase of soaking days, and then keep stable. The *CBR* value and dry-wet stability coefficient of specimens both decline with the increase of cycles and then tend to be stable. The dry-wet cycle is more destructive than the continuous soaking to PTs modified clay in the long run.

• The PTs being the skeleton, the clay playing the functions of cementation and filling, the PTs modified clay can be divided into three structures: suspension-dense, skeleton-dense, skeleton-porosity. As the optimal proportion, its roles of PTs' skeleton and clay's filling both are in full performance, its *CBR* value is greatest.

• The economic efficiency of PTs modified clay as the subgrade filler includes the direct economy and indirect economy. The direct economy is reflected by material prices, being highly significant. The indirect economic benefit of the mixture is embodied in the price of land occupied by the Jinping PTs, it is extremely enormous.

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References

AASHTO. (1993), *AASHTO guide for design of pavement structures*. American Association of State Highway, Transportation Officials, US.

Bakhshizadeh, A., Khayat, N. and Horpibulsuk, S. (2022), "Surface stabilization of clay using sodium alginate", *Case Studies Constr. Mater.*, **16**, e01006. https://doi.org/10.1016/j.cscm.2022.e01006.

Bera, A.K. and Chakraborty, S. (2015), "Compaction and unconfined compressive strength of sand modified by class f fly ash", *Geomech. Eng.*, **9**(2), 261-273. https://doi.org/10.12989/gae.2015.9.2.261.

Chen, Q. (2020), "Road performance and engineering application of soda residue-phosphate tailings- clay admixtures", M.D. Dissertation, Southeast University, Nanjing, China.

Csillag, J., Lukács, A., Osztoics, E., Csathó, P. and Baczó, G. (2006), "Extraction and analysis of soil solution of phosphate rock and acid treated soil", *Commun. Soil Sci. Plant Anal.*, **37**, 2339-2350. https://doi.org/10.1080/00103620600819636.

Ding, Y.F., Wang, J.P., Liu, L.B. and Deng Y. (2019), "Study on the preparation and performance of self-insulation blocks with phosphate tailings", *Multipurpose Utilization of Mineral Resources*, **1**, 96-101. https://doi.org/10.3969/j.issn.1000-6532.2019.01.021.

Dixon-Hardy, D.W. and Engels, J.M. (2007), "Guidelines and recommendations for the safe operation of tailings management facilities", *Environ. Eng. Sci.*, **24**(5), 625-637. https://doi.org/10.1089/ees.2006.0133.

Fang, L., Tang, B., Xu, M. and Jiang, F. (2005), "Expansive identification and classify of subgrade padding in expressway", *J. Highway Transport. Res. Development*, **22**(4), 31-34. https://doi.org/10.3969/j.issn.1002-0268.2005.04.009.

GB 5085.3 (2007), *Identification standards for hazardous wastes - Identification for extraction toxicity*, Ministry of Ecology and Environment of the People's Republic of China, Beijing, China.

GB 6566 (2010), *Limits of radionuclides in building materials*, General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Beijing, China.

Gu, B.W., Zhao, L.W., Hu, J. and Tian, A.G. (2015), "Influence of admixture on making process and property of ooze brick", *Materials Reports*, **29**(2), 446-449.

Haddaji, Y., Majdoubi, H., Mansouri, S., Tamraoui, Y., El bouchti, M., Manoun, B., Oumam, M. and Hannache, H. (2021), "Effect of synthetic fibers on the properties of geopolymers based on non-heat treated phosphate mine tailing", *Mater. Chem. Phys.*, **260**, 124147. https://doi.org/10.1016/j.matchemphys.2020.124147.

Hamdane, H., Tamraoui, Y., Mansouri, S., Oumam, M., Bouih, A., El Ghailassi, T., Boulif, R., Manoun, B. and Hannache, H. (2020), "Effect of alkali-mixed content and thermally untreated phosphate sludge dosages on some properties of metakaolin based geopolymer material", *Mater. Chem. Phys.*, **248**, 122938. https://doi.org/10.1016/j.matchemphys.2020.122938.

Hu, J., Gu, B.W. and Tian, A.G. (2009), "Approach into radioactivity of phosphate tailings from Jinping Phosphate Mine", *Ind. Miner Process.*, **10**, 9-12. https://doi.org/10.16283/j.cnki.hgkwyjg.2009.10.007.

HJ/T299 (2007), *Solid waste-Extraction procedure for leaching toxicity-Sulphuric acid & nitric acid method*, Ministry of Ecology and Environment of the People's Republic of China, Beijing, China.

JTG 3430 (2020), *Test methods of soils for highway engineering*, Ministry of Transport of the People's Republic of China, Beijing, China.

JTG D30 (2015), *Specification for Design of Highway Subgrade*, Ministry of Transport of the People's Republic of China, Beijing, Ch3ina.

JTG D40 (2011), *Specifications for Design of Highway Cement Concrete Pavement*, Ministry of Transport of the People's Republic of China, Beijing, China.

JTG D50 (2017), *Specifications for Design of Highway Asphalt Pavement*, Ministry of Transport of the People's Republic of China, Beijing, China.

JTG E51(2009), *Test Methods of Materials Stabilized with Inorganic Binders for Highway Engineering*, Ministry of Transport of the People's Republic of China, Beijing, China.

Li, M.D., Cong, X., Zhu, L.P., Kong, L.P., Zhang, Z.F., Tian, A.G. and Li, L. (2017), "Experimental study on recycling dredged marine sediment and phosphate tailing to produce earth fill", *Mar. Georesour. Geotec.*, **35**(4), 586-591. https://doi.org/10.1080/1064119X.2016.1213340.

Li, X.Y. (2016), "Experimental study on sintered ceramic from phosphate tailings and its utilization of resource reports", M.D. Dissertation, Chongqing University, Chongqing, China.

Li, Y.J., Mei, Z.H., Zhang, X., Ye, F. and Mei, F.D. (2017), "Mechanical performance and hydration mechanisms of cemented paste backfilling materials with phosphate tailings", *J. Wuhan Univ. Tech.*, **39**(3), 22-26. https://doi.org/10.3963/j.issn.1671-4431.2017.03.004.

Loutou, M., Taha, Y., Benzaazoua, M., Daafi, Y. and Hakkou, R. (2019), "Valorization of clay by-product from moroccan phosphate mines for the production of fired bricks", *J. Cleaner Production*, **229**, 169-179.

https://doi.org/10.1016/j.jclepro.2019.05.003.
Luo, H.B. and Yan, H.M. (2005), "Application of phosphate tailings in subgrade (cushion)", *Highway*, **5**, ,146-148. https://doi.org/10.3969/j.issn.0451-0712.2005.05.032.
Moukannaa, S., Loutou, M., Benzaazoua, M., Vitola, L., Alami, J. and Hakkou, R. (2018), "Recycling of phosphate mine tailings for the production of geopolymers", *J. Cleaner Production*, **185**, 891-903. https://doi.org/10.1016/j.jclepro.2018.03.094.
Moukannaa, S., Nazari, A., Bagheri, A., Loutou, M., Sanjayan, J.G. and Hakkou, R. (2019), "Alkaline fused phosphate mine tailings for geopolymer mortar synthesis: Thermal stability, mechanical and microstructural properties", *J. Non-Crystalline Solids*, **511**, 76-85. https://doi.org/10.1016/j.jnoncrysol.2018.12.031.
Nasiri, H., Khayat, N. and Mirzababaei, M. (2021), "Simple yet quick stabilization of clay using a waste by-product", *Transport. Geotech*., **28**, 100531. http://doi.org/10.1016/j.trgeo.2021.100531.
Ren, Y. and Shao J. (2018), "Study and application of clay modified phosphorus tailings used as embankment filler", *Highway*, **63** (11), 46-49.
Rico, M., Benito, G. and Díez-Herrero, A. (2008a), "Floods from tailings dam failures", *J. Hazardous Mater.*, **154**(1), 79-87. https://doi.org/10.1016/j.jhazmat.2007.09.110.
Rico, M., Benito, G., Salgueiro, A.R., Díez-Herrero, A. and Pereira, H.G. (2008b), "Reported tailings dam failures: A review of the European incidents in the worldwide context", *J. Hazardous Mater.*, **152**(2), 846-852. https://doi.org/10.1016/j.jhazmat.2007.07.050.
Ru, X.H. (2010), "Research on non-fired bricks by blast furnace slag and phosphate tailings", M.D. Dissertation, Wuhan University of Technology, Wuhan, China.
Wang, Z. (2017), "Research on mechanical properties of slag phosphorus tailings clay mixture", M.D. Dissertation, Hubei University of Technology, Wuhan, China.
Wei, Z., Yin, G., Wang, J.G., Wan, L. and Li, G. (2012), "Design, construction and management of tailings storage facilities for surface disposal in China: case studies of failures", *Waste Management Res.*, **31**(1), 106-112. https://doi.org/10.1177/0734242X124622811.
Wu, J., Li, J., Rao, F. and Yin, W.Z. (2020), "Mechanical property and structural evolution of alkali-activated slag-phosphate mine tailings mortars", *Chemosphere*, **251**, 126367. https://doi.org/10.1016/j.chemosphere.2020.126367.
Yang, W.Q., Zhang, H., He, H.T., Cai, Z.J., Pang, J.T. and Xiao, Z. (2021), "Research progress on flotation reagents for beneficiting phosphate rock", *Ind. Miner. Process.*, **50**(11), 29-36. https://doi.org/10.16283/j.cnki.hgkwyjg.2021.11.006.
Yang, Y.H., Wei, Z.A., Chen, Y.L., Li, Y.J. and Li, X.Y. (2017), "Utilizing phosphate mine tailings to produce ceramisite", *Constr. Build. Mater.*, **155**, 1081-1090. https://doi.org/10.1016/j.conbuildmat.2017.08.070.
Yu, H., Huang, X., Ning, J.G. and Zhao, Y. S. (2016), "Improving performance of soil stabilizer by scientific combining of industrial wastes", *Geomech. Eng.*, **10**(2), 247-256. https://doi.org/10.12989/gae.2016.10.2.247.
Zhang, L., You, D.H., Hu, X.Q., Zhang, J., Zhang, Z.H., Li, G.D. and Peng, X.H. (2023), "Research on preparation of high strength ceramsite by using phosphorus tailings and fly ash", *Non-Metallic Mines*, **46**(4), 13- 17.
Zhang, X., Li, Y.J., Hu, C.Y., Mei, F.D., Huang, Z.Y. and Zhou, K.Q. (2018), "Effect of phosphate tailings and tailing mud on properties of cemented filling materials", *J. Hefei Univ. Tech.*, **41**(7), 973-977. https://doi.org/10.3969/j.issn.1003-5060.2018.07.020.
Zhao, X.Q., Liang, T., Yue, Z.C., Zong, Z.L., Li, J.W. and Yin, J.H. (2023a), "Influence of compaction degree on mechanical properties of modified clay with phosphate tailings", *Highway*, **5**, 25-30.
Zhao, X.Q., Shen, Z., Y., Deng, Y.F., Li, J.W., Yue, Z.C. and Liang, T. (2023b), "Freeze-thaw resistance and deterioration mechanism of cement-treated mixture of soda residue and clay", *Chinese J. Highway Transport*, **37**(1). https://doi.org/10.19721/j.cnki.1001-7327.2024.01.000.
Zhao, X.Q., Zhang, Y.H., Li, M.D. and Sun, Y.D. (2012), "Study on factors influencing strength of cement-solidified sea silt road embankment adding phosphate tailings", *Highway*, **11**, 71-75. https://doi.org/10.3969/j.issn.0451-0712.2012.11.017.
Zhao, X.Q., Zhao, C., Li, M.D. and Sun, Y.D. (2011), "Study on optimum water content of solidified silt incorporating phosphorate tailings as embankment", *Highway*, **12**, 34-37.
Zhao, X.Q., Zhao, G., Li, J.W. and Zhang, P. (2019), "Unconfined compressive strength property and its mechanism of construction waste stabilized lightweight soil", *Geomech. Eng.*, **4**(19), 307- 314. https://doi.org/10.12989/gae.2019.19.4.307.
Zheng, K.R., Zhou, J. and Gbozee, M. (2015), "Influences of phosphate tailings on hydration and properties of Portland cement", *Constr. Build. Mater.*, **98**, 593-601. https://doi.org/10.1016/j.conbuildmat.2015.08.115.
Zhuang, X.S., Wang, K., Li, K. and Wang, J.X. (2019), "Experimental study on modified expansive soil of phosphorous tailings-EPS basalt fiber", *Highway Eng.*, **44**(1), 38-43. https://doi.org/10.3969/j.issn.1674-0610.2019.01.007.

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