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The Impact of Phosphogypsum on Enhancing the Compressive Strength of CSA-Treated Sand

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ABSTRACT

Various additives such as fly ash, lime, fibers, and slag have been explored to enhance soil stabilization characteristics and fulfill specific performance criteria. The utilization of Calcium Sulfoaluminate (CSA) cement has garnered considerable attention due to its environmental friendliness compared to ordinary Portland cement (OPC) and its notable durability and early strength development. This study investigates the impact of replacing CSA with phosphogypsum (PG) on enhancing the compressive strength of sand while exploring the potential for recycling waste from phosphorus production. Chemical composition analysis of PG was conducted through X-ray fluorescence (XRF) and X-ray diffraction (XRD), revealing the predominant presence of calcium sulfate hemihydrate along with impurities like fluorine, phosphorus, silicon, and sulfur compounds. The mixture compositions were initially standardized to include 7% CSA and 10% water content for all samples. Subsequently, five types of mixtures were prepared, with CSA replaced by PG in proportions of 10%, 20%, 30%, 40%, and 50%. Uniaxial compressive strength (UCS) and ultrasonic pulse velocity (UPV) tests were conducted at intervals of 3, 7, 14, and 28 days to assess the influence of PG on soil stabilization characteristics. The findings indicate that the optimal replacement level of CSA with PG would be 30%, resulting in the highest strength development after 28 days of curing.

1. INTRODUCTION

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The construction industry is becoming increasingly active, and ensuring the stability and reliability of soil foundations is paramount. Various chemical additives, such as fly ash, lime, slag, and fibers, strengthen soil (Degirmenci et al., 2007). Soil stabilization, the process of mixing soil with appropriate inorganic binding materials, followed by compaction to improve the soil's engineering characteristics, is a crucial aspect of civil and environmental engineering.

Soil stabilization using eco-friendly binders such as calcium sulfate aluminate (CSA) and BOF slag is a process aimed at improving the physical and mechanical properties of soil for construction purposes (Jumassultan et al., 2021, Mustafayeva et al., 2023a, Mustafayeva et al., 2023b, Ocheme et al., 2023, Ocheme et al., 2024, Park et al., 2021, Rauf et al., 2023, Sagidullina et al., 2022a, Sagidullina et al., 2023, Sagidullina et al., 2022b, Subramanian et al., 2023). These methods are an alternative to traditional approaches such as the use of Portland cement and lime, which have a negative impact on the environment. While the use of eco-friendly binders is prominent, identifying the optimum content is crucial. Subramanian (2019) investigated the effect of gypsum content on the strength of CSA-treated sand using unconfined compressive strength (UCS) tests. The study determined that the optimum gypsum content for achieving the greatest strength and stability of the soil with minimal deformation was 30%.

Phosphogypsum (PG), as a by-product of the phosphoric acid production sector, can also be effective for soil stabilization purposes. Yang (2009) stated that 150 million tons of PG are produced annually and is expected to double in the next two decades. This waste material is rich in calcium sulfate ($CaSO_4$), making PG a promising soil stabilizer (Meskini, 2023). This study aims to utilize PG to identify the optimum content for enhancing the strength characteristics of stabilized sand.

2. MATERIALS AND METHOD

2.1 Materials

In this experimental work, quartz sand, CSA cement, and phosphogypsum (PG) supplied by the Taraz KazPhosphat company in Kazakhstan were utilized. An X-ray diffraction (XRD) analysis was conducted to investigate the chemical composition of the phosphogypsum. The main component identified was calcium sulfate hemihydrate, as indicated in red in Figure 1. The composition also includes trace amounts of impurities such as fluorine, phosphorus, silicon, and sulfur.

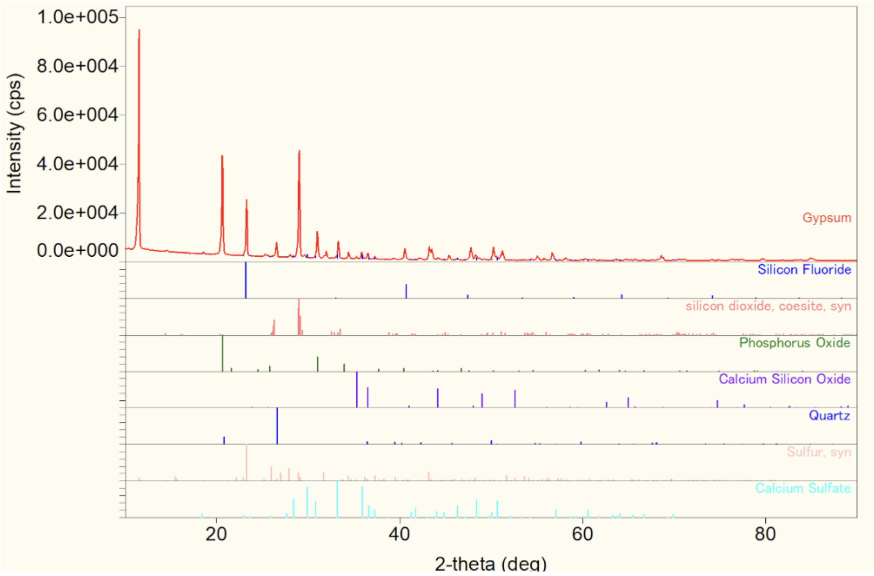

Fig. 1 XRD characterization of PG.

2.2 Sample Preparation

The materials were mixed in different proportions to prepare the samples. Each sample measured 50 mm in diameter and 100 mm in height. To ensure accurate results, sixteen samples (four for each curing day) were prepared for each proportion. The water and CSA cement content were fixed at 10% and 7%, respectively. The PG replacement of CSA ranged from 10% to 50%. The water content was calculated as 10% of the total solids, the CSA content was based on the sand mass, and the PG content was derived from the CSA mass. The following figure illustrates the replacement process. Throughout the experimental work, the PG content was increased, and the CSA content was decreased by 10% increments each time.

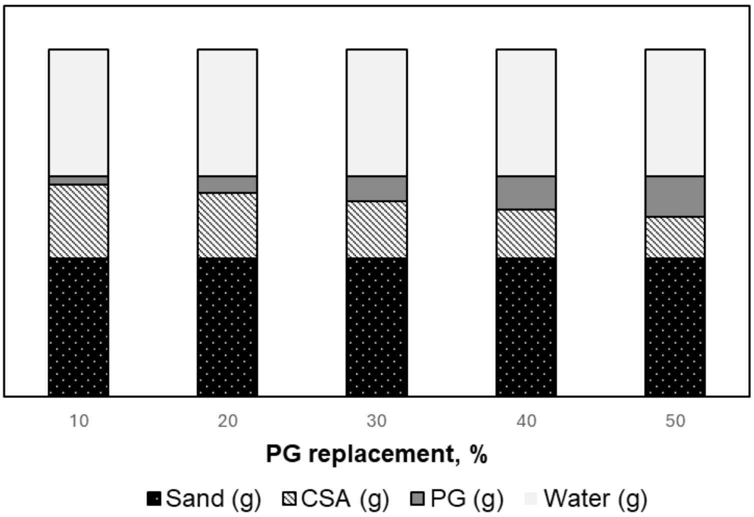

Fig. 2 Proportions of materials for different PG replacement percentages.

2.3 Test Methodology

The test methodology focused on gradually replacing CSA content with PG. The figure below shows the step-by-step sample preparation and testing process, which includes drying raw materials (sand and PG), sieving phosphogypsum, mixing materials, curing samples, and UCS testing.

Sand and phosphogypsum were dried in an oven at 100°C for 24 hours. Raw PG forms clogs, which were removed by passing through a 300 μm sieve. The mixing process begins with weighing the dry components (sand, phosphogypsum, and CSA) and blending them properly. After thorough mixing, water was added, and the mixture was then mixed with a mortar mixer for 10 minutes. Molds were prepared with retainers, and an oil coating was applied to facilitate easier extraction of the samples. The molds were removed after 24 hours. The samples were left to cure for 3, 7, 14, and 28 days at 22°C.

After the curing period, the samples were subjected to a vertical load until failure occurred. The UCS testing included weighing the samples and measuring the peak deviator stress.

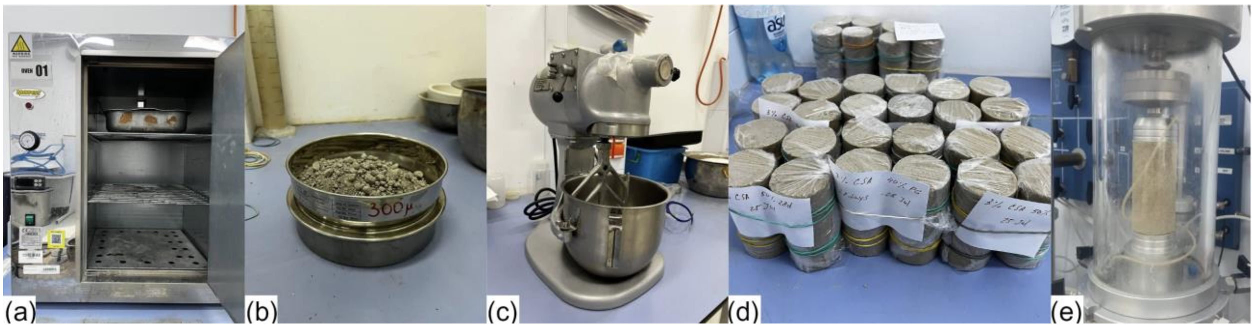

Fig. 3 Test methodology: (a) Drying of sand and PG for 24 hours; (b) Sieving of PG; (c) Mixing of materials; (d) Curing for 3, 7, 14, and 28 days; (e) UCS testing.

3. RESULTS AND DISCUSSION

The study investigated the effect of phosphogypsum on sand treated with 7% CSA cement. Laboratory tests were conducted with different concentrations of phosphogypsum to determine the optimal content that would best improve soil properties. After curing the samples for 28 days, tests were performed to assess strength development. A strong relationship was observed between the application of phosphogypsum and the improvement of cemented sand. The main trends are illustrated in Figure 4, which indicates that a 30% replacement with phosphogypsum may be optimal, as it shows a steady increase in the strength of the samples, with a significant rise on the 14th and 28th curing days.

The early strength development was almost similar for all sample ratios, ranging between 1250 and 1500 kPa, except for the 40% and 50% CSA replacements. A sharp decrease in strength was noted with the 50% proportion. The most prominent strength gain was observed after 28 days of curing. For instance, the peak deviator stress for a 20% replacement was 2350 kPa, and for a 30% replacement, it was 2500 kPa. However, significant drops were observed at 1650 kPa and 1250 kPa for the 40% and 50% replacements, respectively. This indicates that the compressive strength development decreases with increased phosphogypsum content.

The highest strength development for each proportion was observed after 28 days of curing. It can be assumed that ettringite formation is a critical factor, as it is identified as the primary hydration product responsible for both initial and subsequent strength development.

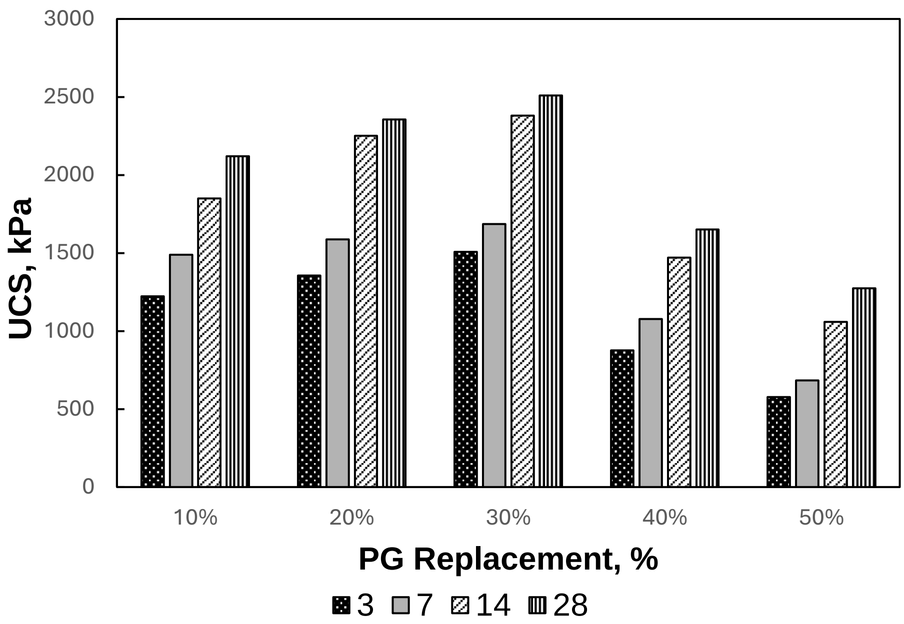

Fig. 4 Strength development over 28 days of curing for various percentages of phosphogypsum (PG) replacement.

4. CONCLUSION

This study investigated the relationship between the application of phosphogypsum (PG) and the mechanical behavior of CSA-treated sand. The key findings from the experimental work are as follows:

1. The optimal replacement ratio of phosphogypsum for CSA-treated sand is identified as 30%. This ratio resulted in the most significant strength gain across all curing days.
2. The peak deviator stress increases with the rise in PG content up to the optimal ratio. However, a significant drop in strength is observed for higher PG content beyond this optimal point.

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