# The Effect of Metakaolin and Glass Factory Waste on the Geotechnical Properties of Cement-Stabilized Anzali Sand Using the DSM Method

**Elahe Khavaninzade[1], Reza Ziaie Moayed[2*]**

1- PhD student of geotechnical engineering, Department of civil engineering in Imam Khomeini International university, Qazvin, Iran, (e-mail: elii.kh94@gmail.com).

2- Professor of Geotechnical Engineering at Department of Civil Engineering in Imam Khomeini International university, Qazvin, Iran (Corresponding Author, phone: 028-3390-1104; e-mail: Ziaie@eng.ikiu.ac.ir).

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## Abstract

Improving loose sandy soils in coastal and marine environments requires treatment methods that provide adequate strength and stiffness while maintaining long-term performance. This study investigates the effects of metakaolin (MK) and glass-factory waste (SF waste) on the mechanical behavior and stiffness of cement-stabilized Anzali sand treated within the framework of the deep soil mixing (DSM) method. Specimens were prepared using 20% Portland cement with 0 or 3% MK and 0 or 3% SF waste, where the additive contents were expressed relative to the dry soil mass. The specimens were cured in fresh water and seawater and evaluated using unconfined compressive strength (UCS), unconsolidated-undrained (UU) triaxial compression, X-ray diffraction (XRD), and field-emission scanning electron microscopy (FESEM). The secant modulus at 50% of peak stress ($E_{50}$) was obtained from the stress–strain curves as an index of stiffness. The results indicate that both additives improve the mechanical response, with the combined 20% cement–3% MK–3% SF-waste mixture providing the most pronounced improvement. After 90 days, UCS reached 6.451 MPa in seawater and 6.347 MPa in fresh water for the combined mixture. Triaxial results also showed increasing peak deviator stress with curing age and confining pressure. XRD and FESEM observations indicated consumption of portlandite, formation of additional hydration products, and a denser cemented matrix. Overall, the combined use of MK and SF waste improved strength, stiffness, and microstructural characteristics of cement-treated Anzali sand, particularly under saline curing conditions.

Keywords: Sandy soil stabilization; Deep soil mixing; Cement-treated sand; Metakaolin; Glass-factory waste; Unconfined compressive strength; E50; Seawater curing.

## 1. Introduction

Chemical stabilization with cement is widely used to improve the engineering performance of loose and weak soils. For cement-treated sands, strength and stiffness depend on cement content, curing time, porosity, particle characteristics, and the physical and chemical properties of the soil–binder system. Nevertheless, the environmental burden associated with Portland cement production has encouraged the use of supplementary cementitious and pozzolanic materials as partial replacements or complementary additives. The use of industrial waste can additionally contribute to waste valorization and reduction of environmental impacts.

In this context, metakaolin is an aluminosilicate pozzolan capable of reacting with calcium hydroxide released during cement hydration and producing secondary cementitious phases. Glass-derived materials rich in reactive amorphous silica can similarly participate in pozzolanic reactions and promote additional C–S–H formation. Previous studies have reported improvements in the strength and microstructure of cementitious and soil–cement systems when metakaolin, silica-rich materials, or waste glass are incorporated [1-9]

The deep soil mixing (DSM) method forms soil–binder columns by mechanically mixing in-situ soil with a cementitious slurry. The method is attractive for ground improvement because it can be implemented with limited soil displacement and without the aggregate extraction required for conventional concrete systems. The present study therefore examines the combined use of MK and SF waste for cement

stabilization of coastal Anzali sand, with particular emphasis on performance under fresh-water and seawater curing. The study further relates mechanical behavior to XRD and FESEM observations to clarify the proposed improvement mechanisms.

## 2. Methodology

Anzali sand was obtained from the Caspian Sea coast near Anzali, northern Iran. Based on the Unified Soil Classification System, the sand was classified as poorly graded sand (SP), with a specific gravity of 2.70 and an in-situ dry unit weight of approximately 1.50 g/cm³. Type II Portland cement was used as the primary binder. The industrial additive was a powdered, bone-white waste generated by a glass raw-material extraction and processing plant in Khoramdasht Industrial Park, Qazvin Province. XRF characterization showed that more than 93% of the waste consisted of $SiO_2$; comparison with published silica-rich materials led the original study to characterize its chemical nature as silica-fume-like. Metakaolin was used as a supplementary pozzolanic material.

Four cementitious compositions were investigated: 20% cement without additives; 20% cement + 3% MK; 20% cement + 3% SF waste; and 20% cement + 3% MK + 3% SF waste. The additive percentages were based on dry soil mass. Dry sand was mixed with the specified binder materials and water at 150 rpm for approximately 2 min before the slurry was introduced into the soil. The resulting homogeneous mixture was placed in cylindrical molds without impact compaction, consistent with the intended DSM-style preparation. The specimens were initially kept for 24 h and subsequently cured in fresh water or seawater for 7, 14, 28, 56, and 90 days.

UCS tests were conducted using an automated 50-kN loading frame in accordance with ASTM D2166. At least three specimens were tested for each mixture, and values deviating by more than 5% from the mean were rejected. UU triaxial tests were performed on the selected optimum mixture at confining pressures of 50, 100, and 150 kPa and curing ages of 28, 56, and 90 days, following ASTM D2850. XRD analyses were conducted on air-dried material over a 2θ range of 5–80° using Cu Kα radiation, while FESEM observations were used to examine the cemented microstructure.

## 3. Results and Discussion

At 90 days, the combined 20% cement + 3% MK + 3% SF-waste mixture produced the highest UCS among the investigated compositions in both curing environments. The measured UCS values were 6.451 MPa in seawater and 6.347 MPa in fresh water. In comparison, the 20% cement reference mixture reached only 1.271 MPa and 2.643 MPa under seawater and fresh-water curing, respectively. The improvement associated with the combined additives is attributed in the study to the simultaneous pozzolanic activity of MK and the silica-rich SF waste, together with their filling effect within the cemented matrix.

The strength-development trends also depended on curing conditions. The reference cement-only mixture exhibited substantial early-age strength development followed by a reduction at later ages, particularly under seawater exposure. In contrast, the mixtures containing MK and/or SF waste generally maintained a more favorable strength-development trend. The combined mixture showed continuous strength gain up to 90 days. This behavior is interpreted as evidence of continued secondary hydration and pozzolanic reactions, which consume part of the calcium hydroxide generated by cement hydration and promote additional cementitious products.

**Table 1. 90-day UCS of cement-stabilized Anzali sand under different curing conditions**

| Mixture | Seawater UCS (MPa) | Fresh-water UCS (MPa) |
|---|---|---|
| 20% C | 1.271 | 2.643 |
| 20% C + 3% MK | 3.936 | 4.424 |
| 20% C + 3% SF waste | 4.107 | 4.644 |
| 20% C + 3% MK + 3% SF waste | 6.451 | 6.347 |

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Stiffness results, expressed by E50, followed a similar improvement pattern. The simultaneous incorporation of MK and SF waste produced the highest stiffness, with the reported maximum value reaching approximately 625.77 MPa under seawater curing at 28 days. The greater stiffness of the combined mixture is consistent with the formation of a denser and more continuous cemented matrix. The study attributes the response to the synergistic action of the two pozzolans: the silica-rich waste promotes C–S–H formation, while the aluminosilicate character of MK contributes to additional alumina-bearing hydration products.

The UU triaxial tests on the selected mixture showed that peak deviator stress increased with both curing age and confining pressure. At 90 days, the maximum deviator stress was 6.35 MPa at a confining pressure of 150 kPa, whereas the corresponding value at 50 kPa was 2.64 MPa. Increasing confining pressure reduced the post-peak stress drop and moderated the brittle response by restraining shear-crack propagation. Conversely, increasing curing age increased peak strength but also tended to produce a sharper post-peak response, reflecting the development of a stiffer and more strongly bonded cemented structure.

Microstructural observations support the mechanical results. XRD patterns showed quartz associated with the original sand, calcite, portlandite, and ettringite, together with broad amorphous regions attributed to hydration products such as C–S–H and C–A–S–H. The relative reduction in portlandite intensity in mixtures containing MK and SF waste was interpreted as evidence of its consumption during pozzolanic reactions. FESEM images showed that hydration products progressively filled voids and formed bridges between sand particles. The combined MK–SF-waste mixture produced a comparatively uniform, homogeneous, and dense microstructure, consistent with its higher strength and stiffness.

## 4. Conclusions

The experimental results demonstrate that the incorporation of MK and glass-factory waste can substantially improve the mechanical and stiffness characteristics of cement-stabilized Anzali sand treated within a DSM framework. The combined 20% cement + 3% MK + 3% SF-waste mixture provided the highest UCS and E50 values and maintained strength development to 90 days. Confining pressure increased peak deviator stress and reduced the severity of post-peak softening in UU triaxial tests. XRD and FESEM observations indicate that the improvement is associated with continued pozzolanic reactions, consumption of portlandite, formation of secondary hydration products, pore filling, and densification of the soil–cement matrix. The results support the potential use of the investigated glass-factory waste together with metakaolin as complementary materials for cement-based improvement of sandy coastal soils.

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