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Alkali-activated binders in soil stabilization – A step towards waste valorization and environmental compatibility

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ABSTRACT: Whenever soil properties on site are insufficient to meet construction-related requirements, soil stabilization is one technique to valorize low-quality soils within capable earth structures. Establishing a circular economy for soils but also for the stabilizing agents is vital to enhance the sustainability of the construction sector. However, state-of-the art stabilizing agents such as cement and lime mainly originate from primary resources and exhibit a considerable environmental impact throughout their production process. This work depicts an approach to enhance the mechanical properties of fine-grained soils while reducing the corresponding environmental impact using alkali-activation technology. Two paths were explored to give indications about the effectiveness and mechanism of alkali-activation in comparison to cement-treatment in soil stabilization. On the one hand, we tested a novel mineral waste-based binding agent as alternative to cement. On the other hand, we tried to alkali-activate two pure soil materials using soluble silicates. In both cases, test specimens were produced in the Proctor device at pre-defined water content and were stored for 7 days in air-tight containers before they were tested for uniaxial compressive strength (UCS). The results revealed high impact of the soil type itself on the effectiveness of soil stabilization using alkali-activation, resulting in UCS improvements up to 307 %. Still, cement-treatment has revealed to be more favorable in the framework of this study. Nevertheless, optimized mix design is assumed to reinforce the importance of alkali-activation in soil stabilization in ecological and economic regards.

KEYWORDS: fine-grained soils, wet soils, brick waste, alkali activators, proctor test, uniaxial compressive strength, dry density.

1 INTRODUCTION

Adequate subsurface properties are a substantial prerequisite for any successful construction operation. However, prevailing soils on site often do not conform to the respective requirements which necessitates technical solutions or a replacement of the deficient soil. Especially the replacement of soil goes along with two major problems. First of all, the excavated soil material is redundant and consequently, is treated as waste ending up in landfills. Solely in Austria, 57% of all accruing wastes belong to excavation materials, with two-thirds of them being directly landfilled (Federal Ministry Agriculture and Forestry, Climate and Environmental Protection, Regions and Water Management Republic of Austria, 2025). This approach not only leads to a waste of resources but also consumes land which could be used more efficiently. Secondly, the soils substitute materials (sand, gravel) are among the most requested materials worldwide – trends increasing – and their mining negatively impacts the environment (Bendixen, et al., 2021). Exemplarily, concrete and asphalt production cover more than 50 % of the US' aggregates demand (U.S. Geological Survey, 2025). Hence, there is a need to valorize lower quality but abundant soil materials for earth works e.g. such as dam constructions and preserve high quality aggregates for high-value products.

Technical solutions such as (chemical) soil stabilization can be applied to improve lower-quality soil's properties satisfying the requirements for earth structures. Therefore, the soil is mixed with mineral binders such as cement and quick lime. These Ca-rich binders have the following effects (Anburuvel, 2024) on the treated soil: In the presence of clay minerals, cation exchange with Na^+ and K^+ takes place, lowering the affinity for water attraction. Therefore, not only the plasticity is reduced, but also attraction among the particle surfaces and edges rises. Then, particles tend to rearrange, flocculate and agglomerate enhancing the soil's shear strength. Remaining Ca is available for hydration (in case of cement), or hydrated lime [$Ca(OH)_2$] formation which increases the alkalinity and further stimulates pozzolanic reaction (of clay minerals). Consequently, improvements with respect to strength, stiffness, plasticity, and potentially density can be achieved, whereas the efficiency of the soil stabilization depends on the soil type and binder used. Besides their effectiveness, Ca-rich binders bear some risks in the presence of sulfates and organics. While organics inhibit the binder's reaction, sulphates can cause a retarded reaction destructing formed structures by excessive expansion and cracking of the stabilized soil due to the formation of expansive ettringite crystals (Firoozi, et al., 2017; Diaz Caselles, et al., 2020; Anburuvel, 2024).

Recently, binders of lower Ca-content were identified as beneficial for treating sulfate rich soils (Behnood, 2018) which, on top, make the calcination process obsolete. One group of low-Ca (binding) agents are alkali-activated materials (AAMs). AAMs are synthesized by mixing an alkaline solution with one or several alumino-silicate precursors, which causes dissolution, followed by gel formation and polycondensation. This reaction results in the formation of a competent matrix yielding proper mechanical properties and durability of respective construction materials (Hassan, Arif and Shariq, 2019). In soil stabilization, the effect of alkali-activated stabilization agents was mainly related to the binding effect of the reaction products (Huang, et al., 2021; Parthiban, et al., 2022). At the same time, clay-rich soils themselves might act as potential (reactive) silica and alumina sources contributing to the reaction. Such behavior was detected, for example, by Sargent *et al.* (2020), who experienced differences in mineralogical composition before and after alkali-activation.

To date, mainly supplementary cementitious materials, such as calcined clays or blast furnace slag are used as alkali-activated binders in soil stabilization. The application of mineral waste-based precursor materials could further increase the sustainability of resulting structures and may also contribute positively in the context of economic considerations. However, more knowledge is required to use mineral wastes in soil stabilization (Behnood, 2018; Parthiban, et al., 2022).

In this study we examined the impact of alkali-activation on two different soil types using conventional and alternative stabilizing agents. Each soil was treated at a water content higher than the respective optimum water content. We mixed the soils either with cement or with sole activators or with a combination of activator and alternative precursor (brick waste). Specimens were produced using a proctor device, were cured and tested using a uniaxial press. The results allowed us to assess the activity of soil particles and brick waste as stabilizing agent compared to cement. Additionally, we evaluated the overall soil response with respect to the treatment.

2 MATERIALS AND METHODS

2.1 *Raw materials*

2.1.1 *Soils*

We used two fine-grained soils originating from two different Austrian localities. On these soils, comprehensive index testing was carried out including grain size distribution (ÖNORM EN ISO 17892-4), proctor tests (ÖNORM B 4418) and direct shear tests (ÖNORM EN ISO 17892-10). Relevant physical and mechanical properties are summarized in Table 1.

Table 1. Index parameter of soil samples.

Analysis	Parameter	Soil 1	Soil 2	Unit
Grain size distribution	Gravel	0.2	1.7	%
	Sand	68.0	21.0	%
	Silt	29.4	39.4	%
	Clay	2.4	37.9	%
	C_u	4.25	-	-
Proctor test	w_{opt}	13.0	19.8	%
	ρ_{Pr}	1.65	1.63	g/cm³
Direct shear test	φ	33.0	18.8	°
	c	32.9	33.6	kPa

2.1.2 *Stabilizing agents*

As reference material we used CEM II/C-M (S-LL) 42.5 N regulated through ÖNORM EN 197-5.

For alkali-activation we tried out three different activators which were:

- Sodium metasilicate pentahydrate ($Na_2SiO_3\ 5H_2O$) abbreviated as *NaM*
- Sodium hydroxide (NaOH)
- Potassium waterglass (Geosil 15517, Wöllner GmbH, $SiO_2/K_2O = 1.7$, $\rho = 1.52$ g/cm³, solid content of 55 wt.%) abbreviated as *WG*

NaM and NaOH were not pre-treated (milled) but used as provided by the manufacturer (granulate material).

As additional reactive precursor we employed brick waste (BW) from construction and demolition waste accruing in Austria. To enhance its reactivity, it was milled to approach cement fineness. Chemical composition and mineralogy were analyzed using X-ray fluorescence (Malvern Panalytical Epsilon 4) and X-ray diffraction analyses (PANalytical X'Pert PRO). Table 2 comprises relevant chemical and mineralogical composition of the BW.

Table 2. Relevant chemical parameters and amorphous content of BW in wt.%.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	$K_2O + Na_2O$	LOI	Amorph
60.5	16.3	6.5	6.0	3.4	3.7	1.8	27.7

2.2 *Methodology and mix design*

As soil and in particular stabilized soil is a multi-phase mixture, a given mix design needs to accommodate for a number of influencing factors. To investigate two different soil types, three activators and one waste-derived precursor, we needed to fix some boundary conditions. With this respect, we kept water content for each soil constant. To consider the most unfavorable case, we fixed it to a value higher than the optimum water content determined by proctor test. The dosage of stabilizing agents we fixed at 9 % referred to the total mass of the test cylinders. Table 3 and Table 4 include the composition of relevant mixtures.

Table 3. Mixtures of soil 1 in wt.% of the total mass.

Mixture	Soil wet	NaM	BW	Cem
S1	100			
S1_NaM9	91	9		
S1_NaM9_BW9	82	9	9	
S1_BW9	91		9	
S1_Cem9	91			9

Table 4. Mixtures of soil 2 in wt.% of the total mass.

Mixture	Soil wet	NaM	NaOH	WG	Cem
S2	100				
S2_NaM9	91	9			
S2_NaOH9	91		9		
S2_WG9	91			9	
S2_Cem9	91				9

2.3 *Sample preparation and testing*

Before the treatment, both soils were dried in an oven at 40 °C.

First, all solid components were blended in a plastic bowl. Then the liquid compounds such as water (& WG) were added. After the materials have been homogenized thoroughly the soil mixtures were compacted in the proctor device with three compaction layers and a standard compaction energy of 0,6 MJ/m³. Subsequently the specimens (Ø 10 cm, h = 12 cm) were pressed out of the Proctor pot and stored in airtight plastic boxes.

After seven days of curing the specimens were tested in the uniaxial press. One specimen was tested for each mix. The specimen's leftovers were captured and dried at 100°C to obtain its dry mass and therefore also its dry density.

3 RESULTS AND DISCUSSION

3.1 *Treated soil 1*

To investigate the impact of soil type/precursor on soil stabilization using alkali-activation, we compared stress-strain relationship of untreated and treated specimen. Figure 1 and Table 5 show the results of uniaxial compressive strength (UCS) testing for untreated soil 1 and treated soil 1 with either 9 % NaM or 9 % BW or a combination of 9 % NaM and 9 % BW. The addition of 9 % NaM led to an increase of the UCS by 20 % while the ultimate strain was increased by 1 %. On the other hand, the addition of BW led to an increase of the UCS by 42 % at unaltered ultimate strain. When both, NaM and BW were combined, ultimate strain follows the one from sole NaM. However, UCS increases by 133% with respect to untreated soil. Therefore, the combination of BW and NaM shows the most significant stabilization effect on soil 1.

The dominance of 9 % NaM + 9 % BW most probably relates to the formation of a binding agent in the pores of soil 1 through the reaction of BW and NaM (Huang, et al., 2021; Parthiban, et al., 2022). At the same time, the soil particles, themselves, show relatively low response to the activation with NaM. Consequently, the stabilization effects in soil 1 might be governed by the reaction of BW with NaM.

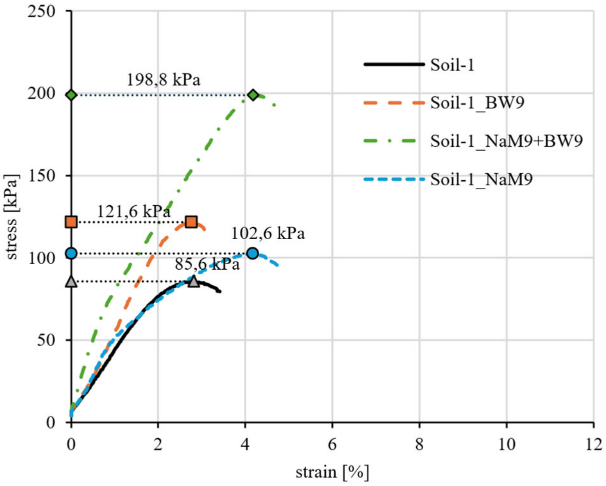

Figure 1. Stress-strain curve of sodium metasilicate mixtures and reference specimen of soil 1.

To assess the overall capacity of alkali-activation to improve soil 1, we compared corresponding specimen to cement-treated specimen. According to Table 5, the addition of 9 % cement achieves an improvement of compressive strength by 1588 %. Therefore, with respect to compressive strength cement stabilization is 12 times as effective as alkali-activation using 9 % BW + 9 % NaM. These findings suggest a clear advantage of cement-treatment over alkali-activation for stabilizing soil 1.

Additionally, Table 5 contains resulting dry densities of specimen as a measure for compactibility. However, no clear relationship between UCS improvement and dry density is derivable. Hence, further investigations are needed to clarify the role of density on the stabilization success.

Table 5. Dry density and UCS of test samples from soil 1.

Mixture	ρd [g/cm³]	UCS [kPa]	Improvement [%]
S1	1,641	85,5	-
S1_BW9	1,668	121,6	42
S1_NaM9	1,571	102,6	20
S1_NaM9_BW9	1,670	198,8	133
S1_Cem9	1,692	1443,4	1588

3.2 *Treated soil 2*

According to grain size distribution (Table 1) soil 2 is much finer than soil 1. While soil 1 has 32 % of particles < 0.063 mm, soil 2 has 77 % of such particles. Increasing fineness suggests a higher incorporation of weathered soil fractions such as clay minerals. Additionally, soil 2 shows high plasticity reaching its UCS at an ultimate strain of 12 % while soil 1 reaches it UCS at an ultimate strain of 3 %. Higher plasticity indicates the existence of surface charges to bound water which is characteristic for clay minerals. Therefore, a contribution within a given alkali-activation reaction from the soil itself such as in Sargent *et al. (2020)* might be more probable when compared to soil 1.

To investigate the impact of soil and activator type on soil stabilization using alkali-activation, we compared stress-strain relationship of untreated and treated specimen with three different activators. Figure 2 and Table 6 show the results of UCS testing for untreated soil 2 against treated soil 2 with either 9 % NaM, 9 % NaOH or 9 % WG. The addition of all three activators led to a significant increase in UCS. Maximum improvement was reached by WG (307 %), followed by NaM (220 %) and NaOH (89 %). The remarkable performance of WG is interesting with respect to its liquid character supplying additional water to the system. However, when compared to the granular materials (NaM and NaOH), also differences in availability and distribution of alkalis are to be expected. Next to UCS, the addition of activators led to significant increase in stiffness, shifting ultimate strain of 12 % into a region of 2 – 4 %. Such an effect on stiffness was also reported by Chami, Cuccurullo and Gerard (2024) who investigated a silty clay soil treated with slag and NaOH. Nevertheless, stabilization effects in soil 2 can be achieved without the addition of supplementary precursor materials such as slag or BW.

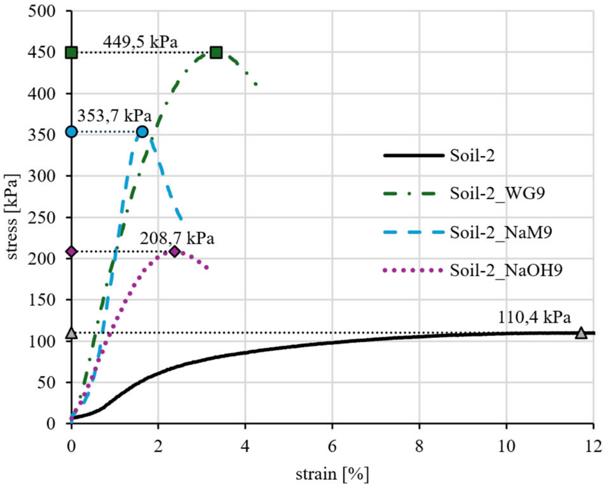

Figure 2. Stress-strain curves of sodium metasilicate mix, sodium hydroxide mix, waterglass mix and reference specimen of soil 2.

Again, we compared stabilization results of alkali-activated soil with cement-treated soil (Table 6). Contrary to the conclusion of Anburuvel (2024), cement stabilization was also quite effective in soil 2 reaching an UCS improvement of 1195%. Therefore, with respect to compressive strength cement addition is roughly 4 times as effective as alkali-activation of soil using WG. However, the enhancement of soil 2 through the addition of 9 % WG might already be sufficient for certain earth structures. Additional improvement might be achieved through the addition of a supplementary precursor (cf. 3.1) and pre-milling of used activators. Hence, further investigations are required, but soil 2 indicates a high effectiveness of alkali-activation approaching the effectiveness of cement.

As in soil 1, no clear relationship between UCS improvement and dry density (Table 6) is derivable.

Table 6. UCS of test samples from soil 2.

Mixture	ρd [g/cm³]	UCS [kPa]	Improvement [%]
S2	1,544	110,4	-
S2_NaM9	1,546	353,6	+220
S2_NaOH9	1,628	208,7	+89
S2_WG9	1,518	449,5	+307
S2_Cem9	1,646	1429,6	+1195

4 CONCLUSIONS

We investigated the overall effectiveness of alkali-activation in soil stabilization using two different soil types, three different activators and one waste-derived precursor material. It enabled us to qualitatively assess the mechanical relevance of such alternative stabilization techniques. Results from UCS testing showed:

- a major impact of the soil type on the effectiveness of stabilization using alkali-activation.
- advantages of cement-stabilization over alkali-activation in the current framework
- higher potential of alkali-activation in soil stabilization for optimized mix designs.

Considering low-quality soil (e.g. soil 2) as a major but unutilized waste stream, as well as its potential to develop favorable properties when treated with alkaline activators, its valorization bears not only ecological but also economic advantages. Even though the stabilization capacity of cement could not be fully reached, results might satisfy individual respective needs. Additionally, the integration of waste-soil or waste-based precursors can reduce the demand for primary resources and process emissions from cement and lime calcination.

However, the gained findings should be treated as indicators and further investigations are necessary to:

- generate statistically reliable datasets
- yield optimized mix designs (especially with respect to lowest possible activator dosages)
- understand the mechanisms as well as effects of mineralogy and other relevant parameters such as water content and density.

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