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SEDIMENTS, SEC 5 • SEDIMENT MANAGEMENT • RESEARCH ARTICLE

Stabilization of river dredged sediments by means of alkali activation technology

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Abstract
Purpose Alkali activation process has been applied to fresh river clay-rich sediments in order to increase their mechanical properties and make them suitable for soil stabilization.
Materials and methods Dredged sediments were mixed with up to 30 mass percent (ma%) of fly ash (FA) or ladle slag (LS) and after curing for 3 days at 60 °C, the bending and compressive strength have been determined. The mixtures which exhibited the highest strengths were further optimized for being used in soil stabilization. For this purpose, the sediment was stabilized with 4 ma% of quicklime (QL) and after 1 h 30 ma% of FA with alkali activator was added and cured for 1, 7 and 28 days.
Results The stabilized sediment has a significantely better geomechanical performance in comparison with the sediment alone. Stabilizing the dredged sediment using alkali activation technology provides high enough strengths to eventually make it suitable for anti-flood embankments.
Conclusions The results confirmed the suitability of the investigated technology for soil stabilization.

Keywords River sediment · Alkali activated materials · Ladle slag · Fly ash · Mechanical strength · Soil stabilization

1 Introduction

Alkali-activated materials (AAMs) have attracted much attention in the last decade as they are competitive materials to bricks, mortar, or concrete and can be used in a variety of construction applications. AAMs are cured pastes made by mixing an aluminosilicate-rich powder (precursor) with alkaline solutions (activators). Amorphous aluminosilicates are dissolved by alkaline solutions (water glass, NaOH, KOH, etc.), followed by a polycondensation reaction that results in a two- or three-dimensional polymer network. The basic result of the polymerization is a hardening of the AAM binders (Provis 2018). Numerous natural aluminosilicate materials are suitable as precursors for the alkali activation process, as are some waste materials (fly ash, bottom ash, bio-based ash and various slags). Various dredged sediments can also be an interesting alternative for the synthesis of AAMs due to their clayey composition. In recent years, the alkali-activated technology has rapidly entered the field of soil stabilization (Rivera et al. 2020; Hanein et al. 2022; Wu et al. 2022a; Maheepala et al. 2022; Miraki et al. 2022; Chen et al. 2023; Huang et al. 2023).

Dredged sediments are formed at dredging operations and are usually disposed of in landfills or used as fill material. They can be beneficially used for substitution of virgin raw materials, for remediation of contaminated sites, for creating new or expanding existing land (reclamation), for creation of habitat to support aquatic organisms and wetlands to improve the natural value of the environment (restoration) or for reinforcement for defence against floods and extreme climatic events (resiliency) (CEDA 2019). However, their high water content and poor geomechanical properties make them unsuitable for many construction applications. Alkali activation is a promising technology to improve the properties of dredged sediments and make them suitable for soil stabilization purposes. For example, a study by Brahim et al. (2022) found that an alkali activation of dredged sediments

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with NaOH resulted in a significant increase in compressive strength and a decrease in porosity. Alkali activation has also been found to reduce the water absorption of dredged sediments and improve their durability and resistance to chemical attack. Similarly, a study by Gokul et al. (2021) found that the alkali activation of soft soil with NaOH resulted in a significant increase in the compressive and shear strength of the soil. A study by Wang et al. (2023a) found that an alkali activation of soft soil with NaOH led to an improvement in soil stability, as evidenced by an increase in the cohesion and friction angle of the soil. In addition, alkali activation was found to improve the durability of soft soils and reduce their susceptibility to weathering. A study by Min et al. (2022) showed the alkali activation of soft soils with NaOH or Na_2SiO_3 significantly improve the freeze–thaw resistance. Alkali activation has also been shown to be an effective method for reducing the environmental impact of soft soils by immobilizing contaminants and reducing the leachability of contaminants. A study by Komaei et al. (2023) found that the alkali activation of soft soils can effectively reduce the leachability of heavy metals.

The main reactive phases in sediments are aluminosilicate (clay) minerals. Their reactivity is closely related to the solubility of Si and Al in alkali media (Werling et al. 2022). Clay based materials are commonly pretreated by calcination at around 800 °C to increase the Si/Al solubility ratio and improve efficiency of the alkali activation (D'Elia et al. 2018). Simultaneously the organic matter, which may also affect the reactivity (Wattez et al. 2021), is removed. The solubility of Si and Al in sediments S1 and S10 in 10 M KOH and 10 M NaOH has been determined in previous study, as a reference values for proving the increase of Si and Al solubility after calcination (Žibret et al. 2023). For S1 the solubility of Si was 115 mg/l in 10 M NaOH and 94 mg/l in 10 M KOH and the solubility of Al was 46 mg/l in 10 M NaOH and 34 mg/l in 10 M KOH. For S10 the solubility of Si was 134 mg/l in 10 M NaOH and 105 mg/l in 10 M KOH and the solubility of Al was 54 mg/l in 10 M NaOH and 36 mg/l in 10 M KOH (Žibret et al. 2023). Alkali activation of uncalcined illite based clay materials is also possible, but it results in lower quality materials (Marsh et al. 2018), which may be suitable only for specific applications, which require lower compressive strengths, like for example "lean concrete" layer between soil and foundation concrete, road sub-base layer or for lean roller compacted concrete for construction of river dams (Gouvas and Orfanos 2014; Ohwofasa et al. 2023; Chandrashekhar et al. 2019). Lean concrete mixtures are mainly based on Ordinary Portland Cement (OPC), the mechanical properties of lean concrete can be improved by adding FA or slags. Because alkali activation of soils decreases the porosity and has ability to immobilize contaminants, the use of alkali activated materials for "lean concrete" layers between soil and foundation concrete may effectively protect the main foundation from the impacts of soil. However, there is a lack of studies investigating the application of alkali activated materials as lean concrete layers. A few papers are foucsing on roller compacted geopolymer concrete (Rahman and Khattak 2021; Patel et al. 2022), which showed higher mechanical properties than similar OPC based concrete (Rahman and Khattak 2021).

Hydropower plants face challenges due to the deposition of sediments in their reservoirs (Parker et al. 2007), reducing their water storage i.e. their capacity for electricity production. Sediment deposition can also cause operational and maintenance issues, affecting the performance of turbines and other components. Large quantities of sediments accumulating at hydropower plant dams worldwide is recognized as one of the most challenges issues in hydro power plant management; only in Slovenia approximately 50,000 m^3 are accumulated annually. The present study features sediments from the river Drava in Slovenia. Drava Power Plants Maribor (DEM), with eight large and five small hydro power plants, is one of Slovenia`s largest hydropower plant companies with water reservoirs of a total capacity of 72.4 million m^3. It produces almost a quarter of the total electricity produced in Slovenia. The largest reservoir on the Slovenian part of the Drava River is Lake Ptuj. Sediments are excavated or pumped to locations within the water body in the safe way i.e. without effecting the river flow or causing environmental threats. Most of the sediment is deposited along the banks of the Drava River and on artificially created islands within the limited space of the river. Therefore, it is necessary to find new solutions for using these sediments i.e. in the construction sector (Basson 2009). Drava river sediments are carbonate-rich illite clay sediments, and contain fragments of various stratigraphic units (Šoster et al. 2017) and some residues of Pb/Zn ores exploited upstream (Šajn et al. 2011; Žibret et al. 2018). Despite their elevated Pb and Zn content, the sediments meet the criteria for use in clay based sector (Ducman et al. 2022) but are also usefull as a precursor for AAM after calcination (Žibert et al. 2023).

In this study first the compressive strength (after 3 days of curing) of alkali activated uncalcined dredger river sediments with addition of FA or ladle slag were determined in order to evaluate the potential suitability for its application as "lean conctere" layer. Further investigations have been made towards assessing untreated sediments with additions of slags and FA for soil stabilization purposes. In previous studies sediments were stabilized with 8 mass percent (ma%) of QL which was enough for the reaching sufficient performance (Ducman et al. 2022). In the presented research the alkali activation technology is used to decrease the amount of QL and further stabilize the soil.

Table 1 Main oxide composition of the used precursors (natural state) measured by XRF. Abbreviations: S1 – 1 year deposited river sediment; S10 – 10 years deposited river sediment; FA1 and FA2 – fly ash batches; LS – ladle slag, LOI – los on ignition

	S10	S1	FA1	FA2	LS
LOI 950 °C	14.63	15.79	0.51	1.14	20.47
Na_2O	1.35	1.23	1.19	0.78	0.30
MgO	4.90	5.33	2.80	2.57	23.44
Al_2O_3	15.44	15.78	22.98	26.25	5.25
SiO_2	48.01	44.87	44.82	42.16	13.80
K_2O	2.23	2.30	2.20	2.43	0.15
CaO	6.15	7.12	12.38	10.20	28.10
Fe_2O_3	5.36	5.49	10.65	12.16	4.70
Other	1.93	2.09	2.47	2.31	3.79

2 Materials and methods

2.1 Materials

AAMs were prepared using two main precursors: 10 years deposited Ptuj Lake sediment (S10) and one year deposited Ptuj Lake sediment (S1). The precursors S10 or S1 were replaced by 0, 10, 20 or 30 ma% of either coal combustion FA from a local thermal power plant (FA1; Traven et al. 2021) or ladle slag obtained from the desulfurization processes at the second stage of steel refining (LS; Češnovar et al. 2019). Two batches of FA with a small variation in their chemical composition (Table 1) were used.

LS was ground to a grain size below 125 µm using a vibrating disk mill Labor-Scheibenschwingmühle TS.250 (Siebtechnik GmbH, Mülheim an der Ruhr, Germany), while the FA was used as received. The sediments S10 and S1 were ground to pass a 90 µm sieve.

The activating solutions were prepared by mixing the Na-water glass (Geosil 34,417: 27.5 ma% SiO_2 and 16.9 ma% Na_2O) with 10 M NaOH or the K-water glass (Betol K 5020 T: 30.1 ma% SiO_2 and 18.5 ma% K_2O) with 10 M KOH. Both water glasses had a mass ratio of $SiO_2/M_2O = 1.63$ (where M represents Na and/or K), while the molar ratio was different, namely $SiO_2/M_2O = 1.68$ in Na-water glass and $SiO_2/M_2O = 2.55$ in K-water glass.

Optimal mixture was further improved by quick lime (QL; CL 90 S, InterCal).

2.2 Methods

The loss on ignition (LOI) of the precursors at 950 °C was determined according to SIST EN 196–2 (2013). The oxide compositions was determined by ARL PERFORM'X sequential X-ray fluorescence (XRF) Spectrometer (Thermo Fisher Scientific Inc., Ecublens, Switzerland) using the UniQuant 5 software (Thermo Fisher Scientific Inc., Walthem, MA, USA). The measurement was performed on fused beads, which were prepared by mixing the ignited sample with Fluxana (Li-tetraborate and Li-metaborat mixed in a mass ratio of 1:1) at a ratio of 1:10. To prevent gluing the melt to the Pt crucible some $LiBr_{(l)}$ (50 ml H_2O and 7.5 g of $LiBr_{(s)}$ from Sigma Aldrich) was added to the mixture before melting.

AAMs were produced by the reaction of precursors (Table 1) with a sodium silicate or potassium silicate solution. The prepared AAM mixtures are stated in Table 2. The activating solution was mixed with precursors to form a homogeneous paste, which was subsequently cast in silicone moulds (20×20×80 mm) and cured for 3 days at 60 °C and R.H. = 50%. After three days, the bending (σBS) and compressive (σCS) strengths were measured using a ToniPRAX (ToniTechnik, Berlin, Germany) at a force rate of 0.05 kN s^{-1}. The geometric density (ρ) has been also determined.

A mixture with 30 ma% FA was selected for further optimization of soil stabilization, as it showed the highest strength in laboratory tests.

The sediment from Lake Ptuj was tested to determine the geomechanical properties, including its initial moisture content—w (SIST EN 17892–1 2015), specific gravity—g_s, (SIST EN 17892–3 2016), liquid and plastic limits w_L, w_p (SIST EN 17892–12 2018), consistency Index (I_c) SIST EN 17892–12 (2018), particle size distribution (SIST EN 17892–4 2017) and permeability *k* (SIST EN 17892-11 2019). Strength properties were evaluated using the unconfined compression strength test (UCS) in accordance with SIST EN 13286–41 (2022). Compacted cylindrical samples with a diameter of 105 mm and a height of 115 mm were used for testing. The standard Proctor test (SPT) following SIST EN 13286–2 (2010) was employed to determine the optimum water content (w_{opt}) and the maximum dry density ($\rho_{d,max}$). For assessing shear resistance, the friction angle (ϕ) and cohesion (c) were determined as per SIST EN 17892–10, while the oedometer modulus (Eoed) was measured following SIST EN 17892–5 (2017). Furthermore, the California bearing ratio (CBR_1) was determined according to SIST EN 13286–47 (2022), and the bearing ratio of saturated samples (CBR_2) was calculated to estimate vertical swelling. The natural sediment (S1) was used for the furter mixtures withough sieving.

A Na-activated AAM mixture where FA replaced 30 ma% of S1 was further optimized for soil stabilization, using a new, large FA2 batch from the same provider (Table 1). The sediment with a water content of 43 ma% was used in all mixtures and pretreated with QL; one series of samples with 8 ma% of QL and the second with 4 ma% of QL which reduce the water content (Wu et al. 2022b). The used QL has a CaO purity > 90%. To obtain a homogeneous mixture, the wet sediments were mixed for 5 min in a 20-l Gostol

Table 2 Prepared AAM mixtures (g)

Sample designation	S10	S1	FA1	LS	Geosil 34417	Betol K5020 T	10 M NaOH	10 M KOH
pure S10 (Na)	100	-	-	-	55.0	-	17.5	-
S10-10FA (Na)	90	-	10	-	55.0	-	17.5	-
S10-20FA (Na)	80	-	20	-	55.0	-	17.5	-
S10-30FA (Na)	70	-	30	-	55.0	-	17.5	-
S10-10LS (Na)	90	-	-	10	55.0	-	17.5	-
S10-20LS (Na)	80	-	-	20	55.0	-	17.5	-
S10-30LS (Na)	70	-	-	30	55.0	-	17.5	-
pure S10 (K)	100	-	-	-	-	55.0	-	17.5
S10-10FA (K)	90	-	10	-	-	55.0	-	17.5
S10-20FA (K)	80	-	20	-	-	55.0	-	17.5
S10-30FA (K)	70	-	30	-	-	55.0	-	17.5
S10-10LS (K)	90	-	-	10	-	55.0	-	17.5
S10-20LS (K)	80	-	-	20	-	55.0	-	17.5
S10-30LS (K)	70	-	-	30	-	55.0	-	17.5
pure S1 (Na)	-	100	-	-	55.0	-	17.5	-
S1-10FA (Na)	-	90	10	-	55.0	-	17.5	-
S1-20FA (Na)	-	80	20	-	55.0	-	17.5	-
S1-30FA (Na)	-	70	30	-	55.0	-	17.5	-
S1-10LS (Na)	-	90	-	10	55.0	-	17.5	-
S1-20LS (Na)	-	80	-	20	55.0	-	17.5	-
S1-30LS (Na)	-	70	-	30	55.0	-	17.5	-
pure S1 (K)	-	100	-	-	-	55.0	-	17.5
S1-10FA (K)	-	90	10	-	-	55.0	-	17.5
S1-20FA (K)	-	80	20	-	-	55.0	-	17.5
S1-30FA (K)	-	70	30	-	-	55.0	-	17.5
S1-10LS (K)	-	90	-	10	-	55.0	-	17.5
S1-20LS (K)	-	80	-	20	-	55.0	-	17.5
S1-30LS (K)	-	70	-	30	-	55.0	-	17.5

planetary mixer, stored in plastic bags and placed in a controlled curing box at the temperature of 20 °C. After 1 h of curing, different quantities of activating solutions were added and mixed again for 5 min. After mixing material was compacted in 3 layers according to the standard SIST EN 13286–2 (2010), cured at 90% RH and 20 °C in a climatic chamber.

The UCS test was performed after 7 and 28 days of curing. The oedometer modulus and shear characteristics were tested after 1, 4 and 7 days of curing. The permeability was tested after 1, 4 and 7 days and $CBR_{1,2}$ after 7 days of curing. The mixtures and conditions stated in Table 3 were applied.

The FTIR spectra of hardened optimized AAM mixture after 1, 7, 28 and 55 days of reaction in the range from 380 cm^{-1} to 4000 cm^{-1} were collected with a resolution of 4 cm^{-1} using a PerkinElmer Spectrum Two in attenuated total reflection mode (Universal ATR with diamond/ZnSe crystal).

Potential changes of the mineralogical composition of the hardened, optimized AAM mixture after 1, 7, 28 and 55 days of the reaction were monitored by XRD analysis, using a PANalytical Empyrean X-ray diffractometer with CuKα radiation (wavelength CuKα1 1.54 Å). The X–ray tube was operated at 45 kV and 40 mA. Samples were measured from $2\theta = 4°$ to 70° while being spinned.

3 Results and discussion

3.1 Preliminary alkali activation test of sediments with additional slag or FA

The effect of replacing 10, 20 or 30 ma% of sediment S1 or S10 by FA or LS on the mechanical properties of the hardened AAMs was evaluated after 3 days of curing at 60 °C. As different SiO_2/M_2O molar ratios of the Na or K-activators were used, the influence of the alkali activator type is not discussed.

The results presented in Figs. 1 and 2 indicate that replacing sediments by both FA and LS improves the mechanical properties of AAMs. In general, the addition

Table 3 Prepared mixtures

Mixture designation	Sediment S1 (ma%)*	Precursor FA2 (ma%)	Quicklime content (ma%)*	Activator/Precursor $Na_2SiO_2 + NaOH$	NaOH/Precursor
S1	100		0		
S1-8QL	100		8		
S1-4QL-30FA2	70	30	4		
S1-8QL-30FA2	70	30	8		
S1-8QL-30FA2-1	70	30	8	1.00	12
S1-8QL-30FA2-2	70	30	8	0.75	8
S1-8QL-30FA2-3	70	30	8	037	4
S1-8QL-30FA2-4	70	30	8	0.25	3
S1-8QL-30FA2-5	70	30	8	0.15	3
S1-4QL-30FA2-1	70	30	4	1.00	12
S1-4QL-30FA2-2	70	30	4	0.75	8
S1-4QL-30FA2-3	70	30	4	0.37	4
S1-4QL-30FA2-4	70	30	4	0.25	3
S1-4QL-30FA2-5	70	30	4	0.15	3

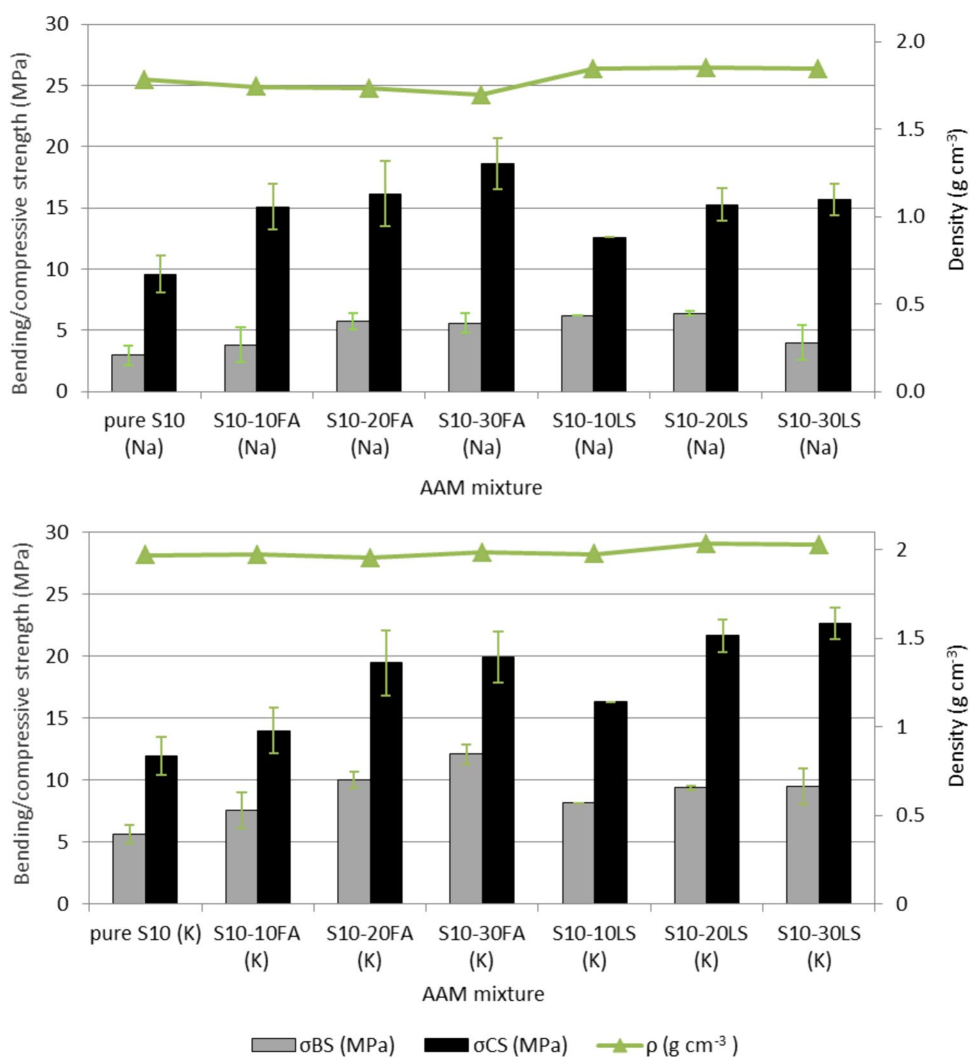


Fig. 1 Effects of FA and LS replacement of sediment S10 on the mechanical properties of AAMs, which were prepared using Na (**a**) or K (**b**) activators. Abbreviations: σBS – bending strength, σCS – compressive strength, ρ—density

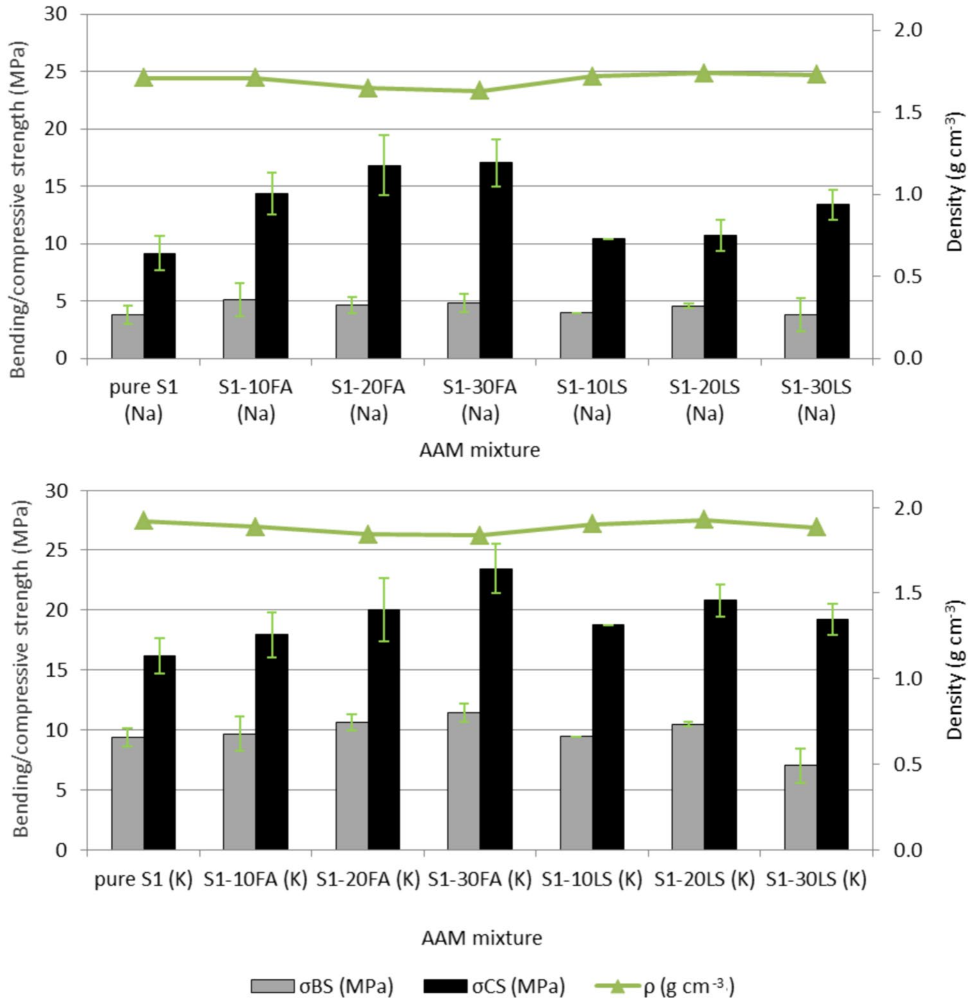


Fig. 2 Effects of FA and LS replacement of sediment S1 on the mechanical properties of AAMs, which were prepared using Na (**a**) or K (**b**) activators. Abbreviations: σBS – bending strength, σCS – compressive strength, ρ—density

of FA resulted in higher compressive/bending strengths and lower or comparable geometrical densities than when LS was added. The exception was the S10 sediment with LS and K-activators, where replacing sediment by LS resulted in slightly higher strengths than when FA was used (Fig. 1b). Similarly, the addition of LS in general improved the strength proportionally (Figs. 1 and 2), with the exception of the S1 sediment with LS and K-activators, where the bending and compressive strengths decreased after replacing 30 ma%. The incorporation of slags into alkali activated mortars provides additional Ca, which commonly results in formation of C-S–H gel and improved strength (Zheng et al. 2021; Žibret et al. 2023). However, high amounts of slags may induce cracking (Li et al. 2020) and consequently decreased strength. The formation of cracks accompanied by decreased strength at 30 ma% content of LS has been already documented in our previous study, which was focused on alkali activation of calcined Drava river sediments, accompanied by detailed microstructural investigations (Žibret et al. 2023). In AAMs from uncalcined Drava river sediments (this study) similar reaction mechanisms as when calcined sediments were used are expected. Calcination increased the reactivity of sediments (Žibret et al. 2023), which results in faster and more intensive polymerization reactions. The present study primary aimed to optimize the mixture, which showed the highest strength, for further soil stabilization applications.

The addition of FA proportionally improved the bending and compressive strength (Figs. 1 and 2). When the Na-activator was used, replacing 30 ma% of sediment by FA resulted in similar compressive strengths if S10 or S1 were the main precursor component, namely 18.6 MPa for S10 (Fig. 1a) and 17.1 MPa for S1 (Fig. 2a). Similarly, when the K-activator was used, compressive strengths after replacing 30 ma% FA were comparable, namely 19.9 MPa for S10 (Fig. 1b) and 19.2 MPa for S1 (Fig. 2b).

The compressive strength of the investigated mixtures was primarily determined in order to assess their potential suitability for use as “lean concrete” layers. Following the classification of concrete, the lean concrete achieved a compressive strength of at least 5 and less than 10 MPa (classes M5 and M7.5) after 28 days of curing under standard laboratory conditions.

In addition, the study aims to develop a new recipe for the in-situ stabilization of dredged river sediments that will meet the geomechanical criteria for the construction of anti-flood river embankment. In contrast to the laboratory tests where alkaline activation of dry precursors was conducted at 60 °C, on-site construction of a flood control dam would be exposed to outdoor atmospheric conditions, resulting in slower strength development and lower ultimate compressive strength (Bing-hui et al. 2014).

3.2 Optimizng mixtures for soil stabilization

River sediments are currently dredged from the bottom of lake Ptuj and deposited on its banks where they naturally dry. The moisture content of the deposited material depends on the drying time and weather conditions. Thus, the water content of material stored for at least 2 years is reduced to 40%, what has been determined when DEM obtained the Slovenian Technical Approval in 2022 for composites made from water sediments of Ptuj Lake for embankments and backfills without dynamic loads. The conducted laboratory tests confirmed that water content of the material stored for at least 2 years was reduced to around 40% (STS-22/0009 2022).

In addition, environmental legislation in this area is expected to tighten in the coming years, which means that the possible use of this material in geotechnical construction should be investigated. Based on the results obtained on the laboratory level (3.1), further optimization for soil stabilizaton were perfomed on sediment from Lake Ptuj (S1) and replacing it by only FA. The mixture S1-30FA(Na) was further tested for soil stabilization with different amounts of QL.

3.2.1 Geomechanical testing of the sediment

Sediment S1 was used for geomechanical testing. Due to the high water content of the naturally dried sediment (43 ma%), the geomechanical properties were insufficient (see Table 4) for using only naturaly dehydrated sediment in geotechnical structures such as road construction, embankments or even backfill layers. It should be emphasized that the term "water content" is used for the mass ratio of water and the dry material in geotechnical engineering.

3.2.2 Geomechanical testing of the stabilized sediment

The use of dredged sediment is very limited due to its high water content (Toda et al. 2020), but some dredged sediment can still be used in some specific hydraulic engineering projects (EcoShape 2023). However, the aim of the present work is to significantly improve the mechanical properties in order to further expand the potential use of sediment with otherwise limited applications. A sufficient stabilization could only be achieved by mixing the sediment with inorganic binders such as QL. The reaction time between the sediment and QL initiated about 1 h after mixing formed gelatinous products (Petry and Little 2002). The tests showed that at least 8 ma% of quicklime were needed for soil stabilization (Ducman et al. 2022). The use of inorganic binders, such as quicklime, for sediment stabilization is a common

Table 4 Physical and mechanical properties of the naturally dried sediment from lake Ptuj

Property	Value
Initial Moisture Content (w) (ma%) [1]	43.00
Specific Gravity (γs) (mg m-^{3})	2.69
Liquid Limit (w_L) (%)	49.10
Plastic Limit (w_P) (%)	41.90
Consistency Index (Ic) (-)	0.40
Particle Size Distribution:	
Particle (< 2.0 mm) (%)	90.00
Particle (< 0.063 mm) (%)	53.90
Particle (< 0.002 mm) (%)	3.80
Classification	mSi
Optimum Water Content—Standard Proctor Test (w_{opt}) (%)	29.50
Maximum Dry Density—Standard Proctor Test ($\rho_{d,max}$) (mg m-^{3})	1.33
Unconfined Composite Strength After Compaction (UCS) (MPa)	0.05
Eodometer Modulus (MPa)	2.55
Shear Resistance:	
Friction Angle (f') (°)	30.50
Cohesion (c') (kPa)	3
Permeability (m s^{-1}) load 200 kPa	2.60E-09
$CBR_{1,2}$	1.10/0.70

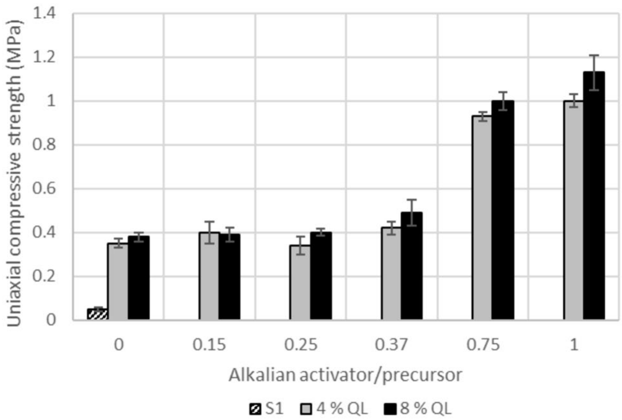


Fig. 3 Uniaxial compressive strength for mixture with 4 or 8 ma% of QL, 30 ma% of FA and different quantities of AA after 7 days of curing

practice in geotechnical engineering. QL, or calcium oxide (CaO), is known for its pozzolanic properties, which allow a reaction with water to form calcium hydroxide ($Ca(OH)_2$). This reaction leads to the development of cementitious properties, making it effective for soil stabilization (Hou and Al-Tabbaa 2018). The mixture successfully decreased the water content of the sediment, but the uniaxial compressive strength (UCS) was still inadequate for anti-flood embankment applications. According to new Slovenian technical requirements, the minimum uniaxial compressive strength is 0.50 MPa after 7 days of curing (TSPI PG.05.300, 2023). The UCS of the sediment (S1) was 0.05 MPa and 0.33 MPa for the mixture with 8 ma% of QL (Ducman et al. 2022) after 7 days of curing. Figure 3 shows that the UCS increased with respect to the precursor percentage and alkali activator (AA) binder. Similarly also Consoli et al. (2019) used mixure with 8 ma% lime and 25 ma% of FA to reach the optimum strength and durability.

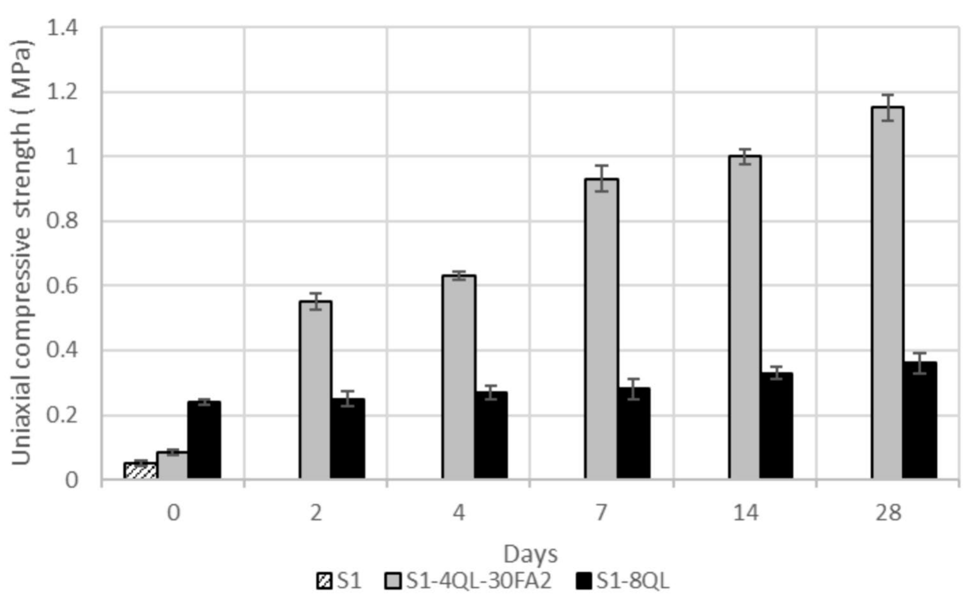
In comparison with the sediment the increase of UCS was 660% (4 ma% QL) to 720% (8 ma% QL). The uniaxial compressive strength was performed after 7 days of curing.

The UCS of samples pepared with QL (4 ma% or 8 ma%), 30 ma% of FA and a AA solution slightly increased with added AA solution (Fig. 3), but significantly increased when the ratio AA/precursor was 0.75 (S1-8QL-30FA2-2). The UCS with 4 ma% QL is 0.93 MPa and with 8 ma% of QL 1.06 MPa after 7 days of curing. UCS increased with 4 ma% of QL for more than 18 times and with 8 ma% of QL more than 21 times in comparison with the sediment (S1). A further augmentation of the AA binder quantity does not have a significant impact on the uniaxial compressive strength of the mixture. In comparison with the present research; dredged sediment with 15 ma% of portlant cement and 6 ma% of Na_2Si0_3 reached 0.22 MPa of UCS after 7 days (Lang and Chen 2021), but for a sediment with a higher initial water content (70 ma%). The UCS for dredged sediment with the same water content (45 ma%) was 0.55 MPa after 28 days with the composite of 15 ma% of cement, slag, calcium oxide, anhydrous sodium metasilicate, magnesium oxide and nanomodifiers (Lang and Chen 2021).

The mixture S1-4QL-30FA2 was used for further research with an AA/precursor ratio of 0.75. The percent of QL was reduced from 8 to 4. This mixture showed a high enough uniaxial compressive strength whereas the lower quantity of QL has a high influence on the final price of the composite and a lower environmental impact.

Stabilization with an AA solution increased the soil strength during curing (Toda et al. 2020). With time the UCS of S1-4QL-30FA2 rapidly increasing for the first 7 days (Fig. 4). After 28 days, the increase of the UCS is 24 times higher compared to the pure sediment. In comparison with the mixture S1-8QL, which used only 8 ma% of QL binder, the increase of UCS is 4 fould. The UCS of the

Fig. 4 Uniaxial compressive strength for the mixture S10-4QL-30FA2 and the mixture S10-8QL and sediment S10



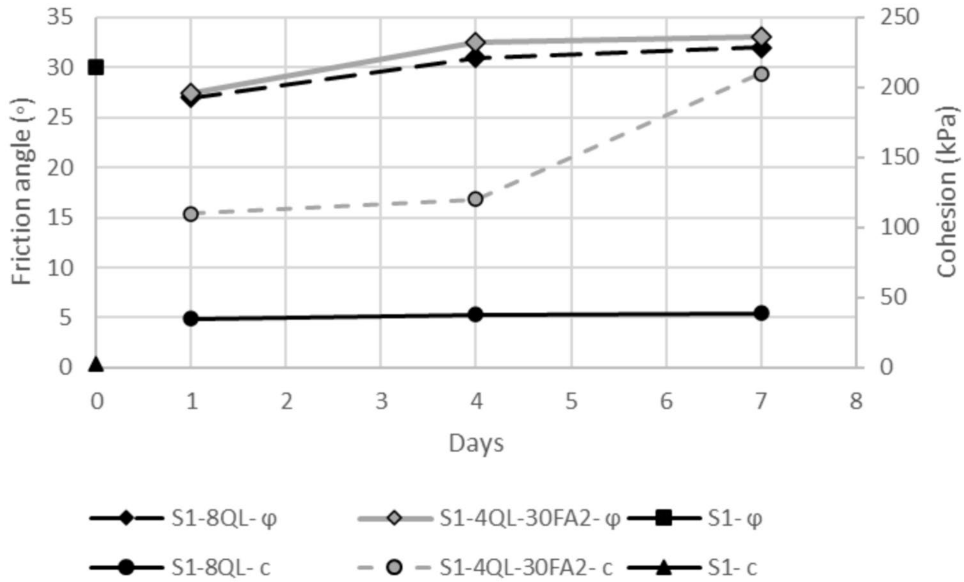


Fig. 5 Friction angle (ϕ) and cohesion (c`) for the mixture S1-4QL-30FA2, the mixture S1-8QL and sediment S10

optimized mixture S1-4QL-30FA2 after 28 days of curing was comparable with UCS reported in similar studies, where AA dredged sediments with FA were used for embankment materials (Dungca and Codilla 2018) or compressed earth blocks (Brahim et al. 2022). Similar values of 28 day UCS tests were reported also for alkali activated industrial kaolin clay with FA (Turan et al. 2022) and AA dredged sediments with a combination of GBFS and FA (Wang et al. 2023b). However, the mechanical properties of the AA materials are closely related to the chemical composition of precursor and activator and to the amount of the reactive amorphous phase. Due to different precursor origin and composition as well as activator type and concentration the UCS values of the aforementioned studies can be only roughly compared.

Shear properties of the mixture are characterised with the friction angle and cohesion (Fig. 5). Adding AAM into the sediment increased the shear properties in comparison with the sediment (Žurinskas et al. 2020). Results from the shear strength testing demonstrated that the AAM is the most effective when the amount of clay is at least 30 ma%. The contact zone between the AAM and clay forms a compact layer via cementitious hydration products. The friction angle increased only for a few degress in comparison with the sediment S1 and sediment with QL (S1-8QL). The opposite results were observed for the cohesion which were much higher for the mixture with AAM even after only one day of curing and it rapidly increased with time. After 7 days of curing, the cohesion was 6 times higher than the cohesion of a mixture with QL (S1-8QL). The cohesion of S1 was only 3 kPa.

The oedometer modulus showed a very low value for the sediment and a higher value for the mixture S1-8QL and the mixture with an AAM binder S1-4Q-30FA2 (Fig. 6). Even after 2 days of curing, the mixture S1-4Q-30FA2 had a higher eodometer modulus than the mixture with QL

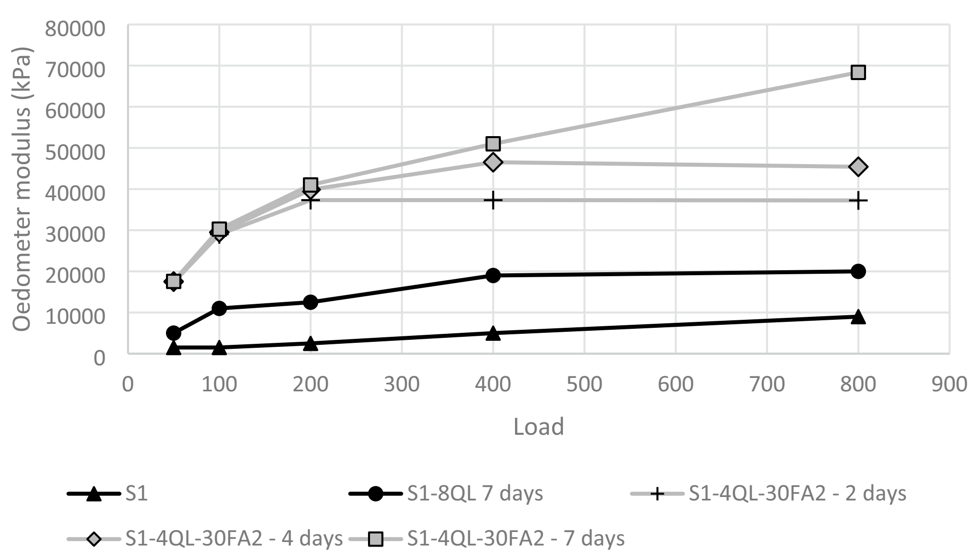


Fig. 6 Oedometer modulus for mixture S1-4QL-30FA2, the mixture S1-8QL and the sediment S1

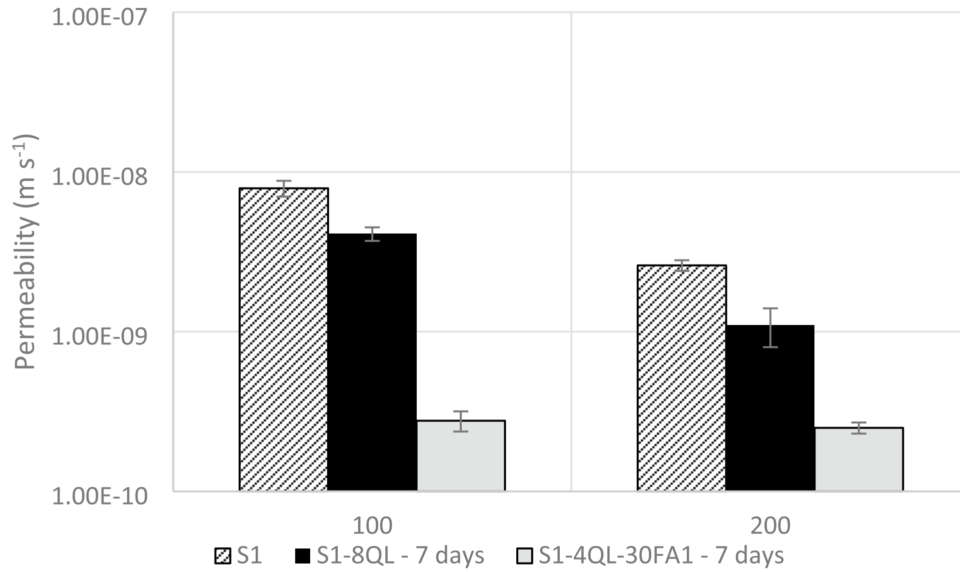


Fig. 7 Results of water permeability coefficient of the sediment (S1), the mixture S1-8QL and S1-4QL-30FA2

(S1-8QL). Under a load of 800 kPa, the oedometer modulus of mixture S1-4Q-30FA2 was 7 times higher that of the sediment (S1) and 3 times higher as the mixture S1-8QL with QL. The activator reduced the volumetric change of the sediment (Mavroulidou et al. 2022) and confirmed that the chemical substances from the waste material can successfully replace the traditional construction material.

The water permeability of the material is crucial in the construction of flood embankments; impermeable material prevents the passage of water, ensuring its stability and effectiveness in flood protection. If the material is permeable, water can seep through the embankment, causing erosion or even complete destruction of the embankment, leading to catastrophic floods (USSD 2011).

The permeability of the sediment is between 10^{-8} and 10^{-9} m s^{-1}, classifying it as a low permeability material (Fig. 7). The coefficient of water permeability depends on the load. With the addition of AAM, the mixture became impermeable ($k < 10^{-9}$ m s^{-1}) and after 7 days it was lowered for one order of magnitude in comparison with the sediment (S1) and mixture S1-8QL.

The California bearing ratio of the sediment (S1) was very low ($CBR_1 < 3\%$) and unsuitable for mechanical compaction (TSPI-P.05.200 2020). Materials suitable for compaction show a $CBR_1 > 25\%$ which was common for the both mixture (S1-4QL-30FA2 and S1-8QL). Mixture S1-4QL-30FA2 reached a CBR_1 of 60% and was 50% higher in comparison with the mixture S1-8QL (Fig. 8). The CBR_1 for the

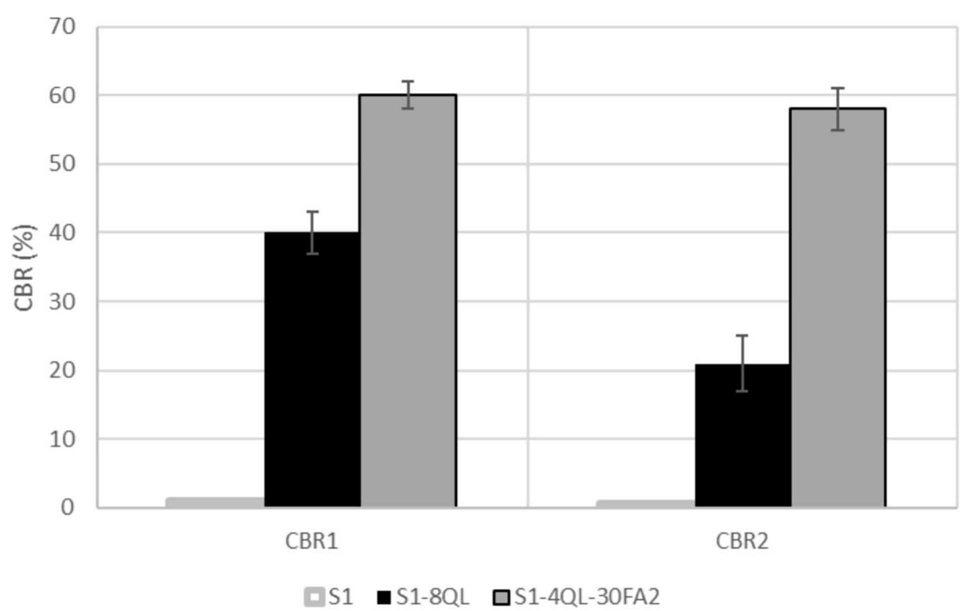


Fig. 8 Results of California bearing ratio (CBR1) and the bearing ratio of saturated samples (CBR2) of the mixtures S1-4QL-30FA2, the mixture S1-8QL and the sediment S1

Table 5 The properties of the sediement, mixture with 8 ma% of QL and mixture S1-4QL-30FA2 cured for 7 days

Mixture designation	Uniaxial compressive strength	Shear strength		Oedometer modulus	Permeability	CBR	
		Friction angle	Coheison			CBR1	CBR2
	Qu (MPa)	f' (°)	c' (kPa)	$E_{oed,200\ kPa}$ (MPa)	K_{200kPa} (m s^{-1})	%	%
S1	0.05	30.5	3	2500	2.60E-09	1.1	0.7
S1-8QL	0.30	32.0	39	12500	1.20E-09	40.0	21.0
S1-4QL-30FA2	0.93	33.0	210	41000	2.50E-10	60.0	58.0
Required value *	0,4*	32[a]	0[a]	> 20000[a]	< 1.00E-08[a]	> 25[b]	7*

*According TSPI 05.300

[a]Design requirements according to the Eurocode 7

[b]According to TSPI 05.200–2

sediment (S1) was only 1.1%. In order to determine CBR_2, the samples were saturated with water. The results indicate that water does not have a significant influence on the bearing capacity ratio of the S1-4QL-30FA2 mixture.

Results of the geomechanical testing of the sediment (S1), a mixture with 8 ma% of QL (S1-8QL) and a mixture with 4 ma% of QL and added AAM showed higher geomechanical properties for the last mixture with AAM (Table 5). The mixture S1-4QL-30FA2 had several times higher geomechanical properties in comparison with the sediment and higher properties in comparison with the mixture containing sedment and 8 ma% of QL. The geomechanical properties are sufficient for anti-flood construction (TSPI PG.05.300 2023) and the material is unpermeable, enableing a higher safety of the embankment.

3.2.3 Gel characterization by infrared (IR) spectroscopy

For the optimized mixture S1-4QL-30FA2, the degree of polymerization at 1, 7, 28 and 55 days of reaction was monitored using FTIR (Fig. 9). According to the infrared analysis of the undried sample stored in sealed plastic bag, the vibration of the H–O-H bonds was evident by a band with a minimum at around 1640 cm^{-1}, indicating unbound water molecules (García Lodeiro et al. 2010; Yusuf 2023). Due to the alkali activation of carbonate-rich illite clays a carbonate band was evident at around 1400 cm^{-1}, accompanied with a sholder at around 875 cm^{-1} (D'Elia et al. 2020). The broad band with a minimum between 955 and 975 cm^{-1} is associated with the asymmetric stretching of Si–O-T bonds (T = Si or Al) in AAM gel (García Lodeiro et al. 2010; Shi et al. 2011; Kalina et al. 2023). Increasing the reaction time shifted the values to lower wave numbers (Fig. 9), which most probably indicates a progressive depolymerization of silicate chains and a formation of a C-S–H gel (Hong and Glasser 2002; Criado et al. 2008; García Lodeiro et al. 2010), driven by Ca-rich phases (Coudert et al. 2019). The presence of the gel was further supported by the bending vibrations of Si–O-T bonds, appearing at around 520 cm^{-1} (Fig. 9) (Yusuf 2023).

The FTIR analysis was accompanied by XRD, which showed that no significant mineralogical changes occurred during 55 days of reaction (Supplement 1).

3.2.4 Environmental context and possible real world applications and implications

The study proposed an optimal lime-alkali activator binder for the stabilization of river dredged sediments with the aim of achieving sufficient mechanical properties for use

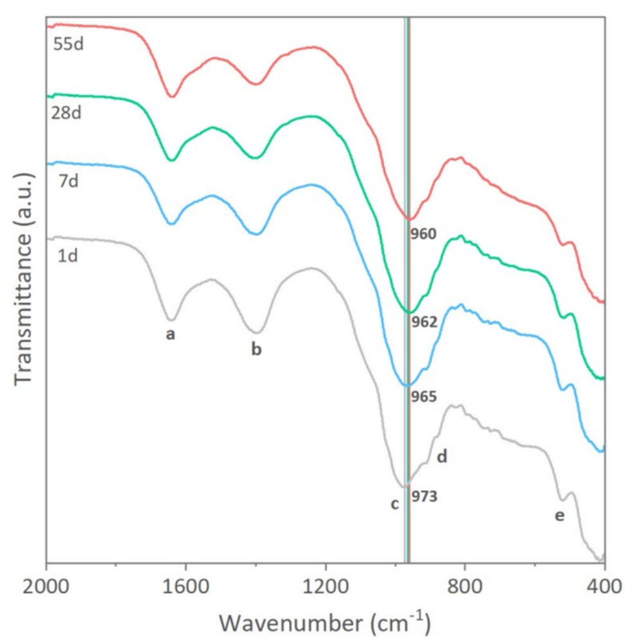


Fig. 9 FTIR spectra of the optimized mixture S1-4QL-30FA2 after 1, 7, 28 and 55 days of reaction. Characteristic bands are indicating: a – unbound water, b, d – carbonates, c,e – aluminosilicate gel

in flood embankment application and minimizing negative environmental impacts.

The amount of QL was reduced by 50% compared to previous blends and the precursor (FA) and alkali activator (AA) were added instead. Two types of AA were tested: potassium-based and sodium- based silicate solutions. It has been confirmed that a potassium silicate solution is better suited to achieve higher early strength, while a sodium silicate solution is better suited to achieve higher strength at a later age. Since early strength is important for industrial applications so that the concrete can be demoulded earlier and processed efficiently, it is crucial to combine the effects of technical performance with those of environmental impact during optimization. Based on the Environmental Cost Indicator (ECI) per m^3, the contribution of sodium-based activators appears to be lower than that of potassium-based activators (Fig. 6 of the cited reference), but a concrete mix with a combination of K-silicate and Na-silicate solutions shows the greatest potential to reduce the ECI. A mix using only Na-silicate and NaOH was identified as the mix with the second highest potential to reduce ECI (Firdous et al. 2022).

The resulting environmental benefits are related to the reduction of the CO_2 footprint, the decrease in energy consumption and the promotion of the circular economy. As lime production is one of the largest anthropogenic sources of CO_2 (Campo et al. 2021; Laveglia et al. 2022), the reduced use of QL in the mix can help to reduce the carbon footprint, which has been further limited by alkali activation (AA) of non-calcined river sediments, although AA usually requires calcination of clay-rich sediments at around 700–900 °C (Žibret et al. 2023). Reducing the lime content and avoiding calcination of sediments simultaneously contributed to lower energy consumption. A recent valorization of untreated dredged sediments as feedstock for AA has shown that AA reduces climate change impacts by 66% compared to OPC, including sediment beneficial recovery (Monteiro et al. 2024). Finally, the construction of flood protection dams by AA does not require on-site transportation and associated energy consumption and emissions, which is an important parameter in life cycle assessment (LCA) scenarios (Monteiro et al. 2024). The local alternative precursors such as dredged river sediments, can therefore effectively reduce the environmental costs of AAM and accelerate the industrial use of such materials (Monteiro et al. 2024).

In addition to improving mechanical properties (Gokul et al. 2021), alkaline activation of sediments can effectively immobilize potentially toxic elements (PTEs) (Komaei et al. 2023). The investigated Drava sediments show elevated Pb and Zn concentrations, which can be attributed to historical Pb/Zn ore mining in the upstream area (Šajn et al. 2011; Žibret et al. 2018). As elevated Pb/Zn concentrations have also been documented in urban rivers not associated with mining (Owens and Rutherford 2023), the presented approach of reusing river sediments with PTEs for on-site river dams could have great potential for widespread application. Further research will focus on the leaching and durability properties of the developed material, which are necessary for evaluating its future real-world application for anti-flood embankments.

In summary, it was confirmed that alkali activation can be used for soil stabilization as it provides uniaxial compressive strength values above 1 MPa after 28 days of reaction, which opens many possibilities to use this technology for embankments, capping layer below the road structure, anti-flood protections, stabilization of the foundation layers, etc.

4 Conclusions

Laboratory tests were performed with sediments dredged from the river Drava and FA slag, and Na- and K- activators were added in order to identified the most promissing mixture with regard to mechanical properties; the highest compressive strength was achieved by replacing sediment by 30 ma% of FA and using Na-water glass as the activator. The mixture was then further optimized for soil stabilization by a 4 ma% QL pretreatment.

Chemically enhanced ground improvement is gaining attraction in the civil engineering industry as a more sustainable alternative to traditional methods like relocating and landfilling unsuitable construction ground. However, the environmental impact of conventional soil stabilizers such as Portland cement or lime is a concern, leading to a global research effort focused on innovative cementing agents.

The geomechanical research showed that adding AAM to the mixture with the dredged sediment improved all tested geomechanical properties and thus enables sediment to be used for embankment of backfill. The QL improved the geomechanical properties of the dredged sediment, but it remains insufficient for anti-flood ambankments. For the optimal binder, the amount of the QL was decreased by 50% and the presursor (FA) and alkali activation (AA) binder was added instead. The final mixture had higher geomechancal property values and lower permeability values, which is desirable for anti-flood embankments. In relation to the initial sediment, the UCS increased to 23 fold, cohesion drastically increased from 3 to 210 kPa and the oedometer modulus at a load of 200 kPa increased to 16 fold. The generation of the C-S–H gel contributed to a denser and cemented sediment matrix. The procedure involving pretreating the sediment with a minor addition of QL, followed by a stabilization using AAM, yielded satisfactory geomechanical properties suitable for the construction of an anti-flood embankment.

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Data availability All final data can be provided by authors.

Declarations

Conflicts of interest The authors declare no conflict of interest.

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