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MODIFICATION OF SOIL SUBGRADE WITH RECYCLED CONCRETE FINES FOR REDUCED ENVIRONMENTAL IMPACT

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Abstract. Ukraine's transition towards an energy-efficient economy, in the context of integration into the European area, represents a complex yet highly significant challenge. The post-war recovery of the country requires comprehensive modernisation of infrastructure in line with the principles of sustainable development and the standards of the European Union. Particular attention is drawn to the road construction sector, one of the most resource-intensive branches of the construction industry. Its development must be fully aligned with the goals of the European Green Deal, which encompass the reduction of greenhouse gas emissions related to the extraction and processing of natural resources, the implementation of circular economy principles, the promotion of economic growth through the increased use of anthropogenic waste as an alternative to primary raw materials, the mitigation of environmental impact, and the active deployment of environmentally driven technologies (Natsionalna ekonomichna stratehiia, 2021). As a result of the full-scale war in Ukraine, substantial volumes of mineral waste have accumulated from destroyed buildings and infrastructure, posing a serious challenge to the national resource management system. The efficient recycling of concrete debris is a key condition for reducing the environmental burden on the natural environment. This article presents research findings on the stabilisation of clayey soil using mineral fines derived from processed waste concrete, with the aim of improving the physico-mechanical properties of the subgrade in road construction.

Keywords: circular economy, sustainable development, soil modification, concrete fines, modified Proctor test, shear strength.

1. Introduction

As a consequence of the widespread destruction of buildings and infrastructure in Ukraine, the amount of mineral waste has considerably increased, with reinforced concrete debris being the most prevalent form. The challenge of managing this waste stream has become particularly urgent in the context of restoring transport infrastructure. One of the promising strategies involves reusing concrete debris in the form of finely ground particulate material (concrete fines), which is produced during the mechanical crushing and sorting of demolition waste using specialised equipment.

In 2018, the United States reported the production of nearly 600 million tonnes of building and demolition-related waste. On a global scale, the annual volume of such waste exceeds 3 billion tonnes, constituting approximately 30–40 % of total waste generated worldwide (Kaptan et al., 2024). Within the European Union, the amount reached around 38.4 million tonnes in 2020, while China exceeded

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1.5 billion tonnes (Bonifazi et al., 2025). This vast magnitude, along with the accelerating trend – from 50 million tonnes in 1980 to 600 million tonnes by 2018 in the US – highlights the pressing challenges associated with waste handling and disposal.

In Ukraine, comprehensive nationwide statistics remain limited; however, an upward tendency in building and demolition-related waste has been repeatedly noted in municipal and institutional reports, especially in connection with post-war reconstruction efforts. Tracking the quantity of such materials is essential for advancing sustainable development and for designing coherent national strategies on waste regulation and management.

Recycled concrete fines have emerged as a promising material for improving soil properties. Research indicates that such fines can stimulate hydration processes, reduce swelling potential, and enhance strength characteristics. In particular, the use of fine fractions for modifying structurally unstable soils has proven effective: they function as a mineral filler, diminishing deformability and contributing to increased mechanical strength.

The use of recycled concrete fines as a mineral modifier for improving soil properties in road earthworks supports circular resource strategies and promotes environmentally oriented construction practices. However, despite their considerable potential, there is currently a lack of systematic data on the effects of concrete fines on the physico-mechanical properties of clayey soils, particularly loams (Mark et al., 2016).

In this context, the aim of the present study is to evaluate the effectiveness of recycled concrete fines as a mineral additive for the modification of loam characterised by high plasticity and susceptibility to deformation. The research methodology includes a detailed evaluation of the particle size distribution and mineralogical characteristics of the recycled concrete fines, as well as the results of laboratory testing of the modified soil.

2. Theoretical part

The extensive destruction of civil and industrial infrastructure in Ukraine, resulting from the full-scale military aggression by the rf, has caused the generation of vast amounts of construction-related waste. A significant portion of this debris comprises reinforced concrete elements (Antoniuk & Kostiuk, 2024; UNDP Ukraine, 2023). To address this situation, the international initiative S3RoU – Safe, Sustainable and Swift Reconstruction of Ukraine – has launched the development of mobile technologies for sorting, crushing, and reusing construction debris, with the goal of ensuring its environmentally safe processing (S3RoU Project description, 2024).

One of the potentially valuable outputs of concrete recycling is concrete fines – the finest fraction formed as a result of mechanical disintegration of concrete, which may include particles of cement paste, quartz, and granite-origin minerals, along with residual hydrated compounds (Fan et al., 2016). Although recycled aggregates have received considerable attention, concrete fines still represent a relatively underutilised material in civil engineering applications.

Owing to their fine particle size, potential residual hydraulic reactivity, and the occasional presence of calcite or carbonation-derived phases, recycled concrete fines may demonstrate characteristics of a mineral activator or modifying agent (Pasquier et al., 2018). These properties create opportunities for their application in improving the structure of clayey soils − especially under conditions of accelerated road infrastructure renewal. The present study focuses on a laboratory-based investigation into the potential of such fines as a stabilising component for roadbed materials, contributing to the implementation of circular economy principles during post-war reconstruction efforts.

Structurally unstable soils are characterised by volume changes resulting from moisture fluctuations, often necessitating reinforcement or improvement measures to address deformation caused by swelling and contraction. Owing to their high plasticity, such soils contribute to premature damage of road pavements during wetting and drying cycles. Moisture variations lead to a reduction in the density and strength of the soil subgrade, which in turn causes shear deformations, depressions, and cracking in the upper layers of the pavement structure. These defects significantly reduce the load-bearing capacity of the soil and increase maintenance and reconstruction costs.

To mitigate common failures related to the deterioration of strength characteristics in moisture-sensitive plastic soils, a variety of stabilisation techniques have been adopted. Among them, cement is frequently applied alongside other binders, including ground granulated blast furnace slag (GGBS), lime, fly ash, silica fume, and various industrial by-products (Novytskyi et al., 2023; Leon et al., 2023 a). The synergistic effect of these mixtures has demonstrated greater efficiency in enhancing soil strength compared to the use of natural aggregates alone.

An alternative approach involves the use of fine fractions of construction and demolition concrete waste generated during the crushing of structural debris (Ujile & Abbey, 2022). Due to the residual content of chemically active phases within the cementitious matrix, these materials can improve the structure and strength of clayey soils while reducing plasticity and swelling potential. Depending on their mineralogical composition, recycled concrete fines may partially replace cement–especially when activated–thereby contributing to a lo wer carbon footprint in construction. Previous studies indicate that the use of such activated materials can achieve strength levels comparable to those obtained with natural aggregates or cement, while ensuring environmentally sustainable reuse of waste.

Research confirms that fine-grained components derived from construction and demolition residues can markedly influence the mechanical behaviour of soils (Singh et al., 2017). Particles under 1.18 mm in size – especially those finer than 0.425 mm – demonstrate a high capacity to occupy voids in clayey matrices, thus promoting improved packing density and structural uniformity after compaction. This leads to lower moisture sensitivity and enhances both shear and compressive strength characteristics.

According to the USCS and ASTM D2487 classification systems, the particle size range for fines is defined as 0.475–0.075 mm. Particles smaller than 0.425 mm demonstrate the greatest technical potential, as they can not only improve compaction but also participate in pozzolanic reactions, provided that the mineralogical composition is suitable. Fines of this size contribute to: enhanced compaction and reduced void ratio; more uniform mixing of clayey soils with cement and other mineral additives; and the formation of a dense microscale environment around soil grains

In addition, screened recycled concrete fines are the most common fractions in concrete waste streams, particularly as a r esult of rapid urbanisation. These fractions are often compared to natural sands or limestone-based powders for their function in concrete or soil stabilisation systems. As a result, fine fractions of concrete waste can be used as an alternative mineral binder (if potentially hydraulically active phases are present) for soil stabilisation or as a partial replacement for cement in construction mortars, reducing the need for primary raw materials.

The hydraulic reactivity of recycled concrete fines is not guaranteed – it is determined by the phase composition rather than particle size or oxide content. Some dust fractions may be predominantly inert (e.g., quartz-based), in which case alternative stabilization strategies become more appropriate, such as mechanical, combined, or alkali activation methods. Recycled concrete fines typically contain a wide range of oxides, including silica (SiO_2), calcium (CaO), aluminum (Al_2O_3), iron (Fe_2O_3), among others. Their actual impact on soil stabilisation largely depends on their mineralogical and phase composition, which governs the material's reactivity (Kerni et al., 2015). In certain samples, a noticeable presence of active phases (e.g., residual Portlantide or unhydrated cement clinker minerals) has been observed, which may participate in hydration or pozzolanic reactions. In such cases, fractions <150 μm have the potential to partially replace conventional binders. However, not all fines exhibit chemical activity. For instance, those dominated by quartz, or other magmatic rock minerals usually display low reactivity, where the primary effect lies in densification and improvement of the soil's grain structure.

In fractions containing carbonates (e.g. calcite), reactivity can be formed under conditions of subsequent alkaline or thermal activation. This suggests the possibility of applying such materials in combination with chemical activators (e.g., lime, sodium hydroxide, ash), particularly for modifying clayey soils (Zhao et al., 2019). Thus, the effectiveness of recycled concrete fines as a stabilising agent is not universal and requires prior chemical and mineralogical assessment. In the absence of hydraulic reactivity, using such fines as an inert filler is considered effective, as it contributes to improved compaction, reduced porosity, and modified capillary behaviour within the soil matrix. Research evidence indicates that mineral fines obtained from construction waste can facilitate better packing of plastic soils by occupying pore spaces. As a r esult, the compacted mixture exhibits higher density, greater mechanical integrity, and increased stiffness. Additionally, these fines help minimise subgrade deformations and enhance the structural stability of the base layer against uneven settlement. Therefore, the use of recycled concrete fines dominated by crystalline, highly stable minerals is consistent with the approach of National Standard of Ukraine 8801:2018 (DSTU 8801:2018, 2018): such materials are employed as a granulometric additive–modifier to improve the grain-size structure of plastic soils; where required, stabilisation with traditional binders may be applied as a subsequent step (Bridgemohan et al., 2023).

In general, the effectiveness of recycled concrete fines as a stabiliser is largely determined by the combination of particle size distribution and mineralogical structure. Careful fractional preparation and, if necessary, additional activation (alkaline, thermal) allow such materials to be used to improve the mechanical properties of clayey plastic soils.

3. Materials and Methods

Materials. A clayey soil was selected for the study. To evaluate its physical properties, a particle size distribution analysis was conducted following the ISO standard 17892-4:2023 (ISO 17892-4:2023, 2023), and the Atterberg limits were determined following ISO 17892-12:2018 (ISO 17892-10:2018, 2018). The results of these tests are presented in Tables 1 and 2, respectively.

Table 1

Physical parameters of the investigated soil

Atterberg limits			particle density ρ_s (g/cm^3)
LL (%)	PL (%)	PI (%)	
38	21	17	2.72

Table 2

Particle size distribution of the study soil

Name of parameter	Sieve analysis								Sedimentation analysis	
Size of sieve holes, mm	2	1	0.5	0.25	0.1	0.08	0.071	0.063	0.063– 0.002	<0.002
Fraction content, A %	–	–	–	–	3.52	16.63	2.92	7.57	47.14	22.22
Total content of particles	Sand								silt	clay
	30.64								47.14	22.22

The soil's classification based on particle size distribution was determined using the Feret classification triangle (Fig. 1), as adopted in international standards. According to its granulometric composition, the soil was classified as a loam.

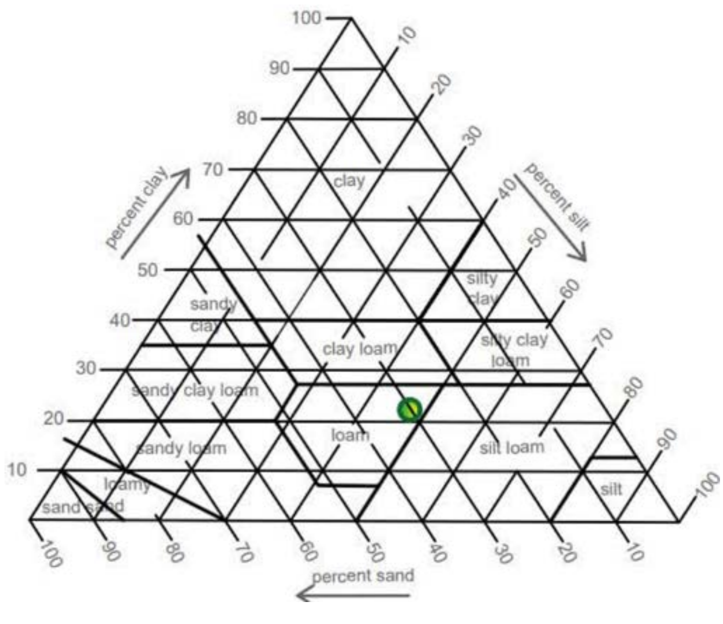


Fig. 1. Soil type identified through grain size analysis

The qualitative phase composition of the loam (Fig. 2 and 3) was determined using X-ray diffraction (XRD) analysis. The diffractometer operated under the following conditions: current (I) = 12 mA, voltage (U) = 30 kV, and scanning speed = 2°/min. The method sensitivity was up to 1 %. The quantitative analysis of mineral composition was performed using Profex software, which utilises the JCPDS database to match calculated phase patterns with the experimental X-ray diffraction data as accurately as possible.

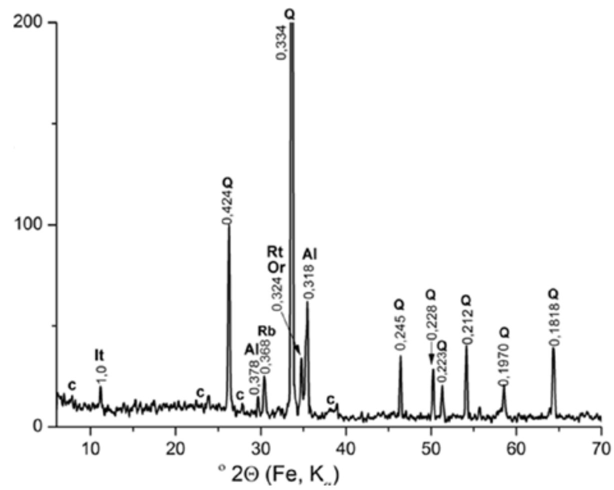


Fig. 2. XRD pattern of sandy-silty loam fraction:

Q – Quartz; It – Illite;
Al – Albite; Or – Orthoclase;
Rt – rutile; Rb – $RbHSO_4$

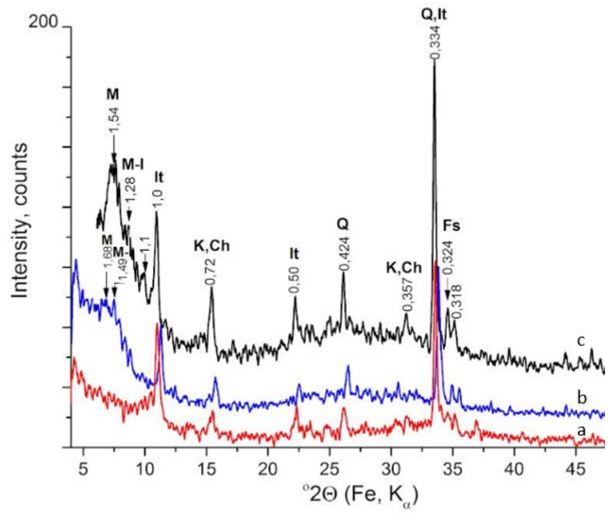


Fig. 3. XRD pattern of clay loam fraction
(*a* – air–dry; *b* – saturated with ethylene glycol;
c – heated at 500 °C): M – Montmorillonite; M–I – Mixed-Illite–Montmorillonite; It – Illite; K – Kaolinite;
Ch – Chlorite; Q – Quartz, Fs Feldspars

Table 3

Distribution of particle sizes in recycled concrete fines

Sieve analysis												
Size of sieve holes, mm	10	5	2.5	1.6	0.63	0.5	0.315	0.14	0.08	0.071	0.063	<0.063 (Silt)
Fraction content, A %	–	0.05	0.69	0.05	0.95	0.19	2.66	50.47	29.80	1.12	4.04	9.99
Total content of particles < Ai, %	100.1	99.96	99.27	99.22	98.27	98.08	95.42	44.95	15.15	14.03	9.99	–

Recycled concrete fines are the finest mineral fraction generated during the industrial crushing and dry screening of concrete rubble from demolished buildings at specialized construction-and-demolition waste recycling plants (Circular Concrete (S3RoU). Analysis of texture by particle size was also performed for the recycled concrete fines (Table 3), and the corresponding granulometric curve was plotted (Fig. 4). The concrete fines predominantly consist of fine particles, with over 50 % passing through the 0.14 mm sieve, corresponding to ultra-fine sand, and nearly 10 % classified as silt, indicating a relatively high content of fine dust fractions.

The uniformity coefficient (U = 3.05) suggests a narrow particle size range, which is typical for poorly graded mineral materials (U < 4). The curvature coefficient (Cc ≈ 1.0) indicates an approximately symmetric distribution of grain sizes centred around the average diameter − a trait often observed in crushed mineral residues with consistent fractional composition.

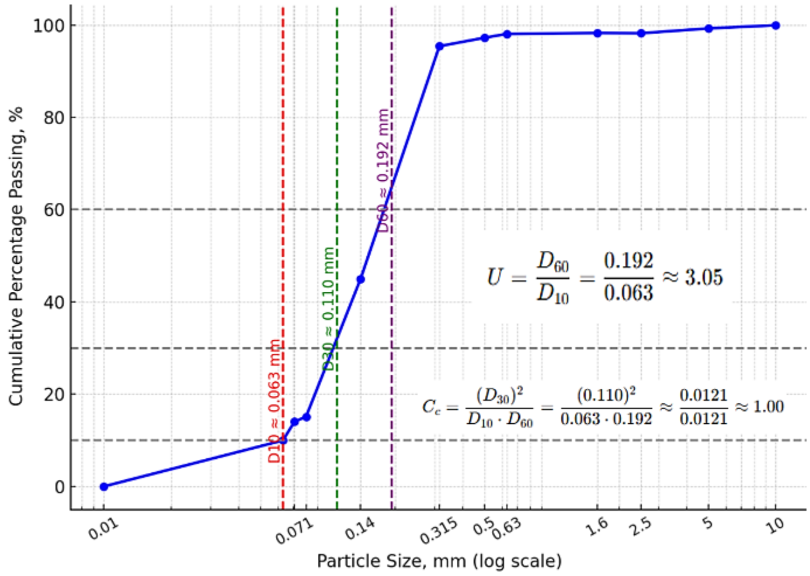


Fig. 4. Grain size distribution diagram
of concrete fines indicating D10, D30, and D60 values

Fig. 5 illustrates the phase composition, which plays a key role in evaluating the properties and potential applications of man-made mineral materials. Given the qualitative and quantitative (Table 4) mineralogical composition (quartz/feldspars) identified by XRD, concrete fines are treated herein as a mineral modifier of plastic soils.

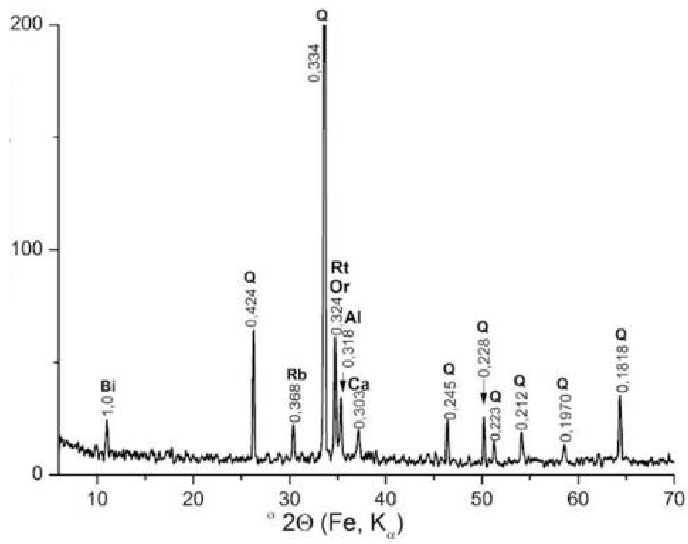


Fig. 5. XRD pattern of Recycled Concrete Fines:
Q – quartz (SiO_2); Ca – calcite ($CaCO_3$); Bi – biotite; Al – albite;
Or – orthoclase; Rt – rutile; Rb – $RbHSO_4$

Table 4

The quantitative mineral content of Concrete Fines

Mineral term	Quartz (SiO_2)	Albite ($NaAlSi2O_8$)	Rutile (TiO_2)	Orthoclase ($KAlSi2O_8$)	Calcite ($CaCO_3$)	Biotite $[K(Fe,Mg)_2 (AlSi_3O_{10})(OH)_2]$	Rubidium hydrogen sulfate ($RbHSO_4$)
Percentage content, %	74	8	5	4	4	2	3

The Circular Concrete / S3RoU project (Circular Concrete (S3RoU), 2025) uses input screening and sorting, including portable rapid field survey methods to identify recyclable rubble, distinguish between normal and alkali-activated concrete, and detect asbestos fibres.

General methods. Loam and concrete particles were mixed in an air-dried state at a specified proportion. The components of the mixture were moistened to the optimal water content, which was determined using the modified Proctor test (EN 13286-2:2010, 2010). To assess the structural stability of the mixture, linear shrinkage tests under natural drying conditions were performed (DSTU B A.1.1-54:94, 1994). Changes in mechanical properties and shear resistance of the modified soil were determined through laboratory direct shear tests (ISO 17892-10:2018, 2018).

4. Results and Discussion

As part of the present study, it was determined that the powdered mineral material obtained by crushing waste concrete in Ukraine predominantly exhibits a cr ystalline structure. The primary constituents are quartz (approximately 74 %) and feldspar group minerals (including orthoclase and albite), derived from coarse-grained granite aggregates. A smaller proportion of calcite (~4 %) is also present. This mineralogical profile indicates limited chemical reactivity under hydration conditions, thereby significantly reducing the potential for activation through thermal or chemical means.

Quartz, in particular, is thermodynamically stable and exhibits chemical inertness within the alkaline environment. Its solubility under standard conditions is extremely low, which prevents it from engaging in hydration processes – even when chemical activators are introduced. Feldspar minerals, being crystalline aluminosilicates, also demonstrate poor solubility in alkaline solutions, and thermal treatment at 600–800 °C does not facilitate the generation of reactive or amorphous phases. Within this system, calcite serves primarily as a pH buffering agent rather than a reactive component.

Although activating these materials is theoretically feasible, it often demands significant energy and material inputs, while resulting in only marginal gains in reactivity. As emphasised in the open letter by RILEM TC UMW, the potential for activating mineral residues should be evaluated with respect to their phase composition, chemical characteristics, and overall reactivity profile (Peys et al., 2025). For crystalline systems with inherently low reactivity – such as mixtures dominated by quartz and feldspar – alternative utilisation strategies may be more practical and efficient.

Recycled concrete fines are characterised by a narrow particle size distribution (U < 4), indicating poor grading. Morphologically, the material consists of fine crystalline particles within the sand–silt size range. XRD analysis confirms the presence of quartz, albite, orthoclase, calcite, biotite, and rutile — all of which are mineral phases with low hydraulic reactivity that primarily serve as inert fillers. These components reduce the plasticity of the soil by physically “diluting” clay minerals. The performance of concrete fines as a mechanical additive could be further improved if the grain size spectrum included a greater proportion of coarse particles and was more evenly graded. Coarser fractions (2–0.5 mm) contribute more effectively to forming a stable granular framework that absorbs shear deformation and enhances the bearing capacity of the soil mass.

Recycled concrete fines represent crystalline materials composed of minerals of magmatic origin, notable for their high physicochemical stability, which accounts for their inert behaviour under typical soil conditions. Within modification systems, these minerals do not engage in chemical bonding, but instead form a structural scaffold that contributes to the mechanical performance of the soil matrix. Therefore, even without active chemical interaction, such materials can serve a valuable technical function in soil improvement applications.

One of the principal indicators used to determine the applicability of modified soil blends in road and water infrastructure projects is the linear shrinkage index measured under air-drying conditions (Leon et al., 2023 b; Venkatarama Reddy & Latha, 2014; Biswal et al., 2019). This parameter reflects the capacity of the material to retain its geometric integrity as it loses moisture. If shrinkage exceeds acceptable thresholds, it can result in surface cracking, detachment from structural components, and compromise of the base’s monolithic behaviour. Observing linear shrinkage behaviour facilitates the analysis of deformation tendencies in the soil composition (Fig. 6), which is essential for anticipating risks under service conditions.

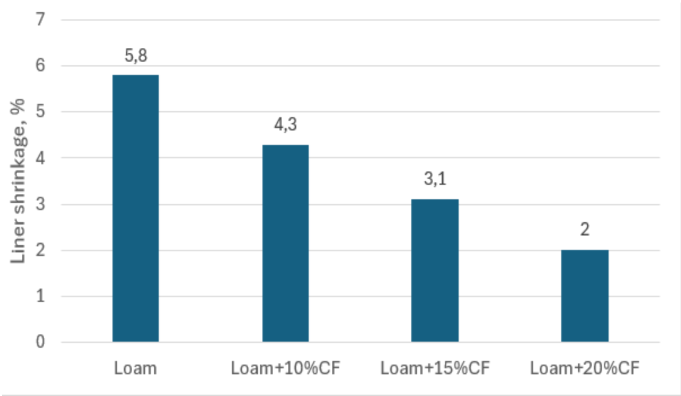


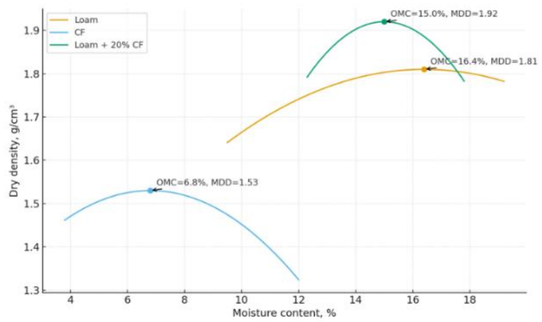
Fig. 6. Effect of concrete fines content on the linear shrinkage of loam after air-drying

Linear shrinkage was evaluated using the standardised method, which calculates the relative change in specimen length following natural drying. This metric reflects the material's susceptibility to deformation due to moisture loss. The resulting values provide insight into the structural integrity of the modified mix under air-drying conditions, aligning with applicable technical standards. When the shrinkage exceeds 4 %, there is an increased likelihood of cracking and non-uniform settlement, indicating that the subgrade may require optimisation − such as increasing binder dosage or adjusting the grain size composition of added mineral agents. Conversely, shrinkage within 2 % is generally regarded as acceptable and reflects adequate structural performance of the soil.

Linear shrinkage is reduced from 5.8 % to 2.0 % when loam is partially replaced with recycled concrete fines. This effect is attributed to several mechanisms: (1) the dilution of the clay fraction through the addition of stable, non-reactive mineral constituents such as quartz and feldspars; and (2) the development of a fine-grained internal framework formed by silt-sized magmatic particles, which helps restrain shrinkage during the drying process. Despite the absence of coarser sand fractions, the inclusion of 20 % recycled fines effectively lowers shrinkage, primarily due to the structural contribution of rigid mineral components that reinforce the integrity of the compacted mixture.

Linear-shrinkage tests showed that a content of 10–15 % concrete fines is insufficient to ensure the structural stability of the soil. Linear shrinkage under natural air-drying is defined as the relative deformation of the soil specimen, and values ≤ 2 % are considered acceptable. A content of 20 % concrete fines meets this requirement, yielding linear shrinkage within the specified limit.

To evaluate the impact of soil modification and to establish optimal compaction parameters for road base layers, the use of the Modified Proctor Test is considered appropriate. This method involves laboratory determination of the maximum dry density of soil at its optimum moisture content under elevated compaction energy. It is particularly suited for base materials where increased load-bearing performance is required and is conducted in accordance with established testing protocols (Leon, 2024; Connelly et al., 2008; Duque et al., 2020). According to the experimental findings (Fig. 7), replacing 20 % of loam with concrete fines (CF) results in higher maximum dry density and a shift in optimum moisture content toward lower values.



Laboratory test report (LOAM)					
Moisture content, %	10	15,2	**16,4**	17,4	18,8
Bulk density, ρ g/cm^3	1,85	2,03	**2,11**	2,09	2,01
Dry density, ρd g/cm^3	1,68	1,76	**1,81**	1,75	1,7

Laboratory test report CF					
Moisture content, %	4,4	5,2	**6,8**	7,14	11,5
Bulk density, ρ g/cm^3	1,5	1,56	**1,63**	1,6	1,53
Dry density, ρd g/cm^3	1,43	1,48	**1,53**	1,49	1,38

Laboratory test report (Loam+20%CF)					
Moisture content, %	13	13,8	**15**	16,7	17,1
Bulk density, ρ g/cm^3	2,05	2,08	**2,21**	2,22	2,2
Dry density, ρd g/cm^3	1,81	1,83	**1,92**	1,9	1,88

Fig. 7. Results of Modified Proctor Test

This behaviour is associated with the microstructural influence of fine mineral particles, which enhance packing by occupying the voids between clay aggregates and improve the overall compactability of the mixture. At the same time, the overall water demand of the mixture declines as a result of the low moisture affinity and chemical inertness of the recycled concrete fines. This behaviour leads to a measurable decrease in optimum moisture content. Additionally, the reduction in the clayey dispersed fraction contributes to lower plasticity and a more favourable particle arrangement, which together enhance the mechanical performance of the compacted material.

In laboratory conditions, shear strength was evaluated by means of the direct shear test. Specimens were formed by compressing samples (previously compacted in the Proctor test) into metal shear rings. Testing was carried out using single-plane shear apparatuses with a movable upper section, where displacement occurred along a horizontal interface. The soil underwent consolidated-drained loading: following full saturation and vertical load stabilisation, a horizontal force was gradually applied. The onset of shearing was identified at the point when the upper section shifted 5 mm relative to the lower box. This method enables the determination of soil cohesive strength and internal friction angle − essential parameters for subgrade stability assessment. The procedure was conducted under vertical loads of 0.1, 0.2, and 0.3 MPa. Table 5 presents statistical estimates derived from peak shear stress values.

Table 5

Mechanical parameters calculated based on direct shear testing

Loam		Vertical pressure 0.1 MPa	Vertical pressure 0.2 MPa	Vertical pressure 0.3 MPa
		Shear stresses τ, MPa		
Minimum value		0.090	0.140	0.190
Maximum value		0.095	0.150	0.210
Average value		0.093	0.145	0.200
		cohesive strength (c), MPa	tan *φ* (internal friction angle)	Internal friction angle, *φ* (degrees)
Normative value		0.037	0.56	29
Calculated values at a given confidence level	0.85	0.032	0.54	28
	0.95	0.029	0.52	28
Loam+ Concrete Fines (20 %)		Vertical pressure 0.1 MPa	Vertical pressure 0.2 MPa	Vertical pressure 0.3 MPa
		Shear stresses τ, MPa		
Minimum value		0.100	0.160	0.210
Maximum value		0.105	0.190	0.270
Average value		0.103	0.175	0.240
		cohesive strength (c), MPa	tan *φ* (internal friction angle)	Internal friction angle, *φ* (degrees)
Normative value		0.033	0.71	35
Calculated values at a given confidence level	0.85	0.024	0.67	34
	0.95	0.019	0.64	33

Data presented in Table 5 demonstrate that incorporating 20 % concrete fines into loam results in enhanced shear performance. The modified soil shows elevated shear stress values across all applied vertical loads, along with an increase in internal friction angle from 28° to 35° (within standard normative limits), suggesting improved particle interlocking. A slight reduction in cohesion is also observed, which is presumably linked to the lower influence of the clay fraction in the overall mixture (El Hariri et al., 2023; Stefanow & Dudziński, 2021; Sharma et al., 2012). The observed improvement in shear characteristics is linked to the densified structure of the modified soil, which contributes to greater interparticle friction. The slight decrease in cohesion can be explained by the reduced presence of clay components, which typically ensure binding in plastic soils. Nevertheless, based on Coulomb's equation ($\tau = c + \sigma \cdot \tan \varphi$), an increase in the internal friction angle (φ) can still result in higher overall shear resistance (τ) under specific vertical stresses (σ) (Fig. 8). These findings confirm the suitability of recycled concrete fines as an effective mineral additive for loam modification.

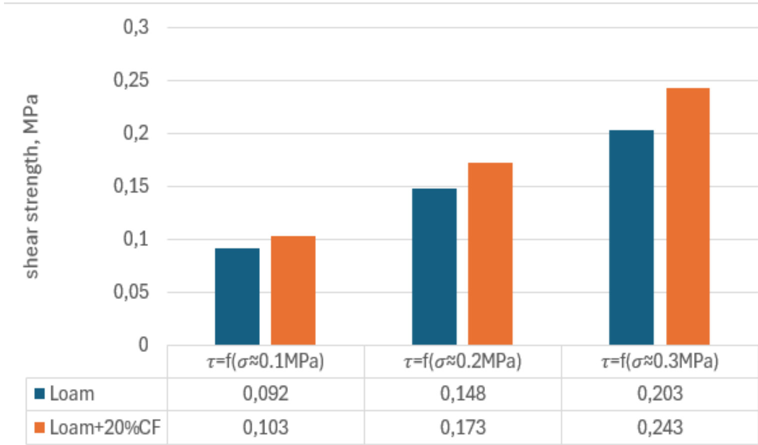


Fig. 8. Shear strength of loam and loam with 20% at different vertical stresses

5. Conclusions

Recycled concrete fines with a p redominant particle size below 0.14 mm, derived from crushed reinforced concrete waste in Ukraine, consist mainly of crystalline phases such as quartz and feldspar. Concrete fines adjust the grain-size distribution of the loam, dilute the clay fraction, improve compaction under the (Modified) Proctor test, and reduce linear shrinkage. It was established that a loam with PI ≈ 17 modified with 20 % recycled concrete fines exhibits improved physico-mechanical properties compared to the natural loam. The CF reduce linear shrinkage under natural air-drying from 5.8 % (natural loam) to 2.0 % (modified loam). Compaction parameters (Modified Proctor) improve: for the natural loam OMC = 16.4 %, MDD = 1.81 g/cm³; for the modified loam OMC = 15.0 %, MDD = 1 .92 g/cm³. Direct shear tests indicate an increase in the internal friction angle from 28° to up to 35°. The overall shear resistance of the loam with 20 % CF increases on average by ~10–20 % across all levels of normal stress (0.1, 0.2, 0.3 MPa). These results confirm that recycled concrete fine fractions can be used as an effective mineral modifier to improve the physical and mechanical properties of loam and can be considered a prerequisite for high-quality soil stabilisation with the formation of frost- and water-resistant material.

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