

Sustainable soil stabilisation using recycled concrete fines for resource recovery from construction and demolition waste: A Ukrainian case study

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ABSTRACT

The accumulation of construction and demolition waste requires resource-efficient and scalable solutions based on the principles of the circular economy and the use of low-carbon materials. This study investigated the effectiveness of the integrated application of recycled concrete fines (RCF) in the stabilisation of two soil types differing in their particle size distribution and mineralogical composition. RCF was utilised as a granulometric correction material, a microfiller, and a component of a low-carbon slag binder. The positive effect of co-grinding ground granulated blast furnace slag (GGBFS) with 20 wt.% RCF on the microstructure development and mechanical properties of the low-carbon slag binder for soil stabilisation was demonstrated. The compaction characteristics determined using the Modified Proctor test, mechanical properties, water resistance, freeze–thaw resistance, and phase formation of soils stabilised with a reference mixture containing 10 wt.% Portland cement (PC) and the developed low-carbon slag binder were investigated. A differentiated approach to the application of RCF depending on the soil particle size distribution was substantiated. RCF in the fine sand fraction proved to be the most effective for highly plastic soils, whereas ground RCF with a specific surface area of 3000 cm²/g was the most effective microfiller for soils with a higher sand content and a lower clay fraction. The developed low-carbon slag binder was shown to enable the effective partial replacement of PC in soil stabilisation. Furthermore, the mineralogical composition of the soil was found to govern the phase formation processes in stabilised soils. The obtained results confirm the potential of the integrated use of RCF and the developed low-carbon slag binder for resource-efficient soil stabilisation and the recycling of construction and demolition waste in geotechnical engineering.

Keywords: construction and demolition waste, circular economy, recycled concrete fines, soil stabilisation, ground granulated blast furnace slag, low-carbon slag binder.

INTRODUCTION

Construction and demolition waste (CDW) is one of the largest waste streams worldwide and represents a major environmental challenge. In the European Union, CDW accounts for more than one-third of the total waste generated, with concrete, bricks, asphalt, and other mineral materials comprising a substantial proportion. These materials have considerable potential for reuse and recycling (European Commission, 2025). Despite their significant resource potential, recycling efficiency varies considerably among countries, highlighting

the need to develop technologies and approaches that maximise resource recovery and enable the production of higher value-added materials.

The construction industry remains one of the largest consumers of natural resources and one of the major sources of anthropogenic environmental impact. According to the United Nations Environment Programme (UNEP, 2025), buildings and the construction sector are responsible for approximately 32% of global energy consumption and 34% of global CO₂ emissions, a substantial proportion of which is associated with the production of construction materials, particularly cement and steel.

In response to these challenges, the international community has identified circular construction, the implementation of low-carbon materials, improved resource efficiency, and material reuse as key pathways towards the decarbonisation of the construction industry. Current international strategies emphasise not only the development of innovative technologies but also the need for their large-scale implementation to achieve a tangible environmental impact (Mikulėnas and Šeduikytė, 2025; Zhang et al., 2026).

The construction and demolition sector is one of the major contributors to environmental degradation. Approximately 2–3 billion tonnes of CDW are generated worldwide each year, accounting for 25–30% of the total annual waste generation. Despite an estimated reuse and recycling potential of 91.25%, only 22.44% of CDW is currently recycled, highlighting a substantial untapped resource and the need to develop and widely implement scalable technological solutions for its high-value utilisation (Sakthibala, 2025).

Among contemporary approaches, particular attention is being paid to technologies that not only enable waste recycling but also maximise the preservation and utilisation of its resource potential by transforming secondary raw materials into high-performance materials with higher added value. Such solutions are fully aligned with the principles of resource efficiency and the circular economy, which are now recognised as strategic priorities for the sustainable development of the global construction industry (Mayer, 2024; Hoxha and Birgisdottir, 2025).

In Ukraine, the challenge of effective construction and demolition waste management has become particularly acute following the onset of the full-scale Russian invasion. The extensive destruction of residential, industrial, and transport infrastructure has resulted in the unprecedented accumulation of construction and demolition waste, creating an urgent need to develop and implement effective waste management strategies based on the principles of the circular economy, resource efficiency, and the reuse of secondary mineral resources to support the country's post-war reconstruction.

According to the KSE Institute, as of November 2024, the total direct damage to Ukraine's infrastructure was estimated at nearly USD 170 billion, of which approximately USD 60 billion was attributed to the housing sector.

Overall, around 236,000 residential buildings were damaged or destroyed, including 209,000 detached houses, 27,000 apartment buildings, and 600 dormitories. The total area of damaged or destroyed housing was estimated at approximately 90 million m², representing about 9% of Ukraine's total residential building stock (Andriienko et al., 2025; Romanenko et al., 2025).

According to the recommendations of the National Institute for Strategic Studies, war-related waste requires the urgent adaptation of Ukraine's regulatory framework through its official inclusion in the National Waste List and the Waste Classification Procedure, harmonised with European legislation (Directive 2008/98/EC). The recommendations also emphasise the need to establish strategic mechanisms for the safe recycling and large-scale reuse of these materials as secondary raw resources during Ukraine's post-war reconstruction in accordance with the principles of the green circular economy (Ivaniuta, 2023; Drebot et al., 2024).

Materials generated as a result of military hostilities should not be regarded as ordinary construction waste but rather as a specific category of potentially hazardous waste contaminated with toxic substances, including heavy metals, dust, asbestos, and residues of explosive ordnance. Consequently, their direct disposal or uncontrolled landfilling is environmentally unacceptable because it poses a long-term risk of soil and groundwater contamination. An environmentally sound approach involves the establishment of dedicated temporary storage sites combined with systematic stepwise sorting. This strategy not only mitigates environmental risks but also enables a substantial proportion of concrete and brick debris (up to 60%) to be recovered for high-quality recycling and subsequent use in post-war reconstruction (Sorochynska, 2026; Shyshkin et al., 2023).

Road construction is one of the largest consumers of natural mineral resources, particularly sand, gravel, and crushed stone. The construction of pavement structures, especially base and subbase layers, requires substantial quantities of mineral aggregates, resulting in intensive quarrying, depletion of natural resources, and additional environmental impacts (Fanijo et al., 2023; Khan et al., 2024). At present, the primary application of recycled concrete aggregate (RCA) is the replacement of natural aggregates in pavement base and subbase layers. Numerous studies have demonstrated

that, following appropriate processing, RCA provides mechanical performance that satisfies the requirements for pavement base materials while simultaneously reducing the consumption of virgin mineral aggregates and the volume of waste sent to landfill (Aytekin and Mardani-Aghabaglou, 2022; Nwakaire et al., 2020).

Considerably less attention has been paid to the reuse of recycled concrete fines (RCF) in road construction, despite their generation in substantial quantities and their potential to serve as a valuable component of an integrated strategy for the recovery and utilisation of construction and demolition waste in geotechnical engineering. Soil stabilisation is one of the key areas of geotechnical engineering, providing an effective means of improving the bearing capacity and long-term durability of pavement structures. Despite this considerable potential, the application of RCF in soil stabilisation remains insufficiently investigated (Raini et al., 2023; Ibrahim et al., 2025).

The use of recycled concrete fines has attracted increasing research interest owing to their multifaceted effects on soil behaviour. Fine concrete particles act as highly effective microfillers. By optimising the particle size distribution and increasing the packing density, the incorporation of RCF promotes the filling of micropores within the soil matrix, thereby reducing its porosity and permeability (Wang et al., 2024; Zhao et al., 2023). This is accompanied by a significant reduction in the plasticity index (PI) and the swelling potential of highly plastic or expansive soils. Furthermore, the physical interaction between RCF particles and the soil skeleton improves compaction characteristics, increases the California Bearing Ratio (CBR), and enhances shear strength (Ahmed et al., 2024; Islam et al., 2023).

In addition to improving the physical and mechanical properties of soils, several studies have reported the residual hydraulic and self-cementing activity of RCF in soil systems. Nevertheless, RCF generally exhibits limited intrinsic reactivity, and its contribution to microstructural development depends on the composition of the parent concrete, the degree of crushing, and the conditions of its interaction with the soil. The potential hydraulic activity of RCF is primarily attributed to the presence of unhydrated or partially hydrated clinker grains retained in the old cement paste, particularly dicalcium

silicate (C_2S) and tricalcium silicate (C_3S), which continue to hydrate upon renewed contact with water, forming additional calcium silicate hydrate ($C-S-H$). A further contribution may arise from pozzolanic reactions between reactive silica- and aluminosilicate-bearing components of the soil and calcium hydroxide ($Ca(OH)_2$) present in the residual cement paste (Ujile and Abbey, 2022; Yang et al., 2019).

An effective strategy involves combining RCF with conventional binders, such as Portland cement and lime, as well as low-carbon cementitious materials, including ground granulated blast furnace slag (GGBFS) and fly ash. Such combinations provide the alkaline environment required to activate reactive aluminosilicate phases and promote the formation of cementitious hydration products, thereby enhancing the mechanical performance of stabilised soils while simultaneously reducing the carbon footprint (Sanei et al., 2022; Biswas et al., 2025).

Based on the literature review presented above, the objective of this study was to evaluate the effectiveness of the integrated application of RCF in soil stabilisation as a granulometric correction material, a microfiller, and a component of a low-carbon slag binder using two soil types with different particle size distributions and mineralogical compositions as case studies.

MATERIALS AND METHODS

Materials

Soils

Two soil types with different particle size distributions and mineralogical compositions were selected to evaluate the effectiveness of RCF in soil systems with contrasting initial characteristics. The physical properties of the soils were characterised by determining their particle size distribution in accordance with ISO 17892-4:2023 and their Atterberg limits in accordance with ISO 17892-12:2018. The particle size distribution results are presented as bar charts, while soil classification based on the sand, silt, and clay fractions was performed using the USDA Soil Texture Triangle (Figure 1). The Atterberg limits are summarised in Table 1.

Although both soils were classified as Silt Loam according to the USDA Soil Texture

Triangle, they differed markedly in the proportions of sand, silt, and clay fractions. In particular, Silt Loam 2 contained almost twice as much sand (33.9% vs. 17.1%) and a substantially lower clay content (9.3% vs. 22.7%) than Silt Loam 1. These differences are expected to significantly influence particle packing, water retention capacity, permeability, and the reactivity of the soil system during stabilisation. Therefore, the investigation of two soils belonging to the same textural class but differing in their particle size distribution made it possible to evaluate the influence of granulometry on the effectiveness of RCF as a material for particle size optimisation and the development of a denser soil matrix.

In addition to particle size distribution, the mineralogical composition of the soils was considered an important parameter in evaluating the performance of the proposed low-carbon slag binder in comparison with conventional Portland cement. The phase composition of the untreated soils was determined by X-ray diffraction (XRD) analysis, and the obtained results were subsequently used to interpret the microstructural development and phase formation processes in the stabilised soil systems. XRD measurements were performed using an operating current of 12 mA and a voltage of 30 kV, with a scanning rate of 2° min^{-1} . The detection limit of the method was approximately 1%.

For a more detailed mineralogical characterisation, Silt Loam 1 was separated into a sand–silt fraction (Figure 2, A) and a clay fraction (Figure 2, B), and XRD analysis was performed separately for each fraction.

XRD analysis showed that the mineralogical composition of Silt Loam 2 (Figure 3) was dominated by quartz, calcite, and feldspars.

Recycled concrete fines (RCF)

The RCF used in this study consisted of the finest thermally treated fraction recovered from construction and demolition waste (Sustainable and Swift Reconstruction of Ukraine, 2026). Prior to processing, the concrete waste was inspected to ensure the absence of asbestos-containing and alkali-activated materials. Following verification, the CDW was sorted, subjected to primary crushing, and mechanically separated using an advanced dry recovery (ADR) system into three product streams: coarse aggregate (4–16 mm), sand (1–4 mm), and a fine fraction (<1 mm). The fine fraction was subsequently thermally treated in a Heated Air System (HAS) at approximately 500 °C to remove bound moisture and undesirable impurities. The thermally treated fine fraction obtained from the HAS process was used as RCF throughout this study.

The particle size distribution of the RCF, determined by sieve analysis, is presented in Table 2.

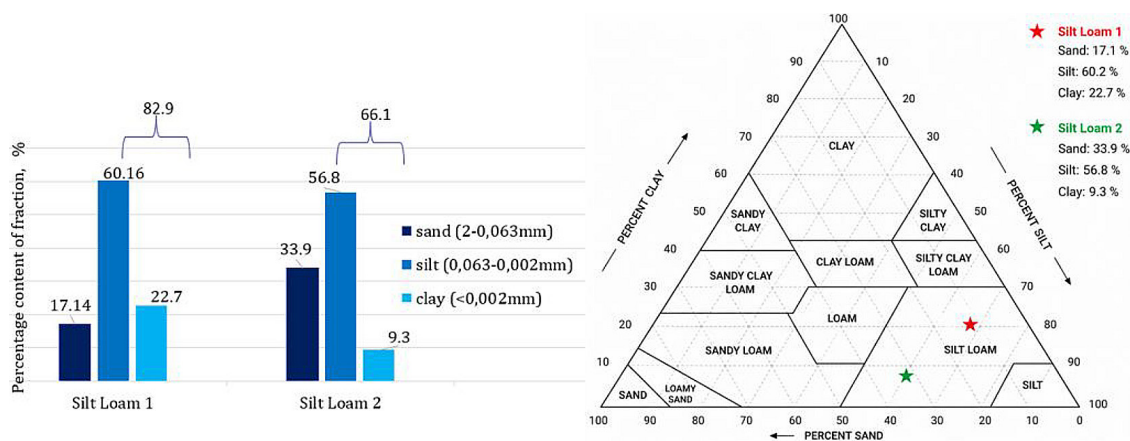


Figure 1. Particle-size distribution and textural classification of the investigated soils

Table 1. Physical properties of study soils

Soil type	Atterberg limits			Particle density (g/cm ³)	Plasticity characteristics
	LL (%)	PL(%)	PI(%)		
Silt Loam 1	33	18	15	2.79	Moderately plasticity
Silt Loam 2	18.2	14.4	3.8	2.62	Low plasticity

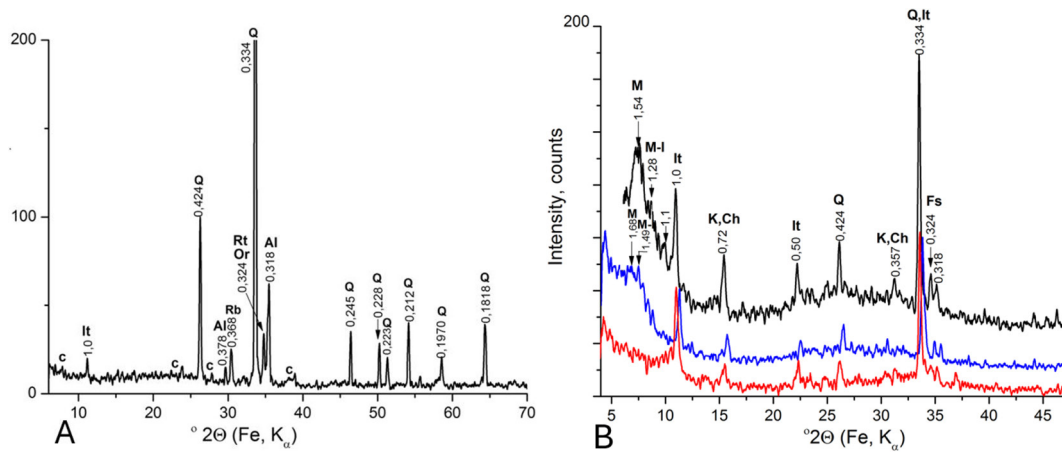


Figure 2. XRD patterns of the sandy-silty (A) and clay (B) fractions separated from Silt Loam 1. Q – Quartz; Al – Albite; Or – Orthoclase; Rt – rutile; Rb – RbHSO₄ M – Montmorillonite, M-I – Mixed- Illite–Montmorillonite, It – Illite, K – Kaolinite, Ch – Chlorite, Fs – Feldspars (Plagioclase)

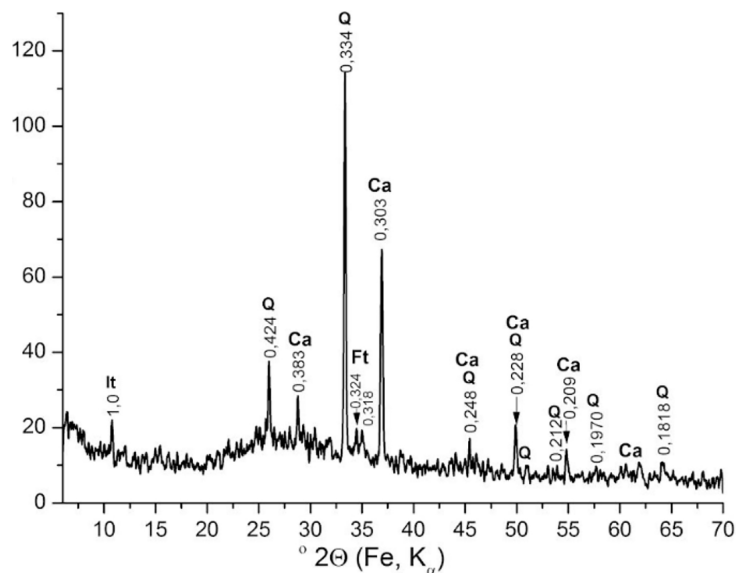


Figure 3. XRD pattern of Silt Loam 2 soil. Q – quartz; Ca – calcite; It – Illite; Ft – feldspars (albite, orthoclase)

The results showed that the two RCF batches, produced during different production periods, exhibited very similar particle size distributions. The dominant fraction was 0.08–0.14 mm, accounting for 80.27 wt.% of RCF1 and 84.49 wt.% of RCF2. This particle size range corresponds to the very fine sand fraction. The content of particles smaller than 0.063 mm (pan fraction) was also similar for both batches, amounting to 9.99 wt.% and 9.16 wt.%, respectively, indicating good reproducibility of the particle size distribution of the material produced at different times.

Based on the results of the sieve analysis, cumulative particle size distribution curves were constructed for the two RCF batches (Figure 4).

Both curves exhibited nearly identical profiles, indicating the high reproducibility of the particle size distribution of the material produced at different times. Minor differences were observed only within the very fine sand size range, whereas the overall particle size distribution remained virtually unchanged.

The XRD patterns of the two RCF batches are presented in Figure 5. The mineralogical composition of RCF was dominated by quartz and feldspars (albite and orthoclase), with a minor amount of calcite. Quantitative phase analysis was performed using Profex software based on Rietveld refinement with reference patterns from the JCPDS database, providing the best fit to the

Table 2. Particle size distribution of RCF obtained at different sampling periods

Sieve size, mm	Fraction content, %		Cumulative content of particles < d _i , %	
	RCF 1	RCF 2	RCF 1	RCF 2
10	-	-	100,10	100
5	0.05	0.30	99.96	99.70
2.5	0.69	0.10	99.27	99.60
1.6	0,05	-	99.22	99.60
1.25	-	0.15	99.22	99.45
0.63	0.95	0.07	98.27	99.38
0.5	0.19	0.08	98.08	99.3
0.315	2.66	4.69	95.42	94.61
0.14	50.47	55.94	44.95	38.67
0.08	29.80	28.55	15.15	10.12
0.071	1.12	0.08	14,03	10.04
0.063	4,04	0.88	9,99	9.16
Pan (<0.063)	9,99	9.16	-	-

Note: RCF 1 – sampled during the second half of 2025; RCF 2 – sampled during the first half of 2026.

experimental XRD data. The quantitative phase composition is summarised in Table 3.

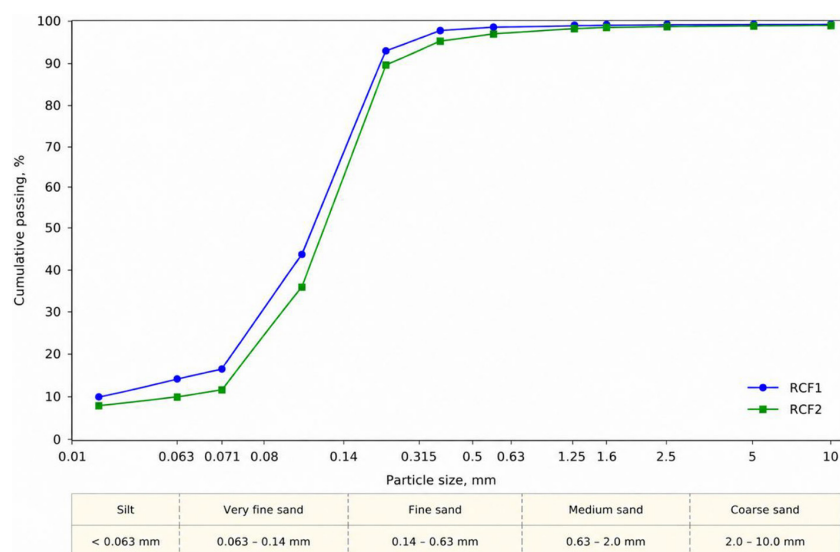
A low-carbon slag binder

Based on the concept of sulfate–alkali activation of ground granulated blast furnace slag (GGBFS), a low-carbon slag binder (SB) was developed for use as a supplementary binder in combination with Portland cement. The principal component of SB was amorphous GGBFS, while phosphogypsum (PG) was used as the sulfate activator (Table 4). Hydrated lime (HL), class CL 90-Q according to EN 459-1, was used as the alkali activator.

XRD analysis of phosphogypsum (PG) was performed to determine its mineralogical composition (Figure 6). The results showed that the principal crystalline phases of PG were gypsum (Gp, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and ardéalite (Ar, $\text{CaSO}_4(\text{PO}_4\text{OH}) \cdot 4\text{H}_2\text{O}$), together with minor amounts of phosphorus-bearing phases (P) and brushite (Br).

Methods

Differential thermal analysis (DTA) was performed on the low-carbon slag binder. The

**Figure 4.** Grain size distribution curves for RCF 1 and RCF 2

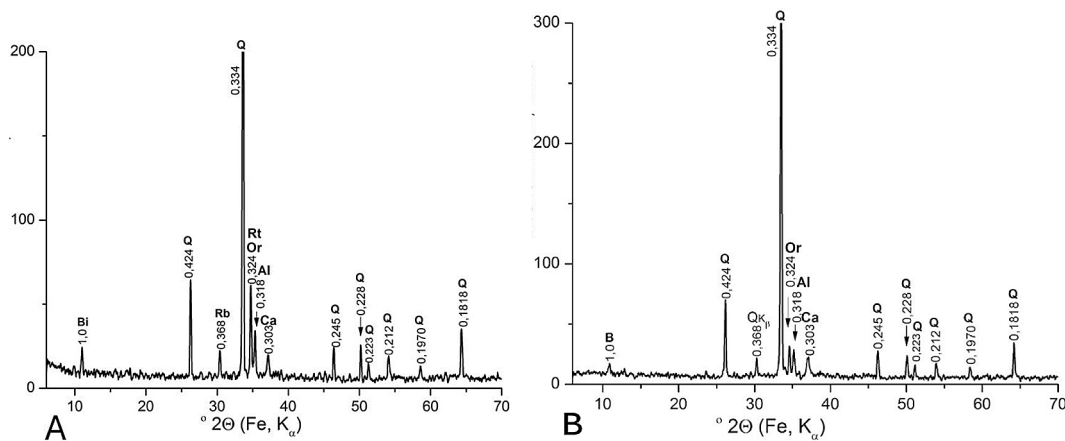


Figure 5. XRD pattern of RCF 1 (A) and RCF 2 (B). Q – quartz (SiO_2), Ca – calcite (CaCO_3), Bi – biotite, Al – albite, Or – orthoclase; Rt – rutile; Rb – RbHSO_4

Table 3. The quantitative mineral content of RCF 1

Mineral term	Quartz (SiO_2)	Albite ($\text{NaAlSi}_3\text{O}_8$)	Rutile (TiO_2)	Orthoclase (KAlSi_3O_8)	Calcite (CaCO_3)	Biotite [$\text{K}(\text{Fe,Mg})_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$]	Rubidium hydrogen sulfate (RbHSO_4)
Percentage content, %	74	8	5	4	4	2	3

Table 4. Chemical composition and specific surface area of raw materials used for preparation of the low-carbon slag binder (SB)

Oxide / Property	GGBFS, wt. %	PG, wt. %
CaO	48.10	38.03
SiO_2	37.18	2.78
Al_2O_3	5.80	0.34
SO_3	3.60	58.03
MgO	3.56	–
K_2O	0.65	0.25
Fe_2O_3	0.48	0.07
TiO_2	0.30	–
SrO	0.16	0.29
MnO	0.15	–
ZrO_2	0.03	0.01
Specific surface area, cm^2/g	3150	2130

samples were heated from 25 to 1000 °C at a heating rate of 10 °C/min under an air atmosphere.

Modified Proctor compaction tests were performed in accordance with CEN/TS 13286-54:2014 to determine the optimum moisture content (OMC) and maximum dry density (MDD) of the investigated soil mixtures.

Cylindrical specimens ($\varnothing 50 \times 50$ mm) of the cement-stabilised soils were prepared by the axial compression method in accordance with

EN 13286-53:2004, Unbound and hydraulically bound mixtures – Part 53: Methods for the manufacture of test specimens of hydraulically bound mixtures using axial compression.

The unconfined compressive strength (UCS) and water resistance coefficient of the stabilized soil mixtures were determined in accordance with 14227-15:2015 Hydraulically Bound Mixtures – Part 15: Hydraulically Stabilized Soils.

Freeze–thaw resistance was evaluated according to CEN/TS 13286-54:2014 Unbound and Hydraulically Bound Mixtures – Part 54: Test Method for the Determination of Frost Susceptibility.

Experimental methodology

Figure 7 illustrates the experimental methodology adopted in this study. The proposed concept for the utilisation of RCF was developed based on its mineralogical composition. XRD analysis showed that RCF batches produced at different times were composed predominantly of minerals of igneous origin, namely quartz, orthoclase, and albite. These minerals are characterised by high melting temperatures, excellent chemical resistance to acidic and alkaline environments, and a highly stable crystalline structure. This mineralogical composition is consistent with the widespread use of crushed igneous rocks, particularly granite and rhyolite, as concrete aggregates in

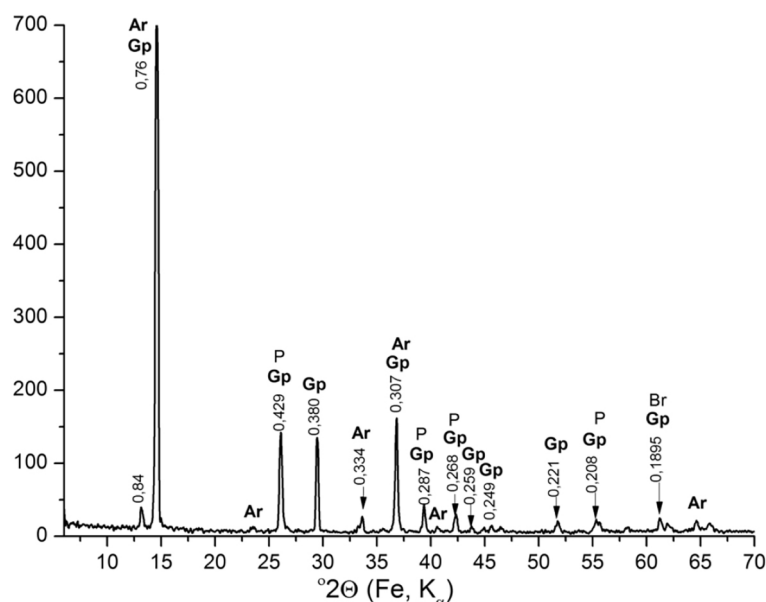


Figure 6. X-ray diffraction pattern of the phosphogypsum. Mineral abbreviations: Gp – gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$); Ar – ardealite ($\text{CaSO}_4(\text{PO}_4\text{OH}) \cdot 4\text{H}_2\text{O}$); P – phosphorus oxide (P_2O_5); Br – brushite ($\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$)

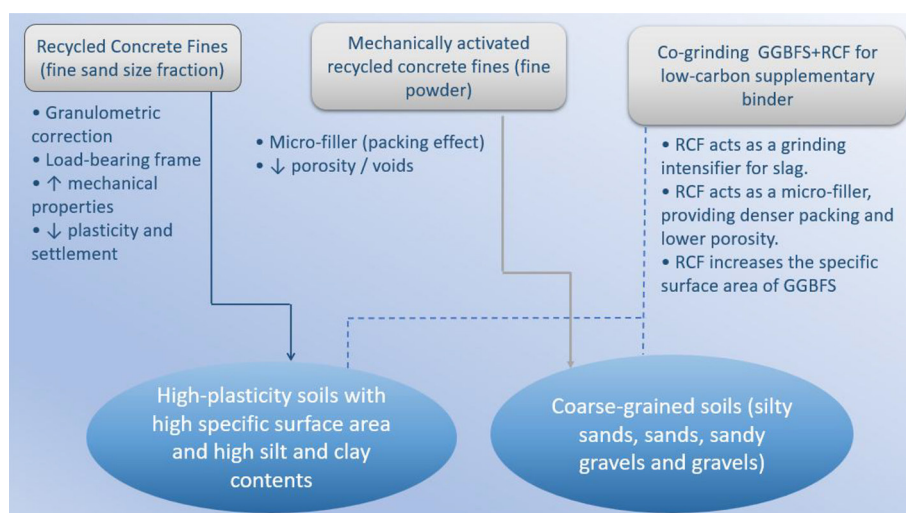


Figure 7. Conceptual framework for the integrated use of recycled concrete fines according to soil granulometric composition

Ukraine. Considering its qualitative and quantitative mineralogical composition, RCF should be regarded not as a waste material but as a valuable secondary mineral resource for geotechnical applications, particularly for combined soil stabilisation. Its use as a mineral filler enables the partial replacement of natural quartz sand, thereby reducing the demand for primary mineral resources while returning the mineral fraction of construction and demolition waste to a new utilisation cycle.

Figure 7 illustrates the conceptual framework for the differentiated utilisation of recycled

concrete fines (RCF) according to the particle size distribution of the soil. In highly plastic soils, RCF in the very fine sand fraction is used as a particle size correction material, improving both the grading characteristics and the mechanical performance of the soil. In coarser-grained soils, mechanically activated RCF is utilised as a micro-filler, enhancing particle packing and increasing soil density. An additional application involves the co-grinding of GGBFS with RCF to enhance slag activation and produce a low-carbon supplementary binder suitable for the stabilisation of different soil types.

RESULTS AND DISCUSSION

Co-grinding of GGBFS with recycled concrete fines

Reducing the use of Portland cement in soil stabilisation is one of the key directions in the development of modern low-carbon geotechnical technologies. One of the most promising approaches is the development of composite binders based on ground granulated blast furnace slag (GGBFS) (Novytskyi et al., 2024; Ahmad et al., 2022). However, the widespread application of GGBFS is limited by its relatively low reactivity during the early stages of hydration, necessitating effective activation. One of the most effective approaches to enhancing the reactivity of GGBFS is to increase its specific surface area, thereby accelerating hydration under sulfate–alkali activation (Zeng et al., 2023; Zhang et al., 2026). In the present study, the mechanical activation of GGBFS was achieved through co-grinding with RCF. It was hypothesised that RCF, composed predominantly of chemically stable quartz and feldspar minerals, would not only enhance the grinding efficiency and increase the fineness of GGBFS, but also act as a microfiller and provide potential nucleation sites for hydration products.

Mechanical activation of GGBFS was carried out using a laboratory vibratory ball mill equipped with steel grinding media. The initial GGBFS had a specific surface area of 3150 cm²/g. After 4 h of grinding, the specific surface area increased to 5590 cm²/g, confirming the high efficiency of the mechanical activation process (Figure 8). As no significant further increase in specific surface area was achieved with prolonged grinding, a grinding time of 4 h was selected as the optimum duration, providing an appropriate balance between activation efficiency and energy consumption. The effect of co-grinding GGBFS with RCF was also investigated. For this purpose, 20 wt.% RCF (relative to the mass of GGBFS) was added to the untreated GGBFS with an initial specific surface area of 3150 cm²/g. The mixture was then mechanically activated in a laboratory vibratory ball mill for 4 h under the same grinding conditions. As a result, the specific surface area of the composite powder reached 6040 cm²/g, exceeding that of the individually mechanically activated GGBFS (5590 cm²/g). These results demonstrate that co-grinding GGBFS with RCF produces a finer composite

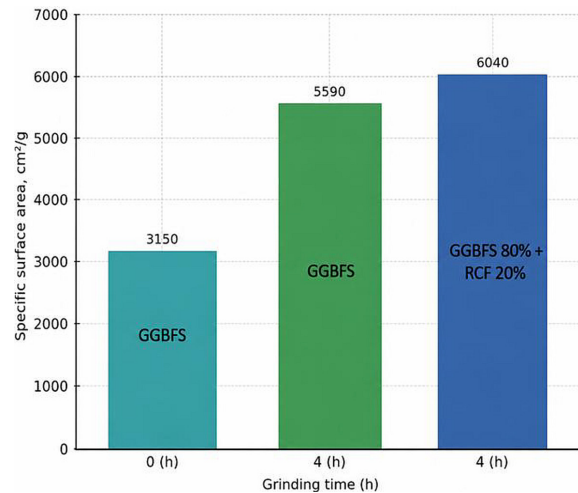


Figure 8. Effect of co-grinding of GGBFS and RCF on specific surface area

powder than mechanical activation of GGBFS alone under identical grinding conditions.

According to the principle of sulfate–alkali activation, hydrated lime (HL) and phosphogypsum (PG) were used to produce the low-carbon slag binder (SB). Three slag binder formulations (SB1–SB3) were developed, differing only in the slag component, while the contents of HL and PG were kept constant (Figure 9). This experimental design made it possible to evaluate the influence of the specific surface area of GGBFS, as well as the effect of its co-grinding with RCF, on the extent of hydration and the physico-mechanical properties of the proposed slag binders.

The mechanical properties of the developed slag binders (SB1–SB3) were evaluated using a procedure based on EN 196-1, adapted to the characteristics of the investigated composite binders. Unlike the standard method, which employs cement–sand mortar prisms, the specimens in the present study were prepared without fine aggregate. The mixtures consisted solely of the components of the low-carbon slag binder, namely GGBFS (or GGBFS–RCF in SB3), HL, PG, and water. Prismatic specimens measuring 20 × 20 × 100 mm were prepared and tested for flexural and compressive strength after 7 and 28 days of curing. As the specific surface area of GGBFS increased, the water demand of the composite binder also increased. Therefore, the water-to-binder ratio (w/b) was adjusted to 0.30, 0.33, and 0.36 for SB1, SB2, and SB3, respectively.

The test results demonstrated that increasing the specific surface area of GGBFS had a positive effect on the development of both compressive

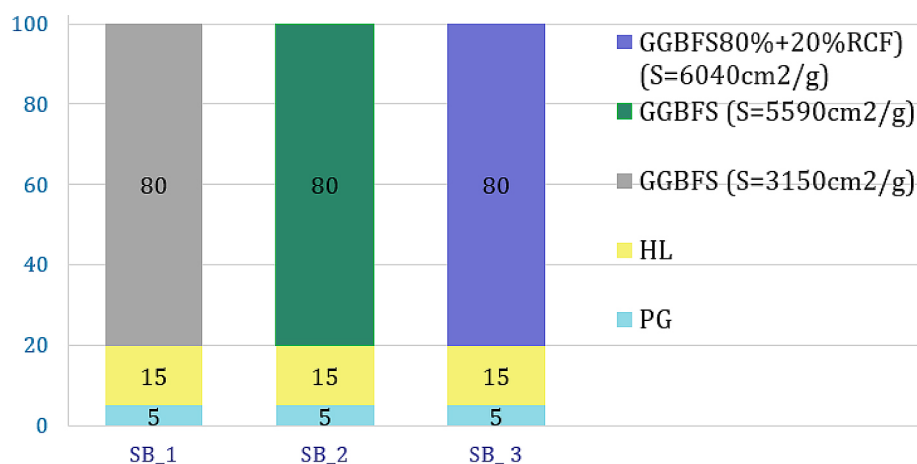


Figure 9. Composition of the low-carbon slag binders based on GGBFS with different specific surface areas

and flexural strength of the developed low-carbon slag binders (Figure 10). For all three formulations, strength increased consistently with curing time from 7 to 28 days, indicating the continuous progression of hydration reactions and the gradual development of the cementitious microstructure. The lowest strength values were obtained for SB1, which was prepared using the untreated GGBFS with a specific surface area of 3150 cm²/g. Mechanical activation of GGBFS to a specific surface area of 5590 cm²/g (SB2) resulted in a substantial increase in both compressive and flexural strength throughout the curing period. The highest strength values were achieved by SB3, which incorporated the product obtained by co-grinding GGBFS with 20 wt.% RCF.

Compared with SB2, SB3 exhibited a particularly pronounced development of early-age strength. After 7 days of curing, its compressive strength was more than twice that of SB2. After 28 days, SB3 still outperformed SB2, with compressive strength and flexural strength being 42.5% and 34.9% higher, respectively. These results indicate that the beneficial effect of co-grinding was most pronounced during the early stages of hydration, while a substantial strength advantage was maintained after 28 days of curing.

Thus, increasing the specific surface area of GGBFS alone resulted in a moderate improvement in the mechanical properties of SB2, whereas the co-grinding of GGBFS with RCF in SB3 produced a substantially greater increase in both early-age and 28-day strength. These findings suggest that the enhanced performance of SB3 cannot be attributed solely to the increased fineness of the slag. Rather, it is likely associated with the acceleration of hydration reactions

and the development of a denser cementitious microstructure, which is directly reflected in the improved mechanical properties of the developed low-carbon slag binder.

The water absorption and open porosity of the developed low-carbon supplementary binders were determined using a gravimetric method based on the masses of oven-dried, water-saturated, and hydrostatically weighed specimens. Water absorption and open porosity were calculated from the measured masses, and the results are presented in Figure 11. SB3 exhibited the lowest values of both open porosity and water absorption, indicating a denser binder microstructure. This improvement is attributed to the microfiller effect of RCF, which promotes more efficient particle packing and pore refinement.

To determine whether the improved properties of the developed binders were primarily associated with matrix densification or with the formation of additional hydration products, XRD analysis was performed. The XRD patterns (Figure 12) showed that the principal hydration products in all three low-carbon slag binder formulations were calcium silicate hydrate (C–S–H), represented by tobermorite (Tb1, 14 Å; Tb2, 9 Å), and ettringite. The presence of Ca(OH)₂ indicates residual HL that had not been completely consumed during the hydration process. In addition, ardealite, originating from the PG used in the binder formulation, was identified in all diffraction patterns.

The lowest intensity of the diffraction peaks corresponding to the hydration products was observed for SB1, prepared using untreated GGBFS with a specific surface area of 3150 cm²/g. For SB2 and SB3, the intensities of the principal

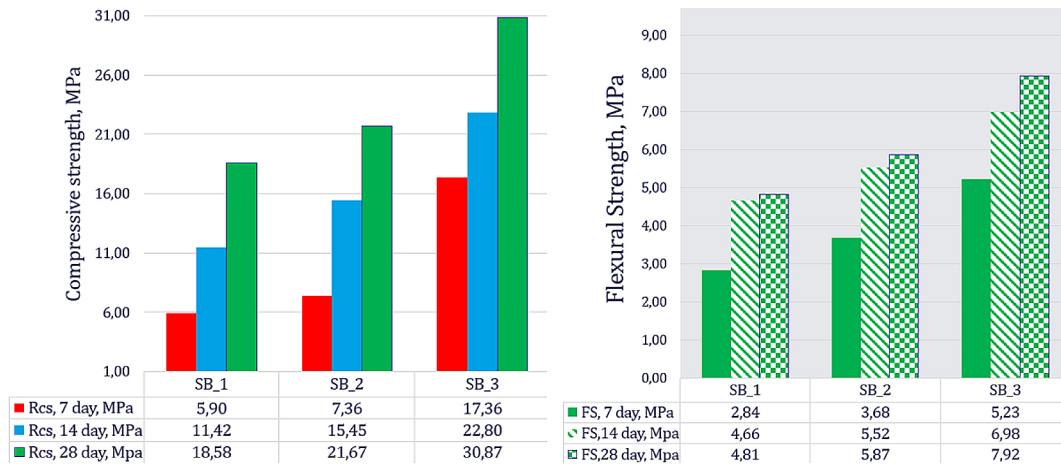


Figure 10. Combined effect of GGBFS specific surface area and curing time on the flexural and compressive strength of the developed low-carbon slag binders

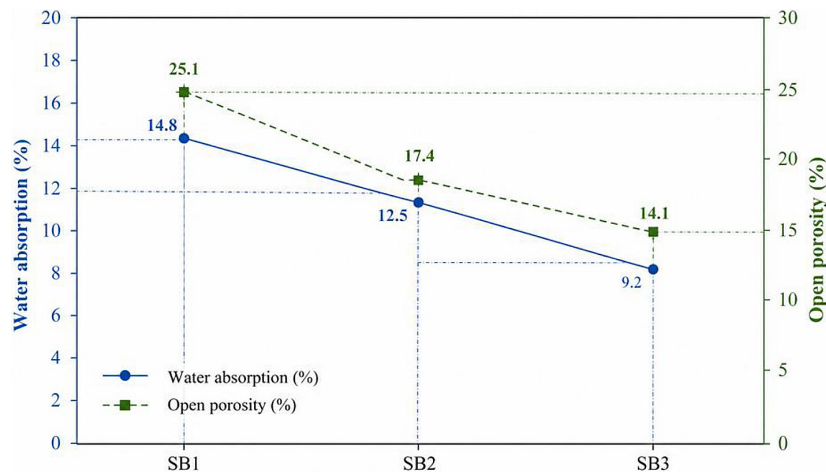


Figure 11. Water absorption and open porosity of the developed low-carbon slag binders

diffraction peaks of calcium silicate hydrate (C–S–H), represented by tobermorite (Tb1 and Tb2), ettringite, and portlandite were comparable, with no significant differences between the two formulations. A distinctive feature of the SB3 diffraction pattern was the appearance of additional peaks corresponding to quartz, orthoclase, and rutile, resulting from the incorporation of RCF into the composite binder. Therefore, the XRD results do not indicate a substantial increase in the amount of crystalline hydration products when comparing SB3 with SB2. These findings suggest that the significant improvement in the mechanical properties of SB3 cannot be explained solely by additional phase formation but is more likely associated with the microfiller effect of RCF, which promotes matrix densification and reduces the porosity of the composite binder.

Quantitative phase analysis was performed using Profex software based on full-pattern refinement of the experimental XRD data. The phase contents are expressed as wt.% of the crystalline fraction, normalised to 100 wt.%, excluding the amorphous phase. The results of the quantitative phase analysis (Table 5) are consistent with the qualitative interpretation of the diffraction patterns and confirm comparable amounts of the principal hydration products in SB2 and SB3. The slightly lower relative content of hydraulically active phases in SB3 is attributed to the presence of additional crystalline minerals introduced with RCF, particularly quartz and orthoclase, which are included in the normalisation of the crystalline fraction.

To further evaluate the hydration processes in the developed low-carbon slag binders, differential thermal analysis (DTA) and thermogravimetric

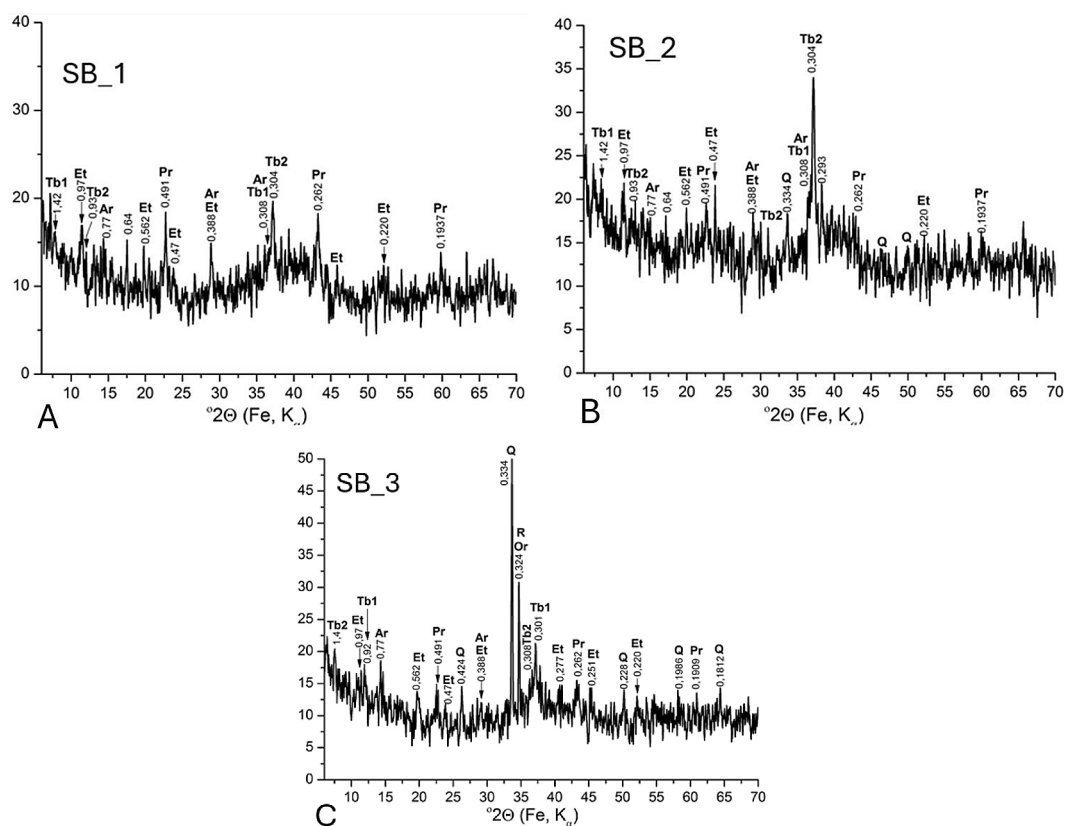


Figure 12. XRD patterns of the developed low-carbon supplementary binders: A) SB1; B) SB2; C) SB3 Phase abbreviations: Tb1 – 14 Å tobermorite; Tb2 – 9 Å tobermorite; Et – ettringite; Po – portlandite; Ar – ardéalite; Q – quartz; Or – orthoclase; Ru – rutile

Table 5. Quantitative phase composition of SB2 and SB3 determined by Profex analysis

Low-carbon slag binders	Mineral	Chemical formula	Content, wt. %
SB2: GGBFS (S = 5590 cm ² /g) -80% HL-15% PG-5%	Ar – ardéalite	CaSO ₄ (PO ₃ (OH))•4H ₂ O	5
	Tb2 – 9 Å tobermorite	Ca ₅ Si ₆ O ₁₆ •(OH) ₂	72
	Tb1 – 14 Å tobermorite	Ca ₅ Si ₆ O ₁₆ (OH) ₂ •8H ₂ O	5
	Et – ettringite	Ca ₆ Al ₂ (SO ₄) ₃ (OH) ₁₂ •26H ₂ O	13
	Po – portlandite	Ca(OH) ₂	3
	Q – quartz	SiO ₂	2
SB3: GGBFS+RCF (S = 6040 cm ² /g) 80% HL-15% PG-5%	Ar – ardéalite	CaSO ₄ (PO ₃ (OH))•4H ₂ O	6
	Tb2 – 9 Å tobermorite	Ca ₅ Si ₆ O ₁₆ •(OH) ₂	68
	Tb1 – 14 Å tobermorite	Ca ₅ Si ₆ O ₁₆ (OH) ₂ •8H ₂ O	3
	Et – ettringite	Ca ₆ Al ₂ (SO ₄) ₃ (OH) ₁₂ •26H ₂ O	8
	Po – portlandite	Ca(OH) ₂	3
	Q – quartz	SiO ₂	7
	Or – orthoclase	KS ₃ AlO ₈	3
	Ru – rutile	TiO ₂	2

analysis (TG) were performed. The DTA/TG curves of SB1–SB3 are presented in Figure 13.

The TG and DTA curves of SB2 and SB3 exhibited similar thermal behaviour. The principal mass loss below 400 °C was associated with the

removal of physically and chemically bound water from the hydration products. SB3 showed a slightly lower total mass loss than SB2, indicating that the higher specific surface area achieved through co-grinding did not result in a substantial

increase in the amount of hydration products. These observations are consistent with the XRD results and suggest that the improved mechanical performance of SB3 is primarily associated with matrix densification resulting from the microfiller effect of RCF, rather than with a significant increase in the degree of hydration.

Based on these results, SB3 was selected for the partial replacement of Portland cement in soil stabilisation, as it exhibited the highest mechanical performance among all the developed low-carbon slag binders.

Performance of soil stabilisation with recycled concrete fines depending on soil granulometric composition

Compaction characteristics

According to its particle size distribution, Silt Loam 1 was characterised by a predominance of the silt fraction (60.2%), while the combined silt and clay content reached 82.9%. Such a grading

may result in insufficient bearing capacity and increased deformability under external loading. To optimise the particle size distribution, a sand-sized fraction of RCF was incorporated into the soil as a particle size correction material. The effectiveness of this approach in improving soil mechanical properties was demonstrated in a previous study (Topylko et al., 2025). The addition of the sand fraction was expected to promote the formation of a stiffer granular skeleton capable of more effectively carrying and redistributing external loads. The effectiveness of the particle size correction and the optimum RCF content were assessed from the improvement in compaction characteristics, primarily through an increase in the maximum dry density determined using the Modified Proctor test. As the investigated mixtures were intended for use in a pavement sub-base layer, their compaction characteristics were determined using the Modified Proctor method, which applies a higher compaction energy than the Standard Proctor method.

In contrast, Silt Loam 2 contained a substantially lower clay content (9.3 wt.%) than Silt Loam 1, while its sand content (33.9 wt.%) was approximately twice as high. Based on its plasticity index ($PI = 3.8\%$), Silt Loam 2 was classified as a low-plasticity soil, indicating that additional particle size correction using RCF in the very fine sand fraction was unnecessary. With this particle size distribution, the natural sand fraction was considered sufficient to provide a stable granular skeleton. Therefore, a different approach was adopted. Instead of modifying the particle size distribution, mechanically activated RCF with a specific surface area of approximately $300 \text{ m}^2/\text{kg}$ was incorporated as a microfiller to enhance particle packing and fill the intergranular voids within the soil matrix.

The results of the Modified Proctor test (Table 6) showed that the incorporation of RCF-sf had a pronounced effect on the compaction characteristics of Silt Loam 1. Increasing the RCF-sf content to 10 wt.% reduced the optimum moisture content (OMC) from 14.8% to 13.3%, while simultaneously increasing the maximum dry density (MDD) from 1.88 g/cm^3 to 1.94 g/cm^3 and decreasing the calculated porosity from 32.6% to 27.3%. These results indicate the formation of a denser soil structure, in which the RCF-sf particles form a load-bearing granular skeleton, while the finer silt and clay fractions efficiently fill the intergranular voids, thereby improving particle packing. A further increase

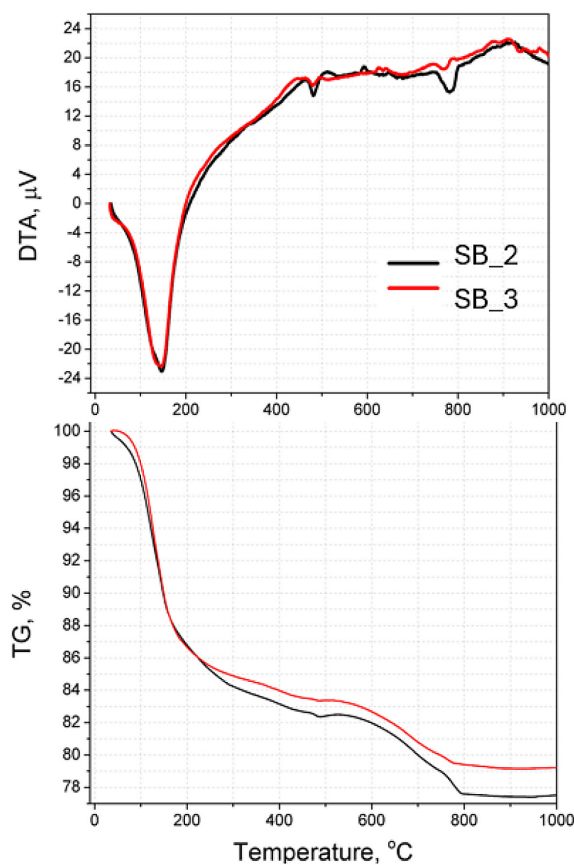


Figure 13. Differential thermal (DTA) and thermogravimetric (TG) analyses of low-carbon slag binders

in the RCF-sf content beyond 10 wt.% resulted in a slight decrease in MDD and a corresponding increase in porosity, indicating that the optimum content of the very fine sand fraction had been exceeded for this soil. Therefore, 10 wt.% RCF-sf was identified as the optimum content of the particle size correction material for Silt Loam 1.

The incorporation of ground recycled concrete fines (RCF-G) resulted in a slight increase in the particle density of the mixtures from 2.61 to 2.65 g/cm³. At the same time, the optimum moisture content gradually increased from 9.2% to 11.2%, reflecting the higher water demand associated with the incorporation of finely ground RCF-G. The MDD increased from 1.87 g/cm³ for the untreated Silt Loam 2 to a maximum of 1.93 g/cm³ at an RCF-G content of 4 wt.%, while the calculated porosity decreased from 28.3% to 27.2%. These results indicate improved particle packing and the formation of a denser soil structure. A further increase in the RCF-G content to 6 wt.% resulted in a slight decrease in MDD to 1.91 g/cm³ and an increase in calculated porosity to 27.9%, indicating the onset of structural loosening caused by an excess of fine particles. As the mineralogical composition of RCF-G is similar to that of Silt Loam 2 and consists predominantly of quartz and feldspars, with only a minor content of clay minerals, increasing the RCF-G content beyond the optimum primarily increases the proportion of relatively inert mineral filler. Therefore, 4

wt.% RCF-G was selected as the optimum dosage for the subsequent stabilisation of Silt Loam 2.

Soil mixture compositions for stabilisation

Following the determination of the compaction characteristics and the optimum RCF content, the soil mixtures for stabilisation were designed. The base mixture for Silt Loam 1 consisted of 90 wt.% soil and 10 wt.% RCF-sf, whereas that for Silt Loam 2 comprised 96 wt.% soil and 4 wt.% RCF-G. The particle size-corrected soil mixtures were subsequently stabilised using either Portland cement (PC) or a composite binder consisting of PC, HL, and slag binder (SB3). The binder contents were calculated with respect to the dry mass of the base soil mixture. The compositions of the investigated mixtures, including the proportions of soil, RCF, and binder components, are presented in Figures 14 and 15.

The components of the soil mixtures were first dry-mixed in the required proportions until a homogeneous mixture was obtained. The mixtures were then moistened to a water content 1.5–2.5% above the optimum moisture content (OMC) determined from the Modified Proctor test. This additional water was required to compensate for the increased water demand caused by the incorporation of the fine binder components, particularly hydrated lime, which is characterised by a high specific surface area. This adjustment ensured that the target maximum dry density

Table 6. Modified proctor test results for soil–RCF mixtures

Silt Loam 1 SL1 (wt.%)	RCF (fine sand fraction) RCF_sf (wt.%)	Optimum moisture content (OMC, %)	Maximum dry density MDD, ρ_d (g/cm ³)	particle density ρ_s (g/cm ³)	Calculated porosity $n = \left(1 - \frac{\rho_d}{\rho_s}\right) 100\%$
100	-	14.8	1.88	2.79	32.6
95	5	14.5	1.89	2.74	31.0
93	7	14.0	1.90	2.70	29.6
90	10	13.3	1.94	2.67	27.3
85	15	12.8	1.91	2.64	27.7
80	20	11.7	1.89	2.62	27.9
Silt Loam 2 SL2 (wt.%)	Ground RCF (SSA ≈ 300 m ² /kg) RCF_G	Optimum moisture content (OMC, %)	Maximum dry density (MDD, g/cm ³)	particle density ρ_s	Calculated porosity $n = \left(1 - \frac{\rho_d}{\rho_s}\right) 100\%$
100	-	9.2	1.87	2.61	28.3
98	2	9.8	1.89	2.62	27.9
96	4	10.5	1.93	2.65	27.2
94	6	11.2	1.91	2.65	27.9

Note: Acronyms and mixture codes used throughout the paper: SL1 – Silt Loam 1; SL2 – Silt Loam 2; RCF-sf – recycled concrete fines (fine sand fraction); RCF-G – ground recycled concrete fines; SL1-10RCF-sf – Silt Loam 1 containing 10 wt.% RCF-sf; SL2-4RCF-G – Silt Loam 2 containing 4 wt.% RCF-G.

could be achieved during specimen preparation. Cylindrical specimens (50 mm in diameter and 50 mm in height) were prepared by static compaction in steel moulds under a pressure of 15 MPa, with the maximum load maintained for 3 min, in accordance with EN 13286-53:2004. The degree of compaction of the prepared specimens ranged from 99% to 101% and was calculated as the ratio of the dry density of the compacted specimens to the maximum dry density determined from the Modified Proctor test.

The mixture containing 10 wt.% PC was selected as the reference composition, as it represents the conventional approach to cement stabilisation of soils. The mixture containing 15 wt.% binder (5 wt.% PC + 5 wt.% HL + 5 wt.% SB3) was designed to evaluate the effect of increasing the total binder content on the physico-mechanical properties of the stabilised soil. The mixture containing 10 wt.% composite binder (3 wt.% PC + 2 wt.% HL + 5 wt.% SB3) was developed to investigate the partial replacement of Portland cement with the low-carbon slag binder. In this binder system, both Portland cement and hydrated lime acted as alkaline activators of GGBFS. However, hydrated lime provides a higher pore solution alkalinity and is therefore a more effective activator of slag hydration.

Mechanical properties and durability of stabilised soils

After moulding, the specimens were cured in sealed chambers above water to provide a humid curing environment and prevent moisture loss. The unconfined compressive strength (UCS) was

determined after 7 and 28 days of curing. A separate set of specimens was used to determine the water resistance coefficient (K_{wr}) (Figure 16, A) and the freeze–thaw resistance coefficient (K_{fr}) (Figure 16, B). The K_{wr} was calculated as the ratio of the UCS of specimens immersed in water for 7 days (conditioning regime adapted from EN 14227-15:2015) to the UCS of the corresponding specimens after 28 days of curing.

The reference mixture stabilised with 10 wt.% PC exhibited the highest unconfined compressive strength (UCS) after 28 days of curing, reaching 8.64 MPa. Following 7 days of water immersion, the UCS decreased to 7.96 MPa, corresponding to a water resistance coefficient (K_{wr}) of 0.92.

Reducing the Portland cement (PC) content to 3 wt.% in the [SL1-10RCF-sf]3PC_2HL_5(SB3) mixture, while maintaining a total binder content of 10 wt.%, resulted in a UCS of 5.76 MPa after 7 days and 7.07 MPa after 28 days of curing. Compared with the reference mixture [SL1-10RCF-sf]_10PC, the 28-day UCS was 18.2% lower. Following 7 days of water immersion, the UCS reached 6.30 MPa, corresponding to a K_{wr} of 0.90. These results demonstrate that, despite reducing the Portland cement content to 3 wt.%, the developed low-carbon binder system maintained satisfactory mechanical performance and water resistance.

To achieve a strength level comparable to that of the reference mixture, the total binder content was increased to 15 wt.%. The [SL1-10RCF-sf]_5PC_5HL_5(SB3) mixture achieved a UCS of 6.12 MPa after 7 days and 8.24 MPa after 28 days of curing. The 28-day UCS was only 4.6% lower than that of the reference mixture

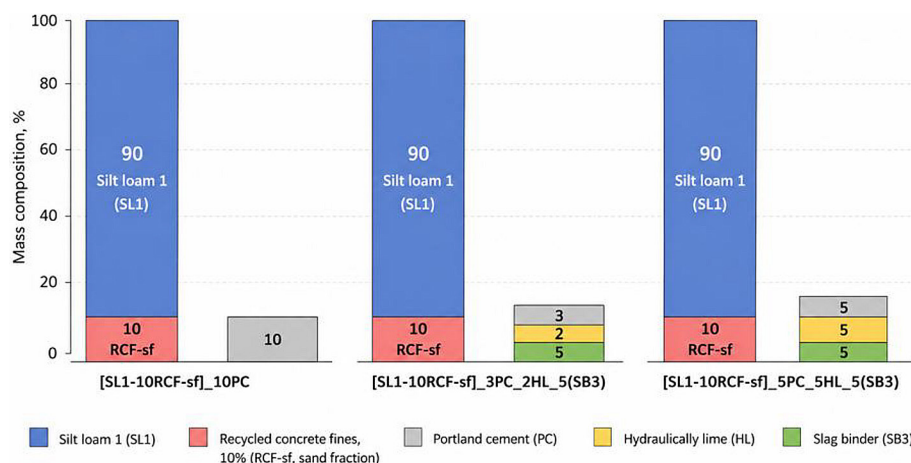


Figure 14. Composition of silt loam 1 modified with 10 wt.% recycled concrete fines (sand fraction) and stabilised with cementitious materials

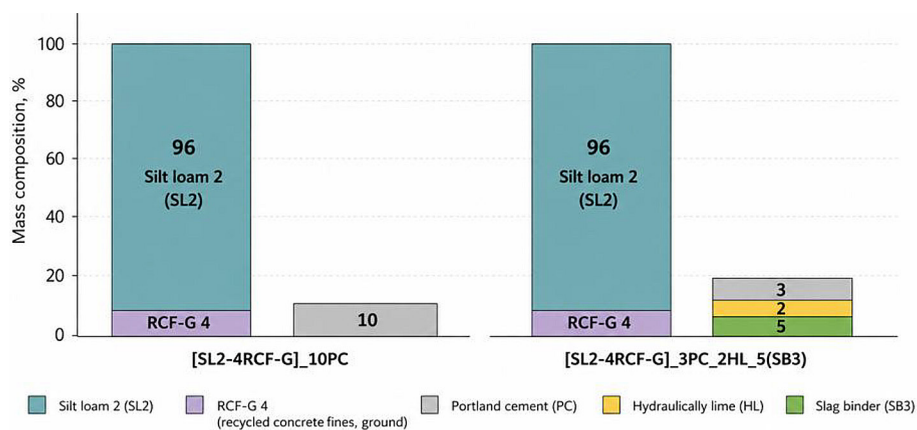


Figure 15. Composition of silt loam 2 modified with 4 wt.% ground recycled concrete fines and stabilised with cementitious materials

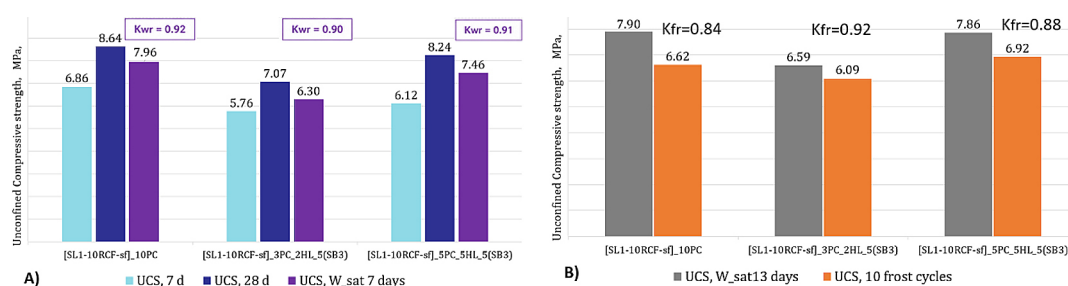


Figure 16. Mechanical performance of stabilised Silt Loam 1: (A) UCS after 7 and 28 days of curing and after 7 days of water saturation; (B) UCS after 13 days of water saturation and after 10 freeze–thaw cycles

containing 10 wt.% PC. Following 7 days of water immersion, the UCS reached 7.46 MPa, corresponding to a water resistance coefficient (Kwr) of 0.91, which was virtually identical to that of the reference mixture.

Freeze–thaw resistance was evaluated in accordance with EN 13286-54. Before the freeze–thaw test, all specimens were cured for 28 days and then immersed in water for 48 h. The specimens were subsequently divided into two series. Series A was subjected to 10 freeze–thaw cycles, whereas Series B remained immersed in water throughout the testing period of Series A. After completion of the freeze–thaw cycles, the specimens from Series A were immersed in water for an additional 24 h to restore thermal equilibrium. Subsequently, the UCS of both series was determined, and the freeze–thaw resistance coefficient (Kfr) was calculated.

The reference mixture stabilised with 10 wt.% PC exhibited a UCS of 7.90 MPa after 13 days of water immersion, which was only slightly lower than that measured after 7 days of water immersion (7.96 MPa). After 10 freeze–thaw cycles, the UCS decreased to 6.62 MPa, corresponding

to a Kfr of 0.84. In contrast, the [SL1-10RCF-sf]_3PC_2HL_5(SB3) mixture exhibited a slight increase in strength after prolonged water immersion. The UCS increased from 6.30 MPa after 7 days to 6.59 MPa after 13 days of water immersion, indicating continued strength development during additional curing under saturated conditions. After 10 freeze–thaw cycles, the UCS reached 6.09 MPa, while the Kfr increased to 0.92, representing the highest freeze–thaw resistance among all the investigated mixtures.

A similar trend was observed for the [SL1-10RCF-sf]_5PC_5HL_5(SB3) mixture. Following 13 days of water immersion, the UCS increased from 7.46 MPa to 7.86 MPa, indicating continued hydration during prolonged curing under saturated conditions. After 10 freeze–thaw cycles, the UCS was 6.92 MPa, corresponding to a Kfr of 0.88.

The mineralogical composition of the sand–silt fraction of Silt Loam 1 is dominated by quartz and feldspars, which are characterised by high chemical stability and low reactivity. The clay fraction, accounting for 22.7 wt.% of the soil, consists predominantly of montmorillonite, kaolinite, and

illite. Among these clay minerals, montmorillonite is the most reactive component. Its aluminosilicate structure can serve as an additional source of reactive aluminosilicate species participating in the formation of additional cementitious hydration products in the presence of PC, HL, and SB3.

Unlike the reference mixture containing 10 wt.% PC, the mixtures incorporating slag binder exhibited a slight increase in UCS when the duration of water immersion was extended from 7 to 13 days. This behaviour may be attributed to the temporary weakening of the soil structure during the initial stage of water immersion, followed by the continued hydration of GGBFS and the formation of additional calcium silicate hydrate (C–S–H) phases during prolonged curing under saturated conditions. These processes contribute to the densification of the stabilised soil structure and the subsequent recovery and increase in strength (Abdila et al., 2022; Yang et al., 2026).

The same testing procedure was applied to the Silt Loam 2 mixtures to determine the water resistance coefficient (K_{wr}) (Figure 17A) and the K_{fr} (Figure 17B). Compared with Silt Loam 1, the Silt Loam 2 mixtures exhibited slightly lower UCS values. This difference can be attributed to the particle size distribution and mineralogical composition of the soil. In particular, Silt Loam 2 contains a lower clay content (9.3 wt.%), while its mineralogical composition is dominated by quartz, feldspars, and calcite. Unlike the reactive clay minerals present in Silt Loam 1, these minerals contribute only marginally to the binder–soil reactions responsible for the formation of cementitious hydration products.

The Silt Loam 2 mixtures exhibited exceptionally high K_{wr} , reaching 0.98 for the reference mixture containing 10 wt.% PC and 0.99 for the mixture incorporating 3 wt.% PC, 2 wt.% HL and 5 wt.% SB3. When interpreting these high K_{wr} values, the specimen preparation conditions should be taken into account. The moulding water content (11–12%), corresponding to the optimum moisture content determined by the Modified Proctor test, ensured the achievement of the maximum dry density (MDD) but may not have been sufficient to allow complete hydration of the cement–slag binder system. Under these conditions, subsequent water immersion likely compensated, at least partially, for the initial weakening associated with water ingress while simultaneously providing favourable conditions for the continued hydration of the binder system.

For Silt Loam 2, the mixture stabilised with 3 wt.% PC + 2 wt.% HL + 5 wt.% SB3 exhibited overall mechanical performance that was virtually identical to that of the reference mixture stabilised with 10 wt.% PC. Considering that slag binders generally exhibit slower strength development than conventional Portland cement systems, this result warrants further analysis to elucidate the possible mechanisms of phase formation responsible for the observed mechanical performance.

In carbonate-containing systems, calcite may react with C_3A derived from PC as well as with Al_2O_3 released during the sulfate–alkaline activation of GGBFS. These reactions may lead to the formation of Hc and Mc phases (Lu et al., 2018; Zajac et al., 2014). Therefore, it can be hypothesised that the 3PC–2HL–5(SB3) binder system provided more favourable conditions for the formation of Hc and Mc than the system stabilised solely with Portland cement.

According to previous studies, the formation of Hc and Mc is associated with an increased amount of hydration products, microstructural densification, and reduced porosity. Furthermore, the formation of these AFm phases contributes to the stabilisation of the hydration phase assemblage, which may enhance the mechanical properties and long-term durability of cementitious materials (Wang et al., 2018; Jiang et al., 2020).

To verify this hypothesis, XRD analysis was performed on Silt Loam 2 specimens stabilised with 10 wt.% PC and with the composite binder 3PC–2HL–5(SB3) after 28 days of curing (Figure 18). Identification of newly formed hydration products in soil systems is challenging because of the high contents of quartz and feldspars, whose intense diffraction peaks may mask the reflections of hydration phases present in much smaller amounts. To improve the detection of these phases, additional specimens were prepared after 28 days of curing. The specimens were ground and sieved through a 50 μm sieve, and the resulting fine fraction was used for XRD analysis.

The diffraction pattern of Silt Loam 2 stabilised with 10 wt.% PC is dominated by the intense reflections of the primary soil minerals, particularly quartz, calcite, and feldspars. Under these conditions, the identification of hydration products, especially ettringite and calcium silicate hydrate (C–S–H), is challenging because these phases are present in relatively small amounts. Moreover, C–S–H is characterised by poor

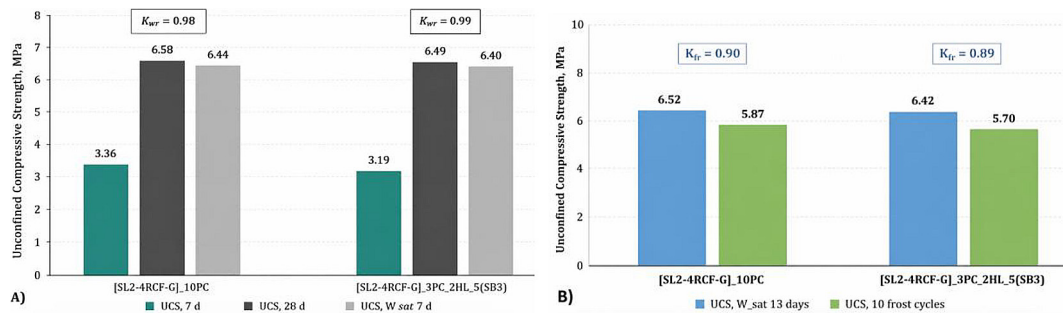


Figure 17. Mechanical performance of stabilised Silt Loam 2: (A) UCS after 7 and 28 days of curing and after 7 days of water saturation; (B) UCS after 13 days of water saturation and after 10 freeze–thaw cycles

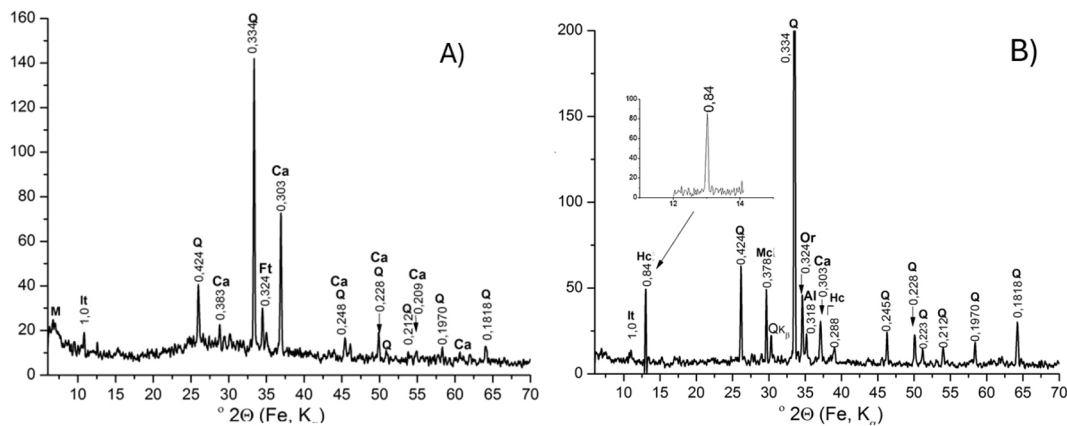


Figure 18. X-ray diffraction patterns of Silt Loam 2 stabilised with (A) [SL2-4RCF-G]_10PC and (B) [SL2-4RCF-G]_3PC_2HL_5(SB3) after 28 days of curing. Hc – hemicarboaluminate; Mc – monocarboaluminate; Q – quartz; Ca – calcite; It – illite; Al – albite; Or – orthoclase; Fs – feldspars (albite, orthoclase)

crystallinity and is typically manifested as a broad amorphous halo, while its weak reflections may be obscured by the much more intense diffraction peaks of the primary soil minerals.

The diffraction pattern of Silt Loam 2 stabilised with the composite binder 3PC–2HL–5(SB3) after 28 days of curing (Figure 18B) revealed the formation of additional hydration phases. The diffraction pattern clearly shows the characteristic basal reflection of Hc at $d \approx 0.84$ nm (8.4 Å), its second-order reflection at $d \approx 0.288$ nm (2.88 Å), and the characteristic secondary reflection of monocarboaluminate (Mc) at $d \approx 0.378$ nm (3.78 Å).

In conventional Portland cement systems, hemicarboaluminate ($C_4A\hat{C}_{0.5}H_{12}$) and monocarboaluminate ($C_4A\hat{C}H_{11}$) are formed primarily through the reaction of calcite with the clinker aluminate phase (C_3A). However, according to Matschei et al. (2007), slag-containing cementitious systems develop under more aluminosilicate-rich conditions, which

significantly increases the potential for the formation of multiple AFm phases. This promotes the reaction between calcite and reactive aluminium species, resulting in the formation of larger amounts of hemicarboaluminate and monocarboaluminate, stabilisation of the AFt phase, a greater overall volume of hydration products, and consequently a denser cementitious microstructure with reduced capillary porosity (Xue et al., 2025; Irassar et al., 2023).

In the present study, when the composite binder 3PC–2HL–5(SB3) was used to stabilise the calcite-bearing Silt Loam 2, reactive aluminium was supplied not only by the clinker C_3A phase but also by the sulfate–alkaline activated amorphous aluminosilicate phase of GGBFS. Based on the experimental results and the available literature, it is reasonable to hypothesise that the incorporation of mechanically co-ground GGBFS–20%RCF within SB3 promoted the formation of Hc and Mc through the interaction of slag-derived reactive Al_2O_3 with soil calcite. The formation of

these low-basic calcium carboaluminate hydrates most likely contributed to microstructural densification, resulting in improved mechanical strength and water resistance compared with the reference mixture stabilised solely with 10 wt.% Portland cement.

CONCLUSIONS

Based on the experimental results, a comprehensive approach to the utilisation of recycled concrete fines (RCF) in soil stabilisation was substantiated, whereby RCF was used as a particle size correction material, a microfiller, and a component of a low-carbon slag binder. Co-grinding ground granulated blast-furnace slag (GGBFS) with 20 wt.% RCF for 4 h increased the specific surface area of the composite powder to 6040 cm²/g, compared with 5590 cm²/g for mechanically activated GGBFS alone. Based on the co-ground GGBFS–20 wt.% RCF system, a low-carbon slag binder (SB3) was developed according to the principle of sulfate–alkaline activation. After 28 days of curing, SB3 achieved a compressive strength of 30.87 MPa and a flexural strength of 7.92 MPa.

A differentiated approach to the application of RCF depending on the particle size distribution of the soil was established. For Silt Loam 1 (sand – 17.14 wt.%, silt – 60.16 wt.%, clay – 22.7 wt.%), the optimum solution was the incorporation of 10 wt.% RCF-sf as a particle size correction material, which increased the maximum dry density (MDD) from 1.88 to 1.94 g/cm³ according to the Modified Proctor test. For Silt Loam 2 (sand – 33.9 wt.%, silt – 56.8 wt.%, clay – 9.3 wt.%), the optimum solution was the incorporation of 4 wt.% ground RCF (RCF-G) with a specific surface area of 3000 cm²/g as a microfiller, which increased the MDD from 1.87 to 1.93 g/cm³ while reducing the calculated porosity from 28.3% to 27.2%.

The particle size-optimised Silt Loam 1 and Silt Loam 2 mixtures were stabilised using composite binder consisting of 3 wt.% PC, 2 wt.% hydrated lime (HL), and 5 wt.% SB3. For Silt Loam 1, the composite binder provided a 28-day UCS of 7.07 MPa, a water resistance coefficient (K_{wr}) of 0.90, and a K_{fr} of 0.92. For Silt Loam 2, the composite binder achieved mechanical performance comparable to that of the reference mixture stabilised with 10 wt.% PC, providing a 28-day UCS of 6.49 MPa, K_{wr} = 0.99, and K_{fr} = 0.89.

The results demonstrated that the mineralogical composition of the soil is a key factor governing the effectiveness of soil stabilisation through its influence on phase formation. For Silt Loam 2, stabilisation with the composite binder (3 wt.% PC + 2 wt.% HL + 5 wt.% SB3) resulted in the formation of highly stable hemicarboaluminate and monocarboaluminate phases, indicating the interaction of soil calcite with the reactive aluminosilicate components of the slag binder

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