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RECYCLED CONCRETE FINES AS A COMPONENT OF COMBINED STABILISATION OF CLAYEY SOILS FOR SUSTAINABLE ROAD CONSTRUCTION

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This study investigates the application of recycled concrete fines (RCF) as a mineral modifier and hydrated lime as a traditional stabiliser of clayey soils used in road foundations. The incorporation of RCF was shown to reduce soil plasticity and improve the compactability of loam due to the skeletal effect of inert crystalline particles. Compressive strength tests confirmed the enhanced strength of the modified mixtures. The addition of lime promoted the formation of hydraulic products, providing further gains in soil strength and stability. A clear synergy was identified between the mechanical action of RCF and the chemical stabilisation by lime, which improves the reliability and long-term performance of clayey soils. The findings highlight the feasibility of this combined approach in road construction, consistent with the principles of the circular economy.

Keywords: recycled concrete fines, modified loam, soil stabilisation, modified Proctor test, unconfined compressive strength (UCS), road construction.

Introduction

The stability of the physico-mechanical properties of soil is a key parameter in the design of road foundations. The structural reliability of the subgrade and the road base directly depends on the soil's ability to withstand loads from traffic and the overlying pavement layers. The higher the soil bearing capacity, the greater the loads that the road structure can sustain without excessive deformation or failure.

In Ukraine, the volumes of construction and demolition waste have been increasing rapidly due to the ongoing war, creating a significant environmental burden. The accumulation of such materials not only occupies vast areas of land but also poses risks to the environment and public health. In this context, recycling and reuse acquire particular importance. One promising approach is the utilisation of recycled concrete fines (RCF) for the modification and stabilisation of clayey soils in road construction, which makes it possible to address both environmental and engineering challenges simultaneously (Circular Concrete, S3RoU).

Plastic clay soil represents one of the major challenges in road construction. Their high content of fine particles and large specific surface area result in excessive water absorption, as well as a pronounced tendency to swell and shrink (Estabragh, A. R., 2013; Dang, L. C., 2016). Without stabilisation, such soils are characterised by low bearing capacity, uneven deformation, and significant volumetric changes under the influence of moisture (Soltani, A., 2019; Seco, A., 2011). These behaviours lead to cracking, rutting, reduced service life of the pavement structure, and increased maintenance and rehabilitation costs. Therefore, the stabilisation of plastic soils is a prerequisite for ensuring the reliability of road foundations (Rahmat, M. N., 2011).

Recycled construction and demolition waste—particularly fine fractions of concrete, brick, and mortar – has demonstrated high effectiveness in improving weak, highly compressible soils (Sosahab, J. S., 2023; Kerni, V., 2015). When applied with rational grading and dosage, such materials reduce plasticity and swelling, increase unconfined compressive strength (UCS), California Bearing Ratio (CBR), and deformation moduli, and improve compaction characteristics.

For clayey soils, the effectiveness of stabilisation largely depends on the type and content of clay minerals. A properly selected ratio of recycled concrete waste to soil reduces volumetric deformations (shrinkage/swelling) and accelerates the long-term consolidation of clayey soils. In foundation reinforcement tasks, recycled concrete waste can function both as a material for rigid inclusions and as a component of combined stabilisation together with fly ash, lime, or Portland cement (Tavala, A. N., 2025; Alam, M. H., 2024). Particularly valuable are fine recycled concrete fractions (RCF), which act as a mineral modifier for the granulometric adjustment of plastic soils. Their use simultaneously reduces waste volumes and the consumption of primary resources.

According to the available literature, recycled concrete fines (RCF) can effectively act as a mineral modifier of clayey soils, improving their structure even without the use of binding agents. It has been shown that incorporating recycled concrete debris into clayey mixtures for road foundations (Ouslimane et al., 2025) enhances compactability, reduces swelling, and improves mechanical performance. The use of limestone dust and fine RCF as stabilisers for clay in amounts of 5–20 % contributes to increased bearing capacity (UCS), reduced linear shrinkage, and lower swelling index (Leon, L., 2024; Sosahab, J. S. & Ardakani, A., 2025; Yan, S., 2023; Amakye, S. Y., 2022). Mixing clay with fine recycled aggregates derived from concrete, brick, and mortar decreases consolidation properties while increasing the stiffness of the foundation – an effect often described as “structural improvement through a rigid aggregate skeleton” (Islam, S., 2022; Nasiri, A., 2024; Lu, X., 2023). Several studies (Raini et al., 2023; Beygi, L., 2024; Solodkyy, S. J., 2019) emphasise that RCF may function as a minimal modifier without the need for large amounts of binders. Conversely, other authors (Pauzi et al., 2024; Ouslimane, N., 2023) note that the addition of recycled concrete aggregate to the road base at moderate dosages (≈10–15 %) improves the California Bearing Ratio and soil structure, whereas excessive recycled concrete aggregate content may reduce the beneficial effect.

Materials and methods

Loam was selected as the clayey soil for this study. According to ISO 17892-12:2018, the tested loam is characterised by the following Atterberg limits: liquid limit LL = 38 %, plastic limit PL = 21 %, and plasticity index PI = 17 %. The particle density of the loam was determined as ρs = 2.72 g/cm³. The grain-size distribution of the loam was assessed in accordance with ISO 17892-4:2023 (Table 1).

Table 1

Particle size distribution of loam

Name of parameter	Sieve analysis								Sedimentation analysis	
Sieve opening, 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

To enhance the structure-forming process and to meet the required physico-mechanical properties of clayey soils that will subsequently be stabilised with binders, it is necessary to employ mineral additives to optimise the grain-size distribution. Recycled concrete fines are the finest mineral fraction produced during industrial crushing and dry screening of concrete debris from demolished buildings using specialised equipment for processing construction and demolition waste. An important characteristic of RCF is its grain-size distribution and mineralogical composition (Fig. 1 and Fig. 2).

According to XRD analysis, the dominant phases are inert, highly stable crystalline minerals: quartz (~70–75 %), feldspars (albite / orthoclase, ~10–12 %), a minor amount of calcite (~4 %), and traces of biotite / rutile. This indicates low chemical reactivity; the material functions primarily as a mineral filler, reducing the plasticity of clayey soils. The grain-size distribution of RCF is characterised by a predominance of very fine sand fractions. Consequently, such fines are expected to contribute to the adjustment of soil grading, improve blending with mineral binders, and enhance soil compaction. Based on the modified Proctor test, RCF is characterised by an optimum moisture content (OMC) of 6.8 % and a maximum dry density (MDD) of 1.53 g/cm³, values typical of sandy inert materials with a porous structure.

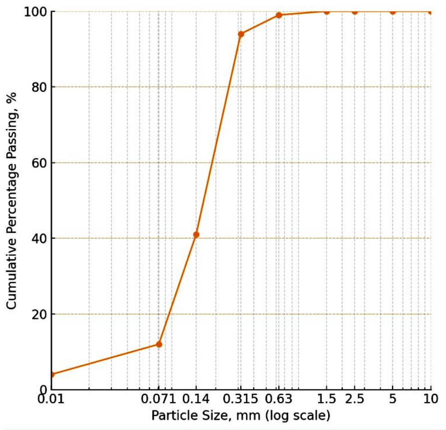

Fig. 1. Particle size distribution of recycled concrete fines

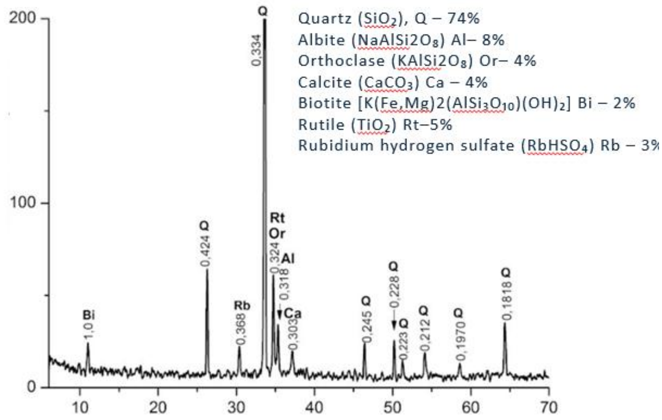

Fig. 2. XRD Pattern and Quantitative Phase Composition of Recycled Concrete Fines

Loam and RCF were mixed in an air-dry state, and the component composition of the mixture was calculated taking material humidity into account. Compaction parameters were determined using a modified Proctor test (EN 13286-2:2010). Test specimens were formed in accordance with EN 13286-53, Unbound and hydraulically bound mixtures. Part 53: Methods for the manufacture of test specimens of hydraulically bound mixtures using axial compression.

Results and Discussion

To evaluate the beneficial effect of mineral additives on the physico-mechanical parameters of plastic soil, the following mixtures were prepared (Table 2). The component proportioning of the mixtures was carried out on a dry mass basis.

Table 2

Component composition of loam modified with recycled concrete fines

Composition of modified loam, %		Acronym
Natural loam	Recycled concrete fines (RCF)	
100	–	NL
90	10	ML10
85	15	ML15
80	20	ML20
75	25	ML25
70	30	ML30

Each composition of the modified loam was tested for changes in the Atterberg limits and plasticity index (Fig. 3). A reduction in LL, PL, and PI was confirmed for loam with the addition of 10–30 % recycled concrete fines (RCF). The decrease in soil plasticity with increasing RCF content can be explained by the higher proportion of fine sand particles in the overall soil matrix.

The slight increase in PL can be attributed to the skeletal effect: fine inert RCF particles densify the loam structure and reduce its void ratio. To reach the plastic state, the soil requires a somewhat higher moisture content, which explains the rise in PL. As part of the clay fraction is replaced by inert RCF grains, the overall demand for adsorbed water per unit mass of soil decreases. However, to achieve interparticle sliding, the soil framework still needs to be “wetted”, which may manifest as a relative increase in PL.

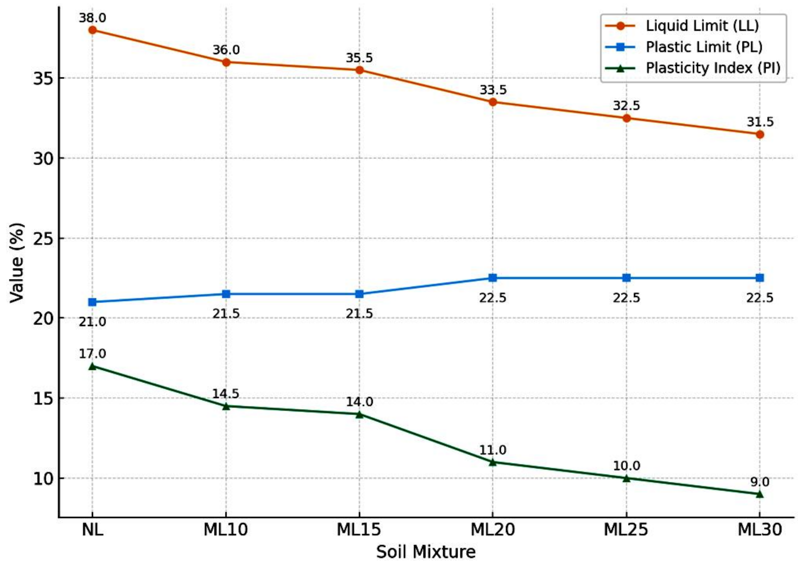

Fig. 3. Effect of RCF Addition on Atterberg Limits of Loam

In natural loam, it is the clay particles with high specific surface area that predominantly determine the liquid limit (LL). With the introduction of RCF, this fraction decreases, and less water is required for the soil to reach the liquid state. Inert RCF grains densify the soil framework and restrict the mobility of clay platelets in water. This also lowers the moisture level at which flow behaviour is observed. At the same time, the plasticity index (PI) decreases significantly – from 17 % in natural loam to about 9 % with 30 % RCF – indicating reduced plasticity and a more stable behaviour of the modified soil.

The observed reduction in plasticity indices is accompanied by changes in compaction parameters. For each mixture (natural loam, NL, and modified blends containing 10–30 % RCF), a modified Proctor test was performed to determine the optimum moisture content (OMC) and maximum dry density (MDD). The obtained compaction characteristics demonstrate the influence of RCF addition on the position of the optimum moisture content and on the compaction behaviour when compared with natural loam.

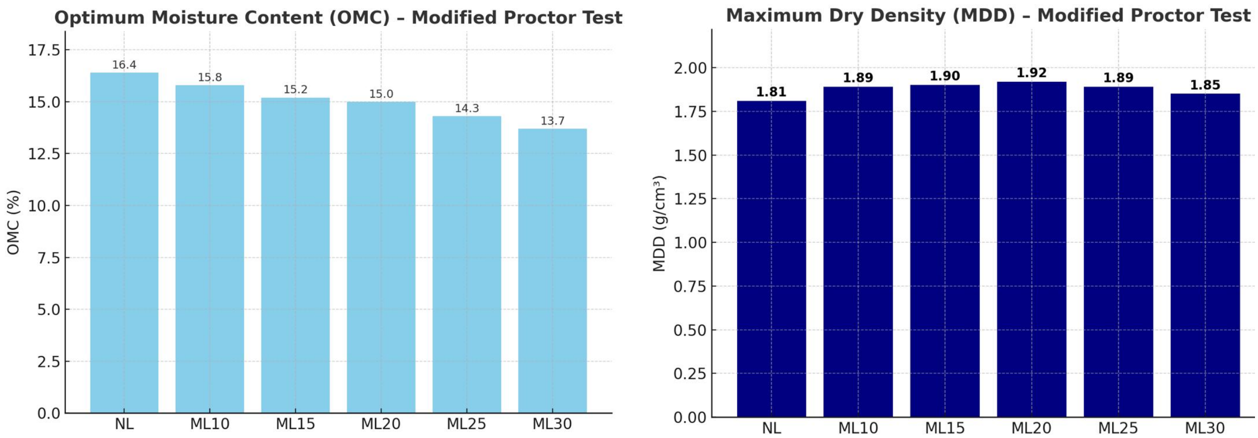

Fig. 4. Results of the Modified Proctor Test

Laboratory tests using the modified Proctor method (Fig. 4) showed that the OMC gradually decreased from 15.8 % to 13.7 %, since a higher content of inert RCF requires less water for compaction. The MDD increased up to ML20 (1.92 g/cm³) and then slightly declined at ML30 (1.85 g/cm³). Thus, an "optimum" is observed at 20% RCF, where the grain-size distribution becomes balanced (packing effect), void ratio is minimised, and density reaches its maximum. At higher dosages (25–30 %), the fine RCF particles generate an excess of dust-sized fractions, which impairs compaction.

After determining the compaction parameters using the modified Proctor test, the next step was the preparation of cylindrical specimens for subsequent strength testing. Samples with a diameter of 5 cm and a height of 5 cm were produced by axial pressing under a load of 15 MPa, in accordance with EN 13286-53. The specimens were formed at the optimum moisture content for each mixture, ensuring the achievement of maximum dry density.

The established compaction trends are in good agreement with the results of unconfined compressive strength (UCS) tests. Like the Proctor curves, where optimum MDD values were observed at 20 % RCF, the ML20 mixture also exhibited the highest UCS (≈2.0 MPa). The increase in UCS up to 20 % RCF can be attributed to framework densification and maximum reduction of porosity, whereas further additions of RCF beyond the optimum lead to a gradual decrease in strength (Fig. 5).

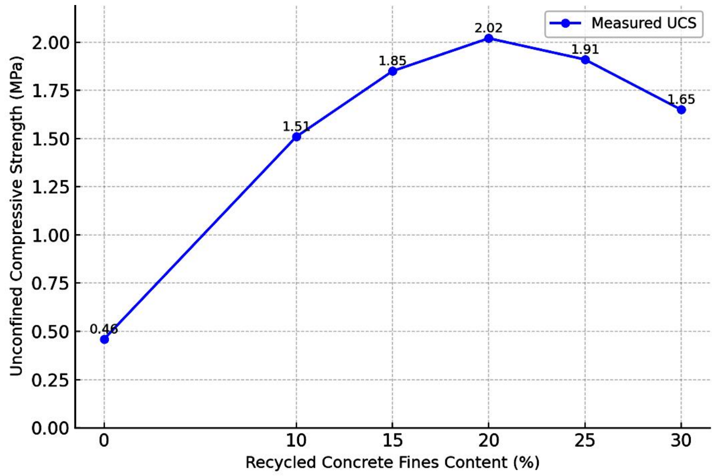

Fig. 5. Unconfined Compressive Strength of Loam Soil Modified with RCF

The results obtained demonstrated that the incorporation of RCF into loam affects soil structure and compactability, forming a denser and more stable framework. However, for the practical implementation of this approach in road construction, it is important to assess not only the modification effect but also the subsequent impact on stabilisation with lime, cement, or other conventional binder systems. To evaluate the effectiveness of stabilisation, 10 % hydrated lime was used, and the mixture compositions are presented in Fig. 6.

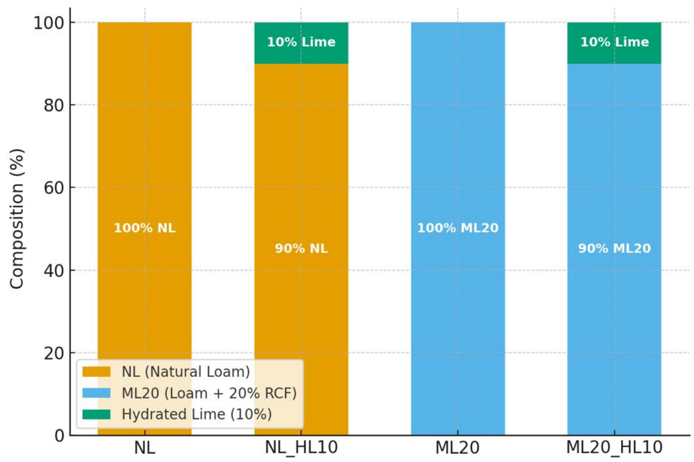

Fig. 6. Composition of soil mixtures with hydrated lime

In accordance with EN 13286-53, specimen compaction was carried out based on the results of the modified Proctor test. For quality control, the degree of compaction (DoC) was used, calculated as the ratio of the actual dry density of the specimen to the maximum dry density obtained from the Proctor test. All prepared cylinders achieved a degree of compaction (DoC) of not less than 0.95, in compliance with the standard requirements and ensuring the reproducibility of the results (Table 3).

Table 3

Compaction characteristics and degree of compaction according to EN 13286-53

Composition of soil	Optimum Moisture Content, OMC, %	Maximum Dry Density, MDD, ρd, g/cm³	Dry density of sample, ρd, g/cm³	Degree of compaction, K $K = \rho d_{sample}/\rho d_{Proctor}$
NL	16.4	1.81	1.81	100
NL_HL10	17.5	1.88	1.86	0.99
ML20	15.0	1.92	1.92	100
ML20_HL10	16.1	1.96	1.93	0.98

Note: the degree of compaction is within the normative range (≥95 %) required by EN 13286-53

The prepared cylindrical specimens were cured for 7, 14, and 28 days under controlled laboratory conditions at a temperature of (20±2) °C and relative humidity above 95 %, without direct contact with water. The interaction of calcium hydroxide with the reactive groups of clay minerals in the loam – specifically aluminum and silicon oxides—leads to the formation of hydraulic products, in particular calcium silicate hydrates (C–S–H) and calcium aluminate hydrates (C–A–H), which provide additional strength gain in the previously modified soil (Consoli et al., 2011).

Fig. 7. Unconfined Compressive Strength (UCS) at Different Curing Times

The higher UCS values observed in the case of lime-stabilised modified loam can be explained by a combined mechanism: inert crystalline RCF particles form a rigid micro-framework that additionally resists external loads and reduces the deformability of the soil matrix, while lime promotes the development of hydraulic products that enhance cohesion and long-term strength (Fig. 7). In contrast, for natural loam stabilised with lime, only a slight strength gain is observed, attributable solely to lime stabilisation.

Conclusions

The incorporation of recycled concrete fines (RCF) into loam improves soil structure through the optimisation of grain-size distribution. As the mineralogical composition of RCF is predominantly represented by highly stable igneous crystals, the effect is mainly mechanical, associated with increased density and deformation resistance of the plastic soil. Fine RCF particles fill the spaces between larger clay aggregates, thereby reducing plasticity and forming a more stable framework. It was established that adding 10–30 % RCF to loam decreases plasticity (PI reduced from 17 % to 9 %). In particular, the compaction parameters confirm enhanced structural stability of the soil due to the skeletal effect of fine inert particles.

According to the modified Proctor test, the most favourable results were observed for loam with 20 % RCF, where the optimum moisture content (OMC) decreased from 16.4 % to 15 % and the maximum dry density (MDD) increased from 1.81 g/cm^3 to 1.92 g/cm^3. Unconfined compressive strength (UCS) tests confirmed that the maximum strength gain was also achieved for loam with 20 % RCF, consistent with the Proctor test results and confirming the optimum additive content. The addition of 10 % hydrated lime increased UCS for both natural loam and the modified ML20 mixture, with the highest value recorded for ML20_HL10 (UCS ≈ 3.3 MPa at 28 days). This highlights the synergy between the mechanical effect of RCF (rigid framework) and the chemical stabilisation by lime through the formation of hydration products. The results obtained demonstrate the potential of the combined approach to clay soil stabilisation, which can be applied to improve technologies in road construction.

List of abbreviations: RCF – Recycled concrete fines; HL – Hydrated lime; LL – Liquid limit; PL – Plastic limit; PI – Plasticity index; OMC – Optimum moisture content; MDD – Maximum dry density; UCS – Unconfined compressive strength; DoC – Degree of compaction.

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ТОНКОДИСПЕРСНИЙ ЗАЛИШОК ПЕРЕРОБЛЕНОГО БЕТОНУ ЯК КОМПОНЕНТ КОМБІНОВАНОЇ СТАБІЛІЗАЦІЇ ГЛИНИСТИХ ҐРУНТІВ ДЛЯ СТАЛОГО ДОРОЖНЬОГО БУДІВНИЦТВА

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У роботі досліджено застосування тонкодисперсного залишку переробленого бетону (RCF) як мінерального модифікатора та гашеного вапна як традиційного стабілізатора глинистих ґрунтів, що використовують у дорожніх основах. Додавання дрібного залишку від переробленого бетону (RCF) до суглинку покращує структуру ґрунту завдяки оптимізації гранулометричного складу. Оскільки мінералогічний склад RCF здебільшого представлений високостабільними кристалічними мінералами, ефект переважно механічний, пов’язаний із підвищенням щільності та стійкості до деформації пластичного ґрунту. Дрібні частинки RCF заповнюють простір між глинистими агрегатами, тим самим зменшуючи пластичність і утворюючи каркас ґрунту. Встановлено, що додавання 10–30 % RCF до суглинку зменшує пластичність (PI зменшується з 17 % до 9 %). Показано, що введення RCF знижує пластичність та покращує процеси ущільнення суглинку завдяки каркасному ефекту інертних кристалічних частинок. Зокрема, параметри ущільнення підтверджують підвищену структурну стабільність ґрунту завдяки скелетному ефекту дрібних інертних частинок. За модифікованим тестом Проктора найсприятливіші результати отримано для суглинку з 20 % RCF: оптимальна вологість (OMC) зменшилася з 16,4 % до 15 %, а максимальна суха щільність (MDD) збільшилася з 1,81 г/см³ до 1,92 г/см³. Випробування на стискання (UCS) показали, що максимальне зростання міцності спостерігалося у суглинку з 20 % тонкодисперсних залишків переробленого бетону (RCF). Це узгоджується із результатами тесту Проктора та підтверджує оптимальний вміст добавки. Додавання 10 % гідратного вапна збільшило UCS як для природного суглинку, так і для модифікованої суміші ML20, причому найвищий показник зафіксовано для складу ML20_HL10 (UCS ≈ 3,3 МПа на 28-му добу). Це свідчить про синергію між механічним ефектом RCF (жорсткий каркас) та хімічною стабілізацією вапном унаслідок утворення продуктів гідратації. Отримані результати демонструють перспективність поєднаного підходу до стабілізації глинистих ґрунтів, що може застосовуватись для удосконалення технологій у дорожньому будівництві.

Ключові слова: перероблений бетонний пил, модифікований суглинок, стабілізація ґрунту, модифікований тест Проктора, міцність на стиск, дорожнє будівництво.