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Mechanical performance and fracture behaviour of roller compacted concrete with organo-mineral additives

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Abstract. In recent years, Roller Compacted Concrete (RCC) has gained increasing attention in pavement construction due to its economic advantages, rapid placement, and the ability to utilize locally available materials. Despite the long history of RCC application worldwide, its use in Ukraine remains limited, which highlights the need for further research and adaptation of this technology to local conditions. An important direction of modern studies is the development of RCC mix designs incorporating partial cement replacement with active mineral additives and the use of a complex plasticizing admixture. This approach aligns with current trends aimed at reducing cement consumption, lowering energy demand, and decreasing CO_2 emissions, thereby contributing to more sustainable and environmentally responsible construction practices. This paper presents the results of experimental investigations of the mechanical properties and microstructure of RCC produced using locally sourced materials. The research methodology included optimizing the mix composition, determining workability parameters, and conducting comprehensive tests on hardened concrete specimens. The results demonstrated that the combined action of the chemical admixture and fly ash promotes densification of the cement matrix, activates hydration processes, and leads to the formation of additional hydration products, resulting in a more uniform and dense microstructure. The optimized RCC mix modified with a superplasticizer and fly ash exhibits a significant increase in compressive and flexural strengths compared to the reference composition. The findings confirm the effectiveness of organo-mineral additives in improving the mechanical performance and durability of RCC, supporting the feasibility of broader implementation of this technology in Ukrainian pavement and industrial construction.

*Keywords**:** roller compacted concrete (RCC), fly ash, superplasticizer, compressive strength, cement replacement.*

Introduction

Analysis of literary sources and problem statement. Roller-compacted concrete (RCC), which gets its name from the construction method used to place it, is a slump-free concrete in the uncured state. It is defined as concrete compacted by a roller according to Reporton Roller-Compacted Mass Concrete (ACI 207.5R-11).

This ensures effective consolidation, which is critical to achieving satisfactory density, strength (compressive strength can be greater than 60 MPa), smoothness, and surface texture. Roller-compacted concrete is manufactured without joints, formwork, finishing, steel reinforcement or dowels.

These properties make compacting concrete with rollers simple, fast and economical. The cost-effectiveness of compacted roller concrete is largely due to high-speed construction methods.

Today, RCC is used when strength, durability and cost-effectiveness are paramount. It is used for the construction and rehabilitation of dams, roads, airfields, parking lots, power plants, roadsides, storage facilities, military installations and other industrial complexes. Depending on the desired thickness and width of the installation, concrete can be placed very quickly - from 60 to 120 meters per hour.

In Ukraine, most cement concrete pavements were built in the 50s...70s of the last century. Almost all of them need repair or have already been repaired using asphalt concrete pavements. Out of about 170 thousand public roads, only 2.4 thousand have cement concrete pavement, which is only 1.4%. In new construction, preference should be given to high-strength concrete pavements (B40 - B60 and above)

Abroad, the estimated service life of rigid pavements is 35-50 years, while in Ukraine it is 25-40 years. The length of roads with cement concrete pavement in Ukraine is about 3 thousand km, which corresponds to a share of 6% for roads with improved pavement [1].

As we can see, despite the significant experience of RCC application in the world, its use in Ukraine remains limited. This is due to a lack of research on optimizing the composition of the mixture adapted to local materials and climatic conditions. An important area of RCC improvement is the introduction of active mineral additives, such as fly ash, as well as the use of modern superplasticizers to improve its physical and mechanical characteristics. This approach helps to reduce cement consumption and, consequently, CO_2 emissions, which meets modern environmental requirements.

Research aim and objectives. The aim of the study is to examine the influence of organo-mineral additives, particularly fly ash and a complex plasticizing admixture, on the physical and mechanical properties, fracture toughness, and microstructure of Roller Compacted Concrete (RCC) produced with locally available materials. To achieve this goal, the study involved an analysis of the current state of RCC application in pavement construction and the feasibility of its implementation under Ukrainian conditions. A modern RCC mix was designed and optimized by partially replacing cement with fly ash and introducing a complex chemical admixture that reduces the water-cement ratio and enhances the concrete’s structural density. Experimental investigations were carried out to determine the mechanical properties, fracture behavior, and microstructural features of hardened RCC, as well as to assess the influence of additives on cement hydration processes. The obtained results made it possible to evaluate the effectiveness of using local materials to improve the strength, durability, and environmental sustainability of concrete pavements.

Materials and methods

The primary binding material in this work was commercial Portland cement CEM I 42.5R, which is readily accessible locally. The cement's mechanical and physical qualities were examined in accordance with DSTU B V.2.7-46:2010, and Table 1 presents the findings.

Table 1. Physical and mechanical properties of the CEM I 42.5R

Specific surface, m^2/kg	Water demand, %	Setting time, min	
		initial	final
340	29.5	160	210

Quartz sand was used as fine aggregate. Its full and partial residues can be seen in Fig. 1.

The role of coarse aggregate was played by gravel of three different fractions (3-8, 5-10, 10-20). Their particle size distribution is shown in Fig. 1.

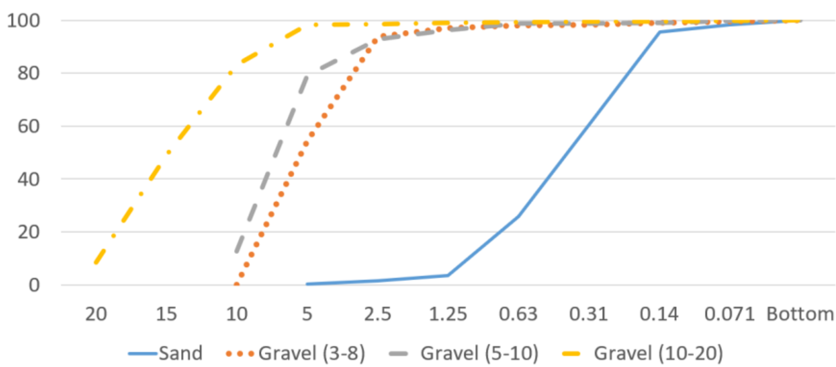

Fig. 1. Granulometric composition of coarse and fine aggregates

Subsequently, fly ash and a chemical admixture with plasticizing and air-entraining effects were used to modify the composition.

All RCC compaction methods involve determining the relationship between density and moisture content in the mixture to achieve maximum density by compacting samples at different moisture levels [2,3].

For a given percentage of cementitious materials, different moisture values are selected, based on which a graph of density versus moisture is drawn. In most cases, the optimal moisture content of aggregates is in the range of 5% to 8%. It is recommended to change the moisture content within these limits, as shown in Figure 1, or within the limits determined on the basis of previous experience with specific aggregates [4,5].

Various methods are available to achieve optimal compaction, such as: proctor method, gyratory compactor, vibration with a load (vibrating hammer) and vibrating table.

In our case, the vibrating hammer was used to form the beam samples, and the proctor method was used to form the cylinder samples.

An organo-mineral additive with a complex air-entraining and plasticizing effect was used as a modifier for rolled concrete. The plasticizing effect is provided by reducing the water-cement ratio (W/C) while maintaining the required rheology of the mixture, which contributes to an increase in the density and mechanical characteristics of concrete. In addition, the mineral component of the additive participates in hydration processes, changing the microstructure of the cement stone and promoting the formation of additional hydrate phases, which improves the adhesion between the cement matrix and the filler [6,7].

To determine the optimal concentration of the additive in the concrete mix, experimental studies were conducted to assess its effect on the rheological, physical, mechanical and fractographic characteristics of the rolled concrete.

Design of concrete composition

The particle size distribution and optimum moisture content of the concrete mix are key factors that influence the formation of its technological properties. The correct selection of the aggregate grain size distribution ensures the density, uniformity and strength of the finished material, while the optimal moisture content contributes to uniform compaction and interaction of the components during rolling. In road concrete, these parameters determine the durability, resistance to external influences and efficiency of the technological process of pavement construction.

In the available literature, the influence of particle distribution on the mechanical, durability, and freshness properties of concrete made by vibropressing has been studied. It is noted that many of these properties depend on the distribution of particles and their specific surface. In addition, the hardened and fresh characteristics of cemented material also depend significantly on the particle size distribution and their surface.

The main goal of all methods of selecting the composition of cement concrete is to create such a packing of aggregate particles that leads to the maximum concrete density at all levels of its structure for each specific case, and to reduce porosity. This will increase not only the strength characteristics of concrete, but, above all, its durability in aggressive environments. This is especially important for road concrete, which constantly operates under the simultaneous effects of mechanical loads from traffic, climatic factors and liquid salt media. The ratio of coarse to fine aggregate plays a special role in increasing the density of concrete [8,9].

Cement is the bonding agent in a concrete mix that ensures its bonding and strength. A large amount of cement can lead to excessive strength, but it can also increase costs and degrade workability. According to the particle size distribution, the optimal amount of cement is added to achieve the required strength and workability of the concrete. The amount of cement used should be kept to a minimum, but the proper strength should be achieved [10].

In our case, it was decided to form three compositions of concrete mix with different cement content. Since C-220 showed the best density and strength characteristics, it was decided to approve it as a control composition and further modify it with organic admixture (fly ash - 100 kg per m^3 and plasticizing additive with air-entraining effect - 0.6 percent by weight of cement C-220M). The composition of the mixtures is given in Table 2.

Table 2. Compositions of cement concrete mixtures

	C-260	C-280	C-220	C-220M
Cement	260	280	220	220
Fly ash , kg	-	-	100	100
Sand	735	710	680	662
Gravel (3-8)	125	120	125	120
Gravel (5-10)	386	386	386	386
Gravel (10-20)	764	764	764	764
Water	117	117	117	109
Admixture, kg	-	-	-	1,9
Vebe time	38	32	39	36
Average density kg/m3	2451.9	2437.2	2470.2	2447.1

Test results

To evaluate the physical and mechanical characteristics of concrete, standard cubic samples measuring 10×10×10cm were tested, made from different concrete mix compositions: C-260, C-280, C-220, and a modified composition C-220M, which contained an organo-mineral additive (fly ash and a complex plasticizer with air-entraining action). After forming, the samples were kept under normal curing conditions (t = 20 ± 2 °C, φ = 95 ± 5 %) until compression testing at 28 and 56 days.

The tests were performed in accordance with the requirements of standards on a hydraulic press with a constant loading rate. Three samples were tested for each composition, and the results were used to determine the average compressive strength. The results are shown in Fig 2.

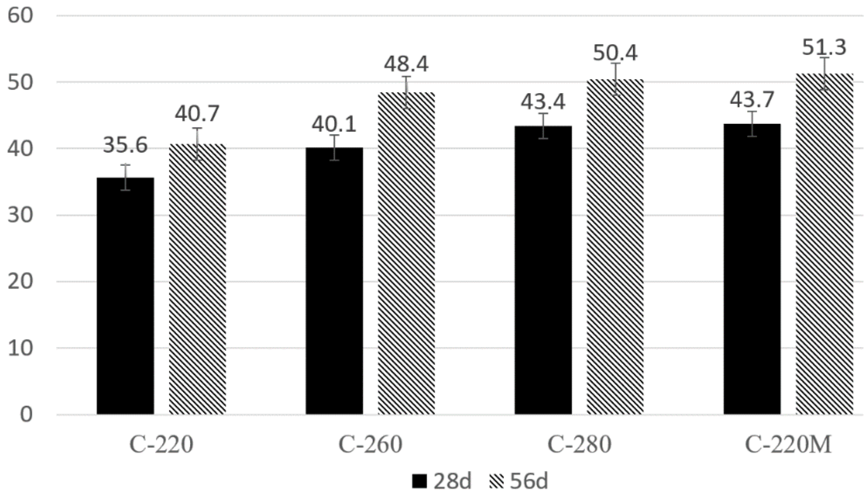

Fig. 2. Compressive strengths at 28 and 56 days, MPa.

The analysis of the results shows that the introduction of an organo-mineral additive significantly affected the strength characteristics of concrete. For the base composition C-220, the average compressive strength was about 42.7 MPa on day 28. The addition of a plasticizer and fly ash to the C-220M composition increased this indicator to 49.5 MPa, after further hardening for 56 days, the strength increased to 54.2 MPa.

The increase in strength can be explained by several factors. First, the introduction of a superplasticizer made it possible to reduce the water-cement ratio without deteriorating the rheological properties of the mixture, which contributed to the compaction of the cement stone and a decrease in porosity. Second, finely dispersed fly ash exhibited pozzolanic activity, entering into secondary hydration reactions with the formation of additional calcium hydrosilicates, which fill micropores and increase the density of the microstructure. As a result, the structure of the concrete became more homogeneous, and the bond between the cement matrix and the aggregate grains became stronger.

This improvement is a key indicator of long-term durability, especially for concrete exposed to freeze–thaw cycles and the action of de-icing salts in real operating conditions. These findings collectively confirm the positive influence of the organo-mineral additive on both the mechanical and durability-related characteristics of roller-compacted concrete.

Conclusions

The results of the experiments showed that the physical and mechanical qualities of roller-compacted concrete (RCC) are much enhanced by the addition of a complex organo-mineral additive that combines the action of fly ash and a plasticizer with an air-entraining effect. When these factors work together, the cement matrix develops more favorably during the hardening process. The material's density and homogeneity noticeably rise as a result of the water-to-cement ratio being reduced, the cement stone structure being compacted, and the hydration processes being more intense. The adjusted mixture exhibits better performance under normal stress circumstances and a more stable structure that is less likely to produce internal flaws.

Furthermore, by optimizing the internal pore structure, these additives help create a material that is more resilient to environmental impacts. A more continuous and defect-resistant cement matrix is formed as a result of the enhanced microstructural development, which is crucial for the long-term performance of RCC under actual operating circumstances. The observed alterations are in line with broad patterns documented in recent research on the use of chemical and mineral admixtures to modify cement-based composites.

The findings verify that adding a complicated organo-mineral to roller-compacted concrete is feasible. By using industrial by-products, this modification allows for the simultaneous improvement of concrete's strength and structural density, reduction of cement consumption, and enhancement of production's environmental performance. In addition to the immediate mechanical advantages, using these additives supports more sustainable material design concepts, which are in line with the current worldwide trend toward resource efficiency.

The enhanced C-220M composition shows promise for use in road and hydraulic engineering projects, where the material must be more durable due to extended static and dynamic stresses. Longer service life and lower maintenance requirements can be supported in these areas by the increased material homogeneity and structural stability obtained via the application of organo-mineral additives.

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Механічні характеристики та поведінка при руйнуванні укочуваного бетону з органо-мінеральними добавками

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Анотація. Останніми роками укочуваний бетон (RCC) привертає все більшу увагу у сфері дорожнього будівництва завдяки своїм економічним перевагам, високій швидкості укладання та можливості використання доступних місцевих матеріалів. Незважаючи на тривалу історію застосування RCC у багатьох країнах світу, в Україні ця технологія поки що застосовується обмежено, що зумовлює потребу у поглибленому вивченні її ефективності. Важливим напрямом сучасних досліджень є розроблення рецептури RCC із частковою заміною цементу активними мінеральними добавками та використанням комплексного пластифікатора. Такий підхід відповідає актуальним тенденціям зменшення цементозатрат, енергоспоживання та скорочення викидів CO_2, що є ключовим для підвищення екологічної стійкості будівництва. У статті представлено результати експериментальних досліджень механічних властивостей і мікроструктури RCC, виготовленого з використанням місцевих вихідних матеріалів. Методика роботи охоплювала оптимізацію складу бетонної суміші, визначення параметрів укладальності та комплексне випробування зразків у затверділому стані. Отримані результати засвідчили, що поєднання комплексної хімічної добавки та золи винесення сприяє ущільненню мікроструктури цементного каменю, активізації гідратаційних процесів і формуванню додаткових гідратних фаз, що позитивно позначається на рівномірності та щільності структури матеріалу. Оптимізований склад RCC, модифікований суперпластифікатором та золою винесення, забезпечує суттєве підвищення міцності на стиск порівняно з контрольним зразком. Отримані дані підтверджують перспективність використання органо-мінеральних добавок для покращення механічних характеристик та довговічності укочуваного бетону, що створює підґрунтя для ширшого впровадження цієї технології в дорожньому та промисловому будівництві України.

*Ключові слова**:** укочуваний цементобетон, зола виносу, міцність суперпластифікатор, заміна цементу.*