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EFFECTS OF PLASTICIZING ADMIXTURES ON THE PERFORMANCE OF LOW-CARBON CONCRETES

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The article presents research results on the influence of technological parameters on the technical and environmental characteristics of low-carbon ready-mix concretes. The study examines the impact of aggregate gradation, cement content, lignosulfonate or polycarboxylate modifiers, and wet fly ash additives on concrete properties. The research demonstrates that clinker- and CO_2-intensity indicators collectively determine the clinker efficiency of concrete. It was established that optimizing aggregate granulometry through the introduction of 2–5 mm crushed stone fraction in combination with a polycarboxylate superplasticizer contributes to the formation of a dense microstructure in the cementitious matrix. This approach ensures obtaining the specified concrete strength class with reduced cement consumption. The research confirms that the rational combination of technological factors affecting concrete mixtures opens prospects for creating modern low-carbon ready-mix concretes that meet sustainable development requirements.

Keywords: low-carbon ready-mix concretes, aggregate gradation, lignosulfonates and polycarboxylate ethers, wet fly ash, efficiency indicators, CO_2 emission indicators.

Introduction

The relevance of the work – the problem of climate change caused by increased carbon dioxide (CO_2) emissions is one of the largest environmental threats of our time (Schneider M., 2019). According to international research, anthropogenic CO_2 emissions caused by industry, transportation, and energy are the main causes of global warming and climate balance disruption, (Watari T., 2022, Promise D.). In Ukraine, there is an increase in industrial CO_2 emissions, and this problem requires active intervention and solution searching (Sanytsky M. a.o., 2021). One of the main sources of CO_2 in the construction sector is the production of building materials, particularly concrete production. The main component of concrete is Portland cement – one of the most carbon-intensive materials, accounting for about 8 % of global carbon dioxide emissions (Damineli B., 2010; Scrivener K., 2018).

According to the requirements of the Paris Agreement, adopted in the UN Framework Convention on Climate Change (UNFCCC), from 2020 to 2050, it is necessary to implement a global low-carbon development strategy aimed at limiting the increase in the planet's average temperature to a level significantly lower than 2 °C (Sabbie A., 2017). By 2030, CEMBUREAU plans to reduce CO_2 emissions during concrete production and construction by 40 %. Specific CO_2 emissions should be reduced to 83.4 kg CO_2 per 1 ton of concrete (Althoey F., 2023). To reduce the ECO_2 indicator, partial replacement of Portland cements in concrete with active mineral additives, particularly thermal power plant fly ash, is envisioned, which is a relevant approach to achieving balanced development in construction (De Grazia, 2023).

To implement the Paris Agreement in the context of measures to reduce climate changes, Ukraine must complete a series of conceptual tasks and strategic steps, including activating the implementation of low-carbon development principles. To achieve this task in the construction industry, several approaches are being considered. Thus, optimization of aggregate composition, that is, the correct selection of different sand and gravel fractions, will minimize the specific surface areas of aggregates in concrete, increasing its density and reducing cement binder consumption (Sanytsky M. a.o., 2024).

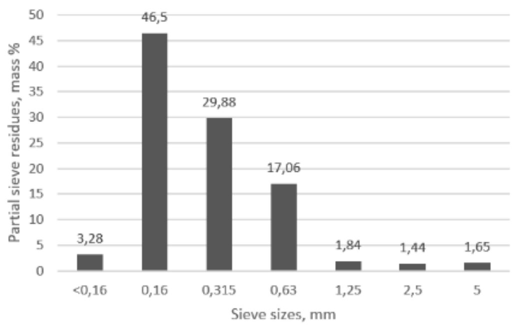
One of the main directions in concrete science is the use of plasticizing additives, such as lignosulfonates and polycarboxylate ethers, which have different effects on the strength of low-carbon concretes. The main difference between these two types of plasticizing additives lies in their effectiveness and impact on early concrete strength. Lignosulfonates provide a moderate plasticizing effect but can reduce early strength, while polycarboxylate ethers provide a significant plasticizing effect and increase the final concrete strength. Therefore, identifying the effects of plasticizing additives contributes to developing methods to increase concrete mixture mobility, which positively affects concrete strength and durability (Rykhlitska O. a.o., 2022). Adding thermal power plant fly ash to the modified concrete mixture provides not only cement savings but also environmental benefits.

The design level of strength and operational properties of low-carbon concretes is achieved through quality composition design, selection of modifying additives, care, bringing the quality of concrete products to the necessary technical condition at the operation stage, and economic efficiency (Kumar A., 2023). One of the most promising ways to achieve this task is to replace part of the cement with other components that have a lower carbon footprint. Such a solution not only reduces CO_2 levels but is also capable of affecting the final product cost, reducing expenses for cement – one of the most expensive components of the concrete mixture. The obtained results can be used in various construction areas where environmental friendliness and reduction of production costs are important (Giergiczny Z., 2020; Zunino F.).

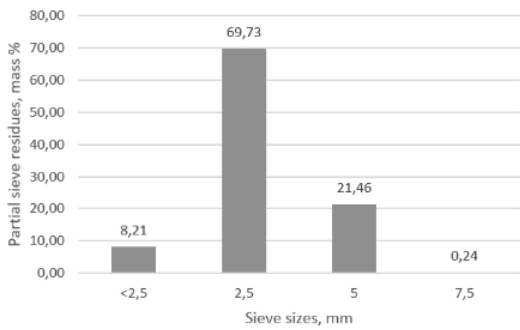
The aim of this work is to assess the impact of aggregate grain composition and modifiers on technical and environmental performance indicators of low-carbon concretes.

Materials and Methods

For the research, Portland cement CEM II/A-LL 42.5R with an activity of 52.0 MPa was used. Chemical composition of Portland cement clinker in %: CaO = 66.18; SiO_2 = 21.44; Al_2O_3 = 5.22; Fe_2O_3 = 4.84; MgO = 0.95; SO_3 = 0.72; R_2O = 0.65. Mineralogical content in %: C_3S = 62.2; C_2S = 15.18; C_4AF = 12.8. For the production of commercial concrete, quartz sands from the Mykolaiv deposit were used with a fineness modulus of FM = 1.70. For research, granite crushed stone of two fractions was applied: 2–5 mm and 5–20 mm. The grain composition of the aggregates is shown in Fig. 1.



a



b

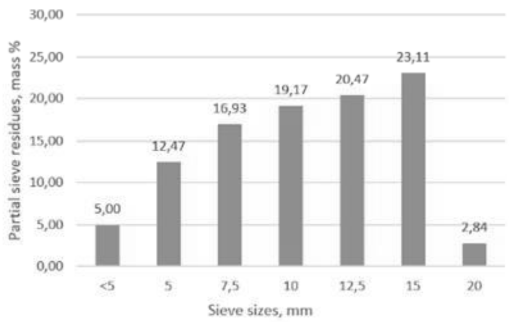


Fig. 1. Fractional compositions of sand (a); crushed stone 2–5 (b); crushed stone 5–20 (c)

c

The calculation of the sieve distribution curve for the fine and coarse aggregate mixture (Fig. 2) was conducted in accordance with DSTU-N B V.2.7-299:2013 (Guidelines for Determining Heavy Concrete Composition, Chapter 7, Section 7.4). The graphical dependence shows the cumulative percentage of particles passing through sieves of various sizes, ranging from 0.16 mm to 20 mm. The granulometric composition curve of the aggregates characterizes the actual aggregate mixture (sand, crushed stone 5–20 mm, and crushed stone 2–5 mm) used to obtain concrete. As shown in Fig. 2, *b,* the designed curve of the aggregate mixture grain composition indicates a satisfactory distribution of particles across different size ranges, which is crucial for ensuring the workability of the concrete mixture and concrete strength.

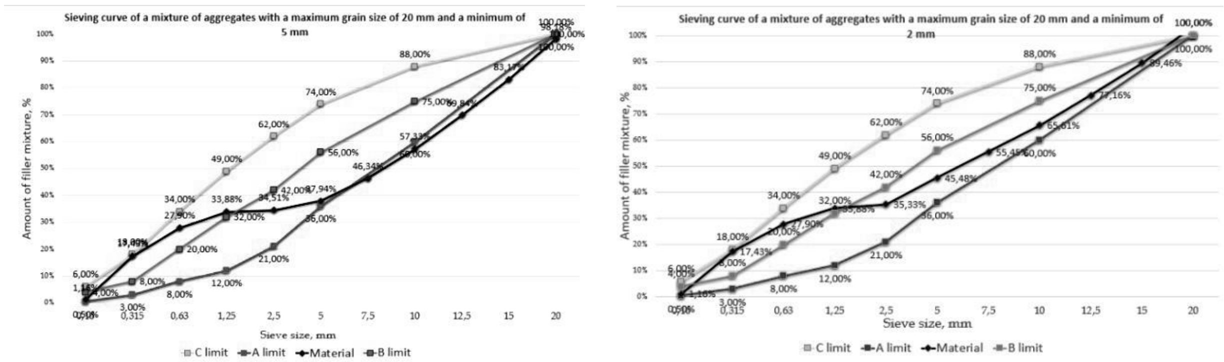
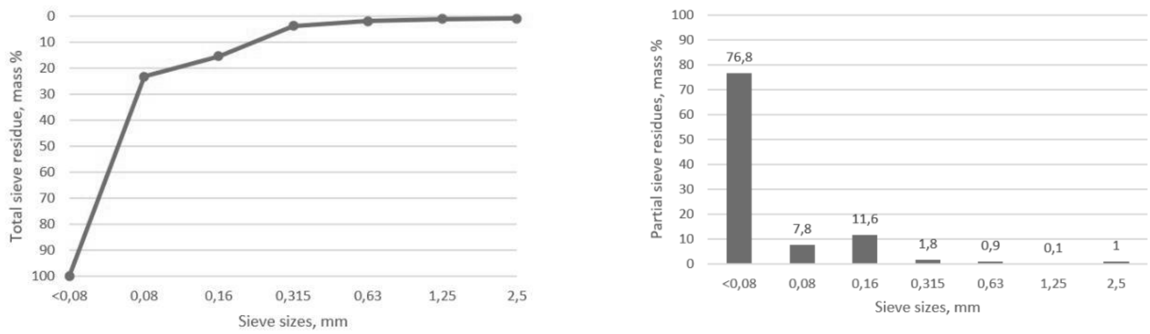


Fig. 2. Grain composition curves of mixtures sand – crushed stone 5–20 (a) and sand – crushed stone 2–5 – crushed stone 5–20 (b)

As an active mineral additive to the concrete mixture, wet fly ash was added, the sieving results of which are presented in Fig. 3, *a, b*. The specific surface area of the fine fraction of this fly ash is 390 m²/kg. This indicates that wet fly ash as an active mineral additive can improve concrete performance (Sanytsky M. a.o., 2024).



a *b*

Fig. 3. Scattering curve (a) and fractional composition of wet fly ash (b)

To improve the quality indicators of concrete mixtures and concretes, a lignosulfonate plasticizer Centrament N9 and a polycarboxylate superplasticizer Muraplast FK 59 were used. The technical characteristics of the additives are as follows: Centrament N9: ρ = 1.145–1.155 kg/dm³; dosage 2–15 g per 1 kg of cement; maximum chloride content – <0.1 %, alkali content – <1.0 %; Muraplast FK 59: ρ = 1.07–1.13 kg/dm³; dosage 2–20 g per 1 kg of cement; maximum chloride content – <0.1 %, alkali content – <4.0 % (MC-Bauchemie Technical Sheets).

Results and discussion

To determine the optimal composition of low-carbon concretes of strength class C20/25, five concrete mixture compositions with different cement consumption were developed and investigated. Calculation of the control composition per 1 m^3 of concrete according to the Bolomey formula showed a Portland cement consumption of 350 kg at *W/C* = 0.62. The experimental study was based on a comparative analysis of concrete characteristics with different compositions to determine the most effective combination of components for achieving optimal strength and environmental performance.

The efficiency criteria for plasticizing additives during concrete mixture testing at constant water-cement ratio and consistency can be evaluated according to DSTU B V.2.7-171:2008. During the experimental studies, the following indicators were determined for each composition:

– Cone slump; bulk density; compressive strength at different hardening periods; environmental performance indicators (carbon footprint).

– Concrete mixture compositions are presented in Fig. 4. The workability of mixtures I–V was CS = 21 cm, with the following average densities: Composition I: ρ = 2384 kg/m³; Composition II: ρ = 2410 kg/m³; Composition III: ρ = 2420 kg/m³; Composition IV: ρ = 2432 kg/m³; Composition V: ρ = 2434 kg/m³.

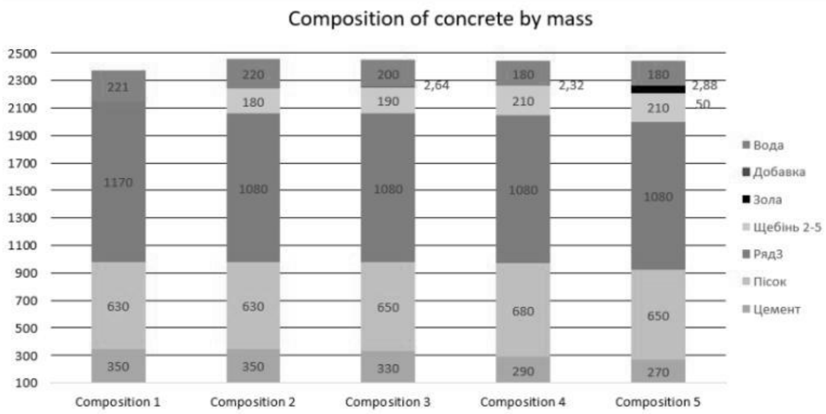


Fig. 4. Concrete compositions by mass

As shown in Fig. 5, for the control composition with Portland cement CEM II/A-LL 42.5 consumption at 350 kg/m³ and a water-cement ratio of 0.62, a strength of 37.91 MPa is achieved after 28 days of hardening. At the same time, with the introduction of plasticizing additives due to the water-reducing effect, an increase in concrete strength is achieved, which allows reducing Portland cement consumption in concrete by 15–20 % while maintaining the specified concrete class. The proposed concrete composition optimization, which includes reducing Portland cement consumption by 23 % (from 350 to 270 kg/m³) by introducing moistened fly ash at 50 kg/m³, optimizing aggregate granulometry, and using the MC Muraplast FK 59 superplasticizer, provides an economic effect. Simultaneously, the strength of concrete compositions IV and V with PCE additive increased to 43.9 and 44.65 MPa after 28 days, respectively. However, this superplasticizer can cause a retarding effect, which leads to some reduction in the early strength of the above concretes.

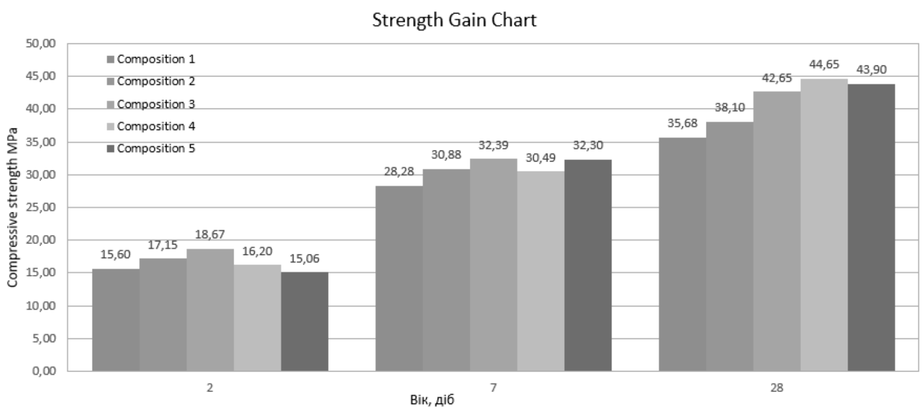
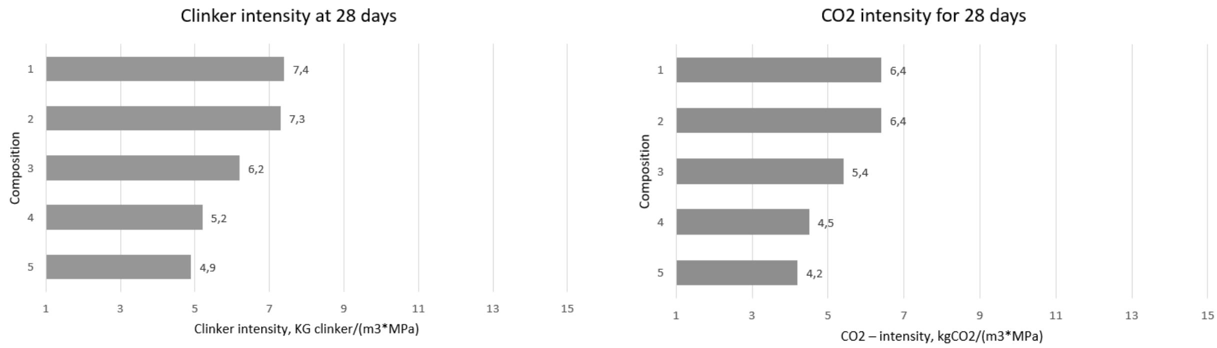


Fig. 5. Kinetics of strength gain of concretes of compositions I–V

The environmental indicators (Fig. 6) of the concrete compositions were determined taking into account the clinker content in Portland cement CEM II/A-LL 42.5R at the level of 80 %. It follows that the clinker and CO_2 intensity indicators decrease for compositions with modifier additives. Thus, composition *V*, compared with composition I, is characterized by a reduced value of clinker and CO_2 intensity by 34 %, which indicates a significant environmental effect.



a *b*

Fig. 6. Clinker intensity (a) and CO_2 intensity (b) of concrete after 28 days of hardening

By the method of quantitative X-ray phase analysis using the Rietveld method for the cementing matrix of sample V, a relatively high content of ettringite (14.9 %) was established. Ettringite is a hydration product formed as a result of reactions between cement, calcium sulfate, and water. The elevated content of calcium carbonate $CaCO_3$ is 25.8 %, resulting from limestone additives in the cement composition and carbonization of part of the calcium hydroxide. Calcium hydroxide $Ca(OH)_2$ (13.3 %) is also recorded – a product of the alite phase hydrolysis. The diffractogram also reveals silica (SiO_2, 18.7 %) as part of the fine aggregate – sand.

Thus, the introduction of plasticizing additives in low-carbon concrete affects the rheology of the mixture, structure compaction, and hydration processes, leading to increased concrete strength. Concrete with LS additive is more affordable and suitable for standard construction works but requires more time to gain strength. Concrete with PCE is more effective in the long-term perspective, providing increased strength and ensuring significant CO_2 reduction due to lower cement consumption (Nagrockienė D., 2013; Dvorkin L. 2023). Minimizing cement content by introducing mineral additives (wet fly ash) and effective plasticizers ensures achieving an environmentally optimal composition of low-carbon concrete and achieving an economic effect of 320 UAH/m³. With an annual production of 30,000 m³ of concrete, the total CO_2 emissions reduction will be 1,737 tons, which is a significant contribution to the sustainable development of the construction industry.

Conclusions

The use of Centrament N9 plasticizer in Composition III showed a significant positive effect. By reducing water consumption by 9.5 % and cement by 5.7 %, the concrete strength at 28 days increased to 42.65 MPa, which is 19 % higher than the baseline composition. The application of Muraplast EK59 superplasticizer in composition IV proved even more effective – with a reduction in water consumption by 18.6 % and cement by 17.1 %, strength reached 44.65 MPa, which is 25 % higher than the baseline composition.

The proposed optimization of concrete composition, which includes reducing Portland cement consumption by 23 % (from 350 to 270 kg/m³), introducing 50 kg/m³ of moistened fly ash, optimizing aggregate granulometry, and using MC Muraplast FK 59 superplasticizer, allowed achieving technical and economic effects. From a technical perspective, the developed concrete composition demonstrates improvement in key characteristics: compressive strength increased by 23 % (from 35.68 to 43.98 MPa), clinker intensity decreased by 34 % (from 7.4 to 4.9 kg/(m³·MPa)), and CO_2 intensity also reduced by

34 % (from 6.4 to 4.2 kg/(m³·MPa)). The ecological aspect of the development is characterized by a significant reduction in the production carbon footprint. A comprehensive analysis of the obtained results convincingly proves that the developed concrete composition using moistened fly ash from the Burshtyn Thermal Power Plant is a technically effective, economically profitable, and environmentally appropriate solution that meets modern construction industry requirements and sustainable development principles.

Prospects for further research

Increasing the clinker efficiency of concretes is achieved through a combination of a number of technological factors that determine the creation of a dense cementing matrix structure. In further research, the influence of various types of low-emission cements and modifiers on the durability of low-carbon concretes should be presented with the aim of improving their operational reliability (Dvorkin L., 2023).

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ВПЛИВ ПЛАСТИФІКУЮЧИХ ДОБАВОК НА ВЛАСТИВОСТІ НИЗЬКОВУГЛЕЦЕВИХ БЕТОНІВ

У статті наведено результати досліджень впливу технологічних чинників на технічні та екологічні індикатори ефективності бетонів. Розглянуто вплив гранулометричного складу заповнювачів, витрати цементу, лігносульфонатних або полікарбоксилатних модифікаторів, добавки зволоженої золи-винесення на властивості бетонів. Дослідження демонструє, що показники клінкер- та CO_2-інтенсивності у сукупності визначають клінкер-ефективність бетону. Використання лігносульфонатного пластифікатора Centrament N9 для бетону показало, що за зниження витрати води на 9,5 % та цементу на 5,7 %, міцність бетону на 28-му добу зросла до 42,65 МПа, що на 19 % перевищує показники контрольного складу. Встановлено, що оптимізація гранулометрії заповнювачів через введення щебеневої фракції 2–5 мм у поєднанні із полікарбоксилатним суперпластифікатором сприяє формуванню щільної мікроструктури цементуючої матриці. Запропоновано склади бетону зі зниженою витратою портландцементу на 23 % (від 350 до 270 кг/м^3) за рахунок введення золи-винесення зволоженої в кількості 50 кг/м^3, оптимізації гранулометрії заповнювачів та застосування суперпластифікатора MC Muraplast FK 59, що дало змогу досягти технічного та економічного ефектів. З технічного погляду, розроблений склад бетону демонструє покращення основних характеристик: міцність на стиск зросла на 23 % (з 35,68 до 43,98 МПа), клінкер-інтенсивність знизилась на 34 % (з 7,4 до 4,9 кг/(м^3·МПа)), а CO_2-інтенсивність зменшилась на 34 % (з 6,4 до 4,2 кг/(м^3·МПа)). Такий підхід забезпечує отримання заданого класу міцності бетону за зниженої витрати цементу. Мінімізація вмісту цементу введенням активної мінеральної добавки (зволоженої золи-винесення) та ефективних суперпластифікаторів забезпечує одержання екологічно оптимального складу низьковуглецевого бетону з досягненням економічного ефекту 320 грн/м^3. Дослідження підтверджує, що раціональне комбінування технологічних факторів впливу на бетонні суміші відкриває перспективи створення сучасних низьковуглецевих товарних бетонів, які відповідають вимогам сталого розвитку.

Ключові слова: низьковуглецеві товарні бетони, гранулометричний склад заповнювачів, лігносульфонати та полікарбоксилатні етери, зволожена зола-винесення, індикатори ефективності, показники емісії CO_2.