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THE EFFECT OF PARTIAL REPLACEMENT OF CEMENT WITH FLY ASH ON THE STRENGTH OF CONCRETE FOR TRANSPORTATION STRUCTURES AND ROAD PAVEMENTS

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Abstract. The effect of replacing part of the cement with fly ash on the strength of concrete for transportation structures and road pavements has been determined.

Portland cement CEM II/A-S 500, crushed stone (5–20 mm fraction), quartz sand with fineness modulus of 2.3, the superplasticizer Polyplast SP-1, and fly ash from the Darnytsia Thermal Power Plant were used in concrete production. The properties of three concrete compositions were investigated. Composition No. 1 (without fly ash) served as the control, with 300 kg/m³ of Portland cement used as the binder. In composition No. 2, 10% of the Portland cement was replaced with 75 kg/m³ of fly ash. In composition No. 3, 20% of the Portland cement was replaced with 150 kg/m³ of fly ash. All concrete compositions included 2.4 kg/m³ of superplasticizer.

All concrete mixtures exhibited equal workability (S1), with the water/cement ratio (W/C) depending on the composition. For the control composition No. 1, the W/C ratio was 0.390. For composition No. 2, the actual W/C ratio, calculated as the total binder content (cement and fly ash), was 0.333. For composition No. 3, the W/C ratio was 0.308. Thus, as the proportion of fly ash in the binder increased, the W/C ratio of the mixtures decreased.

The average density of the control concrete (composition No. 1) and composition No. 2 was approximately equal (2441 kg/m³ and 2446 kg/m³, respectively), while composition No. 3 exhibited a slightly lower density (2423 kg/m³). This can be explained by the fact that replacing part of the cement with a larger mass of fly ash reduces the W/C ratio while simultaneously increasing the spacing of coarse aggregates.

Compressive strength was measured at 7 and 28 days. At 7 days, the compressive strength of composition No. 2, where 30 kg/m³ of cement was replaced with 75 kg/m³ of fly ash, was 6.8% lower than that of the control (composition No. 1). However, at 28 days, the compressive strength of composition No. 2 was 3.8% higher than that of the control. For composition No. 3, replacing 60 kg/m³ of cement with 150 kg/m³ of fly ash resulted in a 28.3% decrease in compressive strength at 7 days and a 14.0% decrease at 28 days compared to the control. Thus, concretes containing fly ash demonstrated slower strength gain compared to concrete using only Portland cement as the binder. Replacing 10% of the Portland cement with a rational amount of fly ash produced concrete with strength comparable to that of the control composition. However, replacing 20% of the Portland cement was not fully compensated by the fly ash.

Therefore, the use of fly ash in concrete for transportation structures and road pavements is both feasible and effective. The introduction of a rational amount of fly ash reduces binder consumption, which has significant ecological benefits and is economically viable.

Keywords: fly ash, concrete, transportation structures, rigid pavement, superplasticizer, strength.

Introduction. A global trend today is the gradual increase in road construction, particularly with rigid pavements. Road construction requires significant quantities of cement concrete for the construction of various types of transportation structures and, in the case of rigid pavements, directly for pavement layers. In Ukraine, as a result of the full-scale invasion, a substantial portion of the transportation infrastructure has been damaged and requires restoration, which will necessitate extensive use of concrete. During the post-war recovery phase, the volume of concrete works in transportation construction is expected to increase further.

One of the strategic goals of sustainable development, as outlined in the UN Framework Convention on Climate Change, is to implement measures to reduce carbon dioxide emissions. The cement industry is a significant producer of CO_2 , making the use of industrial by-products in concrete, capable of replacing part of the cement, along with efficient modifiers, a key aspect of Ukraine's low-carbon development as a European state [1].

An effective secondary material that reduces binder consumption in concrete is fly ash, a by-product of thermal power plants. Thus, the use of fly ash is both environmentally beneficial, due to reduced CO_2 emissions, and economically advantageous [2, 3]. However, in Ukraine, fly ash is rarely used in concretes for transportation structures, and even less so for road pavements. This is due to the specific performance requirements for such concretes on the one hand and the limited experience in using this by-product in transportation construction on the other. Therefore, research into the feasibility of partially replacing cement with fly ash in concretes for transportation structures and road pavements, while ensuring the necessary levels of strength and durability, remains relevant.

Analysis of Research and Publications. Fly ash is a fine-grained product formed from the mineral components of fuel during combustion and collected in specialized filters [3, 4]. Ukraine has a well-developed network of thermal energy plants that produce significant amounts of by-products, including fly ash [5, 6]. The predominant component of fly ash is a vitreous aluminosilicate phase, which consists of spherical particles with hydraulic activity [4]. Thus, fly ash serves as an active mineral admixture that increases the total binder content in concrete. Simultaneously, fly ash acts as a microfiller, influencing the physicochemical processes at the interface between the cement paste and aggregate [7]. Its use reduces the amount of calcium hydroxide formed during the hydration of the binder, thereby improving the corrosion resistance of concrete [2, 7, 8].

In concrete production, fly ash is used either to partially replace cement [4, 7-10] or as a pozzolanic additive [2, 7, 10-12]. Researchers have often determined that replacing approximately 15-20% of the cement mass with fly ash is effective [3, 10]. However, under certain conditions, even greater amounts of binder can be replaced without compromising material properties. For instance, in [9], 80% of the cement in self-compacting concrete was replaced with a combination of industrial by-products, including fly ash, silica fume, and ground granulated blast furnace slag, without reducing compressive strength. This replacement also decreased the concrete's permeability to chloride ions. A similar effect of reduced permeability was observed in studies [11, 12]. In [2], the use of fly ash combined with silica fume and zeolite improved the quality of composite cements and accelerated the concrete production process. Importantly, unlike other pozzolanic additives (such as zeolite or silica fume), fly ash does not require increased dosages of superplasticizer to maintain mix workability. In [12], the fly ash content in concrete ranged from 30% to 40% of the total binder content, with concrete strength ranging from 65 MPa to 85 MPa. Concrete samples with fly ash also exhibited reduced shrinkage compared to control samples. In [13], the incorporation of fly ash enhanced the strength and durability of road pavement concretes, with the maximum effect achieved when fly ash was used in combination with silica fume.

However, when using fly ash to replace part of the cement, it is important to consider that its impact on concrete properties varies depending on the type of cement, the percentage of binder replaced, and the curing conditions [14]. The composition and structure of fly ash are also non-uniform and depend on many factors, including the type of fuel burned, its ash content, and fineness of grinding, combustion temperature, and the residence time of particles in the combustion zone [6].

In the practice of road construction in Ukraine, fly ash is primarily used to stabilize subgrade layers [15], particularly to improve the properties of soil-cement [16]. The Ukrainian standard SOU 42.1-37641918-104:2013, "Fly Ash and Ash-Slag Mixtures from Thermal Power Plants for Road

Works. Technical Specifications," permits the use of fly ash in preparing cement concrete mixes for rigid pavement structures, as well as for concrete products for bridges and culverts [17]. Additionally, [18] highlights the potential for using fly ash in road and airfield construction, particularly in prestressed slabs and monolithic cement concrete pavements.

Therefore, given the available raw material base and the urgent needs of Ukraine's economy, research aimed at improving the efficiency of fly ash use in transportation construction is highly relevant.

The objective of this study is to determine the effect of replacing part of the cement with fly ash on the early-age and design strength of concrete for transportation structures and road pavements.

Materials and Methods. The following materials were used in the experiment for concrete production:

– Portland cement CEM II/A-S 500, manufactured by PJSC Dyckerhoff Cement Ukraine.

– Crushed stone (fraction 5–20 mm) sourced from the Novyi Buh district, Mykolaiv region.

– Quartz sand with a fineness modulus of 2.3, sourced from the Voznesensk district, Mykolaiv region.

– Superplasticizer Polyplast SP-1.

– Fly ash from the Darnytsia Thermal Power Plant (Kyiv).

The properties of three concrete compositions for transportation structures and road pavements were investigated. Composition No. 1 (without fly ash) served as the control, where only Portland cement was used as the binder in the amount of 300 kg/m³. In composition No. 2, 10% of the Portland cement was replaced with 75 kg/m³ of fly ash. In composition No. 3, 20% of the Portland cement was replaced with 150 kg/m³ of fly ash. All mixes included a superplasticizer in the amount of 2.4 kg/m³, which constituted 0.8% of the cement mass in the control composition No. 1. The dosage of superplasticizer remained unchanged when a larger mass of fly ash replaced part of the cement.

All concrete mixes exhibited equal workability, classified as S1, with a slump of 3–4 cm. This corresponds to the requirements of DBN V.2.3-4:2015 "Automobile Roads" [19] for mix workability when using slipform pavers (1–5 cm, depending on the paving speed). Additionally, mixes with this level of workability can be used for producing components of transportation structures. The workability of all concrete mixes was achieved by adjusting the water content with corresponding corrections to the mix design. The compositions of the investigated concretes are presented in Table 1.

Table 1 – Compositions of the Investigated Concretes

No. of composition	Concrete composition, kg/m³					
	Cement	Fly Ash	Crushed Stone	Sand	Superplasticizer	Water
1	300	-	1275	775	2.4	117
2	270	75	1270	735		115
3	240	150	1265	690		120

The workability of the concrete mixtures was determined in accordance with DSTU B V.2.7-114:2002 "Building Materials. Concrete Mixtures. Test Methods" [20]. The compressive strength of the concretes was measured according to DSTU B V.2.7-214:2009 "Building Materials. Concretes. Methods for Determining Strength Using Control Samples" [21].

Results of the Study. Since all concrete mixtures exhibited equal workability, their water-to-cement ratio (W/C) depended on the composition. For the control composition (No. 1), the W/C ratio was 0.390. For composition No. 2, the actual W/C ratio–calculated as the sum of cement (270 kg/m³) and fly ash (75 kg/m³) – was 0.333. For composition No. 3, the W/C ratio, based on the total binder content (cement 240 kg/m³ + fly ash 150 kg/m³), was 0.308. This calculation can be considered methodologically correct since fly ash has a particle size distribution similar to that of cement.

The gradual decrease in the W/C ratio as the proportion of fly ash in the binder increased confirms a well-known materials science principle that this mineral admixture improves the workability of the concrete mixture [10, 11]. In this experiment, the reduction in the W/C ratio was also partly due to the fact that the total amount of binder (cement + fly ash) in composition No. 2 was 45 kg/m³ greater than in composition No. 1, and in composition No. 3, it was 90 kg/m³ greater than in composition No. 1. However, despite the increase in total binder content, the amount of superplasticizer remained unchanged. Consequently, the actual dosage of the superplasticizer for composition No. 1 was 0.8% of the binder mass, for composition No. 2 – 0.696%, and for composition No. 3 – 0.615%.

The experimentally determined values of average density and compressive strength of the investigated concretes are presented in Table 2.

Table 2 – Average Density and Compressive Strength of the Investigated Concretes

No. of composition	Average Density, kg/m³	Compressive Strength at 7 Days, MPa	Compressive Strength at 28 Days, MPa
1	2441	57.0	65.5
2	2446	53.2	68.0
3	2423	40.9	56.3

The analysis of the experimental data presented in Table 2 shows that the average density of the control concrete (No. 1) and composition No. 2 was approximately equal, while composition No. 3 had a slightly lower density. This can be explained by the fact that replacing part of the cement with a larger mass of fly ash reduces the W/C ratio of the mixture, but at the same time, increases the spacing of the coarse aggregate.

Figure 1 presents a diagram based on the data from Table 1, showing the compressive strength development of the investigated concretes at 7 and 28 days.

The analysis of the diagram and Table 1 data shows that at 7 days, the compressive strength of composition No. 2, where 10% of cement (30 kg/m³) was replaced with 75 kg/m³ of fly ash, was only 6.8% lower than that of the control composition No. 1. At 28 days, however, the compressive strength of composition No. 2 was 3.8% higher than that of the control composition. For composition No. 3, replacing 20% of cement (60 kg/m³) with 150 kg/m³ of fly ash resulted in a 28.3% reduction in compressive strength at 7 days. By 28 days, composition No. 3 exhibited a compressive strength that was 14.0% lower than that of the control composition.

Thus, concretes incorporating fly ash demonstrated a slower rate of strength development compared to the control concrete, where only Portland cement was used as the binder. This finding is consistent with results reported by many researchers [3, 4, 10, 22]. Within the scope of this experiment, replacing 10% of the Portland cement with an optimal amount of fly ash, as a by-product of thermal power plants, produced concrete with strength comparable to the control composition. However, replacing 20% of the Portland cement (60 kg/m³) with 150 kg/m³ of fly ash was not fully compensated, which can be attributed to the limited pozzolanic effect of this admixture and possibly the specific quality of the fly ash used from the Darnytsia Thermal Power Plant. It is also important to note that this result was obtained for concretes based on CEM II/A-S 500 cement, which contains up to 20% ground granulated blast furnace slag. The effectiveness of fly ash will naturally vary when using other types of cement.

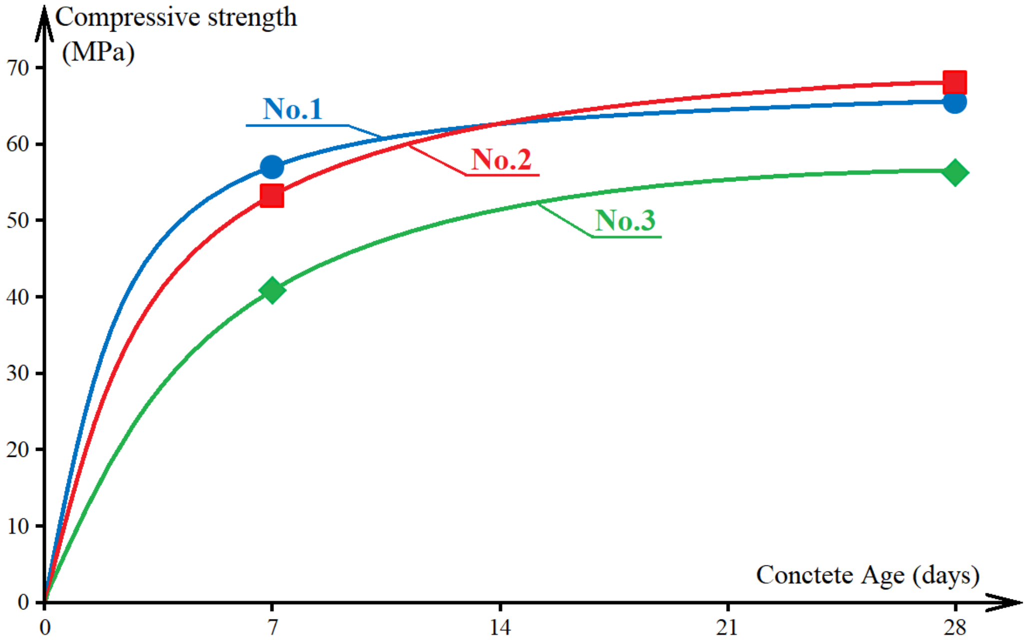

Fig. 1. Compressive strength development of the investigated concretes at 7 and 28 days:
No. 1 – 300 kg/m³ of cement, no fly ash; No. 2 – 270 kg/m³ of cement, 75 kg/m³ of fly ash;
No. 3 – 240 kg/m³ of cement, 150 kg/m³ of fly ash

Conclusions and Prospects for Further Research. Fly ash can be effectively used in concrete for transportation structures, including culverts, and road pavements, enabling a reduction in binder consumption. When using Portland cement CEM II/A-S 500, it is possible to replace 30 kg/m³ of binder with 75 kg/m³ of fly ash from the Darnytsia Thermal Power Plant without compromising the material's strength. The concrete compositions developed in this study, based on their compressive strength, can be used for the construction of rigid road pavements of all categories. For culverts, enhancing the concrete's corrosion resistance is potentially significant, which, according to many studies, can be achieved by using an optimal amount of fly ash.

Expanding the range of concretes in which fly ash, as a by-product of thermal power plants, can be utilized has important environmental benefits in terms of reducing carbon dioxide emissions, as well as being economically viable.

Further research will investigate the effect of fly ash from the Darnytsia Thermal Power Plant on the strength and durability of concretes modified with polycarboxylate additives. In particular, future studies will focus on the impact of partial replacement of Portland cement with fly ash on such critical quality parameters for concretes used in transportation structures and road pavements as frost resistance and abrasion resistance.

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ВПЛИВ ЗАМІНИ ЧАСТИНИ ЦЕМЕНТУ ЗОЛОЮ-ВИНЕСЕННЯМ НА МІЦНІСТЬ БЕТОНІВ ТРАНСПОРТНИХ СПОРУД І ДОРОЖНІХ ПОКРИТТІВ

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Анотація. Визначено вплив заміни частини цементу золою-винесенням на міцність бетонів для транспортних споруд і дорожніх покриттів.

Для виготовлення бетонів використовувався портландцемент ПЦ ІІ/А-Ш-500, щебінь фракції 5-20 мм, кварцовий пісок з Мкр=2,3, суперпластифікатор Поліпласт СП-1 і зола-винесення Дарницької ТЕЦ. Досліджено властивості бетонів трьох складів. Склад №1 (без золи винесення) використовувався як контрольний і у якості в'яжучого в ньому застосовано портландцемент у кількості 300 кг/м^3. У складі №2 10% портландцементу замінено на 75 кг/м^3 золи-винесення. У складі №3 20% портландцементу замінено на 150 кг/м^3 золи-винесення. У всі бетони вводився суперпластифікатор у кількості 2,4 кг/м^3.

Всі бетонні суміші мали рівну рухомість S1 та їх В/Ц залежало від складу. Для контрольного складу №1 значення В/Ц суміші дорівнювало 0,390. Для складу №2 фактичне В/Ц, тобто за умови розрахунку кількості в'яжучого як суми кількості цементу і золи, дорівнювало 0,333. Для складу №3 – 0,308. Тобто у міру збільшення частки золи у в'яжучому В/Ц сумішей знижувалася.

Середня густина бетону контрольного складу №1 і складу №2 є приблизно рівною (2441 кг/м^3 і 2446 кг/м^3), а складу №3 дещо меншою (2423 кг/м^3). Це пояснюється тім, що при заміні частини цементу більшою за масою кількістю золи-винесення у бетоні знижується В/Ц суміші, але одночасно збільшується розсунення крупного заповнювача.

Міцність на стиск бетонів визначалася у віці 7 і 28 діб. Встановлено, що у віці 7 діб міцність на стиск бетону складу №2, у якому 30 кг/м^3 цементу замінено на 75 кг/м^3 золи-винесення, є на 6,8% менше міцності контрольного складу №1. Але у віці 28 діб міцність бетону складу №2 є на 3,8% більше міцності бетону контрольного складу №1. Для складу №3 заміна 60 кг/м^3 цементу на 150 кг/м^3 золи винесення викликала зниження міцності на стиск у порівняння з контрольним складом №1 у віці 7 діб на 28,3%, у віці 28 діб – на 14,0%. Тобто бетони, у складі яких використовувалася зола-винесення, характеризувалися меншою швидкістю набору міцності у порівнянні з бетоном, в якому у якості в'яжучого використовувався лише портландцемент. Заміна 10% портландцементу раціональною кількістю золи дозволила отримати бетон з міцністю, яка є не менш міцності контрольного складу. Проте заміна 20% портландцементу не була повністю компенсована введенням золи.

Тобто можливим і ефективним є застосовування золи-винесення у складі бетонів транспортних споруд і дорожніх покриттів. Введення раціональної кількості золи дозволяє знизити витрати в'яжучого, що має важливе екологічне значення і економічно доцільно.

Ключові слова: зола-винесення, бетон, транспортні споруди, жорстке дорожнє покриття, суперпластифікатор, міцність.

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