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The effect of eco-friendly materials for the stability and durability of building structures

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Abstract

The current development of the construction industry makes it extremely important to find effective ways for increasing the stability and durability of building structures. The introduction of eco-friendly materials and additives, such as fly ash (FA) from combined heat and power plant (CHPP) and recycled concreate, is becoming increasingly urgent, as it improves the properties of concrete mixtures and solves the problem of industrial waste disposal, reducing the negative impact on the environment. The aim of this research is to study the effect of CHPP FA, construction wastes and other environmental additives on the stability, durability, as well as physicomechanical properties of building structures. The research employed several analytical methods, in particular, the compressive strength test according to the ASTM C109 standard. X-ray diffraction (XRD), field emission scanning electron microscopy (FE-SEM), energy dispersive X-ray spectroscopy (EDS), and Fourier transform infrared spectroscopy (FTIR) were also used. These methods evaluated in detail the chemical and granulometric composition of FA, its activity and influence on the physical and mechanical properties of cement compositions. The studies show that the FA introduction into the concrete mixture increase the homogeneity of concrete, reduce cement consumption, and increase compressive strength at different stages of hardening. In particular, the addition of 10% of ash by weight of cement resulted in the improved cement hydration and decreased concrete shrinkage. It was established that with an increase in the specific surface of FA to $S_{spec.}$ = 200 - 250 m^2/kg, the chemical composition increases by 27%, and the strength of samples with an addition of 3% liquid glass increases by 12 - 15%. The introduction of eco-friendly additives into the cement compositions allows to significantly improve the stability and durability of building structures and reduce the impact of the construction industry on the environment. Further research may focus on optimizing the composition of eco-friendly additives for various types of building structures. It is planned to study the thermal conductivity and resistance of the developed concrete mixtures to aggressive environments.

Keywords: engineering, construction education, construction materials, concrete, nanoparticles, eco-friendly materials, sustainable development

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1 Introduction

The issue of using eco-friendly materials, which not only provide high technical characteristics, but also contribute to the preservation of the environment, is becoming increasingly relevant in modern construction [1]. The increasing requirements for the stability and durability of building structures urge the study of the effect of such materials for their quality and operational properties [2]. In recent decades, nanotechnology has significantly transformed various fields of science and technology, contributing to the creation of high-quality, environmentally safe, and durable products. A special place in this process is occupied by the use of nanotechnology in the cement and concrete industry. The article provides the analysis and assessment of the use of eco-friendly components in construction mixtures, in particular concrete, and their impact on strength, service life, as well as the possibility of reducing the negative impact on the environment. The results of this study can be the basis for the development of new approaches in construction aimed at increasing the efficiency of resource use and reducing the environmental footprint of the construction industry [1]. Cement production and consumption, especially in developing countries, have increased significantly in recent decades. Cement plays a key role in economic development, but the process of its production is accompanied by serious environmental problems. The main negative consequences include the emissions of carbon dioxide (CO_2), nitrogen oxides (NOx), sulphur dioxide (SO_2) and suspended particles in the air. This makes cement production one of the most significant factors of environmental pollution in recent decades.

These challenges make researchers to actively look for ways to reduce the harmful effects of cement production. One of the promising directions is the use of nanotechnology, which in recent years has caused revolutionary changes in many fields of science. Nanosized crystallites, due to their unique properties, can significantly affect the characteristics of materials, different from conventional larger crystallites [3]. The studies show that nanotechnology can improve the properties of cement and concrete. For example, the addition of montmorillonite nanoparticles of approximately 0.6% of the cement weight increase the compressive strength of the samples to 13.24% after 56 days compared to the reference samples. This is achieved due to the formation of a denser microstructure of cement paste and a stable binding framework. Further research is still needed despite the progress achieved in the study of microstructure, nanostructure, hydration and mechanical properties of cement and concrete. This is especially true of the introduction of nanotechnology into production, which can significantly improve the stability and durability of building structures, while reducing their environmental impact. The addition of FA, which is a by-product of CHPPs, to the composition of concrete opens up significant opportunities for increasing its environmental friendliness and economic efficiency [4]. FA formed during coal combustion has unique physicochemical properties that can positively affect the characteristics of concrete.

The use of FA reduces the amount of cement in concrete, which significantly reduces CO_2 emissions during its production. This is especially relevant in the context of the current fight against climate change and the need to reduce the carbon footprint of construction materials [5]. FA increases the durability of concrete. It acts as a pozzolanic additive, improving the hydration process and the formation of a denser microstructure, which increases the resistance of concrete to aggressive external influences, such as corrosion or penetration of harmful substances [6]. The use of FA helps to reduce the problem of CHPP waste disposal. Ash, which otherwise could accumulate in landfills and cause environmental problems, finds its application in construction, reducing the need for natural raw materials. The addition of FA to the composition of concrete is an effective solution that improves its technical characteristics and contributes to the sustainable development of the construction industry and environmental protection [7].

The construction industry is increasingly recognizing the importance of integrating secondary materials, such as construction and demolition waste, not only to mitigate environmental impacts but also to conserve valuable resources. itionally, the sector has been resource-intensive, leading to significant waste generation and depletion of natural resources. Bysing and recycling materials, the industry can significantly reduce its ecological footprint. Incorporating secondary materials into construction practices offers several advantages: Utilizing recycled materials diminishes the mand for virgin resrces, thereby preserving naral reserves and reducing the environmental degradation associated with resource extraction. The process of recycling materials typically consumes less energy compared to producing new materials from scratch, leading to energy savings and a reduction in greenhouse gas emissions. Reusing construction waste minimizes the volume of debris destined for landfills, thereby alleviating the strain on waste management systems and reducing landfill-related environmental issues. Employing secondary materials can lead to cost savings in material procurement and waste disposal. Additionally, it can stimulate markets for recycled materials, fostering economic growth within the recycling and construction industries. By embracing the use of secondary materials, the construction industry not only addresses environmental concerns but also promotes sustainable resource management, contributing to a more resilient and responsible built environment.

The aim of this study is to determine the effect of environmental materials on the stability and durability of building structures [8]. The aim involves the fulfilment of the following research objectives:

- Evaluate how the use of eco-friendly additives and alternative raw components in construction materials can improve their operational characteristics;
- Reduce the negative impact on the environment;
- Promote the sustainable development of the construction industry.

2 Literature review

The main difference between recycled and natural concrete is the use of aggregates. The quality of recycled coarse aggregate directly affects the characteristics of recycled concrete, so a detailed study of the properties of these aggregates is important to improve the quality of recycled concrete. In the study of the effect of different sizes of recycled concrete aggregate on the physicomechanical properties of eco-friendly self-compacting concrete. The authors study the potential of using recycled materials in the construction industry [1]. Their results show that the use of recycled concrete aggregate can significantly improve the stability and durability of concrete structures. A number of researchers investigated new eco-friendly materials consisting of waste millet, rice husk, and polystyrene [2]. Their research demonstrates that these materials can effectively replace traditional components in construction materials while improving their environmental performance [4]. The use of eco-friendly materials has the potential to reduce the impact of construction waste on the environment. Bian and others [9] analysed and optimized the mechanical properties of recycled concrete based on aggregate characteristics. Their research found that the right size and shape of aggregates can significantly improve the quality of recycled concrete, which is important for reducing the use of natural resources in construction. The addition of recycled expanded polystyrene to concrete is an example of the use of eco-friendly materials that contribute to the reduction of environmental pollution.

The literature provides examples of replacing mineral aggregates with rice husks. Such a solution can become an alternative to traditional construction materials without impairing their operational properties [3]. In his review, Huseien examines the effect of nanoparticles on the modification of concrete composites. He emphasizes that the use of nanoparticles can significantly improve the mechanical properties of concrete, which can contribute to increasing its durability and stability [5]. The researchers investigated the challenges associated with the modification of geopolymer concrete with nanoparticles, focusing on the technological aspects and techniques that affect the mechanical properties of such materials [6]. Some researchers suggest the use of recycled aggregates in geopolymer concrete. Experimental models were developed to predict the characteristics of concrete structures that contain eco-friendly materials [10]. The use of graphene increases the thixotropy by approximately 80% compared to the reference sample [11]. Similar properties of concrete can be provided by adding carbon nanotubes [12].

The literature also contains the examples of the use of eco-concrete to create green building elements in modern construction [7]. The use of FA and Al_2O_3 nanoparticles is also very common in concrete production technology [13, 14]. This improves its mechanical and microstructural properties and increases resistance to aggressive environments [15, 16]. Positive results regarding the strength of concrete and their mechanical characteristics were found when using slag and coal ash as substitutes for cement to create sustainable concrete infrastructures [17, 18]. Sirico with colleagues [19] investigated the environmental and mechanical performance of low-carbon concrete using solid waste incineration ash as a cement substitute. This approach contributes to the reduction of CO_2 emissions in construction. Twisted polymer fibres improves the physicomechanical properties of concrete and contributes to the strengthening of construction materials [8].

In their work, Turi Gerin et al. [20] focus on the physicomechanical properties of concrete with recycled aggregates, which allows more efficient use of construction waste. Wu and colleagues [21] proposed a new continuous testing method to evaluate the fatigue strength of concrete under high and very high load cycles. This development increases the durability of concrete structures in difficult operating conditions. Response surface methodology was used to determine the dependence of peak stress and elastic modulus of recycled concrete on these variables to establish the regression equations. The literature indicates that the peak stress and elastic modulus of recycled concrete reach the highest values when the coarse aggregate content is 45%. The maximum size of coarse aggregate is 16 mm, and rounded aggregates made up 75% of the total volume [9]. The researchers actively study the effect of various types of nanoparticles on improving the chemical and mechanical properties of cement and concrete. In each study, the optimal percentage of the addition of nanoparticles was determined, at which the most significant improvement in the properties of the material was observed. This optimal percentage depends on the type of nanoparticles, the test conditions, as well as on the physicochemical properties and the amount of materials used. For example, the effectiveness of adding 0.6% of the weight of montmorillonite nanoparticles to cement was established in one of the studies. This increases a compressive strength of the samples to 13.24% after 56 days compared to the reference samples. If 1 weight % of cement is replaced to montmorillonite nanoparticles in cement-binding materials or concrete, this will reduce cement consumption by 1% annually. Accordingly, the CO_2 emissions by the cement industry will reduce by approximately 1% annually.

Reducing CO_2 emissions is an important contribution to combating climate change and reducing the environmental footprint of construction materials [19]. For example, silicon dioxide (SiO_2) can be used as a substitute in amounts up to 4% by weight, depending on the specific study [22]. Nanoparticles of titanium oxide (TiO_2), zinc oxide (ZnO_2), nanofibers and montmorillonite also improve the properties of cement and concrete. Nanotechnology opens up wide opportunities for improving the quality and environmental safety of construction materials. They not only improve the mechanical properties of cement and concrete, but also contribute to reducing the environmental impact of these materials, supporting the sustainable development principles. Using nanoparticles in construction materials is often promoted as an environmentally friendly solution due to reduced cement consumption, reducing CO_2 emissions. However, the environmental effectiveness of such approaches should be assessed in terms of replacing traditional materials and taking into account the energy costs and economic feasibility of producing these additives. The production of nanomaterials, such as modified clays (e.g., montmorillonite (MMT) nano clay), oxide nanoparticles, or nano-silica, is an energy-intensive process involving mechanochemical activation, thermal treatment, or precipitation. For example, synthesising nano-silica via silicate precipitation or vapour pyrolysis requires significant energy inputs, which may negate potential environmental benefits.

In contrast, fly ash is less energy intensive as it is a by-product of thermal power plants (TPPs). However, its activation (e.g. mechanical or chemical grinding) also requires additional energy costs, which should be considered when assessing environmental efficiency [23, 24].

Although nanoparticles show significant potential in improving the mechanical properties of concrete, their widespread use is limited by their high cost. For example, nano-silica costs tens of times higher than traditional pozzolanic additives such as fly ash or metakaolin. On the other hand, adding small concentrations (1-3%) of specific nanomaterials can have a positive effect without a significant increase in cost [25, 26].

The use of fly ash as an additive is economically justified due to its availability and recyclability. However, additional processing is required to improve its activity, which can affect the final cost of the building material [27, 28].

The optimal solution may be the combined use of activated fly ash and minimal dosages of nanoparticles, which will allow combining environmental and economic benefits [29]. For example, adding a small amount of nano-silica (0.5-2%) in combination with gold-cement composites can significantly improve the mechanical properties of concrete without a significant increase in energy costs [30]. As an option, the possibility of using demolition waste and secondary concrete to produce concrete is being considered, which is especially relevant for Ukraine [31, 32].

Further research in this area will help to determine the most effective methods of using nanomaterials and their optimal concentrations, ensuring the sustainable development of construction materials production [9].

3 Methods

3.1 Research design

The effect of eco-friendly materials on the stability and durability of building structures was studied using an integrated approach, which included laboratory tests, chemical analysis, and mechanical tests.

3.1.1 Selection of materials

eco-friendly admixtures such as FA and liquid glass, which have the potential to improve the mechanical properties of concrete and reduce its environmental impact, were selected for the study.

3.1.2 Preparation of samples

concrete samples were made with the addition of 10% FA from the weight of cement and 3% liquid glass. All samples were aged under the same conditions to ensure comparability of results.

3.1.3 Mechanical tests

compressive strength tests were performed in accordance with ASTM C109. This made it possible to determine the optimal proportions of FA and liquid glass that provide maximum strength.

3.1.4 Chemical analysis

The chemical composition of the FA was analysed using X-ray diffraction (XRD) to determine the phase composition of the materials. An analysis of the granulometric composition of ash was also carried out to evaluate its effect on the uniformity and strength of concrete samples.

3.1.5 Microstructural analysis

Field emission scanning electron microscopy (FE-SEM) combined with energy dispersive X-ray spectroscopy (EDS) was used to study the microstructure of the cement stone and reveal the interactions between the additives and the cement matrix.

Fourier transform infrared spectroscopy (FTIR) was used to study the cement hydration and to evaluate the influence of FA on these processes.

3.1.6 Concrete shrinkage analysis

Concrete shrinkage curves were measured to determine the effect of eco-friendly additives on the shrinkage duration and intensity.

The obtained data were analysed and interpreted in order to determine the optimal conditions for the use of eco-friendly materials in the production of building structures.

The mechanical properties of the cement mortar, including compressive and flexural strength, were measured after 3, 7 and 28 days. The compressive strength test was performed according to ASTM C109 [21]. Cubic samples measuring 50 × 50 × 50 mm were prepared for this purpose. A loading rate of 900 N/s was chosen, and the compressive strength of the cement mortar was determined using Eq. (1):

$$f_m = \frac{P}{A}, \tag{1}$$

where f_m is the compressive strength in megapascals (MPa), P is the maximum applied load in newtons (N), and A is the cross-sectional area of the loaded surface in square millimetres (mm^2).

The flexural strength test was conducted in accordance with ASTM C348. Prismatic specimens measuring 160 × 40 × 40 mm were prepared for this purpose and tested at a loading rate of 2640 N/min. The flexural strength of the samples was calculated using Eq. (2):

$$S_f = 0.0028 \times P, \tag{2}$$

where S_f is the flexural strength in megapascals (MPa), and P is the maximum applied load in newtons (N).

3.2 Sampling

A representative set of samples was prepared during the research to assess the impact of eco-friendly materials on the stability and durability of building structures. This sampling strategy ensured both the reliability and generalizability of the results. The sample set comprised multiple series of concrete specimens produced with varying proportions of environmentally friendly additives, such as fly ash (FA) and liquid glass.

3.2.1 Number of samples

A total of 100 concrete specimens were produced and divided into five main groups, each containing 20 samples. Each group varied in composition and in the proportions of the added eco-friendly materials.

3.2.2 Sample composition

- *Group 1:* Control group (CG) without the addition of FA or liquid glass.

- *Group 2:* Samples incorporating FA at 10%, 15%, and 20% of the cement weight.
- *Group 3:* Samples containing 3% liquid glass and FA at 10%, 15%, and 20% of the cement weight.

3.2.3 Selection criteria

All sample groups were prepared and cured under standardized conditions to ensure material consistency and reduce the influence of external variables on the experimental outcomes.

All specimens underwent the same set of tests, including compressive strength evaluation, chemical analysis, and microstructural examination.

3.3 Methods

The microstructure of the materials was studied using the following methods:

1. *X-ray Diffraction* (*XRD*) was used to determine phase identification, measure crystal size and crystallinity. This study used an X-ray diffractometer (EQuniox 3000, Inel Company, France) operating at 40 kV and 30 mV, with CuK-α radiation, λ=1.542

2. *Field emission scanning electron microscopy* (*FE-SEM*) and *energy dispersive X-ray spectroscopy* (*EDS*). A field emission scanning electron microscope (MIRA 3 XMU) was used to study the morphology and microstructure of the samples. To prevent surface charging of the samples during FE-SEM, they were coated with a thin layer of gold.

3. *Fourier Transform Infrared Spectroscopy* (*FTIR*) was used to identify organic compounds containing nanoparticles. This method determines the type of functional groups and connections between molecules. The Fourier transform infrared spectrometer (Tensor 27, Bruker, Germany) was used in this study. The instrument performs 16 scans with a spectral range of 400–4000cm^{-1}, resolution better than 2cm^{-1}, and wavenumber accuracy better than 0.01cm^{-1} (Table 1) [23].

It was found that the corresponding amount of liquid phase melt is formed depending on the mineral composition and temperature of coal combustion, which causes different structure and type of ash particles. As a result, ash particles can have different density, porosity and size, which directly affects their rheological properties and interaction with the cement matrix. The structure of ash particles determines their pozzolanic activity, which, in turn, affects the general mechanical characteristics of concrete structures, in particular their strength and durability (Table 2).

It was found that the formation of the liquid-phase melt during coal combustion depends on both the mineral composition and the combustion temperature. This results in variations in the structure and type of ash particles, which may differ in density, porosity, and size. Consequently, the ash particles influence the homogeneity of concrete components.

The ash particles were composed of both glassy and crystalline phases. The glassy phase primarily consisted of helenite–melanite compositions, while the crystalline phase included quartz grains, calcium silicates, and crystalline aluminates. Variations in ash particle size were associated with changes in shape, internal structure, and mineral composition across different ash fractions.

Experimental data indicated that an increase in the specific surface area of acidic fly ash (FA) improves its homogeneity in terms of both grain size and chemical composition [24]. Specifically, when the specific surface area increased to $S_{spec} = 200–250\,m^2/kg$, the homogeneity of the grain composition improved by 32%, while the chemical composition became 27% more uniform.

Ashes in the composition of mixed binders have pozzolanic activity during hardening, that is, the ability to bind calcium hydroxide with the formation of insoluble compounds at normal temperatures [5]. Figure 1 shows the activity of FA.

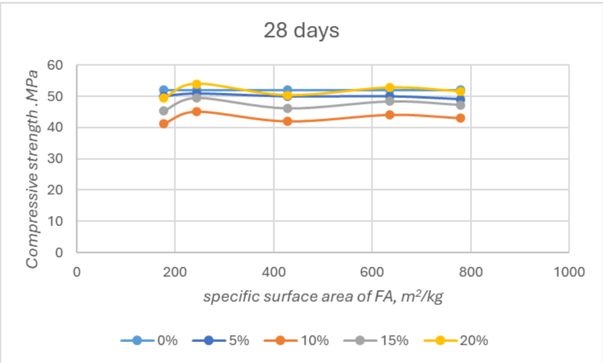

Figure 1. FA activity

Clay baking products exhibit pozzolanic activity in ash: amorphized clay metakaolinite-type substance, amorphous SiO_2, Al_2O_3, Fe_2O_3, and aluminosilicate glass [19].

Recycled coarse aggregate obtained by crushing and fractionating concrete waste was used as the aggregate (Table 3).

Table 1. Chemical composition of FA obtained during coal combustion at the CHPP

Content of oxides, % of weight									
TiO_2	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	P_2O_5	Na_2O	K_2O	∏∏∏
0.5-1.4	51-60	24-32	3.5-8.3	1.1-2.1	0.2-1.5	0.4-0.7	0.1-0.4	0.3-0.7	5.2-5.5

Table 2. Granulometric composition of CHPP FA

Particle size, mm	5	3	1.25	0.63	0.315	0.28	0.14	0.08	0.071	0.005
Share of particles, % of weight	0.08-0.09	0.08-0.09	0.5-1	2.3-3	3.8-5	18-27	41-52	4-6	2-3	2-3

Table 3. Composition of sample mixes for experimental mixtures with aggregates from demolition waste

Mix code Percentage	replacement of natural aggregates by weight, in (%)	Sand (kg/m³)	Natural aggregates (kg/m³)	Aggregates from demolition waste (kg/m³)	Cement (kg/m³)	Water (kg/m³)	Superplasticiser (kg/m³)
R0	0	1140	568	0.00	400	200	2.6
R25	25	1140	427	135	400	200	2.6
R50	50	1140	285	269	400	200	2.6

All mixtures were mixed using a drum-type mixer with dry aggregate inside. Then, water (50% of the total volume) was added to the mixture (for mixing and absorbing the aggregate). Later, cement was added along with 25% water. Finally, the remaining water and superplasticiser were added and mixed for 3 minutes until the concrete components were almost homogeneous.

4 Results

4.1 Using demolition fly ash (fa) as a damping component

The experimental data gave grounds to establish that concrete strength had two maximum values with an increase in the specific surface of FA. Changes in concrete strength depending on the ash concentration make it possible to divide the process into two areas (Figure 2). The first area shows the optimal placement of fine filler in fine-grained concrete. The specific surface area of the samples was in the range of $S_{spec.}$ = 170 – 450 m^2 /kg, with a maximum at $S_{spec.}$= 200 – 250 m^2 /kg. For this area, the linear dimensions of FA particles can be compared with the linear dimensions of sand particles (170-200 μm). Pozzolanic activity of finely dispersed ash also increases. The strength at $S_{spec.}$= 250 - 450 m^2 /kg decreases because the linear dimensions of FA particles (80 - 50 μm) become close to the linear dimensions of cement particles (50 - 60 μm). The contact of cement particles with each other decreased because of the filling of their intergranular space with ash particles.

The second area with an interval of $S_{spec.}$ = 450 - 770 m^2 /kg, with a maximum at $S_{spec.}$ = 600 - 650 m^2 /kg indicates that FA acts as a microfiller in the structure of cement stone. At $S_{spec.}$ = 450 – 650 m^2 /kg, linear sizes of FA particles (5 – 50 μm) are significantly smaller than the sizes of cement particles (50 – 60 μm). The introduction of ash into the concrete mixture leads increases the compressive strength of concrete samples. The compressive strength decreases with an increase in the specific surface more than $S_{spec.}$ = 650 m^2 /kg, as aggregation due to surface forces increases and particles stick together.

Ash in concrete contributes to the formation of a dense structure of the intergranular space of aggregates and a less defective contact zone of aggregates with cement stone. This is explained by a higher degree of cement hydration and the reaction between calcium hydroxide and ash components with the formation of an additional amount of calcium hydrosilicate gel (Figure 3).

Physicomechanical properties of concrete are significantly affected by the destructive processes in the structure of all components and the degree of their interaction in the contact zone. The contact zone greatly affects the deformation and strength properties of ash cement stone. The adhesion strength of FA to cement stone depends on humidity, the content of coked particles, particle size composition and the ultimate size of ash particles.

Gilt cement stone has a number of advantages – reduced water absorption and waterproofing, increased frost resistance, and the possibility of varying the elastic modulus by changing the content of modified ash. Depending on the content of modified ash, gilt cement stone has an elastic modulus ranging from 4,000 to 7,500 MPa, and cement stone has an elastic modulus of 3.5 to 7 times higher. The increased elasticity of gilt cement stone is explained by the nature of the bonds formed during the hardening of viscous gilt cement. Gel-like new formations prevail in the structure of gilt cement stone.

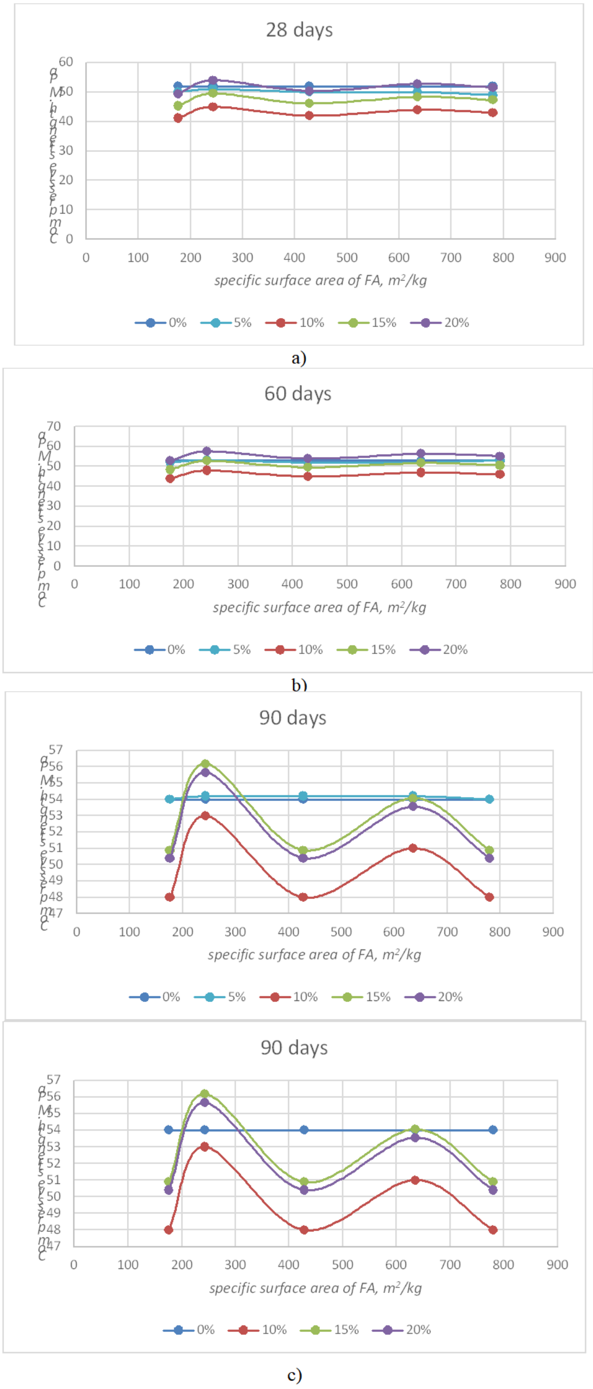

Figure 2. Dependence of compressive strength on hardening time and specific surface area of FA at a) 28days; b) 60 days; c) 90 days

As a rule, the strength of fine-grained concrete samples with the addition of FA is lower than the strength of samples without ash at the age of 7-14 days. Tests showed that the increased strength of samples aged 60 days compared to the strength of samples aged 28 days was 6.6 - 7.0%, and after 90 days – 15.0 - 15.5%.

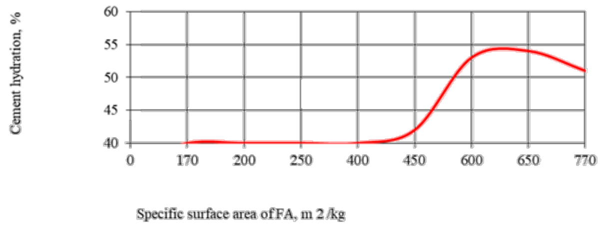

Figure 3. Dependence of the hydration of 28-day-old cement on the specific surface area of FA. The ash content is 10% of the weight of cement

It was established that the introduction of liquid glass additives into the gilt cement concrete mixture has a positive effect on the mechanical properties of concrete. A liquid glass concentration of 3% by weight of cement increases the compressive strength of samples at the age of 28 days by 12-15%. The introduction of liquid glass also accelerates the setting of the concrete mixture by 8-10%. With an increase in the specific surface to $S_{spec.}$ = 600 – 650 m^2 /kg. FA plays the role of microfiller in the structure of gilt cement stone. It contributes to the formation of a denser filling of the intergranular space in the cement stone structure and the formation of a less defective contact zone of the aggregate with the cement stone.

The obtained results of shrinkage deformation showed that the disruption of the structure of the contact zone is directly proportional to the shrinkage of gilt cement concrete (Figure 4).

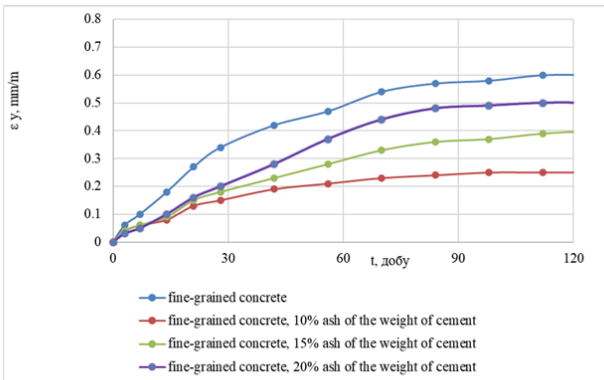

Figure 4. Concrete shrinkage curves

The method of mathematical planning of the experiment was applied to determine the significance of the influence of varying technological factors on the *physicomechanical* properties of concrete. The consumption of FA and cement, the fineness of FA grinding, and the amount of liquid glass additive were considered as variable factors. The following physicomechanical properties were selected: the average density of FA concrete Y_1 and the compressive strength of concrete samples Y_2. The following regression equations were obtained as a result of data processing using a full factorial experiment, which can be used to determine the impact of adopted technological redistributions:

$$Y_1 = 2211 + 26.0X_2 + 27.8X_4 - 31.5X_1X_2 - 34.6X_2X_3;$$

$$Y_2 = 40.1 + 1.8X_1 - 1.5X_2 + 2.6X_4 - 2.4X_1X_4,$$

where X_1 is the cement consumption (kg), X_2 is the fly ash (FA) consumption (kg), X_3 is the specific surface area of FA (m^2/kg), and X_4 is the liquid glass additive content (kg).

The structure of concrete is considered as a system consisting of a matrix (ash cement stone) and its inclusions of fine concrete aggregate (quartz sand). Studies of concrete using X-ray phase analysis showed that concrete with the addition of acidic FA is characterized by a reduced content of free calcium hydroxide $Ca(OH)_2$. Obviously, this is the result of the following chemical reaction:

$$Ca(OH)_2 + Sio_2 + nH_2O = CaOSio_3.H_2O + (n-1)H_2O.$$

The reduced amount of free lime leads to low reactivity in the zone of contact of ash cement stone with sand. The elastic characteristics of fly ash and quartz sand are significantly different from the corresponding characteristics of cement stone. In this regard, the concrete model "quartz sand – ash cement stone" was adopted, supplemented by a contact layer between quartz sand and ash cement stone. The change in the ratio of the elastic modulus of the inclusion (aggregate) and the matrix (ash cement stone) has the most significant effect on the increase in the concentration of tensile stresses E_β/E_m.

The increase in the specific surface of fly ash to S$spec.$ = 200 – 250 m ^{2} /kg entails an increase in the homogeneity of the concrete structure, and a decrease in the stress concentration coefficient η by 16%. It was established that the stresses in the contact zone of the aggregate with the matrix, estimated by the stress concentration coefficient η, are a potential source of microcracks. Ash in the composition of concrete is a damping component. Fly ash grain on the path of the crack will reduce the stress level at its top approximately in proportion to the ratio of the elastic modulus of the phases of the base material and the damper material. The positive effect of damping exceeds the negative effect of defects in the structure of stress concentrators.

The use of fly ash as a damping component has a positive effect on the stress state inside the material structure by reducing the shear stress at the interface with the aggregate. The region of microcrack nucleation and propagation can be predicted by regions of concentration of tensile stresses. According to B. V. Husiev, the increased concentration of tensile stresses is most affected by the change in the ratio of the elastic modulus of the inclusion and the matrix $E_v/E_m = 0.9$–0.5. At the same time, the maximum tensile stress increases by more than 2 times. For concrete under investigation, the elastic modulus ratio is $E_v/E_m > 2$–3.

Table 4. Test results of control samples with an additive of 3% liquid glass (S$_{spec.}$ of ash = 200 - 250 m ^{2} /kg)

Physicomechanical parameters	Ash content, % wt.			
	5	10	15	20
Ultrasound speed, V$_{u.s.}$, km/s	3.8	3.74	3.57	3.41
Flexural strength, R$_{fl}$, MPa	9.8	9.7	9.4	9.3
Compressive strength, R$_{comp}$, MPa	46.1	45.7	42.3	38.4
Average concrete density, ρ_c , kg/m ^{3}	2	2,16	2,19	2,27
Water resistance, MPa	0.8	1	1.2	1.1
Frost resistance, cycles	420	550	700	830
Thermal conductivity, W/(m^2*K)	0.69	0.6	0.55	0.45
Flexural strength in a 5% solution of Na_2SO_4 at the age of 180 days, % of the initial	0.78	0.92	0.96	1.02

The Table 4 presents the physicomechanical properties of concrete samples containing a constant 3% addition of liquid glass and varying percentages of fly ash (5%, 10%, 15%, and 20%). specific surface area of the fly ash used ranges between 200 to 250 m^2/kg.

A gradual decrease in ultrasonic pulse velocity is observed as the fly ash content increases, indicating potential changes in the concrete's internal structure and density.

Flexuraltrength shows a slight decline with higher fly ash content, suggesting a minor reduction in the concrete's ability to resist bending forces.

Compressivetrength decreases with increasing fly ash content, implying that higher fly ash percentages may reduce the concrete's capacity to withstand compressive loads.

An increase inoncrete density is noted with higher fly ash content, which could be attributed to the specific gravity and particle packing characteristics of the fly ash.

Water resistance proves with the addition of fly ash up to 15%, after which a slight decrease is observed at 20% fly ash content.

Frost resistance sigficantly enhances as the fly ash content increases, indicating improved durability of the concrete under freeze-thaw cycles.

Thermal conductivity deeases with higher fly ash content, suggesting better thermal insulation properties in the modified concrete.

The flexural strength reteion in a 5% sodium sulfate solution increases with higher fly ash content, indicating enhanced sulfate resistance over time.

These observations align hxisting literature, which indicates that incorporating fly ash and liquid glass can influence various properties of concrete. For instance, the addition of ash has been shown to improve durability aspects such as freeze-thaw resistance and sulfate resistance, while potentially affecting mechanical properties like compressive strength.

The experimental and theoretical provisions were taken into account in the development of the technological regulation and scheme for the production of concrete with the addition of fly ash and liquid glass. Adding fly ash and liquid glass is appropriate for concrete for low-rise construction of buildings and structures, for pouring floors, for sound insulation, as a masonry mortar. The organization of industrial production of concrete with the addition of fly ash and liquid glass is possible in the conditions of existing enterprises using standard equipment. The use of fly ash, which is multi-tonnage waste, as an additive will reduce the shortage of raw materials and improve the environmental situation.

4.2 Using demolition waste and secondary concrete as a damping component

Concrete without adding waste aggregates (0%, R0) has the highest failure energy, exceeding 115 Nm. As the percentage of waste aggregates increases to 25% (R25), the failure energy decreases, dropping to approximately 108 Nm. However, with a further increase in the percentage of waste aggregates to 50% (R50), the failure energy increases again, approaching 116 Nm. Suppose we assume that the decrease in failure energy at 25% replacement (R25) is due to insufficient adhesion between the new and old aggregates or a change in the structure of the concrete matrix. In that case, it is logical to expect a further decrease in this indicator with an increase in the proportion of waste aggregates to 50% (R50). However, we observe the opposite trend - the failure energy increases at 50% replacement, almost reaching the concrete level without adding aggregates from failure waste (0%, R0) (Table 5).

Conventional concrete with 0% demolition waste aggregate (EB) increases compressive strength over time, typical for concrete, as the cement hydration process continues to strengthen the material during the first 100 days. Concrete with 25% demolition waste aggregate (R25): Has a lower compressive strength at the initial stage (7 days) but shows a significant increase in strength at 28 days, indicating potential pozzolanic activity in the recycled materials. However, by 100 days, the strength decreases again compared to standard concrete. Concrete with 50% demolition waste aggregate (R50): This shows the lowest compressive strength at 7 days, but the strength at 28 days is higher than that of concrete with 25% demolition waste aggregate. On day 100, the compressive strength decreases again but remains higher than concrete's, with 25% aggregates from demolition waste.

Using aggregates from demolition waste in an amount of up to 25% of the volume of coarse aggregate does not lead to a significant decrease in the corrosion resistance of reinforced concrete, while increasing their content to 50% may increase the risk of reinforcement corrosion. To clarify the effect of aggregates from demolition waste on the corrosion resistance of reinforced concrete, further studies are needed using a more significant number of samples, varying the composition of concrete and exposure conditions.

1) Environmental aspects of the use of concrete with the addition of aggregates from demolition waste.

2) Environmental and economic benefits of using construction waste in concrete.

3) Reducing greenhouse gas emissions.

Using construction waste as aggregates in concrete reduces CO_2 emissions by 15–20% compared to traditional concrete. This is achieved by reducing the energy-intensive processes of extraction, transportation and processing of natural raw materials. At the same time, additional emissions associated with the collection and processing of construction waste must be considered.

Every year, 300–500 thousand tons of construction waste accumulates in Ukraine, of which only 5–10% is recycled. Using recycled materials in concrete will contribute to increasing the level of recycling and reducing the burden on landfills.

Table 5. Characteristics of different concrete compositions

Parameter	Traditional concrete (0%, R0)	Concrete with 25% aggregates (R25)	Concrete with 50% aggregates (R50)
Destruction energy, Nm	>115	≈108	≈116
Compressive strength (7 days), MPa	37	35	33
Compressive strength (28 days), MPa	45	48	49
Compressive strength (100 days), MPa	54	52	53
Corrosion resistance	High	Slight decrease	Increased risk of corrosion
Environmental impact	High carbon footprint	Smaller carbon footprint	Environmentally beneficial, but requires further research
Concrete structure	Homogeneous	Possible lack of grip	Improved grip at 50% replacement

4.2.1 Reducing environmental risks

Uncontrolled dumping or burning of construction waste poses a threat of toxic substance pollution of soil, water, and air. The use of this waste in concrete minimises such risks through controlled collection, sorting, and recycling. It is important to ensure environmental supervision and comply with safety standards.

4.2.2 Economic aspects. Reducing construction costs

Construction waste as aggregates can be 20–50% cheaper than natural crushed stone and gravel, which is especially relevant for Ukraine's reconstruction. In addition, their use reduces transportation costs, as such materials are often found near the destruction sites.

The research conducted a comparative analysis of the economic efficiency of using construction waste, fillers, protective coatings, and corrosion inhibitors in concrete (Table 6).

These tables show that demolition and industrial waste can significantly reduce costs. However, a detailed economic analysis is required for each project.

5 Discussion

One of the key aspects of the study of the influence of ecological materials on building structures is the study of the chemical composition and properties of the CHPP fly ash. The chemical composition of fly ash can vary significantly depending on the type of coal and combustion conditions. The main components of ash are oxides of silicon, aluminium, calcium and iron, which gives grounds to consider it as a potentially effective addition to cement. Furthermore, the use of fly ash as a damping component has a positive effect on the stress state within the material structure, reducing the stresses at the interface with the aggregate. This reduces the risk of cracking and increases the resistance of concrete structures to mechanical influences [21]. The obtained results are confirmed by the data of other researchers [5].

The granulometric composition of fly ash also has a significant effect on the final properties of concrete. The use of liquid glass in the production of concrete is a fairly common practice. Fine fractions of ash increase the density of the concrete structure, thereby improving its mechanical properties and durability [33]. The studies conducted on samples with the addition of fly ash in the amount of 10% of the mass of cement showed that such an addition increases the compressive strength of concrete, especially in the later stages of hardening. This can be explained by the fact that an increase in the specific surface area of fly ash leads to the intensification of cement hydration processes. Comparison of these results with literature data revealed that various studies confirm the positive effect of fly ash on the mechanical properties of concrete [8]. The obtained results are confirmed by the works of other researchers who studied the prospects of using fly ash as a partial substitute for cement [1].

Fly ash also significantly reduces cement costs, while improving the eco-friendliness of construction materials [25]. The dependence of the degree of cement hydration on the specific surface area of fly ash is also an important indicator for evaluating the effectiveness of its use. The greater the specific surface area of fly ash, the faster the hydration process occurs, which contributes to the faster increase in concrete strength. This is confirmed by the results of studies that demonstrate an increase in the compressive strength of concrete when adding ash with a specific surface area of 200-250 m^2/kg. Another important aspect is concrete shrinkage, which can lead to cracking and reduced durability of structures [26, 27]. Unlike CHPP fly ash in combination with liquid glass, it is proposed to use glass waste for the production of lightweight concrete [28, 29]. According to the author's results, the combination of glass powder and liquid glass can replace up to 30% of Portland cement and almost double the compressive strength [30].

Our results show that it is possible to use up to 20% of fly ash by weight of concrete, ensuring proper concrete strength. The tests of control samples with the addition of 3% liquid glass showed a significant reduction in concrete shrinkage, which makes such

Table 6. Comparison of environmental and economic benefits of using eco-friendly materials in concreate, Source: author's measurements and [32]

Factor	Usual concrete	Concrete with demolition waste	Concrete with industrial waste (FA)	Concrete with industrial waste (FA) and liquid glass	Concrete with protective coatings and corrosion inhibitors [32]
Cost of raw materials	Basic	20-40% lower	10-30% lower	Base or 5-10% lower	Base or 5-15% higher
Recycling costs	Not applicable	Higher by 10- 20%	5-15% higher	5-15% higher	Not applicable
Transportation costs	Basic	15-30% lower	Basic or 5-20% lower	Basic or 5-20% lower	Basic
Durability	Basic	Similar or 5-10% lower	Similar or 5-15% higher	20-40% higher	20-40% higher
Operational costs	Basic	Similar or 5-10% lower	Similar or 5-15% lower	Similar or 5-15% lower	15-30% lower
Environmental costs	Basic	20-40% lower	15-35% lower	15-35% lower	Similar or 5-10% lower
General economic efficiency	Basic	Higher by 10- 25%	5-20% higher	5-20% higher	15-30% higher

Notes: Percentages are approximate and depend on conditions and materials; "Basic" is a typical level for regular concrete without additives; Economic efficiency is assessed, considering the structure's life cycle.

materials more durable and resistant to negative external influences. So, the research results indicate a significant potential of using fly ash as an effective and eco-friendly component in the composition of concrete, which improves its mechanical properties, increases resistance to external influences and reduce the ecological burden on the environment [31]. The aim of the research is achieved, and objectives of the research are fulfilled, which were to study the influence of eco-friendly materials on the stability and durability of building structures. In particular, the study confirmed that the use of fly ash and liquid glass contributes to increasing the strength of concrete mixtures, reducing cement costs, and solving the problem of industrial waste disposal. The practical use of the research results consists in implementing the provided recommendations on optimizing the composition of concrete mixtures in construction practice. The prospects for the use of developed materials take place in the construction industry. This will reduce the environmental impact of the construction industry and increase its economic efficiency due to the use of energy industry waste.

6 Conclusion

The relevance of the study is the need to introduce eco-friendly construction materials that increase the stability and durability of structures and ensure the industrial waste disposal. The article analysed the studies of famous scientists regarding the influence of eco-friendly materials on the stability and durability of building structures. The use of fly ash as a microfiller and the addition of liquid glass can increase the strength of concrete samples, accelerate the setting of the concrete mixture, and reduce the risk of cracking. The results of the study emphasize the importance of using environmental additives, such as fly ash and construction waste liquid glass, to improve the physicomechanical properties of concrete. The use of fly ash and construction waste provides the possibility of efficient disposal of industrial waste, reducing CO_2 emissions and cement consumption, ensuring a more sustainable and environmentally safe construction. The obtained results can be applied in the construction industry to develop new types of environmentally friendly concrete mixtures using industrial waste, such as fly ash and construction wastes, as additives. The research results can be useful in the design and construction of residential, industrial, and infrastructure facilities, where stability and durability of structures are important. The prospects for future research consist in the further study of the influence of various types of industrial wastes on the physicomechanical properties of building materials. It is also important to investigate the long-term environmental and economic consequences of the use of such materials in construction, in particular their impact on the operational characteristics of buildings in different climatic conditions.

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The authors declare that there is no conflict of interest.

Authorship Contribution

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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