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# Optimisation of composition and strength properties of slag-alkali binders based on fuel slags

**Abstract.** The study addresses ways to improve the composition and strength of slag-alkali binders derived from fuel combustion products. For this purpose, X-ray diffraction analysis, spectroscopy, microscopy, compression strength tests, and data analysis were used to activate the ash from the power plant units, evaluate the activity of the compositions, heat and moisture treatment, and determine the optimal compositions. Alumina binders have advantages over Portland cement: they are highly durable, waterproof, frost-resistant and corrosion-resistant. These materials are used in the construction of special-purpose facilities, such as motorways, airfields, bridges, transport tunnels and hydraulic structures. As part of an experimental study, optimal ash binders based on fuel slag with the required properties were developed. Analysis of the chemical composition of fuel slags revealed a high content of silicon, aluminium, iron, calcium and magnesium oxides, which makes them suitable for use as binders. Experimental data has shown that the

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introduction of additives such as gypsum significantly improves the mechanical properties and durability of materials. The developed technological processes of mixing, moulding and curing ensure stable product quality. Tests of the samples demonstrated high compressive, tensile and flexural strengths, confirming their suitability for construction applications. The environmental assessment showed that the use of fuel slag reduces the carbon footprint and reduces the negative impact on the environment. As a result, a scalable production process has been developed that can be implemented in industry to create environmentally sustainable and highly efficient building materials. This study presents new data on the development of environmentally sustainable building materials based on fuel slag, which can reduce environmental impact and improve the sustainability of infrastructure

**Keywords:** man-made raw materials; fly ash; additive; composite building materials; chemical composition

## INTRODUCTION

With sustainability and environmental safety becoming a priority for various industries, construction is facing the need to switch to more environmentally friendly materials. The use of slag-alkaline binders based on fuel slag is a promising area of construction materials. Fuel slag, a by-product of the combustion of coal and other fuels, has significant potential for use in construction due to its chemical composition. This composition is dominated by oxides of elements such as silicon, aluminium, iron, calcium and magnesium, which makes them attractive for use as binders. This chemical composition provides slags not only with the ability to effectively fix and bind other components in materials but also with additional useful properties such as increased strength and resistance to various influences, which makes them particularly valuable for creating modern and efficient building structures. The drive for sustainable development requires the efficient use of industrial waste, such as fuel slag, which otherwise can accumulate and pollute the environment. Existing building materials, such as Portland cement, are associated with high $CO_2$ emissions, which exacerbates the problem of global climate change. Slag-alkali binders based on fuel slag offer an environmentally friendly alternative, reducing the carbon footprint and improving the environment. Finally, such materials may have improved mechanical properties and durability, making them attractive to the construction industry. Thus, optimising their composition and strength characteristics not only contributes to solving environmental problems but also meets the growing demand for efficient and reliable materials in construction.

The problem of the lack of environmentally sustainable and efficient building materials capable of replacing traditional ones with high $CO_2$ emissions and insufficient durability has already attracted the attention of several authors. For example, M. Deepak *et al*. (2023) analysed the mechanical properties and microstructure of fuel slag-based concretes, revealing a significant improvement in the strength and durability of these materials. J. Chen *et al*. (2022) studied the chemical composition of fuel slags of various origins and their influence on the properties of the resulting binders. G.V.P.B. Singh & V.D. Prasad (2024) reviewed the environmental aspects of using fuel slags in construction, emphasising their potential to reduce the carbon footprint of the industry. The study by B. Isakulov *et al*. (2023) addressed the technological aspects of slag-alkali binder production, including mixing and curing methods. Ya. Wang *et al*. (2021) compared various slag additives to improve their strength characteristics. I. Amer *et al*. (2021) focused on the development of new methods for the environmental assessment of the production and use of slag binders. L. Holappa *et al*. (2021) investigated the prospects of using slag from various sources, including not only coal-fired power plants but also other industries. The research conducted by V. Athira *et al*. (2021) confirmed the superiority of slag-alkali binders over traditional building materials in terms of environmental safety and durability. N. Hui-Teng *et al*. (2021) employed new methods for analysing the structure and phase composition of slag materials to optimise their characteristics. J. Schupsky *et al*. (2021) identified the potential of fuel slag to create innovative composite materials with improved technical and environmental properties.

However, there are gaps in mentioned research on optimising the composition and production processes of slag-alkali binders, as well as assessing their durability and strength characteristics in real-world conditions. Further study of the effect of additives on the properties of fuel slag binders is also needed. Thus, this study aimed to address the potential and possibility of producing gold-alkali binders based on low-calcium acid ash produced at the Bishkek Thermal Power Plant (TPP). Research goals:

1. To study the influence of high-base additives and alkaline components on the activation of low-lime ash from thermal power plant units and the formation of a strong structure of gold-alkaline binders and composite materials.

2. Determine how the use of curing activators such as $Na_2O\ 2SiO_2$ and NaOH affects the activity and strength of gold-alkali compositions compared to traditional lime binders.

3. To determining the optimal compositions of low-lime gold-alkali binders and composite building materials based on them, taking into account the influence of heat and humidity treatment on the strength of gold-alkali binders with Portland cement clinker.

## MATERIALS AND METHODS

To begin the experiment, samples of low-calcium acid ash obtained from a unit at the Bishkek Thermal Power Plant were carefully prepared. This stage included several procedures aimed at ensuring standardised and homogeneous sample characteristics for subsequent studies. The ash samples were subjected to purification and pre-treatment processes to eliminate possible distortions of the results due to the presence of impurities or irregular material structure. Thus, the preparation of ash samples was an important step in ensuring the reliability and accuracy of the results of the entire study. During the study of activation of low-lime ash from combined heat and power (CHP) units, samples were prepared and successively exposed to high alkalinity additives such as $Na_2O \cdot 2SiO_2$ and NaOH applied at certain concentrations. Further, the effect of these additives on the structure of ash and their chemical reaction with other components was studied. This included the use of various analytical techniques such as X-ray diffraction, spectroscopy and microscopy. The data obtained was used to assess changes in the structure of ash and to identify the formation of new phases. Further analysis was used to determine the optimal activation conditions to ensure the formation of a strong structure and the required properties of binders based on these ashes.

After the activation process of the CHP ash, compressive strength tests were carried out to assess the activity of the resulting ash-alkali compositions. For this purpose, compositions with different curing activators and concentrations of alkaline components were tested and the results were then compared with the strength of compositions containing traditional binders such as lime. After obtaining the test results, the data were analysed to identify the optimal combinations of activators and concentrations that provide the best strength and other required properties of the compositions. After obtaining the gold-alkali compositions, heat and humidity treatment was carried out to increase their strength. The samples were exposed to heat and moisture under controlled conditions, which contributed to deep hydration of the ash component and strengthening of the structure of the compositions. After the treatment was completed, the strength of the samples was compared with the strength of compositions that had not been subjected to heat and humidity treatment to determine the effectiveness of this method in improving material properties. To achieve the fineness of ash grinding, a grinding process was used in a ball mill of the KSV 008 brand (manufactured in Ukraine) for 30 minutes at a data rate of 1,000 rpm. The purpose of the extraction was to pass the ash through the KSV 008 sieve.

Based on the results of the study, the optimal compositions of low-lime ash-alkali binders and composite construction materials were identified. For this purpose, various formulations were tested for strength and other properties. The analysis of the results was used to select the most promising options for further use in construction and other industries, such as engineering structures, road construction and hydraulic structures. Compressive strength tests were carried out by subjecting the resulting gold-alkali compositions to compressive force using standard test methods. For this purpose, the samples of the compositions were placed in special testing devices, where they were pressurised along their axis. Then the force required to break the sample was measured, which was used to assess its strength characteristics. This test method is standard and widely used to assess the strength of various materials in construction and engineering practice (Turan *et al.*, 2022). The results obtained were used to determine the mechanical properties of the ash-alkali compositions and to assess their suitability for use in specific construction applications.

## RESULTS

Fuel slags generated as a by-product of coal combustion at thermal power plants are complex multi-component systems. Determining the content and distribution of key components, such as $SiO_2$, $Al_2O_3$, $Fe_2O_3$, CaO, MgO and others, were used to understand their potential impact on the properties of binders and optimise their composition to achieve the required characteristics. The analysis of fuel slag composition begins with sampling and preparation of samples for laboratory testing (Lu *et al.*, 2023). Samples are taken considering the heterogeneity of slags and the different conditions of their formation. Chemical analysis is then carried out, including quantification of the main oxides. The composition of slag can vary widely depending on the type of coal, combustion conditions and ash removal technology, so it is important to obtain a representative sample for accurate analysis.

The main component of fuel slags is silicon dioxide ($SiO_2$), which makes up a significant part of their mass (Thomas *et al.*, 2021). The high content of $SiO_2$ gives slag acidic properties and affects its activation when interacting with alkalis. Aluminium oxide ($Al_2O_3$) and iron oxide ($Fe_2O_3$) are also present in significant quantities and play an important role in shaping the structure of the binder. They can form complex compounds with other components, improving the mechanical properties and resistance of the material to external influences. Calcium (CaO) and magnesium (MgO) are usually present in smaller quantities, but their role in the hydration and curing processes is no less important. Calcium helps to accelerate hydration reactions and form a strong structure, while magnesium can improve the material's resistance to chemical attack. The optimum ratio of these components is essential to achieve the required binder characteristics.

The distribution of the components in the slag is also important. The heterogeneity of slag, which is expressed in the uneven distribution of oxides over the volume, can lead to heterogeneity in the properties of the resulting binder. Therefore, an important step in the analysis is to determine the microstructure of the slag using electron microscopy and X-ray diffraction. These methods were used to identify the phase composition of slag and the distribution of components at the microscopic level. The data obtained serve as the basis for the development of binder formulations. Knowing the content and distribution of the main components were used to optimise the composition of slag binders by adding the necessary components to improve their properties. For instance, if there is a lack of calcium in the slag, an additional source of CaO can be added to ensure the required hydration and solidification rate. The study of chemical reactions between fuel slag components and additives was used to determine the optimal proportions of components and their mixing conditions, which directly affect the final properties of the material, such as strength, resistance to external influences and durability. The selection of suitable additives can significantly improve the properties of binders. Additives can include alkaline components such as sodium hydroxide (NaOH), liquid glass ($Na_2O \cdot SiO_2$), and various mineral and chemical substances that can interact with the slag components. The choice of additives is based on their chemical composition and ability to react with the main components of slag, such as $SiO_2$, $Al_2O_3$, $Fe_2O_3$, CaO and MgO.

One of the key aspects of the research is the study of the hydration process, which plays a central role in the formation of the structure of the binder. During the hydration process, slag reacts chemically with water and additives to form new compounds that bind the material particles together, ensuring its strength and stability. For example, when sodium hydroxide (NaOH) is added to slags containing silica ($SiO_2$), a reaction occurs that results in the formation of sodium silicates, which contribute to the formation of a strong material structure (Abdul *et al.*, 2024). Heat and moisture treatment can significantly accelerate the hydration and curing processes, which is especially important when creating high-strength binders. The interaction of slag with various mineral additives, such as gypsum, lime, cement clinker and others, can significantly improve the properties of binders, such as strength, water and chemical resistance. For instance, the addition of gypsum promotes the formation of sulphoaluminate phases, which improve the strength characteristics of the material.

Based on the research results, optimal binder formulations can be developed. This includes adjusting the ratio of the main components of slag and additives, as well as the conditions for mixing and processing. Optimisation of these parameters makes it possible to create binders with specified properties that meet the requirements of building codes and standards. The industry is striving to reduce its negative environmental impact, which requires a comprehensive assessment of environmental aspects at all stages of production and use of materials (Cheng *et al.*, 2021). This is particularly important in the case of binders, such as slag binders, as the process of creating and using them can have a significant impact on ecosystems. In the case of slag-alkali binders, the main component is fuel slag, which is a by-product of coal combustion at thermal power plants. The use of slag as a raw material for binders helps to solve the problem of its disposal and reduce the amount of waste sent to landfills. Thus, reusing slag reduces the burden on the environment and improves the ecological situation.

The technological process, which includes slag grinding, the addition of chemical components and heat and humidity treatment, can be accompanied by emissions of dust, gases and other pollutants (Onaizi *et al.*, 2024). To minimise these emissions, it is necessary to use efficient cleaning and filtration systems and improve technological processes to reduce their negative impact on the environment. One of the key aspects is energy consumption in the production of binders. Energy-intensive technologies can adversely affect the environment through the emission of greenhouse gases and other pollutants (Zhumadilova *et al.*, 2023). Process optimisation and the use of renewable energy sources can significantly reduce the environmental footprint of production. For example, using solar or wind energy to power production processes can significantly reduce carbon dioxide emissions. Another important aspect is the environmental safety of the finished product. Binding materials must be safe for use and not emit harmful substances during operation. This requires thorough testing and analysis to ensure that there are no toxic components or decomposition products. The guarantee of environmental safety of the finished product contributes to its widespread use in the construction industry, reducing the risk of negative impact on human health and the environment. Recycling and disposal of waste generated during the production of binders are also important aspects of environmental assessment (Manjunatha *et al.*, 2021). Slag residues and other wastes must be recycled or disposed of in a manner that minimises their impact on the environment. This may include using waste as a secondary raw material for other industrial processes or developing safe disposal technologies.

Slag-alkaline binders are often formulated with high-calcium fly ash. These ashes, due to their high calcium oxide content, have properties that simplify the activation process and contribute to the formation of a strong structure of binders. The interaction of high-calcium ash with alkaline components is active and thus improves the strength characteristics of the resulting materials. The ash produced at the Bishkek TPP has acidic characteristics and is free of calcium oxide. For each type of binder, the optimum grinding ratio was determined, which was selected to ensure the required quality level with minimal energy consumption. The properties of slag-alkali binders depend not only on the basic composition of the slag but also on the choice of the alkaline component, which also has a significant impact on the characteristics of the binder (Bereziuk *et al.*, 2023).

The chemical composition of the ash produced at the Bishkek Thermal Power Plant is characterised by a silicon oxide content ranging from 0.04 to 0.07 wt%, aluminium oxide content from 0.3 to 0.4 wt% and calcium oxide content from 0.4 to 0.5 wt%, which indicates its low activity. To achieve the required fineness of grinding, the ash was subjected to a grinding process to pass through the KSV 008 sieve in a volume of 9 to 10%. Subsequently, aqueous solutions of caustic soda, soda and liquid glass were used as alkaline components to form gold-alkali binders. To improve the activity of the ash, lime was added to the composition in various proportions: 0.5%, 1% and 1.5%. The strength characteristics of the obtained binders were determined after heat and humidity treatment (HCT), as shown in Figure 1, as well as after normal curing for 7, 14 and 28 days, shown in Figures 2-4, respectively.

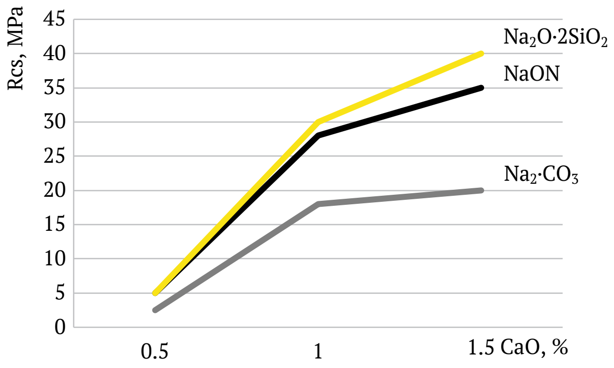


**Figure 1.** Dependence of compressive strength Rcs on CaO content %, after HCT after 1 day
**Source:** compiled by the authors

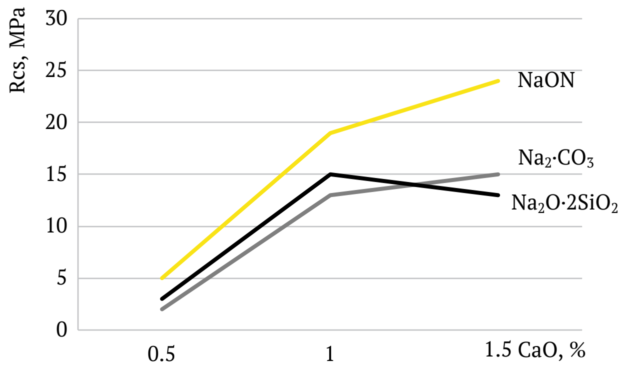


**Figure 2.** Dependence of compressive strength, Rcs on CaO content %, after 7 days of normal curing
**Source:** compiled by the authors

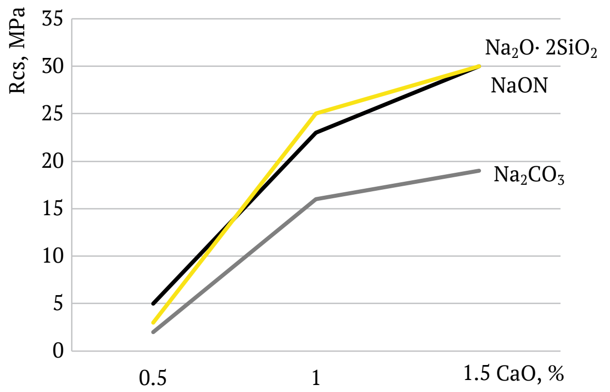


**Figure 3.** Dependence of compressive strength, Rcs on CaO content %, after 14 days of normal curing
**Source:** compiled by the authors

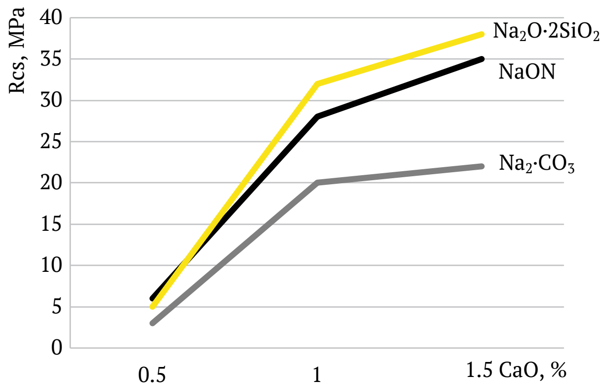


**Figure 4.** Dependence of compressive strength, Rcs on CaO content %, after 28 days of normal curing
**Source:** compiled by the authors

From the data presented, it is possible to conclude that $Na_2O \cdot 2SiO_2$ is the most effective of the alkaline components, as its use contributes to the formation of binders with high strength characteristics, which are estimated in the range from 31.9 to 37.8 MPa. Moreover, the activity of these binders during heat and humidity treatment slightly exceeds the strength values during normal curing, especially at the mature stage at the age of 28 days, reaching 39.6 MPa. Binders containing NaOH have sufficient activity, which is reflected in the strength of 34.4 MPa. An important condition for the synthesis of ash binders based on low-lime ash is the presence of CaO in the binder since composite mixtures without calcium are not capable of hardening. Lime was added in the range of 0.5 to 1.5% of the total ash weight in the preparation of composite mixtures in the study. The samples containing 1.5% lime stood out as having the highest strength compared to other variants of the compositions.

The introduction of sodium hydroxide provides a sufficient amount of Na+ ions for ion exchange of the $2Na+\leftrightarrow Ca_2+$ type, which leads to the disruption of some bonds in the glassy phase of the -Si-O-Si- ash and the formation of shells of silicic acid gel and sodium silicate on the surface of its particles. A gel-like shell formed on the ash particles adsorbs calcium ions from the solution, gradually turning them into low-base calcium hydrosilicates such as CSH. In the process, sodium hydroxide is released in the solution. The released sodium hydroxide reacts again with the surface of the ash particles, which leads to the destruction of their structure. Excess sodium oxide in the cured mass is carbonised. Thus, the entire process of hydration and curing of the binder involves the presence of sodium ions in the curing mass. The addition of Portland cement clinker has the strongest activating effect on ash (Turkoglu *et al.*, 2023). This means that Portland cement clinker promotes a more efficient reaction of fly ash and other components, improving the properties of the binder. Therefore, it was decided to add different concentrations of Portland cement clinker (1, 2, 3, 4, 5%) to the binders. Experimental studies were carried out on mixtures with sodium hydroxide (NaOH) and $Na_2O{\cdot}SiO_2$ liquid glass. These components are also important for shaping the structure of the binder and optimising its properties. The results of the study, including the effect of different concentrations of Portland cement clinker on the characteristics of binders, are shown in Figures 5-8. This data determines the optimal concentration of Portland cement clinker to achieve the desired binder properties.

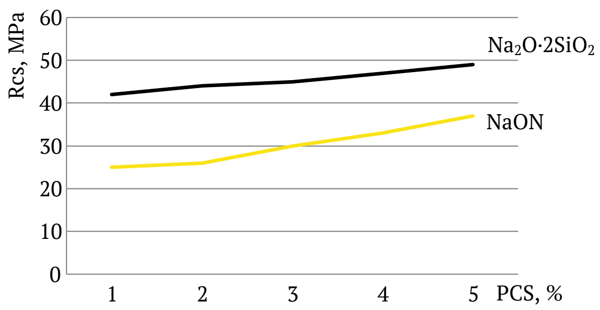


**Figure 5.** Dependence of compressive strength Rcs on PCS content %, after HCT after 1 day
**Source:** compiled by the authors

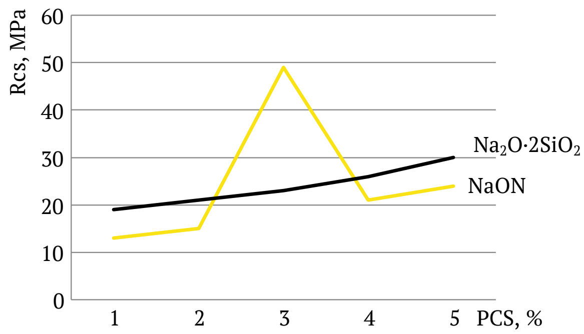


**Figure 6.** Dependence of compressive strength Rcs on PSC content %, after 7 days of normal curing
**Source:** compiled by the authors

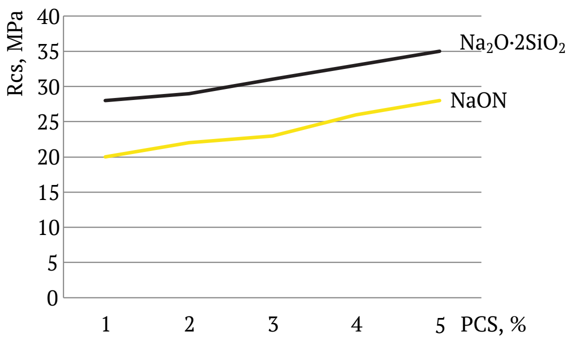


**Figure 7.** Dependence of compressive strength Rcs on PSC content %, after 14 days of normal curing
**Source:** compiled by the authors

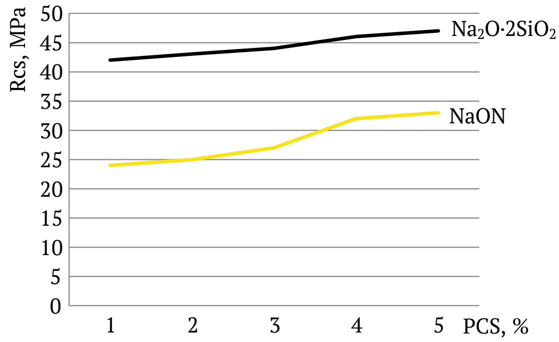


**Figure 8.** Dependence of compressive strength Rcs on PSC content %, after 28 days of normal curing
**Source:** compiled by the authors

When Portland cement clinker is added to alkaline binders, an increase in their activity is observed compared to the activation of fly ash with lime (Vázquez-Rodríguez *et al*., 2023). The hydration process of low-lime ash produces hydrates of aluminium, iron and silicon oxides, which are then applied to the surface of the grains. At the initial stage of interaction between ash and clinker minerals, a film of $Ca(OH)_2$ crystals crystallised from aqueous solution forms on the surface of the ash particles. There is a layer of water between the film that forms and the surface of the ash particles, which remains for a long time. This layer is gradually filled with $Ca_2$+ reaction products that penetrate through the water layer and soluble components of the vitreous phase of the ash. First, calcium hydrosulphates are formed, followed by hydroaluminates and then calcium hydrosilicates.

The presence of alkaline components in the binder material facilitates the above-mentioned processes of ion exchange between Na+ and $Ca_2$+ and the strengthening of newly formed structures. The use of fly ash also accelerates the hydration of clinker minerals, in particular $C_3S$, and over time, the content of low-base calcium hydrosilicates such as CSH(B) increases in the composition of fly ash cement stone, which has a positive effect on the strength of the cement material. During heat and humidity treatment, the processes of structure formation and strength acquisition are faster than under conventional curing conditions. This leads to a deeper hydration of the ash components, which is determined by the higher strength of the samples after heat and moisture treatment compared to samples that are cured under normal conditions. The increase in activity is manifested by an increase in the content of PSC in the ligament. The samples with 5% PCC content have the highest strength - 32.4 MPa from NaOH and 46.8 MPa from $Na_2O{\cdot}2SiO_2$. However, it is not advisable to further increase the amount of PCC in the composition of gold-alkali knitted materials, as this affects production costs.

## DISCUSSION

Optimisation of the composition and strength properties of slag-alkaline binders based on fuel slag is an important task facing the industry and the scientific community. This process involves studying and analysing the composition of fuel slag, determining the optimal proportions of binder components, and studying the impact of various additives and modifications on its strength properties. This aspect was also addressed by P. Krivenko *et al*. (2023), and they concluded that optimising the composition of slag-alkali binders based on fuel slag is an important task for industry and science. It includes studying the composition of fuel slag, determining the optimal proportions of binder components and investigating the effect of additives on its properties. Successfully solving this problem can lead to the creation of new efficient and environmentally sustainable building materials. Furthermore, a study conducted by J. Huang *et al*. (2021) noted that the analysis of the effect of additives on the strength characteristics of slag binders is relevant for the development of materials with improved properties. Additives can improve strength and stimulate chemical reactions by promoting the formation of additional bonds in the material structure (Kombayev *et al*., 2022). However, potential negative effects, such as reduced machinability or increased porosity, must be considered. A thorough study of the effect of additives helps to optimise the material composition to achieve the desired characteristics. This is in line with the results of this study, which confirms that the optimal choice of additives can significantly improve the strength properties of slag binders. The results of the study also reveal the complex effect of additives on the structure and properties of the binder, which is key to its further improvement.

A necessary step in optimising the composition of slag-alkali binders is a detailed study of the composition of fuel slag, which is the main raw material to produce such materials. This includes analysing the content of key components such as $SiO_2$, $Al_2O_3$, $Fe_2O_3$, CaO, MgO and others, as well as their distribution. Studying the composition of slag allows us to determine its potential for use as a binder and select the best methods of processing and modifying it. The mentioned was also investigated by Yi. Gao *et al*. (2022), where the results showed that the study of fuel slag composition is key to optimising the production of slag binders. The analysis of the chemical composition and physical properties of slag assessed its potential as a binder and determined the best methods of processing and modifying it. X. Dai *et al*. (2022) also investigated that the analysis of fuel slag components plays a key role in the development of the optimal composition of slag binders. This analysis allows us to determine the content of key chemical components such as $SiO_2$, $Al_2O_3$, $Fe_2O_3$, CaO, MgO and others, as well as their distribution in the material. The study of these parameters helps to identify the potential of fuel slag for use as a binder and develop optimal methods of its processing and modification, which helps to improve the strength and other properties of slag-alkali binders. It is worth noting that the analysis of fuel slag components is an important stage in the development of slag-alkali binders. With a complete understanding of the slag composition, researchers can determine the optimal proportions and mixing conditions for the various components to achieve the desired binder properties. In addition, component analysis can identify potential obstacles or limitations that may arise when using slag as a binder. This approach contributes to the more efficient use of fuel slag as a valuable resource and the creation of higher quality and more sustainable building materials.

The study of chemical reactions between slag components and possible additives determines the optimal proportions and mixing conditions for obtaining a binder with the required strength properties. For example, the addition of gypsum can improve the strength and water resistance of the binder. Research in this area may also include the influence of various process parameters, such as temperature and processing time, on the characteristics of the binder. This aspect has attracted the attention of many scientists, including W. Guo *et al*. (2021), who emphasise that optimising slag-based binders requires studying the chemical reactions between slag components and possible additives. This determines the optimum mixing ratios and conditions to obtain a material with the desired properties. Additives such as gypsum can improve the strength and water resistance of the material. E. Khobotova & I. Kaliuzhna (2023) concluded that the study of the influence of chemical reactions on the properties of slag-alkali binders is also substantial in their optimisation. Chemical reactions between slag components and additives lead to the formation of new compounds that can significantly affect the properties of the binder. For instance, during the slag hydration process, hydrates of calcium, aluminium and other elements can be formed, which determine the strength, water resistance and other characteristics of the binder. The study of these chemical reactions makes it possible to optimise the composition of the binder and develop new production methods to improve its efficiency and environmental sustainability. These results confirm the above study, as they demonstrate which specific chemical processes and reactions lead to the improvement or change of the properties of slag binders. This is necessary for describing the mechanisms of interaction between material components and their influence on its characteristics. Determining the optimal proportions of the main components for creating a binder may involve adjusting the content of CaO, $SiO_2$, $Al_2O_3$ and other components depending on the required properties of the final product. For example, increasing the CaO content can improve the strength of a material, while increasing the $SiO_2$ content can increase its resistance to water (Yakovkin *et al*., 1998). CaO has an impact on strength, $SiO_2$ on water resistance and $Al_2O_3$ on stability. This creates the possibility of customising the material properties to meet specific needs.

Analysing the environmental impact of the production and use of binders selected the most environmentally sustainable options and developed strategies for their implementation. For instance, the use of fuel slag as a raw material for binders can reduce waste and reduce the environmental impact. N. Cristelo *et al*. (2021) determined that the environmental assessment of the production of slag-alkaline binders plays an important role in the modern construction materials industry. The use of fuel slag as the main raw material for binders reduces waste. The choice of environmentally sustainable production technologies and innovations in materials reduce the negative impact on the environment. This assessment selected the most environmentally sustainable options that meet modern sustainability requirements. It is worth noting the study by B. Gao *et al*. (2021), also showed that the use of fuel slag in the production of binders has significant environmental significance. It reduces waste and minimises the consumption of natural resources, as slag is a by-product of energy production. However, their chemical composition and potential environmental risks, such as heavy metal content, must be addressed. However, the proper use of slag can reduce the negative impact on the environment and contribute to the transition to more sustainable production methods.

Comparing the data obtained in the study, it is possible to conclude that the use of fuel slag as a raw material for binders has its advantages and disadvantages. Positive aspects include reduced waste and lower consumption of natural resources, which contribute to the environmental sustainability of production. However, it is also necessary to address the negative aspects, such as the possible content of harmful substances and heavy metals in slag, which can lead to soil and water pollution if not handled properly. Therefore, it is necessary to take measures to control the quality of slag and develop technologies for its processing to minimise its negative impact on the environment. In general, optimising the composition and strength properties of fuel slag-based cementitious binders is a multi-stage process that requires joint efforts of industry, academia and environmental organisations. This creates materials that not only have the required technical characteristics but also reduce the negative impact on the environment.

## CONCLUSIONS

The study considered the following aspects: the composition of fuel slag, which allowed to determine its potential for use as a binder; the content of the main components of slag, such as $SiO_2$, $Al_2O_3$, $Fe_2O_3$, CaO, MgO and others, which allowed to understand their impact on the properties of the binder; chemical reactions between slag components and additives, which allowed to determine the optimal proportions and mixing conditions to obtain a material with the desired properties; -adjustment of the content of CaO, $SiO_2$, $Al_2O_3$ and other components depending on the requirements for strength, water resistance and other characteristics, which allowed to highlight its key role in the process of optimising the composition of binders.

The study found that the addition of an alkaline component to low-lime ash produced at thermal power plants activates them and promotes the formation of a strong structure, which allows the production of gold-alkali binders and composite materials based on them. The use of Portland cement clinker in combination with alkaline components, such as $Na_2O$-$2SiO_2$ and NaOH, as curing activators, increases the activity of gold-alkali compositions, exceeding the compressive strength of gold-alkali binders with the addition of lime by 10-15%. Heat treatment of gold-alkali binders containing Portland cement clinker increases the compressive strength by 12-15% compared to conventionally cured compositions. This is determined by the deeper hydration of the ash component. Optimal compositions of binding materials based on low-lime ash and composite building materials made from them were identified. An additional area of research could be the study of the long-term impact of various operating conditions on the strength and environmental properties of slag-alkali binders to better assess their potential in construction and environmental impact.

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## CONFLICT OF INTEREST

None.

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## Оптимізація складу та міцнісних властивостей шлаколужних в'яжучих на основі паливних шлаків

**Анотація.** У рамках цього дослідження вивчаються способи вдосконалення складу та міцності шлаколужних в'яжучих, отриманих із продуктів згоряння палива. Для цього було застосовано рентгеноструктурний аналіз, спектроскопію, мікроскопію, випробування на міцність під час стискування, та аналіз отриманих даних для активації зол блоків теплоелектроцентралі, оцінки активності композицій, тепловологісної обробки та визначення оптимальних складів. Зололужні в'яжучі матеріали мають переваги порівняно з портландцементом: вони мають високу міцність, водонепроникність, морозостійкість і корозійну стійкість. Ці матеріали застосовуються в будівництві об'єктів спеціального призначення, таких як автомобільні дороги, аеродроми, мости, транспортні тунелі та гідротехнічні споруди. У рамках експериментального дослідження було розроблено оптимальні зололужні в'яжучі на основі паливних шлаків, що володіють необхідними властивостями. Аналіз хімічного складу паливних шлаків виявив високий вміст оксидів кремнію, алюмінію, заліза, кальцію і магнію, що робить їх придатними для використання як в'яжучих матеріалів. Експериментальні дані показали, що введення добавок, таких як гіпс, значно покращує механічні властивості та довговічність матеріалів. Розроблені технологічні процеси змішування, формування та затвердіння забезпечили стабільну якість продукції. Випробування зразків продемонстрували високі характеристики міцності на стиск, розтягнення і вигин, що підтверджує їхню придатність для будівельних застосувань. Екологічна оцінка показала, що використання паливних шлаків знижує вуглецевий слід і зменшує негативний вплив на навколишнє середовище. У результаті розроблено масштабований процес виробництва, який може бути впроваджений у промисловість для створення екологічно стійких і високоефективних будівельних матеріалів. Це дослідження представляє нові дані про розробку екологічно стійких будівельних матеріалів на основі паливних шлаків, що може знизити екологічне навантаження і поліпшити стійкість інфраструктури

**Ключові слова:** техногенна сировина; зола гідровіддалення; добавка; композиційні будівельні матеріали; хімічний склад