Prospects for the use of ash-alkali binders in the production of building materials by the method of semi-dry pressing

S V Makarenko¹, B M Lozovsky¹, O V Khokhryakov², V G Khozin² and I V Borovskikh²

¹Irkutsk National Research Technical University, st. Lermontov, 83, Irkutsk, 664074, Russia
²Kazan State University of Architecture and Civil Engineering, Department of technology of building materials, products and structures, st. Zelenaya, 1, Kazan, 420043, Russia

E-mail: makarenko_83_07@mail.ru

Abstract. The article deals with the influence of a number of factors on the properties of ash-alkali binders, the values obtained during testing of physical and mechanical parameters of ash-alkali binders such as density, softening coefficient and strength are given. A complete factorial experiment was conducted to determine the optimal composition of the ash-alkali binder and determine the influence of the main factors on its strength. Based on the data of x-ray diffraction analysis, a conclusion is made about the phase composition of the artificially synthesized stone.

1. Introduction
Research on the development of ash-alkali binders and concretes based on them is undoubtedly a promising area, since it is consistent with national projects and several priority goals of the Russian Federation, recently announced by the President, and the implementation of which is planned in the near future, namely:

- national project "Ecology", aimed at improving the environmental situation in the country. Since the building materials industry is one of the most capacious industries capable of processing many types of waste, including ash and slag waste from thermal power plants, the accumulation of which is more than 90 million tons only in the Irkutsk region
- a strategic goal has been set to reduce the cost per square meter of housing and provide affordable housing for citizens. Based on the fact that construction materials account for up to 65% of the estimated construction cost, the developed type of binders and concretes based on it is very attractive from an economic point of view, since it mainly takes into account the use of ash and slag waste and local mineral raw materials in the region.

2. Materials and methods
Taking into account theoretical developments, the main goal of the research was formulated: to establish the optimal ratio between the components of the ash-alkali binder (alkali: ash), to select the most suitable modes of preparation of the press mass, the conditions of forming and heat treatment, as well as to obtain concrete compositions based on ash-alkali binders (hereinafter ZSC). The solution of the problem was
carried out by conducting preliminary studies that give a General idea of the choice of the main factors, before setting up a complete factor experiment, followed by evaluating each factor for the output parameter (in this case, for strength).

The following materials were used as raw materials: caustic soda (GOST R 55064-2012. Technical caustic soda), ash-dump TPP-11, with an initial specific surface of 2800 cm$^2$/g. Preparation of the ash consisted in drying it and grinding it to a specific surface area of 4500 cm$^2$/g. According to X-ray structural analysis (hereinafter X-ray structural analysis), the ash composition is represented mainly by minerals: quartz (28%), mullite (10%), silimanite (2.7%). The total content of the crystalline phase is about 40%, X-ray amorphous - 60%.

The compressive strength of ash-alkali stone and concrete was determined on specimens-cylinders with a diameter and height of 50 mm after conducting TVO or autoclaving and with subsequent holding before testing for two hours.

3. Results
At the first stage, we studied the kinetics of changes in the strength of the ZSP depending on the alkali content and specific surface area (Figure 1), then analyzed the dependence of the change in the strength and water resistance of the ZSP of autoclave hardening on the alkali content (Figure 3).

For testing, mixtures of binder were prepared with different percentages of alkali (5%, 10%, 15%) and specific surface areas of 2800 cm$^2$/g and 4500 cm$^2$/g. Caustic soda (NaOH) was used as an alkaline...
component. The water-solid ratio was taken constant and amounted to 0.12. Technological parameters in all cases were the same: pressing pressure 20 MPa, temperature TVO 80°C, time 12 hours, with autoclave treatment P = 8 atm, isothermal time 8 hours.

For a comprehensive assessment of the influence of factors on the strength of the ash-alkali binder and ranking the factors, we used the method of mathematical planning. It was a 2-level 4-factor experiment ($2^4$). The factors and the interval of variation are given in Table 1, the planning matrix is in Table 2. At the same time, the constant factors for all compositions were the isothermal temperature of 80°C, the time for the temperature to rise to 80°C, the cooling time to 40°C was 2 hours. The preparation of the press mass was reduced to the dosage of the binder components, based on the experimental conditions, followed by mixing the components, pressing in molds - cylinders and conducting heat treatment.

As a result of the experiments, the influence of factors on the strength of the ash-alkali binder was established with subsequent analysis and arrangement in accordance with their significance. The reliability of the presented results was obtained by calculating the confidence interval, homogeneity of variances using Cochran's criteria, checking the model for adequacy taking into account Fisher's coefficients (Table 2 and Table 3).

Table 1. Factors and interval of variation.

| Factors                          | Factor level | Variation interval |
|---------------------------------|--------------|--------------------|
|                                 | -1 | 0   | +1   |
| $X_1$ pressing pressure (MPa)   | 10 | 20  | 30   |
| $X_2$ alkali content from ash mass (%) | 5  | 10  | 15   |
| $X_3$ water-solid ratio (%)     | 8  | 12  | 16   |
| $X_4$, isothermy time hour      | 8  | 12  | 16   |

Table 2. Values of Cochran's coefficients and mean and maximum square deviation according to the test results.

| Indicator name                      | Indicator value |
|-------------------------------------|-----------------|
| max $S^2$                           | 0.124           |
| G estimated / G tabular             | 0.172 / 0.342   |
| Conclusions on dispersion uniformity| G settlement< G Table, means the dispersion is homogeneous |
| $S^2_{[7]}$                         | 0.023           |

Figure 5. Experiment planning matrix $2^4$. 

Table 2. Values of Cochran's coefficients and mean and maximum square deviation according to the test results.
Table 3. Values of Fisher's coefficients and variance of model adequacy.

| Indicator name                        | Indicator value |
|---------------------------------------|-----------------|
| $S^2$ hell                            | 3.46            |
| $F_{obs} / F_{tabular}$               | 1.99 / 2.07     |
| Checking the adequacy of the model    |                 |
| the model is adequate                 | since $F_{obs} < F_{tabl}$ |
| Variance of the regression coefficient| 0.01            |
| Regression coefficient squared error  | 0.0316          |
| Student's coefficient                 | 2.92            |

Based on the results of the study, the regression equations for the ash-alkali binder were obtained: compressive strength after TVO:

$$R_3 = 20.3 + 3.5x_1 - 8.7x_2 + 3.4x_3 - 4.5x_4 - 2.8x_5 + 1.6x_6 + 2.6x_7$$  \(1\)

Table 4. Results of X-ray structural analysis of an artificial stone obtained on the basis of ZSP in the course of autoclaving \((P = 8\text{atm}; t = 8\text{h})\).

| Mineral name   | The content of the crystalline phase in the ZSChV stone on the TPP-11 ash at different alkali concentrations,\% |
|----------------|-----------------------------------------------------------------------------------------------------------------|
|                | 5   | 10  | 15  |
| Quartz         | 25  | 20  | 5.3 |
| Sillimanite +  | 8.7 | 9.1 | 5.8 |
| Mullite        | –   | 3.75| 4.2 |
| Garnanite      | 3.7 | –   | –   |
| Microcline     | 1.5 | 1.8 | 2   |
| Magnetite      | 1.5 | 1.8 | 2   |

Figure 6. Graph of the dependence of the strength of the ash-alkali binder stone on the ash of CHPP-11, depending on the concentration of the amorphous phase, obtained by autoclaving.

At the next stage of the research, the physical and mechanical properties of concretes based on ZSP were determined, taking into account their structure. The analysis of the physical and mechanical characteristics of concrete was evaluated on the obtained optimal composition, while taking into account the influence of the following factors: the percentage of alkali in the mixture, the specific surface of the
ash, the pressing pressure when obtaining samples and the ratio of aggregate to binder (Figure 7). According to the test results, the dependence.

![Figure 7](image)

**Figure 7.** Strength of concrete based on ZSC, depending on the ratio of binder to aggregate.

| Table 6. Average values of quality indicators of concrete based on ash-alkali binder during TVO. |
|-----------------------------------------------|
| Indicator name | Wall stone based on ZSCHV |
| Density \( \rho \), g/cm³ | 1.74 |
| Strength \( R \), MPa | 10 |
| Softening factor \( K_r \) | 0.8 |
| Water absorption \( W \), % | 9.6 |

4. Discussion

From the regression equations, it can be seen that the maximum effect on the strength of the stone is exerted by the concentration of alkali \( X_2 \), while an increase in the heat treatment time \( X_4 \) does not have a positive effect, as indicated by the coefficient in the regression equation. This effect may be associated with changes in the structure of the ash-alkali composite. Factors \( X_3 \) and \( X_4 \) make a correlated contribution of about 10% of the maximum possible result, paired and triple interactions are also quite significant and contribute about 30% of the total contribution of factors. The combined total contribution of all factors, when properly varied, adds about 60% to the strength value at zero. To theoretically substantiate and establish the mechanism of artificial stone formation, an x-ray structural analysis of the compositions of ZSCHV was performed, including during autoclave treatment (table 4, figure 7). Based on the results of x-ray analysis, it was found that sillimanite and mullite have a less pronounced reactivity compared to quartz, although they show it at an alkali concentration of 15%.

Quartz is a more reactive ash mineral. In turn, the strength of the ash-alkaline stone is ensured by the interaction of alkali mainly with the amorphous phase of ash and partial interaction with its minerals.

The higher strength of the stone during autoclave processing is due to the greater completeness of the process between the alkali, the crystalline and the more reactive amorphous component included in the ash.

As a result of the tests, it was found that the physical and mechanical properties of ZSCHB meet (figure 7, table 5) the requirements for heavy concrete on a cement binder (table 6).

5. Conclusion

It was found that to optimize and regulate the compositions of ash-alkali binders and concretes based on them, a complex effect of chemical and technological factors is necessary, which was established by the methods of mathematical planning of the experiment. Based on the X-ray diffraction analysis of the ash-alkali stone, it has been established that the main carrier of the strength of the developed composition is the amorphous component formed as a result of the interaction of the amorphous and partially crystalline part of the ash with alkali. The degree and completeness of the interaction of alkali with ash and the physical and mechanical characteristics of ash-alkali binders, and as a consequence of concrete, depend largely on the conditions of heat treatment. The obtained concrete composition, taking into account its physical and mechanical properties, meets the requirements for heavy and fine-grained concrete. The
peculiarities of the technology for the production of wall stones give reason to believe about the possibility of successful use of concretes based on ash-alkali binders.

References

[1] Babachev G 1987 Ash and slags in the production of building materials p 136
[2] Baranov A T 1960 Buzhevic G A Zolobeton p 223
[3] Dvorkin L I 1991 Ash-alkali binders
[4] Kozlova V By 1975 The use of ashes from thermal power plants in the production of building materials
[5] Logvinenko A T and Savinkina MA 1974 Processes of hydration and hardening of ash binders
[6] Ryabova A G et al. 1990 Ash-alkali binders Cement 11
[7] Savinkina M A and Logvinenko AT 1968 Slag ash binder
[8] Timashev V V, Vorob’eva M A, Ubeev A V and Dyukova N F 1977 Astringents based on ash Coll. scientific. tr. 98 p 194
[9] Grebneva O A, Shirokih A E and Makeeva K I 2020 Efficiency of infrared heating of industrial premises under Siberian conditions Proceedings of Universities. Investment. Construction. Real estate 10(4) pp 552–559
[10] Maizel I V and Bober V A 2020 Intensification of water supply and sanitation systems in the city of Nizhneudinsk. Proceedings of Universities. Investment. Construction. Real estate 10(4) pp 578–587
[11] Kalashnikov M P 2020 Study of the air environment state in the building for the storage of perishable products Proceedings of Universities. Investment. Construction. Real estate 10(2) pp 206–211
[12] Sobolev V I and Chernigovskaya T N 2020 Research into the dynamics of radio telescope foundations using laser vibration measuring equipment Proceedings of Universities. Investment. Construction. Real estate 10(3) pp 420–427
[13] Komarov A K, Ivanov I A and Lundenbazar B 2019 Theory and practice of the use of gabions for forming protective structures Proceedings of Universities. Investment. Construction. Real estate 9(1) pp 78–89 DOI: 10.21285/2227-2917-2019-1-78-89
[14] Peshkov V V 2020 IOP Conf. Ser.: Mater. Sci. Eng. 880 012100