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Research on the Volume Weight of Foamed Composites Based on Brick Waste Using Neural Networks

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Abstract

This paper described the opportunity to use artificial neural networks to predict the chemical reaction result under given conditions. Applied three layers neural network for prediction of the mass content of alkaline trained using the results of the chemical reactions. As inputs were used values of the chemical quantities before the reaction and output values of the chemical quantities after the reaction. HPC technologies and multi-worker technology were used for accurate results.

Keyword: Data Prediction, Parallelization, Neural Networks, Multi Worker Processing.

1. Introduction

The application of a large assortment of composite materials in the industrial and domestic sphere creates one of the global problems of modernity - the problem of utilization of industrial, domestic, and especially construction waste. Production of industrial and domestic materials promotes the formation of a large quantity of waste that demands to recycle, considering rigid ecological requirements. The growth of industrial production also leads to an increase in the amount of waste. In our country, with the growth of population and production, there is a need to build more residential and industrial buildings and facilities. All this contributes to an increase in the consumption of building bricks and their production growth. The production growth inevitably leads to an increase in the number of defective brick products, i.e., an increase in the amount of waste. On the other hand, there is widespread destruction of old residential and industrial buildings consisting mainly of bricks, generating a large amount of brick scrap, which requires rational disposal. There is another important problem - the problem of thermal insulation of residential, office, and industrial buildings. This problem is very urgent in the world. The increase in global warming poses an important task for the construction sector - the task of creating lightweight materials with low thermal conductivity coefficients. At the moment, the world's scientists are researching to create lightweight, foamed materials. This reduces the build's static load and labor costs during construction and transportation. In addition, the presence of many artificial pores in the material gives it good heat and sound insulation properties. Using materials with similar properties can reduce heat loss in winter and maintain a reasonably moderate room temperature in summer (Raj, A., Sathyan, D., & Mini, K. M., 2019; El-Naggar, K. A. M., Amin, S. K., El-Sherbiny, S. A., & Abadir, M. F., 2019). All this, in turn, contributes to reducing the energy consumption required for heating and cooling the premises. The reduction of energy consumption leads to a reduction in carbon dioxide emissions into the atmosphere. According to the international research project "Global Carbon Project," in comparison with 2020, in 2021, carbon dioxide emissions increased by 4.9% and amounted to 36.7 megatons (European Comission, 2022). Thus, creating heat-insulating materials is one of the urgent tasks facing the community of scientists. It is known that the presence of thermal insulation properties in the material implies the presence of a porous structure or inclusions with low thermal conductivity. In our further research, we chose the creation method of the artificial porous structure. One of the main characteristics of porous materials is volume weight, by which we can judge the material's porosity. It was important to study the change in the volume weight of the material by predicting it depending on the ratio of components.

In this regard, in this study, we had the task of studying the volume weight of composites based on brick waste using neural networks.

2. Experimental part

The following materials were used in order to obtain foamed composite materials:

- brick scrap (substandard brick products, broken bricks);
- liquid glass - an aqueous solution of sodium silicate. A thick, translucent liquid (GOST 13078-81);
- sodium hexafluorosilicate is a white, crystalline powder, poorly soluble in water (TU 2621-010-69886968-2013);
- aluminum powder - silver-colored aluminum powder (GOST 5494-95);
- sodium hydroxide - a solid, hygroscopic substance of white color (GOST 2263-79);
- tap and distilled water.

Samples of foamed composite materials based on brick waste were prepared according to the method described in (Gahramanli, Y.N., Hajiyeva, R.Sh., Hasanova, M.B., Samedzadeh, B.A., 2020).

The research on the volume weight of the samples of composite materials was carried out according to GOST 6427-75. Taking into account that the molds for the samples had a strictly defined geometric shape in the form of a truncated cone, the calculation of the geometric volume was carried out by the following formula:

$$V = \frac{1}{3}\pi h \left(\frac{d_1^2}{4} + \frac{d_1 \cdot d_2}{4} + \frac{d_2^2}{4}\right)$$

Where h - the height of the sample, mm; d1 - diameter of the lower part of the sample, mm; d2 - diameter of the upper part of the sample, mm. The main dimensions were measured using a caliper with an accuracy of 0,1 mm.

The known formula carried out the calculation of the volume weight:

$$\rho_i = \frac{m_i}{V_i} \cdot 1000$$

where mi- the mass of the sample measured with an accuracy of 0,001 g; Vi- the geometric volume of the sample, cm3.

3. Obtained results and their discussion

As we know, bulk is one of the most important indicators of porous materials. Monolithic, non-foamed materials have a smaller geometric volume than foamed, porous materials. That is, volume weight is a relatively important indicator of the degree of porosity of the material. With the increasing porosity of the material, its thermal conductivity deteriorates. At the same time, the porous material becomes lighter and creates a less static load on the build. Therefore, to characterize the porosity of the obtained materials, it was very important to study the mechanism of change in their volume weight. The research was carried out by changing two parameters - the alkali concentration in an aqueous solution and the amount of this solution; for the study, samples were obtained using an alkaline solution of 16, 18, and 20%mass. At the same time, the normality of alkaline solution changed in the range of 1-5n. The content of brick waste in the obtained composite materials was 80%mass (Gahramanli, Y.N., Hajiyeva, R.Sh., Hasanova, M.B., Samedzadeh, B.A., 2020).

The results of studies of the volume weight of the composite material depend on the change in the normality of the alkaline solution at the content of the alkaline solution in the initial mixture at 18%mass was considered in (Gahramanli, Y.N., Hajiyeva, R.Sh., Hasanova, M.B., Samedzadeh, B.A., 2020). The results of the studies are shown in Fig. 1.

The figure shows that an increase in the alkali concentration in the solution up to 2n leads to a significant decrease in the volume weight from 1656 kg/m3 to 751 kg/m3, which is almost 2,2 times.

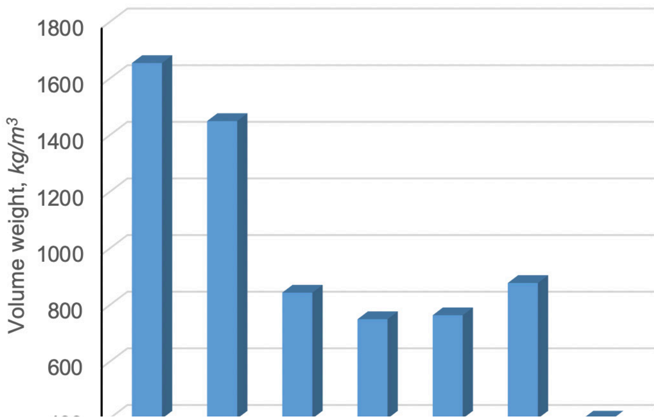

Fig.1. Dependence of change of volume mass of the foamed composite material on the concentration of alkali in the solution.
(alkali solution content in the initial mixture is 18%mass.) (Gahramanli, Y.N., Hajiyeva, R.Sh., Hasanova, M.B., Samedzadeh, B.A., 2020)

The minimum value of volume weight is 751 kg/m3. The increase in the foaming intensity is due to the fact that increasing the alkali concentration leads to the faster dissolution of the oxide film on the aluminum particles and a rapid reaction of gas formation. More intensive formation of hydrogen bubbles contributes to the foaming of the sample and leads to a greater increase in the geometric volume. Increasing the geometric volume while maintaining the mass of the samples leads to a decrease in their volume weight. The reaction of aluminum with an aqueous alkali solution is exothermic and proceeds with the release of excess heat. We found that increasing alkali concentration leads to a more intense reaction and, in accordance with this, a greater heat release. When using aqueous solutions of sodium hydroxide of 2,5n and above, the temperature of the composition as a result of the reaction of gas formation can reach 75-850C. There is intensive water evaporation from the foam composition at such temperature conditions, including water formed in the polycondensation reaction (polymerization). Such a rapid removal of the resulting water from the reaction zone, according to Le Chatelier's principle, contributes to a shift in the chemical equilibrium towards the formation of reaction products, i.e., to the formation of a densely meshed spatial structure. The accelerated formation of such a structure accelerates increasing the viscosity of the already highly viscous system with its subsequent solidification. The conclusion is that an increase in alkali concentration reduces the lifetime of the foamed concrete composition. Such a rapid increase in the system's viscosity leads to a rapid increase in the medium's resistance to the formed gas bubbles.

As a result, the gas bubbles cannot distribute evenly enough in the volume of the material and foam it. This leads to an increase in the volume weight. This fact was established experimentally by us. In addition, foaming in highly viscous media leads to the formation of a fine-pored structure, which is also due to the high resistance of the medium and the inability of the gas bubble to increase in size due to the rapid growth of viscosity. Therefore, the formed bubbles do not increase in diameter and do not form associates of considerable size but remain relatively small. A further increase in the alkali concentration has a negative effect on the curing process itself, loosening the resulting material. A further increase in alkali concentration from 2n to 3n does not lead to a sharp increase in the volume weight.

On the curve of Fig. 1, a minimum is observed. So, increasing the alkali solution concentration from 2n to 3n leads to an increase in volume weight from 751 kg/m3 to 859 kg/m3, approximately in 1,1 time. This fact may also be explained by the presence of more water in the composition at the beginning of gas formation. Due to the lower viscosity of the mixture, the foaming process has time to go more fully; that is, the gas bubbles are distributed relatively evenly, and their volume increases sufficiently. Although the rapid reaction of gas formation and the accompanying release of large amounts of heat due to the high concentration of alkali reduces the lifetime of the foamed mixture as a result of the circumstances mentioned above, nevertheless, there is a slight increase in the volume weight up to 859 kg/m3. A further increase in the concentration of the solution had a negative effect on the curing process of the foamed mixture, loosening the material's structure. At the same time, the material did not harden and became crumbly. The lifetime of the foam concrete mixture was reduced to almost 1-1.5 minutes (Gahramanli, Y.N., Hajiyeva, R.Sh., Hasanova, M.B., Samedzadeh, B.A., 2020; Gahramanli, Y.N., Samedzade, B.A., Hajiyeva, R.Sh., Hasanova, M.B., 2020a; Samedzade, B.A., Hajiyeva, R.Sh., Hasanova, M.B., 2020b).

In order to investigate the effect of further increasing the alkali solution concentration on the volume weight, foamed composites were obtained by introducing 20% wt. of alkali solution. The concentration of alkali varied in the range from 1 to 5n. The results of the studies are shown in Fig. 2 (Gahramanli, Y.N., Hajiyeva, R.Sh., Hasanova, M.B., Samedzadeh, B.A., 2020; Gahramanli, Y.N., Samedzade, B.A., Hajiyeva, R.Sh., Hasanova, M.B., 2020a; Samedzade, B.A., Hajiyeva, R.Sh., Hasanova, M.B., 2020b).

As seen from the figure, an increase in the alkali solution concentration at the entire content in the initial mixture also leads to a sharp decrease in the volume weight. Thus,

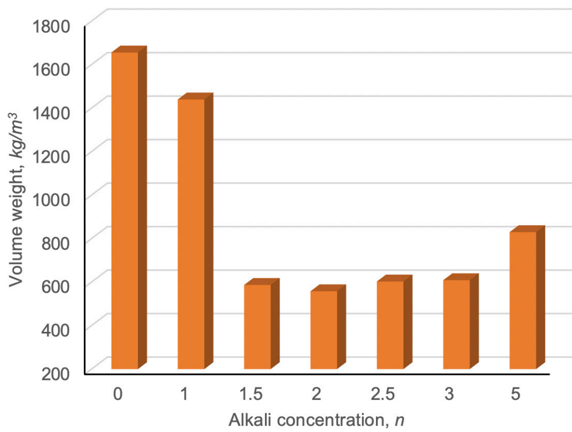

Fig.2. Dependence of change of volume mass of the foamed composite material on the concentration of alkali in the solution. (alkali solution content in the initial mixture is 20%mass.) (Gahramanli, Y.N., Hajiyeva, R.Sh., Hasanova, M.B., Samedzadeh, B.A., 2020)

at an increasing concentration from 0n to 2n, volume weight decreases from 1656 kg/m3 to 558 kg/m3, i.e., practically three times. This is more than in the case of the introduction of 18% wt. alkali solution. This circumstance also has its explanation. The introduction of 20% wt. alkali solution into the initial mixture means more water, significantly reducing the mixture's initial viscosity and increasing its lifetime. This circumstance allows for the complete mixing of the components of the initial mixture. It reduces the resistance of the medium to the process of gas formation due to lower initial viscosity.

Since the increase in viscosity over time is slower, the foaming process can proceed more evenly and efficiently. This contributes to a reduction in the volume weight. Therefore, in this case, the minimum value of volume weight is 558 kg/m3, which is 193 kg/m3 less than in the case of the introduction of 18% wt—alkali solution. A further increase in alkali concentration from 2n to 2.5n leads to a slight increase in volume weight for the reasons mentioned above. However, in this case, this increase in volume weight is only 45 kg/m3, which is also associated with an increase in water content in the initial mixture and a decrease in viscosity. Despite the large exothermic effect of the reaction of gas formation at high alkali concentrations, due to higher water content, the initial mixture's lifetime lengthens, leading only to a slight increase in the volume weight. Further increase in alkali concentration from 2.5n to 3n does not lead to any noticeable changes in volume weight; a horizontal plateau is observed on the curve. However, further, an increase in alkali concentration in the solution up to 5n leads to the increased volume weight of the sample up to 830 kg/m3, i.e., by 221 kg/m3. Despite the high alkali concentration and short lifetime of the initial mixture, it is possible to obtain foamed composites due to the relatively high water content in the initial mixture. However, obtaining foamed composites using highly concentrated alkali solutions is considered inappropriate because of the difficulties in the homogenization of the mixture and the release of excessive heat in the reaction of gas formation (Gahramanli, Y.N., Hajiyeva, R.Sh., Hasanova, M.B., Samedzadeh, B.A., 2020; Gahramanli, Y.N., Samedzade, B.A., Hajiyeva, R.Sh., Hasanova, M.B., 2020a; Samedzade, B.A., Hajiyeva, R.Sh., Hasanova, M.B., 2020b).

In order to predict the volume weight change of samples at 19%mass. An innovative method of neural networks was used for an alkaline solution without conducting appropriate experiments.

4. Usage of neural networks for prediction of the volume weight change and their implementation via HPC technology

Today, artificial intelligence techniques are used to predict and classify different parameters in various aspects of science, including chemistry, physics, materials science, ecology, hydrometeorology, etc. This paper proposes applying an artificial neural network, one of the most valuable techniques of artificial intelligence, for predicting the parameters of the chemical reaction described above. As the training of artificial neural networks requires high computational capabilities, the ADNSU HPC center cluster manager is used to implement the prediction process.

As mentioned above, a multilayer artificial neural network was generated to predict the volume weight change of samples at 19%mass content of alkaline. Data received from conducted experiments were used for training. Scikit-learn library in Python has been used for training the constructed structure, testing, and prediction. The proposed neural network has been constructed using three hidden layers with 512, 256, and 64 nodes as activation functions; in the nodes of the proposed neural network were used ReLU for the first layer and sigmoid function for the second and the third layers.

The main difficulty of neural network implementation for classification or 23redictionn proposed in this approach is related to several shortcomings, such as a long training period or high computational requirements. This drawback makes the usage of the neural network's prediction in practice uncomfortable. To eliminate the mentioned disadvantage, this paper described the results of the parallel training of the neural network using multi-worker training with (Keras Tensorflow, 2022).

Using data-batching technology and capabilities of the ADNSU HPC center constructed neural network has been parallelly trained in 2, 3, 4, and 5 computers with a different number of iterations (table 1).

Table 1. Results of the training in different number of computers

Number of computers	Time required for execution (min:sec:microsec)		
	Iterations = 2000	Iterations = 5000	Iterations = 10000
2	01:48:98	03:29:23	06:56:63
3	02:01:11	03:56:90	07:50:35
4	02:10:25	04:17:71	08:36:72
5	02:23:83	04:43:71	09:26:65

In the used strategy, multi-device synchronous training with a Keras model, each device executes a copy of the model for different data batches; for this reason, we cannot see time reduction during the increase of the computing machines. Conversely, increasing the computational time is observed by the increase of the devices. These results are related to the used strategy, as multi-device synchronous training is helpful for processing databases with a huge training dataset, and the training data in the solved example is not so big, were received inappropriate results by increasing the number of processing devices. In this regard, Slurm technology - scalable cluster management - was used to execute the model in combined devices. Training of the model via 10000 iterations has been executed for about five minutes and received MSE = 3.39 in the training dataset and MSE = 1.1 in the validation dataset.

Predicted values of the parameters for known mass content of alkaline were compared with the real data, visualized, and evaluated errors. Values for the volume weight change for 19% mass content of alkaline were predicted with enough accuracy and can be used for production.

5. Conclusion

Prediction of the chemical parameters using opportunities of artificial intelligence and HPC technology is very beneficial for science and industry. By reducing the time, money, staff, energy, and chemicals, described approach is an excellent example of interdisciplinary research for accurate results and economy. On the other hand, the method should be improved by using the parallelization technique in the training stage, i.e., during the computing of the gradient descent method. This approach will be helpful by involving numerous devices to reduce the training time.

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