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EVALUATION OF THE EFFECTIVENESS OF THE NON-KILNED ASH-SLAG GRAVEL STRUCTURE UNDER THERMAL IMPACT

Atyaksheva A.V.*, Seitova Zh. A., Issataeva A. K., Rysanov D. Yu., Khamitova Ye.M.

Energy Institute of S. Seifullin, Kazakh Agrotechnical Research University, Astana, Kazakhstan

*Corresponding author: sahsa77@mail.ru

Abstract. The article presents an analysis of the stress-deformed state results for gravels based on ash-slag mixtures, with the same specified composition, but different in structure and density under the thermal impact with temperature 500 °C. The evaluation of the gravels structure was carried out in a numerical simulation of the thermostatic structural analysis process. According to the results, the two – component gravel structure shows greater thermal stability. Separation into two component structure leads to a more even distribution of iso Surfaces, which in turn eliminates the possibility of stress surges leading to sharp changes in the structural characteristics of materials accompanied by degradation processes. In two component structure, there is a reduction of a stress intensity resulting from sudden stresses surges and leading to the formation of material failure points. The maximum stress intensity of two component gravel for about $1.8 \cdot 10^6$ Pa in compare of single component for about $2.1 \cdot 10^7$ Pa. The higher thermal viability of two-component gravel is demonstrated by thermal deformation due to a reduction in shear stress, which is (max) $9.03 \cdot 10^5$ Pa, in compare of single component (max) $1.11 \cdot 10^7$ Pa. Such conditions of the stress-deformed state indicate a greater reserve of thermal resistance for two – component gravel in compare of single component gravel and the possibility of its use as a heat protection in the composition of heat-resistant panels or independently in the temperature range up to 500 °C.

Keywords: gravel, structural, ash-slag mix, cement, thermal, deformation, strain, stress.

1. Introduction

The range of materials that can withstand high temperatures today is wide enough. There are lot of materials are available for use in different temperature ranges and operating conditions. However, materials that can withstand high temperatures are usually based on natural components, such as basalt, asbestos, different kinds of clay and so on. Moreover, such materials are usually subjected to high temperature technologies such as roasting, fusion and other (ceramic, pottery, etc.) At the same time, the trend of increasing environmental and economic attractiveness of heat-resistant materials technologies dictates conditions for the need to use production wastes, especially non-utilized waste, reducing costs and minimizing the technological burden on the environment through recycling. One of the most promising areas is related to the specific application of techno-genic waste from energy generation, especially, waste ash-slag mixes, having in its composition both active and inert components. Ash-slag waste is currently widely used for structural lightweight concrete, road construction and as a filler with enhanced thermal insulation properties [1-3]. Today kilned and non-kilned ash-slag gravels are successfully used as fillers. Kilned ash-slag gravel, at bulk density not more than 600 kg/ m³ can successfully solve the problems of providing heat protection functions, including

heat resistance. However, the manufacture of kiln materials generally requires a significant amount of energy in kilns at a temperature not less than 1150 °C – 1200 °C [4]. In this regard, the proportion of kilned materials today is being reduced intensively when replaced by non-kilned materials [5,6]. Non-kilned gravel in uniform density based on ash and slag waste is intensively used as a heat insulation material in construction production and in many works is noted as a material with the use of various complex additives and unconventional thermal treatment as heat resistant material [7,8]. However, the use of superplasticizers, binding fibrous materials, wave heat treatment or other significantly increase the cost of non-burning gravel, which defines it as uncompetitive compared to the numerous varieties of thermal insulation materials based on natural components of the same ranges of heat and heat resistance. Of particular interest for use in heat-resistant materials is non-calcined gravel based on ash-slag wastes from the combustion of coals with mechanical viscosity (Coal Mv) under condition of structuring, in which the strength and heat functions are divided according to the perception of the gravity of the power and heat engineering functions [9,10]. Furthermore, application of ash-slag mixtures, which include refractory ash that has a melting temperature range from 1600 °C to 1800°C and high elastic- plastic properties [11,12], complements thermostable qualities and further determines the ability to produce a material capable of withstanding significant thermal loads.

Thus, the study is aimed at determining the possibility of using a non-kilned ash-slag gravel with a two-component structure in which the strong shell, which is ash-slag cement mix shell, accepts the deformation load, and the inner area, performs thermal functions. Results obtained for thermal stress and high-temperature deformation of stationary convective heat exchange ($T = 500^{\circ}\text{C}$) was possible to evaluate the possibility of using non-kilned, two-component gravel as a filler in heat-resistant materials and as a stand-alone material for use in low temperature furnaces for heating, drying and heat treatment.

2. Material and Methods

The object of the study is a thermal stress-deformation parameters of the non-kilned gravel structure. The aim of the study is to evaluate the efficiency of a structure of non-kilned gravel, based on an ash-slag mixture under temperature impact in conditions of stationary heating in the temperature range from 22 °C to 500 °C. To achieve this, the following objectives are being solved:

- to analyze the equivalent stress and stress intensity during the thermal impact process on single and two component structure ash slag gravel;
- to analyze the total deformation and shear stress of non-kilned gravel with single and two-component structure that occurs during thermal action.

Materials, which are used as samples of non-kilned ash-slag gravels of a single-component structure with uniform density, 2000 kg/ m³ and a two-component structure with density 2500 kg/ m³ and a thickness of shell not no more than 2 mm (first component) and the inner volume of a mixture consisting of ash-slag mixture with density 1800 kg/m³ (second component). Samples of gravels represented on the Fig. 1. For the production of both samples of gravels, a ash-slag mixture from the combustion of Ekibastuz coal containing refractory ash and Karaganda Slag Portland-cement were used (SPC) quality Class 400.



Fig.1. Non-kilned ash-slag gravels: a) – single component structure; b) two component structure.

In this case, the double-layer gravel shell has a closed, evenly distributed porosity at relatively small grain size, optimal for operating conditions of strength and thermal porosity [13,14]. The evaluation of the efficiency of structured non-kilned gravels under thermal impact was carried out on the basis of numerical simulation of thermal heating in conditions of stationary convective heat exchange with heating up to a temperature of 500°C at specified input parameters of cement and ash mixture properties in Ansys CFX (Computational Fluid Dynamics) software environment. For simulation were used Thermal Static and Static Structural modules. Modelling is based on the finite element method in ANSYS APDL (ANSYS Parametric Design Language). The simulation was carried out on physical models of non-kilned gravels in equal volumes of single-component gravel 33510 mm³ (s1), and two-component gravel when dividing functions of volumes (s2) into the volume of the shell is equal 19373 mm³ and internal cavity, filled with 14137 mm³ of ash-slag loose mixture. The physical models of gravel samples are shown on the Fig.2. Numerical simulation was carried out over 3600 seconds in 36-second increments under stress and strain control.

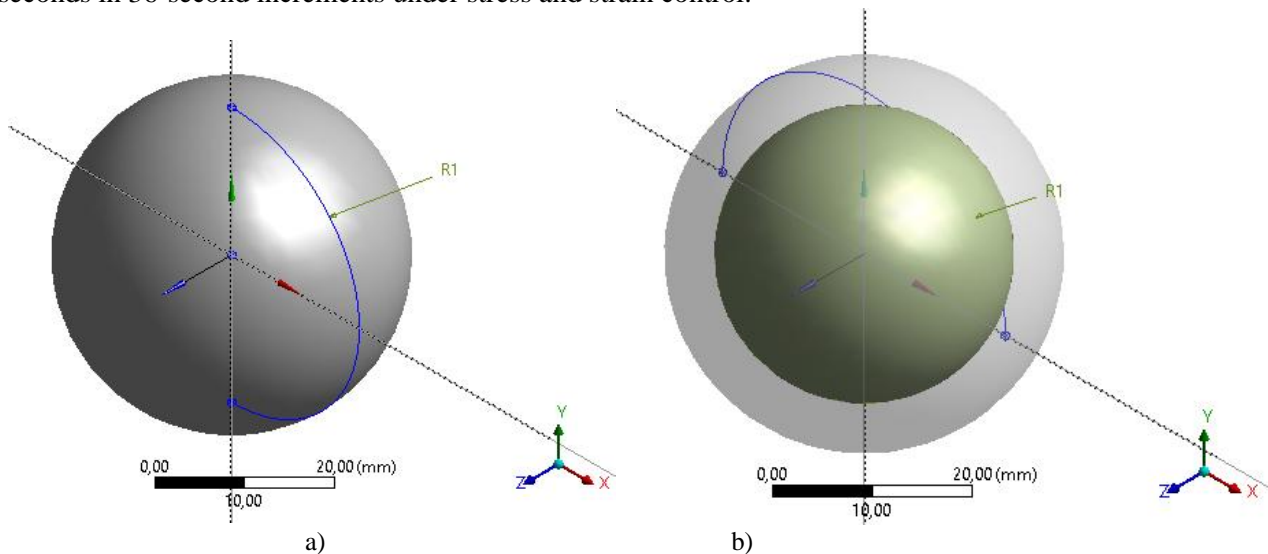


Fig.2. Physical models of non-kilned ash-slag gravels:
a) – single component structure; b) two component structure.

Engineering data for numerical simulation of the test models s1 and s2 materials presented in tables 1 and 2.

Table 1. Physical properties

N	Density, kg/m ³	Coefficient of thermal expansion, °C ⁻¹	Isotropic thermal conductivity, W/m°C	Specific heat, J/kg°C
Ash slag mix	2000	6e-06	0.2	840
Slag Portland-cement	2500	5e-06	1.2	800

Table 2. Elastic – plastic properties

N	Young's Modulus, MPa	Poisson's Ratio, Pa	Bulk Modulus, GPa	Shear Modulus, GPa
Ash slag mix	6000	0.17	3.030	4.564
Slag Portland-cement	2500	0.133	7.356	7.149

During the experiment, a thermal load was applied, approximated to the real conditions when controlling the thermal and stress-deformation parameters of the condition of non-kilned gravel. Heating was carried out for one hour, with parameter control increments of 1 second for 36 seconds after reaching the granule surface at 500 °C.

3. Results and discussion

3.1 Analysis results of the equivalent stress and stress intensity evaluation during the thermal impact process on single and two component structure ash slag gravels

The heat load creates an equivalent stress in the body of gravel of different intensity. Equivalent stress is a value representing the stress arising in different directions and calculated on the basis of three main stresses allowing to estimate, in case of thermal impact, the resistance of the gravels when split due to temperature action [15].

$$\varepsilon_x = \frac{1}{E} \left[\sigma_x - \mu(\sigma_y + \sigma_z) \right] + \alpha \Delta T, \quad (1)$$

$$\varepsilon_y = \frac{1}{E} \left[\sigma_y - \mu(\sigma_x + \sigma_z) \right] + \alpha \Delta T, \quad (2)$$

$$\varepsilon_z = \frac{1}{E} \left[\sigma_z - \mu(\sigma_x + \sigma_y) \right] + \alpha \Delta T, \quad (3)$$

where $(\sigma_x, \sigma_y, \sigma_z)$ is principal thermal stresses in direction x, y, z ; μ is Poisson's ratio; E is Bulk modulus; α is a thermal expansion factor; ΔT – temperature difference at the moment of thermal impact and ambient temperature.

According to Figure 3 the equivalent stress of the two-component structure gravel is less than stress of single component gravel and it consist at temperature 500 °C approximately 1.8106 Pa. Volumetric change of the total stress of a single-component gravel shows the change in structural characteristics with simultaneous thermal degradation of the gravel at the moment of reaching the stress value $\approx 2.1 \cdot 10^7$ Pa (formation both on the surface of gravel and inside isothermal surfaces with uncharacteristic density and energy). At the same time Iso Surfaces of two-component gravel are distributed more evenly without inclusions of uncharacteristic dimensional surfaces. Such conditions of development of tensions indicate the possible beginning of formation of cracks in the body of one-component gravel.

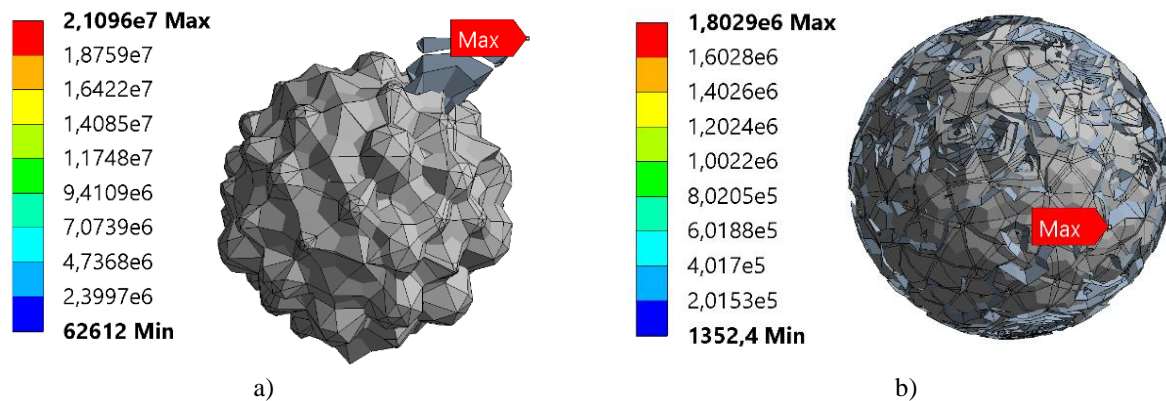


Fig 3. Iso Surfaces of the equivalent stress (Pa) of the single and two component ash slag gravels during the 500°C thermal impact: a – single component structure; b – two-component structure.

The Stress intensity factor, as a measure of tension characterizing the potential for crack formation and development that experiences gravel with different structure and density under thermal heating, has been investigated to confirm the assumption of possible crack formation on the surface of gravel. Figure 4 shows the distribution of the intensity of the tension in ash-slag gravels with different structure [16].

According to Figure 4, the maximum stress intensity at 500 °C has a single component gravel for about $1.80 \cdot 10^6$ Pa in compare of single component $2.27 \cdot 10^7$ Pa. The minimum stress intensity factor of single component gravel is also greater than two-component gravel and it consist of $6.2 \cdot 10^4$ Pa in compare of two component stress intensity factor $1.5 \cdot 10^3$ Pa.

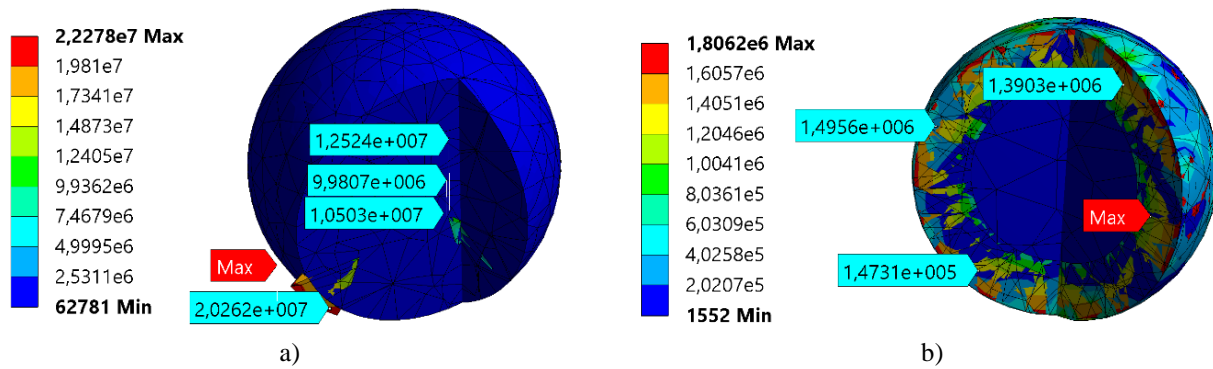


Fig 4. Stress intensity (Pa) of the single and two component ash slag gravels during the 500 ° C thermal impact: a – single component structure; b – two component structure.

In addition, two-component gravel has a more even stress intensity distribution pattern, which is also positive for even load distribution. On the other hand, in single component gravel there are zones with a sharp increase in the intensity of stresses, which indicates a greater probability of cracks formation and possibility flow of processes of destruction. In order to identify the nature of the stress-deformed state of gravels with different structure, a dependence of the stress intensity and equivalent stress on the temperature in the range of their occurrence was identified.

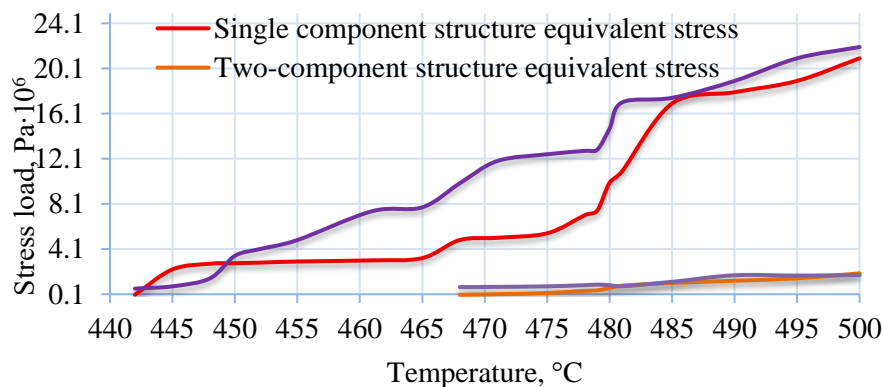


Fig 5. Dependence Stress load (equivalent and stress intensity) of single and two-component ash-slag structure gravel on temperature.

Fig. 5 shows that single component gravel has a greater maximum stress equivalent value of 22 MPA, proportional to the intensity of the stresses of 21 MPA. However, the minimum value of these values for both gravel materials is approximately at the same level and is 0.06 MPA equivalent stress and stress intensity 0.6 MPa and 0.05 MPA equivalent stress and stress intensity 0.1 MPa respectively. But at the same time, the area of occurrence of equivalent stress of two-component gravel is shifted towards higher temperatures and its occurrence begins at a temperature of 468 °C, in contrast to the single component where stresses arise earlier at a temperature of 442 °C. This picture of the stressed state of the granules under thermal impact is directly determined by the plasticity and strength of the gravel, which depends on the structure and speed of the thermal action.

3.2 Analysis results of the total deformation and shear stress evaluation during the thermal impact process on single and two component structure ash slag gravels

Evaluation of deformation state and shear stress of different structure gravels is necessary to determine conditions of occurrence of irreversible degradation processes in the body of gravel material. Irreversible degradation processes usually start when plastic deformation occurs. The beginning of the plastic deformation is the maximum shear stress, showing the points of failure of the material from elastic deformation, in which there is the greatest concentration of stresses and determined by the [17]:

$$\tau_{\max}^b = \frac{1}{2} [\sigma_{\max \text{ prstress}} - \sigma_{\min \text{ prstress}}], \tag{4}$$

where $\sigma_{\max, \min \text{ prstress}}$ are principal thermal stresses for gravel.

Studies have shown that the maximum concentration of stresses occurring in the points of a single-component gravel can be significantly greater than in a two-component gravel body. The maximum shear stress of deformation under thermal static action for single-component gravel is more than 11 MPa, which exceeds tensile strength for this kind of gravels according to patent author data [18] consist no more than 2,4 MPa. The mean value of the maximum shear stress in single component gravel also has a higher value. For two-component gravel, the maximum shear stress of deformation is almost 12 times less and consist for about 0.9 MPa, as shown by the numerical experiments in Fig. 6. However, a single-component gravel has a zones of reaction to the thermal impact, which is expressed as complete material rejection according to figure 6 (a). This leads to sharp in Equivalent stress (von Mises stress) (figure 3(a)), the increase of which indicates rapid plastic deformation with non-reversible loss of material properties at the point.

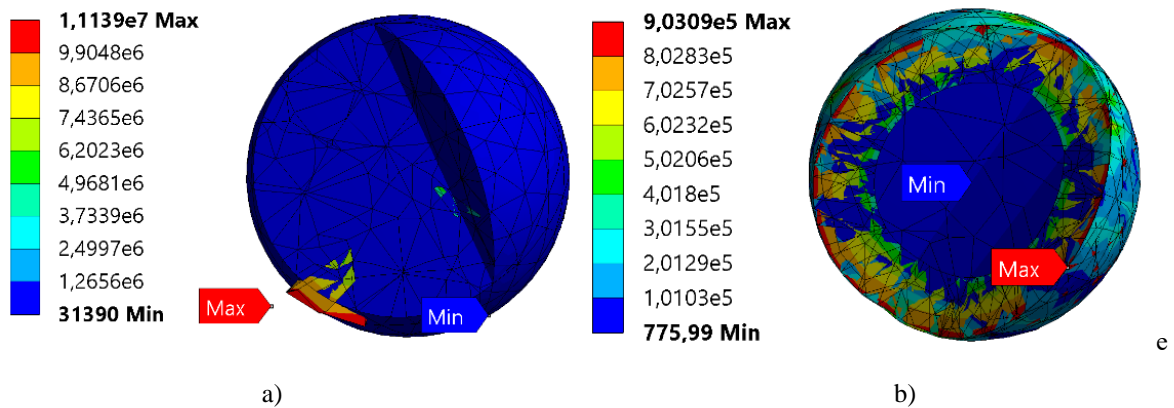


Fig 6. Maximum shear stress (Pa) of the single and two component ash slag gravels at the temperature 500 ° C: a – single component structure; b – two-component structure.

To predict the reaction of gravel to shear stresses caused by thermal action, with the possibility of predicting failure points, a dependence was defined for maximum shear stress from temperature with account of total deformation, represented on the Fig. 7 [19].

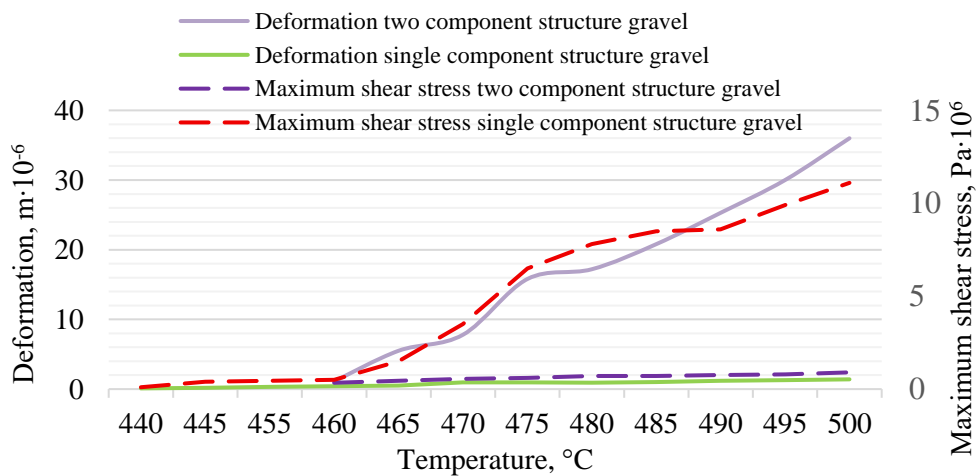


Fig.7. Maximum shear stress (Pa) with account total deformation of the single and two component ash slag gravels at the temperature 500 ° C: a – single component; b – two-component.

According to the fig.7 for single component gravel full deformation during thermal heating is less than for two-component gravel ($1.4 \cdot 10^{-6} \text{m}$ and $36 \cdot 10^{-6} \text{m}$ respectively). But at the same time, the maximum shear stress of single component gravel is much higher than the shear stress of two-component gravel under the same conditions of thermal action. ($0.9 \cdot 10^6 \text{ Pa}$ и $11.1 \cdot 10^6 \text{ Pa}$ respectively). This is determined by the physical-chemical properties of the material, primarily by the coefficient of thermal expansion, which causes a shift due to the uneven size and density of the particles, leading to splitting during thermal heating. In addition, in two-component gravel there is thermal contact resistance at the joint of solid phases (4) caused by violations of the boundaries of the mortar and cement, which reduce the heat flux to the center of the gravel at the mean absolute temperature of the conditional boundary layer during the phase separation of the cement-ash-slag mixture [20, 21]:

$$R_{ashc}^c = \frac{T_c^{abs} - T_{ash}^{abs}}{Q}, \quad (4)$$

$$T_c^{abs} = 273.2 + \frac{1}{2}(t_{ambient} + t_c), \quad (5)$$

$$T_{ash}^{abs} = 273.2 + \frac{1}{2}(t_{ash} + t_c), \quad (6)$$

where R_{ashc}^c is contact thermal resistance between cement and ash slag layers; T_c^{abs} is absolute temperature of the cement- ambient relative layer, K; T_{ash}^{abs} is absolute temperature of the cement- ash slag relative layer, K; Q is heat flux, W/m^2 ; $t_{ambient}$, t_{ash} , t_c are the temperatures ambient, ash-slag mix and cement accordingly, $^{\circ}\text{C}$.

Such conditions reduce the heat flow rate inwards to the center of the gravel and consequently reduce the thermal stress state. As a result, stress-deformed state of gravel, according to the theory of maximum shear stress (theory Tresk) [22], indicate that the strength margin determined by thermal action for single component gravel is lower than for two-component gravel, that reacts to thermal load with the prediction of less damage to the failure material. Thus, with less deformation of single-component gravel, its structure has material fault zones in which the gravels are already breaking down at 465°C .

To confirm the scientific novelty of the studies, model results were compared with experimental data on the stress-deformed state of single-component gravel. For the research, Ust-Kamenogorsk PC, Karaganda SPC and ash-slag mixture of CHP - 2 Astana were used. Research was conducted at the Eurasian University named by L.N. Gumilyov in the development of a fundamentally new ash-slag gravel and were selected in his thesis for the degree of candidate of technical sciences Atiaksheva A.V. "Research and development of non-killed gravel based on the ash-slag mixture, removed by hydraulic means." 05.23.05 "Building materials and constructions". The thermal stress depends on the modulus of elasticity, the coefficient of thermal expansion and is a value less than or equal to the time resistance at tensile strength. Table 3 presents the results of experimental data on time resistance to gravel strain with different diameters.

Table 3. Tensile strength of the ash-slag two-component gravel.

№	Characteristic	Cement								The investigated two-component gravel
		Ust-Kamenogorsk PC				Karaganda SPC				
		gravel diameter								
		5	10	20	40	5	10	20	40	
1	Tensile strength, MPa	3.8	3.6	3.0	3.6	3.1	3.0	2.6	2.0	2.4
2	Young's Modulus, MPa· 10 ⁴	1.82	1.65	1.47	1.28	1.67	1.43	1.25	1.0	0.6

Experimental data confirm simulation studies and scientific novel of the thermal strength of two-component gravel, its use as a heat protection in the composition of heat-resistant panels or independently in the temperature range up to 500°C .

4. Conclusion

Evaluation of the effectiveness of the non-killed as-slag gravel structure under thermal impact in conditions of stationary heating in the temperature range from 22 °C to 500 °C shows on the following results:

1) results of the equivalent stress and stress intensity evaluation during the thermal impact process show, that the two-component gravel has a greater viability in conditions of stationary thermal action at a temperature of 500 °C, as it experiences equivalent stress significantly less ($0.78 \cdot 10^6$ Pa in compare of single component $10.9 \cdot 10^6$ Pa). The two-component gravel also shows a lower stress intensity value ($1.12 \cdot 10^6$ Pa in compare of single component stress intensity value $15.58 \cdot 10^6$ Pa), determining the material's instability and limit of fragility at the moment of thermal exposure.

2) results of the total deformation total deformation and shear stress evaluation during the thermal impact process confirm the assumption of higher thermal stability of gravel two-component structure. Under conditions of less deformation, the appearance of more shear stress indicates that two-component gravel has a greater margin of thermal strength in the temperature range from 460°C to 500°C ($19.94 \cdot 10^{-6}$ m), because its maximum shear stress ($1.14 \cdot 10^6$ Pa) caused by thermal expansion is at a level below the maximum shear stress of single component gravel ($7.23 \cdot 10^6$ Pa) taking into account the deformation of single component gravel having less ($1.21 \cdot 10^{-6}$ m) in the same temperature range and under the same thermal conditions.

Consideration of results of the equivalent stress, stress intensity, total deformation and shear stress for a given size of gravel allows to think that, the two-component structure of ash-slag gravel better accepts the thermal effect in the temperature range from 22 to 500 C. This makes it possible to use two-component gravel in the composition of thermal panels, fine thermal blocks and bricks for thermal protection of low-temperature furnaces and other industrial equipment.

Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRedit author statement

Atyaksheva A.V.: Conceptualization, Data Curation; **Seitova Zh. A., Issataeva A. K.:** Writing Original Draft; Methodology. **Ryasnov D.Yu., Khamitova Ye.M.:** Investigation, Software, Writing Review & Editing, Supervision. The final manuscript was read and approved by all authors.

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AUTHORS' INFORMATION

Atyakshева, Alexandra Vladimirovna - PhD(Eng.), Associate Professor, Energy Institute, S. Seifullin Kazakh Agrotechnical Research University, Astana, Scopus Author ID: 57204188485; <https://orcid.org/0000-0003-2523-3890>; sahsa77@mail.ru

Seitova Zhadra Adilbekovna - PhD (Eng.), Senior lecturer, Energy Institute, S. Seifullin Kazakh Agrotechnical Research University, Astana, Scopus Author ID: 59156439300; <https://orcid.org/0000-0001-7812-2540>

Issataeva, Akmaral Kiyalovna – Master (Eng.), Senior lecturer, Department of Thermal Power Engineering, Energy Institute, S. Seifullin Kazakh Agrotechnical Research University, Scopus ID: 58925932700; <https://orcid.org/0009-0000-6544-1921>; akmadani@mail.ru

Ryasnov, Dmitry - Master student, Energy Institute, S. Seifullin Kazakh Agrotechnical Research University, Astana, <https://orcid.org/0009-0009-7534-651X>; 1_4_9844@mail.ru

Khamitova, Yeldana – Master student, Energy Institute, S. Seifullin Kazakh Agrotechnical Research University, Astana, <https://orcid.org/0009-0008-6684-3488>; yeldanakhmitova73@gmail.com