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THE STUDY OF STRUCTURAL AND MECHANICAL PROPERTIES OF THE DISPERSE SYSTEMS FOR ADDITIVE TECHNOLOGIES

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Abstract.

This paper deals with the study of the structural and mechanical properties of polymineral clays from various fields. The patterns of the influence of moisture in the clay plastic mass on their plastic strength have been studied. The values of structural and mechanical properties of the plastic mass based on polymineral clays with different moisture content have been presented and analyzed. The values of deformation characteristics were used to determine structural and mechanical types of the investigated clays with varying humidity.

Keywords. Polymineral clays, structural and mechanical properties, additive technologies, disperse systems.

Introduction. One of the main trends in the development of modern additive technologies is the development of a set of measures aimed at expanding the range of application of both organic and inorganic materials for the manufacture of products for different purposes. The unique capabilities of the additive manufacturing provide not only an increase in the utilization rate of material and high dimensional accuracy of manufactured products without need for their machining, but also the possibility of creating products of a complex shape, reducing production costs, etc. [1, 2]. Currently, the implementation of the additive technologies widely involves various kinds of plastics and disperse systems of both synthetic and natural origin. One of the commonly available natural materials is polymineral clay and its composites, having long ago found their application in the manufacture of a wide range of construction and refractory materials. The process of forming products by additive method can be fully compared with the plastic molding by extrusion, implemented with various molding equipment (extruder, screw or belt press, etc.). The behavior patterns of plastic masses, depending on the structural and mechanical properties of disperse systems [3-7], will also have a significant effect, as in the case of plastic molding, on an additive process if using clay materials as a base mixture. Subject to the above stated, the objective of this research is to study the structural and mechanical properties of polymineral clays for their use in additive technologies. For our studies we predominantly selected kaolinite clays differing in composition and content of other clay minerals that significantly modifies their granulometry and, especially, colloidal content [8]. To determine the optimum molding moisture content of plastic masses we used clays from Nizhne-Uvelskoe, Latnenskoe (LT-0) and Druzhkovskoe fields. Certain structural and mechanical characteristics allowing for the assessment of the masses in terms of their formability and plasticity are determined with the use of rheometer of various design [9-11]. Plastic strength P_m, or mechanical strength of the structure is the limiting shear stress, which a plastic mass can withstand under static loading. Index P_m is determined using the conical Rebinder rheometer for analysis of the degree of mass uniformity, evaluation of its optimum moisture content and moldability. This rheometer was used to investigate the effect of changes of absolute humidity W_{abs} of the plastic masses obtained from clays of Nizhne-Uvelskoe, Latnenskoe and Druzhkovskoe fields on the change in plastic strength P_m. Absolute humidity in masses ranged from 33% to 73% for clays from Nizhneuvelskoe field, from 24% to 70% for clays from Latnenskoe field, and from 30% to 75% for clays from Druzhkovskoe field.

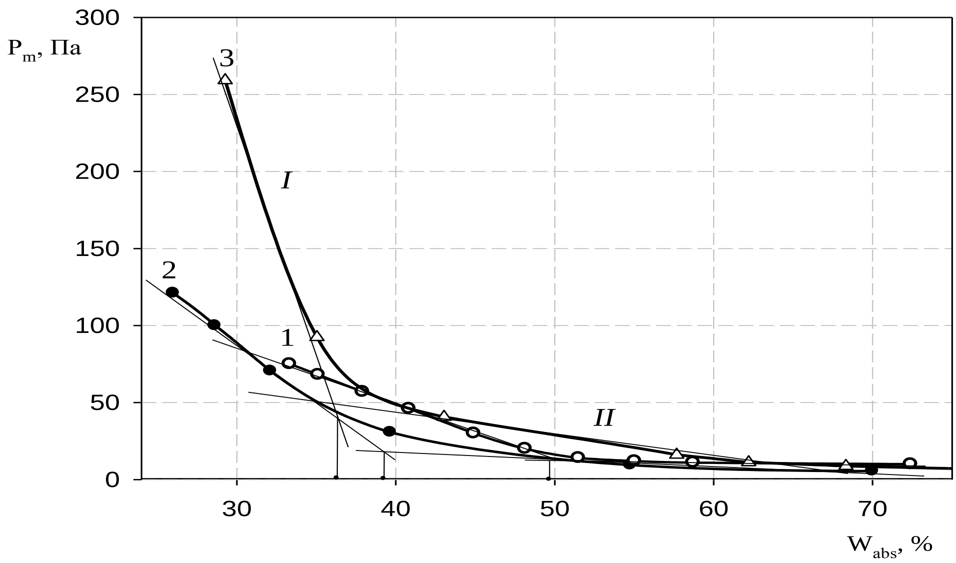


Fig. 1. The effect of absolute humidity W_{abs} on the plastic strength P_m of plastic masses based on clays from Nizhneuvelskoe (1), Latnenskoe (2) and Druzhkovskoe (3) fields.

Humidity was subjected to changes by clay dehydration on a gypsum substrate.Our studies have shown that an increase in humidity results in decreasing P_m. The curve $P_m=f(W)$ (Fig. 1) for all masses may be represented by lines I and II, which have different inclinations to W_{abs}axis and are interconnected by a smooth curve. The slope value of the lines I and II shows an unequal ratio of bound and free water in the masses, as well as the development degree of the hydration shells around the clay particles. The transition point of the first straight section into a smooth curve corresponds to the optimal molding humidity W_{opt}. Subject to graphic determination of optimal humidity level (Figure 1, curve 1), for Nizhneuvelskoe clay it is 49.5%, for Latnenskoe clay (Figure 1, Curve 2) - 38.5%, and for Druzhkovskoe clay (Figure 1, curve 3) - 36.5%. The study found that the optimum absolute humidity of Nizhneuvelskoe clay is 11% higher than of Latnenskoe clay, and 13% hagher than of Druzhkovskoe clay. This is probably due to differences in mineralogical composition and dispersion of clays. Nizhneuvelskoe clay is more highly-dispersive than Latnenskoe and Druzhkovskoe clays. The last two clays are almost similar in their dispersion.

To determine the structural and mechanical characteristics of the plastic masses, we used D.M. Tolstoy rheometer. This device was used to study the masses based on clays from Nizhneuvelskoe, Latnenskoe and Druzhkovskoe fields with different moisture content, from both sides of W_{opt}. (See Fig. 1). According to data obtained in the course of the study, the basic structural and mechanical characteristics and the elastoplastic viscous constants were calculated and shown in Table 1-3.

Table 1: Structural and mechanical properties of Nizhneuvelskoe clay.

W, %	Elastoplastic viscous constants					Main structural and mechanical properties			N_ε, Mj/sec	ε_r, %	ε_s, %	ε_{pl}, %
	E_s, MPa	E_r, MPa	E, MPa	η_{pl}, MPa s	P_k, Pa	λ	$P_k/\eta_{pl}\cdot10^7$, sec^{-1}	θ, sec				
22	6.31	3.83	2.39	1608	354.6	0.622	2.20	674	962	15.2	25.1	59.7
33	2.35	1.63	0.96	735	179.5	0.590	2.44	763	417	17.7	25.5	56.7
38	0.50	0.29	0.18	249	252.3	0.630	10.14	1339	106	21.2	36.1	42.7

Table 2: Structural and mechanical properties of Latnenskoe clay.

W, %	Elastoplastic viscous constants	Main structural and mechanical properties	N_ε, Mj/sec	ε_r, %	ε_s, %	ε_{pl}, %

	E_s, MPa	E_r, MPa	E, MPa	η_{pl}, MPa s	P_k, Pa	λ	$P_k/\eta_{pl}\cdot 10^7$, sec^{-1}	θ, sec				
23	16.80	3.60	2.97	803	4149	0.820	51.668	270	0.64	3.8	17.8	78.4
27	3.18	1.29	0.92	700	556	0.712	7.950	764	0.39	12.5	30.9	56.6
32	2.75	1.05	0.46	507	99	0.710	1.960	1102	0.37	21.2	36.1	42.7

Table 3: Structural and mechanical properties of Druzhkovskoe clay.

W, %	Elastoplastic viscous constants					Main structural and mechanical properties			N_ε, $\frac{Mj}{sec}$	ε_r, %	ε_s, %	ε_{pl}, %
	E_s, MPa	E_r, MPa	E, MPa	η_{pl}, MPa s	P_k, Pa	λ	$P_k/\eta_{pl}\cdot 10^7$, sec^{-1}	θ, sec				
17	11.10	9.14	5.02	3170	5138	0.550	16.2	632	1.98	17.8	21.6	60.6
26	5.06	1.64	1.24	1630	2075	0.760	12.7	1314	0.71	13.9	43.1	43.0
30	1.01	1.28	0.56	641	4267	0.440	66.5	1133	0.30	30.0	23.6	46.4

Based on the ratio of fast (ε_r), slow (ε_s) and plastic deformations (ε_{pl}) we can conclude that the investigated clays refer to structural and mechanical types IV and V according to Nichiporenko's classification (Fig. 2 and 3) [12-14]. It should be noted that the change in the humidity of the masses based on clays from Nizhneuvelskoe and Latnenskoe fields results in no changes in the structural and mechanical type, while an increase in moisture content in the mass based on clay from Druzhkovskoe field leads to a change from type V to type IV. This may indicate a good deformability of the masses, their tendency to plastic failure and high energy consumption during their molding.

An increase in the relative humidity of the masses based on clays from Nizhneuvelskoe and Latnenskoe fields results in a decrease in plastic deformation (Fig. 4, a, b, curves 1) and growth of slow (Fig. 4, a, b, curves 2) and fast (Fig. 4, a, b, curves 3) deformations. Moreover, Nizhneuvelskoe clay shows smoother decrease in its plastic (17%) and increase in fast (6%) and slow (11%) deformations than Latnenskoe clay (fast and slow elastic deformation increases by 18-19%, while plastic deformation decreases by 36%).

It should be noted that the nature of changes in the deformations of the mass based on Druzhkovskoe clay differs from the masses discussed above. As can be seen from Fig. 4 (c), an increase in the relative humidity to its optimum

(26%) causes maximum values in the curve of changes in slow deformation (Fig. 4, c, curve 2) and minimum values in the curves of plastic (Fig. 4, a curve 1) and fast (Fig. 4, c, curve 3) deformations.

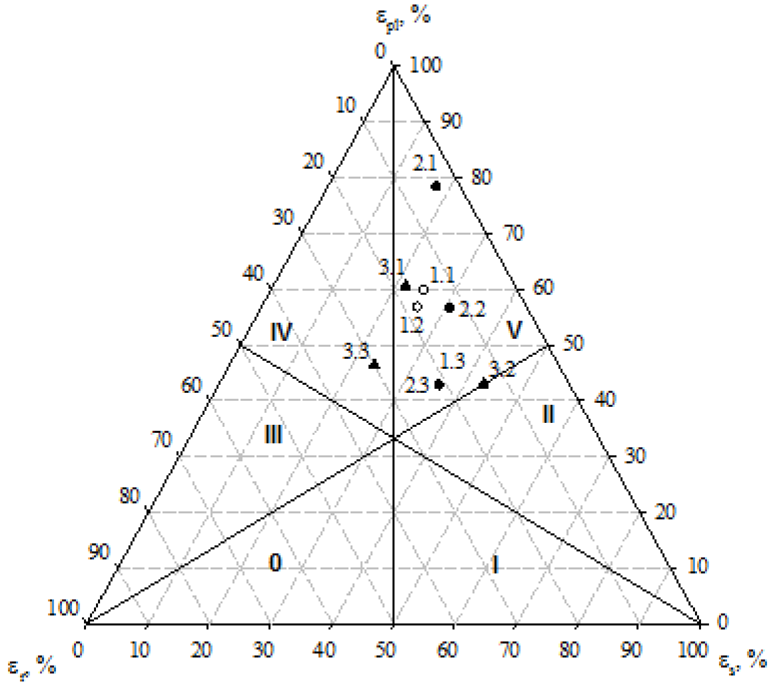


Fig. 2. Structural and mechanical types of clays from Nizhneuvelskoe (1.1-1.3), Latnenskoe (2.1-2.3) and Druzhkovskoe (3.1-3.3) fields at different humidity: 1.1 – 22 %, 1.2 – 33 %, 1.3 – 38 %; 2.1 – 23 %, 2.2 – 27 %, 2.3 – 32 %, 3.1 – 17 %, 3.2 – 26 %, 3.3 –

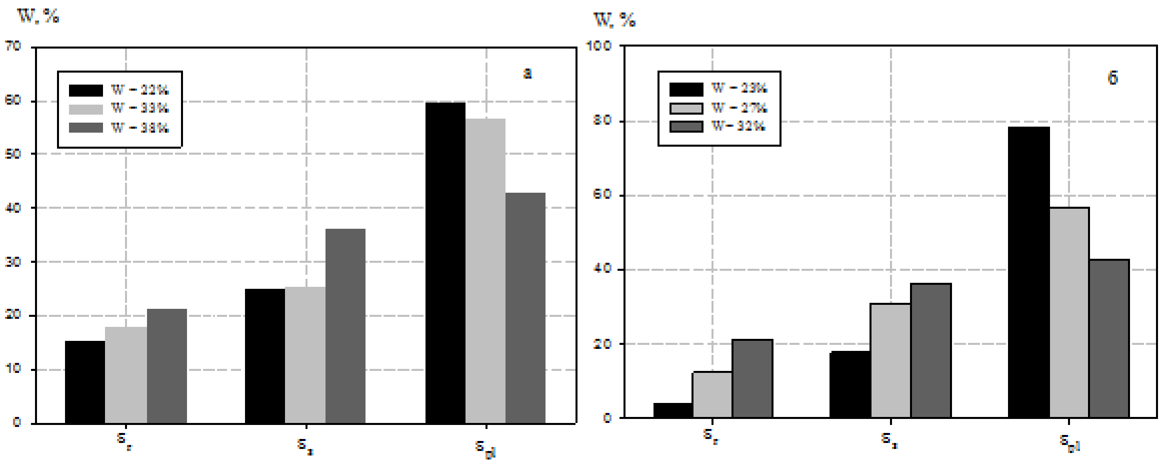
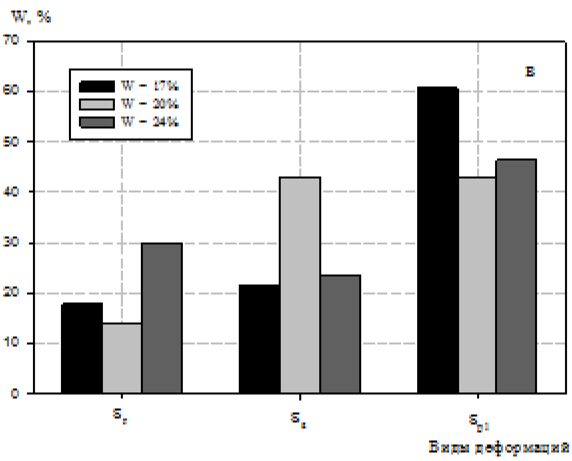


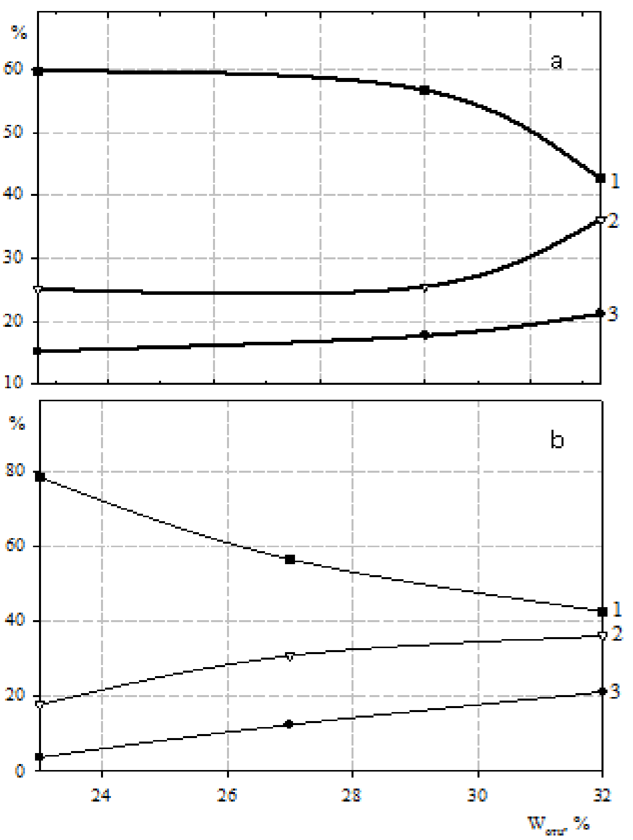
Fig. 3. Diagrams of fast ε_r, slow ε_s and plastic deformations ε_{pl} of clays from Nizhneuvelskoe (a), Latnenskoe (b) and Druzhkovskoe (c) fields.



This change in the structural and mechanical properties provides transition of the mass from structural-mechanical type V to IV with a reduced value of slow deformations (less than 50%). The extremum of the deformation characteristics in the mass based on Druzhkovskoe clay is observed in the range of a maximum change in the flow (Fig. 1).

It follows from Fig. 2 - 3 that the high content of fine particles in the clay increases both the proportion of slow reversible deformations and optimum molding humidity of the system (Fig. 1), and drying shrinkage. This is due to an increase in the hydration layers per volume unit of the disperse system, as well as their overall thickening [15-16].

Increase in humidity leads to decrease in plastic viscosity η_{pl} observed in all investigated clays (Fig. 5) along the entire range of relative humidity values, as well as decrease in the yield point P_k (Fig. 6, curve 2) in the mass based on Latnenskoe clay. It should be noted that the masses based on clays from Nizhneuvelskoe (Fig. 6, curve 1) and Druzhkovskoe (Fig. 6, curve 3) fields, during changes in humidity from 22 to 33% and from 17 to 26%, respectively, are characterized by a reduction of yield point (similar to Nizhneuvelskoe clay), but the further increase in humidity from 33 to 38% and from 26 to 30%, respectively, leads to growth in yield point. This is because the increase in water content of the masses leads to an adsorption increase in films on the new effective surface areas of the particles, in the number of coagulation contacts per volume unit, and overall increase in the structural strength, which leads to an increase in yield point.



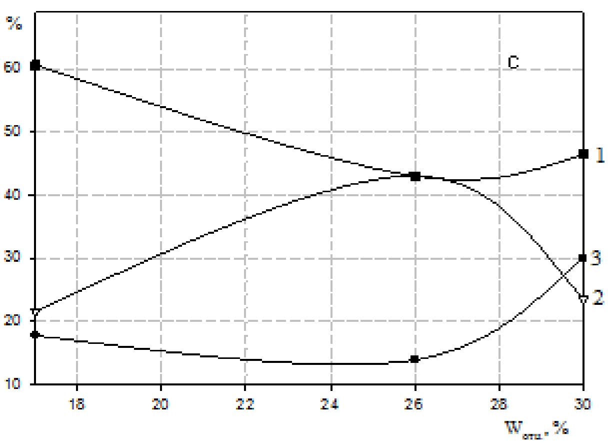


Fig. 4. The ratio of plastic ε_{pl} (1), slow ε_s (2) and fast ε_r(3) deformations to the relative humidity $W_{rel.}$ of clays from Nizhneuvelskoe (a), Latnenskoe (b) and Druzhkovskoe (c) fields.

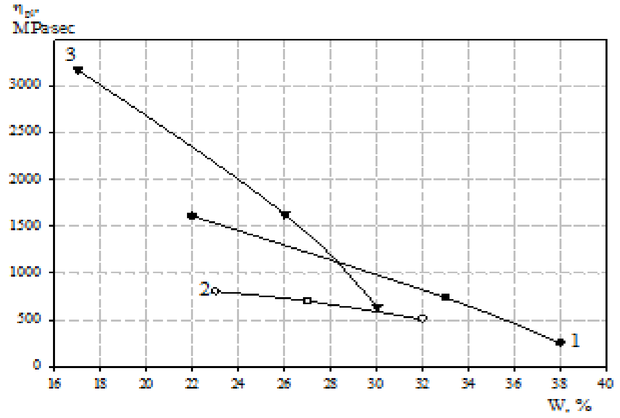


Fig. 5. The ratio of plastic viscosity η_{pl} to relative humidity W of clays from Nizhneuvelskoe (1), Latnenskoe (2) and Druzhkovskoe (3) fields.

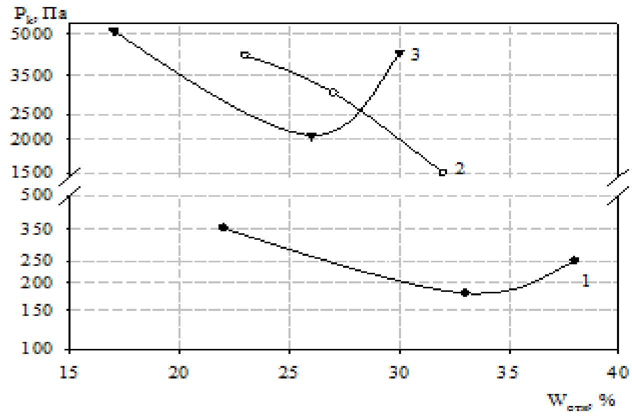


Fig. 6. The ratio of yield point P_k to relative humidity W of clays from Nizhneuvelskoe (1), Latnenskoe (2) and Druzhkovskoe (3) fields.

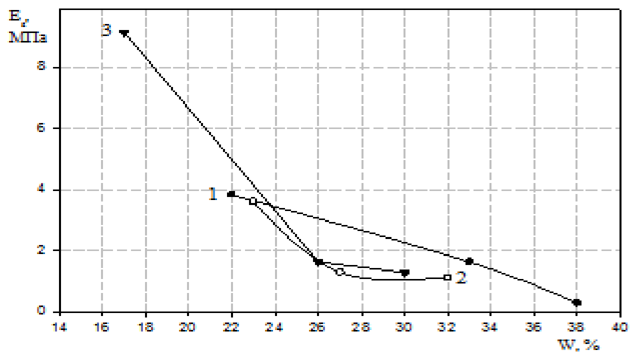


Fig. 7. The ratio of elasticity modulus E_t to relative humidity W of clays from Nizhneuvelskoe (1), Latnenskoe (2) and Druzhkovskoe (3) fields.

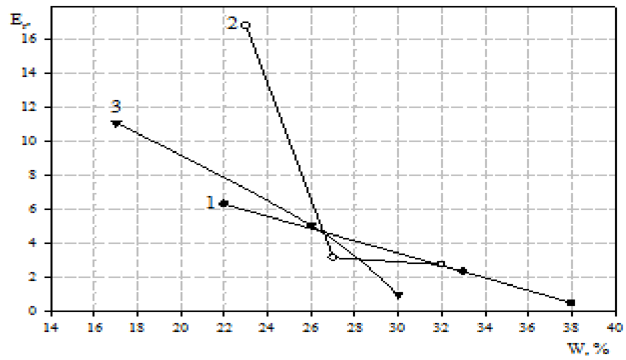


Fig. 8. The ratio of elastic modulus E_r to relative humidity W of clays from Nizhneuvelskoe (1), Latnenskoe (2) and Druzhkovskoe (3) fields.

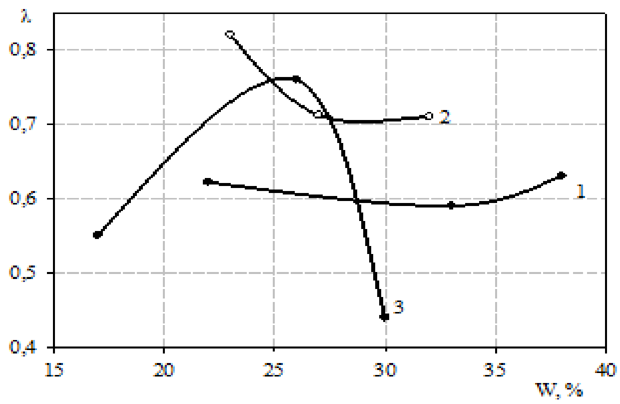


Fig. 11. The ratio of elasticity λ to relative humidity W of clays from Nizhneuvelskoe (1), Latnenskoe (2) and Druzhkovskoe (3) fields.

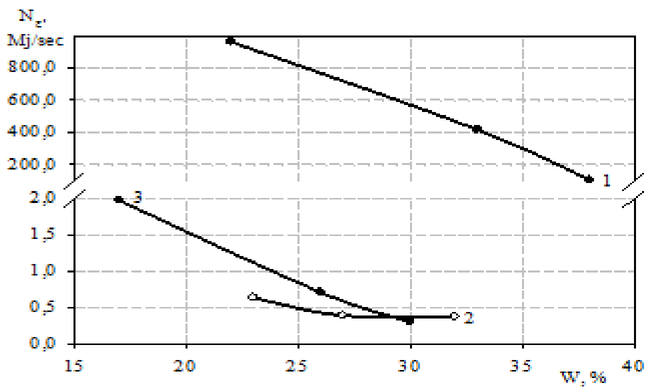


Fig. 12 The ratio of rated deformation modulus N_r to relative humidity W of clays from Nizhneuvelskoe (1), Latnenskoe (2) and Druzhkovskoe (3) fields.

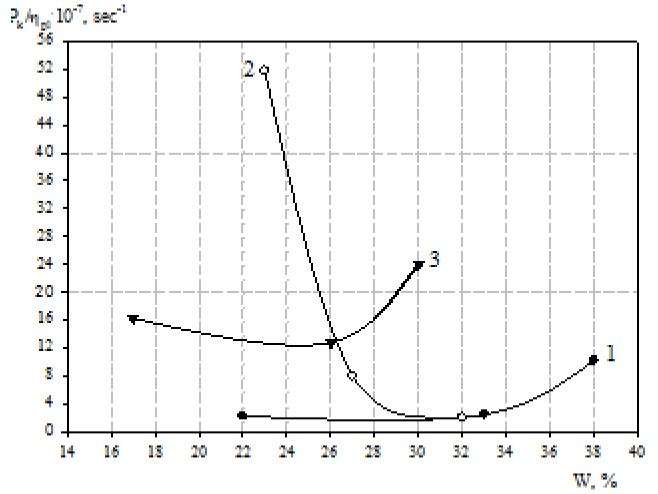


Fig. 9. The ratio of plasticity P_k/η_{pl} to relative humidity W of clays from Nizhneuvelskoe (1), Latnenskoe (2) and Druzhkovskoe (3) fields.

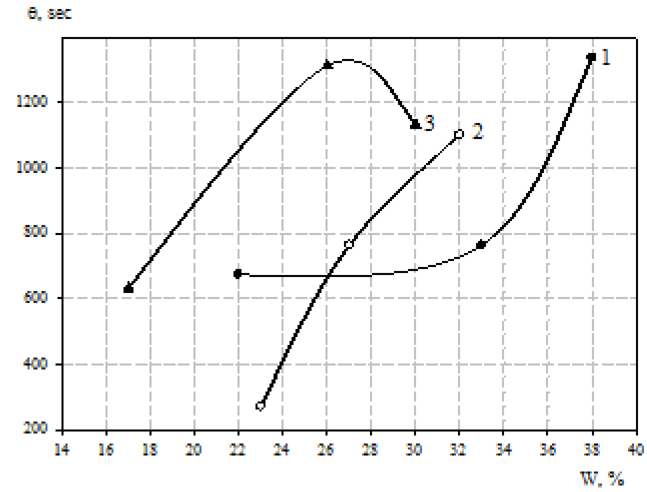


Fig. 10. The ratio of true relaxation period θ to relative humidity W of clays from Nizhneuvelskoe (1), Latnenskoe (2) and Druzhkovskoe (3) fields.

At the minimum value of the relative humidity, the indicators of elastic (Fig. 8) and elasticity (Fig. 7) modules, and the apparent modulus of deformation N_ε (Fig. 12) have the maximum value. This is due to the fact that the formation of hydrated films takes place in less active areas. At the same time, the value of the true relaxation period θ (Fig. 10) has a minimum value. Increasing moisture content to the optimum values leads to a decrease in both elastic and elasticity modules, as well as in rated deformation power. Further increase in the humidity leads to a reduction of these modules to the minimum. At the same time, the true relaxation period of Nizhneuvelskoe and Latnenskoe clays increases to its maximum value, while increasing humidity in the mass based on Druzhkovskoe clay above the optimum leads to a decrease in θ, indicating a decrease in the proportion of slow deformations in the mass.

It should be noted that the increasing humidity of the mass based on clay from Latnenskoe field leads to a significant decrease (6.5-fold) in its plasticity (Fig. 9, curve 3) in comparison with Druzhkovskoe (1.3-fold), while the plasticity of the mass based on Nizhneuvelskoe clay remains practically unchanged. Further increase in the relative humidity leads to growth in plasticity of Druzhkovskoe and Nizhneuvelskoe clays, while the same parameter decreases in clays from Latnenskoe field.

As can be seen from Fig. 11, an increase in humidity of the masses based on clays from Nizhneuvelskoe and Latnenskoe fields leads to decrease in their elasticity values, and then a slight increase is observed. Changes in elasticity values of Druzhkovskoe clay differs in nature from changes of the previous two clays, which is due to redistribution of moisture in the dispersion medium, which also reduces the proportion of slow deformation values in the mass.

Conclusion. Thus, the conducted studies show the predominance of plastic deformations in the clay disperse systems, which positively affect the extrusion process. These findings suggest the applicability of the studied clays in the additive technologies.

Summary. The analysis of the presented experimental findings has established:

- optimum absolute molding humidity W_{abs} of the studied polymineral clays ranges from 37 to 50%, which is equivalent to 26-33% in relative units (W);

- in terms of the ratio of the deformation characteristics, the studied clays refer to structural and mechanical types IV-V, characterized by high values of plastic deformations;

- the humidity change does not lead to significant changes in the structural types of plastic clay masses;

- the analysis of the structural and mechanical properties and elastoplastic viscous constants showed that an increase in humidity of the disperse systems leads to a significant change in the said characteristics and the formation of extrema at certain values.

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