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Rheological Modeling and Mechanisms of Structure Formation in Disperse Systems Based on Organic Binders

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Abstract. Investigating the rheological behavior and mechanisms of structure formation in disperse systems based on organic binders is a critical task for optimizing energy consumption during the production and operation of viscoplastic petroleum products. The objective of this study is to improve the methodology for evaluating the rheological properties of such systems, accounting for their complex internal structure. Based on an extensive dataset obtained from rotational viscometry, a comparative analysis of flow curve approximation accuracy was performed using the Ostwald – de Waele, Shvedov – Bingham, Casson, and Herschel – Bulkley models. It is shown that the application of simplified power-law relationships leads to a substantial overestimation of the yield stress (up to 1000 %) and a misinterpretation of viscous resistance as static structural strength. The effectiveness of the three-parameter Herschel – Bulkley model is substantiated as the most reliable tool for describing the behavior of viscoplastic media (coefficient of determination > 0.99). It is established that the mineral filler acts as a thickening agent without forming a coherent load-bearing framework, even at high concentrations. The percolation mechanism of system reinforcement by cellulose fibers is confirmed, whereby a spatial reinforcing cluster is formed at fiber contents above 2.5 %. The developed empirical model, which describes the yield stress as a cubic function of fiber content and a linear function of polymer content, is recommended for the targeted regulation of the rheological properties of disperse systems. The obtained results ensure the rational use of expensive components and enhance the energy efficiency of production processes and the operational reliability of materials based on organic binders.

Keywords: rheological modeling, viscoplastic disperse systems, organic binders, Herschel – Bulkley model, yield stress, structure formation, percolation mechanism, material energy efficiency

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Реологическое моделирование и механизмы структурообразования дисперсных систем на основе органических вяжущих

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Реферат. Исследование реологического поведения и механизмов структурообразования дисперсных систем на основе органических вяжущих – актуальная задача для оптимизации

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энергозатрат при производстве и эксплуатации вязкопластичных нефтепродуктов. Целью работы является совершенствование методологии оценки реологических свойств таких систем с учетом их сложной внутренней структуры. На основе массива экспериментальных данных ротационной вискозиметрии выполнен сравнительный анализ точности аппроксимации кривых течения с применением моделей Оствальда – де Ваале, Шведова – Бингама, Кассона и Гершеля – Балкли. Показано, что применение упрощенных степенных зависимостей приводит к существенному завышению предела текучести (до 1000 %) и ошибочной интерпретации вязкостного сопротивления как статической прочности структуры. Обоснована эффективность трехпараметрической модели Гершеля – Балкли как наиболее достоверного инструмента для описания поведения вязкопластичных сред (коэффициент детерминации >0,99). Установлено, что минеральный наполнитель выполняет функцию загустителя, не формируя связного каркаса даже при высоких концентрациях. Подтвержден перколяционный механизм упрочнения системы целлюлозными волокнами, формирующими пространственный армирующий кластер при содержании выше 2,5 %. Разработанная эмпирическая модель, описывающая предел текучести как кубическую функцию от содержания волокна и линейную функцию от содержания полимера, рекомендуется для направленного регулирования реологических свойств дисперсных систем. Полученный результат обеспечивает рациональное использование дорогостоящих компонентов и повышает энергетическую эффективность производства и эксплуатационную надежность материалов на основе органических вяжущих.

Ключевые слова: реологическое моделирование, вязкопластичные дисперсные системы, органические вяжущие, модель Гершеля – Балкли, предел текучести, структурообразование, перколяционный механизм, энергоэффективность материалов

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Introduction

The widespread use of structured disperse systems with high binder content [1–11] in modern industrial and infrastructure projects necessitates the improvement of methods for assessing their technological stability. The primary factor ensuring the stability of such systems is the presence of a strong structural framework within the organic binder, capable of resisting shear deformation under static conditions [1, 7, 9]. The quantitative measure of the strength of this structure is the yield stress, which determines the ability of the system to maintain its integrity and prevent segregation under the action of gravitational forces [7].

A number of early scientific studies were based on simplified rheological models describing the behavior of bituminous compositions by power-law relationships without explicitly identifying the yield stress as an independent physical parameter [12, 13]. This approach was justified by the level of computational capabilities available at the time; however, it resulted in replacing the concept of true yield stress with the shear stress corresponding to a unit shear rate. Such substitution introduced significant errors in predicting material behavior, as it failed to account for the actual response of a structured system at rest. Contemporary requirements for structural durability and for reducing the consumption of costly additives call for a revision of the methodological framework and the application of more rigorous constitutive equations.

The theoretical basis for describing viscoplastic media is traditionally founded on the classical Shvedov – Bingham model [14, 15], which assumes the existence of rigid contacts between particles of the dispersed phase that are destroyed only upon reaching a critical shear stress. Mathematically, this model is represented by a linear equation relating shear stress and shear rate through the plastic viscosity and the yield stress. Application of the Shvedov – Bingham model to structured bituminous media provides a first approximation of the yield stress; however, this equation does not account for the viscosity reduction with increasing deformation rate that is characteristic of polymer-modified compositeons [16]. Neglecting the pseudoplastic behavior of the material when linearly approximating experimental data inevitably leads to overestimation of the calculated yield stress values and distortion of the actual structural formation mechanisms. To overcome this limitation, it is necessary to employ more advanced three-parameter models capable of capturing the curvature of the rheological curve in the initial flow region [17, 18].

Theoretical background

The Ostwald – de Waele power-law rheological model [18] has been widely used in past engineering practice and is described by an equation of the form

$$\tau = K\dot{\gamma}^n. \tag{1}$$

In the above relationship (1), K is the consistency index and n is the flow behavior index. The appeal of this model lies in the simplicity of linearizing experimental data in logarithmic coordinates, which significantly facilitated calculations in the absence of specialized software. However, a detailed analysis of the boundary conditions of this equation reveals its fundamental inadequacy for determining the yield stress, since as the shear rate approaches zero, the calculated shear stress also inevitably tends to zero. This implies that the power-law model describes a fluid that begins to flow under an arbitrarily small applied load, which contradicts the physical nature of stabilized organic binders. The practice, adopted in a number of early methodologies [12, 13], of using the shear stress at a unit shear rate as an apparent yield stress represents a mathematical assumption. The stress value calculated at the conventional shear rate of $\dot{\gamma} = 1\ s^{-1}$ characterizes the viscous resistance of a flowing system rather than the strength of the structural framework at rest.

For an adequate description of the behavior of organic binders exhibiting solid-like properties prior to flow onset and pseudoplastic liquid behavior during deformation, it is necessary to apply the generalized Herschel – Bulkley rheological model [19]. The mathematical form of this model is given by

$$\tau = \tau_0 + K\dot{\gamma}^n. \tag{2}$$

Equation (2) combines the advantages of the Shvedov – Bingham and Ostwald – de Waele approaches. The presence of the free term τ_0 makes it possible

to describe the threshold stress required to initiate the breakdown of the structural network, while the power-law component with exponent *n* accounts for the nonlinear reduction in viscosity with increasing shear rate. Application of nonlinear regression methods to fit experimental data using this equation enables high-accuracy extrapolation of the flow curve to the ordinate axis and determination of the true yield stress, excluding the contribution of viscous resistance of the medium [20]. Neglecting the curvature of the initial segment of the flow curve, which is inherent to linear models, leads to systematic extrapolation errors and overestimation of yield stress values. The Herschel – Bulkley model is free from this limitation, as the curvature parameter *n* allows adaptive representation of organic binder structure degradation. This makes it the most advanced tool for assessing the effectiveness of stabilizing additives, as it enables a clear separation between the contribution of mechanical interlocking of fibers, which governs the yield stress, and the contribution of dispersed fillers, which predominantly affect the consistency of the system.

Experimental methodology and data processing

Experimental investigations were carried out on model organic binder systems based on 90/130 grade bitumen. An unactivated dolomite mineral filler, cellulose fiber, and a styrene-butadiene-styrene (SBS) thermoplastic elastomer were employed as the dispersed phase and stabilizing components. Specimen preparation was performed by introducing the modifiers into a preheated binder, followed by intensive mechanical mixing to ensure a uniform distribution of the components throughout the dispersion medium.

The experimental program involved varying the component contents over a wide concentration range, which allowed for the examination of different structural states of the system, from dilute suspensions to highly filled compositions. The mineral filler content was varied from 50 to 200 %, the cellulose fiber content – from 0 to 7.5 %, and the polymer additive content – from 0 to 7 % by weight of the bitumen. The experimental design matrix included eight compositions with different component ratios, which was required to independently assess the contribution of each factor to yield stress formation. The formulations of the investigated organic binders are presented in Table 1.

Table 1

Experimental organic binder compositions

Component	Component content for composition No, % (by weight of bitumen in excess of 100 %)							
Composition No	1	2	3	4	5	6	7	8
Mineral filler	50	25	75	100	37.5	200	25	100
Cellulose fiber	0.25	0.75	1.25	0	2.5	0	7.5	5
Polymer (SBS)	7	5	0	3	1	0	0	0
Note: data according to [12, p. 68].								

The rheological characteristics were determined using a rotational viscometer equipped with a coaxial cylinder measuring system at a temperature

of 160 °C, corresponding to the technological conditions of processing and application of such systems. During laboratory testing, the relationship between shear stress τ and shear rate $\dot{\gamma}$ was recorded for each of the eight compositions. The specimens were subjected to a stepwise increase in shear rate over the range from 1 to 437.4 s^{-1}. The obtained measurement results, representing the primary experimental dataset prior to mathematical processing, are summarized in Table 2.

Table 2

Results of flow curve measurements for organic binders

Shear rate $\dot{\gamma}$, s^{-1}	Shear stress τ, Pa, for composition No							
	1	2	3	4	5	6	7	8
1.0	7.60	2.68	1.55	3.44	0.78	1.35	27.35	8.10
1.8	13.15	4.70	2.27	6.35	1.33	1.43	37.99	12.50
3.0	21.17	7.24	3.59	10.75	2.11	2.04	51.33	18.70
5.4	32.73	12.29	7.40	18.47	2.28	3.45	71.43	29.50
9.0	52.03	19.42	13.40	28.53	4.73	5.67	93.33	42.50
16.2	88.00	33.29	23.10	50.68	8.25	9.83	127.45	63.80
27.0	133.18	53.59	35.70	80.16	27.04	15.68	171.85	88.70
48.6	214.33	91.60	61.30	130.98	24.18	27.08	243.90	125.60
81.0	321.58	149.43	98.24	202.40	39.29	44.16	324.23	177.40
145.8	458.18	245.28	174.82	334.22	68.15	57.70	436.00	266.00
243.0	787.18	379.47	284.88	478.00	108.15	284.75	590.00	395.94
437.4	1286.43	582.80	509.23	659.22	187.50	497.27	819.16	596.11

Before performing the regression analysis, the primary dataset was verified for compliance with the physical criteria governing the flow of structured disperse systems. A fundamental requirement for the validity of rheological measurements under steady-state flow conditions is the monotonic increase in shear stress τ with increasing shear rate $\dot{\gamma}$. Mathematically, this condition is expressed by a positive value of the first derivative of the flow function over the entire shear rate range, i. e. $d\tau/d\dot{\gamma} > 0$.

A detailed analysis of the flow curves constructed from the data of Table 2 revealed local violations of this condition for compositions No 5 and No 6. A graphical illustration of the identified anomalies is presented in Fig. 1. For the flow curve of composition No 5, an anomalous decrease in shear stress from 27.04 to 24.18 Pa was observed within the shear rate interval from 27.0 to 48.6 s^{-1} (Fig. 1a). Such behavior contradicts the thermodynamics of irreversible deformation processes in viscoplastic media and indicates the presence of an instrumental artifact, the most probable cause of which is material slip relative to the smooth measuring surfaces of the rotational instrument.

For composition No 6, a sharp stepwise increase in shear stress is observed in the high shear rate region when transitioning from 145.8 to 243.0 s^{-1}, which cannot be described by classical models of viscous flow (Fig. 1b). The stress increment gradient in this interval significantly exceeds the values characteristic

of the laminar regime, indicating shear dilatancy caused by mechanical jamming of the measuring system by large agglomerates of mineral filler.

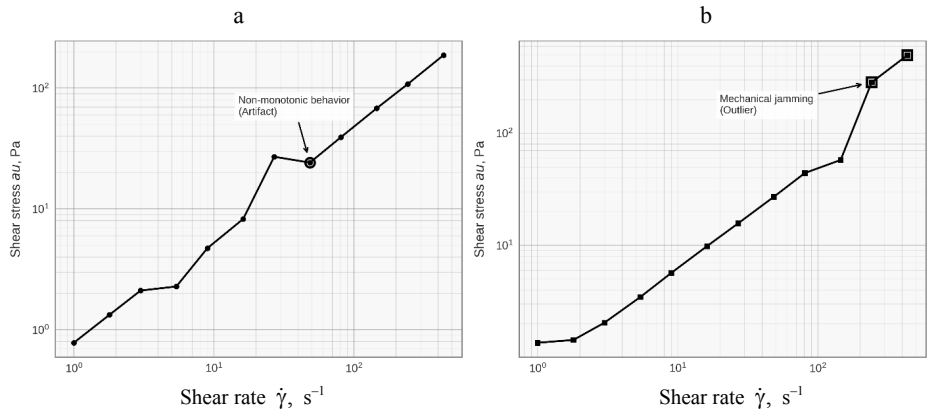

Fig. 1. Verification of experimental data for:
a – anomaly of composition No 5; b – anomaly of composition No 6

The inclusion of these anomalous data points in the dataset for least-squares approximation would inevitably lead to distortion of the regression model parameters and to obtaining unreliable yield stress values. Therefore, the data points corresponding to a shear rate of 48.6 s^{-1} for composition No 5 and to shear rates exceeding 145.8 s^{-1} for composition No 6 were excluded from further mathematical processing as gross experimental errors.

Results of the study

To determine the true rheological parameters of organic binders and to select the most adequate mathematical description of their behavior, a comparative approximation of the experimental data was performed using four different rheological models. The purpose of this stage was to identify the dependence of the calculated yield stress value on the type of constitutive equation applied.

The two-parameter Ostwald – de Waele power-law model (1) was considered as the baseline model, in which the absence of a free term implies that the flow curve passes through the origin. Within this approach, the shear stress at a unit shear rate was adopted as an apparent yield stress.

The second model considered was the classical Shvedov – Bingham viscoplastic model, expressed by the linear equation

$$\tau = \tau_0 + \eta_{pl}\dot{\gamma}. \quad (3)$$

This model assumes the existence of a true yield stress τ_0; however, it postulates a constant plastic viscosity η_{pl} after the onset of flow. Since organic binders are pseudoplastic fluids, their viscosity decreases with increasing shear rate. Therefore, the linear approximation of experimental data using the Bingham model inevitably ignores the curvature of the initial flow region and leads to an overestimation of the intercept on the ordinate axis.

To account for the nonlinear nature of the flow curves, the Casson model [18] was applied, which is described by an equation of the form

$$\tau^{0.5} = \tau_0^{0.5} + (\eta_{pl}\dot{\gamma})^{0.5}. \quad (4)$$

This relationship is widely used to describe aggregatively stable disperse systems, such as pigment suspensions [21, 22] or polymer melts, and allows the gradual breakdown of structural aggregates during deformation to be taken into account.

The most universal approach is the application of the three-parameter Herschel – Bulkley model [17], whose equation is given by (2). This model combines the advantages of the Bingham and Ostwald approaches, enabling the simultaneous determination of the yield stress τ_0 and accounting for the degree of pseudoplasticity of the material through the flow behavior index n [23].

Parameter estimation for all models was performed using the least-squares method based on the verified dataset. The summarized results of yield stress determination for the eight experimental compositions obtained using different mathematical models are presented in Table 3.

Table 3

Comparative analysis of organic binder yield stress values obtained using different rheological models

Composition No	Ostwald – de Waele model (initial method)		Shvedov – Bingham model (linear model)		Casson model (nonlinear model)		Herschel – Bulkley model (generalized model)	
	Yield stress τ_0^*, Pa	R^2	Yield stress τ_0, Pa	R^2	Yield stress τ_0, Pa	R^2	Yield stress τ_0, Pa	R^2
1	8.17	0.985	3.15	0.962	1.44	0.992	1.32	0.999
2	2.74	0.988	1.42	0.958	0.72	0.994	0.68	0.998
3	1.43	0.982	0.85	0.955	0.46	0.990	0.42	0.997
4	4.04	0.989	2.10	0.965	1.10	0.995	0.98	0.999
5	0.76	0.996	0.28	0.981	0.11	0.995	0.08	0.999
6	1.36	0.998	0.35	0.985	0.14	0.996	0.12	0.999
7	27.49	0.991	26.40	0.970	16.81	0.998	17.15	0.999
8	8.65	0.990	9.15	0.968	5.52	0.997	5.85	0.999

Note: for the Ostwald – de Waele model, the apparent yield stress (shear stress at $\dot{\gamma} = 1\ s^{-1}$) is reported.

Analysis of the data in Table 3 demonstrates a pronounced dependence of the results on the selected mathematical framework. The Shvedov – Bingham model exhibits the lowest coefficients of determination (0.955–0.985), which confirms the inability of a linear equation to adequately describe the curvilinear dependence of shear stress on shear rate. In this case, such approximation accuracy leads to a systematic overestimation of the yield stress by 2–3 times compared with nonlinear models.

The Ostwald – de Waele power-law model, despite relatively high correlation indicators, yields physically unjustified results. The values of the apparent

yield stress for compositions with low structural development (e. g. No 6) are overestimated by more than an order of magnitude (1.36 Pa versus the actual 0.12 Pa). This is explained by the fact that the model forcibly extrapolates the data to the origin, substituting static structural strength with the viscous resistance of the flowing medium.

The closest results are obtained using the Casson and Herschel – Bulkley models, which account for the non-Newtonian nature of organic binder flow. The discrepancy between these models for compositions with a well-developed structural framework (e. g. No 1, 2, 7, and 8) does not exceed 6–9 %. However, for systems with low structural strength (compositions No 5 and No 6), the relative deviation of the Casson model increases to 38 %, indicating its insufficient flexibility in describing low shear stress regions.

The highest accuracy in describing the experimental data is provided by the Herschel – Bulkley model, for which the coefficient of determination exceeds 0.997 in all cases and approaches 0.999 for most compositions. This demonstrates that the three-parameter equation most accurately captures the complex rheological behavior of organic binders over the entire range of additive concentrations.

To assess the adequacy of the selected Herschel – Bulkley model, verification was performed not only based on the coefficient of determination but also through residual analysis [24, 25]. Unlike a simple comparison of R^2 values, this approach allows for the identification of systematic biases arising from model overfitting to a limited set of experimental points. Residuals were defined as the difference between measured shear stress values and the calculated values obtained from the Herschel – Bulkley model for each shear rate. Fig. 2 presents an example of residual analysis for composition No 1, which is characterized by pronounced pseudoplastic behavior.

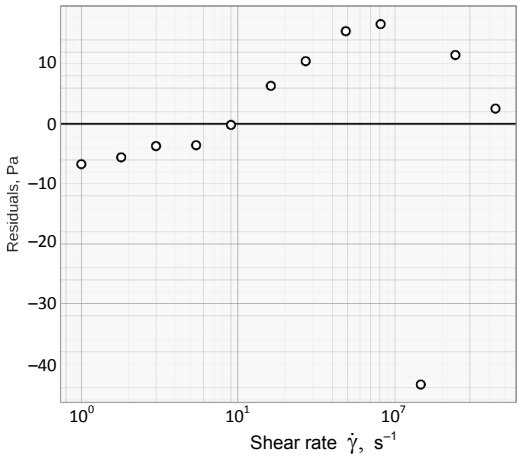

Fig. 2. Distribution of residuals of the Herschel – Bulkley model for composition No 1

Analysis of Fig. 2 shows that the residuals are symmetrically distributed about the zero line and do not form a systematic trend over the entire shear rate range. This indicates the absence of systematic approximation error. The observed

local deviations at high shear rates ($\dot{\gamma} > 100$ s^{-1}) do not exceed the experimental reproducibility limits and do not affect the determination of the yield stress, which is calculated based on data in the low shear rate region. Thus, the Herschel – Bulkley model adequately describes the rheological behavior of structured organic binders over the entire investigated parameter range.

To quantitatively assess the magnitude of errors associated with simplified methodologies, the relative deviation of the obtained results from the reference values determined using the Herschel – Bulkley model was calculated. The resulting data are presented in Table 4.

Table 4

Assessment of relative deviation of calculated values from the adopted reference (Herschel – Bulkley)

Composition No	Ostwald – de Waele model, %	Shvedov – Bingham model, %	Casson model, %
1	+519	+139	+9
2	+303	+109	+6
3	+240	+102	+10
4	+312	+114	+12
5	+850	+250	+38
6	+1033	+192	+17
7	+60	+54	–2
8	+48	+56	–6

Analysis of the data in Table 4 clearly demonstrates the evolution of accuracy in the mathematical description of rheological properties. The application of the Ostwald – de Waele power-law model, despite a high correlation coefficient for the overall flow curve, results in substantial errors in yield stress estimation. For compositions with low structural development (e. g. No 5 and No 6), the error reaches 850–1033 %, which completely distorts the physical interpretation and creates the illusion of a strong structural framework where none exists. The Shvedov – Bingham model also exhibits systematic overestimation, averaging about 120 %, which is attributed to the linear extrapolation of a convex flow curve. The closest results are obtained using the Casson and Herschel – Bulkley models.

Thus, the application of simplified methodologies to modern organic binders is unacceptable. Only the use of the generalized Herschel – Bulkley model ensures the acquisition of reliable data required for predicting technological stability. The refined yield stress values obtained were adopted as the basis for further analysis of the influence of additive composition on binder properties.

At the final stage of experimental data processing, the task of mathematical modeling of the yield stress dependence on the component composition of the organic binder was addressed. The initial dataset comprised τ_0 values obtained using the most accurate Herschel – Bulkley model. The objective of the modeling was to derive an analytical expression enabling the prediction of yield stress.

Preliminary correlation analysis revealed different degrees of influence of the varied factors on the target function. To assess the statistical significance of the contribution of each component, multiple regression analysis was applied [24, 25]. Testing the hypothesis regarding the influence of the mineral filler showed that the correlation coefficient between dispersed filler content and yield stress did not exceed 0.15, indicating the absence of a significant functional relationship. Even when the filler concentration was increased to 200 %, changes in yield stress remained within the experimental confidence interval. Based on Student's *t*-criterion, the coefficient associated with the mineral filler variable was deemed statistically insignificant, allowing this factor to be excluded from the final regression equation without loss of descriptive accuracy.

At the same time, analysis of the influence of cellulose fiber revealed the presence of a strong nonlinear relationship. Approximation of the experimental data using various functions showed that a third-order power function provides the best description of the structure formation process. This is confirmed by a sharp increase in the function gradient at fiber contents exceeding 2.5 %. The influence of the polymer modifier of the SBS type is described by a linear relationship and has an additive character, summing with the effect of fibrous reinforcement.

As a result of mathematical processing using the least-squares method, an empirical regression equation was obtained, describing the dependence of the yield stress on the content of the significant structure-forming components

$$\tau_0 = 0.041x^3 + 0.32y, \tag{5}$$

where τ_0 is the yield stress, Pa; x is the cellulose fiber content, % by weight of the organic binder; y is the polymer content, % by weight of the organic binder.

The adequacy of the obtained mathematical model (5) was evaluated using the Fisher criterion [24, 25]. The calculated F-value significantly exceeds the tabulated value for a significance level of 0.05 by a multiple factor, confirming the statistical reliability of the equation. The coefficient of determination R^2 for the proposed formula is 0.987, indicating that the model explains more than 98 % of the yield stress variation. Graphical verification of the obtained mathematical model is presented in Fig. 3 in the form of a scatter plot illustrating the convergence between experimental yield stress values and those calculated using equation (5).

Analysis of the scatter plot confirms the high adequacy of the proposed model. The experimental data points are clustered along the line of ideal agreement ($y = x$) and almost entirely fall within the ±10 % confidence interval. The root mean square error (*RMSE*) is 0.63 Pa, which does not exceed the acceptable reproducibility limits of the laboratory experiment. The high degree of correlation demonstrates that the cubic dependence on fiber content, combined with the linear contribution of the polymer, correctly describes the physics of the structure formation process over the entire investigated concentration range.

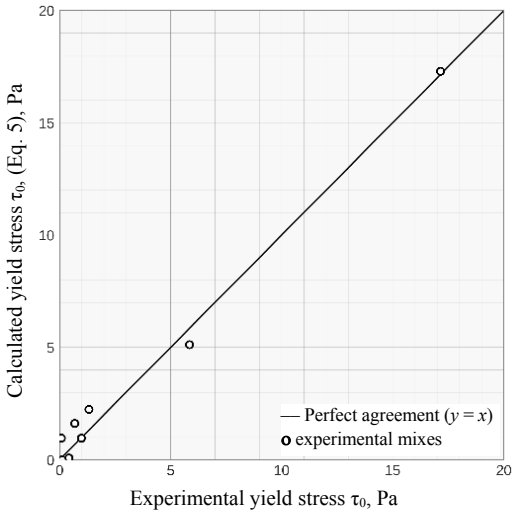

Fig. 3. Comparison of experimental and calculated yield stress values of organic binders

The physical meaning of the first term of the cubic dependence in equation (5) is explained by percolation theory [26–28]. At low fiber contents (up to 2–3 %), individual fibers remain in an isolated state and have a limited effect on structural strength. However, upon reaching a critical concentration, a continuous cluster of interwoven fibers is formed, leading to a sharp, disproportionate increase in shear resistance. The second term of the equation reflects the contribution of the polymer structural network, which reinforces the organic matrix but is less effective than fibers in providing structural retention. A graphical interpretation of the established relationship is presented in Fig. 4.

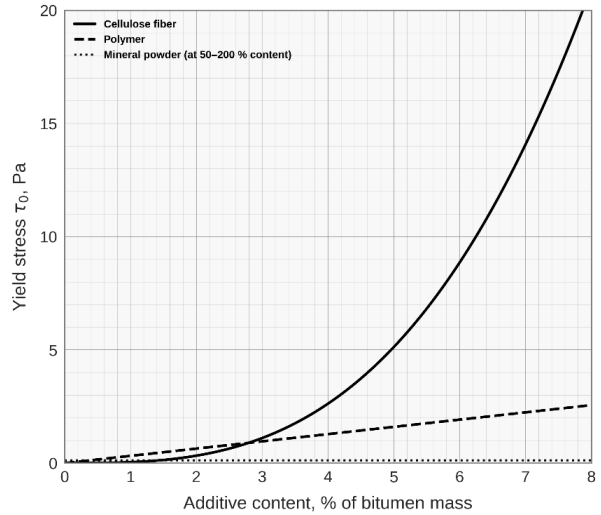

Fig. 4. Dependence of organic binder yield stress on stabilizing additive content

Analysis of the graphical relationship presented in Fig. 4 makes it possible to interpret in detail the physical mechanism of action of each component.

The curve describing the influence of cellulose fiber exhibits pronounced non-linearity, featuring a low-growth region at small concentrations (up to 2.5 %). In this region, individual fibers are present in the dispersion medium in an isolated state without forming contacts with one another, which explains the insignificant increase in yield stress. However, once the percolation threshold [26–28] is exceeded, which for the investigated system is approximately 3.0 %, a sharp change in the slope of the curve is observed. The dependence enters a phase of avalanche-like growth, indicating the formation of a continuous three-dimensional cluster (framework) of interwoven fibers, which is corroborated by other independent studies [29, 30]. It is this structural transition that ensures the attainment of yield stress values in the range of 10–15 Pa, which are necessary for the technological stability of the system.

A fundamentally different pattern is observed for the polymer and mineral filler dependencies. The influence of the polymer is linear with a small slope, indicating an additive strengthening mechanism associated with an increase in the cohesive strength of the organic matrix rather than the formation of a rigid skeleton. The curve corresponding to mineral filler content practically coincides with the abscissa axis, confirming that even at extremely high filler contents, dispersed particles of spherical or irregular shape are incapable of forming a framework able to resist shear under static conditions.

Verification of the adequacy of the proposed equation (5) using the control composition No 7 (fiber content 7.5 %) shows a high level of agreement with the experimental results. The calculated value is 17.3 Pa, which virtually coincides with the experimental value of 17.15 Pa obtained using the Herschel – Bulkley model. Therefore, the developed mathematical model can be used for the scientifically justified selection of stabilizing additive compositions, enabling the minimization of their consumption while ensuring the required technological stability. Furthermore, the targeted selection of effective structure-forming components prevents excessive increases in the viscosity of the dispersion medium. This directly contributes to a significant reduction in energy consumption during mixing and use of materials based on organic binders, thereby increasing the overall energy efficiency of technological processes.

Discussion of results

The data obtained in this study introduce significant revisions to the theoretical concepts of the mechanisms governing the technological stability of highly filled disperse systems based on organic binders. The approach based on the use of simplified rheological models led to an overestimation of the structuring role of mineral filler. The high values of apparent yield stress previously reported for highly filled systems in fact reflected not the strength of a structural framework, but rather a sharp increase in the viscosity of the dispersion medium. Application of the refined Herschel – Bulkley model made it possible to separate these parameters and to demonstrate that even at concentrations up to 200 %, mineral filler acts exclusively as a thickening agent and does not form a coherent network capable of resisting shear under static conditions.

A fundamental outcome of the study is the confirmation of the hypothesis regarding the percolation nature of organic binder strengthening by fibrous additives. The identified cubic dependence of yield stress on cellulose fiber content is of key importance. At the initial stage, at low fiber dosages, the fibers are present within the binder volume as isolated inclusions, which explains the gentle slope of the curve and the negligible increase in stability. However, upon reaching a critical concentration, which for the investigated system lies in the range of 2.5–3.0 %, geometric overlap of the influence zones of individual fibers occurs, leading to the formation of a unified three-dimensional cluster. This point corresponds to the sharp inflection of the curve and the rapid increase in yield stress, a phenomenon that must be taken into account in material design.

The practical significance of the established relationships lies in the possibility of scientifically justified optimization of composite formulations. Attempts to ensure system stability solely by increasing the content of mineral filler or polymer are technologically unsound, as they result only in increased viscosity during mixing, thereby significantly increasing energy consumption. Effective stabilization is achieved only through the introduction of fibrous reinforcing elements in amounts exceeding the percolation threshold. The proposed equation (5) allows for the accurate calculation of the required fiber dosage to achieve a specified yield stress, eliminating reliance on trial-and-error approaches.

It is necessary to note the limitations of the present study, which should be considered when extrapolating the obtained results. The experimental data were obtained for a model organic binder based on 90/130 grade bitumen at a fixed temperature of 160 °C. Since the rheological properties of organic binders exhibit high temperature sensitivity, changes in the temperature regime or the grade of the base medium will require the introduction of correction factors into the proposed mathematical model. The influence of the viscosity of the dispersion medium on the regression equation parameters also requires further investigation.

Establishing a correlation between the determined true yield stress of organic binders and the energy efficiency indicators of technological processes (e. g., power consumption of mixing equipment) constitutes a promising direction for future research. This will enable a transition from laboratory rheological testing to the development of comprehensive quality criteria that account for both the structural-mechanical properties of the materials and the economic viability of their application in industrial and energy sectors.

CONCLUSION

1. Based on the comparative analysis of rheological models, the methodological inadequacy of applying simplified power-law relationships for evaluating the properties of structured organic binders has been demonstrated. It has been established that the use of the Ostwald – de Waele model leads to a systematic error in yield stress determination, which for weakly structured systems reaches up to 1000 %, creating a misleading interpretation of the influence of individual components on the strength characteristics of the material. The three-parameter

Herschel – Bulkley model is substantiated as the baseline research tool, as it provides the highest accuracy in approximating experimental data with a coefficient of determination exceeding 0.99 over the entire shear rate range.

2. Application of the refined calculation methodology made it possible to revise the role of dispersed fillers in binder structure formation. It has been proven that mineral filler, even at high filler contents of up to 200 % by weight of the organic binder, does not form a coherent spatial network capable of resisting shear deformation under static conditions. The true yield stress value for such compositions does not exceed 0.12 Pa, indicating that mineral filler functions as a viscosity modifier of the dispersion medium rather than as a structural stabilizer against segregation.

3. The determining factor in ensuring the technological stability of highly filled disperse systems is the introduction of cellulose fiber, the mechanism of action of which is described by percolation theory. It has been found that upon reaching a critical fiber concentration in the range of 2.5–3.0 %, a rapid increase in the yield stress τ_0 occurs, reaching values of 17.15 Pa at an additive content of 7.5 %. This confirms the formation of a three-dimensional reinforcing cluster capable of bearing load under static conditions.

4. The practical outcome of the study is the development of an empirical mathematical model describing the dependence of the yield stress τ_0 on the component composition of the organic binder. The obtained regression equation, linking the yield stress to a cubic function of fiber content and a linear contribution of polymer, is characterized by a high coefficient of determination ($R^2 = 0.987$) and a root mean square error of 0.63 Pa. This relationship can be applied in the design of composite materials to provide a calculated justification for the required amount of stabilizing additives. Furthermore, the targeted regulation of the composition based on this model allows for the optimization of expensive components and a significant reduction in energy consumption during the mixing of viscoplastic media, thereby increasing the overall energy efficiency of technological processes.

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