

Rheology of Sludges and Residues of Effluent Waters

Leonid Ivanovich Sokolov

Vologda State Technical University, Lenin Street, 15, 160000, Vologda, Russian Federation
post559473@mail.ru

Abstract: Wet dispersed wastes are classified in terms of rheological properties and textural features. Rheological models of non-Newtonian liquids by Newton, Bingham, Ostwald, Herschel–Bulkley are presented. On example of suspensions of grinding sludge using viscometric studies complete rheological curves have been obtained, rheological properties of sludges have been studied, and rheological constants have been determined: yield point, flow index and consistency index. It has been established that strength, yield point, viscosity, stability of sludges are determined by dispersity, bonding energy between solid particles and interaction of disperse phase of sludge with its disperse medium. On the basis of tube viscometer design a commercial facility has been developed for determination of pressure loss within pipeline transportation of sludges and their suspensions. Pressure loss as a function of flow velocity of slurries in 150 mm pipeline has been established. Critical flow velocity of sludge suspensions in commercial pipelines have been determined.

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1. Introduction

The wastes after treatment of domestic and industrial spent waters (residues, slurries) within storage, transportation, disposal and especially within processing into valuable products are exposed to various mechanical impacts. At this, operation of treating facilities and other technological processes should be arranged so that to provide the highest level of sanitary and epidemiological safety. Successful solution of this problem is promoted by knowledge of rheological properties and texture of

the wastes generated within treatment of effluent waters (residues, slurries, tailings). These wastes are real bodies with elasticity, plasticity and viscosity, and since they are deposited from aqueous medium, they are characterized with significant moisture (adherent, capillary, structural, adsorption, osmotic and wetting water).

The wastes (residues, slurries) depending on their composition and disperse structure possess various rheological properties and texture features (Table 1).

Table 1. Classification of domestic and industrial wet dispersed wastes in terms of rheological properties and textural features

Disperse system	Wastes	Typical rheological properties	Typical textural features
Pure liquid	Water	Newtonian viscosity	Watery, liquid
Real solution	Salt solutions, extracting agents, reagents, coagulants	Mainly Newtonian viscosity	Liquid, thick
Colloidal solution	Protein solutions, cloudy solutions, extracts	Newtonian and non-Newtonian viscosity, rheopexy	Liquid, thick, slimy
Liqueous	Solutions of polymers, cellulose, suspensions, emulsions of fats, oil products, glues, suspensions of bentonite clays, starch	Non-Newtonian viscosity, pseudoplasticity, dilatancy, rheopexy, thixotropy	Liquid, thick, ductile, viscous-flow, adhesive
Pasty	Clayish solutions within drilling, sludges, chromium pastes etc., dewatered residues of domestic effluent waters, tars	Non-Newtonian viscosity, thixotropy, viscoelasticity	Thick, adhesive, mushy, rubbery, slimy, ductile, paste-like
Bound soft	Froth pastes after flotation, flotation froth (steady three-phase system: gas-liquid-solid phase)	Plastic viscosity, pseudoplasticity, dilatancy reversible and irreversible, thixotropy, elasticity	Soft, smudgy, slippery, adhesive, elastic, strengthening cells of froth structure
Bound semi-solid	Manure, dewatered residues, sludges (plating, grinding)	Elasticity, plastic viscosity, viscoelasticity	Soft, strong, viscous, sometimes rubbery
Firm and solid	Municipal and industrial garbage	Elasticity, high fluidity and strength, brittleness	Strong, firm, solid, brittle glassy

The most complex rheological properties are those of highly concentrated dispersed systems with spatial structures. Formation of slurries and residues, stipulated with physicochemical, biochemical, colloidal chemical or purely physical processes, is directly related with variation of their rheological properties [1, 2, 3, 4].

Rheological properties of slurries, residues (non-Newtonian fluids) are exposed after exceeding of their yield point [5, 6].

For instance, within simple shear of non-Newtonian fluid at stress τ there appears deformation with certain rate $\dot{\gamma}$. The ratio of shear stress to shear rate $\tau / \dot{\gamma}$ is a rheological constant of fluid and is known as Newtonian viscosity η :

$$\eta = \tau / \dot{\gamma} \quad (1.1)$$

Rheological equation of state of Newtonian fluid is as follows:

$$\tau = \eta * \dot{\gamma} \quad (1.2)$$

The main properties of fluids is viscosity. For non-Newtonian fluids the viscosity [7, 8, 9] is a function of shear rate, that is why it is called apparent or effective viscosity η_{app} (Pa*s). It sufficiently well characterizes behavior of a fluid material, provided that it is known in overall shear rate range of interest.

Instrumental determination of apparent viscosity involves measurement of pair values [τ ; $\dot{\gamma}$] in wide range of $\dot{\gamma}$ for depicting of flow curve and viscosity function.

In order to characterize fluids the flow curves, rheograms, are used, which represent shear stress as a function of shear-strain rate under conditions of simple shear.

Rheogram of Newtonian fluids is a straight line 1 (Fig. 1), passing through the origin of coordinates. All flow curves (2 – 5), which deviate from the straight

line, correspond to non-Newtonian fluids. Herewith, curve 2 illustrates dilatant flow, characteristic mainly for concentrated dispersed systems (suspensions of starch, potassium silicate, various glues with high content of solid phase with regard to liquid phase, whereas the liquid phase is contained in amount sufficient to fill voids between solid particles), when at increase in strain rate the shear is hindered, the yield point; curve 3 shows pseudoplastic flow of structurally viscous fluid (solutions of polymers, cellulose suspensions, wet sludges, for instance, grinding sludge, with asymmetric structure of particles, in which extended molecules are twisted between themselves and decelerate flow at low shear stresses), which is characteristic for "shearing plasticization" due to destruction of structure with increase in strain rate; curve 4 shows non-linear plastic flow characteristic for majority of plastic bodies. Linear portion of curve 5 is characteristic for Bingham fluids and corresponds to ideal plastic flow (dewatered residues and slurries).

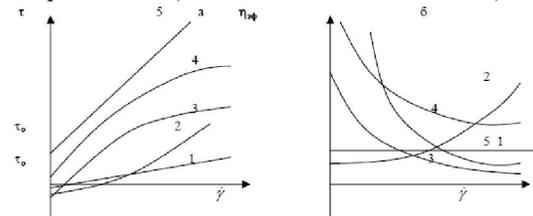


Fig. 1. Flow curve (a) and viscosity functions (b): 1 – Newtonian liquid; 2 – dilatant fluid; 3 – structurally viscous fluid; 4 – non-linear plastic body; 5 – linear plastic body.

Mathematical description of fluid behavior is a background of engineering calculation of flow process. For Newtonian and non-Newtonian fluids the models are applied, which sufficiently well describe their behavior in the stress range of interest (Table 2).

Table 2. Rheological models of fluids *

Author	Equation of state	Shear rate	Viscosity function
Newton	$\tau = \eta * \dot{\gamma}$	$\dot{\gamma} = \tau / \eta$	$\eta = \tau / \dot{\gamma}$
Ostwald	$\tau = \hat{E} * \dot{\gamma}^n$	$\dot{\gamma} = (\tau / \hat{E})^{1/n}$	$\eta_{y\delta} = \hat{E} * \dot{\gamma}^{n-1}$
Bingham	$\tau = \tau_o + \eta_{re} \dot{\gamma}$	$\dot{\gamma} = \frac{\tau - \tau_i}{\eta_{re}}$	$\eta_{y\delta} = \eta_{re} + \frac{\tau_i}{\dot{\gamma}}$
Hershel-Bulkley	$\tau = \tau_o + (\eta_{re} \dot{\gamma})^{n_1}$	$\dot{\gamma} = \frac{(\tau - \tau_o)^{1/n_1}}{\eta_{re}}$	$\eta_{y\delta} = \tau / \dot{\gamma}$

*Legend: τ – shear stress; τ_o – ultimate shear stress; $\dot{\gamma}$ – shear rate; η – Newtonian viscosity; η_{app} – apparent viscosity; η_{pl} – plastic (Bingham) viscosity; n – flow index; n_1 – the same according to Hershel-Bulkley; K – consistency index.

The structures of dispersed slurries and residues in the state of thermodynamic equilibrium can be subdivided into two systems:

1) Systems of solvate (hydrate) type with condensation-crystallization structure are formed within engagement of elements of the same type at interface when concentration of solid phase exceeds critical value. As a result of such significant concentration of solid phase hydrate shells around separate particles contact with each other, and a system is generated with high strength, elastic properties and brittleness. Solvate systems can be generated even with comparatively coarse (0.05–0.15 mm) solid material. In such comparatively coarse systems gravity forces are higher than forces of molecular cohesion between solid particles, and generation of structural bonds is possible only due to liquid shells around solid particles. After destruction they are not recovered. These are mainly wet solid wastes, generated within processing of metals, building element of glass and concrete.

2) Systems of lattice-like (coagulation) type are generated in residues, slurries and suspensions containing colloidal solid particles, that is, particle size below 1 μm . These ultrafine particles within Brownian motion break solvate (hydrate) shells around the particles in the most exposed points (particle corners and edges) or reduce the shells to thickness of monomolecular layer. As a consequence, structural lattices are generated, which exist due to molecular bonds between solid particles. In lattice-like structures of slurries and residues interaction between particles takes place through thin layer of dispersed medium and is stipulated by van der Waals forces (cohesion forces). These structures exhibit properties of non-Newtonian fluids (thixotropy, rheopexy, viscoelasticity and plasticity); they are strongly changed within heating, addition of surfactants, variation of pH and other impacts. Within addition of surfactants in concentration of higher than 1.5 % to residues of effluent waters with mechanic impurities and heavy metals it is possible to observe pseudoplasticity, since there occurs adsorption of surfactant molecules in particle surface and micelle formation. Micelles are of extended rod-like shape, they are twisted in water and decelerate flow at low shear stresses. With increase in concentration of surfactant there occurs smooth transfer to dilatancy and then to thixotropy.

Surfactants and dissolved in water flocculants used as additives within dewatering of residues act as emulsifiers and stabilizers of the dewatered residues and can significantly modify their structural and mechanical properties. Characteristic examples of coagulant structures are residues after biological treatment of effluent waters, composts (residues

mixed with turf). Within dewatering of residues and composts their strength increases, but after certain limit they already are not reversibly thixotropic. Recoverability of residue structure remains in viscoplastic medium when spatial frame is destroyed without breakage of integrity. Within further decrease in moisture content, that is, at transfer to paste-like state, restoration of strength after structure destruction is possible under stress causing plastic strains, which provide real contact over total surface area of the breakage. At the highest degree of structure compression and the lowest thickness of interlayers of liquid medium the recoverability and plasticity disappear, the curve of strength as a function of moisture is kinked. Such ultimate values of moisture for the considered residues of municipal effluent waters and composts amount to 66 % (at density of 1.06 t/m^3) \div 73 % (density 1.07 t/m^3). Herewith, the contact between residue particles is point-like. Within heating of the residue the particle contacts are converted into phase coalescences up to fusing.

Surfactants, including synthetic ones, filtrate water, flocculant solution, compressed active sludge, solutions of biogenic and other salts can be used as a lubricant to decrease viscosity and hydraulic resistance within pipelining of dewatered residues. As is known, the highest velocity gradient (the highest relative velocity U), and hence, the maximum resistance against viscoplastic flow of dewatered residue, stipulated by forces of internal friction occurs at the interface between viscoplastic flow and wall layer. Thus, into this region special fluids (lubricants) are added, the viscosity of which is significantly lower than that of dewatered residues and slurries.

Within selection of lubricant kind it is necessary to consider for technology of residue treatment before and after dewatering, as well as for type of the used dewatering units.

The use of filtrate water as lubricant is practicable when the mixture of wet residue and active sludge is dewatered using centrifuge or presses with flocculant, and if it is absent as well as within application of vacuum-filters and pressing filters it is reasonable to use compressed active sludge.

Quite often dewatered residues of effluent waters during their treatment are mixed with solutions of biogenic salts with the aim of detoxification and improvement of fertilizing properties. In this case in order to decrease hydraulic resistances within conveying of dewatered residues it is reasonable to apply solutions of biogenic salts also as lubricant, which significantly simplifies subsequent processing of dewatered residues and improves working environment for maintaining personnel.

The amount of lubricant added to wall region of pipeline is restricted due to possible increase in moisture of dewatered residues. Therefore, maximum amount of added lubricant should not increase moisture of these residues higher than by 1.0 %.

Within laminar motion of dewatered residues with moisture of 60-85 % in pipelines the three regions can be distinguished (based on well-known Buckingham equation). The first region is the Shvedov mode of motion (the Shvedov creepage), where dewatered residue move as actually integer structure (as solid cylinder the axis of which coincides with the pipeline axis). The residue viscosity in this region is maximum. The second region is a transition area, where destruction of the structural bonds of residue starts near pipeline wall. At this the viscosity decreases. The third region is the Bingham mode of motion, where steady area of viscoplastic flow is formed near pipeline wall. In the transition area velocity decreases somewhat quicker than in the main body. In the wall layer the velocity reaches zero, that is, the thinnest layer of residue, slurry can adhere to pipe wall due to high adhesion. Such mechanism can cause motion of finest particles of residue to the wall, if they possess decreased cohesive ability to two other phases and increased adhesive ability to the material of pipe wall.

Structural mode can be complicated by slippage of residue with regard to the wall, which is observed in the case of plastic highly concentrated coarse systems, including motion of dewatered residue with mean particle size of 0.003 m and higher.

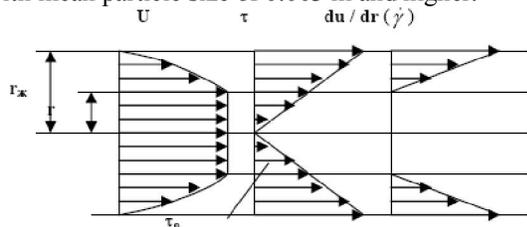


Fig. 2. Distribution of velocities, shearing stresses and velocity gradient in flow of dewatered oil sludge within laminar mode.

Figure 2 illustrates velocity profiles of shearing strains and shear rates in flow of viscoplastic (Bingham) fluid. Contrary to parabolic distribution of velocity over total pipe cross-section in the case of Newtonian fluid, for viscoplastic fluid there exists non-shear region: cylindrical core where shear stress τ is lower than ultimate dynamic shear stress τ_0 . In this region fluid moves as solid body.

For Newtonian and non-Newtonian fluids the critical Reynolds number is different: for Newtonian fluids it is 2100, for Bingham plastic and pseudoplastic fluids it varies from 2000 to 5000.

Cylindrical core of flow of viscoplastic fluid is destroyed only at infinitely high velocity of fluid flow (higher than 15 cm/s). Violation of steady laminar flow occurs not on the pipeline axis but on some intermediate radius between the axis and the pipe wall. Herewith, the velocity of laminar motion is replaced with transversal pulsing velocity of originating eddy motion. Occurrence of pulsation leads to disappearance of flow core. Therefore, peculiar feature of flow of Bingham plastic fluid is that the turbulent mode occurs long before disappearance of core of laminar (structural) flow.

Therefore, lattice-like (coagulation) structures are formed in fine residues, slurries by interaction between particles and molecules through interlayers of dispersing medium. Dispersing medium is continuous aqueous phase, and dispersed medium is separated phase consisting of particles not contacting with each other. At this, phase is a combination of homogeneous portions of the system, separated from other portions by physical interfaces. The interlayer thickness corresponds to minimum of free energy of the system. Thermodynamically stable systems are those, in which particle surfaces are firmly bound with fragments of molecules capable to dissolve in dispersing medium without loss of this bond. In its turn, dispersing medium is in bound state. Frequently these structures have ability to spontaneous recovery after destruction (thixotropy). Increase in strength after destruction takes place gradually, usually to initial strength as a result of Brownian motion of highly dispersed particles within falling on coagulation contacts. The interlayer thickness depends to some extent on content of dispersing medium. When its content increases, the values of shearing properties usually decrease and the system is transformed from solid to liquid state. Herewith, specific surface, that is, dominating particle size, even at constant concentration effects on the state of the system, its strength or viscosity.

The studies were performed with grinding sludge formed within in-process cleaning of lubricating fluids at metal processing and machine building plants. In terms of properties the grinding sludge can be classified as plastic material. The main dispersing medium of the sludge consists of two phases: water and oil products, and the dispersed one consists of oxidized fractions of metal, abrasive and its binder. Free moisture of the grinding sludge contains water soluble sodium salts. The grinding sludge includes oil products used for preparation of modern lubricating fluids and oil products in commercial lubricants: sulfated diesel oil, chlorinated paraffin wax, sodium isopropyl salicylate, mono-, di-, tri-ethanol amines, carbonyl compounds, organic alcohols, tars. In addition, sludges always contain

minor amount of components which are generated as a result of destruction of organic substances in the area of metal processing or added deliberately within adjustment of operational properties of lubricating fluids. The grinding sludges are structured systems. Around separate metal particles, abrasive with particle size of 3 – 150 μm liquid solvate shells are formed which contact with each other, forming structure of coarser associated complexes (aggregations), possessing elastic properties. In the solvate shells coarser particles of solid sludge inclusions are formed with size up to 0.15 mm. Herewith, the forces of gravity exceed the forces of molecular cohesion between solid particles, and structural bonds occur only due to liquid shells. The properties of sludges depend on and are determined by features of solvate system, in the shells of which about 11-64 % of dispersing medium is retained depending on the type of sludge. Stability of such structured system depends on the strength of liquid shell, forces of interaction between separate particles and on interface, as well as on the number of contacts between solid inclusions and dispersing medium in a unit volume. Features of the structure of solvate system and other factors determining stability of associated complexes are influenced by physicochemical properties of slurry solid inclusions, chemical nature of liquid phase and bonding energy in this system. Major amount of the slurry consists of oil phase thickened with iron (Fe), abrasive inclusions, as well as high molecular hydrocarbons and inorganic substances (Na^+ , K^+ , CO_3^{2-} , HCO_3^- , NO_2^- , PO_4^{3-} , SiO_3^{2-} , Cl^-).

In grinding sludge silicon oxide exists in the form of fine particles. The sizes of silicon particles in the sludge were determined using microscope. The sizes are in the range of 1.8 – 80 μm . Effective pore radius is in the range of 1.0 – 60 nm. Total specific surface area of the pores is not higher than $350 \cdot 10^3 \text{ m}^2/\text{kg}$. Some observations of structured grinding sludge systems with solid inclusions in various concentrations and with various degree of specific surface demonstrated that thickening effect of dispersed phase is proportional to its molecular weight, concentration in the system and specific surface. With increase in specific surface of solid phase the surface area of contact with dispersing medium increases. At this, favorable conditions are established for development of various energetic bonds in the system, which leads to formation of strong structures. Therefore, at low shear rates the viscosity of such strongly thickened system significantly increases. At high shear rates this structure is gradually violated: the strength of bonding of solvate shells with surface of solid particles is lost. Then the upper layers of solvate shells are separated

and a portion of bounded dispersing medium is liberated. This is manifested in viscosity decrease with increase in shear rate gradient du/dr .

As is known, the rheological properties can be strongly influenced by anisometry of solid inclusions (ratio of their length to transversal size). However, estimation of the anisometry of solid constituents of the sludge using microscopy revealed that the ratio of their length to diameter or width is close to 1 in 98.8 – 99 cases of 100. Therefore, anisometry in this case should be neglected.

Therefore, strength, yield point, viscosity, stability of grinding sludges are determined by specific surface, bonding energy between solid particles of complexes and interaction of dispersed phase of the sludge with its dispersing medium.

Taking into consideration the aforementioned, the grinding sludges already can be classified as abnormal viscoplastic systems which are able to produce high deformations without lose of integrity, that is, to flow like fluids. However, this assumption should be confirmed experimentally. With this aim it was necessary to know the law of their flow: to obtain complete rheological curves. Using viscometric studies the author obtained complete rheological curves of the sludge suspensions. The flow curves of the considered suspensions are illustrated in Figs. 3-5.

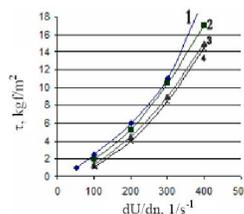


Fig. 3. Flow curves of grinding sludge suspension containing 1 % of solid phase and 50 % of oil products at various temperatures: 1 - 20°C, 2 - 40°C, 3 - 60°C, 4 - 80°C, 5 - 100°C.

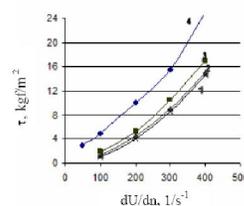


Fig. 4. Flow curves of grinding sludge suspension containing 20 % of solid phase at room temperature and various content of oil products: 1 - 0 %, 2 - 10 %, 3 - 50 %, 4 - 80 %.

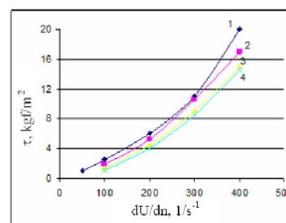


Fig. 4. Flow curves of grinding sludge suspension containing 20 % of solid phase and 50 % of oil products at various temperatures: 1 - 40°C, 2 - 60°C, 3 - 80°C, 4 - 100°C.

For these fluids tangential stress according to Ostwald is determined by equation given in Table 2. Coefficient K depends on consistency of slurry and increases with increase in viscosity. Experimental results are summarized in Tables 3 and 4.

Table 3. Parameters of consistent flow curves of grinding sludge suspensions at room temperature

Type of sludge suspension	Concentration of solid phase, wt. %	Oil products	K kgf·s/m ²	m
Sludge suspension with iron content less than 30 %	3.00	56.00	$5 \cdot 10^{-3}$	1.540
Sludge suspension without oil products	17.00	0.00	$2 \cdot 10^{-3}$	2.145
Sludge suspension with iron content less than 30 %	17.00	9.70	$2 \cdot 10^{-3}$	1.600
Sludge suspension with iron content more than 30 %, including spent emulsol Synthal-2	3.00	80.00	$6.3 \cdot 10^{-3}$	1.480

The values of coefficients in Table 3 correspond to flow of suspensions at room temperature. Within heating to 55°C fluidity of the suspensions decreased. As follows from the table suspension of the sludge with spent emulsol Synthal-2 with concentration of oil products 80 % is a strongly viscous system ($k = 6.3 \cdot 10^{-3}$). Logarithmic flow curves of this type of suspension, determined within heating, evidence that at $t = 45^\circ\text{C}$ the suspension viscosity decreases, and the values of coefficients k and m are $5.2 \cdot 10^{-3}$ and 1.23, respectively. When oil product content in suspensions increases and the coarseness of solid particles slightly decreases the value of coefficient m decreases and approaches unity at solid concentration of 1 wt. % and lower. When content of oil products in suspensions of grinding sludge decreases to zero the value of coefficient m increases and is higher than 2 at zero concentration.

Table 4. Rheological constants

Content of grinding sludge in suspension, %		Temperature, °C	Interval of viscosity variation, P	Yield point, kgf/m ²	k, kgf·s ^m /m ²	m, dimensionless
Solid phase	Oil products					
1	2	3	4	5	6	7
1	10	18	0.85-5.43	0.495	$1.15 \cdot 10^{-5}$	1.971
1	10	40	0.19-5.91	0.330	$3.5 \cdot 10^{-5}$	2.225
1	10	60	0.19-5.21	0.165	$7.8 \cdot 10^{-5}$	2.246
1	10	80	0.18-4.9	0.124	$1.15 \cdot 10^{-6}$	2.333
1	10	100	0.31-4.65	0.12	$1.22 \cdot 10^{-6}$	2.356
3	10	18	0.16-6.11	0.632	$2.5 \cdot 10^{-5}$	2.194
1	50	20	0.94-5.49	0.576	$7 \cdot 10^{-5}$	2.097
1	50	40	0.82-5.37	0.57	$1 \cdot 10^{-6}$	2.3
1	50	60	0.21-4.96	0.536	$1.79 \cdot 10^{-6}$	2.475
1	50	80	0.39-4.83	0.495	$1.77 \cdot 10^{-7}$	2.578
1	50	100	0.98-4.53	0.492	$2 \cdot 10^{-7}$	2.718
1	60	20	0.58-5.39	0.579	$7 \cdot 10^{-4}$	1.881
1	80	40	0.43-4.72	0.565	$1.22 \cdot 10^{-5}$	2.006
1	60	60	0.91-4.6	0.541	$1.35 \cdot 10^{-5}$	2.097
1	60	60	0.62-4.54	0.496	$1.22 \cdot 10^{-6}$	2.344
1	80	100	0.73-4.41	0.49	$2 \cdot 10^{-6}$	2.475
3	0	20	0.92-5.35	0.625	$3.65 \cdot 10^{-5}$	2.267
3	0	40	0.73-5.37	0.59	$1.27 \cdot 10^{-6}$	2.356
3	0	60	0.69-4.90	0.53	$2.05 \cdot 10^{-6}$	2.475
3	0	60	0.66-4.59	0.502	$3.4 \cdot 10^{-6}$	2.513
3	0	100	0.79-4.30	0.496	$3.9 \cdot 10^{-6}$	2.552
3	50	20	1.53-5.90	0.689	$3.81 \cdot 10^{-4}$	1.905
3	50	40	0.46-5.41	0.635	$2.1 \cdot 10^{-5}$	2.135
3	50	60	0.95-5.09	0.608	$4 \cdot 10^{-5}$	2.236
3	50	80	0.94-5.09	0.604	$2.4 \cdot 10^{-6}$	2.5
3	50	100	0.71-4.22	0.601	$1.22 \cdot 10^{-7}$	2.703
7	0	20	0.67-6	0.764	$7 \cdot 10^{-4}$	1.946
10	0	20	1.02-5.53	0.806	$4 \cdot 10^{-4}$	1.873
10	10	20	0.77-5.15	0.746	$2.1 \cdot 10^{-4}$	1.775
17	0	20	1.10-4.45	0.825	$3.7 \cdot 10^{-4}$	1.804
17	50	20	1.44-4.77	0.99	$2.2 \cdot 10^{-4}$	1.664
17	80	20	1.93-4.57	1.319	$6 \cdot 10^{-3}$	1.483
20	0	20	0.69-4.65	0.85	$1.25 \cdot 10^{-4}$	1.96
20	10	20	0.53-4.48	0.925	$2.51 \cdot 10^{-4}$	1.941
20	50	20	2.39-4.36	1.09	$1.15 \cdot 10^{-3}$	1.351
20	80	20	5.2-5.68	1.484	$2.3 \cdot 10^{-2}$	1.03
20	0	40	0.86-4.53	0.83	$8 \cdot 10^{-4}$	1.997
20	0	60	0.94-3.98	0.802	$1.04 \cdot 10^{-5}$	2.006
20	0	80	0.77-4.42	0.761	$6.5 \cdot 10^{-5}$	2.145
20	0	100	1.01-4.19	0.749	$1.22 \cdot 10^{-7}$	2.633
20	10	40	0.91-4.82	0.911	$5 \cdot 10^{-5}$	2.184
20	10	60	0.52-4.95	0.89	$2 \cdot 10^{-7}$	2.762
20	10	80	0.61-4.77	0.856	$6.9 \cdot 10^{-7}$	2.904
20	10	100	0.59-4.54	0.848	$1.56 \cdot 10^{-3}$	2.937
20	50	40	2.37-4.36	0.99	$2.5 \cdot 10^{-3}$	1.428
20	50	60	0.61-5.08	0.981	$3.2 \cdot 10^{-4}$	1.664
20	50	80	0.54-4.77	0.97	$4.7 \cdot 10^{-5}$	1.881
20	50	100	0.6-5.2	0.969	$5 \cdot 10^{-5}$	2.097
20	80	40	2.9-5.81	1.201	$3.49 \cdot 10^{-2}$	1.08
20	80	60	1.33-5.35	1.15	$3.38 \cdot 10^{-4}$	1.834
20	80	80	1.33-5.11	1.01	$1.22 \cdot 10^{-5}$	2.014
20	80	100	1.23-4.83	0.99	$8 \cdot 10^{-5}$	2.05

Therefore, the study of rheological properties of the grinding sludges and their suspensions made it possible:

- 1) to classify them as non-Newtonian fluids;
- 2) to obtain complete rheological curves of their flow;
- 3) to determine the values of yield point, rheological coefficients and their dependence on concentrations of constituents and on temperature, which is required at selection of mode of their pipeline transportation.

It has been established that pipeline transportation of fine grinding sludge can be carried out in different modes. Herewith, a slurry with particle sizes up to 100 μm (as in grinding sludge) exhibits viscoplastic properties already at concentrations above 3 %. At lower concentrations slurries can be pipelined as Newtonian fluids, however, it would require costs for diluting of slurries, preparation of suspensions and additional consumption of power and water resources.

Velocity of pipeline transportation of grinding sludge suspensions should be selected so that to provide minimum possible hydraulic resistances in the pipeline. Transportation of suspensions with critical velocity will lead to settling of particles from the flow onto pipeline bottom. Transportation of suspensions at velocities above critical values is characterized with increased hydraulic resistances. In order to determine the limits of critical motion mode it was necessary under experimental conditions to achieve such velocities at which the suspensions flow is capable to convey strictly predetermined amount of slurry, and at subsequent addition of slurry particles they would inevitably settle onto pipeline bottom.

Experiments on determination of critical velocity were carried out on a pilot facility assembled in the form of tube viscometer with diameter of 150 mm and length of 28.5 m. Schematic view of the facility is illustrated in Fig. 6. The facility consisted of a AR100 pump, the feeding pipeline 2, the 75 m³ cone tank 6, the system of perforated pipes 4, the compressor 5, the overflow wall 7, the supply tank 10, and the samplers 11. The pipeline diameter was stipulated by operating requirements. Pressure loss over the pipeline length was measured by reference pressure gauges 13, which were connected to bottom points of pipeline. The holes in these points were drilled perpendicularly to the pipe axis. The device for pressure measurement included manifold 200 mm in diameter, to which the coupling cock was connected. The pressure gauge was connected with the coupling cock by glass tube fill with glycerol ($\gamma = 1.2 \text{ g/cm}^3$). The experiments on the facility were carried out as follows. Suspension of required concentration was prepared in the tank 6 by agitation of spent lubricating fluids and manually charged slurry with compressed

air. The suspension concentration was varied by addition of spent lubricating fluids from the tank 12. The suspension density was determined by pycnometer method and the concentration by weight method. After preparation of the suspension the pump 1 was activated and the suspension was displaced via the overflow wall 7 from the tank 6 by new portions of spent lubricating fluids, thus filling the tank 3. The volume of the tank 6 is higher by six times than that of the tank 3, hence, the density of the prepared suspension was not varied significantly within its displacement from the tank. Then the valve 8 was opened and the suspension under the pressure head corresponding to the height of the tank 7 (up to 5 m) was supplied into the test pipeline. During the experiments pressure loss was measured on the considered pipeline segments.

The facility provided possibility to charge the required amount of slurry into the system, to prepare suspension of the required consistency and to transport it via horizontal pipeline, to measure the required transport parameters, to discharge slurry from the pipeline and auxiliary tanks and to wash them.

Within study of hydrotransportation of suspensions the hydraulic resistances over the pipeline length and critical velocities were determined. Hydraulic resistances over the pipeline length started during motion of spent lubricating fluids without solid inclusions. It was necessary for estimation of influence of the solid components on pressure loss. The experiments on motion of suspensions of grinding sludges were subdivided into several series. Each series was characterized by constant pressure value preset by the level of suspension in the supply tank, preset value of flow rate and constant values of the suspension concentration and density. Each experimental series included measurements of the suspension flow rate, concentration, density, hydraulic resistances over the pipeline length and critical velocities.

Suspension flow rate was measured using volumetric method, with this aim the measuring tank was incrementally marked in 0.1 m.

After preparation of suspension in the tank 6 a sample was immediately taken for analysis by pycnometer method. One feature was taken into consideration within preparation: slurry into the tank 6 was loaded manually. Therefore, within preparation of next batch of the suspension spent lubricating fluids were fed when the level of lubricating fluids in the equalizing tank 12 was at its minimum. This facilitated addition of about 1 % of slurry detached at pump operation and decreased its artificial dose.

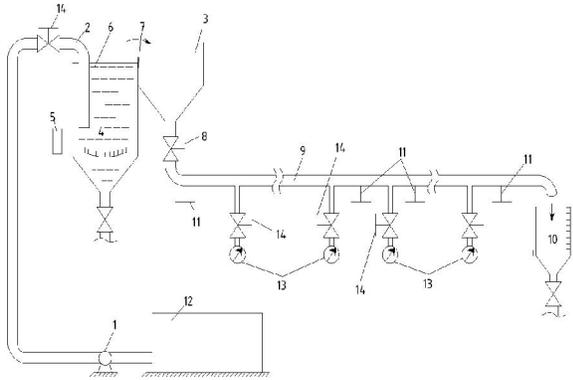


Fig. 6. Schematic view of pilot facility: 1 - pump, 2 - feeding pipeline, 3 - supply tank, 4 - system of perforated pipes for compressed air supply, 5 - compressor, 6 - tank for preparation of suspension, 7 - overflow wall, 8, 14, 15 - valves, 9 - test pipeline, 10 — measuring tank, 11 - samplers, 12 - equalizing tank, 13 - pressure gauge.

Pressure drop over the length of 150 mm pipeline was measured at straight horizontal segments, 12 m, 8 m, and 4 m in length, selected in such a way that to exclude the influence of various local resistances and pump. Before the points of pressure measurement straight approach segments were provided with length of 4.5 m. Pressure gauges were installed in initial and final cross-section of the selected pipeline segment. Factory guaranteed accuracy of pressure measurements by pressure gauges was 2 %. Head losses were determined as follows:

$$h_l = \frac{\Delta p}{g\rho}, \text{ m}, \quad (1.3)$$

where Δp is the pressure loss between the initial and final points of the segment, Pa; ρ is the density of the transported suspension, kg/m^3 ; g is the acceleration of gravity, m/s^2 .

Velocity of transportation of grinding sludge suspensions should be selected with provision for minimum possible hydraulic resistances in the pipeline. Transportation of suspensions with critical velocity would lead to settling of particles from the flow onto pipeline bottom. Transportation of suspensions at velocities above critical values is characterized with increased hydraulic resistances. In order to determine the limits of critical motion mode it was necessary under experimental conditions to achieve such velocities at which the suspensions flow is capable to convey strictly predetermined amount of slurry, and at subsequent addition of slurry particles they would inevitably settle onto pipeline bottom.

The experiments on determination of critical velocity were performed on pilot facility. With this aim the initial (before the pressure gauge) and the final (after the pressure gauge) 150 mm pipeline segment were equipped with samplers. In order to avoid violation of flow structure within sampling the initial sampling point was located at the distance of thirty diameters, 30D (4.5 m) to the point of pressure measurement.

After establishment of flow in the pipeline samples were taken at specified time intervals and analyzed for content of solid phase. The amount of solid in the suspension within its motion before the start of test segment and after it was estimated as mean arithmetic value of individual samples. Critical velocity was achieved by gradual decrease in flow rate at preset concentration up to the initiation of settling of solid particles from the suspension flow. Then the average velocity increased and the procedure was repeated. Critical velocity was determined as mean arithmetic value of several so measured velocities. Analysis of samples taken before and after test pipeline segment at various velocities of suspensions in parallel plane of head loss made it possible to determine the critical velocity. As is known, the critical velocity exceeds the velocity corresponding to minimum head loss. Figure 7 illustrates head loss as a function of velocity within motion of suspension of grinding sludge via pipeline $D = 150$ mm. The kink point B in the curve corresponds to minimum head loss for the preset conditions of hydraulic transport. Segments of the right branches of curve above the point A correspond to the velocity range at which slurry is completely in suspended state within motion of suspensions. The point A corresponds to the critical velocity. The point B in the curves corresponds to the minimum velocity at which pipeline starts to mud up. From Fig. 1 it follows that the minimum velocity of transportation ($D = 150$ mm) for suspensions of grinding sludge with the phase content of 1 %, 2 %, 3 % is 1.905 m/s, 1.9 m/s, and 2.06 /s, respectively. The critical velocities are usually selected by 10-15 % higher than the minimum velocities. We shall set them to 2.04 m/s, 2.13 m/s, and 2.21 m/s, respectively.

Therefore, rheological studies of grinding sludge and its suspensions demonstrated that at concentrations of solid and oil impurities higher than 3%-15% they cannot be considered as Newtonian fluids in terms of their rheological properties. Structural bonds occur at existence of solid particles finer than 100 μm in the liquid. Generation of such bonds depends on molecular affinity between solid and liquid phases and molecular interaction at the interfaces determined by this affinity.

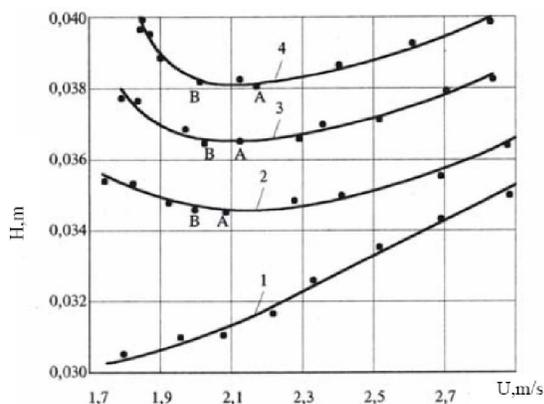


Fig. 7. Pressure loss as a function of velocity within motion in pipeline ($D = 150$ mm) of spent lubricating fluid without solid inclusions (I) and suspension of grinding sludge with density $\rho = 1.078$ t/m³: 2-1 % of solid inclusions; 3-2 % of solid inclusions; 4-3 % of solid inclusions; Point A corresponds to critical velocity; point B corresponds to minimum value or hydraulic resistance.

Pipeline transport of suspensions to reprocessing sites increases environmental safety of the processes, decreases labor and power intensities, as well as transportation costs.

Pipeline transportation of raw materials and wastes [10, 11] provides real background for arrangement of control of rheological properties of conveyed medium in flow, which in its turn provides optimization of technological process.

At present retrofitted and new industrial enterprises are more than ever designed with application of pipelines for transportation of technological mediums.

However, while designing such transport systems the experts have no data for rheodynamic calculations. There are little data with recommendations on application of more rational design of pumps for specific fluid, no studies on commercial pipelines concerning critical velocities of slurry flows.

This work is aimed at presentation of the experimental result and at generalization of discrete data on flow of viscous, abnormally viscous and viscoplastic fluids and technological mediums.

It is the author's opinion that the use of the data in this article would assist to manufacturers, designers and researchers to improve the existing equipment with regard to its integration into automated process lines and efficiency increase.

Corresponding Author:

Dr. Sokolov,
Vologda State Technical University, Lenin Street, 15,
160000, Vologda, Russian Federation
post559473@mail.ru

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