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The Possibilities of Using a Fire Extinguishing Substance Based on Water-Soluble Polymer for Extinguishing Solid Combustible Materials

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Abstract. This research presents the possibilities of using a fire-extinguishing substance based on a water-soluble polymer for eliminating fires at landfills and household waste landfills, the fire load which formed due to solid combustible materials. It has been shown theoretically and experimentally that by changing the concentration of gel-forming additives, the viscosity can be varied, which, directly affects on the evaporation rate and the depth of penetration of the fire-extinguishing agent into the center of the fire. The results of experimental research of gel fire extinguishing agents based on the ECOFLOC A-07 polymer effectiveness are presented.

1 Introduction

Waste landfills are dangerous facilities intended for processing, storing or transporting hazardous materials, the ignition of which can lead to complex emergency situations with major environmental consequences [1, 2, 3].

It should be noted that waste landfills are a heterogeneous mass of substances and materials with different origins and properties (Fig. 1). The physical properties of landfill soils affect the stability of slopes [4]. As a result of the lack of proper waste pressing processes, and constant changes in the surrounding conditions, air voids are formed in landfills [5, 6, 7].

Fig. 1. The largest waste landfill in Ukraine in the village Velyki Hrybovyshti, Lviv region

The process of extinguishing waste landfills is quite complicated, because of heterogeneity of landfills, many different smoldering centers may appear in their layer, which are difficult to find visually.

Due to the variety of substances and materials in waste landfills, they accumulate a significant amount of combustible substances from the composition of solid combustible materials (SCM). It should be noted that about 50 % of landfills consist of organic substances, which emit combustible gases during decomposition and causes a large number of combustion or smoldering centers.

It was established in [7] that the fire hazard of garbage directly depends on the compaction of landfills. The greater the density of garbage, than less possibility of creating a fire because of spontaneous combustion. In [5], a mathematical modeling of the process of exiting combustion products through the waste landfill was performed, which gives information about the spatial branching of heated gas flows, this is basis for a diagram (Fig. 2) of the passage of air flows from the exits.

The geometric relationships between the depth of the fire center (H), the diameter of the surface of the combustion products exit (d), the surface through which entering fresh air masses (the ring between D and d) were established, and developed a calculation model of garbage burning under ignition conditions in the landfill layers [8].

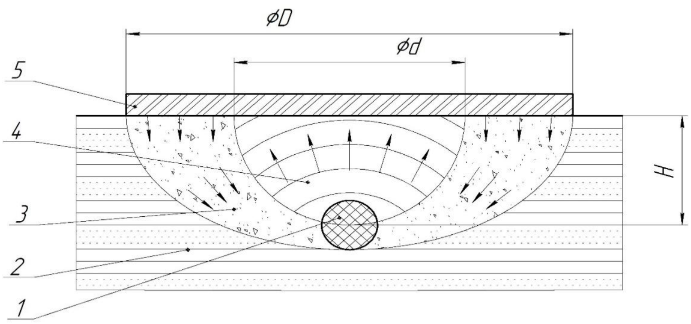


Fig. 2. Cross-section of the waste landfill at the location of the fire center: 1 – fire center, 2 – cross-section of the waste landfill, 3 – air flow from the environment, 4 – flow of combustion products, 5 – layer of protective fire-extinguishing material

Active participation in the combustion process is definitely taken by air coming from the environment through the structure of the landfill. The ratio between the depth of a single fire source and the diameter of a possible air entering is 1:2.

Water, fire-extinguishing powders and air-mechanical foam are using to extinguish fires at landfills [6, 9]. The main material for extinguishing fires is water. However, due to the specifics of the landfill, it is not possible to use water as effectively as possible, because due to the low wetting capacity, the main part of it seeps into the lower layers of the landfill and leads to negative consequences, in particular: the washing away of garbage, the formation of voids, the formation of acid lakes, the occurrence of sinkholes and landslides. Elimination of these shortcomings leads to high water consumption, additional extinguishing of fire centers that occur after the main extinguishing.

To prevent the spread of fire and next fire extinguishing, it is possible an adding in water agents that change its viscosity, for example, high-molecular polymer ECOFLOC A-07 which capable to swelling in water.

The resulting mixture has the ability for absorbing a large amount of water, has a high viscosity for adhesion with vertical and horizontal surfaces, and maintains sufficient fluidity for using in regular firefighting equipment.

While using a gel solution, the water-loaded polymer particles form a multi-layered film of water-filled polymer particles. The evaporation process is slower, since the polymer particles contain water. The outer water-loaded polymer particles closest to the fire begin to absorb heat until the water reaches its vaporization point. Thus, the water-loaded polymer particles that are closer to the surface are protected while the water in the outer layer of the loaded polymer particles evaporates. This process continues until the water in the innermost layer of water evaporates.

The number of layers of polymer particles filled with water directly depends on the concentration of the gel part of the solution - which characterizes the viscosity of the solution. The concentration of hydrogel in aqueous solutions was varied from 0.01 to 0.4 %, depending on the further purpose of the solution.

Hydrogel does not evaporate and tightly covers the source of combustion. The advantage of using hydrogels [10 – 13] is their high flame-retardant effect. By binding water at the molecular level, the gel increases the cooling capacity of water up to 15 times, and forms a protective layer on the surface of the SCM. One liter of gel concentrate is enough to treat an area of 24...40 m^2. In addition, unlike air-mechanical foam and fire-extinguishing powders, hydrogel is environmentally safe.

The resulting gel can be using for extinguishing SCM fires, fires in ecosystems and waste landfills. By changing the viscosity, it is possible to change the technologies of the extinguishing process.

2 Main Part

The purpose of this work is to justify the possibility of using a fire extinguishing agent based on a water-soluble polymer of the ECOFLOC A-07 type for extinguishing SCM.

The proposed ECOFLOC A-07 type polymer solution [8] acquires the property of "sticking" to the burning surface, protects the surface from catching fire, isolating it from oxygen access, increases the cooling capacity, enhances the dilution of the gas medium by water vapor, and has inhibitory properties due to the presence of potassium in composition of the substance and prevents the intensive flow of the solution from the surface of the SCM.

Researched the dependence of the apparent viscosity of the hydrogel from the concentration of the gelling agent and the magnitude of the velocity gradient, or the rate of relative shear rate in different hydrogel movement conditions. When the concentration of the gelling agent changed from a minimum of 0 % to a maximum of 0.35 %, there were changes in the physical properties of liquids from characteristic of Newtonian liquids to non-Newtonian pseudoplastic liquids, which characterized by a decrease in apparent viscosity with increasing shear stress, and thixotropic liquids, which characterized by a time-dependent apparent viscosity under conditions of a constant velocity gradient.

Measurement of the dependence of the apparent viscosity of hydrogel from gelling agent based on polyacrylamide concentration was carried out with using the mathematical model of the ball falling in the hydrogel medium, which is a refinement of the well-known Stokes method.

The force of hydrodynamic resistance to the ball's motion can be expressed in the form of Newton's general equation:

$$F_{fr}(t) = \xi(\mathrm{Re}(t)) \cdot S \cdot \frac{\rho_{gg} \cdot \omega(t)^2}{2}, \mathrm{N}, \tag{1}$$

where $\xi(Re(t))$ – coefficient of hydraulic resistance of a ball moving in a hydrogel medium, which is determined based onof the Reynolds criterion; S is the cross-sectional area of the ball, m^3; $\rho_g = 1000$, gel density, $kg \cdot m^{-3}$; $\omega(t)$ – speed of movement of the ball in the hydrogel medium, $m \cdot s^{-1\ m}$.

The equation describing the dynamics of the ball's motion will look like this:

$$m \cdot \frac{d}{dt}(\omega(t)) = m \cdot (\rho_d - \rho_{gg}) - F_{fr}(t), \mathrm{N}, \tag{2}$$

where m - mass of the ball, kg; $\rho_d = 7800$, the density of the sphere, $kg \cdot m^{-3}$.

The Glift and Gauvin model [14] was chosen to calculate the coefficient of hydraulic resistance to the flow around the sphere, which corresponds to the Rayleigh curve with an accuracy of 2 % in the range: 0.1 < Re < 200000:

$$\xi(\mathrm{Re}(t)) = \frac{24}{\mathrm{Re}(t)} \cdot \left(1 + 0.15 \cdot \mathrm{Re}(t)^{0.686} + \frac{0.42}{1 + \frac{42500}{\mathrm{Re}(t)^{1.16}}} \right), \tag{3}$$

At the same time, the value of the Reynolds criterion is calculated according to the traditional formula:

$$\mathrm{Re}(t) = \frac{\rho_{gg} \cdot d \cdot \omega(t)}{\mu(\omega(t),t)}, \tag{4}$$

where d is the diameter of the sphere, *m;* $\mu(\omega(t))$ – apparent viscosity, *Pa·s***.**

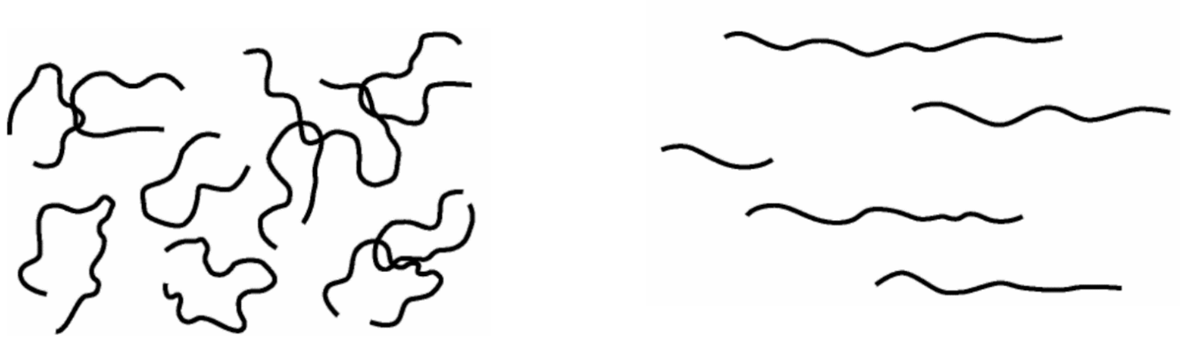
Then, using (1), (2), (3), (4), we will obtain a mathematical model of the movement of the ball in the hydrogel medium to determine the mutual dependence of the time of the ball's fall between the length of the fall and the viscosity in the form of a general system of equations:

$$\begin{cases} \frac{d}{dt}(\omega(t)) = (\rho_d - \rho_{gg}) - \frac{24}{\mathrm{Re}(t)} \cdot \left(1 + 0.15 \cdot \mathrm{Re}(t)^{0.686} + \frac{0.42}{1 + \frac{42500}{\mathrm{Re}(t)^{1.16}}} \right) \cdot S \cdot \frac{\rho_{gg} \cdot \omega(t)^2}{2} \\ \mathrm{Re}(t) = \frac{\rho_{gg} \cdot d \cdot \omega(t)}{\mu(\omega(t),t)} \\ L = \int_{t_0}^{t_f} (\omega(t))dt \end{cases} \tag{5}$$

where $L = 0.25$ – the length of the ball's fall, *m;* t_0, t_f – the time, respectively, of the beginning and end of the fall of the ball, *s*.

It should be noted that for calculation of the apparent viscosity $\mu(\omega(t))$ two different models of the behavior of a pseudoplastic fluid can be used: the first, that the apparent viscosity depends on the speed, the second - to consider the apparent viscosity independent of the speed of the ball.

The dependence of the viscosity on the shear rate can be explained by the fact that the base of the gelling agent is polyacrylamide, which has a linear chain structure. This can explain the decrease in apparent viscosity with increasing values of the relative shear, because in this case there is a transition from an isotropic (Fig. 3 a) to an anisotropic structure (Fig. 3 b), which complicates the eddy flows characteristic of the turbulent regime [15, 16]. At the same time, thixotropic properties of hydrogels are known [17], which can significantly delay the process of transition from isotropic to anisotropic structure.



a b

Fig. 3. Changes in the hydrogel structure depending on the flow rate. a – a liquid in a stationary state; b – fluid in motion.

The need to consider both models is precisely related to the thixotropic properties of hydrogels, because the physical conditions of movement in the hydrogel environment can be such that the structure does not have time to rebuild under the action of flows, remaining isotropic (see Fig. 3 a) and the apparent viscosity, which determined by the structure, remains unchanged.

The using of the first viscosity model can be considered based on the experimental data given, for example, in articles obtained on a rotary viscometer, where during the measurement process there is a stabilization of the change in the hydrogel structure to an anisotropic, that means, that the physical process of measuring the dependence of viscosity from the relative shear has quasi-stationary character, see Fig. 2, and the viscosity measured by this way can be expressed by the formula:

$$\mu(\omega(t)) = \frac{a}{\omega(t)^2 + b\cdot\omega(t) + c} + d, \tag{6}$$

where *a, b, c, d* – experimental steels.

While conducting experiments using the Stokes method, it turned out that using the first viscosity model has large discrepancies with the results of experiments, for example, the time of falling of a ball with a diameter of 3.5*mm* in a medium with a gelling agent concentration of 0.35%, calculated according to the first model was 0.384 s, while the experimentally measured time was 128.08 s.

Therefore, taking into account the results of calculations according to the mathematical model (5) and experimental data, which showed the presence of specific physical processes in the hydrogel environment with clearly expressed thixotropic properties, manifested in the form of a delay in the transition from isotropic to anisotropic structure [18], in the conditions of measurement according to the method Stokes, the second model of viscosity was adopted, which considers the apparent viscosity to be independent of the speed of the ball. Data of experiments on determining the time of falling of a ball at a given length of fall (0.250*m*) and the data of viscosity calculations by numerically solving the system of equations (5) allowed us to find the dependence of the apparent dynamic viscosity from the gelling agent concentration (Fig. 4).

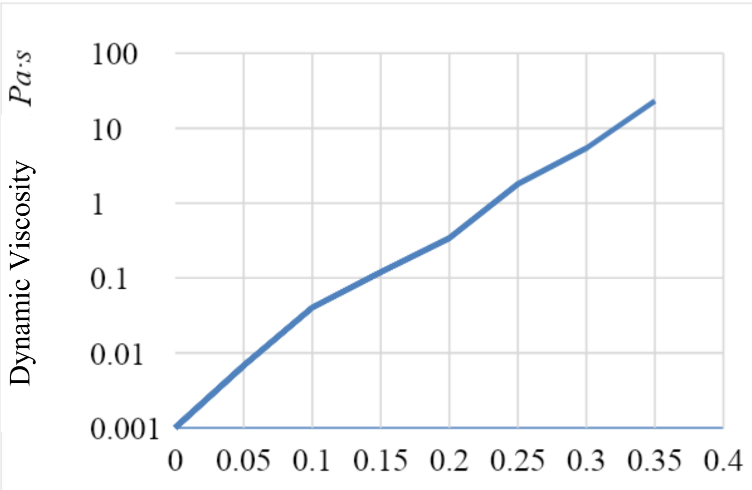


Fig. 4. The dependence of the apparent dynamic viscosity from the gelling agent concentration

It is known that the movement of liquid in a porous medium is described by Darcy's law. Based on the initial conditions regarding the absence of a pressure gradient for our case in a one-dimensional space (vertical), the value of the liquid flow rate percolating through the porous environment of the landfill takes the form:

$$v = k_{pen} \cdot \frac{\rho \cdot g}{\mu}, \text{ м·с-}^{1}, \tag{6}$$

where k_{pen} – the Darcy coefficient, or the permeability coefficient that depends on the physical and chemical properties of the porous medium and is determined experimentally, m^2, (D); ρ – the density of the liquid seeping through the porous environment of the landfill, kg·m^3; *g* – magnitude of the acceleration of the Earth's gravity, m·s^{-2}; m is the dynamic viscosity of the seeping liquid, Pa·s.

Research on the experimental determination of relative fire-extinguishing efficiency during the extinguishing of class A fires with finely sprayed jets was carried out taking into account the methods and results of research. The installation diagram is shown in Figure 5.

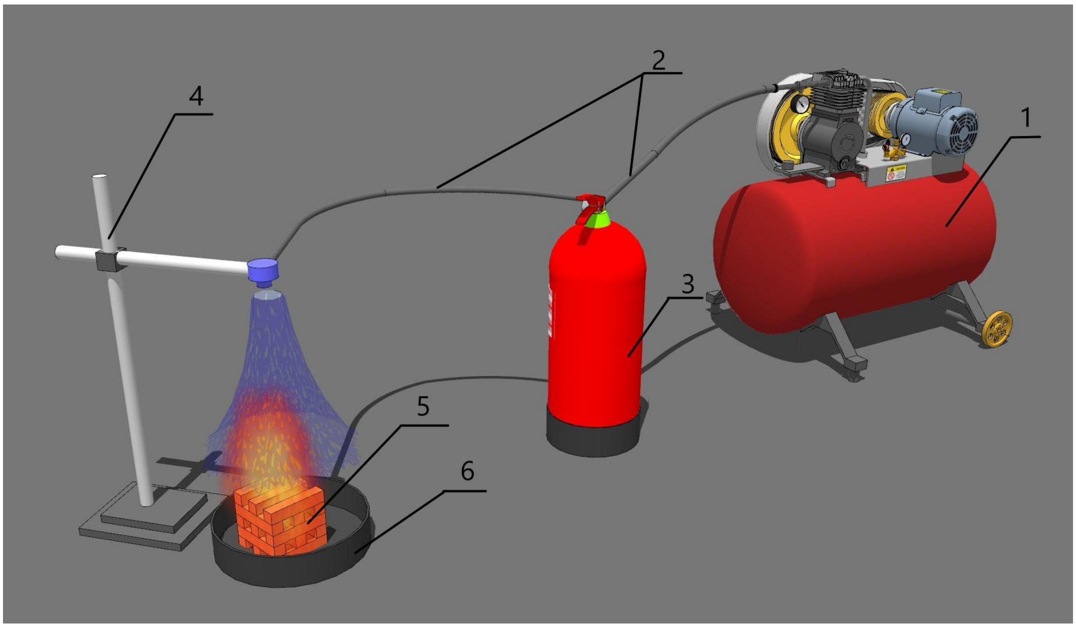


Fig. 5. Schematic representation of the stand for determining the relative fire-extinguishing efficiency of water extinguishing substances during extinguishing class A fires, where: 1 – compressor; 2 – supply pipelines of compressed air and fire extinguishing agent; 3 – test device based on the water fire extinguisher; 4 – tripod; 5 – non-standard model fire; 6 – pan

Relative quenching efficiency for *i*-th fire-extinguishing agent is calculated according to the following formula:

$$E_i = \frac{M_0}{M_i} \cdot \frac{T_0}{T_i} \qquad (7)$$

where M_0 – conditional consumption of reference extinguishing agent, kg; M_i – conditional consumption of fire extinguishing quantity for *i*-th composition of the fire-extinguishing substance, kg; T_0 – time spent on extinguishing using a reference extinguishing agent, s; T_{and} – the time spent on extinguishing using the extinguishing quantity *i*- th warehouse, s.

Previous studies have shown that when using only water (as a fire-extinguishing substance) it was not possible to extinguish the model fire, therefore, when conducting further experiments, a water solution with the addition of 0.2 % of AFFF foaming agent was used as a reference for comparison. It was compared with the effectiveness of extinguishing with a solution of ECOFLOC A-07 polymer at a concentration of 0.35 % with the addition of 0.2 % of foaming agent AFFF. Studies have shown that the relative efficiency of extinguishing with the proposed substance is 1.3.

Figure 6 presents photos of model fires after extinguishing with selected compositions of fire-extinguishing substances in laboratory conditions.

a b

Fig. 6. The general appearance of the model fire after extinguishing: a – with a solution of ECOFLOC A-07 type polymer in a concentration of 0.35 % with the addition of AFFF foaming agent 0.2 %; b – water with addition of AFFF foaming agent 0.2 %.

3 Conclusion

1. The proposed approach for determining the dynamic viscosity of the hydrogel creates opportunities for calculating the concentration of the gel-forming component to ensure the necessary flow rate of the liquid percolating through the porous environment of the landfill in the process of fire extinguishing.

2. An advantage in using the gel fire-extinguishing substances based on the ECOFLOC A-07 polymer compared to water was experimentally established, which may be due to the implementation of a complex of fire-extinguishing/fire-protective effects:

– the cooling effect is enhanced due to the delay of the supplied fire-extinguishing substance precisely in the combustion center;

– the insulating effect is realized due to the increase in the adhesion of the aqueous fire-extinguishing substance to the SCM and the formation of a gas-tight layer on the surface of the waste landfill;

– the phlegmatizing effect is enhanced as a result of diluting the gas medium by water vapor due to an increase of water in the combustion center;

– the inhibitory effect is realized due to the presence of potassium salts in the structure of the polymer gelling agent.

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