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Study of rheological properties of thermostable paints obtained by modification of silica sol

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Исследование реологических свойств термостабильных красок, полученных путем модификации золя кремнезема

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Abstract

This study investigates the rheological properties of heat-resistant composite paints modified with a synthesized organosilicon modifier based on silica sol and liquid glass. The modifier was prepared by the chemical modification of silica sol with an organic component and incorporated into paint formulations at different concentrations. The effects of modifier content on the viscosity and density of the coatings were evaluated using standardized testing methods in accordance with GOST and ASTM requirements. The results demonstrated that increasing the modifier concentration gradually increased the viscosity of the paint systems due to the formation of a stronger three-dimensional network between the modifier molecules and colloidal silica particles. At the same time, the coating density slightly decreased because of the lower density of the organic modifier, while the structural integrity of the coatings was maintained. Comparative analysis showed that paints containing 4–6 wt.% modifier exhibited the best balance between rheological behavior, storage stability, and application properties. The synthesized modifier improved the processing characteristics and is expected to enhance the thermal performance of the coatings. These findings demonstrate that the developed modifier is a promising additive for producing high-performance heat-resistant paint systems with improved rheological properties and potential applications in protective coatings for industrial and construction materials.

Аннотация

В данном исследовании изучаются реологические свойства термостойких композитных красок, модифицированных синтезированным кремнийорганическим модификатором на основе золя диоксида кремния и жидкого стекла. Модификатор был получен путем химической модификации золя диоксида кремния органическим компонентом и введен в состав красок в различных концентрациях. Влияние содержания модификатора на вязкость и плотность покрытий оценивалось с использованием стандартизированных методов испытаний в соответствии с требованиями ГОСТ и ASTM. Результаты показали, что увеличение концентрации модификатора постепенно повышает вязкость лакокрасочных систем за счет образования более прочной трехмерной сетки между молекулами модификатора и коллоидными частицами диоксида кремния. В то же время плотность покрытия незначительно снижается из-за меньшей плотности органического модификатора, при этом структурная целостность покрытий сохраняется. Сравнительный анализ показал, что краски, содержащие 4–6 мас.% модификатора, демонстрируют наилучший баланс между реологическим поведением, стабильностью при хранении и свойствами нанесения. Синтезированный модификатор улучшает технологические характеристики и, как ожидается, повысит тепловые свойства покрытий. Полученные результаты демонстрируют, что разработанный модификатор является перспективной добавкой для производства высокоэффективных термостойких лакокрасочных систем с улучшенными реологическими свойствами и потенциальным применением в защитных покрытиях для промышленных и строительных материалов.

Keywords: heat-resistant paint, silica sol, liquid glass, organic modifier, rheological properties, viscosity, density, thermal stability.

Ключевые слова: Термостойкая краска, золь диоксида кремния, жидкое стекло, органический модификатор, реологические свойства, вязкость, плотность, термическая стабильность.

Introduction

Today, the construction and finishing materials market is extremely diverse. High competition in this field drives the search for new, technologically advanced solutions to meet consumer needs[1,pp.1 – 2].

Ease of use and process speed play an important role in construction. Today, coatings containing silicate groups rightfully hold a leading position in terms of corrosion protection and thermal stability. Combining high efficiency, quality, and application speed, these monolithic bonding coatings have proven themselves to be heat-resistant, waterproof, protective, and anti-corrosion materials[2,pp.3 – 4].

The main obstacle to the widespread adoption of this type of material is the difficulty of applying them. The need for complex and expensive equipment and skilled workers, along with the low lightfastness of most systems, significantly limit the use of this type of coating[3,pp5-6].

Thermally and photostable coatings in the form of monomolecular (one molecule thick) layers or thin films are produced by treating materials with solutions, emulsions, or (less commonly) double water—substances that interact poorly with water but adhere strongly to surfaces.

The existing multi-stage technology for producing and using thermally stable polymers has led to lengthy synthesis, reduced yields of the target product (especially under laboratory conditions), and hinders the transition to a continuous process.

Experimental industrial process control provides the most optimal process flowsheet for their production using hetero functional condensation and hydrolysis, which simplifies the technology and reduces labor costs, energy, and material consumption[4,pp.4 – 5].

Acrylic acid, silica sol, liquid glass, and ethylene glycol were used as fillers during the synthesis process using the technology for developing thermally stable polymer composites using the developed method. In the Republic of Uzbekistan, large-scale measures are being taken to ensure fire safety of buildings and structures by creating and improving modern fire-fighting equipment and systems.

In this area, in particular, a number of studies are being conducted to create fire-resistant building materials based on local raw materials and to improve the quality of fire extinguishing methods and technical equipment[5,p.1].

Today, scientific research is being conducted worldwide to develop new, environmentally friendly, and cost-effective methods for synthesizing highly effective fire-resistant expanding polymer composite coatings from inexpensive raw materials and their application in the oil and gas, chemical, medical, and various construction industries[6,p.2].

Since the 20th century, SiO_2 nanoparticles have been widely used in many products, and since the 1960s, metallic nanoparticles have been used. It has been established that compacts of these very small (~10 nm) crystals possess unique physical properties that can be exploited for various engineering purposes[7,pp.8 – 9].

Many applications of nanocomposites are based on the properties of individual nanoparticles (sensors, medical diagnostics, homogeneous catalysis, etc.). At the same time, there are important areas requiring self-assembling nanoparticle composites (nanoelectronics, optoelectronics, photonics, heterogeneous catalysis, etc.).

Currently, much attention is being paid worldwide to the development of fire protection products based on modern technologies and their use to improve the fire resistance of building structures and materials. Accordingly, targeted scientific research in areas such as creating models of the mechanisms of physico-thermochemical processes occurring in protective coatings under the influence of heat; developing compact, accurate, and rapid methods for assessing the impact of fire-retardant fillers on the fire safety of building structures and materials; and creating a new generation of highly effective heat- and fire-protective coatings based on readily available natural resources is important. Conducting scientific research in the above-mentioned areas confirms the relevance of the topic of this dissertation[8,pp.1 – 2].

Materials are evaluated for their heat resistance, fire resistance, and resistance to sunlight and heat during the summer months. Thermal conductivity, flame resistance, and other factors are important thermal insulation properties, chemical stability of suspensions, and performance characteristics that influence the quality of the material.

In turn, these properties are achieved through the presence of silicate groups in the material and metal oxides in the paint. Studying these properties allowed us to investigate the thermal degradation of paint and varnish compositions on wood and rheological properties such as viscosity, adhesion, and density[9,pp.3 – 5].

Research object and methods

The study subjects were heat-resistant modifiers obtained by modifying liquid glass and silica sol, as well as paint samples containing modifiers in various percentage ratios. The study was conducted in accordance with the requirements of GOST 8420 – 74 and GOST 11066-74 for studying the rheological properties of paints and varnishes, as well as using product analysis methods compliant with international standards (ASTM).

Research results

In laboratory studies, an organic modifier obtained by reacting acrylic acid with ethylene glycol and silica sol were reacted in various weight ratios. A total of four different samples were prepared, and the resulting heat-resistant modifier was added to gray and red paints at a rate of 4 % by weight. The viscosity of the resulting paints was studied in accordance with the requirements of GOST 8420 – 74 (Table 1)[10,pp.1 – 3].

Table 1.

The influence of the concentration of colloidal silicon dioxide and modifier on the viscosity of the system

№	Quantity of components (g) in mass ratio		Type of pigment	Paint KO 8101 amount kg	Viscosity [VZ-246 (Ø4 mm)(s)]
	Silica sol	Modifier			
1	95	5	Red pigment (Iron Oxide Red 130)	2.5	53.3

№	Quantity of components (g) in mass ratio		Type of pigment	Paint KO 8101 amount kg	Viscosity [VZ-246 (Ø4 mm)(s)]
	Silica sol	Modifier			
2	90	10		2.5	54.3
3	85	15		2.5	56.7
4	80	20		2.5	59.1
5	95	5	Silver pigment (Iron Oxide Black 750 and KRONOS 2190 mixture)	2.5	55.1
6	90	10		2.5	56.3
7	85	15		2.5	58.2
8	80	20		2.5	63.9

Table 1 shows how the viscosity of a heat-resistant paint and varnish composition changes as a result of varying the mass ratio of colloidal silica to modifier. In the experiments, the paint volume for all samples was assumed to be the same—2.5 kg—and the viscosity was determined using a VZ-246 viscometer (Ø4 mm).

The table results show that as the modifier content increased from 5 % to 20 %, the systems viscosity steadily increased. This is explained by the formation of a spatial lattice structure due to the interaction of modifier molecules with colloidal silica particles and an increase in the internal resistance of the system.

For compositions using red pigment (iron oxide red 130), the viscosity was 53.3, 54.3, 56.7, and 59.1 s, respectively. With an increase in modifier content from 5 % to 20 %, viscosity increased by 5.8 s, or 10.9 %. Specifically, a significant increase in viscosity was observed in the 15–20 % modifier range, indicating the formation of stronger structural bonds in the composition.

A similar trend was observed in systems using gray pigment (a mixture of black iron oxide 750 and KRONOS 2190). Viscosity values were 55.1; 56.3; 58.2; and 63.9 s, respectively. The difference between the initial and final values was 8.8 s, or 16.0 %, indicating a stronger effect of the modifier on viscosity in the gray pigment composition.

When comparing the two pigment types, the viscosity of the gray pigment-based compositions was higher than that of the red pigment sample at all concentrations. The difference was 1.8 s at 5 % modifier, 2.0 s at 10 %, 1.5 s at 15 %, and 4.8 s at 20 %. In particular, the sharp increase in viscosity in the gray pigment system at 20 % modifier concentration is explained by the high dispersion of these pigment particles and their stronger physicochemical interaction with the modifier.

Table 2.

The influence of modifier concentration on the viscosity (at 20°C) of the obtained TB-1 (heat-stabilized paint)

	The amount of modifier in the paint %	Ø2 mm nozzle(s)	Ø4 mm nozzle(s)	Ø6 mm nozzle(s)
Plain white enamel sample KO-811	0	102.1	56.5	35.3
Paint containing gray pigment KO-8101	0	107.6	57.2	39.0
TB-1	2	109.3	59.4	41.7
TB-1	4	112.7	60.2	45.2

	The amount of modifier in the paint %	Ø2 mm nozzle(s)	Ø4 mm nozzle(s)	Ø6 mm nozzle(s)
TB-1	6	114.4	63.3	47.4
TB-1	8	117.9	65.2	49.1
TB-1	10	119.7	71.1	52.3

The effect of modifier concentration in the heat-resistant paint TB-1, presented in Table 2, on viscosity at 20°C was studied using viscometers with nozzles of various diameters (Ø2, Ø4, and Ø6 mm). For comparison, widely used industrial paints KO-811 with white enamel and KO-8101 with gray pigment were used as control samples.

The table results show that the viscosity of the control samples with a Ø2 mm nozzle ranged from 102.1 to 107.6 s, with a Ø4 mm nozzle from 56.5 to 57.2 s, and with a Ø6 mm nozzle from 35.3 to 39.0 s. These values represent standard rheological properties for industrial paints. When the modifier was introduced into the TB-1 composition, the viscosity gradually increased for all nozzle diameters. At a modifier content of 2 %, the viscosity was 109.3 s for a Ø2 mm nozzle, 59.4 s for a Ø4 mm nozzle and 41.7 s for a Ø6 mm nozzle. With an increase in the modifier content to 10 %, these values reached 119.7 s, 71.1 s and 52.3 s, respectively. The results show that with an increase in the modifier content from 2 % to 10 %, the viscosity increased :from 109.3 s to 119.7 s for a Ø2 mm nozzle, i.e. by 10.4 s (9.5 %); From 59.4 s to 71.1 s for a 4 mm nozzle, an increase of 11.7 s (19.7 %); in a 6 mm nozzle, the time increased from 41.7 s to 52.3 s, an increase of 10.6 s (25.4 %).

Furthermore, the increase in viscosity with increasing modifier content is nearly linear, indicating that the modifier molecules form a strong spatial network with colloidal silicon dioxide and binder components. This results in increased structural integrity of the paint, reduced pigment particle deposition, and improved coating formation.

When comparing TB-1 samples with KO-811 and KO-8101 industrial paints, a clear increase in viscosity is observed as a result of the modifiers use. In particular, when using 8–10 % modifier, the viscosity of TB-1 is significantly higher than that of control samples, confirming its high rheological stability[11,pp.5 – 8].

Overall, the experimental results showed that with increasing modifier concentration in TB-1, the paints viscosity increases and its processing properties improve. A modifier content of 4–6 % provides an optimal balance between paint wear resistance, storage stability, and coating properties, while a modifier content of 10 % provides the highest viscosity, but ease of application in industrial settings must also be considered. These results confirm that the modifier plays an important role in optimizing the composition of TB-1 heat-resistant paint.

Table 3.

Change in density of enamel paint with different concentrations of modifier (at 20°C)

% heat-resistant modifier in KO 8101 paint	Empty pycnometer weight, g.	Mass of the pycnometer with the test substance, g.	Pycnometer volume at test temperature, ml.	Sample density g/sm³
0	20	51	20	1,3 g/sm³
2	20	50.94	20	1,297 g/sm³
4	20	50.90	20	1,295 g/sm³
6	20	50.78	20	1.289 g/sm³

% heat-resistant modifier in KO 8101 paint	Empty pycnometer weight, g.	Mass of the pycnometer with the test substance, g.	Pycnometer volume at test temperature, ml.	Sample density g/sm³
8	20	50.74	20	1.287 g/sm³
10	20	50.70	20	1.285 g/sm³

Based on the data presented in Table 3, it can be concluded that changes in the coating density as a result of increasing the amount of heat-resistant organic modifier in the paint composition were determined using the pycnometric method. In the experiments, the mass of the empty pycnometer (20 g) and the volume of the pycnometer at the test temperature (20 ml) remained constant, and the amount of modifier in the paint composition varied in the range of 0–10 %. This allows us to accurately estimate the dependence of the obtained results on the amount of modifier.

According to the results, the density of the control sample without the addition of modifier was 1300 g/sm³. With an increase in the modifier content to 2 %, the density decreased to 1.297 g/sm³, at 4 % — to 1.295 g/sm³, at 6 % — to 1.289 g/sm³, at 8 % — to 1.287 g/sm³, and at 10 % modifier — to 1.285 g/sm³. Overall, increasing the modifier content from 0 % to 10 % decreased paint density by 0.015 g/sm³, or approximately 1.15 %.

The mass of the test substance in the pycnometer also gradually decreased with increasing modifier content. Specifically, this value decreased from 51.00 g to 50.70 g. This indicates that the modifier has a relatively low-density organic structure and reduces the average density of the paint and varnish composition.

The decrease in density is explained by the penetration of modifier molecules into the silicate binder phase and a slight increase in free volume in the composition. Moreover, the presence of carbon chains and functional groups in the organic modifier creates a lower density compared to the inorganic binder phase. As a result, its bulk density decreases slightly without reducing the overall mass of the composition.

This change is considered positive from a practical perspective, as a slight reduction in coating density improves paint flow, reduces coating mass, and optimizes material consumption when coating large surfaces. Moreover, the very small decrease in density (1.15 %) means that the structural integrity of the composition is maintained, and the addition of the modifier does not negatively affect the mechanical stability of the coating.

These results are also consistent with the adhesion and heat resistance results obtained in previous experiments. That is, although paint density decreases slightly with increasing modifier content, its adhesion and heat resistance improve significantly. This confirms that the synthesized organic modifier is capable of improving performance while simultaneously lightening the paint composition[11,pp.1 – 5].

Conclusion

The present study demonstrated the successful preparation of a heat-stable modifier by modifying silica sol with a synthesized organic modifier and confirmed its applicability in the formulation of heat-resistant paint coatings. Rheological investigations showed that the composition of the modifier significantly affects the technological properties of the coating[12,pp.4 – 7].

The optimum silica sol-to-organic modifier mass ratio was determined to be 4:1, providing the most favorable rheological characteristics. Under these conditions, the viscosity reached 59.1 s for the red coating and 63.9 s for the gray coating. The gray coating based on pigment K 8101 exhibited higher viscosity, density, and adhesion, making it the most suitable formulation for heat-resistant applications.

The scientific novelty of this work lies in establishing the relationship between the composition of the silica sol-based modifier and the rheological behavior of heat-resistant coatings, as well as identifying an optimal formulation that enhances coating performance. The synthesized modifier improves viscosity, structural stability, adhesion, and consequently the thermal stability of the coating.

Compared with commercially available heat-resistant coatings such as KO-8101, KO-811, KO-814, Elcon, and Certa, the developed silica sol-modified coating offers a water-based silicate system with improved rheological stability and strong adhesion while employing a relatively simple synthesis route based on readily available raw materials. Unlike conventional silicone-organic coatings, which generally require organic solvents, the proposed formulation provides an environmentally friendlier alternative while maintaining the characteristics required for heat-resistant protective coatings[13,pp.11 – 13].

Therefore, the developed modifier represents a promising material for manufacturing heat-resistant coatings intended for metal structures, industrial furnaces, pipelines, exhaust systems, and other equipment operating at elevated temperatures[14,p.2]. The obtained results provide a scientific basis for further optimization and industrial application of silica sol-modified heat-resistant coating systems.

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