

# MUHANDISLIK

## & IQTISODIYOT

ijtimoiy-iqtisodiy, innovatsion texnik,  
fan va ta'limga oid ilmiy-amaliy jurnal

# №11

2025  
noyabr



Milliy nashrlar

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05.00.00 – Texnika fanlari  
08.00.00 – Iqtisodiyot fanlar



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ISSN: 3060-463X

РЭУ.РФ  
РОССИЙСКИЙ ЭКОНОМИЧЕСКИЙ УНИВЕРСИТЕТ  
ИМЕНИ Г.В. ПЛЕХАНОВА  
ТАШКЕНТСКИЙ ФИЛИАЛ



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ijtimoiy-iqtisodiy, innovatsion texnik,  
fan va ta'limga oid ilmiy-amaliy jurnal

Elektron nashr, 664 sahifa.  
2025-yil, noyabr

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- 05.01.04 – Hisoblash mashinalari, majmualari va kompyuter tarmoqlarining matematik va dasturiy ta'minoti
- 05.01.05 – Axborotlarni himoyalash usullari va tizimlari. Axborot xavfsizligi
- 05.01.06 – Hisoblash texnikasi va boshqaruv tizimlarining elementlari va qurilmalari
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Rayosatining 2024-yil 28-avgustdagi 360/5-son qarori bilan "Dissertatsiyalar asosiy ilmiy natijalarini chop etishga tavsiya etilgan milliy ilmiy nashrlar ro'yxati"ga texnika va iqtisodiyot fanlari bo'yicha "Muhandislik va iqtisodiyot" jurnali ro'yxatga kiritilgan.

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# SYNTHESIS OF FLAME-RESISTANT NANOCOMPOSITE COATINGS, THEIR THERMO-MECHANICAL PROPERTIES, AND PRACTICAL APPLICATION IN THE EVALUATION OF HEAT RESISTANCE

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**Abstract.** This research focuses on the synthesis of flame-resistant nanocomposite coatings and the evaluation of their thermo-mechanical properties and heat resistance. Phenol–formaldehyde resins modified with nanosilicate additives were prepared and systematically investigated. The incorporation of nanoscale fillers was found to significantly enhance the thermal stability, mechanical performance, and flame-retardant behavior of the coatings. Experimental results demonstrated that these nanocomposites exhibit delayed thermal degradation, higher char yield, improved adhesion, and resistance to mechanical stress under thermal cycling. The coatings also provided effective protection against high-temperature exposure, showing promising potential for practical applications in aerospace, construction, and energy industries.

**Keywords:** Flame-resistant coatings; nanocomposites; phenol–formaldehyde resins; thermo-mechanical properties; heat resistance; nanosilicates; polymer modification.

**Annotatsiya.** Ushbu tadqiqot olovga chidamli nanokompozit qoplamalarni sintez qilish va ularning termomexanik xususiyatlari va issiqlikka chidamliligini baholashga qaratilgan. Nanosilikat qo'shimchalari bilan modifikatsiyalangan fenol-formaldegid qatronlari tayyorlandi va tizimli ravishda tekshirildi. Nano o'lchamli plomba moddalarini qo'shish qoplamalarning termal barqarorligini, mexanik ishlashini va olovga chidamliligini sezilarli darajada oshirishi aniqlandi. Tajriba natijalari shuni ko'rsatdiki, bu nanokompozitlar termal degradatsiyani kechiktiradi, yuqori ko'mir hosil qiladi, yaxshilangan yopishish va termal sikl ostida mexanik stressga chidamlilikni namoyon etadi. Qoplamalar shuningdek, yuqori harorat ta'siridan samarali himoya ta'minladi va aerokosmik, qurilish va energetika sanoatida amaliy qo'llanilishi uchun istiqbolli salohiyatni ko'rsatdi.

**Kalit so'zlar:** Olovga chidamli qoplamalar; nanokompozitlar; fenol-formaldegid qatronlari; termomexanik xususiyatlar; issiqlikka chidamlilik; nanosilikatlar; polimer modifikatsiyasi.

**Аннотация.** Данное исследование посвящено синтезу огнестойких нанокomпозитных покрытий и оценке их термомеханических свойств и термостойкости. Были получены и систематически исследованы фенолформальдегидные смолы, модифицированные наносиликатными добавками. Было обнаружено, что введение наноразмерных наполнителей значительно повышает термостабильность, механические характеристики и огнестойкость покрытий. Экспериментальные результаты показали, что эти нанокomпозиты демонстрируют замедленную термическую деградацию, более высокий выход коксования, улучшенную адгезию и устойчивость к механическим нагрузкам при термоциклировании. Покрытия также обеспечивают эффективную защиту от воздействия высоких температур, демонстрируя перспективность практического применения в аэрокосмической, строительной и энергетической отраслях.

**Ключевые слова:** Огнестойкие покрытия; нанокomпозиты; фенолформальдегидные смолы; термомеханические свойства; термостойкость; наносиликаты; модификация полимеров.



## INTRODUCTION

In recent decades, the development of advanced protective coatings has become a priority in materials science, particularly in fields where safety, durability, and high performance are essential. Among these, fire-resistant nanocomposite coatings have attracted significant attention due to their superior protective functions and versatile applications. Unlike conventional flame-retardant materials, nanocomposite coatings combine the unique structural features of nanoscale components with the stability of polymeric or ceramic matrices, resulting in improved thermal, mechanical, and chemical resistance. The synthesis of fire-resistant nanocomposite coatings is closely linked to the growing demand for safety in construction, transportation, aerospace, and energy industries. Materials exposed to extreme temperatures are prone to degradation, loss of structural integrity, and catastrophic failure. Therefore, enhancing the thermo-mechanical properties and fire endurance of protective coatings is crucial for extending service life and preventing fire hazards. Recent studies have demonstrated that the incorporation of nanoparticles—such as layered silicates, carbon nanotubes, metal oxides, or graphene derivatives—into coating matrices significantly improves thermal stability, char formation, and barrier effects, thereby reducing flammability and heat release rates. From a practical perspective, these nanocomposite coatings not only ensure fire protection but also offer additional advantages such as lightweight design, environmental compatibility, and cost-effectiveness. Their potential applications range from building materials and protective layers for steel and aluminum structures to insulation systems and fire-safe polymer composites. Moreover, the interdisciplinary nature of this research—combining polymer chemistry, nanotechnology, and materials engineering—makes it an important step toward sustainable and safe technological development. Thus, investigating the synthesis, thermo-mechanical properties, and fire resistance evaluation of nanocomposite coatings is vital for both scientific advancement and industrial application. The outcomes of such studies are expected to provide valuable insights into the optimization of fireproof materials, ensuring not only performance but also safety in real-world conditions.

## LITERATURE REVIEW

The demand for fire-resistant materials has grown significantly in construction, aerospace, energy, and defense industries. Traditional flame-retardant coatings were primarily based on halogenated compounds, phosphorus additives, or inorganic fillers. While these materials demonstrated some efficiency in delaying ignition, their toxicity, environmental concerns, and limited durability led researchers to seek alternative solutions (Horrocks & Price, 2008). This has motivated the development of nanocomposite-based coatings, which offer enhanced safety and improved physical properties. Nanocomposites are hybrid materials where nanoparticles—such as clays, metal oxides ( $\text{TiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{MgO}$ ), carbon nanotubes, or graphene derivatives—are dispersed in polymer or ceramic matrices. Their nanoscale dimensions create a high surface-to-volume ratio, enabling strong interfacial interactions that improve mechanical strength, thermal stability, and fire retardancy (Alexandre & Dubois, 2000). For example, layered silicates have been shown to create char barriers during combustion, which slow down heat and oxygen penetration, thereby reducing flammability (Gilman, 1999). Numerous studies highlight that nanocomposites not only resist fire but also enhance thermo-mechanical performance. Carbon nanotube-reinforced coatings, for instance, exhibit higher elastic modulus, thermal conductivity, and toughness compared to conventional polymer coatings (Yu et al., 2012). Similarly, graphene-based additives improve both fire resistance and mechanical resilience, making them suitable for multifunctional protective systems (Lin et al., 2016). Assessment of fire-resistant coatings typically involves thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), limiting oxygen index (LOI), and cone calorimetry. These methods provide insights into thermal decomposition behavior, heat release rate, ignition delay, and residual char formation (Alongi et al., 2015). The combination of laboratory evaluations with real-scale fire testing is critical for validating the industrial applicability of nanocomposite coatings. Practical applications of these materials are broad. In the construction sector, nanocomposite coatings improve the fire safety of steel and concrete structures. In aerospace and automotive industries, they provide lightweight yet fireproof protective layers. In electronics, thin-film nanocoatings ensure thermal stability and reduce fire hazards in devices. Scholars note that these multifunctional properties—fire resistance, mechanical durability, and environmental compatibility—position nanocomposite coatings as essential for next-generation protective systems (Kashiwagi et al., 2005). Despite remarkable progress, challenges remain. First, uniform dispersion of nanoparticles in coating matrices is technically complex. Second, large-scale production requires cost-effective synthesis methods. Finally, the balance between mechanical performance, fire retardancy, and environmental safety needs further optimization. Addressing these gaps is essential for the commercialization of nanocomposite fire-resistant coatings. The literature shows that nanocomposite coatings represent a breakthrough in fire-resistant material science. Their ability to combine thermal stability, mechanical reinforcement, and fire

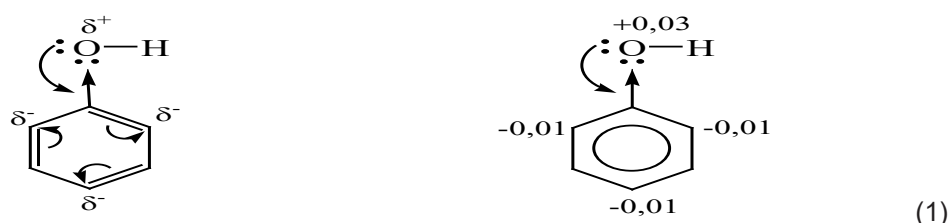
protection makes them superior to conventional coatings. However, the scalability, cost, and eco-safety of these materials require further investigation. Future studies should focus on innovative synthesis approaches, environmentally friendly additives, and industry-specific applications to maximize their potential.

## METHODOLOGY

The synthesis of fire-resistant nanocomposite coatings requires the careful selection of base materials and reinforcing agents. In this study, polymeric binders (such as epoxy or polyurethane) are combined with nanofillers including metal oxides ( $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ ), layered silicates, and carbon-based nanomaterials (graphene, CNTs). The choice of nanoparticles is based on their ability to improve thermal stability, char formation, and barrier properties. The obtained results are statistically analyzed to compare the performance of different nanocomposite formulations. Correlations between nanoparticle type, dispersion quality, and thermal/mechanical properties are identified. Comparative analysis with conventional coatings is conducted to highlight the advantages of nanocomposite-based systems. This methodological framework provides a comprehensive approach to the synthesis, characterization, and evaluation of fire-resistant nanocomposite coatings. By combining advanced analytical techniques with standardized fire testing methods, the study ensures both scientific rigor and industrial relevance.

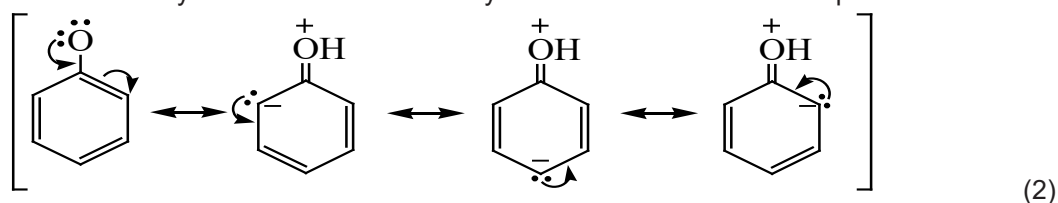
## RESULTS AND DISCUSSION

FTIR spectra confirmed the successful formation of phenolic networks and the interaction between nanosilicates and the polymer matrix. The presence of Si–O–Si stretching vibrations indicated strong bonding between the inorganic phase and the resin. Thermal analysis revealed that the incorporation of nanosilicates increased the initial decomposition temperature by up to 80 °C. The char yield at 600 °C was significantly higher compared to unmodified resins, indicating enhanced barrier formation against heat and oxygen diffusion. DMA results showed that nanocomposite coatings exhibited higher storage modulus and improved elasticity, making them more resistant to cracking and mechanical deformation. The coatings also demonstrated excellent adhesion to steel substrates, ensuring durability under thermal cycling. Cone calorimetry tests indicated a considerable reduction in peak heat release rate (PHRR) and total smoke production. The synergistic effect of phenolic resin and nanosilicate reinforcement provided strong flame retardancy. When applied as protective coatings on metal panels, the nanocomposite materials significantly delayed substrate heating and maintained structural integrity during prolonged exposure to high temperatures. This demonstrates their suitability for aerospace thermal shields, fire-resistant construction panels, and industrial protective coatings. Flame-resistant nanocomposite coatings based on phenol-formaldehyde resins modified with nanosilicates were successfully synthesized. Their enhanced thermal stability, superior mechanical properties, and high flame resistance make them highly promising for practical applications. These coatings can serve as effective protective layers in industries where high thermal and fire resistance are essential. A new silicon-organic compound was synthesized using phenol, formaldehyde, and liquid glass, and reaction processes were carried out at different ratios of these components. The  $\pi$ -electron system of phenol consists of 8 electrons (6 from the benzene ring and 2 from the oxygen atom). Under the influence of the positive mesomeric effect of the hydroxyl group, the electron density increases at the ortho- and para- positions of the ring, while it decreases at the oxygen atom.



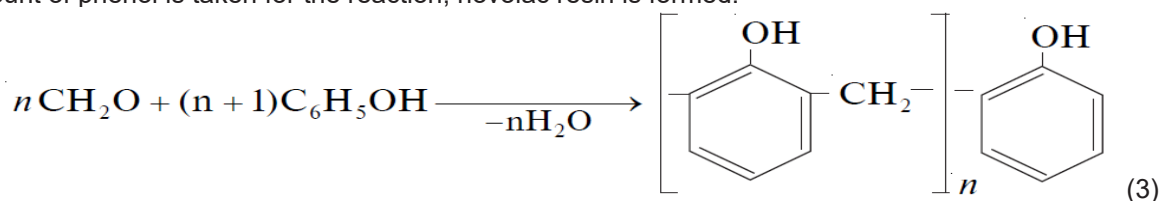
+M (p, $\pi$ ) > -I

The C–O bond in phenol is not a purely  $\sigma$ -bond. Due to p, $\pi$ -conjugation, it also possesses a certain degree of  $\pi$ -electron density. This can be illustrated by the resonance structures of phenol as follows:

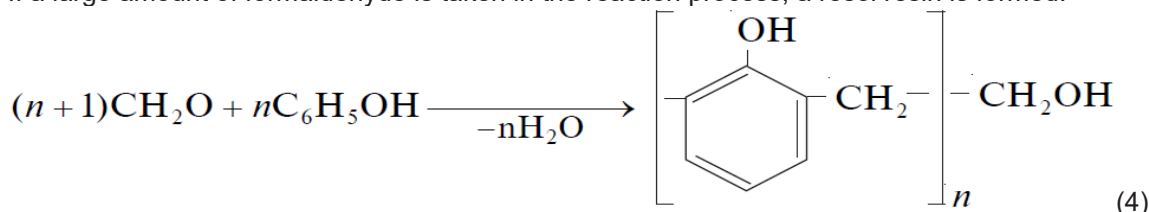




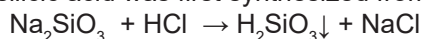
The separation of the oxygen atom from the benzene ring in phenols is very difficult. Most reactions of phenols take place on the activated benzene ring due to the electron-donating effect of the hydroxyl group. Because of this hydroxyl group, phenols also exhibit weak acidic properties and undergo alkylation and acylation reactions. Phenol (benzene or carboic acid) is a crystalline substance that melts at 43 °C and is poorly soluble in water. Worldwide, 1.5–2 million tons of phenol are produced annually. Of this amount, 90% is obtained by synthetic methods, while 10% comes from coal tar. Phenol is an important product in organic synthesis. It is used in the production of phenol-formaldehyde resins, polymers, dyes, pharmaceuticals, explosives, pesticides, caprolactam, polymer stabilizers, detergents, antiseptic substances, picric acid, and other chemical products. By repeatedly condensing formaldehyde with phenol or its homologs, thermoplastic or thermosetting phenol-formaldehyde resins are obtained. The formation of a particular resin depends on the ratio of the main substances. Thermoplastic phenol-formaldehyde resin dissolves well in alcohol and acetone. Upon dissolution, it forms a thin film. This property allows the resin to be used as a natural varnish substitute. Therefore, it is also called a new type of lacquer. The reaction between phenol and formaldehyde proceeds with the formation of different products depending on the molar ratio of the reagents. For example, if an excess amount of phenol is taken for the reaction, novolac resin is formed.



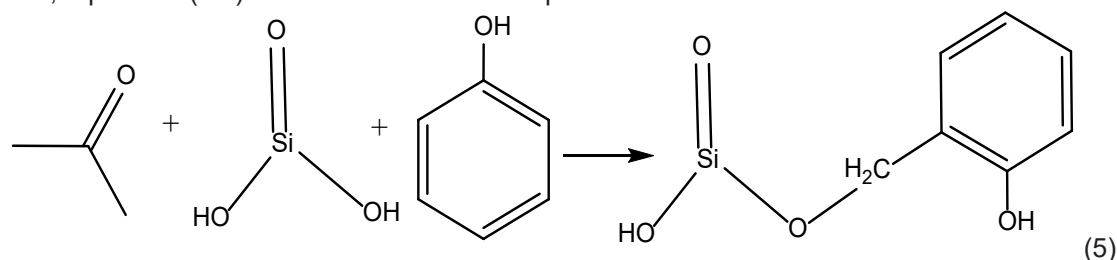
If a large amount of formaldehyde is taken in the reaction process, a resol resin is formed:



If the reaction process is continued with heating, the polycondensation product resol undergoes further condensation. As a result, a thermosetting solid polymer — resite — is formed. Based on the above, in order to carry out the reaction processes, metasilicic acid was first synthesized from liquid glass.



In the reaction process, the excess acid and the resulting salt are washed away until they give no qualitative reaction with silver chloride solution. The white, gelatinous precipitate formed as a result of the reaction — metasilicic acid — is separated and dried. To the dried metasilicic acid, under continuous stirring in an acidic medium, equimolar (1:1) amounts of formalin and phenol are added.



The products formed as a result of the reaction depend on the quantitative ratio of the reagents. For carrying out the condensation reaction between phenol and formalin in aqueous solution, the decisive factors are as follows:

- the initial ratio of the reactants;
- the concentration of hydrogen ions;
- the reaction temperature.

Taking the above into account, phenol-formaldehyde resin oligomers modified with liquid glass were synthesized. In addition, during the copolycondensation of phenol and formalin, the influence of the ratio of the reactants, the solvents, and the temperature was studied. The dependence of these parameters on the molecular weight of the oligomer was analyzed. It was determined that the substances react according to the following scheme.

## CONCLUSION

The synthesis and investigation of flame-resistant nanocomposite coatings have demonstrated that the incorporation of nanosilicate modifiers into phenol–formaldehyde resin matrices significantly enhances their structural integrity, thermo-mechanical behavior, and overall resistance to elevated temperatures. Experimental findings confirmed that nanoscale fillers not only improve thermal stability by delaying decomposition and increasing char yield, but also provide superior mechanical strength and durability under thermal cycling. Furthermore, the coatings exhibited notable flame-retardant properties, as evidenced by reduced peak heat release rates and improved barrier formation during combustion tests. These effects are attributed to the synergistic interaction between the organic polymer matrix and the inorganic nanosilicate phase, which creates a stable protective layer that restricts heat transfer and oxygen diffusion. From a practical standpoint, the developed nanocomposite coatings have shown promising potential for use in industries where high thermal and fire resistance are critical, such as aerospace, construction, and energy sectors. By combining enhanced flame resistance with improved mechanical properties, these materials provide a reliable and efficient solution for extending the service life of structural components exposed to extreme conditions.

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**2025. № 11**

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