DOI: 10.23968/2500-0055-2026-11-1-73-83

MODERN TRENDS IN THE CHEMICAL MODIFICATION OF "GREEN" BUILDING MATERIALS

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Abstract

Research objective is to conduct a comprehensive theoretical analysis of modern methods for modifying lignocellulosic building materials (LCBM), including wood, non-wood plant raw materials, and composites based on them. The main focus is on overcoming the natural limitations of LCBM use, such as hygroscopicity, biodegradability, and low fire resistance, through chemical modification with organoelement compounds (OEC). **Methods** include analysis and synthesis of traditional modification methods; detailed systematic analysis of the mechanisms of action of organoelement modifiers; comparative assessment of the effectiveness of various methods and compounds. **Results**: traditional methods (impregnation with preservatives, fire retardants, water repellents), polymer impregnation and thermal treatment, as well as innovative approaches using nanotechnologies are considered. The mechanisms of action of OECs, classified by key elements: organosilicon compounds (OSC), organophosphorus compounds (OPC), organoboron compounds (OBC), organometallic systems (OMS), and multicomponent compositions, are analyzed in detail. It is shown that OSCs primarily provide hydrophobization and geometric stabilization, OPCs and OBCs address fire protection and biostability challenges, while polyfunctional systems (P-Si-B-N) combine comprehensive protection with minimal impact on mechanical properties. Special emphasis is placed on the environmental benefits and durability of modified materials that align with the principles of "green building." The review presents recent advances in this subject area, highlighting the promise of OECs for creating competitive, environmentally friendly, and safe next-generation building materials.

Keywords: lignocellulosic building materials; wood modification; organoelement compounds; organosilicon compounds; organophosphorus compounds; organoboron compounds; fire protection; hydrophobization; biostability; thermal modification.

Introduction

Lignocellulosic building materials (LCBM), which include wood of various species, non-wood plant raw materials, and composite materials based on them, represent a renewable resource for the construction industry. Their distinctive features include environmental friendliness: the production of LCBM typically requires less energy than the production of steel, concrete, or plastics (Nässén et al., 2012; Alekseeva and Valeeva, 2023). Furthermore, many LCBMs are recyclable, compostable, or can be used for energy recovery at the end of their life cycle (Wojnowska-Baryła et al., 2020). LCBMs can regulate indoor humidity, creating a comfortable environment (Alapieti et al., 2020) and are energy-efficient as they have excellent thermal insulation properties reducing the need for heating/cooling (Wu et al., 2025). Moreover, they are lightweight: the lower weight of LCBM structures compared to concrete / brick reduces foundation costs and possess high strength-to-weight ratio: despite its relatively low density, wood exhibits high bending, compressive, and tensile strength, allowing its use for load-bearing structures subjected to significant loads (Niemz et al., 2023). Besides, high construction speed is an advantage as prefabrication of structural elements (especially CLT, Glulam) and ease of assembly accelerate the process (Ilgın et al., 2023). High thermal and acoustic insulation properties of LCBM reduce the need for additional materials (Krestyaninova and Yuminova, 2017), and vapor permeability of LCBM contributes to a healthy microclimate and prevents moisture accumulation indoors (Shams et al., 2024). The last but not the least is seismic resistance as LCBM structures possess good flexibility and ability to absorb earthquake energy (Ugalde et al., 2019).

However, the natural characteristics of LCBM (hygroscopicity, biodegradability, low fire resistance) necessitate modification. The main methods for modifying LCBM are as follows. Impregnation involves introducing chemicals into the pores and cell

For citations: For citations: Stepina, I., Strokova, V., Il'ina, V. (2026). Modern trends in the chemical modification of "green" building materials. Architecture and Engineering, No 1 (11), pp. 73–83. DOI: 10.23968/2500-0055-2026-11-1-73-83.

walls of wood under pressure or without it (Groshikov and Ovsyannikov, 2014; Usikov et al., 2016).

Methods

The following research methods were used in this work. Analysis and generalization of traditional modification methods. This stage is fundamental and belongs to the category of theoretical research methods. Its goal is to form a coherent picture of the current state of scientific development in the field of material modification.

Detailed systemic analysis of the mechanisms of action of organoelement modifiers. This is a key theoretical-experimental method aimed at uncovering the essence of the processes that occur when modifiers are introduced into a material. Systemic analysis implies considering the object not in isolation, but as a complex of interconnected components.

Comparative assessment of the effectiveness of various methods and compounds. This is an analytical stage that often concludes a study or a major part of it. It allows for a transition from scattered data to specific conclusions and practical recommendations. It includes elements of qualimetry (the science of quality measurement).

Results

The following *types of modifiers* are used:

– *Preservatives (biocides):* copper, chromium, arsenic, ammonium salts, boron compounds. The purpose of preservation is protection against fungi and wood-boring insects. The effectiveness of preservatives is quite high, but they pose environmental problems when biocides leach from the protected material (Mazanik, 2011).

– *Fire retardants:* phosphorus, nitrogen, boron salts; intumescent coatings that expand when heated, forming a thick layer of foam or char residue. The purpose of using fire retardants is to reduce flammability and slow flame spread. Fire retardants introduced into LCBM by impregnation demonstrate high efficiency but can leach out and reduce the strength of the substrate (Luneva and Petrovskaya, 2011).

– *Water repellents:* waxes, oils, silanes, siloxanes reduce water absorption and prevent swelling (Braekemaier et al., 2015). They are highly effective for protection against liquid water but do not prevent equilibrium moisture content.

The advantages of impregnation are its relative simplicity, well-established technologies (especially for preservatives and fire retardants), and the possibility of deep impregnation. However, leachability of many compositions, potential toxicity and environmental risks, possible deterioration of mechanical properties, and changes in appearance highlight the disadvantages of this method. Polymer impregnation involves filling cell cavities (lumina) with monomers followed by their polymerization inside the wood. Monomers used include styrene, methyl methacrylate (MMA), furan resins, and vinyls. This method achieves a significant increase in hardness, wear resistance, compressive strength, dimensional stability (due to pores "plugging"), biostability, and reduced water absorption of LCBM (Gulyaev et al., 2023). However, this method is characterized by high cost, significant increase in wood density, complexity of the process (requiring vacuum / pressure, polymerization initiators), possible deterioration of workability, and toxicity of some monomers. This method does not solve the problem of flammability (some polymers are flammable) (Kuzmin et al., 2022).

Thermal modification of wood involves heating wood to 160–240 °C in an oxygen-free environment for several hours. This leads to the degradation of hemicelluloses (the main source of hygroscopicity), partial restructuring of lignin and cellulose (Hill et al., 2021), resulting in a significant reduction in hygroscopicity and equilibrium moisture content; improved dimensional stability (less swelling / shrinkage); increased biostability (resistance to decay fungi); color change (wood acquires darker shades). However, this also results in a decrease in bending strength / impact toughness, increased brittleness of the wood, and practically no reduction in flammability (Sokolov, 2023).

The advantages of the thermal modification method are its environmental friendliness, excellent dimensional stability of thermally modified wood, high biostability, and aesthetic appearance. The disadvantages of this method include the energy intensity of the process and limitations on treatment thickness (Sokolov, 2023).

Nanotechnologies in LCBM modification involve using nanomaterials (e.g., nanoparticles of metals and oxides, nanocellulose, carbon nanotubes, nanoclays) for impregnation with nanoparticle dispersions, incorporation into composites (particleboard, fiberboard), and application of nanocoatings (Shamaev et al., 2022). This provides biocidal properties for LCBM (using Ag, Cu, ZnO nanoparticles); UV protection (using TiO_2, ZnO nanoparticles); fire protection (using nanoclays, metal hydroxide nanoparticles); hydrophobicity (using SiO_2 nanoparticles (Kilyusheva et al., 2020) and silanes); strengthening (using nanocellulose and carbon nanotubes) (Shamaev et al., 2022). Advantages of this modification method include high efficiency at low concentrations of components used and multifunctionality. However, disadvantages such as the high cost of nanomaterials, difficulty of uniform distribution and fixation in wood, safety concerns, and ecotoxicity of nanoparticles require further research in this direction.

Chemical (reactive) modification of LCBM is based on the chemical interaction of a modifier (including nanoscale) with the hydroxyl groups ($^-$OH) of cellulose, hemicelluloses, and lignin, forming covalent bonds. Significant advantages of this method are deep and stable modification of LCBM properties, environmental friendliness of many reaction products, high biostability, dimensional stability, and reduced flammability of LCBM (Bazarnov et al., 2004). The use of organoelement systems as modifiers, combining inorganic elements (Si, P, B, N) with organic compounds, enables unique mechanisms for controlling LCBM properties due to high affinity for the substrate (Pokrovskaya, 2009). This review analyzes recent advances in this area, focusing on Russian and international research.

The wide range of organoelement compounds (OECs), whose use can influence the structure of wood and thereby modify its properties to varying degrees, ensures increased interest from researchers in finding ways to develop rational formulation and technological solutions for creating various types of modifiers.

Based on the key element in the organoelement modifiers (OEMs), they can be divided into the following enlarged groups (Figure):

- organosilicon compounds (OSCs);
- organophosphorus compounds (OPCs);
- organoboron compounds (OBCs);
- OEMs based on other elements (Sn, Cu, Zn);
- multicomponent systems.

Organosilicon compounds (OSCs). Their mechanism of action involves the formation of hydrophobic siloxane (Si-O-Si) networks on the surface or in the pores of LCBM, or covalent bonding of OH groups of cellulose / lignin / hemicelluloses via silane coupling agents. Thus, OSCs provide hydrophobization of the substrate, increased dimensional stability, improved weather resistance, and moderate increase in thermal stability. For example, alkylalkoxysilanes (particularly methyltrimethoxysilane, MTMS) penetrate and polymerize in cell walls; siloxanes (silicone oils / resins) form water-repellent films; silazanes, which contain nitrogen atoms, possess high penetrating ability and not only hydrophobize the LCBM surface but also increase bio- and fire resistance (Hill, 2006).

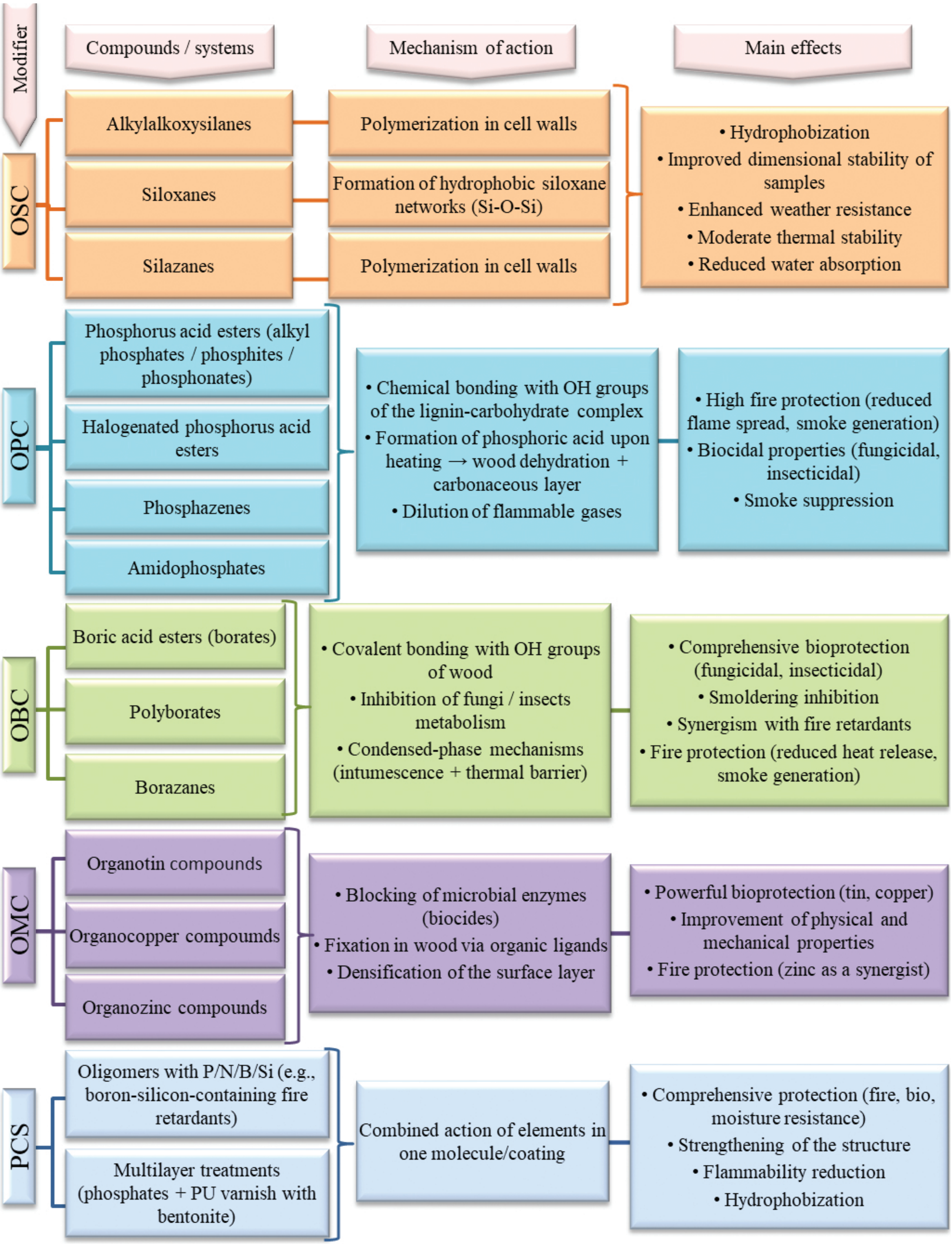
The features of the composition, properties, and mechanism of action of OSCs ensure increased interest in these types of compounds for use as modifiers to improve the performance properties of building materials and products based on wood, which is confirmed by the analysis of publications on research results from leading scientific schools working in this direction.

For instance, the work (Lisyatnikov et al., 2021) examined the interaction of one-component polyurethane and an organosilicon compound from the alkoxysilane group – tetrapropoxysilane. The composition is intended for obtaining a hydrophobic coating with improved performance properties to protect building structures made of LCBM from the effects of technogenic and natural factors. The interaction mechanisms of one-component polyurethane with tetrapropoxysilane were studied using spectroscopy.

The product of the interaction between the polymer and tetrapropoxysilane is a three-dimensionally crosslinked polymer in which polyurethane macromolecules are crosslinked by organosilicon molecules. The chemical reaction is based on the interaction mechanism of isocyanate groups with reactive groups of alkoxysilane. The effect of the modifier on the surface structure of the cured coating was studied using a microscope. The contact angle of the modified and unmodified composition was determined, as well as the concentration of tetrapropoxysilane at which the coating acquires hydrophobic properties. The effect of tetrapropoxysilane on the adhesive characteristics of the polymer composition, as well as the change in hardness of the composition at various alkoxysilane concentrations were studied. Chemical modification of polyurethane allows its properties to be varied in the desired direction without deteriorating its other characteristics (Lisyatnikov et al., 2021).

The work (Sèbe and Jéso, 2000) investigated the dimensional stabilization of maritime pine sapwood through chemical modification with hydrophobic organosilicon compounds. Modification was carried out by esterification, using various chemically synthesized models containing trimethylsilyl groups: 3-trimethylsilylpropanoic anhydride (I), 2-trimethylsilylmethylglutaric anhydride (II), and trimethylsilylethenone (III). Grafting was confirmed by infrared spectroscopy and ^{13}C and ^{29}Si CP MAS NMR analysis; corresponding elements were detected in the wood cell walls. Dimensional stabilization induced by groups I and II proved stable over three cycles of oven drying followed by water soaking and surpassed stabilization induced by acetylation. However, the graft from group III was found to gradually hydrolyze to an acetyl group via a metallotropic rearrangement. Further investigation of the hygroscopicity and swelling of wood modified with groups I and II showed that dimensional stabilization is due to a bulking effect, not a change in substrate hygroscopicity. Specifically, the bulky grafts of groups I and II are believed to swell locally in the wood cell wall, revealing regions with new hydroxyl groups accessible to water (Sèbe and Jéso, 2000).

The work (Mai and Militz, 2004) described a wide variety of organosilicon compounds for application to wood. Some compounds, such as organo-functional silanes, mainly applied in combination with tetraalkoxysilanes (sol-gel process), as well as chlorosilanes and trimethylsilyl derivatives, have been proposed for full impregnation treatments of wood. Additionally, other systems such as plasma coating with hexamethyldisiloxane and



Modifier	Compounds / systems	Mechanism of action	Main effects
OSC	Alkylalkoxysilanes	Polymerization in cell walls	• Hydrophobization • Improved dimensional stability of samples • Enhanced weather resistance • Moderate thermal stability • Reduced water absorption
	Siloxanes	Formation of hydrophobic siloxane networks (Si-O-Si)	
	Silazanes	Polymerization in cell walls	
OPC	Phosphorus acid esters (alkyl phosphates / phosphites / phosphonates)	• Chemical bonding with OH groups of the lignin-carbohydrate complex • Formation of phosphoric acid upon heating → wood dehydration + carbonaceous layer • Dilution of flammable gases	• High fire protection (reduced flame spread, smoke generation) • Biocidal properties (fungicidal, insecticidal) • Smoke suppression
	Halogenated phosphorus acid esters		
	Phosphazenes		
	Amidophosphates		
OBC	Boric acid esters (borates)	• Covalent bonding with OH groups of wood • Inhibition of fungi / insects metabolism • Condensed-phase mechanisms (intumescence + thermal barrier)	• Comprehensive bioprotection (fungicidal, insecticidal) • Smoldering inhibition • Synergism with fire retardants • Fire protection (reduced heat release, smoke generation)
	Polyborates		
	Borazanes		
OMC	Organotin compounds	• Blocking of microbial enzymes (biocides) • Fixation in wood via organic ligands • Densification of the surface layer	• Powerful bioprotection (tin, copper) • Improvement of physical and mechanical properties • Fire protection (zinc as a synergist)
	Organocopper compoumds		
	Organozinc compounds		
PCS	Oligomers with P/N/B/Si (e.g., boron-silicon-containing fire retardants)	Combined action of elements in one molecule/coating	• Comprehensive protection (fire, bio, moisture resistance) • Strengthening of the structure • Flammability reduction • Hydrophobization
	Multilayer treatments (phosphates + PU varnish with bentonite)		

Classification of organoelement modifiers for lignocellulosic building materials microemulsions containing mainly silane and siloxane mixtures have been developed for wood surface treatment. The effects associated with the different types of treatment range from increased dimensional stability, durability, and fire resistance to enhanced wood hydrophobization. In cases of decay and fire resistance, combining silicon-based systems with other chemicals is required to obtain satisfactory results. Due to the excellent water-repellent properties and weather resistance of some treatment types, it is recommended to apply silicon-modified wood in hazard class III conditions (EN 335, above ground exposure) (Mai and Militz, 2004).

In the work (Proshina et al., 2013), comparative studies were conducted on the impregnation process of wood with solutions of organosilicon compounds, using gamma-aminopropyltriethoxysilane and hexamethylsilane (solutions in hexane and white spirit), as well as urea-formaldehyde copolymer and machine oil, followed by drying. It was shown that impregnating wood with gamma-aminopropyltriethoxysilane improves the characteristics of products made from natural wood (Proshina et al., 2013).

The work (Azarov et al., 2012) investigated the effect of nanodispersions of organoelement compounds on the strength properties of mycologically degraded wood. As chemical modifiers, the authors proposed using organoelement compounds, primarily organosilicon nanodispersions in aqueous media, namely polyorganosiloxanes. The main physical and mechanical properties of these polymers are associated with the high flexibility of their macromolecules and relatively low intermolecular interaction. Preliminary studies show that upon interaction of samples with polyorganosiloxanes, an increase in physical and mechanical properties is observed. Moreover, compressive strength increases by 16 %, and static bending strength increases by 18 %. During the interaction of polyorganosiloxane and cellulose, a process of interaction between the hydroxyl groups of cellulose and the hydroxyls of the organosilicon composition, possessing the greatest activity, is observed (Azarov et al., 2012).

When treating wood with hexamethyldisilazane, only trace amounts of silicon were found in the substrate composition (Pokrovskaya, 2009). This indicates the low reactivity of silazanes towards components of the lignin-carbohydrate complex of wood cell walls, leading the author to the necessity of preliminary phosphorylation of the substrate to increase the degree of silylation. Organophosphorus compounds were used for this purpose (Pokrovskaya, 2009).

Organophosphorus compounds (OPCs) are capable of forming multifunctional protection systems through chemical modification of wood. They provide a complex effect: fire protection, hydrophobization, strengthening, and bioprotection, making them indispensable in construction and restoration. The protective mechanism of these types of organoelement compounds manifests upon heating and is associated with the formation of phosphoric acid, dehydration of wood, and formation of a carbon layer. This is accompanied by dilution of combustible gases with non-combustible ones. Due to the presence of functional groups in their composition, OPCs can chemically bond with OH groups of the components of the lignin-carbohydrate complex (LCC) of LCBM cell walls. Consequently, OPCs provide a high level of fire protection (leading to reduced flame spread rate and decreased smoke generation). Furthermore, OPCs typically possess bioprotective properties (exhibiting fungicidal and insecticidal effects). Examples of such compounds include alkyl phosphates / phosphonates (dimethyl methylphosphonate – DMMP), which are effective fire retardants; halogenated phosphates (e.g., tris(chloropropyl)phosphate – TCPP), which have increased effectiveness due to P and Cl synergy but are environmentally unsafe; phosphazenes, which are non-halogenated, thermally stable fire retardants; amidophosphates/phosphoramidates, which can chemically bond with wood (Lowden and Hull, 2013).

The work (Portnov and Mikhaleva, 2020) analyzed the influence of phosphorus-containing organic materials on the fire hazard of wood. A correlation was identified between thermodynamic criteria (Gibbs free energy) and the physicochemical properties of modified wood (Portnov and Mikhaleva, 2020).

The study (Pokrovskaya and Portnov, 2017) examined the process of modifying wood with phosphorous acid esters to reduce fire hazard properties. Thermodynamic parameters of the modified wood surface were determined. High values of free surface energy were substantiated when studying the surface structure and surface layer of modified wood. The relationship between the energy characteristics of the modified wood surface, the effectiveness of surface layer modifiers, the surface layer structure, and the fire hazard characteristics of wood was shown. Based on the obtained data, the possibility of optimizing modifiers when creating protective compositions according to thermodynamic criteria was demonstrated (Pokrovskaya and Portnov, 2017).

The work (Pokrovskaya and Portnov, 2015) presented results examining the influence of surface treatment of wood with compositions based on alkyl esters of phosphorous acids on fire hazard characteristics such as fire-retardant efficiency group, flammability and ignitability index, flame spread index, and smoke-producing ability. Additionally, the bioprotective effectiveness of the modifiers used was studied. It was concluded that the most effective protective compositions for wood are esters of phosphorous acid, particularly diethyl phosphite, which is an effective smoke suppressant. Based on the obtained data, a fire-bioprotective composition for wood was developed (Pokrovskaya and Portnov, 2015).

The study (Afanasyev and Korotkov, 2012) examined the effectiveness of impregnating amidophosphates for fire protection of wood materials. Using the highly informative method of NMR spectroscopy, the processes occurring during the synthesis of the base product OSA-1 were studied. A mechanism for the fire-retardant action of this composition was proposed. The warranty period for fire protection of wood under atmospheric exposure conditions was calculated (Afanasyev and Korotkov, 2012).

The article (Pokrovskaya, 2018) describes the strengthening of partially destroyed wood samples from an Anglican church through surface modification. The first layer of the multilayer coating is nitrilotrimethylphosphonic acid, which forms covalent bonds with the substrate, partially strengthening the wood. The second layer is an epoxy resin solution, forming covalent bonds with the first layer coating, with the hydroxyl groups of the first layer participating in the curing of the second layer. A two-layer coating is formed, whereby the strength of the wood increases by 2–2.5 times, water absorption decreases by 3 times, and mass loss during combustion does not exceed 9 % according to GOST 27484-87 (Pokrovskaya, 2018).

Organoboron compounds (OBCs). This type of compound exhibits complex protective action: biocidal – disrupting the metabolism of fungi / insects; inhibiting smoldering and showing synergy with other fire retardants. They are often introduced as boric acids / esters. Examples include boric acid esters with glycols / glycerol, which improve boron fixation and leachability; N-alkyl borates (bis(N-cyclohexyldiazeniumdioxyborane) – "Kholil") are used as antiseptics and fire retardants; borazanes (boron-nitrogen rings) antisepticize and act as fire retardants for LCBM (Kartal et al., 2004; Leonovich and Politov, 2021).

In the study (Namyslo and Kaufmann, 2009), a new type of chemical wood modification for its permanent functionalization with organoboron compounds was developed and applied. This is achieved by covalent attachment of metalloid substituents to wood hydroxyl groups via benzotriazolyl-activated benzoic acid. Thus, standard modification procedures in wood chemistry, such as acetylation, are improved by avoiding the loss of half the reagent in the case of acid anhydrides or the release of corrosive hydrochloric acid in the case of carboxylic acid chlorides. In this case, the boron atom could contribute to solving a long-standing problem in the field of wood protection: the chemical fixation of an organoboron compound through a well-defined covalent bond. Accordingly, this avoids the insufficient long-term availability of traditionally common boron compounds as wood preservatives caused by leaching. The study was also extended to arylsilyl compounds as a second type of organometallic substance that could potentially be used for subsequent chemical reactions via ipso-substitution. The presented wood modification reactions yielded weight percentage gains ranging from 14 to 31 % on beech wood, spruce wood, and pine sapwood sawdust (approx. 500 μm in diameter) or pine sapwood veneer chips (Namyslo and Kaufmann, 2009).

To reduce flammability, oriented strand boards (OSB) were coated with a polyelectrolyte complex (PEC) consisting of sodium polyborate (SPB) and polyethyleneimine (PEI) using a simple two-step process (Rodriguez-Melendez et al., 2024). This PEC treatment imparts self-extinguishing behavior to OSB during combustion and reduces total heat release by 21 % and total smoke release by 79 %, increasing time to ignition by 18 % compared to untreated OSB. Furthermore, the PEI / SPB coating adds virtually no weight (5.8 wt.%) to the OSB, preserving visual aesthetics and mechanical properties. The main fire-retardant effect is achieved through condensed phase action via a combination of intumescence and thermal barrier mechanisms (Rodriguez-Melendez et al., 2024).

Modifiers based on organometallic compounds (OMCs), which include: organotin, organocopper, organozinc compounds. Organotin compounds (e.g., tributyltin oxide (TBTO)) are potent biocides but are highly toxic, so their use is restricted by the international convention – ROTEX. Organocopper compounds – components of modern preservatives like ACQ (Alkaline Copper Quaternary) and Cu-HDO (Bis-(N-cyclohexyldiazeniumdioxy)-copper) – provide fungicidal action; the organic substituent (often quaternary ammonium or a nitrogen complex) improves copper fixation in wood and provides additional biocidal effect (Freeman and McIntyre, 2008). Organozinc compounds are sometimes used as co-biocides or in combinations for fire protection (synergists).

Within the framework of the study (Belyaev et al., 2021), a multifunctional protective composition for wood based on arabinogalactan and mechanically activated polymineral sand was developed, capable of enhancing its physical and mechanical properties. Surface modification of wood with organomineral compositions leads to an increase in its density, hardness, and strength. The hardness of treated wood is 24 % higher, and compressive strength along the grain is 20 % higher than that of untreated wood. After treatment, the wood surface darkened and slightly yellowed, which does not preclude its use in building construction and renovation. Results of measuring color coordinates of the surface of modified samples indicate the stability and durability of the developed protective coating even after 4 months of exposure to atmospheric conditions. Based on the slight return of color coordinates of treated wood to the values of original wood, it can be concluded that there is partial leaching of the composition (Belyaev et al., 2021).

Multicomponent monomers/oligomers are compounds containing simultaneously phosphorus (fire protection) and / or nitrogen (fire retardant synergist, biocide) and / or silicon (water repellent, thermal stabilizer) and / or boron (biocide and fire retardant) in one molecule, ensuring their polyfunctional action.

In the study (Kurbanova and Ismailov, 2015), a boron- and silicon-containing oligomeric fire retardant based on sodium metasilicate with sodium tetraborate was developed, having an initial oxidation temperature above 350 °C. It can be used as a fire retardant in the production of paints, varnishes, and enamels to improve the appearance and protect objects (including those based on LCBM) from corrosion and high-temperature exposure. The maximum yield of the oligomeric fire retardant in the temperature range of 70-80 °C, the recommended application concentration in production of 6–7 %, and the simplicity of the production technology ensure economic efficiency. Boron- and organosilicon resins, due to their excellent qualities, find diverse applications (Kurbanova and Ismailov, 2015).

To develop a comprehensive approach to ensuring the durability of wooden structures, the work (Mikhaleva et al., 2021) proposed a multilayer treatment with compositions of dimethyl phosphite and polyurethane (PU) varnish with nanosized bentonite particles. The basis is phosphorylation, i.e., surface application of the most effective phosphorus-containing fire retardants to wood samples, which, in combination with bentonite-modified PU varnish, provides polyfunctional protective properties. As a result of this multilayer treatment, the material becomes classified as low-flammability (mass loss less than 20 %), while acquiring high moisture and biostability. Achieving fire, bio, and moisture resistance and increasing the strength of partially destroyed wood provides polyfunctional protection, making it possible today to preserve and extend the service life of many wooden structures, including monuments of wooden architecture (Mikhaleva et al., 2021).

As a result of research conducted at the Moscow State University of Civil Engineering (National Research University) under the guidance of Professor E.N. Pokrovskaya (Pokrovskaya and Koteneva, 2003; Pokrovskaya et al., 2004; Sidorov and Koteneva, 2008), it was established that organophosphorus compounds, being effective fire retardants and biocides, can surface-modify wood under “mild” conditions. This suggested the possibility of creating an impregnating composition based on phosphorus- and organosilicon compounds, considering the occurrence of chemical interaction between them and the wood surface layer, which would possess a long-term complex protective effect. Based on the analysis of the ability of various classes of phosphorus- and organosilicon compounds individually to undergo chemical interaction with the wood surface layer, components were selected for the development of a multicomponent fire-bio-moisture protective composition (Pokrovskaya and Koteneva, 2003; Pokrovskaya et al., 2004; Sidorov and Koteneva, 2008).

The works (Koteneva et al., 2010; Koteneva, 2011; Stepina et al., 2014) demonstrated the high effectiveness of boron-nitrogen compounds as antiseptics and fire retardants for LCBM, due to the synergistic effect of boron and nitrogen atoms in their composition. Moreover, the chemical bonds formed between the molecules of boron-nitrogen modifiers and the components of the lignin-carbohydrate complex of plant raw material cell walls are resistant to hydrolysis due to the boron-amine coordination within the modifier, which excludes nucleophilic attack by water molecules. This ensures long-term protection of LCBM against biocorrosion and ignition.

Systematizing the presented material, the main mechanisms of action of OEMs and the resulting effects and properties of the LCBM surface can be identified (Fig.). OSCs act through the formation of hydrophobic siloxane networks (Si-O-Si) and covalent bonding with OH groups of cellulose / lignin / hemicelluloses, polymerization in cell walls, and formation of water-repellent films. This ensures hydrophobization of the substrate (main effect), increased dimensional stability, improved weather resistance, moderate thermal stability, and reduced water absorption. OPCs participate in forming chemical bonds with OH groups of wood components. Upon heating, they form phosphoric acid, causing wood dehydration and formation of a carbon layer, while diluting combustible gases, thereby providing high fire protection for LCBM (reduced flame spread, smoke generation), biocidal properties (fungicidal, insecticidal), and smoke suppression. Boron-nitrogen compounds (BNCs), through covalent bonding with OH groups of wood components, become firmly fixed in the substrate composition, inhibiting the metabolism of fungi / insects and providing condensed-phase mechanisms (intumescence + thermal barrier) for fire protection. OMCs are fixed in wood via organic ligands, blocking microbial enzymes, densifying the surface layer, and providing fire protection for the substrate. Multicomponent systems combine the action of elements (P and / or N and / or Si and / or B) in one molecule / coating, providing comprehensive protection for LCBM (fire, bio, moisture resistance).

Conclusions

Chemical modification of lignocellulosic materials with organoelement systems is a strategic direction for creating next-generation building materials that align with the ideology of “green building”. Modern research confirms that:

– OSCs are indispensable for hydrophobization and geometric stabilization, but their potential is fully realized in hybrid systems;

– OPCs and BNCs address the issues of fire protection and biodegradation, with boron-containing complexes showing high potential in preventing their leaching from wood products;

– polyfunctional compositions (P-Si-B-N) are a key trend, providing comprehensive protection with minimal impact on the mechanical properties of wood.

Thus, the modification of lignocellulosic materials with organoelement compounds creates prerequisites for positioning wood as a competitive, environmentally friendly, and durable building material consistent with the principles of sustainable development.

Funding

The work was carried out at the Moscow State University of Civil Engineering (National Research University) within the framework of the University Development Program “PRIORITY 2030”. Project 3.1 “Scientific Breakthrough in the Construction Industry — New Technologies, New Materials, New Methods.”

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СОВРЕМЕННЫЕ ТЕНДЕНЦИИ В ХИМИЧЕСКОМ МОДИФИЦИРОВАНИИ «ЗЕЛЕНЫХ» СТРОИТЕЛЬНЫХ МАТЕРИАЛОВ

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Аннотация
Цель исследования: проведение комплексного теоретического анализа современных методов модифицирования лигноцеллюлозных строительных материалов (ЛЦСМ), включая древесину, недревесное растительное сырье и композиты на их основе. Основное внимание уделено преодолению природных ограничений использования ЛЦСМ, таких как гигроскопичность, биоразлагаемость и низкая огнестойкость, посредством химического модифицирования элементорганическими соединениями (ЭОС). **Методы**: анализ и обобщение традиционных методов модифицирования; детальный системный анализ механизмов действия элементорганических модификаторов; сравнительная оценка эффективности различных методов и соединений. **Результаты:** рассмотрены традиционные методы (импрегнация консервантами, антипиренами, гидрофобизаторами), полимерная пропитка и термическая обработка, а также инновационные подходы с использованием нанотехнологий. Детально проанализированы механизмы действия ЭОС, классифицированных по ключевому элементу: кремнийорганические (КОС), фосфорорганические (ФОС), борорганические (БОС) соединения, металлоорганические системы (МОС) и поликомпонентные композиции. Показано, что КОС обеспечивают преимущественно гидрофобизацию и стабилизацию геометрии, ФОС и БОС — решают задачи огнезащиты и биостойкости, а полифункциональные системы (P-Si-B-N) сочетают комплексную защиту с минимальным влиянием на механические свойства. Особый акцент сделан на экологических преимуществах и долговечности модифицированных материалов, соответствующих принципам «зеленого строительства». В обзоре представлены последние достижения в рассматриваемой предметной области, подчеркивая перспективность ЭОС для создания конкурентоспособных, экологичных и безопасных строительных материалов нового поколения.

Ключевые слова: лигноцеллюлозные строительные материалы; модифицирование древесины; элементорганические соединения; кремнийорганические соединения; фосфорорганические соединения; борорганические соединения; огнезащита; гидрофобизация; биостойкость; термическое модифицирование.