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Up-to-Date Solution of the Resource Saving Problem - Use of Forestry Sector Waste in Composite Materials

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Abstract

Solving the problem of creating effective composite materials for special structures and products on the basis of widespread plant raw materials, as well as man-made origin raw materials, is an important economic task, that provides the reduction of the construction cost, increase of reliability, environmental improvement. The most important in the solution of designated problem is ensuring joint operation of components of different nature, such as polymer resins, fibre-glass, wood and others. Modern technologies of composite materials require accounting processes and events proceeding at phase boundaries which promote a radical change in properties of phase interface surfaces and, accordingly, the structure and properties of the composite as a whole.

The reliability of results and conclusions of the work is specified by results of fundamental studies in the field of material science, in particular composite materials on the basis of thermosetting resins, as well as wood science, scientific statements of polymer-impregnated concrete technologies developed by scientists of the Russian Federation leading in this area.

Main numerical results and quantitative laws received probabilistic assessment on the basis of statistical processing of the experimental results: composite materials with the use of products of wood and man-made waste deep processing were created on the basis of theoretical generalizations and experimental studies; from the perspective of provisions of physical and colloid chemistry, physical chemistry of a surface and mechanics of composite materials, for the first time assessments were given of the properties of structure-forming components of wood fibre-glass composite material, which determine the operational characteristics and manufacturing technology of products; dependences of the main mechanical characteristics of the polymer-sand matrix of composites on the resin of the furfural-acetone monomer on the mass fraction and properties of main components, technology of their dosing and mixing were determined; the role of the synergistic effects of the component' interaction was assessed, their optimal amount so as to obtain the set properties of the final composite and economic feasibility was determined.

Conclusions and recommendations found application in the formulation development and separate technologies of manufacturing products which have passed bench and performance tests.

Keywords: *wood and industrial waste, composites, transport construction.*

Introduction

The world practice shows that the most commonly used material, in particular for transport construction products, is wood. So sleepers on its basis form up to 80% of their total number being at the same time the least endurable.

The main reasons for this are the mechanical wear and rotting of wood, especially at attachment points of rails to sleepers. To replace sleepers in Russia it is necessary to cut down annually up to 12 million m^3 of forests, which are «lungs» of the planet, trees at the age of 80…100 years are to be cut down.

The problem of the rational and full use of the saw milling and wood processing waste as secondary technological raw materials took on the paramount significance long ago and retains its relevance until now.

The aim of the study is development and solution of scientific and practical problems of creating the construction composite materials and products for special purpose industrial and transport facilities on the basis of wood deep processing products, man-made and local raw materials which meet requirements to their strength, stress-strain behaviour, crack resistance and durability under the effect of physical factors and providing specified characteristics in the special operational conditions.

The positive role of environmental and social aspects of setting up the production of products from wood fibre-glass composite material (CM) is that its use on a wide-scale basis will allow finding application for huge amounts of agricultural waste, forestry sector and the wood processing industry as a raw materials for the production of furfural, FAM resin and a reinforcing filler.

Chemical industry waste will also be used - pyrite drosses, which can be processed into a flour - the perfect filler, which improves strength and hydrophobic characteristics of polymer composites, as well as used machine oil and divinyl styrene thermoplastic elastomer - a by-product of rubber production, promising modifying agent - oxalic aldehyde solution.

In a context of the above, this work takes on the special significance in a context of expected global changes in the planet's atmosphere when as a result of warming and possible flooding forests will die and the amount of oxygen will decrease. Hence, the forest fund already today shall be preserved, using solid wood for construction products only where it can not be replaced by other materials.

The important factor which determines the development prospects of new design sleepers is extremely irregular development of railways on the territory of Russia. So, in the Russian Federation in seven subjects there are no railways at all, and in more nine subjects railway system is underdeveloped, resulting in the fact that the average density of the railway network is 5 km per 1,000 km^2 of area, while in Canada, having similar nature and climatic conditions, this figure is 6.7 km (by 35% more), in the United States - 27.7 km (5.5-fold more), and in countries of the Western Europe and Japan the excess is an order of magnitude and more times.

Interesting is the foreign experience of manufacturing new sleepers from used rails (Gedrite company), and in Japan - from the ground plant raw materials by compaction method with the use of polymer adhesives and binders. Similar techniques of manufacturing sleepers are offered in Russia too, for example, using the fractured wood pulp, resole resin and bakelite varnish or half-sleepers for underground from log pieces of birch [1]. However, the compression increases the cost of CM sleeper, causes destruction of wood cell walls, resulting in its increased water absorption with all attendant consequences.

Foreign experience shows, for example, the foam polyurethane reinforced with long glass fibres is applied by Voest-Alpine company (Australia) and by Sekisui Chemical company (Japan) for the manufacture of under-rail pads of the underground [1]. Use of this material as a binder in conditions of our country does not make sense, since Russia has the possibility to apply for the same purposes furfural acetone resin FAM, which is much cheaper than polyurethane.

Carried out analysis of properties of materials, used for special purpose products, in Russia and abroad revealed their shortcomings and proposed to use available in the Voronezh State Forest Engineering Academy (VSFEA) experience of obtaining CM on the basis of thermosetting resins (polyester unsaturated - PN-15, furfural acetone - FAM, etc.) [1].

Evidence of the increased interest to the problem of the railway network expansion is the adoption of the large-scale state program "Strategies of the railway transport development" of the Russian Federation until 2030 [2]. For the period till 2030 and, in the long term, after 2030 it is planned to expand the network of railways mainly in sparsely-populated areas with severe climatic conditions [2].

Taking into account this circumstance, it is possible to assume that for the development of railways in the north-east of the country it will be needed to use more durable low-maintenance sleepers, obtained on the basis of wood conversion products and polymeric binder.

Intensive replacement of wooden sleepers with reinforced concrete leads to the large, but as a rule, economic losses not taken into account in conditions of the so-called "market relations", which are formed from physical and technical and mechanical deficiencies of the reinforced concrete - heavy weight, electrical conductivity, brittleness, limited corrosion resistance and, most importantly, rigidity resulting in wear and tear of rails and tyres of rolling stock wheel pairs. Yet, in the absence of accounting these losses by line services of railways, a situation is formed when the initial cost of the reinforced concrete sleeper happens to be lower than the cost of the railway sleeper from new composite materials, for example, the wood-based fibre-glass composite material (WFGCM) and devoid of the above mentioned shortcomings [1 3]. Wood-based fibre-glass composite material for more than 70% consists of components which can be obtained on the basis of forestry sector waste and wood processing productions or are such - this is furfural acetone resin FAM (binder of the polymer matrix), as well as wood chips, slices of tree-length logs, etc. (reinforcing fillers).

It is conceived to be highly relevant to use wood waste in the direction of getting a very valuable product - furfural and its derivatives. Polycondensation of furfural with acetone makes it possible to obtain FAM resin, which is a binder in the production of chemically resistant structural and lining composite construction materials (CCM).

Fibre-glass composite material

The main objective of our researches was the creation of CCM, which have the high corrosion resistance under conditions of in a highly aggressive corrosive environment of electrolytic productions and, in addition, are capable to withstand the long-term operational loads. This material is called fibre-glass polymer concrete (FGPC) [3], or, in new terminology, - fibre-glass composite material (FGCM).

The necessary condition for the formation of a FGCM monolithic structure is sufficient wetting with resin (adhesive) of fibre-glass reinforcement (substrate) containing lubricating substance and introduced into the polymer concrete mixture in the process of moulding. At that take place: introduction of micro- and macro-fibres of glass into a resin; diffusion of large molecules of adhesive to substrate surfaces through substantially removed very thin layer of lubricating substance, liquefied as a consequence of high temperatures of polymerization exothermic reaction, and then - establishing enough strong hydrogen bonds completing the adsorption process. Hardening of the system, which is accompanied by cross-inking of oligomer molecules, is the last stage of creating strong adhesive bonds in fibre-glass - polymer matrix separation zone.

Thus, we simultaneously used to explain the mechanism of links formation in the separation zone three theories - the theory of surface wetting and theories of mechanical and molecular adhesion.

The lubricating substance acts the part of a plasticizing layer which contributes to increase of FGCM strength as a result of the local relieving shear stresses arising in the fibre-glass - polymeric matrix separation zone due to the high volume shrinkage of FAM resin, as well as in a view of difference of elastic moduli and thermal expansion factors of its components.

Medium of the polymer matrix provides a high long-term strength and rigidity of FGCM operated under conditions of liquid aggressive environments of chemical productions, increased temperatures (up to 100 °C) and the electric current. The viability of the proposed theoretical conditions of FGCM monolithic structure formation is confirmed experimentally [1, 3].

Fibre-glass composite material on FAM showed the high efficiency when used as a construction material of bodies of technological baths, tanks-settlers, chemical-resistant prefabricated monolithic floors subjected to the combined effect of a constant load, liquid and gaseous aggressive media, temperature and electric current [3].

This material can be applied for device housings of wood chemical productions, for example, pyroligneous acid collectors in the process of wood thermal decomposition, energy chemical installations for its processing, production of acetic acid by extraction method, equipment in the production of ethyl acetate, furfural, as well as in outer layers of wood fibre-glass composite material in order to increase its crack resistance [3].

Main compositions of FGCM and their rated mechanical characteristics are given in Table 1 and 2.

Table 1

Compositions of composite construction materials in % by weight

CCM components	Type of material			
	Fibre-glass composite material, reinforced			Wood fibre-glass composite material
	by fibre-glass filaments	by fibre-glass chaff	by fibre-glass mesh	
1	2	3	4	5
furfural acetone resin FAM	19.0	25.0	25.0	21.0
Quartz sand	71.0	53.0	51.3	41.0
Andesite powder	–	16.0	14.0	–
Quartz powder	–	–	–	12.0
Benzene sulphonic acid (BSA)	3.0	4.0	3.5	4.0
Fibre-glass filament	7.0	–	–	–
Fibre-glass chaff	–	2.0	–	–
Fibre-glass mesh	–	–	5.2	0.3
Retarder of BSA crystallization reaction (glycerine)	–	–	–	0.7
Lead chloride	–	–	–	3.0
Graphite or technical carbon black	–	–	–	3.0
Wood chips	–	–	–	15.0

Table 2

Main rated characteristics of composite construction materials

Characteristic	Type of material			
	FGCM reinforced			WFGCM
	by fibre-glass filaments	by fibre-glass chaff	by fibre-glass mesh	
1	2	3	4	5
Modulus of rupture, MPa at:				
tension	65.0	4.7	9.0	7.0
compression	64.0	82.0	78.0	20.0
pure bending	81.0	11.4	14.5	20.0
compression parallel to	–	–	–	60.0

grain chipping shear	7.0 –	8.6 –	9.0 –	7.0 12.0

End of the table 2

1	2	3	4	5
Instantaneous elastic moduli 10^4 MPa at:				
tension	1.36	0.82	1.31	1.25
compression	1.16	1.11	1.33	1.30
pure bending	1.63	1.90	1.61	1.30
Poisson's ratio	0.19	0.26	0.25	0.25
Ultimate extensibility, %	0.55	0.035	0.42	0.45
Ultimate compressibility, %	0.20	0.31	0.25	0.21
Volume weight, g/cm^3	1.60 - 1.80			1.0 - 1.4

Wood fibre-glass composite material

The new trend in the use of waste of timber and woodworking industries - creation on their basis of sleepers for railways, including logging, as well as the tram tracks.

At the present time in major road tracks lie is about 300 million pieces of wooden sleepers, manufactured from high-grade woods at the age of 80-100 years. Considering the fact that service life of sleepers in the track is 13-19 years, therefore it is 6-7-fold shorter than the period of renewal of the forest of such age. Main reasons for escaping wooden sleepers out of the track is their mechanical wear and rotting, and the primary reason is just wear due to which fail from 30 to 60% of placed sleepers. This explains the main causes of their acute shortage.

Referring to literary sources at the beginning of the work on WFGCM creation, we found no publications on any theoretical studies which explain the compatibility of furane resins and wood, although there were indirect evidences to that.

So, A.F. Nikolayev [4] notes that it is interesting to use FAM resin as a fireproof finishing for wood imparting it hydrophobic properties and protecting against rotting. V.M. Khrulev [5] writes that wood impregnation by resin reduces its water absorption by more than two-fold, increases the compression strength, static bending, shear parallel to the grain, resistance to abrasion and hardness.

When theoretical justification and experimental fact confirmation of compatibility of FAM oligomer and wood, the new construction corrosion resistant wood fibre-glass composite material (WFGCM) was created, as matrix of which serves FGCM [3] described above, and reinforcing filler is wood chips.

The potential chemical activity of WFGCM components, which were of interest to us, was revealed. So mono- and difurfuryl acetone included in FAM composition have a large number of reactive groups - hydroxyl OH and carbonal C = O. Free energy or energy potential of wood filler molecules is expressed by the status of radicals of sub-molecular structures of cellulose fibre macromolecules. The content of active functional groups in it is, % [6]; hydroxyl - 1.19; aldehyde CHO - 0.95; carbonal - 0.15; carboxyl COOH - 0.05.

The initial guarantor establishing emergence of the bond between the resin (adhesive) and the wood (substrate), is, as noted above, wetting.

Contact angles of wetting were determined for systems of smooth or rough wood surface - FAM resin (oligomer), hardened in the presence of benzene sulphonic acid (BSA). For the first case, the contact angle of wetting was equal to 8º, for the second - 5º, therefore, it is highly polar relative to the wood, and the roughness increases its hydrophilic properties [1].

Wetting is accompanied by the second act of FAM and wood interaction - physical adsorption performed by Van der Waals forces, the heat of which is insignificant (about 2.36 kcal/mole). In its turn the physical adsorption proceeds simultaneously with the dipole-dipole interaction, at that there arise hydrogen bonds with the heat of 6.8 kcal/mole.

Analysis of the structural schemes of molecules of interacting WFGCM components, constituting FAM resins - mono- and difurfuryleden acetones and pulp wood and lignin, showed the possibility of occurrence of hydrogen bonds by the scheme of dipole-dipole interaction and interaction of their hydroxyl groups with forming ester bonds that promote strong adhesive connection in the phase interface zone, confirmed experimentally. The process is completed by hardening the system, accompanied by compression of the wood reinforcing filler due to shrinkage forces [1, 7].

It is clear from the above that the process of formation of adhesive bonding is very complex, its phases are mutually entangled in time.

Since occurrence of strong adhesive bonds between FAM resin and wood FAM was established, further researches were directed at the development of specific WFGCM composition and obtaining its mechanical characteristics, which would meet the requirements to railway sleepers.

Composition and mechanical properties of WFGCM are shown in Tables 1, 2.

The role of each of components contained therein, as well as in FGCM is as follows:

- polymeric binder - furfural acetone resin FAM is the product of binding furfural and acetone at component mole ratio of 1.0: 1.5;

- anhydrous benzene sulfonic acid - BSA - catalyst of FAM resin hardening;

– glycerine – retarder of BSA crystallization reaction;

- inorganic fillers - river quartz sand and quartz powder - ground sand with a specific surface area of 2,500 ... 3,000 cm^2/g, determined in accordance with GOST. Their moisture content shall not exceed 1%, and acid resistance shall be not less than 97 ... 98%;

- technological carbon black of 2226 M, PM-50, P-323 grades or graphite flour of GE-3 or GE-4 (GE) grades are introduced to reduce internal stresses in the volume of a polymer matrix in the hardening process, increase of the water resistance and the frost resistance;

- lead chloride - introduced for binding BSA, at that the insoluble salt complexes are formed, which become the centre of FAM resin crystallization and suppress BSA toxicity;

- mesh with a cell size of 5 ... 15 mm on the basis of fibres from aluminium borosilicate composition glass is introduced to increase the crack resistance under the effect of alternating loads;

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- chips - reinforcing filler from small-sized wood or waste of timber sector with the element length of 150 ... 200 mm and conditional cross section area of (15x30) mm^2, dried to a moisture content of 7-8%. Chips reduce WFGCM weight and its rigidity.

Static tests of new form sleepers for the transverse bending in the under-rail and middle sections were carried out in accordance with GOST 10629-88. It was revealed that ultimate bending strength of WFGCM sleepers practically coincide with rated. Sleeper weight for general purpose railways is 150 kg, against 200..300 kg - reinforced concrete sleeper. Performance tests of sleepers conducted on Eletskaya track distance of SER showed their good quality. More than 100 million gross ton-kilometers of freight were transported by them in three years.

Recommendations for additional protection of the sleeper surface with hydrophobic solutions were issued based on low molecular weight polyethylene, divinyl styrene thermoplastic elastomer and wood rosin in kerosene, that 2-3-fold increases WFGCM crack resistance due to reducing swelling pressure of the wood reinforcing filler and proportionate to it relative strains. Besides, the wood filler, to impart to it hydrophobic properties, is impregnated with used machine oil containing combustion products [7].

One of the most economical variants to establish serial production of sleepers from the wood fibre-glass reinforced composite material is the use of the equipment and the vacancy areas of the existing sleeper-sawing shops and factories. Sleeper-sawing waste in the form of wood pieces, etc. can be used as reinforcing filler for sleepers. High-quality wood drying is not required. In the absence of sleeper timber, and this is obviously the short term outlook, since trees at the age of 80 ... 100 years is becoming less in accessible areas of timber logging, sleeper sawing shops could completely change to logging blank frames and casting directly sleepers, that would guarantee them against closing as unprofitable what has already happened with plants for furfural production, since it became unclaimed too.

The payback of capital investments in the production of WFGCM sleepers occurs four-fold faster compared to composite sleepers, used in Japan [1]. They are profitable to produce, taking into account the operational terms of all types of railways by owners and, in the first place, the timber sector - the main manufacturer of furfural, produced from waste wood, and reinforcing filler - wood chips from log pieces of 150 ... 200 mm in length, which are cut from the substandard wood [1 7].

Thus, to date the problem is solved which is connected with the creation of sleepers from composite materials, obtained on the basis of wood waste; designing their composition, study of durability, resistance to cyclic loads; developing calculation methods and the original moulding technology provided by the use of wood chips as a reinforcing filler and the chemical nature of the production; carrying out operational testing of new form sleepers recommended for wood logging and general purpose railways, underground, as well as tram tracks, development of technological specifications and receipt of safety and health certificate.

Conclusion

As the demand for corrosion-resistant construction materials in the Russian Federation and abroad is huge, the forest industry and wood chemical productions can become main suppliers of them. This will improve the environmental and social situation in regions wherein wood is logged and processed, since practically all the forest sector waste can be used, new jobs will be created that is extremely important at the present stage of development of Russia.

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