Structure and Properties of Wood-Polymer Composites (WPC)

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TABLE OF CONTENTS

CHAPTER ONE

INTRODUCTION

1.1. Short description of WPC

The classic composition of WPC is represented as a polymer (polyethylene, polypropylene or polyvinyl chloride), a filler, binder additives and dyes. First, all of these components are mixed in a mixer and then the granules are produced from this mixture. Some manufacturers pass the granulation stage. This makes it possible to save on electricity and the purchase of expensive equipment, but this leads to the poor mixing and connection of components with each other and, accordingly, a lower density of the composite. This further leads to problems in the operation of the products and facilities where they are used. There is an increased swelling, expansion and desaturation of products in a relatively short period of time.

What is a composite? We have talked a little about the polymer, but more details are required about the fillers. Classically, the ideal filler should meet the following requirements: to be as dense as possible, to contain the minimum quantity of moisture, and not promote the swelling, expansion and reduction of the durability of a product. In our experience, the ideal filler is wood flour from hardwood, having a particle size of no more than 400 microns and a moisture content of no more than 5%. Unfortunately, there are very few producers of flour with such properties, and this is a problem.

Unfortunately, many beginners are referred to as filler, only as a component that reduces the cost of the product.

They fill the mixture with everything and absolutely do not think about the consequences of using raw materials of low quality or unsuitable for WPC products. As a filler they use: rice husks, waste from the production of sunflower oil, milled waste from wooden construction debris (pallets), and waste from the manufacturers of MDF and particleboard. All these fillers can contain a large number of all kinds of impurities and can be very unstable regarding chemical properties and sometimes just harmful to health during processing. In the operation of structures, they lead to cracking, swelling, strong expansion and rapid destruction of the products.

But to have a high-quality polymer and filler is not enough. We need to bind them together, which requires high-quality chemical components and, most importantly, the knowledge and skills of technologists and equipment adjusters. With them we have a major problem and we should not think that this is so simple. What you need to buy or read somewhere on the forum is the right formula; hiring people without the relevant knowledge and skills is not a way out. You need to know not only what to mix and how to mix it, by looking at the finished formula, but also have colossal experience in the processing of polymers. Also, quite a lot of companies have appeared in the recent past, trading in WPC recipes, but without any experience in its processing, since it simply does not exist, due to the newly emerged industry. They, for example, believe that they can change calcite for wood meal and do nothing more. In fact, by attracting competent specialists in the field of polymer processing, it is absolutely possible to increase the resistance of composites to low temperatures or high humidity. It is possible to make the material less flammable, where required and to increase the strength of the product if larger loads are to be expected. Summarizing the above, it should be said that the manufacturers should not treat the WPC as a product in which you can use household and construction waste and you do not have to worry about attracting high-class specialists. It should be understood that this is quite a complex, but also reliable material with the correct approach to its production.

All these advantages just follow on from what was said above about the composition of the WPC and its correct mixing. The right selection of components should provide all these benefits. Components should have the following properties:

Moisture-resistant – the ratio of polymer and filler, exceeding the amount of filler contributes to the deterioration of moisture resistance.

Ecologically clean. The manufacturers of WPC on the basis of polyethylene talk about the lack of ecological compatibility of PVC, but do not give any justified arguments.

Now we will cite a number of press releases of independent organizations that investigated the safety of PVC materials: In May 1997, the Council of the Municipal Economy of Canada after a series of independent studies approved the use of PVC pipes for the installation of water pipes and sewerage in Canadian cities. This recommendation was made by the Council after 6 months of public disputes and research, which involved supporters and opponents of PVC. The recommendation even included a number of presentations by various organizations (including ECVM – the European Union of PVC Manufacturers and Converters), convincingly proving the profitability and even the necessity of using PVC pipelines in the city economy. In November 1997, the results of a joint independent study of the Ministry of Health and the Ministry of Food Industry of the Netherlands on the use of PVC as a packaging material were published. The report emphasizes that as a result of incineration of PVC packaging films in the dumps, dioxin release is minimal and below the MPC, determined by the relevant EU standards. The research was carried out according to the price, universality, durability and ecological purity criteria of all types of packaging materials (wood, paper, polymers, glass, ceramic, and metal).

In June 1998, the Swedish National Environmental Protection Agency (EPA) published the report on its research into PVC. The report states that the use of PVC materials is entirely acceptable, even if they contain "environmentally unfriendly additives (organic salts of lead, tin, etc.), since they do not migrate from the composition of PVC polymers." In addition, it was stressed that the instillation of PVC waste products and materials is "the destruction of valuable raw materials" and that the "direct burning of PVC materials does not generate dioxins more than burning traditional fuels (oil, coal, and gas)." This report can be considered particularly favorable for the PVC industry, since it was in Sweden that there was a hot debate about the safety of PVC. Simultaneously with the EPA report, a press release was published by the Swedish State Inspectorate of the Chemical Industry, which proved to be even more positive with respect to PVC than expected. It only critically assesses the role of phthalates in plasticized PVC, and points out that there are no objective reasons for banning lead or tin as stabilizers for rigid PVC. This is especially true for the use of PVC products in construction.

A powerful campaign against the use of PVC materials in the construction of the Olympic complex in Sydney for the Olympic Games in 2000 forced the Australian Independent Institute for Scientific and Industrial Research "GSIRO" to conduct independent research on this issue. As a result of their conduct, in September 1997, GSIRO published the official report, which concluded that PVC is "... environmentally friendly building material ... and the negative impact of PVC building materials is not greater than that of other building materials". Thus, all of the above convincingly proves the environmental safety of PVC building materials (PVC windows and doors, finishing PVC profiles (siding, claying, etc.), PVC cable ducts, PVC pipelines and much more). We believe that in modern conditions there should not be unreasonable accusations of one type of building materials in favor of others. Free competition of building materials in the market leads, in the final analysis, to the progress of the construction industry as a whole.

Let's consider some more properties of PVC materials.

Fire resistance;

Polyvinyl chloride is a self-extinguishing material, while polyethylene has a low flame resistance. You can make a composite with the G2 flammability class. At the same time, also important here are the amount of wood flour in the composition of the composite and the presence of special additives that increase the resistance to burning;

Resistance to pests; and

PVC material is not susceptible to pests – a huge advantage over wood, no need to process.

Other characteristics are:

Simple installation, perfect appearance – does not require constant processing.

1.2. Manufacture of WPC

Currently, the use of polymer composites filled with wood (WPCs) for the production of decking is becoming increasingly popular. WPCs are mainly used for outdoor use. In particular, such boards are used to produce the floors of terraced premises, siding, decorative fences, fence systems, steps, universal profiles, various accessories and parts. Figures 1.1, 1.2 and 1.3 show photographs of sites for which the WPC has been used. Among them are an outdoor gazebo, a fence in the territory of a shopping center and the interior of a restaurant, where siding is used. Thus, products made from WPC are used for the exterior and interior.

Fig. 1.1. Outdoor gazebo terrace

Fig. 1.2. Fence in the territory of the shopping center

Fig. 1.3. Siding in the interior of a restaurant

The most common materials for the production of decking are polyvinyl chloride (PVC), polypropylene (PP) and polyethylene (PE) (the last two belong to the class of polyolefins). Naturally, secondary polymers produced by recycling are used for the production of such boards. Wood flour or the wood fibers of various species of tree are used as the filler.

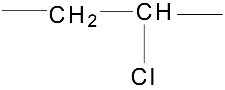
In the literature there is quite limited information on the production of WPC products and the dependences of their physical and chemical properties on the composition of the polymer matrix [1-6]. These studies examine a variety of wood-polymer composites and their properties, such as limiting mechanical properties and rheological properties. The cycle of works is devoted to the study of WPC based on PVC [7-11], which is the main matrix polymer in the production of products of this kind. PVC serves as a polymer matrix mainly in the form of primary material. This material is described in both the foreign and domestic literature. Methods of manufacturing WPC are set out in detail in the works [12-14]. WPC materials are widely used in construction [15-16]. Since such composites are used in conditions of moisture, temperature, and UV radiation, as well as under the influence of mechanical stress of different types, evaluation of product quality and a comparison of different types of terrace boards should be carried out taking into account all of these factors. Thus, in the study of mechanical properties important characteristics are the modulus of elasticity in tension and compression, impact toughness, resistance to cracking, bending and tensile strength, and hardness. In the analysis of thermal effects, the most important characteristics are relaxation transitions in the material during heating, associated with the glass transition of polymers, changes in the degree of crystallinity, the melting point of the crystal phase, the coefficient of thermal expansion and changes in the size of products with an increase in temperature in a certain direction (in the directions of length, width, and thickness) to a given value of the product.

Among the influences of weather conditions, the most important indicator is resistance to water and water absorption, as well as to UV irradiation for a certain time exposure. The strength properties of WPCs are described, for example, in [17-19] (Table 1). It can be seen that the lowest strength and modulus of elasticity are characteristic of polyethylene-based composites. As for polypropylene-based composites, these articles present a wide variation of experimental data, especially on strength properties. At the same time, the lowest strength properties are in the intervals below the properties of PVC-based composites.

1.3. The structure of WPC. Matrix polymers: polyvinyl chloride, polyethylene, polypropylene

Let's focus on the methods of producing polymers that are used for the manufacture of WPC.

Polyvinyl chloride (PVC). The chemical structure of PVC is as follows:



$$-CH_2-\underset{\displaystyle Cl}{\underset{|}{CH}}-$$

The main methods of synthesis of PVC are as follows:

1. The suspension method

A liquid monomer (vinyl chloride) under pressure is dispersed in water in the presence of gelatin or polyvinyl alcohol. The polymerization initiator is dissolved in a monomer. Peroxydicarbonates are used as the initiators, for example, ethylhexyl peroxydicarbonate. The size of PVC particles in this method of polymerization depends on the type of stabilizer used, its quantity and mixing intensity. As a result of polymerization, a polymer suspension is formed in water, which is separated from the aqueous phase by centrifugation or filtration. The particle sizes in suspension polymerization range from 50 to 200 microns and even higher.

2. Emulsion and micro-suspension methods

With emulsion polymerization, vinyl chloride is added to the water containing a small amount of emulsifier. Emulsifiers use various Soaps (for example, triethanolamine, sodium salts of organic acids, etc.), and also apply a water-soluble initiator (for example, hydrogen peroxide, alkali metal persulfate, etc.). In contrast to suspension PVC, emulsion PVC and micro-suspension are isolated, bypassing the stage of mechanical dewatering. Carrying out the drying of latex in the spray drying apparatus, in which droplets are suspended in the liquid phase the polymer particles are transformed into solid particles, which are a grain – dry agglomerates of latex globules. Particle size, shape, porosity and strength to a large extent determine the properties of PVC powders (flow-ability, their ability to be further processed into materials and products), as well as the technological and operational characteristics of the latter. Moreover, the process of form and structure formation and the final properties of the dry product depend both on the properties of the drying object itself (latex, dispersion), and on the conditions of the spraying and drying process. The particle sizes of emulsion and micro-suspension PVC are practically identical and are 1-5 microns. Another type of PVC is the so-called extender. The prevailing particle sizes are 20-50 microns.

Polyvinyl chloride is one of the main polymeric materials used in almost all fields of technology and everyday life. More than 50% of the total production of polyvinyl chloride is used in construction. Mainly window frames and doors are made of this material. A large amount of PVC is also used in the production of wallpapers and wall coverings, linoleum, floor tiles, etc. Architectural molding construction products made of PVC are of special importance. Their role is especially great in precast large-panel construction, the installation of improved types of windows and doors, when used as roll, tile and sheet materials for finishing walls and ceilings, flooring, stairs, stair railings, treads, skirtings, screens, blinds, and handrails. Polyvinyl chloride materials are used for finishing the joints of large-panel and large-block buildings, and in the production of built-in furniture. PVC is particularly widely used for the manufacture of water pipes and pipes for irrigation and for irrigation and drainage systems, including large diameter pipes and corrugated pipes.

For the production of building materials PVC is used in a plasticized and non-plasticized form. Plasticized PVC is used for the manufacture of roll and tile products for floors, decorative films, flexible hoses, and molded products; unplasticized polyvinyl chloride is used to produce pipes, profile moldings, hard roofing sheets, etc.

Micro-suspension powder polyvinyl chloride is used in the manufacture of plasticized and rigid polymer products: light- and heat-resistant cable plastic, medical plastic, film materials, artificial leather, linoleum, high-strength pipes, construction profiles, the manufacture of plastisols and plastigels, etc.

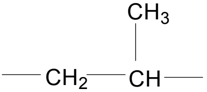
Currently, polyvinyl chloride is widely used for the manufacture of terrace boards, which are used for the construction of a large number of facilities.

Another polymer used for the manufacture of WPCs is polyethylene. The chemical structure of this polymer looks like this

$$—CH_2—CH_2—$$

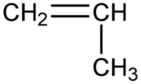
Polyethylene is produced in two types – high-pressure polyethylene (low density) and low-pressure polyethylene (high density). The first one (HDPE) contains a significant number of branches from the backbone, and the second (LDPE) practically does not contain such branches. Therefore, HDPE crystallizes worse; the degree of crystallinity is about 60%. LDPE crystallizes better and its degree of crystallinity can reach 90%, but usually it lies in the region of 70-80%. HDPE is produced by the polymerization of ethylene $CH_2{=}CH_2$ by a radical mechanism in a tubular reactor; the pressure in the first zone is 25 MPa, and the initial temperature is 70°C. Further, the ethylene mixture with the initiator is heated to 180°C and enters the second zone, where polymerization occurs at a high temperature (190-300°C) and pressure (130-250 MPa). As the initiator benzoyl peroxide is used, etc., LDPE is produced with the use of catalysts and activators at a temperature of 70-95°C and a pressure to 3.3 MPa.

Another polymer used for the manufacture of WPCs is polypropylene. The chemical structure of polypropylene looks like this:



$$—CH_2—\underset{}{\overset{\overset{\displaystyle CH_3}{|}}{CH}}—$$

It is prepared by the catalytic polymerization of propylene



$$CH_2{=}CH{-}CH_3$$

The catalysts of Ziegler-Natta $TiCl_4$, $AlCl_3$ are used. Depending on the methods of production and the catalytic system, three types of macromolecular structure are formed: atactic, isotactic, and syndiotactic polypropylene. These products are the stereoisomers, which differ in the location of the substituents – CH_3 in relation to the plane of the backbone. Depending on this, they possess different crystallinity and properties. Atactic polypropylene possesses low crystallinity and low density, which reaches 0.83 g/cm^3, as well as heat resistance. Isotactic polypropylene possesses a high degree of crystallinity, and a large modulus of elasticity, and density. The melting point of polypropylene is 170°C.

1.4. The application of WPC in building

Recently, in the technology of construction materials there has been a preference in the use of mixes of various materials, each of which possesses unique properties. One of the relatively innovative solutions in the modern market of building materials is the WPC – the wood-polymer composite.

When creating a composite material, it often combines completely different components, producing the final product with the best quality. This quality is due to the specific properties of each component of the composite material. As we mentioned above, in the case of WPCs a compound of wood and plastic is applied. As a result, useful and attractive performance properties of the final product are obtained. First, the WPC is characterized by high strength, easily bearing the load on the compression, characterized by elasticity and resistance to impact. All these properties are inherent to the WPC due to its wood component. Secondly, the plastic present in the material makes it possible not to be afraid of the tree's characteristic vulnerability to decay. WPC is resistant to moisture, not subject to corrosion. At the same time, the material is flexible and easy to process, allowing you to produce parts of constructions with high accuracy.

From the point of view of environmental friendliness, this composite material also has a great advantage as the wood components are used as practically worthless waste shavings and sawdust left over from wood processing. The polymer component is usually formed from recycled plastic, which is also the waste of production and operation. This primarily applies to polyethylene and polypropylene.

Generally speaking, wood-polymer composites have been manufactured and used relatively recently, and as we mentioned earlier, the dependence of its physical-chemical and mechanical properties on the composition of the polymer matrix and wood filler has not been fully studied. So, we should expect that in a short time, the production and diversity of building products from WPC will be expanded. However, already now there is a sufficient number of different building elements based on WPC. The first thing to mention is the decking, or terrace board. In fact, terrace board produced from WPC is now the only fully-fledged alternative to natural wood. Structurally, the decking boards constitute the outer frame in combination with the internal ribs filled with wood-polymer composite.

The elements have a groove-comb locking system, which facilitates the installation process. The colors and designs of the material are also very diverse, which make it very attractive to solve various interior problems. There are also bilateral varieties of material – with relief design and ribbed cutting.

Another interesting product of WPC is Planken, or facing panels. They represent a worthy replacement for siding on the basis of polyvinyl chloride; thus panels from WPC are a little heavier and thicker, and are more reliable in operation. Moreover, Planken has a higher performance in the field of heat insulation and noise absorption. The principle of installation of such panels is virtually identical to the principles of working with siding panels made of PVC.

Another type of WPC product is distinguished by excellent strength and service life – so-called forms of small architecture, such as railings, and fences. Traditionally, such elements of construction are made of wood, metal or concrete, but the advantages of WPC are obvious: the material does not require a heavy substructure and is easily mounted using conventional screws. The construction will be absolutely resistant to weather conditions, will not require additional staining and will retain an attractive appearance for a long time. Such a fence is not afraid of fungus and easily tolerates frost, rain and solar heating.

In choosing a WPC, you should consider the composition of the polymer used. For example, a PVC-based WPC is more durable and reliable than a WPC in which the matrix polymers are PE or PP. We will present proof of this assertion below. Also, cheap material with polyethylene contains a larger percentage of the wood component and is made without the addition of certain additives, through which small producers tend to save. As a result, the product may be exposed to sunlight. What happens in this case, the reader will be able to see a little further on.

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CHAPTER TWO

MECHANICAL PROPERTIES

2.1. Deformability, tensile, compressive, and bending strength

Tensile tests and bending were carried out on the instrument from LLOYD Instruments LR5K Plus (USA). The blades according to GOST 11262 were used.

Figure 2.1 shows the stress-strain curves of the HDPE-based samples.

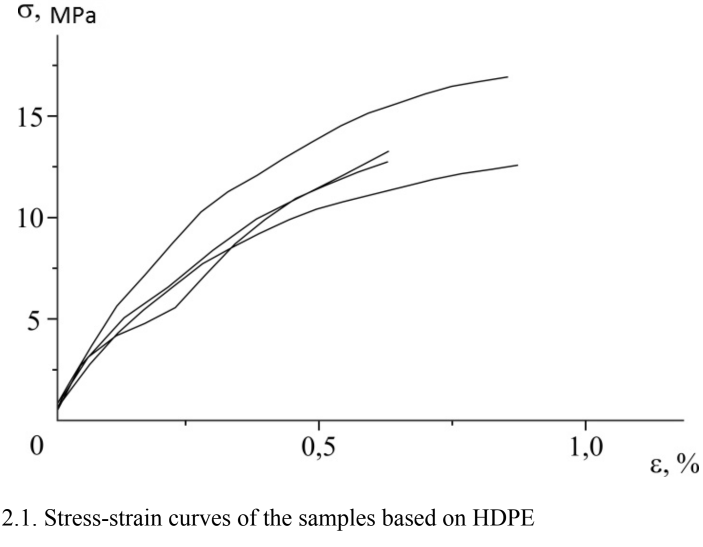

Fig. 2.1. Stress-strain curves of the samples based on HDPE

Figure 2.2 shows the stress-strain curves of the samples based on PVC.

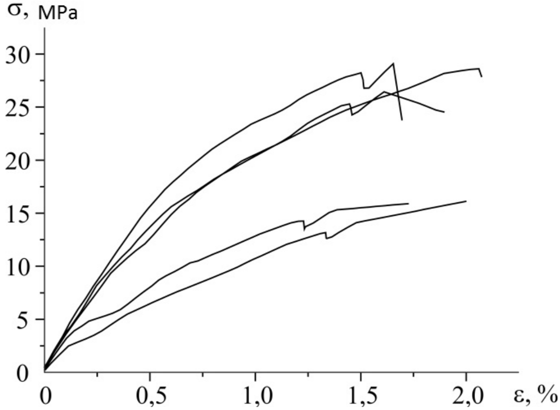

Fig. 2.2. Stress-strain curves of the samples based on PVC

The dependencies of stress from deformation are not linear throughout the stress-strain curve. This means that the modulus of elasticity of the samples decreases with increasing strain. This phenomenon is observed for many composite materials that detect nonlinear mechanical behavior with increasing strain. It consists in the fact that the structure of the material is broken; the cavities in the material have appeared, and the modulus of elasticity decreases with increasing deformation. For PVC-based materials, this change in the slope of the stress-strain curves occurs at several large deformations than for materials on the basis of the HDPE. Therefore, the comparison of the elasticity modules of these two materials is not quite correct.

The results of the calculations of strength, failure strain and elastic modulus are summarized in Table 2.1.

Table 2.1. The results of tensile tests

The samples based on HDPE			
№	Tensile strength, σ_p, MPa	Elongation at break, ε_p, %	The modulus of elasticity in tension, *E* MPa
1	13.4	0.62	4980
2	16.9	0.85	4730
3	13.1	0.66	4720
4	12.7	0.86	4230
Average value	14.0	0.75	4660

Table 2.1 shows that the samples based on PVC possess significantly greater strength than those based on HDPE. This is quite understandable, since the glass transition temperature (softening) of PVC is 70°C, and for HDPE it is estimated at -60°C. HDPE is a semi-crystalline polymer and the amorphous regions at room temperature are in the rubbery state, resulting in relatively small strength values.

Tensile strength measurements at 18^{o}C of the 1-6 series PVC-based samples were carried out on a universal testing machine LLOYD Instruments LR5K Plus. The stretching velocity was 50 mm/min. The stress-strain curve for sample 2 in the example is shown in Figure 2.3. The ultimate fracture strain is also shown in this figure.

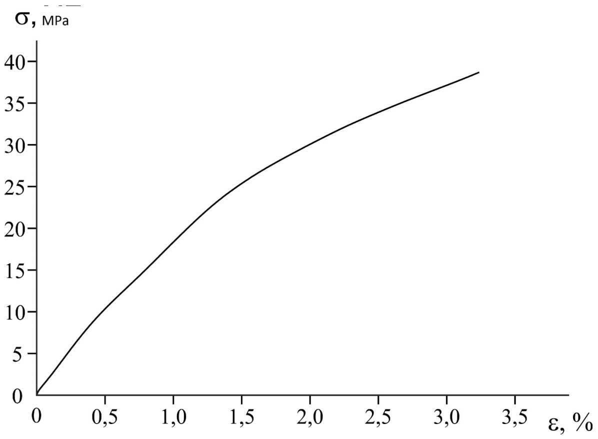

Fig. 2.3. The average stress-strain curve for specimen 2; σ_p = 38.5 MPa, ε_p = 2.88%

In addition to strength, the most important characteristic of the material is the ability to exercise significant deformations, i.e. the absence of brittleness. From Table 2.3, it can be clearly seen that materials based on PVC are destroyed at much greater deformations than HDPE-based materials. This is the main advantage of PVC-based materials.

Bending tests were carried out on the same LLOYD Instruments LR5K Plus (USA) instrument with the replacement of the loading device for the three-point bending. The results of the measurements are given in Table 2.2.

Table 2.2. Results of bending tests

№	Rigidity, N/m	Modulus of elasticity in bending, MPa	Bending strength, MPa
The samples based on HDPE			
1	35408	7082	33.6
2	31183	6237	31.1
3	18603	3721	24.8
4	30158	6032	30.1
5	32405	6481	32.4
6	29560	5912	30.3
Average value	**29536**	**5910**	**30.4**
The samples based on PVC			
1	18491	3698	44.1
2	19502	3900	49.6
3	22891	5631	54.3
4	30668	5054	48.2
5	24479	3955	39.8
6	23579	4715	46.3
Average value	**23268**	**4492**	**47.0**

The bending strength for samples based on PVC is higher than that based on HDPE. In addition to strength and elongation at break, experiments were carried out to measure impact toughness at positive and negative temperatures, and also to obtain stress-strain curves for a large number of PVC-based WPC samples, that are somewhat different in the formulation and target additives always present in these composites.

The bending strength is measured at 18°C. The measurements were carried out on the "Dinstat" instrument using the cantilever method. The dimensions of the samples are 10 × 15 × 3.5 mm. The bending strength σ_b is calculated by the formula

$$\sigma_b = m \cdot 6/bh^2, \qquad (2.1)$$

where m is the bending moment (kg·cm), b is the width of the sample (cm), and h is the thickness of the sample (cm). The results of the measurements are shown in Table 2.3. The spread of data is small. The greatest average of bending strength is observed for samples 1 and 3, the smallest one – for sample 4.

The values of strain deformation at break are given in Table 2.3. The tensile strength values are shown in Table 2.4.

Table 2.3. Bending strength

№	σ_b, MPa			Average value $\sigma_{b,av}$, MPa
1	64.7	72.0	70.1	68.9
2	54.9	57.6	62.4	58.3
3	72.0	67.2	67.2	68.8
4	63.7	54.0	54.7	57.5
5	57.8	67.2	67.2	64.1
6	62.7	67.2	67.2	65.7

The values of strain deformation at break are given in Table 2.5. The tensile strength values are shown in Table 2.4.

Table 2.4. The tensile strength values at 18°C

№	σ_p, MPa			Average value $\boldsymbol{\sigma_{av}}$, **MPa**	The modulus of elasticity in tension, *E*, MPa			Average value $\boldsymbol{E_{av}}$, **MPa**
1	18	27.0	29.0	**25.0**	950	2200	2300	**1820**
2	39.0	33.5	-	**38.5**	2300	1900	-	**2100**
3	27.0	27.0	40	**34.0**	1800	2300	2050	**2050**
4	22.2	23.9	34,6	**27.4**	2200	2400	1550	**2050**
5	32.5	41.1	23,4	**32.0**	2450	3400	2800	**2880**
6	20.3	40.7	25,7	**26.0**	2500	2600	2950	**2680**

Table 2.5. Strain deformation at break

№	ε_p, %			Average value $\varepsilon_{av,\%}$
1	2.2	2.9	2.9	**2.67**
2	2.55	3.2	-	**2.88**
3	1.55	2.22	2.67	**2.15**
4	1.92	2.54	3.04	**2.50**
5	3.0	2.9	1.8	**2.57**
6	1.6	3.1	1.5	**2.07**

Stress-strain curves for each sample were rebuilt in the middle of the curves, and the average values of bending strength $\sigma_{b,av}$ were determined Also, the modulus of elasticity by the tangent of the slope angle of the initial section of the stress-strain curve is determined by the mean curves.

Table 2.4 shows that sample No. 2 possesses the highest tensile strength and sample No. 1 possesses the lowest tensile strength. There is a significant variation in bending strength values in parallel measurements, which sometimes reaches 50% (e.g. for samples 5 and 6). This indicates that the samples are not quite uniform. As for the modulus of elasticity, its average values are in the range from 1125 to 3000 MPa. The tensile strain at break is shown in Table 2.5. This value is in the range from 1.6 to 3.2%. All the above results are obtained in [1].

The data obtained in [2] show that the tensile strength of WPC based on HDPE is 11.9 MPa. When replacing the HDPE on copolymers of ethylene with vinyl acetate (EVA) tensile strength is considerably reduced and is in the range from 8.4 to 5.5 MPa; the mentioned value is typical for a material containing 25% of EVA.

The strength of WPC based on polyethylene is also included in the conclusion of the testing of core products, represented by the research center "Wood-polymer composites" (OOO nits "DPK") of 05.03.2015, by one of the Russian manufacturers of WPC based on PE. According to this conclusion, bending strength is in the interval from 45.8 to 52.0 MPa, and tensile strength is in the range from 21.0 to 26.1 MPa. For comparison, we give the intervals of these values for the WPC based on PVC: the interval of bending strength is from 57.5 to 68.9 MPa, and the tensile – from 25.0 to 38.5 MPa.

Thus, a detailed analysis of the mechanical properties of wood-polymer composites shows that the WPC properties based on the PVC matrix polymer significantly exceed the WPC properties based on matrix polymers such as polyethylene and polypropylene. Particularly valuable is the fact that the PVC-based WPC has approximately the same impact resistance at 21°C as the positive temperature of 18°C. Under static loading, the bending and tensile strength of PVC-based materials is on average 25-32% and 19-64% higher than polyolefin-based materials – polyethylene and polypropylene.

2.2. Impact strength

First, let us consider the results of measurements of the impact strength at 18°C (Table 2.6*a*). Specimen No. 2 possesses the highest specific impact strength A (the value of A is 8.9 kJ/m^2); and Specimen No. 3, whose value is 4 kJ/m^2, possesses the lowest specific impact toughness. For Specimen No. 2, the Sharpie specific impact strength with a notch is 5.7 kJ/m^2; the attenuation coefficient is 5.7/8.9 = 0.64. In general, the specific impact strength values show that the impact failure is not brittle and is at the level of a large number of polymer materials. It should be noted that the specific impact strength of WPC based on HDPE and copolymers of ethylene with vinyl acetate was studied in [2]. The values A_i of the specific impact strength obtained in [1] are higher than in [2]. Thus, the value A = 4.8 kJ/m^2 without a notch for HDC based on HDPE, and based on copolymers of ethylene with vinyl acetate is in the interval from 5.2 to 6.3 kJ/m^2. For WPC based on PVC, the A values range from 4.3 to 8.9 kJ/m^2, i.e. resistance to the impact loading of WPC based on PVC is significantly higher than on the basis of HDPE.

Table 2.6*a*. Specific impact strength at 18°C

№	A, kJ/m^2		Average value A_{av}, kJ/m^2
1	6.9	5.1	6.0
2	8.9	5.7*	8.9
3	4.0	5.4	4.7
4	5.1	4.6	4.8
5	4.6	4.6	4.6
6	4.3	6.3	5.3

* Sharpie specific impact strength with a notch.

Consider the results of measurements of the specific impact strength at negative temperatures. The measurements were carried out at 0°C and -20°C, and their results are shown in Table 2.6*b*.

Table 2.6*b*. Specific impact strength at negative temperatures

№	Specific impact strength, A, kJ/m^2			$A_{av,}$ kJ/m^2	T°C
1	4.6	6.9	7.7	6.4	0
2	4.3	4.0	-	4.2	-21
3	6.3	5.7	-	6.0	-21
4	4.0	4.6	4.6	4.4	0
5	4.0	5.4	-	4.7	-21
6	4.9	4.9	-	4.9	-21

The greatest specific impact toughness is possessed by sample No. 1 (the value of A = 6.4 kJ/m^2 at 0°C); the smallest impact strength is possessed by sample No. 2, the value of which is 4.2 kJ/m^2 at -21°C. In general, the specific impact strength at negative temperatures shows that impact damage is not brittle and is at the level of a large number of polymer materials. For sample No. 2, the specific impact strength at negative temperatures is twice as low as at normal temperatures. For the other samples, the specific impact strength is approximately the same at negative temperatures and at ordinary temperatures. It should be noted that the data on specific impact toughness at negative temperatures are important for the regions of Russia, where winter conditions take place within 8 months.

2.3. Cracking

Resistance to cracking was tested on a special device that allows for the free fall of the metal striker from a given height to the surface of the decking board. The device meets the following requirements:

- the radius of the spherical surface of the striker hitting the product is 25.0 ± 0.5 mm;
- the mass of the falling striker is 1000 ± 5 g;
- the drop height of the striker is 1000 ± 2 mm.

This test complies with European standard DIN EN 477 and Russian GOST 19111.

The tests were carried out on ten samples of each segment (private, commercial and premium) size (350 × 140) ± 2 mm and a thickness equal