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Physical-mechanical properties of composite material based on polyester fibres and mineral binder

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Abstract. Most metal railway bridges have reinforced concrete slabs as the substructure for the ballastless bridge deck. The slabs are laid on the longitudinal metal beams of the span structures with a rubber-wood interlayer in-between so that to level the base and evenly distribute the load. It is easy to lay, and its physical and mechanical characteristics ensure even load distribution and minimize stresses in the slabs. However, due to the biodegradation of wood, such an interlayer is of low durability. Ukrainian State University of Railway Transport has developed a rolled composite material made of bulk non-woven material made of anisometrically oriented polyester fibres and sand-cement mineral mixture for the interlayer, which is being laid by implementing a technological solution. As shown, it is advisable for the composite material to provide the deformation modulus E close to the integral deformation modulus of the rubber-wood interlayer, which is yet to be explored. The experimental studies of the strength f and the integral deformation modulus E of the rubber-wood interlayer were performed. It was found that for pine wood, f and E are 58 and 5.5 MPa, and for oak these values are144 and 7.9 MPa, respectively. The physical and mechanical properties of the composite interlayer were also investigated. The compressive deformation diagrams were obtained for the composite material with $\varepsilon = f(\sigma)$ and $\sigma = f(\varepsilon)$ at different types of cement (Portland cement and calcium-aluminate cement), the thickness of non-woven material 10 and 20 mm, S:C ratios from 0 to 2, the consumption of mineral mixture (M) per 1m^3 of non-woven material (NM) (M:NM) from 167 to 1,000 kg/m^3. It was found that the values f and E increase if the thickness of non-woven material and the S:C ratio decrease, while the consumption of the mineral mixture per 1 m^3 of non-woven material increases. The diagrams of dependency of f and E on the S:C ratio and M:NM were constructed. The regression equations were obtained and their solution was used to develop compositions of composite mineral that provide E = 144 MPa, for example, a composition based on Portland cement, non-woven material with a thickness of 10 mm, S:C = 0.11, and M:NM = 1,000 kg/m^3. Some compositions of the composite material for the interlayer are recommended.

1 Introduction

Most metal railway bridges have reinforced concrete slabs as the substructure for the ballastless bridge deck. The slabs are laid on the longitudinal metal beams of the span structures. A rubber-wood interlayer (mainly hardwood and reinforced rubber) is placed between them to level the base and evenly distribute the load. This interlayer is easy to lay, and its physical and mechanical characteristics ensure even load distribution and minimize stresses in the slabs. Unfortunately, due to alternating wetting and drying as well as biodegradation of wood, such an interlayer is of low durability and requires replacement much earlier than it is needed for reinforced concrete slabs due to their resource exhaustion. Ukrainian State University of Railway Transport (UkrSURT) has developed a rolled bulk nonwoven composite material (BNCM) made of anisometrically oriented polyester fibres and sand-cement mineral mixture for the interlayer, which is being laid by implementing a technological solution. However, the dependence of the physical and mechanical properties, in particular, deformational properties of the developed rolled composite material on its composition, as well as the deformational properties of the rubber-wood composition, has yet to be thoroughly studied.

2 Literature review and problem statement

The rolled composite material developed at UkrSURT is made of a BNWM of anisometrically oriented polyester fibres and mineral sand-cement mixture [1, 2]. If necessary, some additives, such as curing accelerators and corrosion inhibitors, can be added to the mixture. According to [3], the sequence of laying the interlayer made of this material is as follows. The composite material is produced in the form of BNWM rolls saturated with mineral mixture by means of pouring. Local supports are laid on the cleaned upper deck of the beams, the thickness of which corresponds to the design thickness of the interlayer. The rolls are immersed in water, after which they are rolled out in several layers on the top deck of the beams with a total thickness greater than the design thickness of the interlayer. Slabs are laid on local supports, which compact the material with their weight, meanwhile the material acquires the necessary physical and mechanical properties as the cement hardens.

As shown in [4], a ballastless bridge deck on long spans is prone to track disturbances due to long-term deflection deformations of the span structures. These deformations are compensated for by the thickness of the interlayer. However, the authors did not substantiate the required physical and mechanical properties of the interlayer.

As shown in [1], the physical and mechanical properties of the interlayer affect the stress-strain state of slabs up to the formation of cracks in them. The compressive strength f of the interlayer, taking into account the slab laying technology, should be at least 1 MPa after one day, and 5 MPa after two days. The recommended deformation modulus E of the interlayer is not less than 10,000 MPa, but the diagrams in [1] show that the stresses E in the slabs are insignificantly affected, and the stresses in the interlayer itself with a decrease in E from 35,000 to 2,000 MPa even decrease 1.5 – 1.8 times. Therefore, it is advisable to provide E for the composite material close to the integral deformation modulus of the rubber-wood composition, which also has not been sufficiently studied.

In [5, 6], the effect of fibre on the physical and mechanical properties of the composite material based on cements of different compositions is studied. However, in [5] the effect of a much lower fibre content than in [1, 2] is investigated. In [6] the interaction between cement hydration products and the fibre surface is investigated together with the effect of the composition of cement and additives, rather than the amount of fibre, on the physical and mechanical properties.

The required physical and mechanical properties in the early stages of hardening (1-2 days) for Portland cement are achieved by means of chemical additives, such as electrolyte salts, anionic surfactants [7], multicomponent active mineral additives [8], etc. Using electrolyte salts, the hardening is accelerated and the physical and mechanical properties are improved due to the interaction of these salts with the aluminate phases of Portland cement clinker with the formation of *AFm*- [9, 10, 12] and *Aft*-phases [11, 12], calcium hydrosulfo-, hydronitro-, hydrocarbo-, and hydrochloro-aluminates. Calcium-aluminate (alumina) cement achieves high physical and mechanical characteristics in the early stages, and the introduction of electrolyte salts can also accelerate hardening [13]. However, these studies do not describe the deformation properties of composite materials based on these cements, including those dispersed with reinforced fibre.

3 Aim and objectives of the study

The aim of the study is to determine the dependence of physical and mechanical properties on a composition of rolled composite material made of polyester fibres and mineral mixture and to develop a composition based on them that will provide the required physical and mechanical properties of the underlayer between reinforced concrete slabs of a railway bridge deck and steel bridge beams.

The research objectives are: to develop a research methodology; to experimentally study the relationship between stresses and deformations of a rubber-wood composition and a composite material made of polyester fibres and mineral mixture and determine their deformation modulus and strength limit; to construct and analyse the dependence of the deformation modulus and the strength limit of the composite material according to its composition; and to determine the composition of the composite material that will provide a deformation modulus corresponding to the deformation modulus of the rubber-wood composition.

4 Development of research methods

The physical and mechanical properties of the rubber-wood composition and the composite material developed were studied on samples, the shape and method of manufacturing of which were chosen based on the design and laying technology of the interlayer made of them (Fig. 1).

The samples of rubber-wood composition (Fig. 1, a) were consisted of a cube of pine or oak wood with an edge size of 50 mm, on which a plate of reinforced rubber (conveyor belt) 10-mm thick and 50 × 50 mm in size was applied (Fig. 1, c). The ratio of the thickness of the reinforced rubber to the wood in the interlayer was 1:5. The samples were compressed across their fibres on a hydraulic press in stages, meanwhile the distance between the press plates was measured. Based on the results of measurements of three samples, deformation diagrams (graphs of the relationship between stress and relative deformation $\sigma = f(\varepsilon)$, $\varepsilon = f(\sigma)$) were constructed; they were used to determine the deformation modulus *E* and compressive strength *f* of the rubber-wood interlayer.

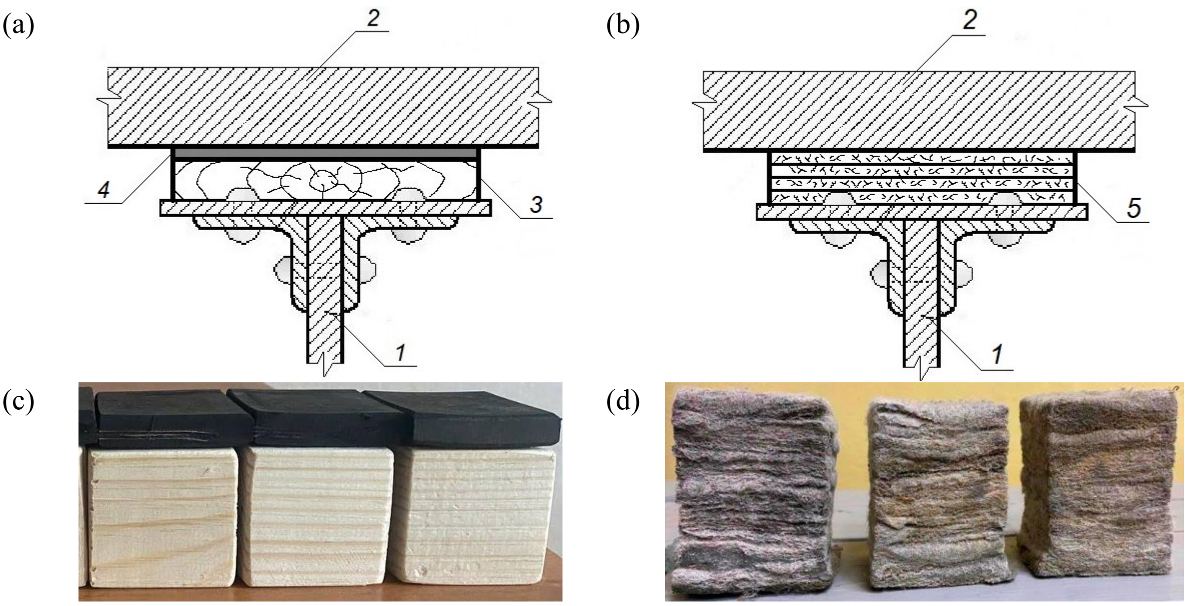

Figure 1. The interlayer between steel bridge girder and reinforced concrete slab: a, b – construction diagrams; c, d – laboratory samples of rubber-wood (a, b) and composite (c, d) interlayer: *1* – steel bridge beam; *2* – reinforced concrete slab; *3* – wooden board; *4* – reinforced rubber; *5* – layers of composite material

The composite material samples (Fig. 1, d) were made of mineral mixture and BNWM of anisometrically oriented polyester fibres 10-mm thick with a density of 100 g/m^2 and 20-mm thick with a density of 200 g/m^2. The mineral mixture consisted of Portland cement CEM I 42.5 R EN 197-1 (IFCEM, Ukraine), calcium-aluminate cement Isidac 40 EN 14647 (Çimsa, Turkey), sand DSTU B V.2.7-32-95 of the Bezlyudivka deposit (Ukraine) with a particle size distribution of 1.0-1.1 (very fine). During the experiment, the composition of mineral mixture and its consumption per 1 m^3 of BNWM varied. In the mineral mixture, the sand to cement (S:C) mass ratio varied from 0 to 2. The consumption of the mineral mixture per 1 m^2 of 10-mm thick BNWM varied from 3.33 to 10 kg/m^2

(M:NM from 333 to 1,000 kg/m^3), per 1 m^2 of 20 mm-thick BNWM – from 3.33 to 20 kg/m^2 (from 167 to 1,000 kg/m^3).

The mixture components were weighed, poured into a mixer and mixed thoroughly for at least 3 minutes. Sheets of 200×200 mm were cut from BNWM. A mould for the preparation of BNWM with a size of 200 × 200 mm (Fig. 2) was installed on the vibrating platform and lined with a plastic film so that the edges of the film extended above the sides of the mould (Fig. 2, a). A BNWM sheet was placed on the bottom of the mould, the vibrating platform was turned on, and the pre-weighed dry mixture was slowly and evenly poured on top (Fig. 2, b). During the vibrations, the mixture was levelling with a brush, until the mixture visibly stopped penetrating deep into the BNWM. The film with the material was taken by the edges, removed from the mould, and wrapped (Fig. 2, c).

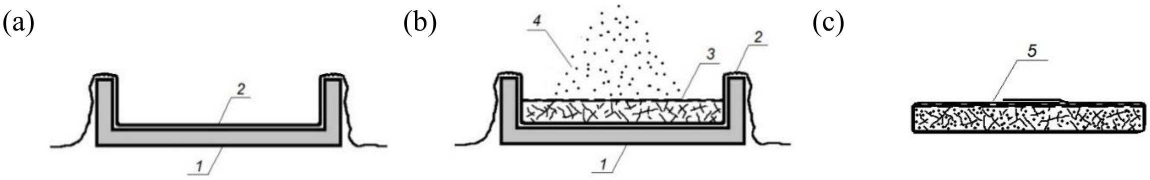

Figure 2. Production of composite material samples: a – plastic film in the mould; b – the mould with BNWM and mineral mixture; c – composition taken from the mould and wrapped in the film; *1* – mould; *2* – plastic film; *3* – BNWM; *4* – dry mix; *5* – finished sample

The composite material samples were made as follows: in the film, in which a 200×200 mm sheet was wrapped, holes were pierced with an awl in a checkerboard pattern at a distance of 30 mm from each other. The sheet, wrapped in the perforated film was immersed in water for 3 min, after which it was cut into 50×50 mm pieces together with the film. The film was removed from the pieces and they were placed layer-by-layer in the mould cavity (Fig. 3, a, b). The number of layers chosen ensured that the mould cavity was filled to the top. The sample was pressed with a punch with an artificial weight (Fig. 3, c). The total weight of the punch with the artificial weight was taken the same as the technological pressure on the interlayer from the weight of the reinforced concrete slab during the installation of the ballastless bridge deck:

$$p = m/(nlb) = 2{,}500/(2\cdot 189\cdot 20) = 0.33 \text{ kg/cm}^2, \quad (1)$$

where m is the weight of the slab, 2,500 kg; n is the number of longitudinal beams, 2; l is the length of the slab, 189 cm; b is the width of the interlayer (beam), 20 cm.

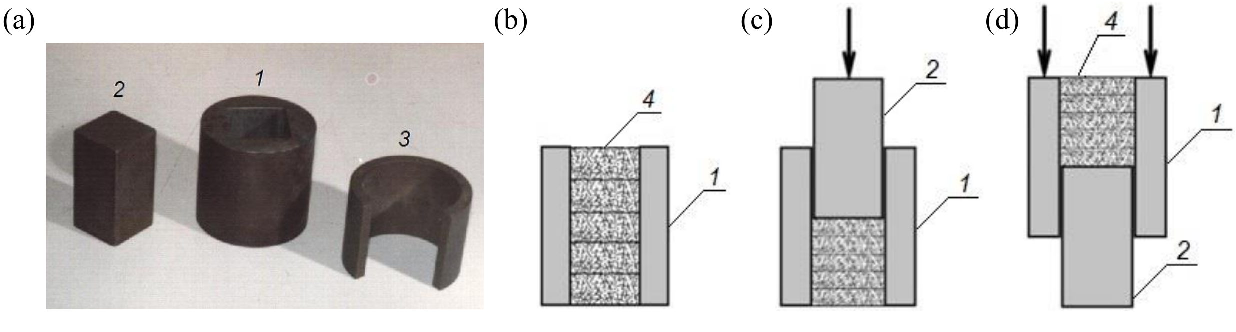

Figure 3. Formation of composite material samples for testing: a – mould; b – composite material laid in the mould cavity layer-by-layer; c – compaction of the sample with a punch; d – extraction of the sample from the mould cavity by a punch with an extraction ring; *1* – mould cavity; *2* – punch; *3* - extraction ring; *4* – sample

Thus, the total mass of the punch with a cross-sectional size of 5×5 cm with the artificial weight was 5·5·0.33 = 8.25 kg; the holding time under pressure was 3 min. After the sample was under pressure, the mould was turned over and the sample was squeezed out using an extraction ring (*3* Fig.

3, a, d). The height of the sample h_i was measured by means of an electronic calliper and the compression ratio was determined:

$$K_{cr} = h/h_0, \tag{2}$$

where h_0 is the initial height of the sample (mould cavity).

Nine samples were made out of each composition of the composite material. The moulded samples were covered with a polyethylene film and kept at a temperature of 20 ± 3°C. After curing during one and 28 days, the mass, size, average density ρ, deformation modulus E, and compressive strength f of three samples were measured or determined. The values E and f were found by compressing the samples in stages on a hydraulic press, by measuring the distance between the press plates at four points and taking the average value. The compressive stress was brought to 39 MPa. Based on the results of the measurements of three samples, the deformation diagrams, i.e., the dependency graphs between stress and relative deformation $\sigma = f(\varepsilon)$, $\varepsilon = f(\sigma)$ were constructed. The deformation modulus was determined according to the diagram as the tangent of its slope angle $E=\sigma/\varepsilon$ for a maximum stress in the interlayer under a load of 5 MPa. Due to the absence of visible fracture, the compressive strength f was taken as the beginning of the yield point or the place from which the slope of the curve $\sigma = f(\varepsilon)$ began to decrease clearly. At the age of 28 days, water absorption was determined depending on the weight W_m.

5 Results and discussion

The compressive deformation diagrams of the rubber-wood composition samples (Fig. 1, b) are shown in Fig. 4, a. During the test, the samples underwent significant deformations due to the rubber content and suddenly collapsed brittle due to the wooden content. The compressive strength of the samples was 5.5 MPa for pine wood and 7.9 MPa for oak (Table 1). The integral defromation modulus of the rubber-wood composition was 58 MPa for pine wood and 144 MPa for oak wood.

The physical and mechanical properties of the composite material of different compositions (Fig.1, d) were used for building the compression deformation diagrams $\varepsilon = f(\sigma)$ and $\sigma = f(\varepsilon)$. Some of the diagrams $\sigma = f(\varepsilon)$ are shown in Fig. 4, b, c. During the test, no obvious destruction of the composite material with a violation of its structural integrity was identified, the material was deformed gradually. In most samples, the yield point was observed to be more distinct with a higher mineral mixture content.

The diagrams of the dependence of f and E on S:C and M:NM for different BNWM thicknesses and different types of cement were constructed (Fig. 5). The analysis of these diagrams showed that the values of f and E increased with a decrease of the BNWM thickness and the S:C ratio, as well as with an increase in the consumption of mineral mixture per the BNWM (M:NM). The studied compositions of the composite material reached the maximum values: E – 163 MPa and f – 16 MPa (Fig. 5, a, Table 1).

In order to clarify the compositions that will provide deformation characteristics similar to the rubber-wood composition, the approximated dependencies of E on S:C were constructed (Fig. 6). These dependencies were well approximated with correlation coefficients close to 1 by means of the quadratic equations shown in Fig. 6. In these equations, $y = E$, x = S:C.

Fig. 6 shows that the deformation modulus is the same as in the rubber-wood composition made of both pine wood (58.3 MPa) and oak wood (144.3 MPa), which can be provided only by a composite material with BNWM 10-mm thick with a mineral mixture consumption of 1,000 kg/m^3. By substituting the values 58.3 and 144.3 as y in the equation $y = 48.62x^2 - 170.3x + 162.5$, the following is obtained:

$$48.62x^2 – 170.3x + 104.2 = 0 \tag{3}$$

$$48.62x^2 – 170.3x + 18.2 = 0 \tag{4}$$

By solving the quadratic equations, the values x = S:C = 0.11 and 0.79 were obtained; this can provide the deformation modulus of the interlayer E = 144.3 and 58.3 MPa, respectively.

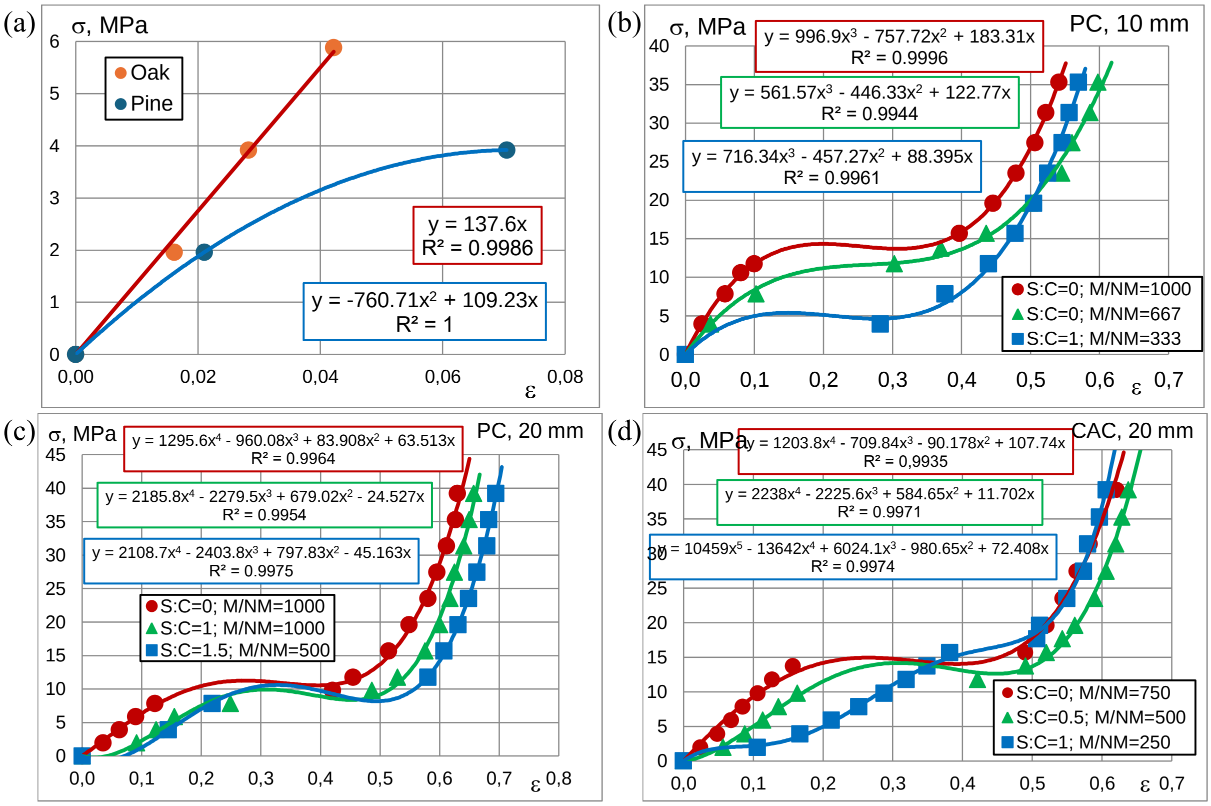

Figure 4. Deformation diagrams (relationships between the relative deformation ε and the compressive stress σ): a – rubber-wood composition with the ratio of the reinforced rubber thickness to the pine or oak wood thickness 1:5; b, c – made of a rolled composite material based on Portland cement (b, c) or calcium aluminate cement (d) and BNWM with a thickness of 10 mm (b) and 20 mm (c, d) with different S:C mass ratios and consumption of the mineral mixture per 1 m^3 of BNWM (M:NM), kg/m^3

Table 1. Physical and mechanical characteristics of the rubber-wood composition and rolled composite material

Material	Mineral mixture composition (S:C)	Deformation modulus *E*, MPa	Compressive strength *f*, MPa
Rubber-wood composition (1:5) made of oak wood	–	144.3*	7.9*
made of pine wood	–	58.3*	5.5*
Composite material based on Portland cement and BNWM, 10 mm thick, mineral mixture consumption with M:NM = 1,000 kg/m^3	0	162.8*	15.7*
	0.11	144.3	12
	0.79	58.3	7
with M:NM =667 kg/m^3	0.63	58.3	7
Composite material based on calcium-aluminate cement and BNWM, 20 mm thick, with mineral mixture consumption M:NM = 500 kg/m^3	0	84.9*	9.8*
	0.26	58.3	7
with M:NM = 750 kg/m^3	0.89	58.3	7

* Experimentally obtained values

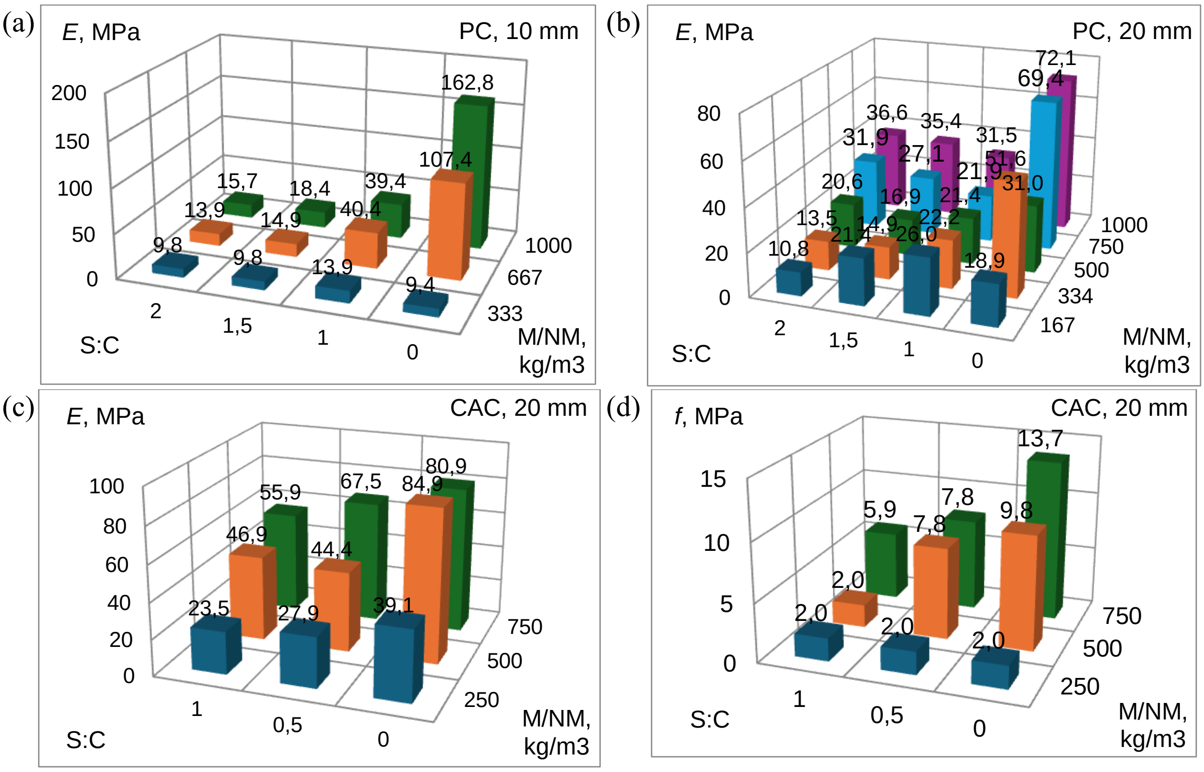

Figure 5. Dependences of the deformation modulus E (a, b, c) and the compressive strength f (d) of the composite material based on Portland cement (a, b) and BNWM with a thickness of 10 mm (a) and 20 mm (b, c, d) on the S:C mass ratio and the consumption of mineral mixture per 1 m^3 of BNWM (M:NM)

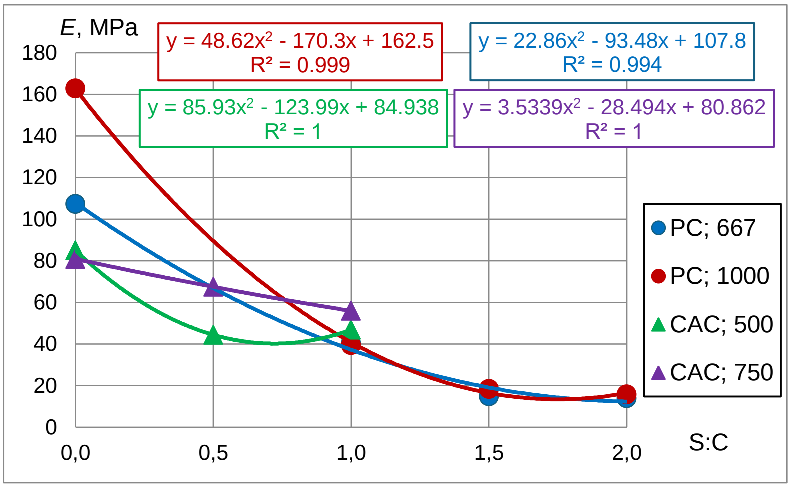

Figure 6. Dependence of the deformation modulus E of the composite material based on Portland cement (PC) and calcium-aluminate cement (CAC), and BNWM with a thickness of 10 mm (for PC) and 20 mm (for CAC) with the consumption of mineral mixture M:NM 500, 667, 750, 1,000 kg/m^3 on the S:C mineral mixture composition

Fig. 6 also shows that a deformation modulus of 58.3 MPa, similar to that of the rubber-pine wood composition, is provided by compositions of the composite material with BNWM 20 mm thick with a mineral mixture consumption of 500 to 750 kg/m^3. Substituting the value of 58.3 into the other equations, shown in Fig. 6, the following is obtained:

$$22.89x^2 - 93.48x + 49.5 = 0 \quad (5)$$

$$85.93x^2 - 123.99x + 26.638 = 0 \quad (6)$$

$$3.5339x^2 - 28.494x + 22.562 = 0 \quad (7)$$

The solution of these equations gives the values x = S:C = 0.63, 0.26 and 0.89, respectively; this will provide the deformation modulus of the interlayer E = 58.3 MPa.

The compositions of the composite material obtained are shown in Table. 1. It is recommended to use such compositions for the interlayer, which is arranged in accordance with [3].

6 Conclusion

An original methodology has been developed for the experimental study of the dependence between stresses and deformations of a rubber-wood composition and composite material made of polyester fibres and mineral mixture; their deformation modulus E and compressive strength f were determined.

The dependence between the stresses σ and the deformations ε of a rubber-wood composition and composite material made of polyester fibres and mineral mixture of different compositions was investigated; their deformation moduli E and the compressive strengths f were determined. It was found that the integral deformation modulus E of the rubber-wood composition is 58.3 MPa for pine wood and 144.3 MPa for oak wood, and the compressive strength is 5.5 and 7.9 MPa, respectively.

The dependences of E and f of the developed composite material on its composition, i.e., the type of cement (Portland cement or calcium-aluminate cement), the S:C ratio in the mineral mixture, the consumption of the mineral mixture per 1 m^3 of BNWM (M:NM) at different thicknesses of BNWM were investigated. The material underwent significant deformations, but no destruction of structural integrity was observed. The values of E and f decrease with an increase of the S:C content in the mineral mixture and a decrease in the consumption of mineral mixture per 1 m^2 and 1 m^3 of BNWM (M:NM).

The dependencies of E on S:C are well approximated by quadratic equations with correlation coefficients close to 1. By solving these equations, it was obtained the S:C values that provide E = 58.3 and 144.3 MPa. In particular, when using Portland cement, BNWM with a thickness of 10 mm, the consumption of mineral mixture M:NM = 1,000 kg/m^3 is 0.11 and 0.79, respectively. When using calcium-aluminate cement, BNWM with a thickness of 20 mm, E = 58.3 MPa can be achieved at M:NM = 750 kg/m^3 and S:C = 0.89. These compositions are recommended for the underlayer laid implementing the patented technology.

The obtained dependencies can be applied to the development of a composite material formulation for similar interlayers of structural elements, such as the leveling-distribution layer between the bearing parts of bridge spans and the undergirder blocks. For this purpose, it is advisable to study a composite material produced under higher technological pressure and to conduct detailed investigations, including electron microscopy studies, of the interaction between cement hydration products and polyester fibers.

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