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# THE EFFECT OF THE SIZE AND SHAPE OF WOOD PARTICLES ON THE TENSILE STRENGTH PERPENDICULAR TO THE PLANE OF THE PARTICLEBOARD: EXPERIMENTS AND MODELING

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## THE EFFECT OF THE SIZE AND SHAPE OF WOOD PARTICLES ON THE TENSILE STRENGTH PERPENDICULAR TO THE PLANE OF THE PARTICLEBOARD: EXPERIMENTS AND MODELING

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One of the problems of sustainable development is the technologies improvement for the rational use of wood and other raw materials of plant origin. The literature reflects a large amount of applied research that was conducted to justify new technologies for the production of particle boards (PB). The main attention in the known works is paid to the influence of the particle size distribution on the strength of PB. The influence of particle shape on the PB strength has been studied to a lesser extent. In this regard, this article considers the influence of the shape and size of particles on the tensile strength perpendicular to the plane of the PB. A geometric analysis of the particle shape is performed. It was taken into account that the PB strength depends on the shape and size of the particles, as well as on the number of adhesive contacts between particles. To obtain quantitative estimates, formulas were substantiated confirming that an increase in the length of the particles and a decrease in their transverse dimensions lead to an increase in the PB strength. Experimental research methods were used, and mathematical modeling of the sample failure area was performed.

*Key words: engineering, modeling, composite material, particle board, tensile strength*

### INTRODUCTION

Particle boards (PB) are used in construction, furniture production, as well as for the manufacture of containers and packaging. The PBs production increases over time. New types of PB appear [1, 2]. Contemporary PB technologies [3, 4, 5] allow the rational use of large volumes of low-quality wood (Fig. 1), as well as waste from the processing of reed [6], bamboo [7] and other types of raw materials of plant origin [8], which contributes to the increase environmental safety and sustainability of socio-economic development [1, 6].

The disadvantages of PBs include the potential for formaldehyde emission. However, modern technologies can significantly reduce the influence of this factor [9, 10, 11].



Figure 1: Wood as a raw material for the manufacture of PB

The goals of new technologies are not only to reduce formaldehyde emission, but also to ensure sufficient strength of PBs under various mechanical influences. As a result, there is a problem of comparative assessment of the strength of PBs obtained by conventional and new technologies. This article examines the tensile strength perpendicular to the PB plan. Such tests are stipulated by the EN 319 standard [12].

The purpose of this work: the development of a methodology for the comparative strength of PB under tension perpendicular to the plan of the board.

### MATERIALS AND METHODS

To achieve the stated goal, the methods of experimental and theoretical research were used.

Experimental studies were carried out in the laboratory for quality control of at the "Karelia DSP" enterprise. The samples were taken from the board having 16 mm in thickness. The samples, in the form of square test pieces, were produced in the format of 50 x 50 mm. Figure 2 shows an sequence of samples preparation for testing. Figure 3 shows a sequence of tensile testing of sample perpendicular to the plan. The sample is glued to the upper and lower auxiliary plates (using polyvinyl acetate glue). Sufficient strength of the adhesive joint is guaranteed by pressing and holding for 6-12 hours (Fig. 2).



Figure 2: A photograph of the samples (test pieces), each bonded to upper and lower test blocks, according to the EN 319

The load from the testing machine is transferred to the lower loading block and causes tension of the sample located in the middle of the three-plate stack (bottom accessory plate; sample; upper accessory plate) (Fig. 3). This method of sample preparation was used to reduce the cost of sample preparation and simplified of the device for testing on tensile perpendicular to the plane of the PB.

Taking into account the importance of environmental aspects [10, 11], we note that the emission of formaldehyde contained in the PBs under study is not more than 7 mg per 100 g. board, which corresponds to the environmental safety class E1 (i.e. emission tolerance is not more than 10 mg per 100 g. board) (from <https://www.kareliad-sp.com/>, accessed on 2020-10-10 ).

As for the mechanical side of the problem, we note that the particles have an oblong form (Fig. 4 and 5). A dimensionless criterion of shape, for instance, ratio between length and thickness of the particle can be. The longer the particle is, the more it has adhesive contacts with other particles, i.e. the higher the strength of internal bonds in sample (Fig. 4). Therefore, the choice of the particle length as a criterion for the particle size corresponds to the logic of this study. Geometrically, an ellipsoid was chosen to model each particle. A more detailed discussion of the classification of particles can be found, for example, in articles [13, 14].



Figure 3: The testing sequence of sample

The ratio of the semi-axes of the ellipsoids was chosen as a dimensionless criterion for particle size. This issue is discussed in more detail in a separate section of current article.

The adequacy of particle modeling by ellipsoids is confirmed by the analysis of the rupture surface (Figure 4) and the results of sieve analysis (Figure 5). Taking into account this circumstance, a model of the PB failure region was proposed in the form of a mechanical system of contacting ellipsoids (Fig. 6). Mechanical interaction of ellipsoids is provided by adhesive joints made in accordance with known technologies [1, 3, 11].



Figure 4: The fracture surface of the sample



Figure 5: Particles after sieving



Figure 6: Post-test sample (top) and failure area model (bottom)

Analysis of the rupture surface of the samples after testing (Fig. 4 and 6) showed that when tensile perpendicular to the plan of the PB, the adhesive joint resists mainly the separation of one wood particle from another. This is a kind of delamination for which adhesive joints are most vulnerable [15]. An additional vulnerability of internal bonds arises due to the fact that wood particles in the sample are oriented in such a way that they tension perpendicular or almost perpendicular to grain (Figures 4 and 6), i.e., in the direction of the least strength of wood as anisotropic material [16].

Note that when PB bends, the adhesive joints in the tension zone resist the displacement of some particles relative to others. In other words, wood particles resist tension mainly along the fibers. This is an important consideration, but this article only deals with the tension perpendicular to the PB plane.

### THEORY AND MODELING

Ignoring irregularities on the rupture surface of the sample (Fig. 4 and 6), we consider this surface as a plane. Let us denote  $A$  - the area of the horizontal projection of the sample (Fig. 4).

As noted above, an ellipsoid with semi-axes  $a$ ,  $b$  and  $c$  was chosen as a model of a wood particle (Fig. 7). The longest axis is  $2a$  axis, as presented in the figure 7; this chosen as the characteristic size of particle.

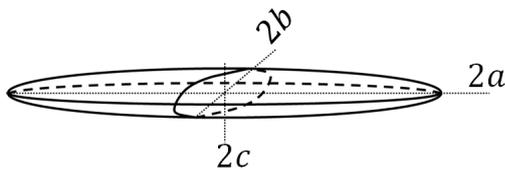


Figure 7: Geometric particle model

From Figure 4 it follows that the smallest axis ( $2c$  axis) of the ellipsoid should be perpendicular (or nearly perpendicular) to the PB plan. Accordingly, the axes of the ellipsoid of length  $2a$  and  $2b$  are parallel to the PB plan. Internal tensile forces (stresses) act at the points of projection of the particle onto the horizontal plane (Figure 7). The area of this projection for an individual particle is equal to  $\bar{A}=\pi ab$ . Therefore, the factor  $\varphi=b/a$ ,  $0<\varphi\leq 1$  can be chosen as a criterion for the shape of wood particles. Then  $b=\varphi a$ ,  $\bar{A}=\pi\varphi a^2$ .

Analysis of the area of rupture (Figures 4 and 6) clearly shows that each particle is contacting with other particles. Let's designate  $n_{contact}$  - the number of contacts of one particle. Obviously, with an increase of the characteristic one particle size, the number of contacts increases. Let  $n_{contact}=\beta a$ , where  $a$  is the largest semi-axis of the ellipsoid;  $\beta$  - coefficient of proportionality, constant. The  $\beta$  coefficient is equal to the number of contacts per unit length of the particle.

Let's proceed to the analysis of the total number of contacts in the rupture plane (Figure 4).

An ellipse with semi-axes  $a$  and  $b$  (Fig. 7) can be in-

scribed in a rectangle whose area is  $4ab$ . Suppose that such rectangles without intersection occupy the entire area of the above-mentioned horizontal projection of sample A (Figure 4). Then the number of particles on the horizontal projection of the sample is approximately equal to  $N_{particle}$ :

$$N_{particle} = \frac{A}{4ab} = \frac{A}{4\varphi a^2} \quad (1)$$

Using (1), we can determine the total number of contacts of all particles in the fracture plane:

$$N_{contact} = n_{contact} N_{particle} = \beta a \frac{A}{4\varphi a^2} = \beta \frac{A}{4\varphi a} \quad (2)$$

From the above, questions arise: what is the practical significance of relation (2)? Is it possible to use formula (2) in calculations to justify new PB technologies? To substantiate the answers, let us consider a comparative assessment of the strength of two PBs obtained using the old and new technologies. By analogy with (2), we write:

$$N_{contact}^{old} = \beta \frac{A}{4\varphi^{old} a^{old}}; N_{contact}^{new} = \beta \frac{A}{4\varphi^{new} a^{new}} \quad (3)$$

Substitute expressions (3) into the relation  $N_{contact}^{new}/N_{contact}^{old}$  and define  $N_{contact}^{new}$ :

$$N_{contact}^{old} = N_{contact}^{old} \frac{\varphi^{old} a^{old}}{\varphi^{new} a^{new}} \quad (4)$$

The strength of the PB at tension perpendicular to the plan depends on a number of factors, which include: size and shape of particles, particle size distribution, type of adhesive, material of particles, temperature and duration of pressing, degree of compaction [1, 2, 5]. In current work, we focus only on the influence of two factors, namely the size and shape of the particles. Accordingly, all other factors are assumed to be the same when comparing PB options. Taking this circumstance into account, we come to the conclusion that the strength of the PB sample with the number of contacts  $N_{contact}^{new}$ , obtained using the new technology, will be higher than the strength of the sample obtained using the old technology, if  $N_{contact}^{new} > N_{contact}^{old}$ . This inequality, taking into account relation (4), is equivalent to inequality (5):

$$\frac{\varphi^{old} a^{old}}{\varphi^{new} a^{new}} > 1 \quad (5)$$

If we take into account that the particle shape factor of the equality  $\varphi=b/a$  is used above, then relations (4) and (5) can be rewritten in the form (6) and (7), respectively:

$$N_{contact}^{new} = N_{contact}^{old} \frac{b^{old}}{b^{new}} \quad (6)$$

$$\frac{b^{old}}{b^{new}} > 1 \quad (7)$$

In relations (6) and (7), the effect of the particle shape is not taken into account explicitly. Nevertheless, relations (6) and (7) are equivalent to relations (4) and (5), respectively, since  $b=\varphi a$ . However, for practice, relations

(4) and (5) are preferable, since they allow one to obtain relative quantitative estimates of the strength of PB, taking into account the influence of not one, but two factors: the characteristic size and shape of particles.

In the manufacture of PB, a mixture of particles of various shapes and sizes is used (Figure 5). Particle fractions differ, as noted above, in form factor  $\varphi$  and characteristic size  $a$ . Accordingly, the strength of the board should be determined taking into account all contacts between particles of different fractions. Let  $n$  be the number of particle fractions,  $\tilde{C}_i$  – the share of particles of fraction  $i$  (by mass);  $\tilde{C}_1 + \tilde{C}_2 + \dots + \tilde{C}_n = 1$ . Then, using relations (3), we can write:

$$N_{contact}^{old} = \frac{\beta A}{4} \sum_{i=1}^{n_{old}} \frac{\tilde{C}_i^{old}}{\varphi_i^{old} a_i^{old}}; \quad (8)$$

$$N_{contact}^{new} = \frac{\beta A}{4} \sum_{i=1}^{n_{new}} \frac{\tilde{C}_i^{new}}{\varphi_i^{new} a_i^{new}}$$

Taking into account relations (8), by analogy with (4), we obtain:

$$N_{contact}^{new} = N_{contact}^{old} \left( \sum_{i=1}^{n_{new}} \frac{\tilde{C}_i^{new}}{\varphi_i^{new} a_i^{new}} \right) \left( \sum_{i=1}^{n_{old}} \frac{\tilde{C}_i^{old}}{\varphi_i^{old} a_i^{old}} \right)^{-1} \quad (9)$$

## RESULTS AND DISCUSSION

Consider a model example. Let  $n_{new} = n_{old} = 2$  and  $\varphi_i^{new} = \varphi_i^{old} = \varphi$ . Then from (9) it follows:

$$N_{contact}^{new} = N_{contact}^{old} \frac{(\tilde{C}_1^{new} a_2^{new} + \tilde{C}_2^{new} a_1^{new}) a_1^{old} a_2^{old}}{a_1^{new} a_2^{new} (\tilde{C}_1^{old} a_2^{old} + \tilde{C}_2^{old} a_1^{old})} \quad (10)$$

Using relation (10), one can estimate the effect of  $a_2^{new}$  and  $\tilde{C}_2^{new}$  on the relative number of particle contacts  $N_{contact}^{new}/N_{contact}^{old}$ . Let  $a_1^{old} = a_2^{old} = a_1^{new} = 1$ ;  $a_2^{new} = k a_2^{old}$ ,  $k = 0.1, \dots, 5.0$ ;  $\tilde{C}_1^{old} = 1$ ;  $\tilde{C}_2^{old} = 1 - \tilde{C}_1^{old}$ ;  $\tilde{C}_1^{new} = 1 - \tilde{C}_2^{new}$ ,  $\tilde{C}_2^{new} = 0, \dots, 1$ . Results of calculations using formula (10) are shown in plots (Figures 8 and 9).

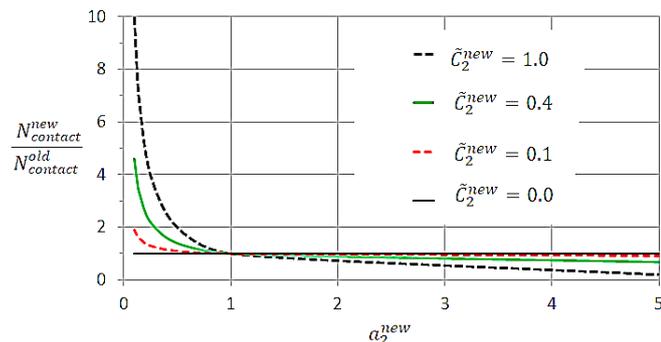


Figure 8: Influence of particle size  $a_2^{new}$  on the relative number of adhesive contacts

In Fig. 8 it can be seen that with a decrease in the particle size (i.e.,  $a_2^{new}$ ), the number of the above adhesive contacts of the particles increases nonlinearly. Growth occurs if  $a_2^{new} < a_2^{old}$ . If  $a_2^{new} > a_2^{old}$ , then the number of adhesive contacts of the particles decreases. The influence of the size and shape of reinforcing particles on the strength of composites is known [17]. In this case, an

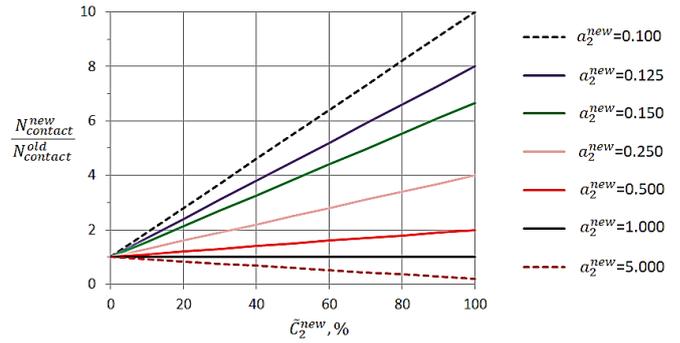


Figure 9: Particle mass fraction effect size  $\tilde{C}_2^{new}$  on the relative number of adhesive contacts

attempt was made to obtain quantitative estimates of this effect. Analysis of the reinforcing properties of micro-particles is beyond the scope of this work, since it belongs to another area of research [17].

As shown in Fig. 9, the relative number of the above-mentioned adhesive contacts depends linearly on the concentration  $\tilde{C}_2^{new}$ . Changes in the number of these contacts are most sensitive to changes in the concentration of small particles, which is also shown in Fig. 8. Therefore, from a practical point of view, it is most effective to control the number of adhesive contacts (and hence the PB strength), first of all by changing the number of fine particles.

Since the strength of the PB is proportional to the number of adhesion contacts between particles on the rupture surface, formula (9) can be proposed to adjust the particle size distribution of particles in accordance with the tensile strength criterion perpendicular to the PB plan. The numbers  $n_{new}$  and  $n_{old}$ , as well as the values  $\tilde{C}_i^{new}$ ,  $\tilde{C}_i^{old}$ ,  $a_i^{new}$ ,  $a_i^{old}$ ,  $\varphi_i^{new}$  and  $\varphi_i^{old}$  are determined by processing the results of sieve analysis (Fig. 5).

Thus, on the basis of relation (2), the calculation formulas (4), (5) and (9) were obtained, which can be used to substantiate new solutions aimed at improving the technologies for the production of PB.

Relationships (4), (5), (8) and (9) predict that the number of adhesion contacts of particles is  $N_{contact}^{new}$ , and hence the strength of the PB is the greater, the smaller the shape factor  $\varphi = b/a$ . If  $b$  is a constant then the coefficient  $\varphi$  increases with decreasing size  $a$ . However it follows from the same formulas that an increase in the size  $a$  decreases the number of particle contacts. But this is only an apparent contradiction, since the efficiency of particles of a certain shape depends on the characteristics of the stress-strain state of the material. In some cases, particles with a coefficient  $\varphi \approx 1$  are effective; in other cases particles with a coefficient  $\varphi \approx 0.05$  may be more effective. The influence of particles of a certain shape and size depends on their mass fraction and is determined by the coefficients  $\tilde{C}_i^{new}$  and  $\tilde{C}_i^{old}$  in formula (9).

It is pertinent to note as a side note that the relationship between the length and thickness of a particular member, called the "slenderness ratio", is one of the key characteristics used in engineering calculations (e.g. [18, 19]).

It is known from the literature that an increase in the length of particles and a decrease in their transverse dimensions lead to an increase in the strength of PB. Such particles can be, for example, nanocellulose fibers [20, 21]. In [20], it was experimentally proved that the mechanical characteristics of PB can be significantly improved when using glue with the addition of nanocellulose in the amount of 1% of the adhesive mass. The increase in strength due to the use of particles in the form of fibers is predicted by formulas (4) and (9), which indirectly confirms their adequacy. However, the influence analysis of nano- and micro-particles requires a separate approach [17, 21, 22].

From relations (4) and (5) it follows that the characteristic size  $a$  should also be considered as a factor that significantly affects the strength of PB. With a decrease in the characteristic size  $a$ , the number of particles that can fill the surface of possible destruction of the sample increases. Small particles fill the gaps between the larger particles. As a result, the number of adhesive contacts of the particles increases and the strength of the PB increases. This conclusion is confirmed by the experiments (Figures 2-6). Figure 6 shows a sample in which the middle layer is made up of relatively coarse particles compared to top and bottom layers. Naturally, when tension perpendicular to the PB plan, the sample breaks in an area in which the number of small particles is minor. This kind of destruction is predicted by formulas (4), (5) and (9). Nevertheless, the following more detailed analysis of the experimental data is required.

**EXPERIMENTAL DATA ANALYSIS**

Let us consider an example of estimating the strength of a sample three-layer PB using the formula (9). In Fig. 6 shows one of the samples studied, in which the middle (inner) layer consists of relatively large particles in comparison with the outer (upper and lower) layers. Raw for the PB was none debarking wood aspen (60%), and

Table 1: Granulometric composition of wood particles

| $i$ | Size pass-through (MM)<br>( $2b_i^{outer}$ and $2b_i^{inner}$ )* | Sieve residue (% by weight)          |                                      |
|-----|--|--------------------------------------|--------------------------------------|
|     |  | Outer layer, ( $\bar{C}_i^{outer}$ ) | Inner layer, ( $\bar{C}_i^{inner}$ ) |
| 1   | 5.00   | 0.0                                  | 24.9                                 |
| 2   | 3.15   | 0.0                                  | 17.3                                 |
| 3   | 2.00   | 0.2                                  | 29.8                                 |
| 4   | 1.00   | 12.5                                 | 21.9                                 |
| 5   | 0.5  | 44.5                                 | 4.1                                  |
| 6   | 0.2  | 32.6                                 | 1.2                                  |
| 7** | 0.12***  | 10.2                                 | 0.8                                  |

\* $b_i^{outer}=\varphi a_i^{outer}$  and  $b_i^{inner}=\varphi a_i^{inner}$   
 \*\* Pallet.  
 \*\*\* Average particle size in the pallet ( $2b$  by Fig 7)

a mixture of conifers (pine, spruce) (40%). The particle size distribution was determined before making the PB using sieve analysis (Fig. 5, and Table 1). Bulk density of wood particles: 309 kg/m<sup>3</sup>, moisture content: 4%. Particle thickness (size  $2c$  in Fig. 7): 0.60 ... 0.73 mm.

Let's designate  $N_{contact}^{outer}$  and  $N_{contact}^{inner}$ , respectively, the number of contacts in the break conditional plane of the outer or inner layer. Then, using relation (9), can be write:

$$\frac{N_{contact}^{outer}}{N_{contact}^{inner}} = \left( \sum_{i=1}^{n_{outer}} \frac{\bar{C}_i^{outer}}{\varphi_i^{outer} a_i^{outer}} \right) \left( \sum_{i=1}^{n_{inner}} \frac{\bar{C}_i^{inner}}{\varphi_i^{inner} a_i^{inner}} \right)^{-1} \quad (11)$$

Here  $n_{outer}=n_{inner}=7$  (Table 1). It is assumed that  $\varphi_i^{outer}=\varphi_i^{inner}=\varphi$ ;  $a_i^{outer}=b_i^{outer}/\varphi$ ,  $a_i^{inner}=b_i^{inner}/\varphi$ . Then relation

(11) leads to the estimate  $\frac{N_{contact}^{outer}}{N_{contact}^{inner}} = \frac{367}{69} = 5.3$ , that is, the number of adhesive contacts per unit area in a possible plane of break of one from outer layers is 5.3 times greater than the number of adhesive contacts per unit area in a possible plane of break of the inner layer. Logically assume that the strength is proportional to the number of adhesive contacts in the plane (or in the surface) of break of the specimen, then the strength of the one outer layer is approximately 5.3 times greater than the strength of the inner layer. Consequently, relation (11) predicts material fracture of the inner layer of the sample (Fig. 6).

Thus, the results of this work make a certain contribution to improving the understanding of the influence of the shape, size and mass fraction of wood particles of various fractions on the tensile strength perpendicular to the plan of the PB, do not contradict the literature data about the effect of particle size and their geometric shape on the PB strength [20, 23, 24].

An increase in the strength of PB with a decrease in particle size is known from practice and experimental laboratory studies (e.g. [23, 24]). Despite this, in order to accelerate the development of innovations, it is advisable to preliminary quantify the predicted relative strength of the PB when tensile perpendicular to the board plan. Such estimates can be determined by formulas (9) and (11).

At the same time, it should be noted that estimate (equal to 5.3) obtained by formula (11) is determined approximately, since possible differences between  $\varphi_i^{outer}$  and  $\varphi_i^{inner}$  are not taken into account. Besides, a possible change in the strength of the adhesive contacts was ignored. To take into account the influence of these and possibly other factors, it is advisable to continue research.

**CONCLUSIONS**

An analysis of the literature showed that, due to the complexity of the problem, experimental methods were mainly used to quantify the strength of PB. At the same time, in the studies known in the literature, questions of the influence of particle size on the strength of PB prevail. The influence of the shape and mass fraction of particles of various fractions has been studied to a lesser extent

and are still of great scientific and practical interest. In the presented work, the calculation formulas are substantiated for determining the quantitative assessment of the effect of sizes, as well as the shape and mass fraction of particles of various fractions on the strength of PB. However, these formulas are only valid when tension perpendicular to the PB plan.

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