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Strength and thermal conductivity properties of thermowood-cement composition and factors influencing these indicators

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Abstract. The paper studies the ways that technological characteristics of thermal wood concrete (TWC) production have on its strength and thermal conductivity properties. TWC is a new, effective wood-cement composition of authors' development. To produce it the authors used crushed thermally modified wood (TMW) with a certain shape and size as a filler. The research is rationalized by the fact that currently we are facing a lack of both fundamental and applied experimentally confirmed data on TWC. The paper discusses the studies of the compressive strength and thermal conductivity of four groups of TWC samples that were obtained with three types of filler, differing in size and shape, molding method and strength class of cement-sand mortar. The authors determined general impact patterns of the above-mentioned factors on strength and thermal conductivity properties, as well as specific indicators. Moreover, the paper describes the strength classes and grades of TWC that ranged from B1.5 to B3.5 and from M25 to M50, respectively. Thermal conductivity for standard samples ranged from 0.21 to 0.4 W/(mK). It has been concluded that TWC with a finer TMW filler has the most balanced combination of strength, thermal conductivity and deformation properties. Following the results, the authors proposed practical recommendations for TWC production, and further courses for its improvement and research.

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1. Introduction

While developing new materials, an important task is seen in acquiring fundamental knowledge on their operational, technological and other properties. Thermowood-cement composition or thermal wood concrete (TWC) is a new, previously unstudied building material of original development. The paper studies its strength, thermal conductivity properties, as well as technological factors that influence them. Standard TWC samples made in the laboratory are the objects under study.

Being environmentally friendly and with high thermophysical properties, nevertheless, the modern wood-cement compositions have a number of disadvantages associated with the properties of natural wood [1–5], namely:

1) hyper sorption of water and moisture, as well as associated shrinkage loss and swelling;

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2) discomfort and danger of operation due to the formation of mold and fungal lesions accompanied by destruction;

3) content of extractives and acids that negatively affect the formation of cement stone in composites.

Nowadays, the work is underway and a number of technological solutions have been offered to boost the properties of wood-cement compositions that can be done by minimizing the negative factors from arise when using natural wood [6–8]. Those solutions cover a wide range of methods for wood aggregate pre-treating [9], adding chemicals and other substances to mixtures [10–13] and employing chemical modification of wood [14–16]. Despite the successful results, the above-mentioned solutions did not bring any breakthrough improvements in the strength and protective properties of wood-cement compositions.

An effective solution to these problems can be the use of thermally modified wood (TMW) filler [17–22].

In this regard, we are witnessing a rising interest in developments done to create wood-cement compositions based on the use of TMW, namely wood-polymer composition (WPC), plywood and wood concrete [23]. The authors discuss current researches in modeling the processes of thermal modification of crushed wood, determining the hygroscopicity and swelling pressure of TMW, as well as the degree of thermal modification. As it concerns the operational and technological properties, so far, we may give only experimental data on compressive strength, the search for a rational water-cement ratio, the bulk density of particles (fillers) estimations from TMW and others.

Other relevant works [24] that study mortars based on hydraulic binders, where crushed TMW obtained from waste. It was proved that compared to mortar with untreated wood particles, mortars with wood chips showed better flexural strength and compressive strength due to improved adhesion between the wood aggregate and the cement stone. Compared the standard solution the crushed wood aggregate has lower strength, nevertheless, it shows higher levels of flexural toughness and impact strength.

However, some major features that differ TWC from wood concrete and mortars based on TMW, can be found in fine aggregate (sand), a various shape and size of the TMW aggregate, the general recipe, the processes of preparing raw materials and molding. Hence, resting on the results of exploratory studies, we can refer to higher density, physical-mechanical and other properties of TWC compared to analogues [25].

By analyzing research works, the authors concluded that the developed material has no close analogues and is essentially new.

Therefore, based on individual scientific, technical and technological approaches in the field of thermal modification and production of building materials supervised by Dr. V.Yu. Chernov (Yoshkar-Ola), the authors started the development and piloted research aimed at creating innovative, effective TMW-cement composite materials [26]. The use of TMW as the main coarse aggregate in concrete minimizes the negative properties of natural wood described above.

Today in the field of industrial production of new composite material at the Scientific and Production Association “MariTermoWoodIndustries” (Yoshkar-Ola) developed and implemented technology and equipment for thermal modification of wood (Patent Russia no. 2724421), which allowed to reduce significantly the cost of production of TMW and thereby, according to preliminary calculations, ensure the profitability of TWC production (Patent Russia no. 2790390) and products made from it.

The objective of this paper is to study the strength and thermophysical properties of the proposed TWC, as well as to estimate the influence the production (technological) factors might bring. The tasks include the production of standard TWC samples of several groups with different mix formulations and molding methods, studies on compressive strength and thermal conductivity, additionally, determining technological factors that influence the properties under study.

2. Methods

2.1. Obtaining Development Samples

The research in this work is piloted, since there are no objective data on the material being developed, its recipe production parameters and technological requirements. The authors of the work were facing with the issue of creating the first samples with properties close to the maximum expected – these are low thermal conductivity (at the level of aerated concrete), average compressive strength (at the level of expanded clay concrete), low moisture and water absorption (at the level of heavy weight concrete with mineral fillers). The authors decided on the size and shape of the coarse TWC aggregate, the class of the cement-sand mortar and the molding method to be used as variable factors when obtaining TMW samples. These factors are significant as based on the existing general provisions of wood science and concrete science and have the most impact on the physical, mechanical and thermophysical properties of wood-cement compositions.

Thus, to study the general influence of variable factors, 4 varieties (groups) of samples were described (Table 1, Fig. 1).

Table 1. Description of the characteristics of the development samples groups.

Group #	Name of sample	Relative content of components, % of volume: (cement / sand / TMW chips / water)	Description of the key features of sample manufacturing
1	Vibrocast TWC samples with large TMW filler and class of cement-sand mortar M150 (class B12.5). Main group	7 / 27 / 55 / 11	The filler used was crushed TMW in the form of an oblique parallelepiped with all dimensions (length, width, thickness) in the range from 15 to 20 mm (Fig. 1, a).
2	Vibrocast TWC samples with large TMW filler and class of cement-sand mortar M400 (class B30). Comparing group	13 / 22 / 53 / 13	Compared to other groups, the strength of the cement-sand mortar was higher by increasing the content of the cement binder. The rest is similar to the 1st group.
3	Vibrocast TWC samples with medium TMW filler and class of cement-sand mortar M150 (class B12.5). Comparing group	7 / 27 / 55 / 11	The filler used was crushed TMW in the form of an oblique parallelepiped with dimensions: length from 15 to 20 mm, width from 10 to 20 mm and thickness from 5 to 10 mm (Fig. 1, b). The rest is similar to the 1st group.
4	Vibration-pressed samples of TWC with fine TMW filler and class of cement-sand mortar M150 (class B12.5). Comparing group	7 / 29 / 60 / 4	Samples obtained by pressing a semi-dry mixture with preliminary soaking of TMW filler, having dimensions: length from 10 to 20 mm, width from 5 to 20 mm and thickness from 2 to 5 mm (Fig. 1, c). The sizes and shapes varied.

a) b) c)

Figure 1. Relative comparison of size and shape of TMW filler.

The filler for all groups of samples was used from TMW of predominantly deciduous species (*Tilia europaea*, *Populus tremula*) with the COLOR+ treatment modes using AST technology (185 °C) (Patent Russia no. 2724421). However, the existing equipment for grinding wood was not suitable due to the difference in the elastic properties of natural and TMW, which affects the cutting process, namely, such material, during high-speed cutting in standard grinding equipment, broke and crushed into a dusty form. This is not suitable for obtaining TMW-cement composition. Therefore, grinding to the specified sizes and forms of thermal modification chips was performed on specially designed equipment (Patent Russia no. 2804105).

While producing the development samples, in addition to the TMW filler, the mixture included Portland cement M 500 (marked 42.5N (CEMII/A-K)) (GOST 25328-82), clean pit sand of class I of fine and medium fraction (GOST 8736-2014) and process water (GOST 23732-2011) in appropriate proportions to obtain a solution of class B12.5 (M150) and B30 (M400) without chemical additives and other components.

2.2. Setting the Research

In accordance with standard research methods, for each of the described groups and separately for each type of a test, the authors made 10 pieces of cubic samples with dimensions of 100×100×100 mm (Fig. 2).

Figure 2. Appearance of the finished sample of group 4 for research (the side surface is cut off at the front to visualize the interior distribution of crushed TMW filler).

The mixture was prepared in a gravity-type concrete mixer, thus, subsequently the samples were produced using a vibrating table in specially made steel matrices with a removable bottom. The same matrices were used for vibrocasting as for vibrocompression, however, tiles were added to squeeze from above and form a sample from a semi-dry TMW-cement mixture. Uniform distribution, compaction and better adhesion between the cement paste and the TMW particles (Fig. 2) occur as a result of the simultaneous action of compression and vibration, namely, with the help of pressure arising from the punch and the operation of the platform vibrator. The size and shape of the sample corresponds to the matrix in which the TMW-cement composition is placed.

Subsequent exposure for both molding methods employed a simplified non-standard method and included exposure for 28 days until the design (grade) strength was reached at a temperature of 20 °C and a relative humidity of 60±5 %. Such conditions were chosen to obtain the material under less favorable hardening conditions, which is typical for simple and low-tech (non-factory) production conditions.

2.3. Methodology for Studying Strength and Thermal Conductivity Properties

Methods for studying the strength and thermal conductivity properties of TWC were in accordance with the basic requirements for testing concrete comparably with current standards (GOST 10180-2012 and 30256-94), as well as taking into account practical recommendations for the use of test measuring equipment.

The authors used a universal testing machine (UTM) SHIMADZU 50 kN (Shimadzu Corp, Japan) to study the strength of the TWC. Data processing and calculation of compressive strength (R, MPa) was performed on the maximum destructive load and the working cross-sectional area of the sample according to the formula:

$$R = \alpha \frac{F}{A},$$

where F – maximum breaking load, H; A – sample working section area, mm^2; α – scale factors (equal to 0.95 for the indicated shapes and sample sizes).

Thermal conductivity of the TWC was carried out with an automatic thermal conductivity meter by the probe method MIT-1 (LLC Scientific Development and Production Enterprise Interpribor, Chelyabinsk). For this purpose, a blind hole with a diameter of 6.2 mm and a depth of 80 mm was made in the central part of the samples. Litol-24 lubricant was used for tighter contact in the hole of the measuring probe rod with the material.

Studies of thermal conductivity of a wall block manufactured using a standard industrial method based on the vibrocompression method are also of scientific and practical interest. Therefore, the blocks with “euro holes” with dimensions 390×190×190, which are most popular in practice, were also manufactured (Fig. 3). Thermal conductivity studies on them were carried out by obtaining a hole and measuring in the central part of the block, namely in the center of the middle partition, from the side wall (Fig. 3).

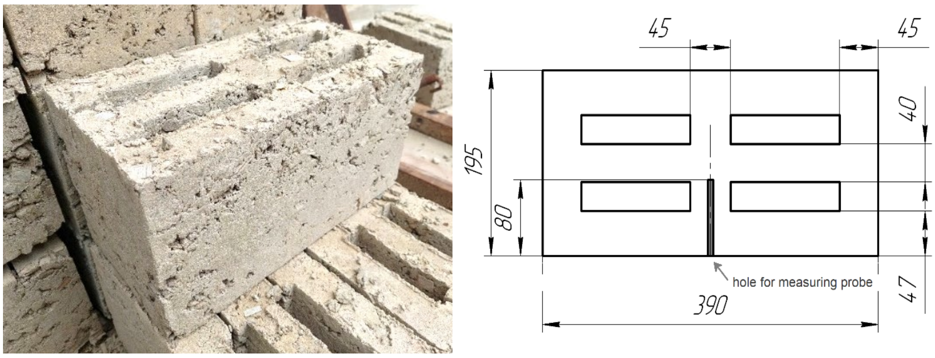
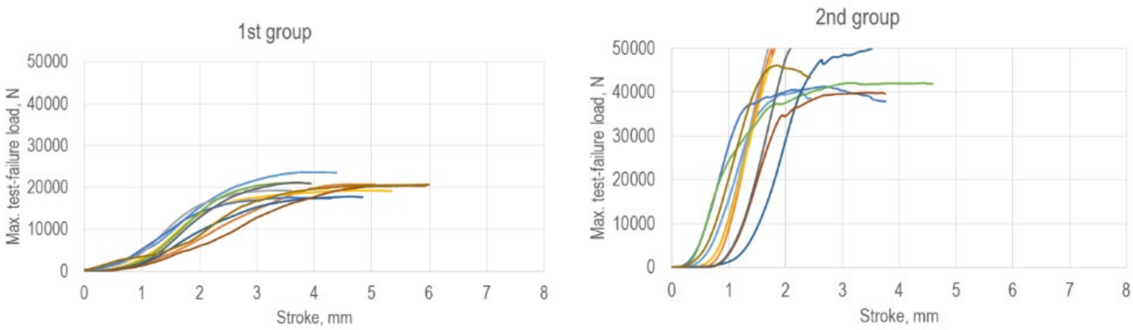


Figure 3. Appearance of blocks ready for research (left) and their dimensions with the location of the hole for the thermal conductivity meter (right).

3. Results and Discussion

3.1. Studies on the Strength of Thermal Wood Concrete

TWC strength studies were performed individually for each 10 pieces-group of samples. The main results are given in Table 2 and Fig. 4, as well as group-averaged diagrams of loading (Fig. 5).



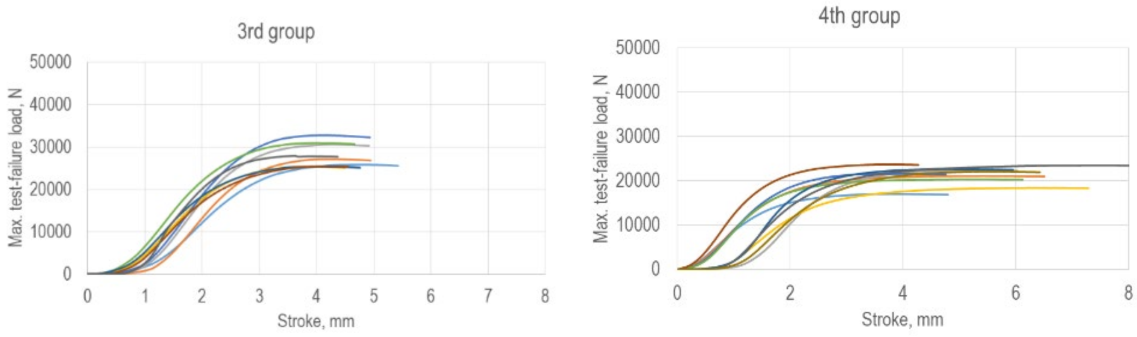


Figure 4. Sample diagrams of loading for each group (see Table 1).

Due to technical limitations of the specified UTM, it was impossible to construct complete diagrams of loading in dynamics for the 2nd group of samples. However, the results for the maximum breaking load were gained on another hydraulic testing machine without constructing diagrams and were taken into account in subsequent data processing and calculation of the average compressive strength for the group.

Table 2. Main statistical indicators of TWC strength.

Statistical indicators of TWC strength, MPa	Groups of samples			
	1	2	3	4
Average (R)	1.98	4.53	2.67	2.11
Maximum	2.34	5.00	3.05	2.47
Minimum	1.82	3.99	2.29	1.74
Standard deviation	0.162	0.367	0.242	0.229

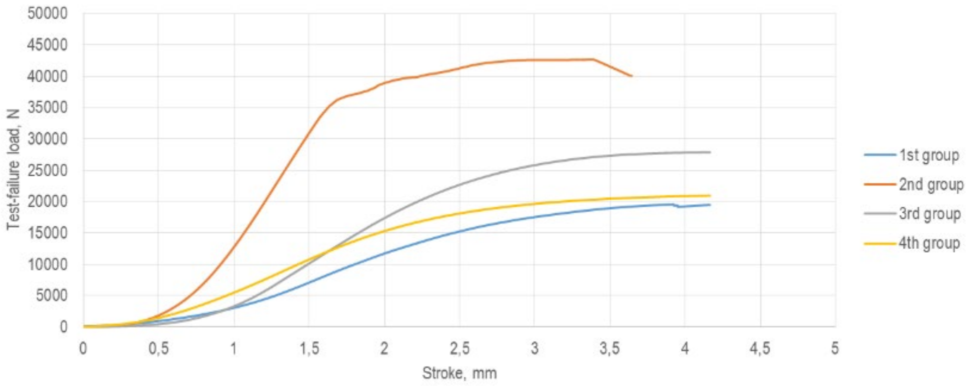


Figure 5. Average loading curves of samples for each group.

3.2. Studies of Thermal Conductivity of Thermal Wood Concrete

Studies of the thermal conductivity of TWC were also performed for samples in a volume of 10 pieces in each group. The main results are given in Table 3 and Fig. 6.

Table 3. Main statistical indicators of TWC thermal conductivity.

Statistical indicators of TWC thermal conductivity, W/(mK)	Groups of samples				Thickened block with “euro holes”
	1	2	3	4	
Average (λ)	0.32	0.28	0.40	0.21	0.31
Maximum	0.37	0.35	0.49	0.29	0.38
Minimum	0.26	0.21	0.31	0.16	0.25
Standard deviation	0.041	0.051	0.062	0.038	0.052

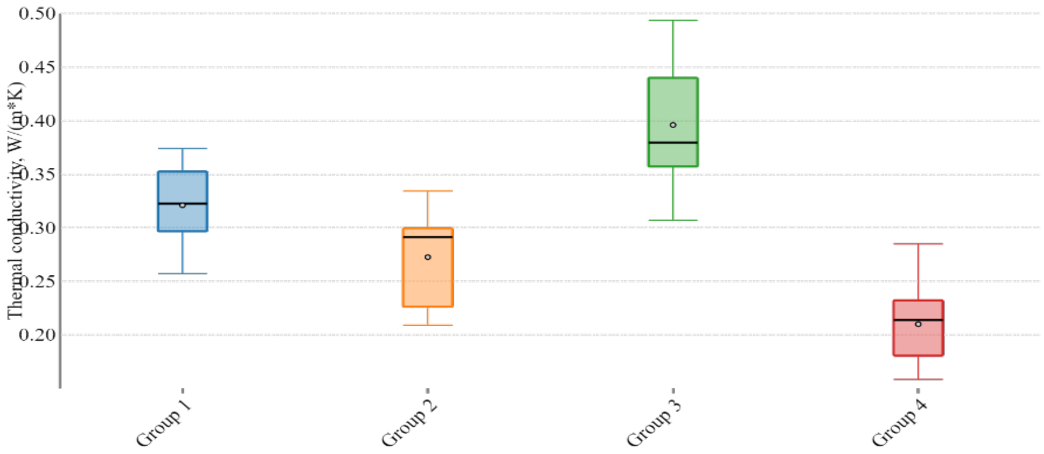


Figure 6. Diagrams of the range of TWC thermal conductivity by groups.

3.3. Comparative Analysis and Discussion

The increased content of cement binder and the grade (class) of cement-sand mixture (mortar) used to produce it both have a significant influence on the strength of TWC. When comparing the average data, the excess strength of samples from grade M400 mortar (the 2nd group) relative to grade M150 (the 1st group) was 2.3 times or 129 %.

Initially, the authors expected an increase in thermal conductivity due to an increase in the strength of the material, but the results turned out to be the opposite, namely, for samples with a higher grade of mixture, an insignificant decrease in thermal conductivity was observed by approximately 1.14 times or 12.5 %. Probably, this may be explained by the difference in thermal conductivity of the hydraulic cement binder and fine mineral filler and the difference in their relative content in the resulting mixture. That is, while manufacturing the M400 mixture, a smaller amount of fine filler in the form of sand and a larger amount of Portland cement were used, which could have a similar effect. However, this disclosure should be tested by performing special studies in this course. In this case, we can draw a general conclusion that the increased content of cement binder has a positive effect on the strength and thermophysical properties of the material under study.

The size of crushed thermally modified filler (the 1st, 3rd and 4th groups) does not have a significant effect on the strength properties of TWC. However, in the 3rd group with medium-sized TMW fillers (see Table 1), we observe a higher strength of the samples, exceeding the 1st group (main) by 35 %, and in the 4th group samples with the smallest filler sizes (see Table 1) strength also turned out to be 7 % higher than the first group. Along with strength and thermal conductivity, the 3rd group of samples had the highest value, which differed from the main group by 25 %, and the 4th group, on the contrary, had the lowest thermal conductivity, which was lower than the relative main group by 34 %.

The authors compared the results given with wood concrete based on natural wood [3, 4] and TMW [6, 23], which proved the advantages of choosing a smaller aggregate size for thermal wood concrete in terms of thermal conductivity properties and the nature of destruction. Nevertheless, the samples with an average aggregate size (the 3rd group) showed the best results in terms of strength.

Based on the nature of the destruction of the samples, we can conclude that the cement content and the size of the TMW filler affect the pattern and nature of the deformation of the wood-cement composition. In compression tests, samples with large TMW filler (the 1st and 2nd groups) were destroyed along the boundary of the filler and the hardened cement-sand mortar, and the nature of destruction according to GOST 10180-2012 had a satisfactory appearance, close in shape to a sand-glass. On the contrary, in the 3rd group during testing there was less destruction of the structural integrity of the samples, and in the 4th group we observed only slight surface damage in the particles of thermally modified filler.

At the end of testing samples of the 3rd group and especially the 4th group, elastic recovery after compression was noticeable, which indicates the high elastic-deformable properties of TWC, which probably have an inverse relationship with the size of the wood filler. For a proper understanding of the deformations and destruction of TWC, it is reasonable to perform special studies in this course.

The data obtained as a result of the tests made it possible to determine the strength class and grade strength of TWC (Table 4).

Table 4. Classification of TWC by strength.

Strength indicators	Groups of samples			
	1	2	3	4
The coefficient of variation, %	8	8	9	11
Brand strength	M25	M50	M25	M25
Strength class	B1.5	B3.5	B2	B1.5

Overall, the results for studying the compressive strength of TWC are close to those for testing wood concrete based on TMW [23, 24] and are approximately equal to 5 MPa. Still, direct comparing will be wrong, since the materials are not homogeneous, besides, the variable factors adopted in the studies do not correspond to each other.

The 4th group of samples proved to have the best thermal conductivity indicator, which is associated with the smallest size of the crushed thermally modified aggregate among the presented groups and, consequently, with a smoother distribution throughout the material and a higher percentage in the cement-sand mixture.

The 3rd group of samples is also of high interest, as it is highly thermally conductive and has increased strength compared with other materials similar in recipe. Initially, the authors expected that the 3rd group would show average values between the 1st and 2nd group of samples. Additional studies would be preferable.

TWC blocks showed higher thermal conductivity than the 4th group of samples similar in recipe and production method. This could be explained by the fact that the probe of the thermal conductivity meter was inserted into the hole obtained in the middle partition wall of the block, with a 50 mm thickness, instead of the permissible minimum standard 100 mm. Based on the known ratios of thermal conductivity of solid and hollow blocks (on average 1.5–1.75 times), the expected thermal conductivity of hollow blocks made of TWC (Fig. 3) ranged from 0.12 to 0.14 W/(mK).

Thus, the most heat-efficient material is the 4th group TWC – obtained from fine TMW filler (see Table 1) corresponding to standard technological wood chips in shape and size, and also used for the production of wood concrete. The size and shape of the TMW filler do not have a significant role on the strength of the composition, therefore, one should use cement-sand mortar of increased grade strength to obtain TWC with increased strength properties. Samples of the 2nd and 4th groups have the most balanced thermophysical and strength properties, additionally the authors recommend their production methods for practical implementation. However, studies should be performed on moisture and water absorption, water resistance and frost resistance of TWC in order to obtain the thorough and objective information on the material (composition) under study.

4. Conclusions

1. The greatest influence on the strength properties of TWC is exerted by the cement binder content in the cement-sand paste (the 2nd group), while with an increase in the amount of cement, the compressive strength also increases by more than 2 times. The size of the TMW filler has a noticeable effect. It was found that the TMW-cement composition has a strength 1.3–1.4 times higher than that of similar samples (the 1st group) with other filler sizes. There is also a difference in the strength of TWC concrete of different molding methods, namely, the strength of the TMW-cement composition obtained by vibration casting is 1.3–1.4 times higher than that of the vibration-pressed one.

2. The best ratio of strength and thermal conductivity properties were found within TWC made with the use of TMW filler characterized by the following dimensions: length from 10 to 20 mm, width from 5 to 20 mm and thickness from 2 to 5 mm – the 4th group. These dimensions are the closest to technological wood chips. While performing strength tests, these TWC samples were most efficient in preserving their structural integrity and showed the highest elastic recovery after unloading.

3. The grade and increased content of cement hydraulic binder in the cement-sand mixture used to make TWC both have a positive impact on the strength properties of TWC. Meanwhile, cement hydraulic binder slightly reduces the thermal conductivity of TWC.

4. The strength of the recommended TWC samples is 2.11 MPa (the 4th group) and 4.53 MPa (the 2nd group), which corresponds to grades M25 and M50 or strength classes B1.5 and B3.5, respectively. Their thermal conductivity is 0.21 W/(mK) and 0.28 W/(mK), accordingly. It is necessary to note that in case the TMW filler of the 2nd group samples was coarse, then based on the identified patterns when using fine TMW filler as in the 4th group, samples of the 2nd group would have shown better strength and thermal conductivity properties.

5. The thermal conductivity can be in the range of 0.12–0.14 W/(mK) when manufacturing a hollow building material from TWC, for example, in the form of a standard block with “euro holes”.

6. We should note that for this work specifically, the authors obtained the strength and thermophysical properties of TWC under simplified curing conditions, without heat and moisture treatment and any chemical additives that increase plasticity, strength, frost resistance and other properties. Thence, one can improve the properties of TWC, like other concrete with the indicated methods.

7. The results and patterns acquired in this work are fundamental and can serve as the basis for more in-depth research of the material, as well as finding optimal ratios of recipe factors and making high-quality TMW-cement compositions. Furthermore, the authors are expecting to continue researches on moisture and water absorption, water resistance, frost resistance, etc., as well as to develop an optimization model and method for getting the material, relying on the functional purpose (the ratio of physical-mechanical and thermophysical properties) and the economic efficiency of the production of TWC.

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