MANUFACTURING ARBOLITIC BUILDING PRODUCTS USING SOLAR ENERGY

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ABSTRACT

This article examines the potential of using arbolite as a building material based on agricultural waste, thereby solving the problem of product recycling and quality. This article introduces some innovative methods of thermal arbolite processing using climatic resources – solar energy. This article examines the potential of treating arbolite by various methods of heat treatment, at which the solar energy utilization is the optimal one. There are new data on the physical and technical arbolite testing, as well as on the structural studies of material. The temperature field and the hardening kinetics of a product, shaped in a metal die, were simulated at mixed convective and radiative heat treatment of product surface to solve technological problems of treating arbolitic products with heat using solar energy. The introduced technology underwent the technical and economic analysis.

KEYWORDS

Arbolite, solar energy, temperature condition, rice husk, solar heat treatment.

1. INTRODUCTION

Natural raw materials can be rationally utilized with industrial and agricultural waste for some materials to be produced depending on the combination of their strength, thermal conductivity and other properties [1-2]. Such materials is may include arbolite, intended for residence and public walling. Arbolite is known to be an effective heat insulating material.

Low-density arbolite-made products are characterized by excellent construction, physical, technical and hygienic properties. They are drillable, cuttable and overcoatable. Arbolite is a durable ecological material that has high heat-saving properties. Its thermal conductivity is 0.08-0.17 W/(mK). This figure 2.5-3.5 times exceeds the LECA thermal conductivity and 4-5 times – the brick thermal conductivity. Twice less utilities are required for heating the space with 30 cm walls of thick arbolite than for heating the space with 75 cm brick walls (three bricks separating the street and the room).

Arbolitic blocks are intended for non-bearing walling. They are also used as heat and sound insulating material placed in walls, partitions and coatings. Arborlite is undecayable and cannot be invaded by fungi and microorganisms. Arborlite does not burn – it outperforms many popular construction, physical, technical and hygienic properties. They are drillable, cuttable and overcoatable. Arbolite is a durable ecological material that has high heat-saving properties. Its thermal conductivity is 0.08-0.17 W/(mK). This figure 2.5-3.5 times exceeds the LECA thermal conductivity and 4-5 times – the brick thermal conductivity. Twice less utilities are required for heating the space with 30 cm walls of thick arbolite than for heating the space with 75 cm brick walls (three bricks separating the street and the room).

Arbolite blocks have a large-pore structure, contributing to a perfect air exchange and humidity regulation in the room. Arborlite can be easily machined – sawed (any block can be sized at any time), drilled, cut. This material keeps screws and nails. Its noise reduction coefficient (NRC) is in the range from 0.17 to 0.6 (at 125-2000 Hz), while for bricks and wood NRC is under 0.04 (at 1000 Hz) and 0.06-0.1, respectively. The arbolitic blocks have special surface that contributes to high-quality adhesion between the block and concrete/coating material without additional reinforcement. The weight of arbolite wall blocks is significantly lower than of many other building materials. This allows using a cheap lightweight foundation and significantly reducing the complexity and cost of construction and installation work. If the maximum permissible loads are exceeded, the arbolite does not crack as almost all the concrete materials do. In fact, it shrinks and restores its shape in a while. This allows going through the building settlement without damage.

Arbolite production enterprises are located mainly in the regions with large base of woodworking, sawmilling and logging waste. In Kazakhstan and Central Asia, large-scale arbolite production is based on plant waste. Such agricultural wastes include chopped bulruch, hemp or flax sheave, rice husks and straw, etc. Although there are numerous studies in the field of arbolite technology improvement, further search for ways to efficiently utilize the industrial and agricultural waste, and thereby increase the product quality, is relevant. Therefore, it is advisable to increase the rate of industrial and agricultural waste utilization in order to save resources [2]. Such a program will undoubtedly promote a significant expansion of the range of building cement composites produced at a new technical level, such as the arbolite and fibrolite. At this point, arbolitic products are reasonable to produce for low-rise and rural construction.

The Kyzylorda Region has a significant mineral resources (oil, gas, polymetallic ore, uranium and salt) potential. This region is the fourth in row by oil production. Rice production is centered mainly in the Kyzylorda Region. In the Republic of Kazakhstan, rice growing is currently around the corner of a new stage, which should contribute to its effective development. At this point, rice growing effectiveness should be improved through the utilization of rice husks, which output is 12-14% at rice processing. The Kyzylorda Region produces up to 5 thousand tons of husks annually. Thus, it is relevant to investigate the ways for effective rice husk utilization. Climatic resources (solar and wind energy) occupy a special place in the region. Therefore, it is time to develop the resource-saving and energy-saving technologies in the Kyzylorda Region.

This article examines new methods of treating arbolite with heat using solar energy. The issues of heavyweight concrete treatment with heat have been studied by Aruova L.B. (L.N.Gumilyov Eurasian National University) and other professors under the guidance of Krylov B.A. (Research Institute of Concrete and Reinforced Concrete) since 2000 [3-7]. In the Republic of Kazakhstan, building and construction sector is two-way (prefabricated cast-in-situ construction) and developing at a rapid pace. Some countries are orientated only toward the cast-in-situ construction, but this solution is not the best, as both types of construction have their advantages and disadvantages.
Thus, developing both is the rational option. In all technologically advanced countries (France, Germany, the USA, Sweden, etc.), the share of prefabricated construction is 40%. It is slightly lower (20%) only in the seismic regions, such as Japan [8-14]. In the Republic of Kazakhstan there is a good industrial base for the prefabricated construction that was developed during the Soviet period and continues to develop.

At the same time, precast concrete industry is a major heat consumer, while the heat treatment is the most energy-consuming technological process (over 70% of heat goes for treatment). In the Republic of Kazakhstan, southern regions are characterized by a dry hot climate. At this point, solar heat treatment is the most rational method to be applied for reducing the energy consumption during the prefabricated reinforced concrete production. The following effective methods have been recently introduced for treating the reinforced concrete products with heat using the solar energy in the open workshops and on the solar grounds. Solar Treatment is combined with the Light Heat-Insulating Covers (including solar chambers with heat-accumulating elements). There has been also introduce the solar heating method implying for the application of special membrane forming compounds. As the mixed methods of solar heat treatment appeared, the solar energy could be used for treating the concrete and reinforced concrete products with heat all year round. At this point, prefabricated reinforced concrete production will be less energy consuming.

Factories begin to learn the solar heat treatment methods for manufacturing not only standard concrete, but also the arbolitic building products. The variety of solar heat treatment methods allows choosing the optimal and cost-efficient method. Solar heating technology, applied for the production of various types of concrete, raises the energy utilization ratio through the internal source (heat evolution) at the stage of concrete hardening acceleration. At the same time, soft heating and cooling modes contribute to the high-quality product manufacture. Methods of treating concrete with heat using solar energy should take a proper cell in the industry. Various research results are being currently commercialized. Conducted studies have shown solar energy is a beneficial method for treating concrete with heat. The purpose of this research is to design and introduce the cost-efficient and environmentally friendly technologies and methods of arbolitic building products manufacture with product hardening intensification, driven by the solar energy utilization.

2. METHODS

We have designed some methods for mixed solar heat treatment of arbolites in the workshops and on the solar grounds through the solar systems with a circulating intermediate coolant. The method is to manufacture high-quality products year-round by utilizing the solar energy in the autumn-spring and winter periods using solar systems with a circulating intermediate coolant, as well as traditional types of energy in case of zero solar energy accumulated. At this point, products go through the summer heat treatment (HT) at the solar power ground. In the autumn-spring-winter periods, when the solar radiation comes down to near zero rates, a year-round solar system with an intermediate coolant is introduced to the process. Solar heat treatment is carried out under the light cover at soft modes with the chamber temperature max fixed as 700. The product rise temperature (rise time: 4-7 hours) increases at the isothermal hardening time of 6-7 hours. The product cools down to 35°C.

Since the chamber bottom is filled with water, the climate inside the chamber is 100% humid. The 24-hour concrete strength is 50-70% R28. This method of solar heat treatment will provide a year-round heat treatment with the possibility of saving nature and 50-100% of traditional fuels, as well as manufacturing high-quality products. Solar HT method, intended for application through a solar system with an intermediate coolant, was designed for arbolitic building products (Innovation patent No. 2020. Heat Treatment Method for Arbolitic Building Products published in Kazpatent on February 19, 2014). At the moment, heat treatment issue, put forward in relation to almost every type of concrete (including light concrete) and implying for non-traditional energy (solar energy) utilization, is becoming more relevant.

The new solar heat treatment charts, designed for arbolitic products and intended for application in the dry hot environment of the Kyzylorda Region (Republic of Kazakhstan) will allow saving nature (no emissions from fuel burning) and 50-100% of traditional fuels, as well as manufacturing high-quality products at low cost. The method is to manufacture the high-quality concrete products year-round, utilizing solar energy at max with the year-round solar systems in the autumn-spring and winter seasons (Kazpatent No. 31795 Solar Chamber for Heat Treatment of Concrete Products; Bulletin No. 18 dated December 30, 2016). At this point, light solar chamber undergoes heat treatment on the solar grounds next to the solar system in summer. In the autumn-spring-winter periods and in cloudy weather, additional energy sources will compensate the lack of solar energy. In the case when the light chamber is on use with the solar system in the autumn-winter-spring periods, the lid is advisable to place at the angle of 35°C.

Soft heat treatment is carried out at the max temperature of no more than 70°C in a light chamber: temperature rise time is 5-7 hours, conditional isothermal holding time is 5-7 hours, cooling-down temperature is 35-50°C. The humid hardening environment is created by wet tarpaulin covering the products. Concrete strength reaches 50-70% R28 at 24-hour age. The mixed type of solar heat treatment in light solar chambers, intended for application under zero solar radiation, allowed manufacturing high-quality products with high physical and technical characteristics. This method of heat treatment will contribute to a year-round treatment and high-quality manufacture and will allow saving nature and almost 100% of traditional fuel.
Hot and dry weather is a serious problem for concrete technology, as it sparks many negative consequences. Therefore, destructive processes that occur during the concrete shrinkage, sparked by intensive dehydration in dry weather, can be frozen by efficient concrete care.

3. DATA, ANALYSIS, AND RESULTS

3.1 Arbolite

In the course of experimental research, we have manufactured arbolite according to the GOST 19222-84. As raw materials, we have used the portland cement, lime, ash collected at the Kyzylorda Combine Heat and Power Plant, organic plant-based filler (hogged chips) and agricultural waste (shredded rice straw, cotton plants, bulrush and rice husks). The blown sand was used as a mineral additive, while the fluid glass was used as a chemical additive. We have used the collected ash as an active mineral additive, according to the Building codes and regulations.

Table 1: Arbolite Composition

| Composition | Concrete M400, kg/m³ | Shredded Rice Straw, kg/m³ | Water, 1/m³ | Fluid Glass +CaCl₂ kg/m³ | Foaming Agent, 1/m³ |
|-------------|----------------------|---------------------------|-------------|-------------------------|---------------------|
|             | 370                  | 200                       | 400         | 9+4.5                   | 60                  |

We have treated the 200x300x600 mm arbolite blocks, which composition is indicated in Table 1, with heat in the light solar chambers with and without an intermediate coolant. The Table 2 and Figure 5 illustrate that the solar heat treatment of arbolite blocks with a film-former was carried out in a light chamber with an intermediate coolant at the following temperature regimes: max temperature – 52-53°C; cooling-down temperature – 20 °C. The conducted research does not allow recommend the intensified modes of heat treatment. The attempt to steam the arbolite as ordinary concrete leads to strength reduction, since steaming sparks the increase in internal stress due to cubic deformations of the filler that break the integrity of the material structure. At the same time, wood filler releases more sugar, poisoning the cement.

The best results were obtained at the soft low-temperature treatment: heat temperature – 40-50 °C; relative humidity – 80%. At this mode, arbolite acquires the stripping strength after 18-20 hours. However, its strength does not exceed 25-40% of the brand product strength, while the moisture content remains within 30-35%. Products should be also indoor stored at 16-18 °C for at least 7-14 days for the strength to be improved and the moisture content to be reduced to standard values. After that, products can be sent to storage with any temperature-humidity conditions (natural storage without humidification). Product hardening is an important technological process in the arbolite production, so it is important to study the hardening process and the choice of optimal acceleration methods [3-4, 15-18]. In any case, arbolite should be treated with heat at 40 °C and 50-60% humidity to get the process to be effective. The temperature rise above 40 °C leads to a decrease in the product strength due to stress-strain properties of wood and other cellulose-containing fillers.

In the case of arbolite products, heat treatment mode should provide not only the required transport and design strength, but also the handling moisture content in products that would not exceed the target value. The moisture content can be reduced if products are treated with heat in conditions conducive to moisture evaporation from the arbolite. Such heating should be carried out at a temperature of no more than 40 °C in chambers equipped with thermoelectric heaters (TEHs), heating devices, infrared heating elements or gas burners with additional ventilation installed. No heat treatment is allowed in saturated steam or steam-air medium, as well as on thermal trays. Composition of a concrete mixture, based on portland cement binders, is selected with regard to target concrete class and grade in accordance with the current regulatory documents. We have also took into account the experience of previous developments.

There were studied the strength characteristics of arbolite hardened in a solar chamber [19]. The arbolite composition was selected by measurement, based on the manufacturing conditions fixed for a heat insulating material B0.35-B3.5 with an average density of 458-700 kg/m³. At the end of electric heat treatment, each composition was adjusted with regard to temperature and dilution factors affecting the arbolite structure formation. The compressive strength of 15 Grade Arbolite, based on rice husks, reaches 1.61 MPa at hardening in the solar chamber.

Table 3: Arbolite strength characteristics

| Filler                | Grade | Compressive Strength, R, MPa | Prismatic Strength, Rp, MPa | Rp/ R  | Tangent Modulus of Elasticity, MPa |
|-----------------------|-------|-----------------------------|-----------------------------|--------|----------------------------------|
| Rice husks            | 15    | 1.61                        | 1.18                        | 0.73   | 680                              |

3.2 Arbolite concrete structure and phase formation

3.2.1 Materials and Methods of the Experiment

The powdered mixture of cement and rice husk undergone the X-ray diffraction at the room temperature with a diffractometer. An X-ray tube used for the analysis had an accelerating voltage of 30 kV and a current of 10 mA. The phase analysis was carried out in a semi-automatic mode using a PDF database containing 400 candidates. The most closely resembling thereof were selected in manual way.
4. RESULTS

The X-ray scattering spectra (diffraction pattern) are introduced for both groups of samples (Figures 6 and 8; Tables 4 and 5). The pattern illustrates the phase components as color segments, indicating their shares in percentages.

![Figure 6: X-Ray Diffraction Pattern of an Arbolite Sample. Heat Treatment in a Solar Chamber](image)

Table 4: Semi-Quantitative Phase Analysis of Sample 2

| No. | Ref. Code  | Compound Name          | Chemical Formula | Semi Quant [%] |
|-----|------------|------------------------|------------------|----------------|
| 1   | 01-086-1629 | SiO2, quartz low       | SiO2             | 12             |
| 2   | 01-086-2339 | Calcite, high, syn     | Ca(CO3)          | 9              |
| 3   | 01-086-0402 | Tricalcium silicon pentaoxide | Ca3SiO5   | 25             |
| 4   | 01-084-0148 | Calcium chondrodite    | Ca5(SiO4)2(OH)2 | 36             |
| 5   | 01-080-0942 | Olivine, syn           | Ca2(SiO4)       | 19             |

Numbers 1 and 2 indicate the Gaussian approximations made with a special program. The calculated curve is marked with a dark blue line. The phase concrete composition of samples 1 and 2 is the same, only the concrete factor is different. The morphology of samples 1 and 2 is a key to understanding the hardening mechanisms of concrete made with rice husks and hardened with/without a film. In concrete with a film, rice husk surface is smooth without significant defects, and hence, with no crystal formation centers (Figure 7). The microphotographs of concrete, mixed with rice husks and hardened without a film, reveals a multiple defect formation – pores and cracks became filled with crystallizing agents. This is most likely to cause the strengthening of the adhesion bond between the husk surface and the structure-forming substrate that forms the concrete nanostructure, even if the cement moves far from the rice husk surface (Figure 9). Thus, full-scale structural researches on concrete composites allow us to substantiate the application of the film-based hardening method that improves the adhesion relations between the concrete nanocrystals.

4.1 Electron-microscope investigation of arbolite samples, hardened in the light chamber

![Figure 7: Sample 2 Morphology: a – 2000x zoom, b – 4000x zoom;](image)
4.2 Electron-microscope investigation of arbolite samples, hardened outside the light chamber

The arbolite structure analysis, conducted after the solar heat treatment, has revealed that the phase chemical composition of the new growth crystals does not differ from the cement stone composition, formed under normal conditions. This proves that their quality is good.

4.3 Numerical Simulation of Solar Heat Treatment, Carried Out in Relation to Arbolitic Building Products

The solution of technological problems, related to the solar heat treatment of arbolitic building products, requires the temperature field and the hardening kinetics of a product, shaped in a metal die, to be simulated for the case of mixed convective and radiative heat treatment [16, 19]. Let us consider the two-dimensional numerical simulation technique [20]. Nonlinear parabolic equations serve as the basis for many mathematical models. The nonlinear heat conduction (NLHC) equation is often applied in line with the basic conservation laws. The boundary value problems for the nonlinear heat conduction equation are of current interest. The NLHC equation differs from the linear one at the point, when the heat conduction coefficient (HCC) turns to be dependent on temperature. Thus, many methods for solving the problems of mathematical physics cannot be applied to solve the nonlinear equation. Despite a lot of researching on the processes of nonlinear heat conduction, there are still no analytical solutions.

The mathematical model, where the temperature field is described for the arbolitic block by a two-dimensional NLHC equation with variable constants and heat sources that takes into account the exothermic heat release of cast product, is as follows:

\[
\begin{align*}
C(x,y)\left[\frac{\partial^2 T(x,y)}{\partial x^2} + \frac{\partial^2 T(x,y)}{\partial y^2}\right] &+ \frac{\partial}{\partial x}\left[\lambda(x,y)\frac{\partial T(x,y)}{\partial x}\right] + \frac{\partial}{\partial y}\left[\lambda(x,y)\frac{\partial T(x,y)}{\partial y}\right] + F(x,y) + Q(x,y) &\quad (1)
\end{align*}
\]

The out-the-chamber heat effect is given by the combined boundary conditions of the second and third kind:

\[
\lambda(x,y)\left[\frac{\partial T(x,y)}{\partial x}\right]_{x=R} = \alpha_1 T(x,y)_{x=R} - \frac{t_{av}}{c_v} + q_{ex}(x,y) &\quad (2)
\]

Thus, many methods for solving the problems of mathematical physics cannot be applied to solve the nonlinear equation. Despite a lot of researching on the processes of nonlinear heat conduction, there are still no analytical solutions.
Calculation results were obtained at the following basic data: conservative difference schemes, and then solved by sweeping along the rows and columns [22-23].

The natural air temperature \( t_f \) varies from 20 °C to 38 °C.

The manufacturing process started in 11 a.m. Calculation results coincide with the experimental data with sufficient accuracy. Thus, method that was applied for numerical simulation of the temperature field can be applied to solve practical problems.

Notations:

- \( t(x,y) \) - temperature, °C;
- \( \lambda(x,y) \) - HOC of either the arbolite, or the metal, W/(m\(^2\)*°C);
- \( c(x,y) \) - specific heat of either the arbolite, or the metal, kJ/(kg*°C);
- \( \lambda \) - arbolite/metal density, kg/m\(^3\);
- \( F \) - cement factor, kg/m\(^3\);
- \( Q_3 \) - exothermic heat release, kJ/kg;
- \( a \) - coefficient of heat transfer from the metal dies sides, W/(m\(^2\)*°C);
- \( q_{\text{flow}} \) - coefficient of heat transfer from the die base, W/(m\(^2\)*°C);
- \( q_{\text{ver}} \) - coefficient of heat transfer from the outside-the-chamber surface of the block: a
- \( q_{\text{vert}} \) - solar radiation flow to the block sides, W/m\(^2\);
- \( q_{\text{diff}} \) - diffuse solar radiation flow, W/m\(^2\);
- \( t_{\text{in}} \) - initial block temperature, °C.

5. DISCUSSIONS

The conducted researches on arbolite do not allow recommending traditional intensified modes of heat treatment [19, 27]. The attempt to steam the arbolite as ordinary concrete leads to strength reduction, since steaming sparks the increase in internal stress due to cubic deformations of the filler that break the integrity of the material structure. At the same time, the wood filler releases more sugar, poisoning the cement. The best results were obtained at the soft low-temperature treatment: heat temperature - 40-50 °C, relative humidity – 80%. At this mode, arbolite acquires the stripping strength after 18-20 hours. However, its strength does not exceed 25.40% of the brand product strength, while the moisture content remains within 30-35%. Products should be also indoor stored at 16-18 °C for at least 7-14 days for the strength to be improved and the moisture content to be reduced to standard values. After that, products can be sent to storage with any temperature-humidity conditions (natural storage without humidification).

We have found that heat treatment of arbolite using solar energy will be way more effective at 40 °C and 50-60% humidity. The temperature rise above 40 °C leads to a decrease in the product strength due to stress-strain properties of wood and other cellulose-containing fillers. We have analyzed the tensile strength and compressive strength of arbolites treated with solar heat. It turned out that in a dry hot climate, the strength of selected arbolites is directly proportional to the amount of WDFF (water-dispersible film formers) added: the lower is that amount the higher is the strength. The strength of arbolitic samples that have been undergoing the solar heat treatment for 24 hours is up to 75-80% of the strength that the brand arbolite has. The compressive strength of 15 Grade Arbolite, based on rice husks, reaches 1.61 MPa at hardening in the solar chamber. The solar heat treatment of arbolitic blocks with a film-former was carried out in a light chamber with an intermediate coolant at the following temperature regimes: max temperature – 52-53°C; cooling-down temperature – 18-15 °C. The intermediate coolant temperature reached 69-68 °C. Maturity degree was 1000-950 degrees/hour.

The arbolite structure analysis, conducted after the samples underwent different methods of solar heat treatment, has revealed that the phase chemical composition of the newgrowth crystals does not differ from the cement stone composition, formed under normal conditions. This proves that their quality is good. This can be explained by the fact that unlike the electric heat treatment and steam heat treatment, the soft solar heat treatment, carried out with a gradual rise and fall of temperature, favorably affects the product structure.
formation. At the research end, we have determined the relationship between the time of solar energy intake and the arbolite growth, the solar energy effect on the temperature fields of products with different sizes and surface areas, treated with solar heat. We have also determined the characteristic features of treated arbolite structure and the most important qualities of arbolites that were alike the concrete treated with solar heat under normal conditions. We have designed some new types of lightweight solar chamber technology, intended for application with film formers and in combination with solar systems with an intermediate coolant.

6. CONCLUSION

The transition from traditional methods of heat treatment to mixed solar heat treatment with solar energy utilization will save the manufacturer some arbolite production costs, namely ~ 2237.7 tenge/m³ (USD 6.84). Therefore, our mixed solar heat treatment technology, designed for manufacturing the arbolitic building products using film formers, allows stepping back from traditional steam heating for 5-6 warm months in areas with a hot climate. In the cold season, however, mixed technology allows saving up to 70-100 kg of equivalent fuel and 0.6 t of water per one m³ of product, and thus, saving 2237.7 tenge per one m³ of product (USD 6.84). The actual economic effect of manufacturing 1000 m³ of arbolitic building products using mixed solar heat treatment with film-formers was 2237700 tenge (USD 6843.11). Conducted researches lay ground for a positive assessment of introduced methods and for recommendations, made for a wide-scale application of solar heat treatment in manufacturing arbolitic building products.

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