Technological capabilities of manufacturing heat insulating materials based on crushed cotton plant stems

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Abstract. Today's priority in construction lies in three primary areas: ecology, energy efficiency and cost-effectiveness. It means that the most important task it to construct environmental, energy-efficient and cost-effective buildings and structures. To erect houses having such characteristics, primary elements of a structure (brick block, etc.) must be made subject to the conditions that provide for the above characteristics. The prevailing trend in construction is the production of environmental, energy-efficient and cost-effective construction materials. This research is intended to develop an energy efficient procedure to make heat-insulating materials based on crushed cotton plant stems. To achieve this goal, the authors have addressed the following issues: describing the process of making a heat-insulating material based on crush cotton plant stems; analysis of energy-efficient characteristics of manufacturing materials based on crushed cotton plant stems; and analysis of environmental friendliness of such a material. The research applies the deductive method based on mathematical modelling. The subject of the research is the procedure to make a material based on crushed cotton plant stems. The primary conclusion and outcome of this research is that papercrete based on crushed cotton plant stems has such advantages as cost-effectiveness, environmental friendliness, energy efficiency and low resource demand in manufacturing and operation. The resulting strength of papercrete allows using it as a heat insulating material to erect low-rise buildings.

1 Introduction

Society development is directly or indirectly related to construction development. Progress in the field of construction is achieved, among other things, also by evolution of construction materials. Construction materials represent natural or artificial materials, compositions and products made of them, used in construction to manufacture structures and to erect buildings and structures. Today, the use of secondary agricultural resources as important feedstock for making construction materials is of high importance, especially in the Republic of Chad located in the central part of the African continent and having developed agricultural

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production. Moreover, using the wastes of the energy industry to partially replace the primary binder in concretes and cement mortars is also a perspective trend of scientific progress in the construction industry [1].

Using secondary resources of agriculture and industry wastes will reduce the use of natural mineral resources and will improve the environmental situation. Moreover, this improves strength characteristics of materials and increases the life cycle of structures [2].

It must be noted that materials and procedures to manufacture and use them in the area of construction must be energy-saving. Using the principles of energy saving ensures the following advantages: reducing the demand in energy when making construction materials thanks to the use of low-energy production technologies; using efficient heat-insulating materials for the construction of residential and public buildings, which can reduce heat losses via enclosing structures [2]. Therefore, developing new energy-saving manufacturing technologies for heat-insulating materials using large-tonnage man-made wastes will make it possible to manufacture cheap construction materials and address the issues of secondary agriculture and industry resources.

This paper is intended to develop an energy-efficient procedure to manufacture heat-insulating materials based on crushed cotton-plant stems. This goal is achieved by solving the following tasks: describing the process sequence for making heat-insulating materials based on crushed cotton plant stems; analyzing energy-efficient characteristics of its manufacture procedure; analyzing the environmental profile of the material. The subject matter of this research is the procedure to manufacture a material based on crushed cotton plant stems. Research methods are principles of mathematical modelling of nonstationary heat and mass transfer.

2 Materials and methods

2.1 Procedure for making heat-insulating papercrete based on crushed cotton plant stems

The process of making a heat-insulating material based on crushed cotton plant stems includes the following stages: collection and crushing of cotton plant stems; soaking the crushed stems; preparing the papercrete mixture; pressing and vibration; drying; inspection of finished products; consumption. Figure 1 schematically shows the manufacturing process of papercrete blocks made of crushed cotton plant stems.

The preparation process of manufacturing the heat-insulating papercrete starts with collection of cotton plant stems, their crushing, rejection according to screening parameters, transportation to the production site, and stacking. The crushed cotton plant stems should be less than 40 mm long, 10 mm wide and 5 mm thick [3]. Crushing is followed the soaking for no more than 2 days to decrease the concentration of sugars and gluconates, which reduces the cement core effect on delayed setting of the papercrete mixture and curing of papercrete and improves the final fire resistance [4]. This is followed by drying and sieving of the crushed product to sort the most optimum parts.

The primary manufacturing process of the heat-insulating papercrete using crushed cotton plant stems includes the following primary operations: preparation of the feedstock mixture; molding; pressing and vibration; drying and removal from the mold. To improve strength properties of papercrete, the feedstock mixture is injected with a low amount of chemical additives of various purpose: curing accelerators (calcium chloride, calcium nitrate, aluminum sulphate); porosity regulators (liquid-glass foaming agent, liquid glass, neutralized air-entraining resin); those improving protection against steel reinforcement bars (alkylsulfate paste); improving bactericide and insecticide properties (saponified wood tar,

saponified wood pitch), and those simultaneously regulating various properties (sodium ethylsilicate, sodium methylsilicate, polyhydrosiloxane) [5]. If regulatory requirements are met, papercrete products have the following characteristics represented in Tables 1 and 2 [5, 6].

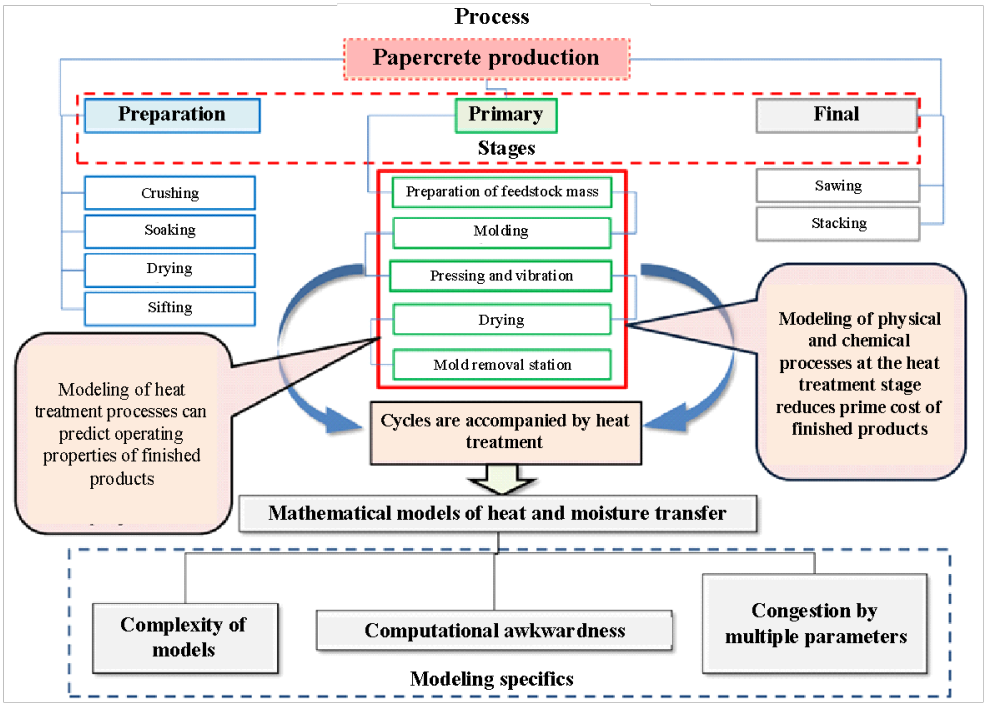

Fig. 1. Process of manufacturing papercrete blocks made of crushed cotton plant stems.

Table 1. Strength of papercrete dried to constant mass [6].

Type of papercrete	Compressive strength class	Axial compressive strength grade	Mean density, kg/m3, for papercrete made of crushed cotton plant stems
Heat-insulating	B0,35	M5	400-450
	B0,75	M10	450-500
	B1,0	M15	500
Structural	B1,5	-	500-650
	B2,0	M25	600-700
	B2,5	M35	700-800
	B3,5	M50	-

Table 2. Heat conductivity of papercrete dried to constant mass [6].

Filler type	Heat conductivity of papercrete, W/(m·°C), at mean density, kg/m^3								
	400	450	500	550	600	650	700	750	800
Crushed cotton plant stems	0.07	0.075	0.08	0.095	0.105	0.11	0.12	-	-

2.2 Energy efficient procedure to manufacture structural heat-insulating materials based on crushed cotton plant stems

A new trend in construction is energy-efficient materials and technologies. Energy use is taken into account at all life cycle stages of the construction material, product or structure. The main indicator of efficiency in the production of construction materials or erecting buildings is the reduced prime cost at all stages of the facility life cycle. Energy efficient materials have improved physical and mechanical properties. They reduce expenses for the period of operation. This approach is formulated in Federal Law No. 261 On Energy Saving and Improving Energy Efficiency and Making Changes to Certain Legal Acts of the Russian Federation [7]. Table 3 gives primary energy expenses for the most common construction materials [2].

Table 3. Example of primary energy expenses for the most common construction materials and their environmental comparison [2].

Type of material	Primary energy expenses for production of feedstock and manufacturing of material kW· h/m^3
Aluminum	7250
Polystyrene	18,900
Mineral wool	10,000
Cement	1700
Fiberboard	800
Ceramic brick	500
Aerated concrete	450
Lime-sand mortar	350
Wood building materials	180
Construction materials made of vegetation-origin feedstock (cane, straw, flax piles, etc.)	9

To manufacture energy-saving materials such as heat-insulating papercrete, the initial feedstock (crushed cotton plant stems) is an organic filler that provides reduced weight of products and gives a solution of environmental issues [8]. The evaluation of environmental effects of construction materials is given in Table 4 [2].

Table 4. Evaluation of environmental effects of construction materials.

Type of construction material	Negative effects of production and use of construction material as per its life cycle stages						Environmental evaluation of damage (total score)
	Ecosystem damage	Deficiency	Emissions	Energy	Health	Waste	
Wood	1	1	1	1	1	1	6
Natural stone	3	2	1	2	1	1	10
Ceramic materials	2	1	1	3	1	1	9
Glass and other mineral metls	3	1	2	3	1	1	11
Metallic	3	2	3	3	2	1	14
Based on mineral binders	3	1	2	3	2	2	13

Based on synthetic polymers	3	3	3	3	3	3	18
Using large-tonnage man-made wastes	2	1	2	2	2	2	11

Table 4 gives assessment of negative effects for each eco-factor: 3 points – highest negative effect; 2 points – medium negative effect; 1 point – lowest negative effect. In accordance with the level of negative effect for each eco-factor, we must define the scale of total negative environmental burden and human burden for the materials given in the table: 1 to 6 – low burden; 7 to 12 – medium burden; 13 to 18 – high burden [9]. According to the indicators represented in Tables 3 and 4, construction materials made of vegetable feedstock have a high environmental score. Therefore, a structural heat-insulating material based on crushed cotton plant stems is environmentally friendly, and its use as an energy-efficient material will save heat and energy for the operation period of buildings and structures.

This material may serve a basis for environmental comfort of people, guarantee its health safety and promote environmental protection against contamination with man-made wastes. Using breathing materials keeps the harmony between people, their dwelling and nature without detrimental effects on future generations. Materials with environmental characteristics have the following advantages: safety for human health and environment and minimal burden, high repairability and easy interchangeability, as well as ability to dispose after the end of life.

3 Results

When developing the sequence of process operations for manufacturing the structural heat-insulating material based on crushed cotton plant stems, the authors have developed a mathematical model describing each specific process. The essence of the mathematical model is developing experimental data to find dependencies of heat-physical characteristics of the material (heat conductivity, heat capacity) versus humidity and temperature, as well as transfer coefficients (heat loss, weight loss, weight conductivity) versus drying process parameters [9].

$$q_{t.k.u}(\tau) = q_{t.k.}(\tau) + q_{t.u}(\tau) = \alpha_c[t_a + t_s(\tau)] + \sigma_{1-2}\left\{\left[\frac{T_a(\tau)}{100}\right]^4 - \left[\frac{T_s(\tau)}{100}\right]^4\right\} = \alpha_{eff}\,[t_a(\tau) - t_s(\tau)], \quad (1)$$

where α_{eff} *is the efficient heat loss coefficient*, $\frac{W}{м^2 \cdot K}$; α_c is the convection heat loss coefficient, W/($m^2 \cdot K$);
σ_{1-2} *is the mutual radiation coefficient*, W/ ($m^2 \cdot K^4$);
t_s, T_s *is the temperature on the brick surface*, ℃, K;
t_a , T_a is the ambient temperature, ℃, K.
For the heat flux with evaporated moisture, the following equation is true [10, 11]:

$$q_{m.k.}(\tau) = \beta[P_s(\tau) - P_a(\tau)] \cdot r^*, \quad (2)$$

where β is the weight loss coefficient, s/m;
$P_s(\tau)$ is the partial pressure of saturated water vapor above evaporation surface, Pa;
$P_a(\tau)$ is the partial pressure of water vapor in the air environment, Pa.

Traditionally, in [10, 11], the problem of nonstationary weight conductivity (moisture diffusion) along the block thickness is recorded as follows:

$$\frac{\partial u_i(x,\tau)}{\partial \tau} = k_i \frac{\partial^2 u_i(x,\tau)}{\partial x^2};\ \tau > 0; 0 < x < R_s\,, \quad i = 1\ for\ the\ brick\ block, i = 2\ for\ the\ flooring \tag{3}$$

where $u(x,\tau)$ is the function defining the moisture value at time τ in the pint with coordinate x,

k is the weight conductivity coefficient (moisture diffusion coefficient in solid), (m^2/s).

In what follows, we omit index i to simplify the calculations.

The initial condition (moisture distribution by block thickness) looks as follows:

$$u(x,\tau)|_{\tau=0} = u_0(x) \tag{4}$$

In a partial case of even initial condition, it is recorded as follows:

$$u(x,\tau)|_{\tau=0} = u_0 \tag{5}$$

Boundary conditions:

a) on the external surface of the block:

$$q_{m.k.}(\tau) = -k\rho_o \frac{\partial u(x,\tau)}{\partial x}|_{x=R_s}\,, \tag{6}$$

where ρ_o is the dry material density, kg/м^3.

This condition defines density of the moisture flux supplied from the internal layers to the surface.

b) on the lower surface of the block:

$$q_{m.m.}(\tau) = -k\rho_o \frac{\partial u(x,\tau)}{\partial x}|_{x=0} \tag{7}$$

It means that the moisture flux coming from internal layers to the lower surface must be equal to the flux coming to the soil under the filtration transfer mechanism.

Solving the boundary problem in the form of expression (3)-(7) similar to [11] can be represented as follows:

$$u(x,\tau) = \frac{1}{R_S}\int_0^{R_S} u_0(x)dx - \frac{1}{R_S\rho_0}\int_0^{\tau} [q_{m.k.}(\tau^*) - q_{m.m.}(\tau^*)]d\tau^* + \frac{2}{R_S}\sum_{m=1}^{\infty} cos\ cos\ (\pi m\underline{x})\ ex(-\pi m Fo_m)\ \int_0^{R_S} u_0(x^*)\ cos\ cos\ (\pi m\xi^*)\ dx^* - -\frac{2}{R_S\rho_0}\sum_{m=1}^{\infty} cos\ cos\ (\pi m\underline{x})\ exp\ exp\ (-\pi m Fo_m)\ \int_0^{\tau} [q_{m.k.}(\tau^*) - (-1)^m q_{m.m.}(\tau^*)]d\tau^*, \tag{8}$$

where x^* is the coordinate in the range $[0, x]$,

τ^* is the time variable in the range $[0, \tau]$,

$\xi^* = \frac{x^*}{R_S}$ is a dimensionless coordinate,

$\underline{x} = \frac{x}{R_S}$.

Let us consider the dimensionless coordinate:

$$\left(\underline{x}, Fo_m\right) = \frac{u(x,\tau) - u_P}{u_P} \tag{9}$$

Let us also designate:

$$\left(\underline{x}, Fo_m\right) = \frac{u_0(x,\tau)-u_P}{u_P} \tag{10}$$

Hence, let us revise the first addend of the right part:

$$[1] = \frac{1}{R_S}\int_0^{R_S} \frac{u_0(x,\tau)-u_P+u_P}{u_P}dx = \int_0^1 [U_0(\underline{x})+1]d\left(\frac{x}{R_S}\right) =$$
$$= \int_0^1 U_0(\underline{x})d\underline{x} + \int_0^1 d\underline{x} = \int_0^1 U_0(\underline{x})d\underline{x} + 1 \tag{11}$$

Let us consider the second addend.
To make it dimensionless, let us divide by u_P:

$$[2] = -\frac{1}{u_p}\frac{1}{R_S\rho_0}\int_0^\tau [q_{m.k.}(\tau^*) - q_{m.m.}(\tau^*)]d\tau^* = -\frac{1}{u_p\rho_0}\int_0^\tau [q_{m.k.}(\tau^*) - q_{m.m.}(\tau^*)]d(\frac{\tau^*}{R_S}) \tag{12}$$

Let us place $u_p\rho_0$ under the integral sign:

$$[2] = -\int_0^\tau \left[\frac{q_{m.k.}(\tau^*)}{u_p\rho_0} - \frac{q_{m.m.}(\tau^*)}{u_p\rho_0}\right] d(\frac{\tau^*}{R_S}) \tag{13}$$

Let us multiply and divide by the complex $\frac{k}{R_S}$:

$$[2] = -\int_0^\tau \left[\frac{q_{m.k.}(\tau^*)}{u_p} - \frac{q_{m.m.}(\tau^*)}{u_p}\right]\frac{R_S}{k}d\left(\frac{k\tau^*}{R_S R_S}\right) = -\int_0^{Fo_m} \left[\frac{q_{m.k.}(\tau^*)R_S}{ku_p} - \frac{q_{m.m.}(\tau^*)}{ku_p}\right] dFo_m^* \tag{14}$$

$$F^*o_m = \frac{k\tau^*}{R_S^2} \tag{15}$$

Fourier mass exchange number changing in the range $[0,\ Fo_m]$
Let us also designate:

$$Ki_{m.k.}(Fo_m^*) = \frac{q_{m.k.}(\tau^*)R_S}{ku_p\rho_0} \tag{16}$$

- Kirpichev criterion along the external boundary.

$Ki_{m.m.}(Fo_m^*) = \frac{q_{m.m.}(\tau^*)R_S}{ku_p\rho_0}$ – Kirpichev criterion along the internal boundary.

Hence:

$$[2] = -\int_0^{Fo_m} [Ki_{m.k.}(Fo_m^*) - Ki_{m.m.}(Fo_m^*)]dF^*o_m \tag{17}$$

Let us transform the third addend:

$$[3] = +2\sum_{m=1}^{\infty} cos\ cos\ (\pi m\underline{x})\ exp\ exp\ (-\pi m Fo_m)\ \int_0^1 \left[\frac{u_0(\xi^*)-u_P+u_P}{u_P}\right]\cdot cos\ (\pi m\xi^*)d\xi^* \tag{18}$$

Further transformations give:

$$[3] = +2\sum_{m=1}^{\infty} cos\ cos\ (\pi m\underline{x})\ exp\ exp\ (-\pi m Fo_m)\ \left\{\int_0^1 [U_0(\xi)+1]cos\ (\pi m\xi)d\xi\right\} \tag{19}$$

Let us transform the curly bracket:

$$[3] = \left\{\int_0^1 \quad U_0(\xi)\, cos\, cos\, (\pi m\xi)\, d\xi \; + \int_0^1 \quad cos\, (\pi m\xi) d\xi\right\} \tag{20}$$

Let us transform the second integral in curly brackets:

$$\int_0^1 \quad cos\, cos\, (\pi m\xi)\, d\xi = \frac{1}{\pi m}\int_0^1 \quad cos\, cos\, (\pi m\xi)\, d(\pi m\xi) = \frac{1}{\pi m} sin(\pi m\xi)\Big|_0^1 = \frac{1}{\pi m}[sin(\pi m1) - \; sin(\pi m0)] \tag{21}$$

Thus, the second integral in formula (21) turns zero.
Therefore:

$$[3] = +2\sum_{m=1}^{\infty} \quad cos\, cos\, (\pi m\underline{x})\; exp\, exp\, (-\pi m Fo_m)\; \left\{\int_0^1 \quad U_0(\xi) cos\, (\pi m\xi) d\xi\right\} \tag{22}$$

Let us go to the 4th addend in formula (8).
By transforming the integral in this addend similar to the integral in the first addend, we will have:

$$[4] = +2\sum_{m=1}^{\infty} \quad cos\, cos\, (\pi m\underline{x})\; exp\, exp\, (-\pi m Fo_m)\; \int_0^{Fo_m} \quad [Ki_{m.k.}(Fo_m^*) - (-1)^m Ki_{m.m.}(Fo_m^*)] d(Fo_m^*) \tag{23}$$

The overall solution is as follows:

$$\left(\underline{x}, Fo_m\right) = \frac{u_0(x,\tau) - u_P}{u_P} == \int_0^1 \quad U_0\left(\underline{x}\right) d\underline{x} - \int_0^{Fo_m} \quad \left[Ki_{m.k.}\left(Fo_m^*\right) - Ki_{m.m.}\left(Fo_m^*\right)\right] d\left(Fo_m^*\right) + 2\sum_{m=1}^{\infty} \quad cos\, cos\, \left(\pi m\underline{x}\right)\; exp\, exp\, \left(-\pi m Fo_m\right)\; \int_0^1 \quad U_0(\xi)\, cos\, cos\, (\pi m\xi)\, d\xi - 2\sum_{m=1}^{\infty} \quad cos\, cos\, \left(\pi m\underline{x}\right)\; exp\, exp\, \left(-\pi m Fo_m\right)\; \int_0^{Fo_m} \quad \left[Ki_{m.k.}\left(Fo_m^*\right) - (-1)^m Ki_{m.m.}\left(Fo_m^*\right)\right] d\left(Fo_m^*\right) \tag{24}$$

Let us consider some partial cases.
I. Even initial distribution of moisture content:

$$U_0\left(\underline{x}\right) = \frac{u_0(x,\tau) - u_P}{u_P}\Big|_{\tau=0} = U_0 = \frac{u_0 - u_P}{u_P} \tag{25}$$

The first and the third addends in formula (25) change.
- First addend:

$$\int_0^1 \quad U_0\left(\underline{x}\right) d\underline{x} = \int_0^1 \quad U_0 d\underline{x} = U_0 \tag{26}$$

- Third addend:
Let us consider the integral:

$$\int_0^1 \quad [U_0(\xi)]\, cos\, cos\, (\pi m\xi)\, d\xi = \frac{1}{\pi m}\int_0^1 \quad cos\, U_0 cos\, (\pi m\xi)\, d(\pi m\xi) = \frac{U_0}{\pi m} sin\, sin\, (\pi m\xi)\Big|_0^1 = 0 \tag{27}$$

Thus, the third addend of equation (25) is zero.
We finally have:

$$\left(\underline{x}, Fo_m\right) = U_0 - \int_0^{Fo_m} \left[Ki_{m.k.}\left(Fo_m^*\right) - Ki_{m.m.}\left(Fo_m^*\right)\right] d\left(Fo_m^*\right) - 2\sum_{m=1}^{\infty} cos\ cos\left(\pi m\underline{x}\right)\ exp\ exp\left(-\pi m Fo_m\right) \int_0^{Fo_m} \left[Ki_{m.k.}\left(Fo_m^*\right) - (-1)^m Ki_{m.m.}\left(Fo_m^*\right)\right] d\left(Fo_m^*\right) \quad (28)$$

II. Linear dependency of Kirpichev criteria in process time:

$$Ki_{m.k.}(Fo_m) = A_{m.k.}Fo_m + B_{m.k.} \quad (30)$$
$$Ki_{m.m.}(Fo_m) = A_{m.m.}Fo_m + B_{m.m.} \quad (31)$$

Substitution of (30) and (31) in (29) leads to the following equation:

$$\int_0^{Fo_m} \left[Ki_{m.k.}(Fo_m^*) - Ki_{m.m.}(Fo_m^*)\right] d(Fo_m^*) == \int_0^{Fo_m} \left[A_{m.k.}Fo_m^* + B_{m.k.}\right] d(Fo_m^*) - \int_0^{Fo_m} \left[A_{m.m.}Fo_m^* + B_{m.m.}\right] d(Fo_m^*) == \frac{A_{m.k.}Fo_m^2}{2} + Fo_m B_{m.k.} - \frac{A_{m.m.}Fo_m^2}{2} - Fo_m B_{m.m.} == \frac{A_{m.k.} - A_{m.m.}}{2} Fo_m^2 + \frac{B_{m.k.} - B_{m.m.}}{2} Fo_m \quad (32)$$

In a similar way, let us record as follows for the integral of the third addend:

$$\int_0^{Fo_m} \left[A_{m.k.}Fo_m^* + B_{m.k.}\right] d(Fo_m^*) - \int_0^{Fo_m} (-1)^m \left[A_{m.m.}Fo_m^* + B_{m.m.}\right] d(Fo_m^*) = \frac{A_{m.k.}}{2} Fo_m^2 + Fo_m B_{m.k.} - (-1)^m \left[\frac{A_{m.m.}}{2} Fo_m^2 + Fo_m B_{m.m.}\right] = \frac{A_{m.k.} - (-1)^m A_{m.m.}}{2} Fo_m^2 + \frac{B_{m.k.} - (-1)^m B_{m.m.}}{2} Fo_m \quad (33)$$

Substitution of (25) and (26) in formula (28) leads to the following:

$$\left(\underline{x}, Fo_m\right) = U_0 - \left\{\frac{A_{m.k.} - A_{m.m.}}{2} Fo_m^2 + (B_{m.k.} - B_{m.m.}) Fo_m\right\} - 2\sum_{m=1}^{\infty} cos\ cos\left(\pi m\underline{x}\right)\ exp\ exp\left(-\pi m Fo_m\right) \left\{\frac{1}{2}\left[A_{m.k.} - (-1)^m A_{m.m.}\right] Fo_m^2 + \left[B_{m.k.} - (-1)^m B_{m.m.}\right] Fo_m\right\} \quad (34)$$

III. Even initial distribution of concentrations and constant values of Kirpichev criteria:

$$\left(\underline{x}, Fo_m\right) = U_0 - (Ki_{m.k.} - Ki_{m.m.}) Fo_m - 2\sum_{m=1}^{\infty} cos\ cos\left(\pi m\underline{x}\right)\ exp\ exp\left(-\pi m Fo_m\right) \left[Ki_{m.k.} - (-1)^m Ki_{m.m.}\right] Fo_m \quad (35)$$

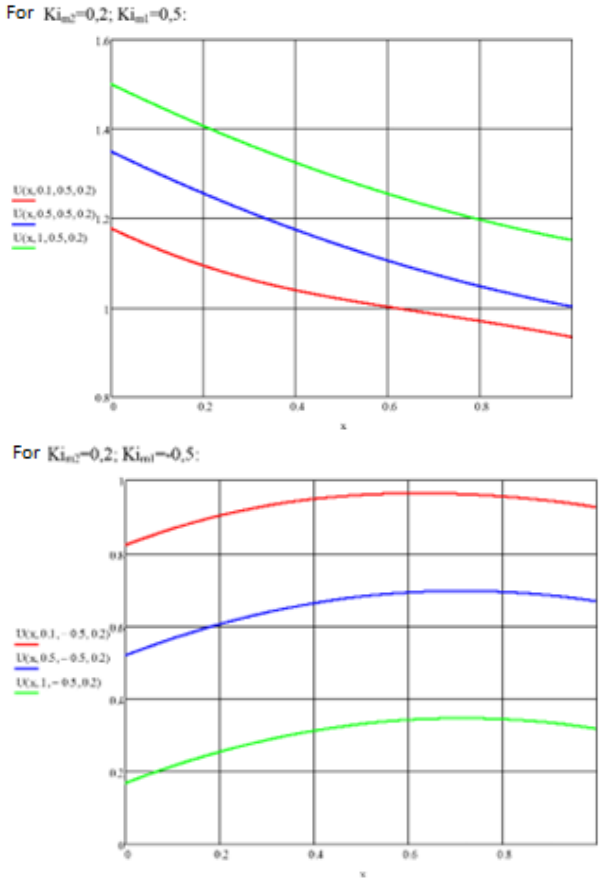

Fig. 2. Dependency of papercrete drying on feedstock humidity and density.

4 Conclusion

The authors have come to the following conclusions:

1. Advantages of papercrete made of crushed cotton plant stems include cost effectiveness, environmental friendliness, energy efficiency and lower resource demand in manufacturing and operation. The required strength allows using them as construction materials to erect low-rise buildings [5].
2. The papercrete production procedure is simple and easy to use.
3. Making papercrete from secondary agricultural resources and industry wastes is one of the most important methods to develop innovative economy in the Republic of Chad.
4. The suggested procedure to manufacture structural heat-insulating papercrete of crushed cotton plant stems is supported by the mathematical model.

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