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## Article

# The One-Way Analysis of Variance of Heat-Storage Materials Used in Building of Poultry Houses

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**Abstract:** In this study, a procedure for selecting the optimal heat-accumulating material based on phase transitions for the economical maintenance of poultry farms by applying ANOVA to complex solid bodies' thermodynamic parameters is described. The relevance of the topic is due to its importance for the development of an energy-saving technology based on the release or absorption of significant heat during the crystallization or melting of materials. The applicability of one-way ANOVA for the selection of the optimal material with a specific functional purpose was demonstrated. As result, the best composition for maintaining a normal temperature regime in poultry farms that could meet all the requirements imposed on heat-storage materials was determined. It was found that magnesium sulphate heptahydrate is such a material.

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## 1. Introduction

Poultry farming is the most energy-intensive livestock industry due to the high level of mechanization and automation across the entire production cycle, ranging from incubation to poultry cultivation and slaughter [1].

The share of energy costs in the cost structure of broiler chicken meat is 7–10%, depending on the season [2]. In the context where the growth in energy tariffs is ahead of the price appreciation rate for the sale price of broiler chicken meat, the development of measures to reduce unit production costs is an important task for the management of any enterprise. All of this highlights the urgency of developing economic approaches to the regulation of energy costs.

Currently, energy-saving technologies are increasingly being developed in construction in order to address the problems of saving heat and the rational use of energy and heat resources and thereby develop energy-efficient buildings by accumulating heat in building envelopes [3].

This has resulted in the formation of new directions in the production of energy-saving building materials, such as heat-accumulating materials and phase-change materials [4]. Phase-change materials (PCMs) can store latent heat energy in addition to the typical sensible energy capacity of current building materials, allowing them to store significantly more energy during the phase change process (solid to liquid and vice versa) [5]. In the context of conserving fossil fuels and curbing environmental pollution, it has been found that PCMs have immense scope for incorporation in various systems in sustainable poultry farming [6]. Many current researches persistently suggest the use of nanoparticles to solve problems related to phase-change materials' low thermal conductivity, supercooling, leakage, phase segregation and inflammability [4].

Heat-storage materials (HSMs) with phase transition-type melting-crystallization have been widely employed for heat storage in various fields of production and across the national economy: in the construction industry to provide comfortable conditions

in residential and industrial buildings [7]; in the agricultural sector to maintain normal temperatures in greenhouses [8]; for vehicles operating at elevated and low temperatures (e.g., when starting an internal combustion engine) [9]; and to battle supercooling and low thermal conductivity [10].

HSMs have been successfully used for heat removal under high thermal loads and for protection against overheating surfaces in various devices [11,12]. A classic example of the use of HSMs is in maintaining a pre-set room temperature by periodically absorbing and separating the heat of the phase transition [13]. Furthermore, HSMs are used in the manufacture of work clothes for builders, fitters and workers in housing and communal services who must work in harsh winter conditions.

Another application of HSMs is in the development of various structural products. Thus, in [5], the authors described the design of a wall with HSMs based on microcapsules of polymers, inside of which there is a substance (mainly paraffin or Glauber's salt) that has a phase transition at near-ambient temperatures.

Micron-sized capsules have been introduced into various building materials (putty, plaster, CPD, fibreboard, etc.). These capsules are highly durable and, therefore, do not require changes in building material technology (Figure 1). Excess heat absorbed during the day is released at night to "smooth" temperature fluctuations, creating a balanced microclimate for indoor environments.



**Figure 1.** Building material with micron-sized capsules [5].

Different types of HSMs are used in a variety of heat exchangers and boilers. A whole spectrum of HSMs have been developed that differ in their temperature stabilization, thermal capacity and thermal conductivity. The desire to create a material with low average density and reduced thermal conductivity has led to the creation of a large number of heat-insulation and structural-insulation materials that help the protective structures of buildings and structures reduce heat loss and can be used to isolate industrial equipment and thermal networks. The use of HSMs in the composition of heat carriers in chemical oil-refining plants or in enclosing structures makes it possible to increase the efficiency of these facilities [14–16].

A wide range of studies have aimed at the development of heat-storage technology based on the latent heat of the liquid  $\leftrightarrow$  solid phase transition in materials [11]. The main requirements for HSMs are the presence of a sufficiently high enthalpy melting value  $\Delta H_L$ , stable and repeatable endo- and exothermic effects across multiple thermal cycles relative to the melting point of  $T_L$ , a controllable hypothermia value for the  $\Delta T^-$  liquid phase relative to  $T_L$  and available and low-cost materials that meet environmental safety standards. The main materials that meet these requirements are the crystalline binders of various salts. Salt hydrates have a rather high heat of fusion and represent inorganic PCMs.

The aim of this study was to determine the optimal conditions for keeping broiler chickens with the use of HSMs. A single-factor ANOVA was used to determine the best composition that would meet all the requirements for HSMs in the process of building poultry houses.

The rest of the paper is structured as follows. The second section defines the cyclic thermal analysis method and reviews the relevant literature. The third and fourth sections present the methodology used for the empirical analysis and data. The fifth and sixth sections present and discuss the main results of the analysis, and the final section outlines the main conclusions.

## 2. Background

With the rise in the price of natural gas, which is the main energy source for the heating systems of buildings, the question of the feasibility of switching to alternative methods of heating has increased in importance.

An important application area for HSMs is in energy-supply systems with alternating heat absorption and generation, such as heliosystems with different levels of energy input and heat consumption [17].

To reduce the cost of energy production, conversion and distribution systems—which comprise the medium that generates heat—various materials that undergo phase transformation have been investigated.

Under energy-saving conditions, the construction of poultry houses, the operation of which is based on the use of heat accumulators with long-term storage of heat energy, remains an issue. The effect of such savings could be to make the poultry cheaper and more accessible to the consumer.

In the energy consumption structure of poultry houses, the largest share corresponds to variable consumption—electricity (77.2%), steam (87.3%) and water (95.9%). The auxiliary units include heat supply workshops (electricity: 13.4%), which provide uninterrupted heating of the enterprises with the help of pumps, and water supply shops (steam: 5.1%), which raise the temperature of cold water with the help of steam [18]. To meet the growing demand for low-cost, environmentally friendly products, high-performance multi-purpose poultry houses are needed that function all year round. Heating costs in existing heated poultry houses account for more than 50% of the costs of the finished products [18].

The main parameters of the microclimate in the poultry industry are normal air exchange, temperature–humidity and the light mode [19]. Poultry breeders have identified the optimal temperature and humidity parameters for the air in poultry houses, which have been approved by technological design standards (Table 1).

**Table 1.** Optimal temperature and humidity parameters for the air in poultry houses.

	Eggs	Meat
Air temperature in the poultry house	16–18 °C	16–32 °C
Relative air humidity	50–70%	60–70%

The main influence on air quality comes from the poultry themselves, which are sources of carbon dioxide, as well as nitrogen- and sulphur-containing components in manure litter.

To keep the poultry healthy and productive, the concentration of harmful gases in the air should not exceed acceptable zoo hygiene norms, and these should be maintained regardless of the season, weather conditions or other relevant factors [19].

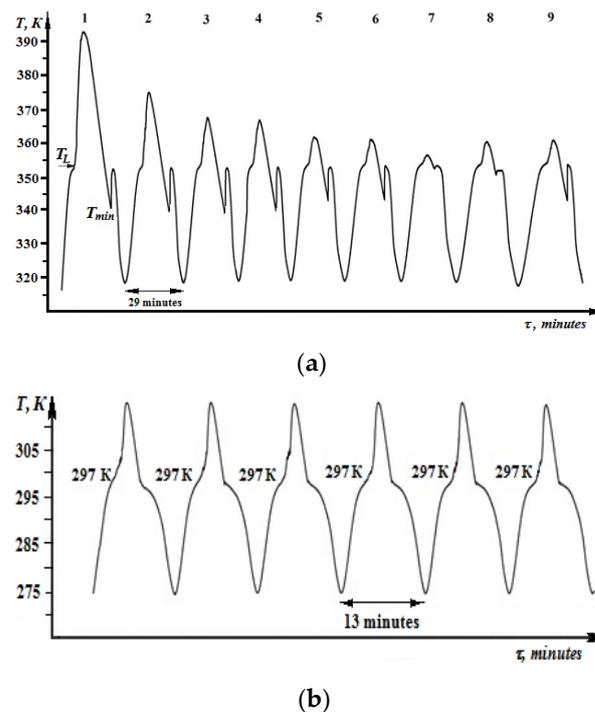
According to [20], stunting and impaired development of poultry, reduced feed conversion, elevated numbers of cases of chronic respiratory disease, post-vaccination complications, limb problems, ascites and sudden death syndrome are only some of the problems that occur against the background of a sub-optimal climate in the poultry industry. In addition, it has been established that [21], in the production of meat, eggs, milk and other products of animal origin, the creation of an optimal microclimate for animals reduces the

total cost of production. In the context of broiler meat production, all the components of the process, from parent production to broiler production, will be more productive if the climate is controlled effectively.

### 3. Cyclic Thermal Analysis (CTA) Method

In the study of phase transformations, a special place is occupied by periodic processes or thermocycles, which ensure that experiments can be repeated in the same conditions. This is addressed by the CTA method (see [11,12] for details). In the CTA method, the information source is a whole group of parameters characterizing the melting processes and the crystallization kinetics of supercooled melts. The parameters are as follows: the melting temperature of the liquids for the alloy; the quasi-temperature of crystallization (or the solidity temperature for alloys); the liquid phase overheating relative to the melting point; the temperature at which structural changes take place in the liquid phase; the critical melt temperature overheating; the heat of melting or crystallization; the time of melting or crystallization; the incubation period for new phases; the isothermal holding time of the melt; the degree of crystallinity; the time of embryo coagulation; and the heating and cooling rates.

Thermocycling is carried out at a specific temperature range including a phase transition. Aleksandrov and co-authors [22] used the CTA method to explore phase transformation kinetics in a vacuum. The CTA method was carried out by reaching the smallest difference between the furnace temperature and that of the samples under special regimes with the on or off mode selected. To detect new endothermic and exothermic effects, each degree was tested, and then the detected phase transition was thoroughly investigated through thermocycling. For this purpose, the lower bound of the thermocycles  $T_{low}^- < T_L$  was kept constant and the upper bound was raised or lowered from that of the previous cycle (Figure 2a). Each subsequent thermocycle differed from the previous one, and the furnace was turned off after a longer time than the furnace shut-down in the previous thermocycle. The CTA results were proven to be repeatable from cycle to cycle (Figure 2b). The accuracy of the maintenance of the set temperature in the operating range was 2 °C.

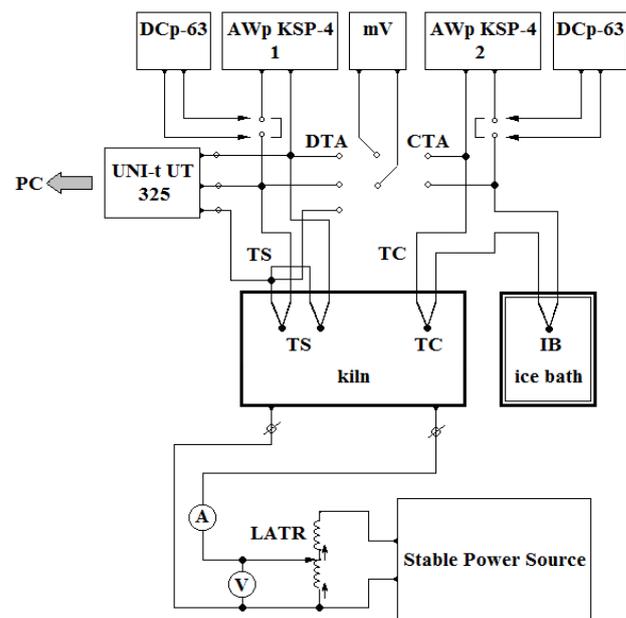


**Figure 2.** Cyclic thermograms characterizing the influence of melt overheating on supercooling (a) for the example of naphthalene and the reproducibility of thermal effects (b) for eutectic alloys with 50 masses. % O-terphenyl—50 mass. % dibenzyl—50 mass.

To implement the CTA method, a cyclic thermal analysis setting has been designed and described [11,12]. It is considered in the next section.

#### 4. Cyclic Thermal Analysis Setting

The installation described in this paper was intended for direct temperature measurement depending on time in accordance with the CTA method. In addition, the invented device made it possible to use the DTA method and simultaneously combine the cyclic thermal analysis (CTA) and differential thermal analysis (DTA) methods. It allowed the study of the nature of phase transformations and the construction of a state diagram (see Figures 3 and 4).



**Figure 3.** Scheme of settings for thermography of substances using CTA and DTA methods. DCp-63—PP-63 DC potentiometer, KSP-4—auto-write potentiometers, LATR—laboratory autolab auto-transformer, TS—temperature sensor, IB—temperature isothermal block, DTA—differential thermal analysis, CTA—cyclic thermal analysis.



**Figure 4.** Experimental setup for thermography of substances using thermal analysis technique.

Installation diagram. The structural diagram of the installation for cyclic thermal analysis is shown in Figure 3. It consists of the following functionally related parts and systems: the measuring system, the voltage stabilization system and the control system.

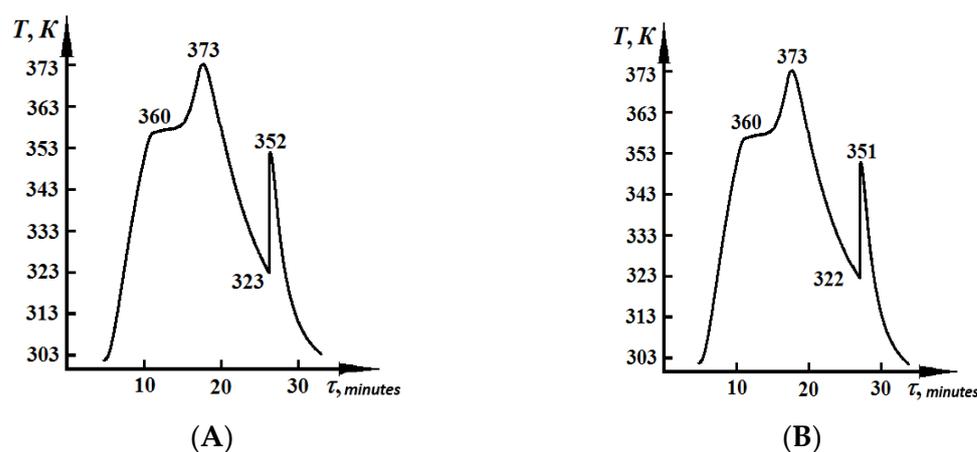
#### 4.1. The Measuring System

The measuring system includes thermocouples, a B7-23 universal voltmeter, a PP-63 DC potentiometer and KSP-4 automatic self-writing potentiometers with a scale of 1, 2 and 5 mV or with temperature recorded with the help of a UNI-t UT 325 digital two-channel thermometer via an RS 232 interface on a PC (Figure 4). The maximum temperature error of the measurement instrument was 0.5 K and the phase transition enthalpy measurements were between 1.5 and 2.0 kJ/kg. The temperature recording response of the instruments was  $\sim 0.25$ – $0.35$  K, as the average temperature fluctuation did not exceed 0.25 K in the range of 20–120 °C and the temperature drift did not exceed 0.35 K for several hours. Cross-checking for the unit of sensitivity of thermal effects in the DTA (0.2 to 0.4 kJ/kg) was undertaken.

#### 4.2. Thermocouples

Chromel-alumel and copper chrome thermocouples with diameters of 0.1 to 0.5 mm were used for various substances. Thermocouples with unprotected spans and a thin layer of glass were used. However, thermocouples with an unprotected end were generally used because the substances in question were not active with respect to the thermocouples. The ends of the thermocouples were located in the middle of the sample. The experiments were carried out in a specially manufactured, "limitless" resistance furnace or a low-density, ceramic, hollow resistor PE used as a furnace, covered with thermal insulation material on the outside. To obtain higher cooling speeds during thermographing, samples in glass ampoules were placed in a Samsung RT22SCSW freezer operating at a temperature of  $-20$  °C. Measuring instruments were calibrated according to the ASTM E967 standard [11].

Experiments were carried out with the CTA method to determine the influence of the purity of the samples on the melting and crystallization parameters. For this purpose, CHDA-brand m-terphenyl was chosen and subjected to additional cleaning through recrystallization. Figure 5 shows the heating and cooling thermograms for m-terphenyl with the same heating and cooling speeds of 0.08 K/s.



**Figure 5.** Experimental thermograms for heating and cooling of m-terphenyl of analytical grade (A) and preliminarily purified m-terphenyl (B).

Figure 5 shows that the melting and hypothermia temperatures were practically unchanged for both non-sealed and cleaned samples. The difference between the hypothermia temperatures for proprietary and additionally refined hydrocarbons was  $\pm 0.5$  °C.

## 5. Materials and Methods

This study aimed to determine the best crystalline salt hydrates for use in the composition of heat-storage materials (HSMs). Previous theoretical and experimental data [11,23,24] were obtained and subjected to thermal analysis. Potential salts were searched for based on the following criteria:

- Melting temperature greater than 300 K and lower than 331 K;
- Coefficient  $\lambda$  of thermal conductivity (W/m·K) between 0.50 and 0.65;
- Overheating of the melt below the melting temperature;
- Easily available;
- Material cost < EUR 5 per kilogram;
- Hazard class between 3 and 4 (ecological safety).

Salts selected for analysis are listed in Table 2.

**Table 2.** Selected salts.

	Formula	Name	CAS Number
A	Na <sub>2</sub> CO <sub>3</sub> ·10H <sub>2</sub> O	Sodium carbonate decahydrate	6132-02-1
B	NaHPO <sub>4</sub> ·12H <sub>2</sub> O	Di-sodium hydrogen phosphate dodecahydrate	10039-32-4
C	Na <sub>2</sub> SO <sub>4</sub> ·10H <sub>2</sub> O	Sodium sulphate decahydrate/Glauber's salt	7727-73-3
D	Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> ·5H <sub>2</sub> O	Sodium thiosulfate pentahydrate	10102-17-7
E	MgSO <sub>4</sub> ·7H <sub>2</sub> O	Magnesium sulphate heptahydrate	10034-99-8
F	CaCl <sub>2</sub> ·6H <sub>2</sub> O	Calcium chloride hexahydrate	7774-34-7
G	Zn(NO <sub>3</sub> ) <sub>2</sub> ·6H <sub>2</sub> O	Zinc nitrate hexahydrate	10196-18-6
H	FeCl <sub>3</sub> ·6H <sub>2</sub> O	Ferric chloride hexahydrate	10025-77-1
I	Na <sub>2</sub> SO <sub>3</sub> ·7H <sub>2</sub> O	Sodium sulphite heptahydrate	10102-15-5
J	Na <sub>2</sub> CH <sub>3</sub> COO·3H <sub>2</sub> O	Sodium acetate trihydrate	6131-90-4

One-way analysis of variance (ANOVA) was used to determine the best composition for the heat-storage materials (HSM) based on crystalline hydrates that would meet all requirements.

One-way analysis of variance is used to compare several averages.

ANOVA involves a comparison of the “factor variance” caused by factors and the “residual variance” due to random causes.

We used one-way ANOVA to determine the average difference in the utility of HSMs (selected salts). There were 13 salt utility categories, which were numbered from 1 to 13 (Tables 3 and 4).

The statistic used to value the variance of a random variable was calculated as follows:

$$T_D = \frac{1}{n-1} \left( \sum_{i=1}^n x_i^2 - \frac{1}{n} \left( \sum_{i=1}^n x_i \right)^2 \right) \quad (1)$$

Below are two known definitions from a course on mathematical statistics [25].

**Definition 1.** *The best estimates are those that have the properties of consistency, unbiasedness and efficiency.*

**Definition 2.** *If the hypothesis  $H_0$  about the equality of averages is true, then (1) is an unbiased estimate. The most effective estimate is the one with the lowest variance.*

An unbiased estimate, the variance of which is bounded by a constant, is consistent [25]. Table 3 presents the physical characteristics of selected salts marked with Roman numerals.

**Table 3.** Physical characteristics of selected salts (HSMs).

Salt	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII
A	305	247	0.53	12	0.5	1.93	2.43	1.44	1.11	0.34	0.26	3+	130
B	308	260	0.52	15	2.0	1.55	3.18	1.52	1.49	0.03	0.90	3++	100
C	306	270	0.50	13	10	1.92	3.26	1.49	1.45	0.04	0.23	4-	140
D	321	209	0.60	19	44	1.46	2.40	1.73	1.67	0.06	0.34	4+	250
E	322	201	0.61	16	3.5	1.6	2.10	1.68	1.58	0.10	0.33	4	160
F	302	170	0.63	14	15	1.45	2.19	1.62	1.51	0.11	4.74	3	200
G	309	150	0.54	18	3.0	1.55	2.30	1.83	1.81	0.02	1.01	3-	190
H	310	200	0.55	17	1.5	1.34	1.93	1.63	1.60	0.03	1.39	4-	180
I	301	179	0.51	11	1.0	1.82	2.79	1.47	1.46	0.01	0.57	3	150
J	331	275	0.62	9	53	2.0	2.80	1.45	1.40	0.05	1.31	4-	300

In Table 3, I—melting temperature  $T_L$ ; II—melting enthalpy  $\Delta H_{LS}$  (kJ/kg); III—coefficient  $\lambda$  of thermal conductivity (W/m·K); IV—overheating  $\Delta T_k^+$  of melt (K); V—undercooling  $\Delta T^-$  (K); VI and VII—heat capacities  $c_p^s$  and  $c_p^L$  (kJ/kg·K); VIII and IX—densities  $\rho_S$  and  $\rho_L$  (g/cm<sup>3</sup>); XI—price of the HSM (EUR/kg); XII—hazard class; XIII—number of thermal cycles.

For the ANOVA analysis, a summary table of the increasing utility of the HSMs was compiled and marked with points from 1 to 10 (1 indicates “good”, 10 indicates “bad”) (Table 4). Consider, as an example, the first column (melting point) of Table 4. Since substance I has the lowest melting point (I—Na<sub>2</sub>SO<sub>3</sub>·7H<sub>2</sub>O—sodium sulphite heptahydrate (first column of Table 3)), the number 10 was put in the corresponding cell. The substance F (CaCl<sub>2</sub>·6H<sub>2</sub>O—calcium chloride hexahydrate) has a slightly higher melting point (302 degrees), so the digit 2 was put in the corresponding cell of the first column. The other columns of Table 4 are filled in the same way.

**Table 4.** Summary table of increasing degree of utility of HSMs.

Salt	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII
A	8	4	7	3	1	2	5	10	10	10	2	2	9
B	6	3	8	6	4	6	2	6	6	3	6	1	10
C	7	2	9	4	8	3	1	7	8	5	1	9	8
D	3	5	4	10	9	8	6	2	2	7	4	6	2
E	2	6	3	7	6	5	9	3	4	8	3	7	6
F	9	9	1	5	7	9	8	5	5	9	10	4	3
G	5	10	6	9	5	7	7	1	1	2	7	5	4
H	4	7	5	8	3	10	10	4	3	4	9	10	5
I	10	8	10	2	2	4	4	8	7	1	5	3	7
J	1	1	2	1	10	1	3	9	9	6	8	8	1

## 6. Results

As mentioned above, the main purpose of one-factor variance analysis is to compare the variance in the investigated feature caused by the action of a factor with the variance in the error measurement of this feature. If the difference between them is significant, the factor has a significant influence on the topic under study. This task was undertaken with the help of the Excel application package.

Table 5 presents the results of the ANOVA. The results confirmed that the smallest variance was for factor 5 (in our case, this was MgSO<sub>4</sub>·7H<sub>2</sub>O—magnesium sulphate heptahydrate—the variance of which was 4.73).

**Table 5.** One-way ANOVA.

Groups	Score	Sum	Mean	Variance
Line 1	13	73	5.62	12.26
Line 2	13	67	5.15	6.14
Line 3	13	72	5.54	9.10
Line 4	13	68	5.23	7.36
Line 5	13	69	5.31	4.73
Line 6	13	84	6.46	7.94
Line 7	13	69	5.31	7.90
Line 8	13	82	6.31	7.73
Line 9	13	71	5.46	9.44
Line 10	13	60	4.62	13.92

The results from testing the hypothesis of the equality of the mean are given in Table 6, from which it can be seen that, since the calculated value was less than the table value ( $F = 0.44 < F_{\alpha=0.05} = 1.96$ ), the zero-hypothesis should be accepted. Therefore, our estimates were unbiased.

**Table 6.** Analysis of variance.

Source of Variance	SS	df	MS	F	<i>p</i> -Value	F
Between groups	34.35	9	3.82	0.44	0.91	1.96
Within groups	1038.15	120	8.65			
Sum	1072.50	129				

In accordance with definitions 1 and 2, it was concluded that magnesium sulphate heptahydrate  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$  would be the most effective salt for the composition of heat-storage materials as it had the smallest variance among all the presented salts and its variance was bounded by a constant.

## 7. Discussion and Conclusions

In this paper, ten heat-storage materials appropriate for poultry house construction were considered. These materials were selected as a result of thermal experimental analysis and from consulting references. Based on the hydration/dehydration cycle and the analysis of variance (ANOVA), magnesium sulphate ( $\text{MgSO}_4$ ) was chosen as the best seasonal chemical heat-storage composite material. During the summer, the material stores heat through an endothermic dehydration reaction, and heat used for space heating is released in winter by rehydrating the material [23].

Thermal energy storage systems could make important contributions to reducing our dependency on fossil fuels, as well as to more efficient and environmentally benign energy use [26]. As demand for thermal comfort in buildings rises, the energy consumption correspondingly increases.

Magnesium sulphate is a composite material that can be used for long-term thermal energy storage. Among the potential candidates, magnesium sulphate was found to be the most appropriate thanks to its high energy density, the compatibility of its storage temperature with solar collectors, the availability of the chemical reaction compounds and its non-toxicity [27]. The literature analysis [27] also confirmed that  $\text{MgSO}_4$  is a suitable material under both high humidity and high dehydration temperatures, and it has been proven to be stable under varying hydration conditions.

Based on all these results, the form-stable composite was proven to be a promising thermal energy storage material suitable for long-term storage purposes thanks to its good thermal properties and thermal and chemical reliability. In addition to its mechanical properties,  $\text{MgSO}_4$  can also be considered a new construction material with potential uses thanks to its characteristics of being lightweight and having low thermal expansion and high fire resistance, etc. [4].

Further research should focus on the optimisation of the host material properties and the evaluation of the density of the energy storage system under real operating conditions in large-scale experiments.

**Author Contributions:** Conceptualization, methodology, software, formal analysis, data curation, visualization, writing—original draft preparation, O.A.; validation, investigation, resources, writing—review and editing, T.Z.; formal analysis, writing—review and editing, A.-H.V. and R.V. All authors have read and agreed to the published version of the manuscript.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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