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The ecological and economic analysis of using Thermopor plaster for thermal insulation

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Abstract
Plaster plays an important role in the building industry. Besides an aesthetic function it provides the protection of external walls from weather conditions. In the paper thermo insulating Thermopor plaster was described. Its chemical and physical properties and manner of using were defined. The impact on the environment with the use of LCA technique was examined. Thermopor plaster can fulfil a thermo insulating function. The economic and ecological analysis of applying this plaster in the thermo insulation of the external walls of the building was conducted. The use of Thermopor plaster on external walls brings ecological benefits. The reimbursement of ecological cost related to the use of this plaster appears already after 2 to 5 years, depending on the source of heat used, which results from the decrease of thermal energy consumption for heating the building. For economic reasons, the partial reimbursement of cost is obtained as a result of the reduction of heating cost. Although Thermopor plaster has thermo insulating properties similar to typical insulating materials, such as polystyrene or mineral wool, the economic cost of using the plaster for thermo insulation becomes several times higher.

Introduction

LCA analysis is more and more commonly used in different aspects in the building sector [1]. A wide review of papers concerning the implementation of LCA in the building industry can be found, among the others, in the paper [2]. LCA can be used for the evaluation of building materials (including thermo insulating ones), as well as for the selection of the most favourable ones for regard of the impact on the environment [3]. LCA is also used for the assessment of the thermal phase of using the building [4] and the whole life cycle of the building [2]. In Europe about 50% of final energy is used in buildings [5]. Therefore, it leads to the necessity of the improvement of the energetic efficiency of buildings. A great reducing potential of final energy use in the building industry is created by thermo insulation or thermo modernization of buildings [6, 7].

Plaster plays a significant role in the building sector. It provides the protection of the external wall from weather conditions (e.g. acid rain), and also protection from the influence of internal conditions (e.g. water steam). It can also protect construction wooden elements from fire. It plays an aesthetic function as well [8]. Plaster can also fulfil a thermo insulating function. Heat insulating plasterer's mortars should fulfil the following conditions: thermal conductivity coefficient $\lambda < 0.21$ W/mK and bulk density in the loose state smaller than 700 kg/m^3 [9]. Thermopor plaster analyzed in the article fulfils these conditions, and has also other favourable properties. The ecological and economic benefits of using Thermopor plaster for the thermo insulation of external building walls were examined.

Properties and possible applications of Thermopor thermo insulating plaster

The main ingredient of Thermopor plaster is bims granule. It is created as a result of freezing basalt lava mixed with volcanic gases (water steam and carbon dioxide) and ash. The bigger the content of gases in bims, the lighter it becomes. It is possible to obtain white bims with great porosity, up to 84% [10, 11]. Obtaining this aggregate is similar to extracting gravel. The output is washed and sieved. For the production of Thermopor the fraction 1.5–2.0 mm is used [8]. In Europe there are bims mines in, among the others: Iceland, Italy, Germany, Greece and Turkey. In Turkey, which has the biggest resources of this raw material (about 7.4 mld m^3), the reserves are estimated for about 40 years of intensive mining [8].

Thermopor plaster is an industrially mixed dry plaster consisting of: mineral bond according to DIN EN 459 (2.8% of lime), mineral bond according to DIN EN 197-1 (1.2% cement) and natural filler (96% of bims). This mortar, after being mixed with water, is ready to use and binds hydraulically. It is plastic and durable in the raw state, easy to prepare and use. It can be put manually and also with help of plasterer's aggregates. It is suitable for putting single layer with thickness up to 30 mm, with several layers it is possible to obtain the thickness up to 80 mm. This plaster can be used on external walls on mineral surfaces possible to plaster, wall building materials and floors, walls with building materials from hydraulically tied bond according to DIN 1164, DIN 1060, DIN 4211, and also on walls from natural standardized building materials according to DIN 1053 (e.g. wall brick, silicate brick), as well as on concrete and cellular concrete [8]. It can also be put on internal walls. A white and uniform surface is obtained. It can be covered with mineral paints: lime, cement or silicate according to DIN EN 13300 (with any colour) without the restriction of wall diffusion [12].

Thermopor plaster can be used in new buildings, and also in renovations of old buildings (has a tendency to dry rooms). It is not covered with fungi or seaweeds and due to a suitable ratio of adhesive powers to cohesive ones it does not absorb water. Therefore, it can be used on bases and other walls endangered with periodical moisture or salt. After applying this plaster a snow-white elevation is obtained, where mechanical damages do not become an aesthetic problem (substance is uniform) [12].

More important technical parameters for Thermopor (based on [13]) were presented in table 1. Let us consider that thermo insulating properties (thermal conductivity $\lambda = 0.054$ W/mK) are not much worse than typical thermo insulating materials (λ in the range of 0.03–0.05 W/mK). This plaster should be kept in dry rooms. The expiry date is 18 months. It can be painted after about 40 hours since being put.

Table 1. Technical parameters for Thermopor plaster (elaborated on the basis of [12])

Appearance and consistency	White powder
Density of dry mass	334 ±10% [kg/m^3]
Thermal conductivity (after 120 days)	0.054 [W/mK]
Resistance to compressing	CS II 1.84 [N/mm^2]
Adhesion	0.46 [N/mm^2]
Moisture absorption	W1 0.204 [kg/m^2] min 0.5
Diffusion coefficient (after 120 days)	4.80
Flammability class (DIN 4102-1: 500C)	A1
Consumption for 1 cm of thickness	4 [kg/m^2]

The manner of using the plaster looks in the following way. For a bag of mixture (8 kg) it is necessary to prepare about 4 dm^3 of water, pouring it into a clean container. Then the granule is added intensively stirring with a mixer or helical agitator for about 2–4 minutes until a uniform plastic mass is obtained. The ground for plaster must be bearing and free from substances weakening plaster adhesion. It can be dry or moist (but it cannot reveal pressing moisture). The hardened plaster cannot be used again with pouring water [12]. The plaster does not require either coating or polishing. It can be used with the temperatures of at least +5°C. As it was mentioned before, the maximum thickness of a single layer can amount up to 30 mm. Greater thicknesses can be obtained in two working cycles on wet. The plaster needs to be protected against water evaporating too fast, against insolation and wind. During plastering works it is necessary to obey DIN 18550 norm.

The environmental analysis of Thermopor plaster

Thermopor plaster was subject to the life cycle analysis LCA of a product in order to define the influence of the production of this material on the environment. The methodology of the environmental assessment of the existence cycle LCA was developing intensively in the 90s of the previous century [14, 15, 16]. Nowadays, LCA method is standardized and described in norms PN-EN ISO 14040:2009 and PN-EN ISO 14044:2009.

The assessment of the environmental impact of products is supported by a great number of commercial computer programmes. Taking application possibilities and huge widespreading into consideration, it is advisable to focus on SimaPro programme in version 7.1 (established by Pre Consultans B.V. company from Holland). In this programme 21 assessment methods were applied, out of which the procedure Ecoindicator 99 was used in the article.

The procedure enables to allocate eleven impact categories to three defined categories of damage: human health, environment quality and natural resources consumption. The above procedure also enables to carry out weighing and presenting the final result of LCA in Pt[1].

As a functional unit 1 m^3 of plaster was accepted. A significant element in the first phase of LCA is to define the borders of the system and quality of needed data. The system borders range from the stage of obtaining raw materials to the stage of embedding (including the consumption of energy necessary for the plastering process). The environmental aspects connected with creating machines and devices used in the production process were not included within the system borders. The results of the LCA analysis of Thermopor plaster were compared with the inclusion of three categories of damage (Table 2), as well as eleven impact categories (Table 3).

Table 2. LCA results – three categories of damage [own study based on SimaPro programme]

Damage categories	[Pt/m^3]
Human health	2.5511
Ecosystem quality	0.3299
Raw materials	3.1541
Total:	6.0351

Table 3. LCA results – eleven impact categories [own study based on SimaPro programme]

Impact categories	[Pt/m^3]
Carcinogenic compounds	0.4473
Organic substances	0.0003
Non organic compounds	1.6294
Climate change	0.4730
Radiation	0.0011
Ozone hole	0.0000
Ecotoxicity	0.0365
Acidification/Eutrophication	0.1927
Land use	0.1007
Minerals	0.0062
Fossil fuel	3.1479
Total:	6.0351

The biggest impact on the environment among damage categories takes place in category of raw materials (see Table 2). For regard of impact categories the greatest influence on the environment takes place in the category of fossil fuel and non organic compounds (Table 3).

[1] Value 1 Pt corresponds to 10^3 of units of annual environmental load for one inhabitant in Europe

The impact of Thermopor on the environment is of a similar size as for typical thermo insulating materials, e.g. for polystyrene it amounts to 4.88 Pt/m^3, and for mineral wool 6.08 Pt/m^3 [4]. Thermopor plaster has also favourable results in comparison to cement plaster, for cement plaster the impact on the environment is over two times bigger, it amounts to 12.92 Pt/m^3 [12].

The ecological benefits of using Thermopor plaster on external building walls

For regards of thermal conductivity coefficient, Thermopor plaster can be also treated as a thermo insulating material. In this part the ecological benefits resulting from the thermo insulation of external building walls were defined, with the use of the method proposed in the paper [4]. Although the production of Thermopor causes the increase of the environment load, but as a result of applying this plaster on the external walls the demand of the building for energy to heat is reduced substantially and as a consequence the energy consumption in the phase of building use.

Ecological cost K_S (negative impact on the environment) for 1 m^2 of the wall surface can be assigned from the formula:

$$K_S = d \cdot K_l \quad [\mathrm{Pt/m^2}] \tag{1}$$

where:

K_S – ecological cost of plastering [Pt/m^2];
K_l – LCA analysis result for 1 m^3 of Thermopor plaster [Pt/m^3] (see Table 2);
d – thickness of plaster [m].

With a particular thickness d of thermo insulating plaster, coefficient of heat transfer U for a wall with a layer of plaster will be [17]:

$$U = \left(\frac{1}{U_o} + \frac{d}{\lambda} \right)^{-1} \quad [\mathrm{W/m^2K}] \tag{2}$$

where:

U – heat transfer coefficient of a wall with a layer of thermo insulating plaster [W/m^2K];
U_o – heat transfer coefficient of a wall without a layer of plaster [W/m^2K];
λ – thermal conductivity coefficient for Thermopor plaster [W/mK];
d – as already defined in the paper.

As a result of putting thermo insulating plaster on the external walls of the building the demand for thermal energy in the thermal phase of the building usage decreases and as a consequence a negative impact of the building on the environment is also reduced. Ecological profits Z_S (for 1 m^2 of the area of external building walls) obtained in the phase of the building usage as a result of applying Thermopor plaster are the following:

$$Z_S = \left(E_{Uo} - E_U\right)\frac{n}{p} \quad [\mathrm{Pt/m^2}] \tag{3}$$

where:

- Z_S – ecological profits in the phase of the building usage obtained as a result of applying Thermopor plaster [Pt/m^2];
- E_{Uo} – LCA analysis result of one year thermal phase of the building usage, for external building walls with coefficient of heat transfer U_o (without a layer of plaster) [Pt/year];
- E_U – LCA analysis result of one year thermal phase of the building usage, for external building walls with coefficient of heat transfer U (with a layer of plaster) [Pt/year];
- n – length of period for using thermo insulating plaster [year];
- p – area of external walls for the whole building [m^2].

Summarizing, ecological benefits O_S for the environment which appeared as a result of applying Thermopor plaster is the following amounts:

$$O_S = Z_S - K_S \quad [\mathrm{Pt/m^2}] \tag{4}$$

For the analysis the thickness of plaster equal to a single layer $d = 0.03$ m was accepted. Ecological cost (assigned from the formula (1)) is then the following $K_S = 0.1811$ Pt/m^2.

The heat transfer coefficient for building walls without a layer of plaster $U_o = 0.30$ W/m^{2}K was accepted (in Poland external building walls must have heat transfer coefficient not bigger than 0.30 W/m^{2}K, according to the Regulation of Infrastructure Minister [18]). The heat transfer coefficient for a wall with a layer of plaster will amount $U = 0.26$ W/m^{2}K (from the formula (2)).

The studies were conducted for a house with a garage having the usable floor area of $P_u = 156.1$ m^2 and the area of external walls of $p = 158.7$ m^2 (building cubature 390 m^3). The thermal phase of the building usage was studied. For determining the value of a building demand for heat the computer programme Herz OZC version 3.0 was applied. Three types of heat sources were considered:

(E1) hard coal boiler, $G_o = 10.90$ PLN K/W ($= 126 \cdot 10^{-6} \cdot 24 \cdot 3605$), at the cost of obtaining heat for heating purposes 126 PLN/MWh, (boiler efficiency of 80%, fuel calorific value of 29 MJ/kg and the price 769 PLN/t);

(E2) natural gas boiler, $G_o = 30.37$ PLN K/W ($= 351 \cdot 10^{-6} \cdot 24 \cdot 3605$), at the cost of obtaining heat for heating purposes 351 PLN/MWh, (boiler efficiency 90%, fuel calorific value of 31 MJ/m^3 and the price 2.63 PLN/m^3);

(E3) electric energy boiler, $G_o = 50.18$ PLN K/W ($= 580 \cdot 10^{-6} \cdot 24 \cdot 3605$), at the cost of obtaining heat for heating purposes 580 PLN/MWh, (electric energy price 0.58 PLN/kWh).

The prices were taken from [19]. The number of $Sd = 3605$ degree days[2] was taken (several years' average in Poland for the years 1980–2004 [20]).

The results of LCA analysis of one year thermal phase of the building usage, for external walls without a layer of plaster E_{Uo} (for $U_o = 0.30$ W/m^{2}K) and with a layer of plaster E_U (for $U =$ 0.26 W/m^{2}K), depending on heat source type, were presented in table 4.

Table 4. LCA analysis result of one year thermal phase of the building usage [own study based on SimaPro programme]

Heat source →	E1	E2	E3
E_{Uo} [Pt/year]	347	221	873
E_U [Pt/year]	337	214	847

In the analyzed cases after applying Thermopor plaster (for each heat source, in each year of thermal phase of the building usage) the environment load was reduced at about 3%.

From the formula (3) ecological profits Z_S were assigned in the phase of the building usage, as well as from the formula (4) ecological benefits O_S obtained as a result of applying Thermopor plaster. The durability of cement-lime plaster amounts to 50–80 years [21]. Therefore, the period of usage was assumed as $n = 50$ years. The results were presented in table 5.

Table 5. Ecological profits and benefits [source: own study]

Heat source →	E1	E2	E3
Z_S [Pt/m^2]	3.151	2.205	8.192
O_S [Pt/m^2]	2.970	2.024	8.011

The obtained ecological profits Z_S are repeatedly bigger than ecological cost K_S. The greatest ecological benefits O_S were obtained with using the electric energy boiler E3 as a heat source (see Table 5 and Fig. 1), because the greatest difference of

[2] The figure of degree-days of a heating season is a quantitative factor defining heating energy demand of houses and public utility buildings, it is determined on the grounds of the climate data for a particular town. It is calculated when the whole day external air temperature is lower than the assumed base temperature.

$E_{Uo} - E_U = 26$ Pt/year was obtained for this source (see Table 4). It is worth noticing that the ecological payback period (the period after which ecological profits already exceed ecological cost) was: 3 years for E1, 5 years for E2 and 2 years for E3.

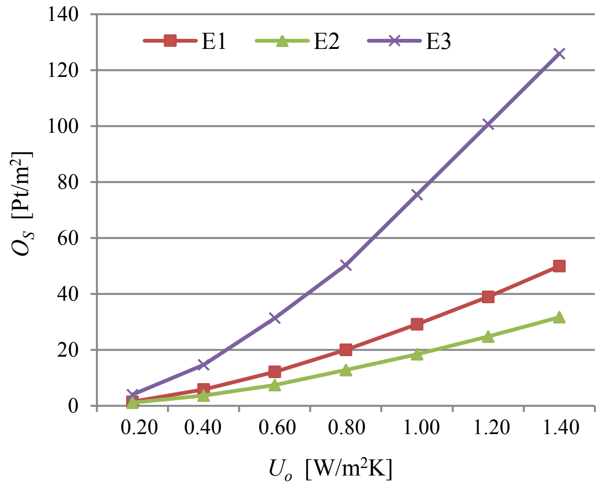

Fig. 1. Ecological benefits O_S depending on U_o [source: own study]

Figure 1 presents the dependence of ecological benefits O_S [Pt/m^2] from heat transfer coefficient for a wall without a layer of plaster U_o [W/m^{2}K] for three analyzed heat sources. The ecological payback period takes place no later than after 50 years for all three analyzed heat sources, even already for the wall with a very good coefficient of heat transfer $U_o = 0.20$ W/m^{2}K ($U = 0.18$ W/m^{2}K).

The economic benefits of using Thermopor plaster for the thermo insulation of external building walls

The economic cost K_E of using Thermopor plaster for the thermo insulation of external building walls are connected with, first of all, the cost of purchasing plaster and cost of performance. The cost in relation to 1 m^2 of the wall area amounts:

$$K_E = K_m \cdot d + K_w \quad [€/m^2] \tag{5}$$

where:

- K_E – economic cost of applying the plaster [€/m^2];
- K_m – cost of 1 m^3 of the plaster [€/m^3];
- K_w – cost of performance for 1 m^2 of the wall area [€/m^2];
- d – as already defined in the paper.

With the use of Thermopor plaster there is the energy saving due to the reduction of the demand for energy to heat the building. The economic profits Z_E are the following [4, 22]:

$$Z_E = S_n G_o (U_o - U) \quad [€/m^2] \tag{6}$$

where:

- Z_E – economic profits in the phase of the building usage due to Thermopor plaster use [€/m^2];
- G_o – annual heating cost in relation to 1 m^2 of the wall area [€ K/W];

$$S_n = \sum_{t=1}^{n} \left(\frac{1+s}{1+r} \right)^t = \frac{1-q^n}{q^{-1}-1}, \quad \text{where} \quad q = \frac{1+s}{1+r}$$

- r – real annual interest rate;
- s – real annual growth (in percentage) of heating cost,
- n, U, U_o – as already mentioned in the paper.

For economic regards the application of Thermopor plaster for the thermo insulation of external building walls generates the benefits O_E of the amount:

$$O_E = Z_E - K_E \quad [€/m^2] \tag{7}$$

In the further part of the article the rate of 1 € = 4.1 PLN was assumed. According to the data from [13] $K_m = 575$ €/m^3 and $K_w = 30$ €/m^2 were accepted. The thickness of plaster and other necessary data were assumed the same as presented in point 4. The economic cost (assigned from the formula (5)) was obtained of the amount of $K_E = 47.25$ €/m^2.

The economic profits Z_E in the phase of the building usage assigned from the formula (6), as well as the economic benefits O_E obtained due to the application of the Thermopor plaster from the formula (7). The values of interest rates were accepted as $r = 5\%$ and $s = 3\%$. The results were presented in table 6.

Table 6. Economic profits and benefits [source: own study]

Heat source →	E1	E2	E3
Z_E [€/m^2]	3.38	9.43	15.58
O_E [€/m^2]	–43.61	–37.11	–30.51

Unfortunately in case when external walls have coefficient of heat transfer $U_o = 0.30$ W/m^{2}K, then with the analyzed heat sources the cost of using Thermopor plaster is not returned after 50 years. Although Thermopor plaster has thermo insulating properties comparable with typical thermo insulating materials, but a layer of plaster has a limited thickness, moreover, the economic cost of using the plaster for thermo insulation is bigger than of typical thermo insulating materials [4].

Figure 2 presents the dependence of economic benefits O_E [€/m^2] from the heat transfer coefficient for the wall without a layer of plaster U_o [W/m^{2}K] for three analyzed heat sources. The economic payback period would take place no later than after 50 years for heat source E3 for the wall with heat transfer coefficient $U_o \geq 0.54$ W/m^{2}K ($U = 0.42$ W/m^{2}K), for E2 with $U_o = 0.71$ W/m^{2}K ($U = 0.51$ W/m^{2}K) and for E1 with $U_o = 1.32$ W/m^{2}K ($U = 0.76$ W/m^{2}K).

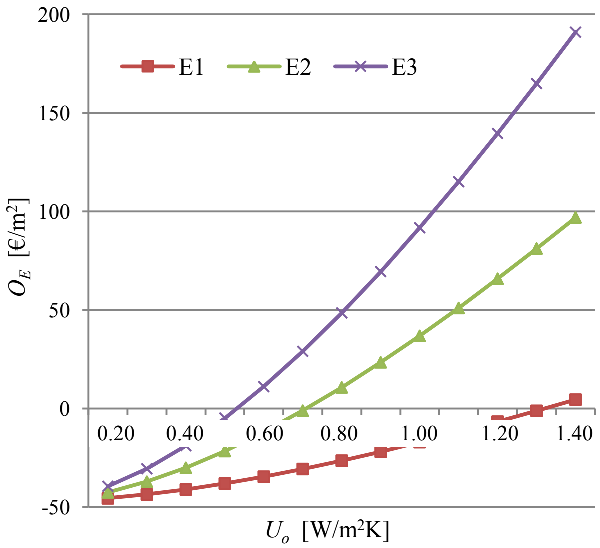

Fig. 2. Economic benefits O_E depending on U_o [source: own study]

The economic benefits also depend substantially on the annual heating cost G_o. The greatest profits were obtained for source E3, for which G_o is the biggest (see formula (6), Table 6 and Fig. 2).

Conclusions

Thermopor plaster has mechanical properties comparable with cement plaster. It has a far smaller density (about 334 kg/m^3) from cement plaster (about 1600 kg/m^3). Thermopor plaster is characterized by very good adhesion. It can be used on concrete, Ferro concrete, brick, wood, glass, steel and replasters (regips). It has desirable properties: vapour permeability, freeze resistance and resistance to water transfer. The mentioned properties are particularly essential in terms of plaster durability [23]. Moreover, it also has good thermo insulating properties, comparable with typical thermo insulating materials (heat conduction coefficient equals 0.054 [W/mK]).

The conducted environmental analysis, with use of LCA technique, of applying the plaster for the thermo insulation of external building walls proves ecological benefits. The ecological payback period connected with using the plaster takes place already after 2 to 5 years, depending on heat source used, which results from the reduction of thermal energy consumption for heating the building.

The economic analysis shows partial return of economic cost due to the reduction of the demand of energy for heating and as a consequence heating cost. Although Thermopor plaster has thermo insulating properties similar to typical insulating materials, such as polystyrene or mineral wool, the economic cost of using the plaster for thermo insulation is repeatedly higher.

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