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Heat-insulating gypsum based plaster compositions

1. Introduction

When developing lightened heat-insulating materials on the base of calcium sulphate (increasingly important in construction) the possibilities to introduce various lightweight aggregates and the limits of their content have been studied [1, 2]. The purpose of this particular study has been to develop the compositions for interior plaster coverings, with fine perlite as basic filler. It is known that entering of perlite grains (of low thermal conductivity) in gypsum matrix can significantly improve heat and sound insulation properties of the composite, with not only its density being lowered, but, unfortunately, its strength as well.

To strengthen the composite a part of perlite could be replaced with cenospheres. These hollow alumina-silica microspheres (formed as a part of fly ash) are known [3-6] as efficient filler due to their form, waterproofness, low density and thermal conductivity. The preliminary experiments showed that certain dosages of metakaolin, plasticiser and latex could improve gypsum matrix, structure and properties of the composite.

2. Preliminary trials

To determine the upper limit of the content of heat-insulating component the method of electro-thermal analogy was used in preliminary model experiments. The method helps to establish the proportions in "conductor – insulator" systems, at which the electrical conductivity changes abruptly; percolation conductivity jump takes place (or percolation resistance jump at certain content of insulator). The conductive media was modelled with carbon powder, lightweight filler particles served as the insulator.

The estimated value of percolation threshold for perlite grains (and for cenospheres as well), near 80 volume percents (Fig. 1), approximately corresponds to theoretical value

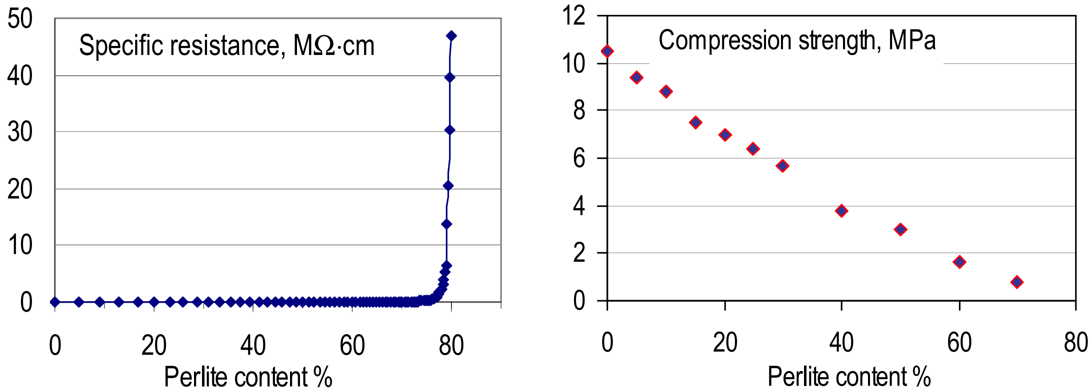

Fig.1: Specific electric resistance and compression strength in dependence of the content of perlite in carbon powder (left) and in gypsum matrix (right)

of percolation threshold [7]. At this zone of high concentration of insulating particles the conducting paths become blocked, specific resistance increases steeply (electric conductivity of the mix falls). The indicated percents hold for thermal conductivity too, though instead of jump a smooth fall in the region of percolation is observed. This can be explained [8] by comparable values of thermal conductivity of the components.

The decrease in heat conductivity with increase of the content of light filler in gypsum matrix is accompanied by reduced strength (Fig. 1). At the content close to 80% the material loses its soundness and begins to fail because of the lack of the binder. Plots in Fig. 2 show the possibilities to strengthen the material through introducing of cenospheres and metakaolin.

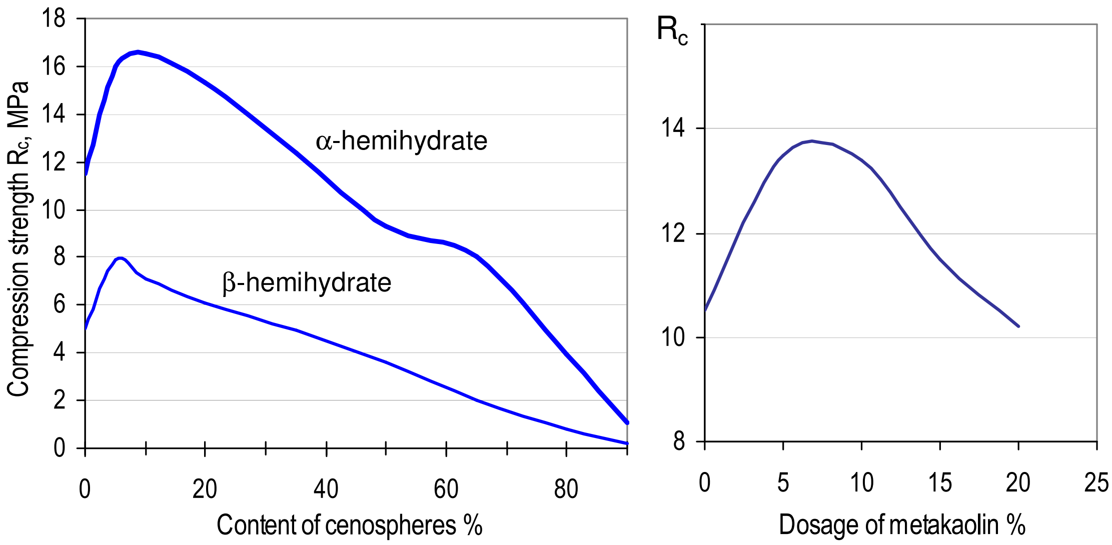

Fig.2: Strength of gypsum composite vs. contents of cenospheres and metakaolin

3. Multifactor experiment and ES-models

The results of preliminary studies allowed multifactor experiment to be designed so that non-linear experimental-statistical (ES) models [9-11], describing individual and combine effects of the components on the properties of gypsum plaster compositions, could be built. Presented in Tab. 1 four composition factors X_i (i = 1…4), normalised to $-1 \le x_i \le +1$, were varied in the experiment. Used as a binder was α-hemihydrate to provide sufficient strength at high content of heat-insulating filler. The following statistics characterise the grain size distributions of the light fillers: perlite – in the range 1.0-124.3 μm, with the average 6.6 and median 3.5; microspheres – from 1.0 to 197.8 μm, with average and median values 22.7 and 11.4 respectively; the modes of both distributions lie near lower boundaries of the ranges.

The properties (Y) of dry and liquid mixes and of hardened material were determined for 18 compositions, corresponding to 2nd order three-level optimal design of experiment (No 57 in [12]), which allows 4-factor ES- models of kind (1) to be built.

$$Y(x) = b_0 + \sum_i b_i x_i + \sum_i b_{ii} x_i^2 + \sum_{i<j} b_{ij} x_i x_j \qquad (1)$$

Tab.1:
Values of varied dosages of the components

i	Factor X_i	Levels		
		$x_i = -1$	$x_i = 0$	$x_i = +1$
1	Quantity of perlite sand (*P*, volume parts for 1p. of gypsum)	10	15	20
2	Quantity of cenospheres (*CS*) and metakaolin (*MK*) in their mixture (5% of binder volume)	5% *CS*	by 2.5% *CS* + *MK*	5% *MK*
3	Dosage of superplasticiser (*SP*) (% of gypsum volume):	0.5	0. 75	1.0
4	Content of latex (*L*) (% of liquid mix volume)	1	1.5	2

Given in Tab. 2 are the coefficients of ES-models built for the properties considered

Tab.2:
Coefficients of ES-models for 6 properties of heat-insulating gypsum plaster compositions

	ρ	R_c	R_b	λ	ln R_A	τ
b_0	538.9	1.13	0.55	0.109	-1.322	0.416
b_1	-51.4	-0.61	-0.26	-0.016	-0.531	-0.027
b_2	5.4	0.06	± 0	± 0	-0.226	-0.007
b_3	16.0	0.06	-0.04	± 0	-0.208	-0.031
b_4	-7.7	0.05	0.05	-0.003	0.162	-0.021
b_{11}	30.7	0.38	0.07	0.012	± 0	± 0
b_{22}	± 0	0.30	0.08	± 0	0.348	0.028
b_{33}	-19.7	-0.17	-0.04	± 0	± 0	± 0
b_{44}	± 0	± 0	0.05	-0.007	± 0	± 0
b_{12}	± 0	± 0	± 0	± 0	-0.220	-0.028
b_{13}	-14.0	± 0	-0.04	± 0	± 0	-0.053
b_{14}	11.0	± 0	0.04	0.003	-0.093	-0.042
b_{23}	± 0	0.08	± 0	± 0	-0.086	-0.020
b_{24}	-9.6	-0.07	± 0	-0.006	± 0	-0.020
b_{34}	-7.5	-0.09	-0.03	-0.005	0.113	-0.043

below. These are density ρ (кг/м^3), compression and bending strength, R_c and R_b (MPa), adhesion strength R_A (MPa), thermal conductivity λ (W/m/K), coefficient of sound conductivity τ (the ratio of energy of the sound that passed through a barrier to energy of falling sound waves [13]); "± 0" in Tab. 2 signifies that corresponding effect of the factors is statistically insignificant. It should be remarked that it would be better to include CS and MK in factor system independently so that the influence of 2-fraction filler could be evaluated. In particular, the positive or neutral synergetic effect of mixing perlite grains and fly ash microspheres, with grain size distributions characterised above, on compression strength and other properties might be revealed.

4. The fields of properties in composition coordinates

The models describe the fields of material properties [11, 14] in four coordinates of the composition. In Tab. 3 the fields are presented by their basic generalizing indices (G, numerical characteristics of the fields): minimal and maximal levels of the field of each property, coordinates of extrema (i.e., compositions providing the best and the worst levels), absolute and relative increment (decrease) that could be achieved by changing the mix proportion.

Tab.3:
Generalizing indices of composition fields of 6 properties

G *Y*	ρ	R_c	R_b	λ	R_A	τ
Y_{min}	469.3	0.51	0.24	0.086	0.09	0.15
Y_{max}	672.5	2.56	1.03	0.147	0.99	0.54
$\Delta = Y_{max} - Y_{min}$	203.2	2.05	0.79	0.061	0.90	0.39
$\delta = Y_{max} / Y_{min}$	1.4	5.0	4.3	1.7	11.4	3.5
$\boldsymbol{x}_{min}$ x_1, x_2 x_3, x_4	0.8, −1 −1, −1	0.8, −0.1 −1, −1	+1, 0 +1, −0.5	0.5, +1 +1, +1	+1, 0.7 +1, −1	+1, +1 +1, +1
$\boldsymbol{x}_{max}$ x_1, x_2 x_3, x_4	−1, +1 +1, −1	−1, +1 0.7, −1	−1, +1 −0.4, +1	−1, +1 +1, −1	−1, +1 −1, +1	−1, +1 +1, −1

As could be expected, the compositions that would provide the best levels of individual properties ($\boldsymbol{x}_{min}$, $\boldsymbol{x}_{max}$, Tab. 3) lie in different formulation zones. However quite considerable drops in the levels of the majority of the properties over whole formulation region indicate to possibilities for providing various requirements to the material through various dosages and to the possibility of compromises.

The curves in Fig. 3 visualise 1-factor local fields of compression strength at fixed values of other 3 factors ($x_{i.min}$, $x_{i.max}$), which provide the minimum and maximum of R_c. As expected, there is governing decreasing effect of perlite on the strength (on R_b and

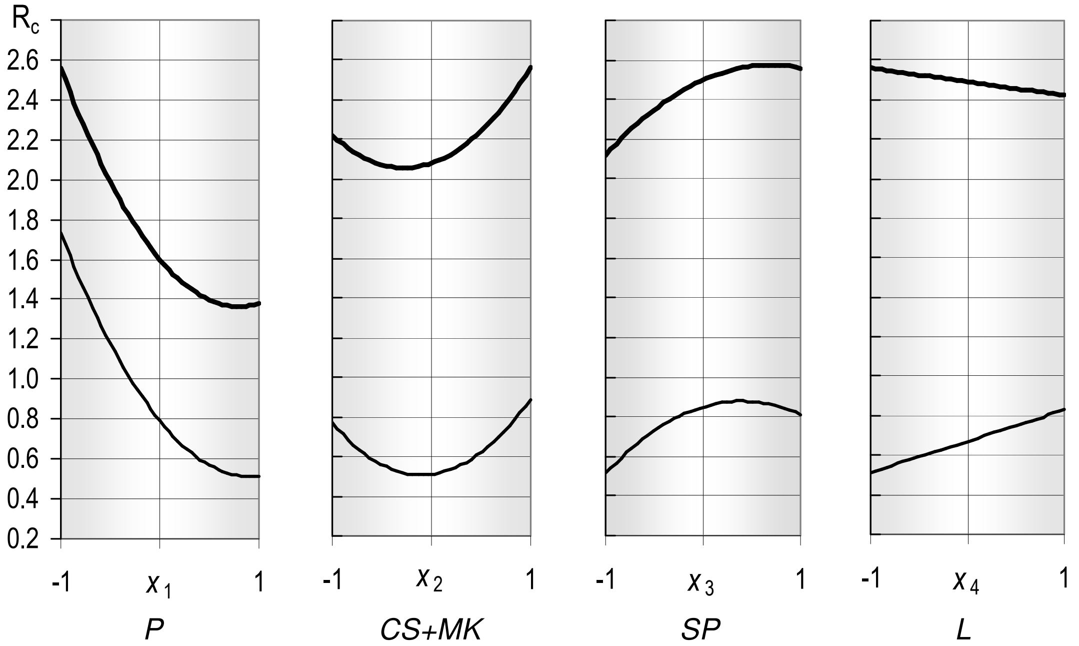

Fig.3: The influence of the components on compression strength in zones of its maximum and minimum

R_A as well, but on the density and heat conductivity too). It turns out that 5% of metakaolin (x_2 = +1) introduced in gypsum matrix is preferable for strength than 5% of microspheres (x_2 = –1) and even more preferable than the mixture of these additions. The positive influence of superplasticiser and the ambiguous effects of latex on R_c can be also seen.

Judging by coefficients of ES-models (Tab. 2), generalising indices of the property fields the models describe (Tab. 3), and graphic representations of the influence of the components (such as in Fig. 3 and others), the increased content of latex actually enhances the adhesion and contributes to low thermal conductivity. This decrease of λ could be explained by forming the structures, in which matrix layers become less branched and isolated by perlite-latex layers, with heat paths blocked by perlite grains.

The combined influence of perlite and latex on sound conductivity coefficient is presented with local fields $\tau(x_1, x_4)$ at various content of cenospheres, metakaolin, and superplasticiser (Fig. 4).

At low dosage of the latter the matrix is not good enough for soundproofing, no matter what *CS+MK* mixture is introduced. Metakaolin in gypsum matrix helps perlite to fulfill its soundproofing role (compare the left squares with the upper right square in Fig. 4). The increased dosage of metakaolin at sufficient quantity of superplasticiser moves τ_{min} to the upper contents of perlite and latex.

Minimal levels of the fields $\tau(x_1, x_4)$ and possible decrease of sound conductivity due to certain values of *P* and *L* represent the contribution of perlite with latex in improving soundproofing ability of the material in dependence of *CS+MK* and SP (Fig. 5).

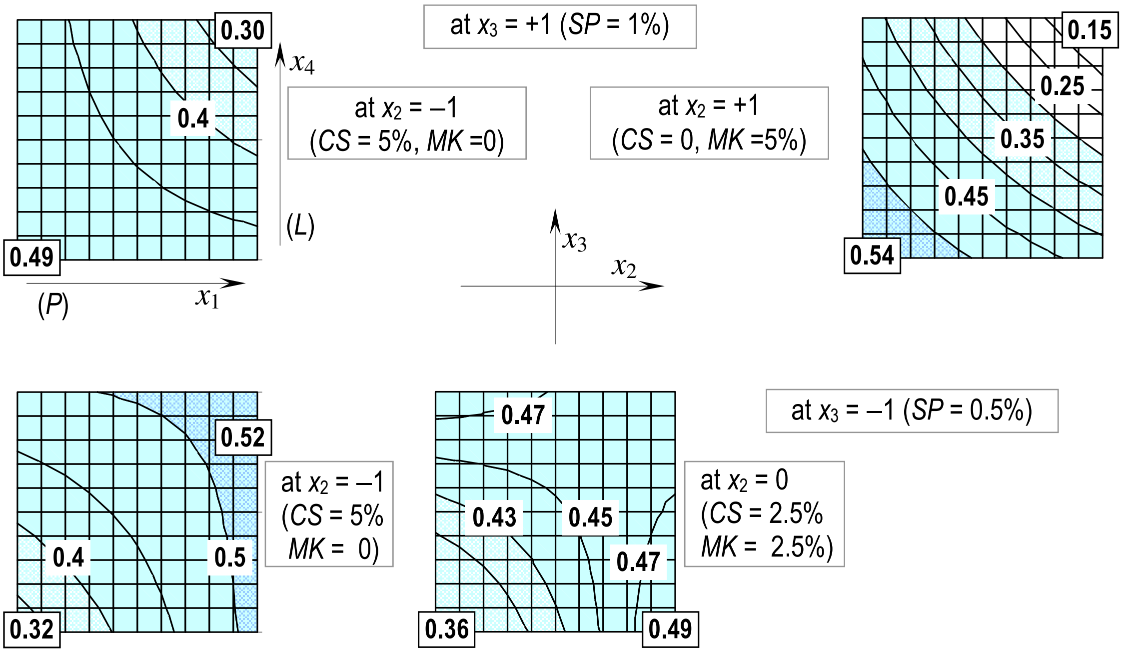

Fig.4: The fields of τ in coordinates of P and L (normalised x_1 and x_4) at various dosages of CS+MK and SP (i.e., x_2 and x_3)

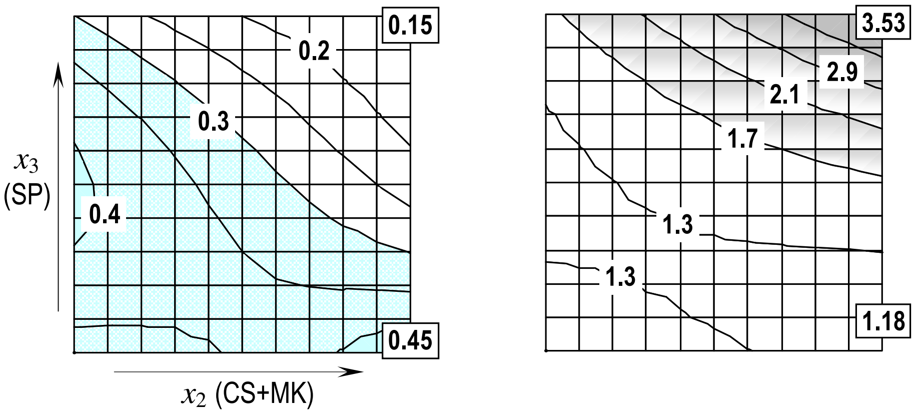

Fig.5: Minimal τ (left) and relative decrease $\delta\tau$ (right) achieved due certain contents of perlite (x_1) and latex (x_4) in dependence on quantities of cenospheres, metakaolin (x_2), and superplasticiser (x_3)

5. Acceptable and optimal compositions

ES-models in tandem with Monte Carlo method make it possible to scan the fields of properties in composition coordinates and thus to determine acceptable dosages of the components, at which certain requirements to plaster compositions are fulfilled. In particular, according to Ukrainian specifications such materials must provide the following levels of properties:

$$R_c \geq 1 \text{ MPa},\ R_b \geq 0.5 \text{ MPa},\ \lambda \leq 0.2 \text{ W/m/K},\ R_A \geq 0.2 \text{ MPa}.$$

The region of compositions that would comply with these requirements comprises about 62% of whole four-dimensional region of dosages studied (by index Ω – the size of acceptable region [11,14]).

It seemed reasonable to find such of acceptable compositions that would provide as low density and sound conductivity as possible. To find the compromise between the minima of ρ and τ under restrictions on other properties indicated above used was iterative random scanning of composition fields [14-15].

The following optimal compromise composition with following levels of the properties has been obtained:

P = 16.5 (x_1 = 0.3); CS = 0, MK = 5% (x_2 = +1); SP = 1% (x_3 = +1); L = 2% (x_4 = +1);

ρ = 502 kg/m^3, R_c = 1.2 MPa, R_b = 0.54 MPa, λ = 0.09 W/m/K, R_A = 0.21 MПa, τ = 0. 26.

As can be seen in Tab. 3, heat conductivity of all lightened compositions, in whole formulation region under study, is below the level required for common heat-insulating plaster mortars. It is important that adhesion can be substantially increased. Evidently the set of the components under discussion allows the high performance plaster compositions to be get, answering the special purposes.

Specifically, the following optimisation problem has been also solved:

$$\rho \rightarrow \min, \lambda \rightarrow \min, R_A \rightarrow \max, \tau \rightarrow \min, \text{ with } R_c \geq 1,\ R_b \geq 0.5 \text{ MPa}.$$

The compromise composition found:

P = 16 (x_1 = 0.2); CS = 5, MK = 0% (x_2 = –1); SP = 1% (x_3 = +1); L = 2% (x_4 = +1).

The levels of the properties are:

ρ= 516 kg/m^3, R_c = 1.1, R_b = 0.57 MPa, $\boldsymbol{\lambda}$ = 0.10 W/m/K , R_A = 0.44 MPa, τ = 0.38.

6. Conclusions

The lightened heat insulating and soundproofing gypsum based compositions for indoor plaster coverings have been developed. On results of preliminary trials, including those on model systems, the dosages of the components that should be varied in designed multifactor experiment were defined. ES-models built on results of this experiment have allowed the individual and combined effects of fine perlite, fly ash microspheres, metakaolin, superplasticiser, and latex on heat conductivity, on compression, bending, and adhesion strength, on the density, and on sound conductivity of the composites to be analysed and the optimal compromise mix proportions to be found.

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