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Article

Enhancing dry mix mortar strength with natural fillers and polymers

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Abstract. Dry mix mortars are becoming more and more popular in the world's building materials market. Therefore, the issue of increasing the technological and mechanical properties of stucco mixes is relevant. The aim of the paper is modification of lightweight dry stucco mixes with fine limestone and perlite as well as with hydroxyethyl methyl cellulose and dispersible polymer. In order to investigate the different mixes, an 18-point experiment was designed. Density, compressive strengths and crack resistance of dry plaster mixes were studied using requirements of standard. Mathematical models were obtained for the compositions as a result of processing the experimental data. The regularities of the fillers' and additives' influence on the properties of the mixes were established, depending on their amount and combination. It was observed that methyl hydroxyethyl cellulose improves the crack resistance and compression strength, and contributes to a slight decrease in density. The crack resistance of plaster mortars changes more than 1.5 times, the most crack-resistant compositions have an average amount of porous fillers.
Keywords: dry mix mortar, cellulose ether, dispersiblolymer, crack resistance, compression strength.

1. Introduction

The modern construction industry places dry mixed mortar amongst the most versatile materials. There are different kinds of dry mortars for specific purposes: masonry mortar, plastering mortar, ground mortar, tile adhesive, insulating mortar, self-leveling, water-proof mortar, repair mortar, wall putty, and so on. Dry mix products provide excellent technical properties meeting the stringent performance requirements. Normally, the composition of the mixes contains a raw materials binder, fillers, and various modifiers are used to give mortars new properties. Currently, the most popular modifiers are cellulose esters [1-2], superplasticizers [3], thickening agents [4], air entraining agents [5], accelerating and retarding agents [6], defoaming agents [7], hydrophobic agents [8], plasticizing agents [7], shrinkage compensation agents [9]. All of the raw ingredients are mixed together proportionally in a special factory and transported to the construction site since the ingredients and their proportions in each product are sometimes very complicated. However, there are a number of advantages of dry mix mortar: they have consistent strength and other properties like adhesion, frost resistance, etc.; mixing time is reduced because it is stirred automatically, pumped, and applied by machine; there is 30% less wastage of sand and cement due to constant correct composition of mixtures; they are easily transported in a simple container; industrial working conditions are improving.

Nowadays, the application of sustainability principles in construction encourages the development of new materials with improved hygrothermal performance [10-11]. Enhancing energy efficiency and sustainability in the built environment is crucial, necessitating the mitigation of energy demand and optimization of energy preservation mechanisms within buildings. Developed nations primarily witness substantial energy utilization attributed to space conditioning (heating, cooling, air

conditioning) and lighting systems in both residential and comme'cial constructions. In developed countries, buildings' energy consumption constitutes a substantial quantity, ranging from 20% to 40% of the overall energy consumption, exceeding that of the industrial and transportation sectors in both the EU and the USA [12–16]. Good thermal quality of buildings is necessary to ensure energy efficiency and healthy indoors [17]. Lightweight plasters are inherently characterized by low thermal conductivity and it is possible to improve the thermal performance of the outer walls by using them. To achieve enhanced thermal performance of mortars, lightweight aggregates are integrated into the composition of mortars. Expanded perlite [18], vermiculite [19–21] waste crushed ceramics [22-23], zeolite [24], sintered fly ash [25], pumice [26-27], etc. are typical representatives of porous aggregates.

The main goal of the present study is a comprehensive analysis of the effect of additives and porous fillers and the replacement ratio of expanded perlite by fine limestone in the composition of eighteen specimens of lightweight mortars on their mechanical properties.

2. Methods

2.1 Characteristics of Materials

The components of the mortars tested in this study are the following:

– Additive-free cement M500 mark (PC I-500-N D0), European quality certificate EN-197-1 [28], CEM I 42.5N, specific surface – 300 m^2/kg, fineness 11.3%;

– ground lime, content of CaO+MgO – 73% by weight, water demand 70%, bulk density – 0.5 kg/dm^3;

– Quartz sand European quality certificate EN DIN 12904 [29], density – 2.04 g/cm^3, particle size modulus – 1.1. Content of dust and clay particles is 0.3%, with no clay in the lumps, moisture content – 3.6%, sifted through a sieve of 0.63, SiO_2–99.4%, Al_2O_3–0.35%, Fe_2O_3–0.005±0.01%, CaO–0.28%, MgO–0.16%;

– Ground limestone – shell rock, with specific surface $S_{s.d.}$=400 m^2/kg, sifted through a sieve of 0.63 mm. The chemical and mineralogical composition: SiO_2–2.52%, Al_2O_3+Fe_2O_3–2.02%; CaO–52.1%, MgO–1.32%, SO_3–0.22%;

– expanded perlite sand fraction 0.16–1.05, the porosity of granules 34.6%, average density (including pores) 1.56 g/cm^3, heat conductivity at 25±5°C not more than 0.052 W_t/m°C;

– Water-retaining additive, methyl hydroxyethyl cellulose Tylose MH60010 P4 (Shin-Etsu Chemical, Japan) [30], water-soluble non-ionic cellulose ether a derivative of the natural cellulose, active substance content of cellulose methyl ether: 2-hydroxyethyl ether 90–95%, NaCl ≤ 1.5%, particle size < 125 μm, minimum 90%, viscosity 50000-90000 MPa/sec, water solubility > 10 g/L (20°C);

– Adhesion improving additive, re-dispersible powder Vinnapas 5034N (Wacker Chemie AG, Germany) [31], copolymer powder of vinyl acetate and ethylene, the active substance content being min. 98% of copolymer powder of vinyl acetate and ethylene, particle size > 400 μm.

– Air-entraining additive, wetting, and plasticizing agent Hostapur OSB (Clariant AG, Switzerland) [32]. Active substance content 90–98% of olefin sulfonate and sodium salt, particle size 72μm;

– Water-repellent Vinnapas 8031H (Wacker Chemie AG, Germany) [31], active substance content of a triple copolymer of ethylene, vinyl laurate, and vinyl chloride ≥ 98%, particle size > 400 μm.

2.2 Design of Experiment

The mix design was carried out using the D-optimality criterion [33] of the experiment. The study involved the determination of material property values denoted as *Y* across 18 compositions, using an experiment design with 4 factors and 3 levels. The experiment encompassed variations in the dosages of four key components, expressed in weight parts per 1000 weight parts of the dry mix:

limestone (designated as X_1), perlite sand (X_2), methylcellulose ether (X_3, Tylose MH60010), and dispersible polymer (X_4, Vinnapas 5034N). Other component proportions remained constant. Table 1 provides the natural factor levels (component dosages, represented as X_i) within the normalized range ($X_{i.min} \leq X_i \leq X_{i.max}$).

Table 1 – Levels of composition factors in the experiment – contents of components in 1000 w.p. of dry mix

i	Composition Factors (*X*)	Minimal, Central, and Maximal values		
		$x_i = -1$	$x_i = 0$	$x_i = +1$
1	Mass parts of limestone, X_1	60	80	100
2	Content of perlite, X_2	30	40	50
3	Dosage of Tylose, X_3	1	1.15	1.3
4	Dosage of Vinnapas, X_4	1	1.5	2

The construction of second-order models in this design facilitates a quantitative representation of the gathered data. These models delineate the individual and combined impacts of composition factors on properties denoted as *Y* by use of second-order polynomial experimental-statistical (ES) models, as described in Eq. (1), wherein the coefficients *b* possess specific physical interpretations [34].

$$Y(\boldsymbol{x}) = b_0 + \sum_{i=0} b_i x_i + \sum_{i=1} b_{ii} x_i^2 + \sum_{i<j} b_{ij} x_i x_j \quad (1)$$

where: *b* – parameters (coefficients) to be –stimated; *x* – vector of normalized factors; $x_i = (X_i - X_{0i})/\Delta X_i$, $X_{0i} = (X_{i.min} + X_{i.max})/2$, $\Delta X_i = (X_{i.max} - X_{i.min})/2$; $X_i = x_i \cdot \Delta X_i + X_{0i}$.

2.3 Preparation of specimens and research methods

All raw materials underwent precise measurements using a laboratory scale. Subsequently, thorough blending of all components was performed with a spatula to achieve uniform ingredient distribution. Water was introduced into the dry mixture and mixed for 60 seconds at low speed using a hand mixer. The water quantity was precisely regulated to attain mortars with consistent spread diameters of 16–17.0 cm, by DIN 18555 [35], as illustrated in Figure 1.

Figure 1 – Testing the freshly prepared mixture to evaluate the needed consistency

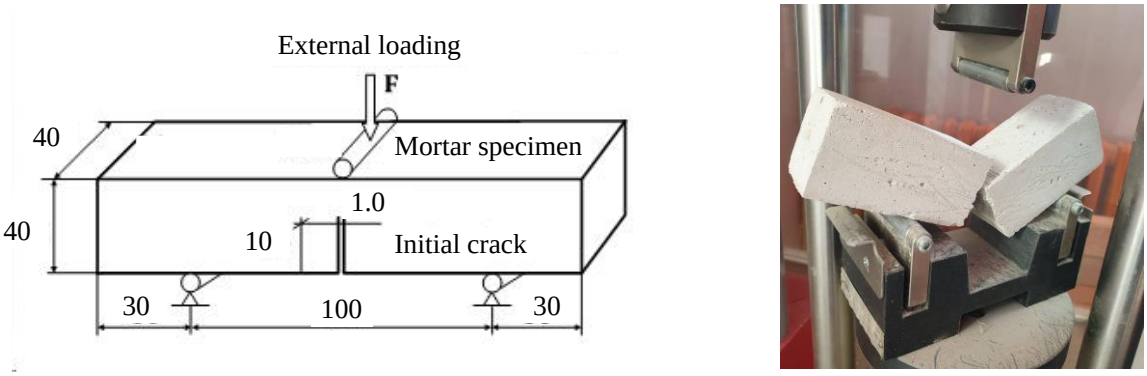
The bulk density was assessed by measuring the dimensions and dry mass of 40 × 40 × 160 mm beam samples, following a 28-day curing period at an air temperature of 20 ± 2 °C and a relative humidity of 65 ± 5%.

The compressive strengths of matured mortar samples were evaluated by the guidelines outlined in EN 1015-11:2020 [36]. For each composition, as per the experiment design, three specimens were subjected to testing. The compressive strength (f_c, MPa) was definite by examining the remnants of the specimens following tensile strength testing, which was conducted using a hydraulic press following the standard protocol.

The crack resistance of the composite was determined by the critical stress intensity factor (K_{1c}) (2), on cracked specimens, on a 3-point test scheme (Figure 2). The dimensions of the specimen are 160 mm × 40 mm × 40 mm and the initial crack length is 10 mm × 1 mm K_{1c} is determined from the Eq. (2):

$$K_{1c} = G_{n.s.} \sqrt{\pi \cdot l} \quad – \quad (2)$$

where: $G_{n.s.}$ - nominal stresses (without considering their concentration) in the weakene–section at the tip of the crack at critical load; l - notch length.



a) Three-point notched specimen test b) Specimen after the test

Figure 2 – Three-point test scheme

Nominal stresses in the cross section can be found by the Eq. (3):

$$G_{n.s.} = \frac{(G \cdot M)}{b(h-2)2} \quad (3)$$

where: M – critical bending moment; b – sample width; h – s“mple height.

3. ”esults and Discussion

The diagram "squares on square" in Figure 3 displays the joint influence of 4 composition factors on density in coordinates of composition factors normalized to dimensionless $-1 \leq x_i \leq +1$.

The results presented in the diagram indicate that the amount of cellulose contributed to a slight decrease in the density of the plaster mortars by increasing the uniformity of the mixture. An increase in the percentage of perlite in most of the factor space of the experiment, naturally, reduced density of the plaster mortar. On the other hand, in mixtures with a large dosage of re-dispersible powder Vinnapas, the amount of perlite practically did not affect density. The effect of the amount of ground limestone (x_1) on density is even more dependent on the dosage of the re-dispersible powder (x_4). However, density is reduced with the increasing amount of limestone in the mix with $x_4=-1$ (about 2 w.p. of Vinnapas), which is the desired technical result. Density reduction is attributed to the porous nature of limestone. Overall, density exhibited nearly 1.3 times. The lowest density recorded at 1046 kg/m^3 at the maximal values of all factors, except for the re-dispersible powder Vinnapas, were applied minimally. The impact of Vinnapas can be elucidated by its effect on the distribution of aggregates within the mortar; it promotes even dispersion instead of surface floating, thereby leading to a more densely packed mortar. Consequently, this has the potential to improve the thermal insulation characteristics not only of the mortar but also of the entire construction.

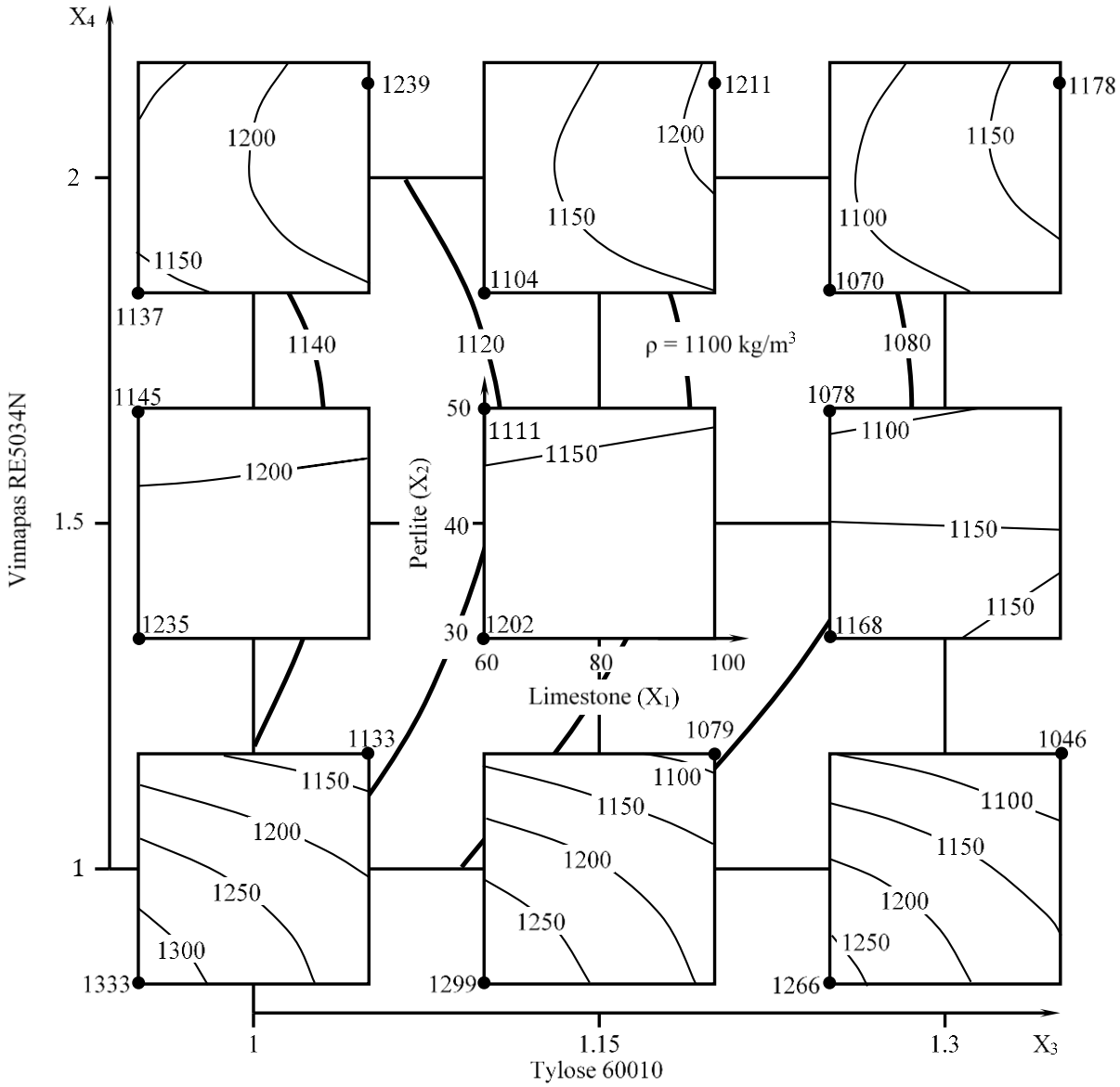


Figure 3 – The density isolines, influenced by varying limestone and perlite contents and changing with Tylose and Vinnapas dosages

The curves in Figure 4 show 1-factor local fields of the properties at fixed values of other factors providing the minimum and maximum level of compressive strength. Looking at the measured data, one can see that the compressive strength of mortars ranges from 4.08 to 8.8 MPa and changes more than twice. In this case, the most durable are the compositions with an average amount of limestone (x_1), at the highest content of perlite (x_2) and Tylose (x_3) and at a rather high dosage of Vinnapas (x_4). The amount of perlite at which the mortars reach maximum strength depends on the dosage of Tylose methyl hydroxyethyl cellulose. This is a positive effect, because some studies have reported that, regardless of the content of cellulose, the mechanical strength of mortar significantly decreased [6-37]. However, with the higher level of x_3 and the higher amount of perlite x_2, the maximum strength can be achieved. The above mentioned effects of the influence of the mineral frame can be explained by a change in the packing of its particles, but it cannot be regarded that the strength of the composite is ensured by low-strength perlite and limestone. An indirect confirmation of the latter stems from the fact that the most durable mortars in the region are obtained with the maximum amount of re-dispersible Vinnapas powder and methyl hydroxyethyl cellulose, that is, factors that affect the cement matrix more.

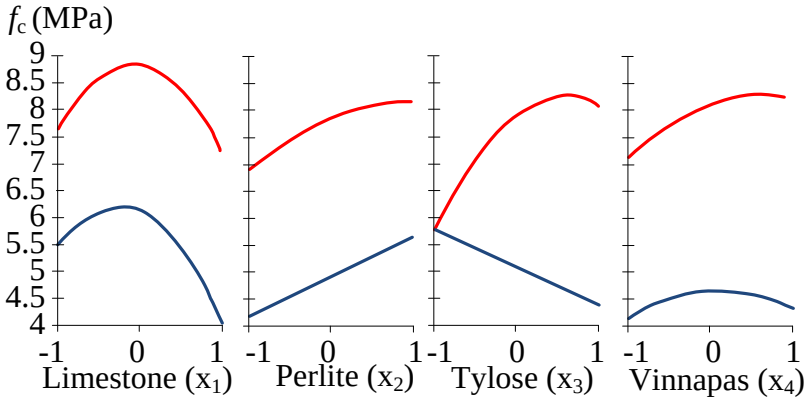


Figure 4 – The individual impacts of component content on compressive strength (f_c) in regions characterized by both minimum and maximum values

Mineral binders, providing high compressive strength, cannot always provide good bending tensile strength. Inhomogeneities, which include aggregate and filler grains, also affect the formation and development of critical microcracks and significantly change the pattern of concrete destruction.

Figure 5 shows the crack resistance of investigated mixes. The curves in Figure 5 show that under the influence of varying compositional factors, the crack resistance varied from 0.12 to 0.16 MPa. The most crack resistant ($K_{1c} \approx 0.16$ MPa·m$^{0.5}$) compositions are the ones with an average amount of limestone $x_1 \approx 0$. The effect of both limestone and redispersible powder was quite apparent in the amount range of –1 to 0 with the crack resistance growing, while a further increase of mentioned additives leads to a decrease of K_{1c}.

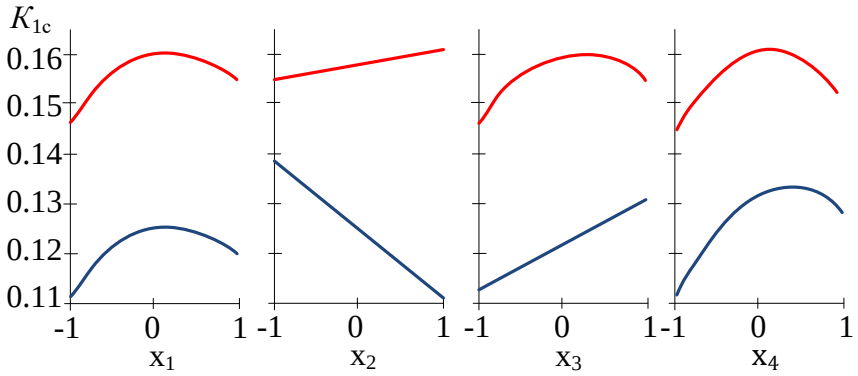


Figure 5 – The individual impacts of component content on crack resistant (K_{1c}, MPa·m$^{0.5}$) in regions characterized by both minimum and maximum values

Changing the amount of perlite did not have a noticeable effect on K_{1c}. While cellulose ethers can slightly increase crack.

4. Conclusions

To achieve the reduction of the heat transfer coefficient, the effects of two types of porous fillers and two polymer modifiers on the technological and mechanical properties of dry mix mortars were evaluated and discussed. The following conclusions can be drawn as the main outcomes of the current study:

– The effectiveness of additives varies widely, depending on the composition of the mortar. The application of expanded perlite resulted in a decrease in density. However, as compared with the mixtures with a large dosage of re-dispersible powder Vinnapas, the amount of perlite did practically not affect density;

– Re-dispersible powder induces the aggregate to be evenly distributed inside the mortar. This leads to a density increase due to denser packing of the mortar;

– The inclusion of methyl hydroxyethyl cellulose into the lightweight plasters improved the crack resistance and compression strength. This effect can be attributed to the fiber-bridging action by cellulose molecules;

– In general, when the content of porous fillers was no more than the medium amount, this had the best improvement effect on the mechanical properties).

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