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A technical evaluation on the determination of thermal comfort parametric properties of different originated expanded and exfoliated aggregates

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Abstract
Nowadays, with increasing global warming, there are increasing concerns about energy saving in many branches in the world. One of these branches is the construction sector. In the construction sector, various building materials are produced to minimize energy losses from buildings. Among these construction materials, cement mortars are widely used. Cement mortars are produced from various raw materials and aggregates. The aggregates, which have expansion properties between these aggregates, have high insulating properties due to their porous structures. In this study, four different expanded/exfoliated aggregates, which are expanded perlite (EP), expanded clay (EC), expanded glass (EG), and exfoliated vermiculite (EV), with suitable unit weight and pore structure for thermal insulation were used in cement mortar. At the end of the experimental study, the thermal behavior of the cement mortars produced was investigated. According to the results of the research, it was determined that the cement mortar produced with expanded perlite was the most suitable for the heat insulation between the tested aggregates.

Keywords Expanded perlite · Expanded clay · Expanded glass · Exfoliated vermiculite · Thermal comfort · PACS · 81.05.Rm · 44.90.+c

Introduction

The use of porous and lightweight aggregate materials is very important because of the advantages such as lightness, porosity, resistance to atmospheric conditions, and thermal performance in terms of today's building industry (Ceylan and Saraç 2017). Among these aggregate materials, material derivatives which have been expanded by heat treatment and/or which have been subjected to the opening process are finding increasingly widespread use. The most obvious examples of these materials are expanded perlite, expanded clay, expanded glass, and exfoliated vermiculite aggregate derivatives. However, detailed technical data on the thermal comfort parameters described above for these materials cannot be found sufficiently. For this purpose, a comprehensive research work was carried out. The parameters of these four expanded aggregates were experimentally studied on different cement mortar compositions. A mortar may not only contain natural aggregates, they may also contain semi-natural and artificial aggregates, providing wall compatibility, reversibility, and comfort (Bayraktar et al. 2018). The fact that the thermal comfort in today's buildings is ensured under optimum conditions has been put into practice as an inevitable rule in the regulations and standards as well (Bilgin and Arici 2017; Kılınçarslan et al. 2018). Furthermore, the overheating and overcooling of the areas where people live has negative effects on human psychology and physiology (Topay 2013; Topay and Parladir 2015; Çetin 2015; Çetin et al. 2018). For this reason, reducing the heat transfer of construction materials in areas where people continue to live will reduce the overwarming or overcooling of the environments and reduce the negative impact on people. When considering those, expanded/exfoliated aggregates are important raw materials for

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Table 1 Physical properties of the expanded/exfoliated materials

Lightweight aggregate	Hardness (MOHS scale)	Specific gravity (g/cm^3)	Bulk density (kg/m^3)	Water absorption (%)	pH
EP	4.5–5.0	2.30	40–80	70	6.6–8.0
EC	5.0–5.5	2.51	200–300	20	7.5–8.0
EG	5.5–6.0	2.10	150–250	12	9.0–9.5
EV	1.0–1.5	2.20	60–160	50	6.5–8.5

Table 2 Chemical properties of the expanded/exfoliated materials

Lightweight aggregate	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	MgO	TiO_2
EP	74.4	14.3	0.7	1.8	3.4	4.6	0.4	0.1
EC	66.7	18.9	3.9	0.8	4.5	–	1.7	–
EG	71.0	1.9	0.5	7.8	–	–	2.1	Trace
EV	35.2	24.7	10.1	0.2	–	Trace	–	1.6

energy efficient and sustainable buildings (Abidi et al. 2015; Chung et al. 2015). In this paper, thermal comfort aspects and technical performances of expanded perlite, expanded clay, expanded glass, and exfoliated vermiculite aggregate as various porous semi-artificial aggregates were experimentally analyzed in detail to be used in cementitious composite mortar as raw materials. A comparative discussion for these expanded/exfoliated aggregates based on the parameters such as thermal conductivity (λ), specific heat, heat storage capability, heat diffusion coefficient, cooling rate, amount of heat required for 1 °C temperature increase in 1-cm thickness application, and thermal transmittance (*U*-value) is given as numerical evaluations in the paper. All these parametric values are compared with a control mix as well as the performance effects that these aggregates will provide when used in cementitious composite mortar.

Materials and methods

Four different types of expanded/exfoliated materials are investigated in this study. These are expanded clay (EC), expanded perlite (EP), expanded glass (EG), and exfoliated vermiculite (EV). CEM I 42.5 Portland cement is used as a binder, lime is used as a pH stabilizer, calcite is used as a filler, and a polymer is used as a consistency adjuster. Tables 1 and 2 show the physical and chemical properties of the expanded/exfoliated materials, respectively. The materials given in Table 3 are mixed with the specified proportions, and cementitious composite mortar samples are produced.

In order to make a comparison between products easier, the grain sizes of the aggregates evaluated in mortar combinations were used as 0/2 mm. Also, cement and A/C ratio in all mixtures were kept constant for a more accurate comparison. However, the W/C ratios of the mixtures differed in order to produce similar consistency products due to the difference in water absorption capacity of the aggregates used in the study. In each mixture combination, 12 pieces of 5×5×5-cm cube specimens were produced and the compressive strength values were tested on these samples. Three pieces of 20×40×3-cm rectangular specimens were produced for each mixture combination, in order to determine the thermal properties of the specimens. TS 825 (TS 825 2013), TS EN 998-1 (TS EN 998–1 2011), and TS EN ISO 6946 (TS EN ISO 6946 2017) standards were used for conducting the tests, calculations, and evaluation of the results.

Table 3 Mixture proportions by weight

Mixture	Cement (%)	Lightweight aggregate (%)	Lime (%)	Micronized calcite (%)	Polymer (%)	A/C	W/C
E0 (control)	30	0	7.2	62	0.80	0.00	1.22
EP	30	24	7.2	38	0.80	0.80	2.57
EC	30	24	7.2	38	0.80	0.80	1.75
EG	30	24	7.2	38	0.80	0.80	1.64
EV	30	24	7.2	38	0.80	0.80	2.48

Table 4 Physical and mechanical properties of tested samples

Mixture	Fresh density (kg/m^3)	Dry density (kg/m^3)	Consistency (mm)	28 days compressive strength (N/mm^2)	Thermal conductivity, λ (W/mK)	Specific heat (J/kgK)
E0	1272	1237	150 ± 2	3.19	0.326	780
EP	701	425	150 ± 2	0.69	0.095	1080
EC	975	772	150 ± 2	1.34	0.161	965
EG	799	574	150 ± 2	1.18	0.119	950
EV	750	487	150 ± 2	0.96	0.104	980

Results and findings

Physical, mechanical, and thermal comfort properties of the composite mortar samples were experimentally investigated. The research findings of these properties are given in Tables 4 and 5.

When Table 4 is examined, it could be concluded that mortars consist expanded/exfoliated aggregates that are very lightweight materials (425–772 kg/m^3), when compared with the control sample (1237 kg/m^3). The lightest sample is produced with EP aggregate (425 kg/m^3). The lightweight structure of cement mortar samples produced with EP is expected to show an improvement in the thermal behavior of the material. According to the TS EN 998-1 standard, a lightweight mortar is required to have a dry hardened density of less than 1300 kg/m^3. When test specimens are compared with this criterion, dry densities of test specimens are considerably below the standard predicted value (701–975 kg/m^3). In relation to the low density of the samples, the compressive strengths were found to be low (0.69–1.34 MPa) compared to the control sample (3.19 MPa). Nevertheless, TS EN 998-1 standard indicates that compressive strength for thermal insulation mortars should be minimum 0.40 MPa. The compressive strength values obtained accordingly provide the necessary criteria. It is seen that the cement mortar with the highest compressive strength is produced with EC aggregate. The reason for this is that the aggregate strength of the expanded clay aggregates is higher. TS EN 998-1 standard contains two thermal conductivity groups T1 and T2. Products with a thermal conductivity of less than 0.1 W/mK are classified as class T1 and products with a thermal conductivity from 0.1 to 0.2 W/mK are included in class T2. As a function of low density, the thermal conductivity coefficient of cement mortar produced with EP was found to be quite low (0.095 W/mK). EP aggregate cement mortar specimens can be classified as T1 according to TS EN 998-1. The other specimen combinations are classified as T2. The low thermal conductivity coefficient is one of the most important parameters that will affect the energy saving in the area where it will be applied. Their specific heat values are high, which means that they needed to be more heated to make them warm compared with traditional plasters/mortars. Their heat storage capacity is low. That means they do not store heat, when they heated. Constructing the walls of buildings with the materials that store less heat storage capacity contributes to energy saving by preventing the heat consumption by the walls, when energy is used to heat the indoor. Moreover, the mortars produced by the expanded/exfoliated aggregates cool more slowly than the conventionally used mortars when heated (Table 5). While the cooling rate of control sample is 23.3 s, cement mortars with expanded/exfoliated aggregates' cooling rates change 65 to 71 s. When the interior environment is heated, it is inevitable that the wall elements are heated slightly. At the same time, if the cooling time of the wall element is high, the wall element will take longer to cool down again when the heating of the indoor environment is stopped. During this time, when the indoor environment is reheated, the wall element will not get heat again because it is already warm and there will not be any

Table 5 Thermal comfort properties of the samples

Mixture	Heat storage capability (J/m^{3}K)	Heat diffusion coefficient (× 10^{-6}) (m^2/s)	Cooling rate (sec)	Amount of heat required for 1 °C temperature increase in 1-cm thickness application (cal)	Thermal transmittance (3-cm mortar thickness + 19-cm concrete masonry block "λ = 0.14 W/mK") (W/m^{2}K)
E0	0.965	0.642	23.3	2305	0.635
EP	0.459	0.211	71.0	1097	0.545
EC	0.745	0.231	65.0	1780	0.588
EG	0.545	0.225	66.5	1303	0.565
EV	0.477	0.226	66.2	1139	0.554

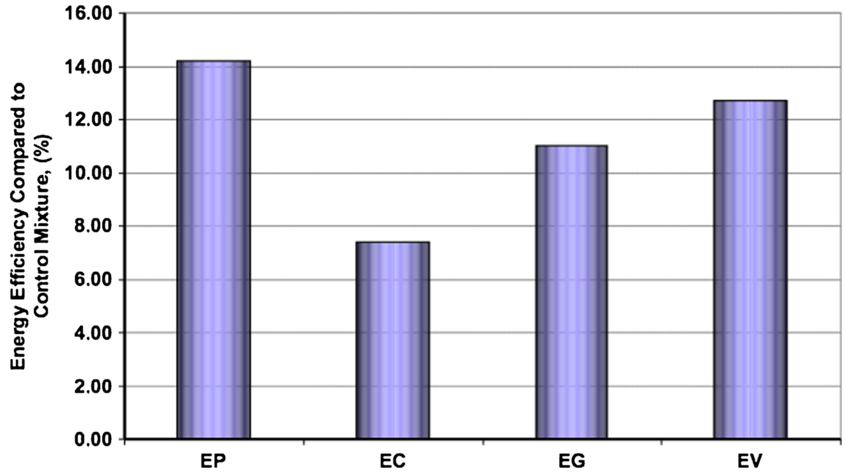

Fig. 1 Energy efficiency compared to control mixture, according to the *U*-values of the samples

energy losses. It could be concluded from Table 5 that cement mortars with expanded/exfoliated aggregates carry the heat slowly because of less heat diffusion coefficient of them. Also in this study, in order to understand how the samples can affect energy savings, the *U*-values of the samples are compared, and energy efficiency of each mixture combination graphically given in Fig. 1, according to the *U*-values.

When the composite cement mortars produced in this study are applied to the surface of a wall element ($\lambda = 0.14$ W/mK) with a thickness of 3 cm, the *U* values of the new wall combination are given in Table 5. If Table 5 and Fig. 1 are examined together, it is observed that composite mortars with EP aggregate are much energy efficient (%14.2), when compared with the control sample. This is due to the fact that the pores forming the inner structure of the expanded perlite make the heat difficult to transmit. Secondly, the mortars produced by the expanded vermiculite, known to be very resistant to heat, appear to be effective in energy saving.

Conclusions

In this study, four different expanded/exfoliated aggregate types were compared in terms of thermal performance in the production of cement mortar separately. The use of aggregates with expansion properties in cement mortar has been found to significantly reduce the unit weight of the mortar. Accordingly, it has been found that thermal performance of them is better than conventional cement mortars. It can be said that the samples with the best thermal properties are the cement mortars produced with expanded perlite among these four aggregate types. According to the results of this study, it is highly efficient to use aggregates with expansion properties to produce heat-insulated cement mortars. It is observed that composite mortars with EP aggregate are much energy efficient (%14.2), when compared with the control sample.

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