Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Cement & Concrete Composites 27 (2005) 41–47
Cement & Concrete Composites
www.elsevier.com/locate/cemconcomp

The effect of foam polystyrene granules on cement composite properties

A. Laukaitis [a,*], R. Žurauskas [a], J. Kerienė [b]

[a] Institute of Thermal Insulation, Vilnius Gediminas Technical University 28, Linkmenu Str., LT-2600 Vilnius, Lithuania
[b] Faculty of Fundamental Sciences, Vilnius Gediminas Technical University 11, Saulėtekio Al., LT-2040 Vilnius, Lithuania

Received 25 September 2002; accepted 22 September 2003

Abstract

Crumbled recycled foam polystyrene waste as well as spherical large and fine blown polystyrene waste is used to produce the filler for a light thermo-insulating composite, the matrix of which is light foam cement. For better cohesion, fillers are hydrophilizated with foam cement surfactant solution.

Polystyrene granules and foam cement concrete interaction schemes are discussed. The investigation of foam cement concrete and polystyrene granule contact zone showed that the contact of these two materials is very close, without any fractures or microcracks. Adherence of the two components depends on the size and shape of granules used.

When a polystyrene granule is ripped out of foam cement concrete, the emerged "hole" closely repeats the structure of the granule and there is some polystyrene residue left in it. This proves the fact that foam cement concrete contact zone is stronger than the polystyrene granule material. When fine polystyrene granules are used, it disintegrates along the contact zone. Such composite has the lowest adhesion strength, however, it is stronger in comparison with a composite, made with different foam polystyrene granules, provided by better macrostructure. Strength and thermal conductivity of the composite depend on its density, the filler, its sort and amount used, and is defined by regression equations.

Keywords: Recycled polystyrene wastes; Polystyrene granules; Interaction; Lightweight foam composite; Contact zone

1. Introduction

The reduction of energy consumption in construction, production of thermal-insulation materials, and the solution of environment problems by recycling of industrial and domestic waste are becoming greater problems. There are many lightweight composites that contain recycled fillers, including waste glass [1], fly ash [2,3], kraft pulps from sisal and banana waste [4], recycled acryl nitrite butadiene styrene [5], steel slag [6], lightweight crushed bricks, lightweight expanded clay aggregate [7], rubber powder, tyre rubber, micronized tyre fibre and milled electrical cable waste [8].

Foam polystyrene and its waste are used for various purposes [9–11]. Ravindrayah [9] indicated that by replacing 10%, 20%, 30% of the coarse aggregate by solid volume with polystyrene beads, the density of concrete reduces from 2455 kg/m^3 to 2330, 2210 and 2080 kg/m^3, respectively. It was shown that such polystyrene aggregate concrete is more durable when it is subjected to sulfate attack or freeze-thaw cycles.

Gypsum blocks containing 50–70% crumbled polystyrene foam beads were discussed by Sayil and Gurdal [10]. The density of such composite changed from 690 to 208 kg/m^3, and the thermal conductivity coefficient decreased from 2.74 to 0.183 W/m °C.

Expanded polystyrene waste was used in a synthesis process to obtain effective polyelectrolytes application, which caused a decrease of turbidity and concentration of solved contamination and improved quality parameter of purified water [11].

Adhesion of the composite with the matrix is very important in the process of manufacturing composites. Polymers and organic admixtures interact with the components of Portland cement when coming into contact with water [12].

In the process of investigating contact zone between most widely used fillers—quartzite, limestone, basalt, it

* Corresponding author. Tel.: +3702-750001; fax: +3702-752629.
E-mail address: termo@aiva.lt (A. Laukaitis).

0958-9465/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconcomp.2003.09.004

was established that, in contrast to basalt and quartzite, limestone reacts with cement paste, causing the formation of porous material in the contact zone, provided by produced CO_2 gas [13]. In the course of investigation of the contact zone between cement, stone and filler—river gravel, it was found that a thin porous layer, consisting of $Ca(OH)_2$ and ettringite, formed on the filler [14]. After adding silica fume into the cement paste, the C–S–H reacts with the surface of the filler. Such concrete has greater compressive strength, provided by increased adhesion between matrix and fillers.

The organic origin fillers, containing plenty of amorphous SiO_2, e.g. rice husk, at temperatures of about 40 °C reacts with $Ca(OH)_2$ in contact with water to form a kind of C–S–H gel ($Ca_{15}SiO_{35}H_2O$). The C–S–H gel looks like flocs in morphology, with a porous structure and large specific surface [15]. When investigating fibrous materials' adhesion with composite matrixes [16–19], it was established that porosity of contact zone and adhesion depend on the material, of which fibres are made of and the way they were inserted into the mixture. Adhesion and mechanical cohesion [17] exist between fibrillated propylene fibre and hardened cement paste. Polypropylene or nylon fibres' breaking away from cement matrix takes place across the surfaces of the fibres [18].

Major properties of higher density (1000–1500 kg/m^2) foamed concrete have been extensively investigated by various researchers [19–22], while technological parameters and essential properties of lightweight concrete were described in [23–26].

The Institute of Thermal Insulation is conducting research to create a thermo-insulating composite, the matrix of which is lightweight foam cement concrete and fillers foam polystyrene granules [27]. This paper presents summarized scientific research data describing the interactions between 3 different kinds of polystyrene granules, including domestic foam polystyrene waste, with the composite matrix and the composite properties.

2. Raw materials and research methods

The following materials were used:

(1) Portland cement (CEM I 42,5 R) manufactured by "Akmenės cementas" Joint-stock company, used as binding material. Initial setting time of Portland cement is 140 min, final setting time—190 min (EN 196-3). Chemical and mineral compositions are described in Table 1.

(2) Surfactant, which contains 2% of sulfonol and 0.3% bone glue hydrosolution. In this mixture sulfonol acts as foaming agent, and bone glue as stabilizer. The ratio of sulfonol and bone glue in the solution is 1:0.15.

(3) Polystyrene granules of three types: blown (large + fine) and crumbled. Gradation are described in Table 2. Crumbled granules are produced by mechanically disintegrating unusable or poor quality polystyrene slabs and from recycled polystyrene foam plastic. The composite matrix–foam cement was obtained by mixing cement, water and foam in a horizontal 20 dm^3 agitator (shaft at 50 RMP). The foam was beaten in a horizontal beater. The beating lasted 5 min. The foam volume expanded by 40 times. The Portland cement and water was poured into the horizontal agitator and mixed for 3 min. The required amount of foam added and mixture was mixed for another 5 min. Hydrophilizated polystyrene granules were then added and the material mixed for a further 3 min. The ratios between the polystyrene granules and foam cement were varied as part of the experimental design. In order to simplify the process of formation, the estimated component additions were measured by volume. The following ratios between foam cement and foam polystyrene granules were used: 1:1;1:2;1:3.

After casting into the forms $100\times100\times100$ mm and $400\times400\times400$ mm the polystyrene granules and foam cement composite were allowed to harden for 28 days at ambient conditions. After 28 days the thermal conductivity was determined according to EN 12667 by single-

Table 1
Chemical and mineral cement compositions

Chemical	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	R_2O	Others
%	20.42	5.01	4.02	64.49	3.86	0.72	0.76	0.32

Mineral	C_3S	C_2S	C_3A	C_4AF
%	62.0	12.0	7.5	11.0

Table 2
Grading of polystyrene granules

Size of sieve mesh (mm)	Large granule partial residue on sieve (%)	Fine granule partial residue on sieve (%)	Crumbled granule partial residue on sieve (%)
10.2	43.93	1.45	1.02
5.0	55.92	60.89	28.27
2.5	0.05	37.62	63.85
<2.5	0.10	0.03	6.86

specimen symmetrical heat flow meter FOX 304 (USA) at the average temperature 10 °C and the average temperature difference across the specimen 20 °C. The specimen size 305 × 305 mm, thickness 30–80 mm, heat flow meter calibrated according to EN 12667.

Granules were hydrophilizated in two ways: by soaking and by vacuuming. For hydrophilization, the solutions of the blowing agent and water were used. According to the first method, small nylon net bags with the granules were immersed in water or blowing agent solution for 5, 10 or 15 min. Then, the bags with the granules were taken out and, when the liquid had dripped, they were shaken and weighed. The procedure was repeated until the weight of the bag became constant.

The method of vacuuming was applied in the following way.

The test was carried out in the desiccators, in which dry specimens were first placed and a vacuum formed for 1 h at 0.95 atm. The desiccators were then filled with 30–40 °C boiled water, while maintaining the vacuum. After 1 h the specimens were placed into a tub with water and kept in a refrigerator at 4 °C for 19 h. Hydrosaturation after the vacuuming process was assessed.

The structure of the interacting foam cements and polystyrene granules, their contact zone, and zones of mechanical fracturing after 28 days at normal hardening conditions were researched with an electronic scanning microscope (Stereoscan S4-10). The surface of the specimen was observed after fracture using an optical microscope (MBS–9).

Compression strength of specimens was determined by EN 679 at 10% deformation and bending strength according to EN 1351.

3. Results and discussion

The observation of the surfaces of polystyrene granules of all three types by using an electronic scanning microscope revealed that the morphology of the surfaces of blown (fine + coarse) and crumbled granules obtained by mechanically disintegrating unusable or poor quality polystyrene slabs varies to a large extent (Fig. 1).

Coarse granules have regular spherical shape and uniform surface made up of small ''honeycomb'' cavities separated from each other by thin pellicles (Fig. 1a).

Crumbled granules are of irregular shape. They are obtained by disintegrating a composite material consisting of interconnected granules of small diameter (about 2 mm). The shape and the uneven surface of these particles are determined by the specific character of disintegration of the above material. The process of crushing is not uniform throughout the material, with some granules breaking away from the others, while in other areas, the granules are breaking apart leaving the contact zone intact. As a result, the crumbled granules obtained are of intricate shape and morphology. Much of their surface area is made up of ''honeycomb'' cavities separated by fine pellicles, which, unlike those found on the surface of coarse granules, are damaged to a larger extent (Fig. 1b). Fine granules are spherical, with their morphology being completely different from that of coarse and crumbled particles. Their surface seems to be made of small ''merged'' bubbles (Fig. 1c). There are no such deep cavities as can be observed on the surface of coarse granules.

The above differences in the surface structure of the granules observed determine their different performance in a composite.

Hydrofilling. When creating an effective thermal-insulating composite, it is necessary to know how much water is used to moisten granules, because foam cement mass is very sensitive to changes of water and cement ratio.

The lowest water absorption appears when hydrofilling large polystyrene granules—only about 1%. Water absorbed by fine granules during the same period of time was ≈1.9%, water absorption for crushed granules is 2.3% (assessing according to volume during the first 5 min). Water absorption for granule hydrofilling occurs rapidly and does not change over time. In the process of producing polystyrene granule and foam cement composite, the first 5 min, when it is still being mixed in the agitator, are the most important. The foam

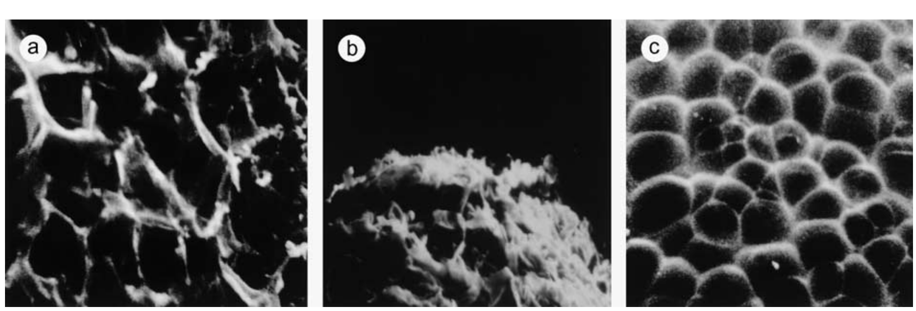

Fig. 1. Polystyrene granule microstructure: (a) large (X120); (b) crumbled (X120); (c) fine (X120).

cement concrete bulk is subject to mechanical loading (agitator's blades) and there is a danger of disintegration of foam cement porous structure.

Polystyrene granules do not adhere to dried cement paste well, because the filler is hydrophobic and its surface is statically charged. Because of these factors, the concrete becomes less homogenous and its component cohesion—weaker. All of this influences the strength of concrete. In order to straighten these deficiencies, we used the surfactant solution.

Examining polystyrene granule hydrosaturation, it was expedient to review hydrofilling of all three kinds of granules separately. Hydrosaturation of large and fine polystyrene in sulfonol and bone glue solution is 1.36–1.95 times greater than in water.

Hydrosaturation of crumbled polystyrene granules in the solution of sulfonol and bone glue is by 3.5–4.0 times greater than that of other kinds of granules (Fig. 2) due to their open structure.

Even though polystyrene granules, under the influence of sulfonol, reach sufficient hydrofilling level, vacuuming allows for even higher hydrofilling level—3.64–4.55 times more compared to maximum values when hydrofilling takes place in about 20 °C sulfonol and bone glue solution.

However, this method turned out to be rather complicated, therefore it was not used in further investigation. Hydrofilling of specimens was achieved by using the first method.

Density. The increase of polystyrene granule concentration in the composite is directly related to decreasing of specimens' density (Fig. 3). When the ratio

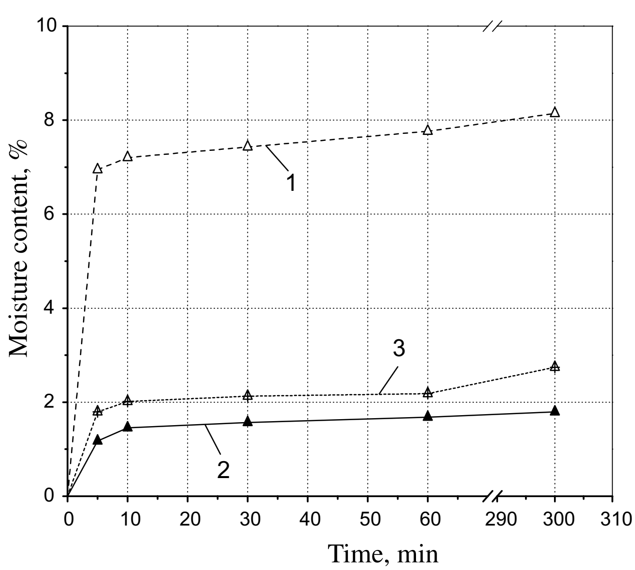

Fig. 2. Kinetics of foam polystyrene granule hydrosaturation (by volume) in the solution of the blowing agent: (1) crumbled granules; (2) large granules; (3) fine granules.

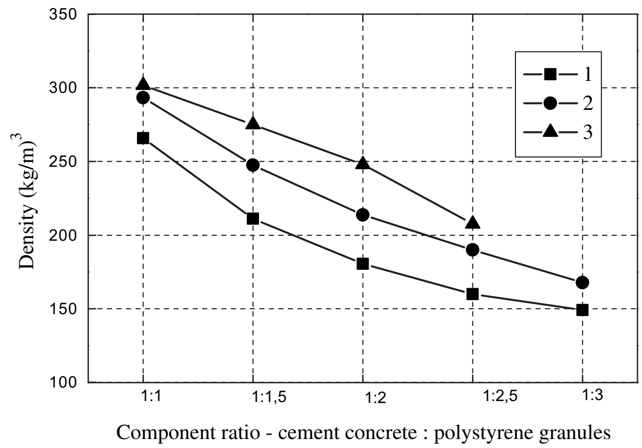

Fig. 3. Composite density dependence on the ratio of components: (1) large polystyrene granules; (2) fine polystyrene granules; (3) crumbled polystyrene granules.

by volume is 1:1 (foam cement and polystyrene granules), the lowest density is that of a composite, in which fine granules are used, making about 266 kg/m^3. The density of a composite with large granules is approximately 293 kg/m^3, crushed granule composite density—302 kg/m^3. When the ratio is 1:2 (foam cement and polystyrene granules), the density a composite, in which fine granules are used, is 181 kg/m^3, the density of a composite with large granules—214 kg/m^3, crushed granule composite density—248 kg/m^3. The lowest material density is obtained when they are mixed at the ratio of 1:3 (foam cement and polystyrene granules), the density of a composite, in which large granules are used, is 149 kg/m^3, the density of a composite with fine granules—167.8 kg/m^3, and crushed granule composite was not able to be manufactured at this ratio due to the crumbling of specimens.

When there is a fixed ratio between foam cement and polystyrene granules, the highest decrease of density takes place when using large granules.

3.1. Contact zone between granules and foam cement

Photographs obtained by using an electronic scanning microscope (Figs. 4–6) allow us to identify major factors influencing the disintegration of foamed cement and granule composite. When a composite made up of foamed cement and coarse granules is crushed, the granules break apart, not ripping out from the binding material, while a layer of the binder covering the granule surface remains intact at all contact zones between the surfaces of the granules and foamed cement (Fig. 4a). On the photograph (Fig. 4b) showing a part of the contact zone, one can see that very good cohesion between the granules surface and foamed concrete remains after the composite had been crushed. In this composite, the pores of foamed cement and polystyrene granules

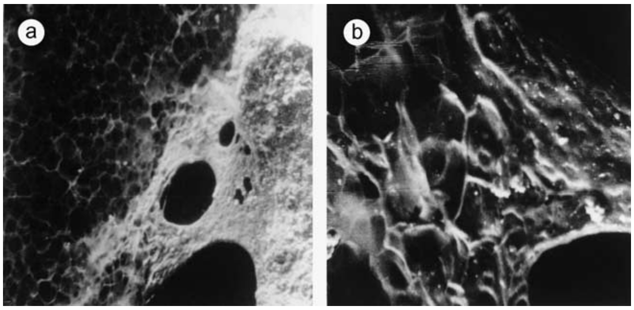

Fig. 4. Microstructure of the contact zone of large granules (on the left) and foamed concrete (on the right): a × 30; b × 120.

Fig. 5. Microstructure of the contact zone of crumbled granules (on the left) and foamed concrete (on the right) (× 120).

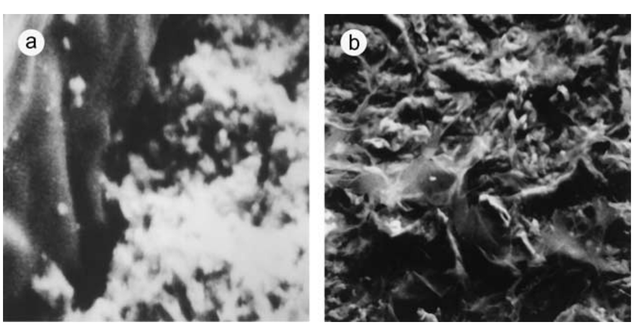

Fig. 6. Microstructure of the contact zone of fine polystyrene granules and foamed cement: (a) contact zone of granule and foamed concrete (×300), granule on the left, foamed concrete on the right; (b) "shell" surface after the separation of the granule (× 120).

are not intercommunicating. In most cases, the thickness of the cementing membrane (pellicle) separating a pore of foamed cement from a polystyrene granule is not less than 10 μm. This can be clearly seen in Fig. 4a.

When a composite made up of foamed cement and crumbled granules disintegrates, the granules do not separate from the binder though being broken apart. The fact that the granules do not separate from the composite may be accounted for strong cohesion between their surfaces and foamed concrete (Fig. 5).

When a composite made up of foamed cement and fine granules is crushed, disintegration can be observed at the granule-foamed cement contact zone. The behavior of fine particles during disintegration of the composite, which is different from that of coarse particles, is determined by the specific structure of these particles made of small "merged" bubbles (Fig. 1c). The surface of fine granules, unlike the surface of coarse particles, are free from deep cavities into which foamed cement binder may penetrate. Therefore, the adhesion strength of fine granules and foamed cement is not so high as in the case of coarse particles. This can be clearly seen if the contact zones of fine (Fig. 6a) and coarse (Fig. 4b) granules with foamed cement are compared.

In composite disintegration, a fine granule torn out from foamed cement, leaves a shell-shaped cavity on its surface, exactly repeating the structure of the torn-out particle. Small pieces of thin polystyrene pellicle are found at this area (Fig. 6b). These scraps are of irregular shape, having no definite structure. They do not completely cover the surface of the "shell" (Fig. 6), being found only at some spots. These small pieces of polystyrene were formed in the process of composite disintegration when a thin layer separated from the granule surface.

Strength. The compression strength gained by the composite complies with the standard foamed concrete compression strength. Since polystyrene granules were used, the comparison method was adjusted for 10% deformation, similar to the case of lightweight thermal insulating materials. When the deformation reaches 10%, the failure of the specimens is observed.

The compressive strength of the investigated material depends on its density and the type of granules used. Fine granules allow for the highest composite compressive strength, which is on average by 40% higher than when large granules are used and 68% higher than when crumbled granules are used. When composite density is 150 kg/m^3 obtained at a ratio of 1:3 its compressive strength is 0.25 N/mm^2 (Fig. 7). Large granule composite reaches such strength only when its density is 230 kg/m^3. For crumbled granule composite this barrier is 250 kg/m^3. This can be explained by the structure of the specimens. Using of fine granules creates a structure of polystyrene granules, evenly spread in the foam cement. Pores of foam cement in such composite are not destructed and its bulk structure is formed as uniform monolith with fine polystyrene granule inclusions. The foam cement structure in the large granule composite is damaged, and the pores are partially disintegrated.

The dependence of compression strength values on density, when various types of granules are used, is described in terms of the regression (Fig. 7). Correlation coefficients for composite with fine granules are 0.984, for this with large granules—0.985 and for the case of crushed granules—0.977. Average square deviation is 0.3, 0.15 and 0.21 N/mm^2, respectively.

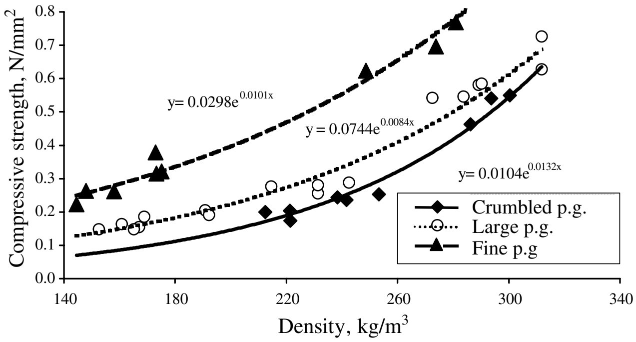

Fig. 7. The influence of composite density on compressive strength.

Composite bending strength is generally proportional to composite density (Fig. 8). For the fine granules the above strength is described by the linear equation. Correlation coefficient is 0.906, average square deviation—0.25 kN/mm^2.

Modulus of elasticity (Table 3) depends on composite density and beads.

As expected, the lowest value of the modulus of elasticity was obtained for the composite with crumbled granules, while for the density 200 kg/m^3 the results were not satisfactory because of the high spread in values.

Thermal conductivity coefficient. Thermal conductivity coefficient of the composite depends on the type of granules used and the composite density. Variation of the composite density has greater influence on the thermal conductivity coefficient than the type of granules used (Fig. 9).

The dependence of thermal conductivity coefficients on density, when various types of granules are used, is described in terms of the regression equations (Fig. 9).

Correlation coefficients for a composite with fine granules are 0.803, for that with large granules—0.986 and in the case of crumbled granules—0.937. Average square deviation is 0.00535, 0.001936 and 0.00382 W/(m·K), respectively.

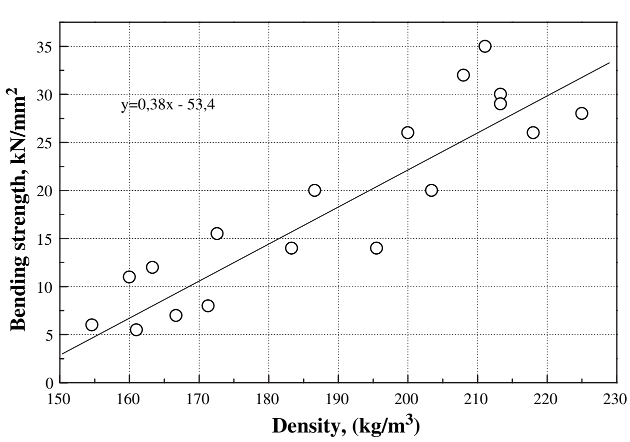

Fig. 8. The influence of composite density on the bending strength of composite with fine granules.

Table 3
Modulus of elasticity, N/mm^2

Size of composite	Density (kg/m^3)		
	200	250	300
With fine granules	200	400	700
With large granules	150	250	500
With crumbled granules	–	150	300

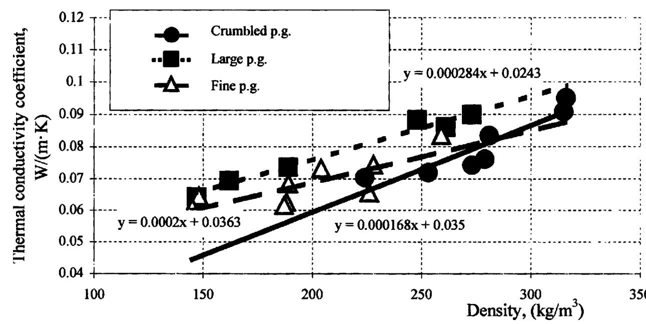

Fig. 9. The influence of composite density on thermal conductivity.

In the case of composites with the same density, the thermal conductivity coefficient is the lowest of the composites, containing crumbled granules.

In order to obtain a composite with the lowest thermal conductivity, it is necessary to choose such component ratio, where the portion of polystyrene in the composite would be maximal, because the density of produced items mostly depends on the portion of foam cement in it.

The lowest coefficient of thermal conductivity 0.06 W/(m·K) was obtained for a composite with the ratio of cement to fine polystyrene granules being 1:3.

Lightweight composite thermo-insulating material is designed for insulating floors, roofs, partitions, wall cavities, etc.

4. Conclusions

Recycled polystyrene waste as well as blown polystyrene granules can be used as the filler for a lightweight thermo-insulating foam cement composite. The density of such composite is 150–170 kg/m^3, thermal conductivity coefficient 0.06–0.064 W/m·K, compressive strength 0.25–0.28 N/mm^2.

In order to increase the cohesion of polystyrene granules with the binding agent (foam cement), the granules have to be hydrophilizated. This can be done using a 0.2% sulfonol and 0.03% bone glue hydrosolution. The highest hydrophilization level is reached within the first 5 min.

Researching the contact zone between foam cement and polystyrene granules it was established that their contact is very close, without microcracks and fractures. The cohesion of the two components depends on the size and shape of the granules. Large and crumbled granules adhere to the binding agent better.

A "shell", remaining after tearing out a polystyrene granule from foam cement concrete, exactly repeats the structure of the torn out granule, there is polystyrene residue in it. This shows that the contact zone is stronger than the polystyrene granule material. When the polystyrene granule is fine, it disintegrates across the contact zone. The cohesion strength of such composite is the lowest.

The bending and compressive strength of the created composite material depends on its density and the type of granules used. The highest composite compressive strength of 0.75 N/mm^2 is reached when fine granules are used at a density of 275 kg/m^3. This is determined by more even macrostructure of the composite. In order to utilize domestic waste or polystyrene waste only and reach the crushing strength similar to that of fine polystyrene granule fillers, the composite density has to be increased.

Strength characteristics of the composite can be assessed using the regression equations offered.

The thermal conductivity of the composite also depends on the same factors (density and the type of the filler). It can be assessed using the regression equations as well.

References

[1] Ducman V, Mladenovič A, Šuput JS. Lightweight aggregate based on waste glass and its alkali-silica reactivity. Cem Concr Res 2002;32:223–6.

[2] Varughese KT, Chaturvedi BK. Fly ash fine aggregate in polyester based polymer concrete. Cem Concr Compos 1996;18(2):105–80.

[3] Kearsley EP, Wainwright PJ. The effect of high fly ash content on the compressive strength of foamed concrete. Cem Concr Res 2001;31:105–12.

[4] Savastano Jr H, Warden PG, Couts RSP. Brazilian waste fibres as reinforcement for cement-based composites. Cem Concr Compos 2000;22(5):379–84.

[5] Palos A, D'Souza NA, Snively CT, Reidy RF. Modification of cement mortar with recycled ABC. Cem Concr Res 2001;31:1003–7.

[6] Yue YL, Li GZ, Xu XS, Zhao ZJ. Properties and microstructures of plan-fiber-reinforced cement-based composites. Cem Concr Res 2000;30:1983–6.

[7] Alduaij J, Alshalch K, Haque MN, Ellaythy K. Lightweight concrete in hot coastal areas. Cem Concr Comp 1999;21(5–6):453–8.

[8] Bignozzi MC, Saccani A, Sandrolini F. New polymer mortars containing polymeric wastes. Part 2. Dynamic mechanical and dielectric behaviour. Compos Part A: Appl Sci Manufactur 2002;33(2):205–11.

[9] Sri Ravindrarajah R. Bearing strength of concrete containing polystyrene aggregate. Durability of Building Materials and Components, 8, 1999. Institute for Research in Construction, Ottawa, Canada. p. 505–14.

[10] Sayil BM, Gurdal E. The physical properties of polystyrene aggregated gypsum blocks. Durability of building materials and components, vol. 8, 1999. Institute for Research in Construction, Ottawa, Canada. p. 496–504.

[11] Bajdur W, Pajaczkowska J, Makarucka B, Sulkowska A, Sulkowski WW. Effective polyelectrolytes synthesised from expanded polystyrene wastes. Eur Polym J 2002;38(2):299–304.

[12] Chandra S, Flodin P. Interactions of polymers and mixtures on Portland cement hydration. Cem Concr Res 1987;17:875–90.

[13] Tosong AW, Landsdale JC, Cripps CJ. Aggregate-cement paste interface. Part I. Influence of aggregate geochemistry. Cem Concr Res 1999;19:1019–25.

[14] Shondeep LS, Yaya D, Piere-Claude A. Microstructural study of aggregate/hydrated paste interface in very high strength river gravel concretes. Bond Cementitious Compos Symp Boston, Mass, 1987, Pittsburgh, 1988. p. 111–6.

[15] Qijum Y, Sawayama K, Sugita S, Shoya M, Isojima Y. The reaction between rice husk ash and $Ca(OH)_2$ solution and the nature of its product. Cem Concr Res 1999;29(1):37–43.

[16] Bentur A. Interfaces in fibre reinforced cements. Bond Cementitious Compos Symp, Boston Mass, Pittsburgh, 1988. p. 133–44.

[17] Rice KE, Vodran G, Kunbargi OH. Bonding of fibrillated polypropylene fibers to cementitious materials. Bond Cementitious Compos Symp, Boston Mass, Pittsburgh, 1988. p. 145–52.

[18] Youjiang W, Li Victor C, Backer S. Analysis of synthetic fiber pullout from a cement matrix. Bond Cementitious Compos Symp, Boston Mass, Pittsburgh, 1988. p. 159–65.

[19] Kearsley EP, Wainwright PJ. The effect of porosity on the strength of foamed concrete. Cem Concr Res 2001;32:233–9.

[20] Baozhen S, Erda S. Relation between properties of aerated concrete ant its porosity and hydrates. Pore structure and materials properties. In: Proc Int RILEM Congress, Versailles, France, 1997. p. 232–237.

[21] Kearsley EP, Wainwringht PJ. The effect of high fly ash content on the compressive strength of foamed concrete. Cem Concr Res 2001;31:105–12.

[22] Kearsley EP, Wainwringht PJ. Ash content for optimum strength of foamed concrete. Cem Concr Res 2002;32:241–6.

[23] Laukaitis A. Influence of technological factors on porous concrete formations mixture and product properties. Summary of the research report presented for habilitation. Kaunas, University of Technology, 1999. p. 70.

[24] Girnienė I, Laukaitis A, Dudik A. Influence of surfactants on the foam properties. Mater Sci (Medžiagotyra), Kaunas, Technologija 2000;6(4):316–20.

[25] Sinica M, Dudik A, Laukaitis A. Influence of foam cement and porized concrete structure on its drying deformations. Mater Sci (Medžiagotyra), Kaunas, Technologija 2000;6(4):321–4.

[26] Girnienė I, Laukaitis A. The effect of the hardening conditions on foam cement concrete strength and phase composition of new formations material. Mater Sci (Medžiagotyra), Kaunas, Technologija 2002;8(1):77–82.

[27] Žurauskas R, Laukaitis A, Kerienė J, Dudik A. Investigation of binder and expanded polystyrene granule contact zone in thermal insulation composition material. Mater Sci (Medžiagotyra), Kaunas, Technologija 2001;7(1):38–44.