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Effect of porosity on physical properties of lightweight cement composite with foamed glass aggregate

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Abstract. This paper reports on a study of physical properties of lightweight cement composite. We investigate the possibility of replacing traditional aggregate with Granulated Ash Aggregate (GAA) and above all with Granulated Expanded Glass Aggregate (GEGA). For this purpose, 15 specimens of different percentage share of each aggregate in total aggregate volume were tested: 0%, 25%, 50%, 75% or 100% of foam glass aggregate (GEGA) partially replaced by ash aggregate (GAA) content in the cement composite. The water-cement ratio was constant and equal to w/c=0.5. Three grain sizes were analyzed: 2mm, 4mm (both GEGA) and 8mm (GAA). Numerical simulations of concrete specimen behavior under static loading were conducted with the implementation of elastic plastic model of each component. The study shows a significant impact of grain type and size on physical properties of lightweight concrete. Due to lower density of foamed glass aggregate, specimens shows various apparent density and porosity, which affect concrete properties. Compressive strength of concrete decreases with the increase in foam glass aggregate content; however specimens show different workability and in consequence porosity of lightweight concrete.

1 Introduction

In order to meet the increasing requirements for engineers to face more and more challenging structural designs new solutions need to be sought. On the one hand, structures need to be greater, more durable and reliable, on the other hand, standards for material itself are more demanding, *e.g.* for materials thermal conductivity. Hence, considering concrete as a part of material engineering [1] [2], the use of new components like lightweight foamed aggregate is investigated [3].
Lightweight concrete (LWC) with foamed aggregate has been a subject of study *e.g.* [4], [5]; however, our study presents a new approach to lightweight cement composite design considering Granulated Expanded Glass Aggregate (GEGA) as a concrete component instead of commonly used Granulated Ash Aggregate (GAA).

2 Composite components

In LWC design the following foamed aggregates were subjected to analysis: GEGA (Fig. 1a) of two grain sizes: 2 mm and 4 mm, and GAA (Fig. 1b) grain size 8 mm. The purpose of the study was to investigate the influence of aggregate share and its grain size on physical properties of LWC. In the tested specimens the aggregates always constituted about 70% of the whole lightweight composite volume. Due to high impact of aggregate parameters on the physical properties of the whole composite they were defined and listed in Table 1.

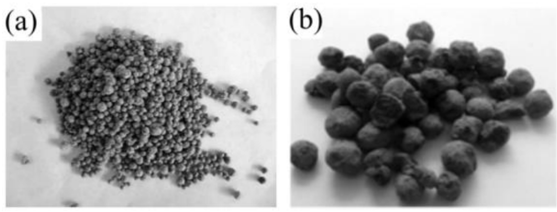

Fig. 1. Aggregates: (a) Granulated Expanded Glass Aggregate GEGA, (b) Granulated Ash Aggregate GAA.

Table 1. Physical properties of aggregates.

Property	GAA 8 mm	GEGA 4 mm	GEGA 2 mm
Water absorption WA_{24} [%]	16.5	17.8	15.2
Volume density ρ_a [Mg/m^3]	1.35	0.35	0.38
Density of dried grain ρ_{rd} [Mg/m^3]	1.25	0.31	0.34
Density of saturated grain ρ_{ssd} [Mg/m^3]	1.29	0.33	0.36.
Porosity p [%]	37	42	37
Crumble indicator X_r [%]	17.8	25.9	22.3
pH after 24h	11.1	11.9	11.9
Bulk density in loose state ρ_b [Mg/m^3]	0.68	0.18	0.20

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The Portland cement CEM I 42.5R was applied as a binder according to EN 197-1. The morphological characteristics of components were investigated by means of Scanning Electron Microscope (SEM).
The main component of lightweight aggregates is silica SiO_2 (from 52% to 63%) and less significant components are Na_2O, CaO, MgO and Al_2O_3. Regarding cement, CaO is the main component, amounting to 63%, while the content of silica SiO_2 is about 22%. All content is listed in Table 2.

Table 2. The chemical compositions.

Component	Content [%]		
	GAA	**GEGA**	**Cement**
SiO_2	52.82	63.33	21.7
Al_2O_3	24.28	0.74	6.1
Fe_2O_3	7.5	–	3.1
CaO	4.5	14.19	63.4
MgO	3.19	2.98	1
SO_3	0.43	0.32	3.9
K_2O	0.2	0.57	0.64
Na_2O	–	13.35	0.16
Loss of roasting	7.1	4.53	–
Na_2Oeq	–	–	0.7
$(Na_2Oeq) = Na_2O + 0.658\ (K_2O) = 0.7$			

3 Porosity

Lightweight concrete (LWC) contain pores (empty spaces inside material), which may correspond to anywhere between a dozen and several dozen percent of total volume. Porosity is the result of the use of porous lightweight aggregate, where the amount of pores can be up to 67 %. Two types of pores can occur in LWC: open pores (o) and closed ones (c) (see Fig. 2). Open pores (o) are connected with each other and with material surface, thus they are permeable to liquids and gases. Closed pores (c) are isolated and not connected. LWC containing only closed pores are impermeable for liquids and gases, thus is commonly use as thermal and acoustic insulation.
Pores in material have a considerable impact on its mechanical properties, which increase with increasing porosity. Hence, density and porosity investigation is a crucial parameter in manufacturing process control and quality of the final product. Differences between LWC with various porosity concern also different behavior of material after immersion in fluid.

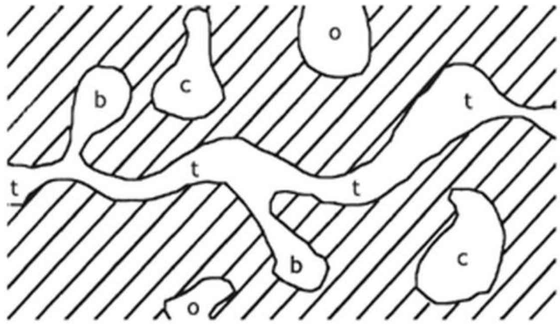

Fig. 2. Types of pores in lightweight concrete: o - open, c - close, t – transportation, b – blind.

The amount and the size of space between grains depend on the pores (voids content) of aggregate skeleton (composition) and on the amount of mortar surrounding the aggregate grains and filling the pores. Porosity of LWC increases when the void content of the aggregate skeleton is higher and when pores fulfillment is lower. The highest porosity is obtained when only one or a maximum of two fractions of large aggregate is applied and the decreased amount of cement grout is used instead of cement mortar. The role of the cement grout is to merge individual grains. When its amount increases, the voids of aggregates are being filled. Thus the void content is the property of lightweight concrete, which is independent of the porosity of the grains itself. The porosity of lightweight aggregate is bound with an aggregate skeleton structure and with grain shape.
The grain shape (Fig. 3a) affects physical properties of the aggregates listed in Table 1, while properties of aggregates have a great impact on the volumetric weight and on physical properties of hardened LWC.

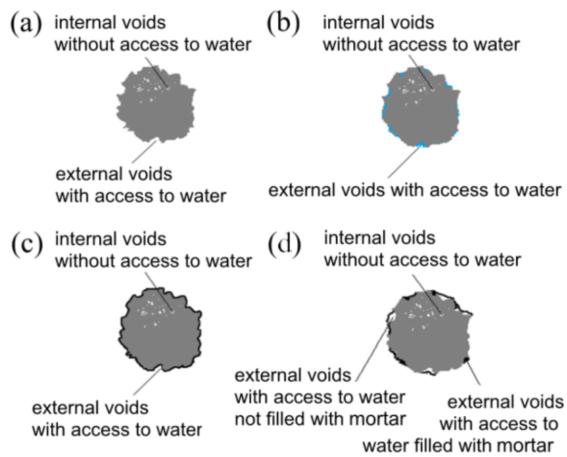

Fig. 3. Grain density: (a) apparent, (b) volume, (c) dried grain, (d) effective.

The aggregates volume density ρ_a was determined according to EN 1097-6 as a ratio of a dried aggregate sample mass to the volume that it takes in water with internal voids without access to water and external voids

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with access to water (Fig. 3b). According to EN 12697-5 it is called apparent grain density. The density of dried grain ρ_{rd} was calculated according to PN-EN 1097-6 as a ratio of dried aggregate sample mass to the volume it takes in water with internal void without access to water and with external void with access to water (Fig. 3c). According to PN-EN 12697-5 it is denoted as the density of saturated grain ρ_{pdd}. The effective grain density is a ratio of dried aggregate mass to the volume with internal voids without access to water, external voids with access to water and with the volume of empty spaces (Fig. 3d).

4 Experiments

4.1 Description

In order to examine physical properties of LWC with different aggregates fifteen specimens were investigated. Samples were prepared according to the authors' triangle rule (Fig. 4).

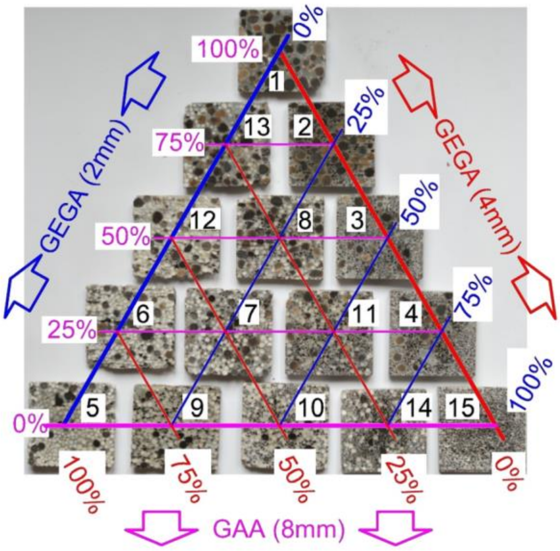

Fig. 4. Investigated specimens in the authors' triangle.

The percentage share of each aggregate in total aggregate volume is assumed in intervals 0%, 25%, 50%, 75% and 100% and listed with specimens' designation in Table 3.

The water-cement ratio is constant at w/c=0.5, thus 250 kg of water and 500 kg of Portland cement CEM I 42,5R were used. No admixtures or supplements were added.

A series of experiments was carried out in order to investigate physical properties of lightweight cement composite: strength, porosity and density.

Compressive strength was determined by means of Controls Advantest 9 machine with capacity of 300 kN (Fig. 5) on cubic specimens and dimensions 5x5x5 cm.

During concrete mix density examination, air content and consistency was investigated using a shock table inquiry. Afterwards, the concrete mix was placed into steel mold and stored in 20˚C. After demoulding the specimens were kept in water. Experimental tests were carried out 28 days after the microscopic examination (Fig. 6).

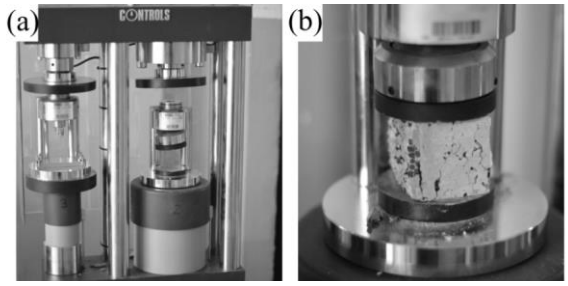

Fig. 5. Compressive machine Controls Advantest 9: (a) overall view, (b) investigated specimen.

Table 3. Participation of aggregates.

Specimens designation	GEGA 2 mm		GEGA 4 mm		GAA 8 mm	
	[%]	[kg/m^3]	[%]	[kg/m^3]	[%]	[kg/m^3]
LWC 1	0	0	0	0	100	574
LWC 2	25	65	0	0	75	431
LWC 3	50	130	0	0	50	287
LWC 4	75	194	0	0	25	144
LWC 5	0	0	100	245	0	0
LWC 6	0	0	75	184	25	144
LWC 7	25	65	50	123	25	144
LWC 8	25	65	25	61	50	287
LWC 9	25	65	75	184	0	0
LWC 10	50	130	50	123	0	0
LWC 11	50	130	25	61	25	144
LWC 12	0	0	50	123	50	287
LWC 13	0	0	25	61	75	431
LWC 14	75	194	25	61	0	0
LWC 15	100	259	0	0	0	0

Porosity was determined on specimens with dimensions 2x2x2 cm. After removing dust, the samples were dried and weighed (m_1). Afterwards, the air was removed and the specimens were saturated with kerosene by keeping them in boiling fluid for two hours. Next, the specimens

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were set to cool in kerosene to the temperature of 20°C was achieved. The prepared samples were hydrostatically weighed (m_3) in fluid. The next step was to determine the mass immediately after removing the specimens and wiping them with a cloth (m_2). Accuracy of all weighing amounted to 0.02 g. Apparent density (ρ_p) and opened porosity (p_o) were calculated from equations, respectively:

$$\rho_p = \frac{m_1 \rho_c}{m_2 - m_3}\left[\frac{g}{cm^3}\right] \quad (1)$$

$$p_o = \frac{m_2 - m_1}{m_2 - m_3} 100\% \quad (2)$$

where m_1 is mass of dried samples, m_2 is mass of samples saturated is kerosene, m_3 is mass of samples saturated in kerosene and weighted in it, ρ_c is density of kerosone used for saturation and for hydrostatic weighting (ρ_c=0.8241 g/cm^3).

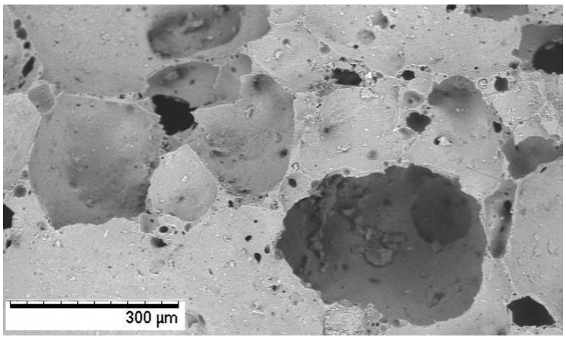

Fig. 6. Microscope picture of specimen.

4.2 Results

The experimental results were listed in Table 4, containing compressive strength of specimens, their apparent density and porosity. The list order was assumed according to specimen strength.
As shown, material properties are always related to its porosity. LWC containing lightweight aggregates made from foam glass (GEGA) is characterized by high porosity and relatively low apparent density. Specimens with porosity in the range of 15 % and 20 % (LWC 1, LWC 2, LWC 3) obtained the highest compressive strength 13-21 MPa. Concrete with porosity in the range of 45 %-65% (LWC 6 and LWC 9) show compressive strength of about 4 MPa.
However, specimen properties are not only affected by porosity alone, but the selection of lightweight aggregate does as well. The highest compressive strength was obtained for specimens consisting of lightweight aggregates GEGA 2 mm and GAA 8 mm in various proportions.
Specimens that were characterized by the highest porosity 67 % (LWC 5) containing only aggregate GEGA 4 mm show compressive strength of approximately 13 MPa and apparent density 1078 kg/m^3.

Table 4. Specimen properties.

Specimens designation	Apparent density [kg/m3]	Porosity p_o [%]	Compressive strength [MPa]
LWC 2	1378	17.7	**21.35**
LWC 1	1560	20.8	18.65
LWC 3	1177	16.0	13.43
LWC 5	1078	**67.0**	12.49
LWC 8	1117	24.0	10.10
LWC 13	1304	25.6	8.92
LWC 11	1041	20.1	6.99
LWC 15	1002	**15.2**	6.86
LWC 14	1060	19.3	6.37
LWC 10	903	26.4	5.44
LWC 12	1059	36.6	5.38
LWC 6	1028	45.0	4.59
LWC 7	1058	27.4	4.29
LWC 9	929	65.9	4.21
LWC 4	877	22.1	3.72

5 FEM modeling

Fifteen specimens were modeled using Finite Element Method by means of shell elements. The specimen geometry was assumed according to a section obtained through the middle of the cubes with dimensions 5x5x5 cm, *i.e.* square 5x5 cm was received.
The results are presented on specimen 13 (Fig. 7).

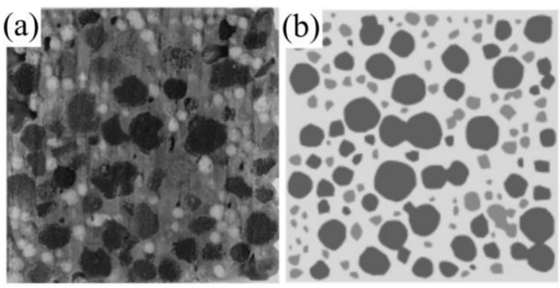

Fig. 7. Specimen 13: (a) geometry with aggregate decomposition, (b) FEM model.

FEM models were created using shell quadratic and triangle elements of size around 0.25 mm. For specimen 13 the total number of elements is 16959 while the total number of nodes is 16081. With the assumption of isotropy, material parameters (stiffness modulus, Poisson ratio and strength) were taken from [1] and are listed in Table 5. For nonlinear analysis ([6], [7]) the elastic plastic models were taken into account, where the value of stress in each component cannot exceed its strength.

Table 5. Material parameters.

Material parameters	Material			
	GAA 8 mm	GEGA 4 mm	GEGA 2 mm	Mortar
Stiffness modulus [GPa]	18.9	4.7	3.8	23.9
Poisson ratio	0.1	0.1	0.1	0.167
Strength [MPa]	9.8	1.5	1.8	52.8

The specimens were acted upon by force representing the real one converting load value to 1 mm thickness. Hence, for specimen 13 instead of 22.31 kN (see strength in Table 3) the force equal to 0.4462 kN was applied. The HMH stress map is presented in Fig. 8.

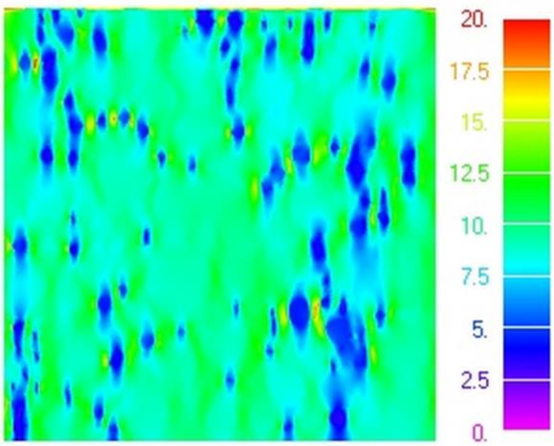

Fig. 8. HMH stress map for specimen 13 [MPa].

As it can be observed, the analyzed specimen failure occurs due to capacity exhaustion of the aggregate (GAA and GEGA 4 mm), which are the weakest element in the composite with strength, for GEGA 4 mm, equals 1.5 MPa (blue color in Fig. 8). It is a confirmation of what was observed during experiments (e.g. Fig. 5b).

6 Conclusions

The purpose of the paper was to study the possibility of applying lightweight concrete (LWC) in such structures as structural elements or extenders and insulation material. Hence, mechanical properties of 15 different material and aggregate grain size specimens were investigated.

Considering mechanical properties, the lightweight aggregate is the weakest component in concrete, nevertheless, analyzing other physical properties such as density (mass) or porosity it was revealed that the material offers multiple advantages, *e.g.* high thermal or acoustic insulation. Low density and in consequence low self-weight allow reducing the total weight of a structure by up to 35%. Furthermore, it can decrease cross-section are or the amount of necessary reinforcement; hence the cost of construction can be reduced. The manufacturing and the curing of lightweight concrete can be investigated analogously to the traditional one [8].

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