ISSN 2029–9990 | JOURNAL OF SUSTAINABLE ARCHITECTURE AND CIVIL ENGINEERING
DARNIOJI ARCHITEKTŪRA IR STATYBA | 2013. No. 2(3)

Mechanical and Thermal Properties of Lightweight Concrete Made from Expanded Glass

Girts Bumanis*, **Diana Bajare**, **Aleksandrs Korjakins**

Institute of Materials and Structures, Faculty of Civil Engineering, Riga Technical University, Kalku st.1, LV 1658, Riga, Latvia.

**Corresponding author: girts.bumanis@rtu.lv*

crossref http://dx.doi.org/10.5755/j01.sace.2.3.2790

Lightweight concrete has become a popular construction material because of several advantages it holds over conventional concrete. Lightweight concrete is characterized by good compressive strength, durability and the most important advantages – low density and improved properties of thermal conductivity. Typical lightweight concrete aggregates are expanded clay or shale, natural porous materials like vermiculite or pumice. In this research, new type of lightweight aggregates was used, namely, expanded glass granules made from waste glass. Loose bulk density, water absorption, material density and material porosity were determined for the expanded glass granules. Microporosity of granules was observed and visual inspection of their microstructure was done by using scanning electron microscope (SEM).

The aim of the study was to identify a relation between mechanical and thermal properties of the lightweight concrete made from expanded glass aggregates. Six different concrete mixes with different amount of expanded glass granules and quartz sand were produced. Properties of fresh concrete like density and flow table test were tested. Flexural and compressive strength as well as density, water absorption and porosity were determined for 28 days old lightweight concrete samples. Thermal conductivity of lightweight concrete was determined and relation between thermal and mechanical properties was identified.

Keywords: *expanded glass granules, kightweight concrete, mechanical and thermal properties.*

1. Introduction

Due to the various useful properties of the lightweight concrete, application of this construction material for the civil engineering purposes becomes more and more popular. Lightweight concrete provides low density, which reduces dead loads in constructions and good thermal conductivity, which allows using it in building envelope construction elements as effective thermal insulation and load bearing material. Lightweight concrete application in construction reduces building costs, eases construction and has the advantage of being a relatively 'green' building material (Tommy Y. LO et al. 2006). Nowadays various lightweight concrete types are invented for using at the construction sites. Expanded clay, shale or glass as well as natural porous materials like vermiculite or pumice are typically used as aggregates in the lightweight concrete mixtures. Lightweight concrete made from expanded glass granules is one of the latest types of concrete. It is made by incorporating the expanded glass granules into the cement paste matrix. The density of expanded glass could vary from 480 to 1600 kg/m^3 (US Patent 7695560, 2011). Lightweight concrete specimen's density made with expanded clay aggregate could be 1.6 times higher compared to the concrete specimen made with expanded glass aggregates (J. Jasaitiene et al. 2010). However Wasserman and Bentur showed that the same aggregate density does not lead to the same concrete strength (Wasserman, Bentur 1998). Traditional lightweight concrete application in construction industry is precast lightweight concrete blocks made from expanded clay aggregates or foamed concrete blocks. Cast-in-place lightweight concrete application in construction industry has become popular in recent years. Lightweight concrete made from expanded glass granules provides both casting types. It could be used as pre-casted concrete for production of blocks and cast-in-place lightweight concrete. Cast-in-place concrete provides much wider range of concrete application e.g. wall structures, floor thermal insulation and floor and roof screeds.

Regarding to the recycling of the deconstruction materials several investigations were performed by different researchers. Consequently model of recycling lightweight concrete with aggregates containing expanded glass has been proposed. The researchers concluded that recycling of concrete made from lightweight aggregates improves life cycle of the material, and there is no more remaining waste concrete from the lightweight concrete with aggregates containing expanded glass. The materials could be brought back to the life cycle of a product as much as it is possible to innovate production processes and concrete waste material from expanded glass aggregates can be incorporated into the recycling process (D. Kralj 2009).

Because of the low density of expanded glass granules the compressive strength of this material is relatively low. For aggregates with density less than 1000kg/m^3, the elastic modulus and the compressive strength of aggregate concrete are strongly affected by the volume fraction of aggregate (Y. Ke et al. 2009). Producers of lightweight expanded glass granules indicate the compressive strength from 0.45−0.55MPa. By incorporating such material in cement matrix concrete compression strength could be limited due to the expanded glass granule compressive strength. Lightweight aggregate outer shell thickness, macroporosity and broken grains percentage all affect the aggregate strength (Y. Ke et al. 2009). The weakest component of lightweight aggregate concrete is not the cement matrix or the interfacial transition zone but the aggregates. So the mechanical performances of lightweight concrete are not only controlled by the cement matrix quality but also the aggregate volume in concrete and the aggregates properties (Chi JM 2003). Mechanical properties of the lightweight concrete therefore are ensured by the strength of cement matrix and particle packing. There are two basic ways of increasing compressive strength of this composite material. One of them is to change expanded glass granule volume in lightweight concrete mixture. Therefore, the strength is obtained by the cement paste volume changes in concrete mixture design. Other option is improving of the lightweight concrete mechanical properties by incorporating fine aggregates as sand in the concrete mixture design. The optimal amount of expanded glass aggregate and the corresponding strength of cement mortar matrix can be determined and suitable expanded glass pellet can be chosen for an allotted concrete density and compressive strength (R. Nemes 2006). Both solutions affect thermal properties of the lightweight concrete. In order to increase the mechanical strength, specimen's thermal insulation capacity should be slightly reduced because with the increase in density the compressive strength increases faster than the coefficient of thermal conductivity (J. Jasaitiene et al. 2010). Since sand and cement paste provides high thermal conductivity increasing their volume in lightweight concrete could lead to the thermal conductivity and density increase of the material. To perform a research on the thermal conductivity and compression strength changes due to the expanded glass granule volume and sand incorporation effect, both methods were tested. The amount of sand aggregate in lightweight concrete affects its mechanical and physical properties, such as strength, material density and thermal conductivity. The influence of different sand quantity on the properties of lightweight concrete made from expanded glass aggregates was tested. Various lightweight concrete mixtures were prepared to identify relation between mechanical and thermal properties of incorporating various amounts of expanded glass granules and sand in the mixtures including three lightweight concrete mixtures with different expanded glass granule amount and three lightweight concrete mixtures with different amount of sand. Mechanical and physical properties were tested and thermal conductivity were observed.

2. Methods

Cement

The materials used in this study were commercially available raw materials, cementations materials and admixtures. CEM I 42.5N cement was produced in cement production plant Cemex in Latvia. Physical and mechanical properties of cement were tested and results are given in table 1. The chemical composition of cement was tested and results are given in table 2.

Expanded glass granules

Expanded glass granules used in this research are commercially available material made by Penostek. Granule fraction 0/5mm was used in lightweight concrete (Fig. 1).

Fig. 1. *Expanded glass granules*

Physical and mechanical properties of the expanded glass granules were determined including bulk density, thermal conductivity, compressive strength and water absorption. The bulk density of expanded glass granules were 187-230 kg/m^3, the material density was from 250–280 kg/m^3. The water absorption was 120–130 % by dry sample mass. The thermal conductivity of 40 mm thick granule layer was from 0.069–0.071 W/(m·K).

Grading analysis for expanded glass granules was applied to obtain grading curves for further lightweight concrete mixture design. Grading analysis is given in Fig. 2. Sizes of the granules ranged from 0.25mm to 5.6 mm. Since most particles are in range of 0.5–4mm, this is important factor for concrete mixture design, because particle distribution affects lightweight concrete mechanical properties.

Expanded glass granule pore structure analysis was performed at the Faculty of Material Science and Applied Chemistry of the Riga Technical University.

Mercury intrusion porosimeter Pore Master 33 (MIP) was used to measure pore size distribution in the interval from 0.0064 to 950 µm and porosimeter NOVA 1200E - pore size distribution in the interval from 0.35 to 200 nm. Expanded glass granules with fraction 0.5/1mm, 2/4mm and 4/5.6mm were tested.

Table 1. Physical and mechanical properties of Portland cement

Cement producer, type	Setting start time, h	Setting end time, h	Compressive strenght, MPa				Blaine fineness cm^2/g	Particles 45µm sieve, %	Particles 30µm sieve, %	Normal consistency, %
			1d	7d	14d	28d				
CEM I 42.5N	2:52	3:23	14.0	27.7	43.3	53.6	3862	3.5	10.7	27.0

Table 2. Chemical properties of Portland cement

Cement producer, type	Compound, %									
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	Cl
CEM I 42.5N	19.33	4.26	3.05	61.94	3.19	3.18	0.16	1.26	0.28	0.07
			Mineralogical compound, %							
			Naeq	LSF	SR	AR	C_3S	C_2S	C_3A	C_4AF
Cemex CEM I 42.5N			**0.99**	**101.32**	**2.65**	**1.39**	**63.23**	**7.75**	**6.12**	**9.28**

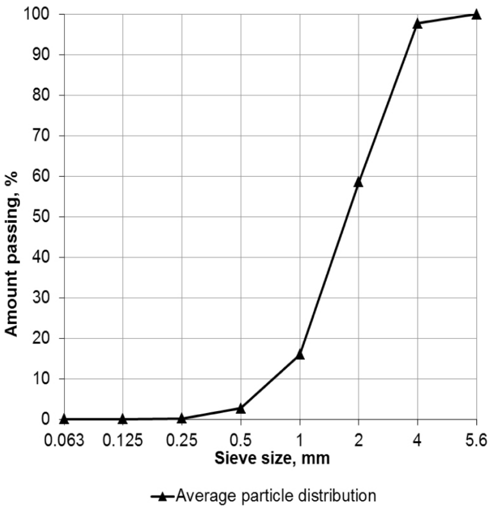

Fig. 2. Expanded glass granule grading analysis

Different methods for pore structure investigations were used because MIP measures refer mainly to the large capillary porosity while gas sorption method measures the finest pores more accurately, as it is suggested by J. Thomas and H. Jennings (Thomas J. and Jennings H. 2009). Defined pore radius showed negligible difference between various fractions of expanded glass granules. As it is seen from the Table 3, pore radius varies from 0.586 to 3.35 nm for expanded glass granules with fraction 0.5/1 mm and from 0.586 to 0.758 nm for fraction 4/5.6mm. Pore volume is $2.056–7.113x10^{-4}$ cm^3/g for granule fraction 0.5–1mm. At the same time granules with fraction 4/5.6 mm have volume $1.354–8.636x10^{-3}$ cm^3/g. It may be concluded that fraction 0.5-1mm have pores with less radius than fraction 4/5.6 mm. Pore surface area was 0.2809-4.996 m^2/g for granule 0.5/1mm fraction. It is larger for granules with fraction 4/5.6mm ranging from3.031–14.83 m^2/g. Pore structural analysis results are given in table 3.

Micro structural analysis of the glass granules has been done by scanning electron microscope TESCAN Mira\ LMU Field-Emission-Gun. Pore size and its distribution in expanded glass granules were observed and granule internal and external wall thickness was determined. In addition, energy-dispersive X-ray spectroscopy (EDX) was used to determine the chemical characterization of expanded glass granules. Overall view of expanded glass granules with fraction 2/4mm is given in Fig.3 and Fig.4. Internal pore diameter varies from 79.58–453.60 µm. Pores with smaller diameter are concentrated close to the granule surface while inside the granule pore diameter was from 135.52–453.60 µm. Expanded glass granule external walls have much denser structure than the internal granule structure.

External walls consisted of much smaller pores and the thickness of pore walls increased. Granule outer shell must provide closed structure to avoid any interaction between granule inside structure and outer environment.

Due to the brittle structure of granule walls, holes in the granule surface have formed that could lead to the further wall collapse and granule pores could fill with outer substance.

Table 3. Expanded glass granule Pore structural analysis

Granule fraction, mm	Sample weight, g	Sample volume, cm^3	Pore radius, nm	Pore volume, cm^3/g	Pore surface area, m^2/g
0.5–1	0.4264	0.7814	1.550–3.353	**$2.056–7.113x10^{-4}$**	0.281–4.996
2–4	0.3705	1.2290	1.700–3.809	**$1.038–7.533x10^{-3}$**	2.641–12.230
4–5.6	0.1938	0.7226	1.750–3.758	**$1.354–8.636x10^{-3}$**	3.031–14.830

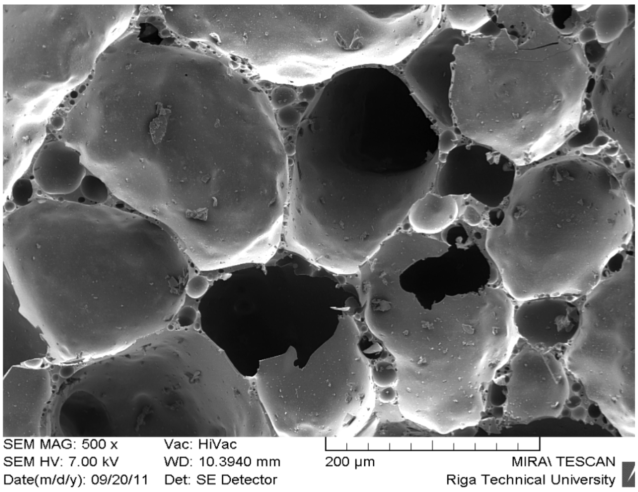

Fig. 3. *Expanded glass granule inner pore microstructural analysis with SEM*

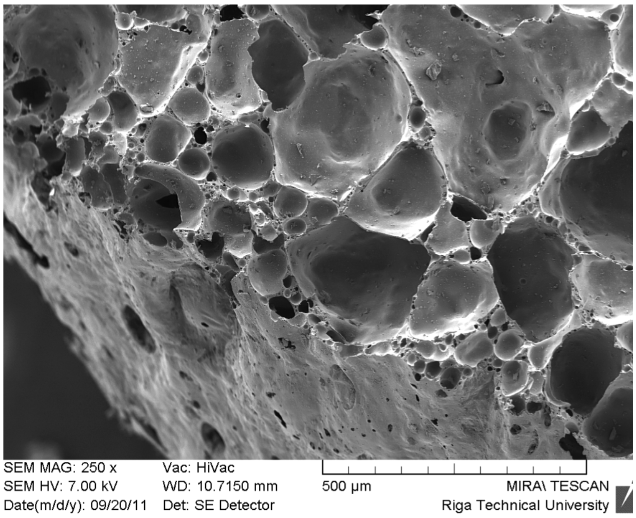

Fig. 4. *Expanded glass granule outer shell microstructural analysis with SEM*

Lightweight concrete mixture composition

Six different mixtures of lightweight concrete with expanded glass granules were prepared (table 4). Cement content, limestone powder and chemical admixtures for all six mixtures was constant, cement amount being 480 kg, limestone powder amount – 118.8 kg and chemical admixtures – 0.7 kg, 0.02 kg and 0.5 kg respectively. The chemical admixtures were used to ensure workability of lightweight concrete and to control setting time of concrete. First, three mixes with different amount of expanded glass granules were prepared.

The chosen amount of expanded glass granules were 300 kg, 400 kg and 500 kg. The amount of necessary water was chosen to ensure lightweight concrete constant workability.

Due to the high water absorption of expanded glass granules, the amount of water increased proportionally to the amount of expanded glass granules added to the mix. To ensure proper workability and fresh concrete properties, water cement ratio was increased. The water cement ratio for mixture GG300 was 0.81 and it increased to 0.97 for mixture GG500.

The other three concrete mixtures were with different sand amount and constant expanded glass granules amount in the mass of cement. The 0.3/2.5 mm sand fraction was used to improve concrete packing and mechanical properties. Sand was added in amount of 100, 200 and 300 kg respectively. As it is seen in Table 4, with the additional incorporation of sand in the mixture, W/C ratio increased to 0.97 due to the higher amount of fine aggregates to ensure same workability as control mixture. W/C ratio was equal for all three mixtures with incorporated sand.

Lightweight concrete mixing procedure consisted of dosage of materials and homogenization of dry mixture with electric hand mixer. Half of necessary water was added and mixing continued for 1 minute. Rest of water was added and mixture was mixed for 1 minute. If additional water was necessary mixing continued for 30 seconds. Mixture was cast in prismatic molds 40x40x160mm. For thermal conductivity plates with dimension 300x300x50mm were prepared. Molds were filled by half and then evened with trowel, and then rest of mold was filled.

Fresh lightweight concrete properties were determined. Cone slump test and consistence of fresh mortar by flow

Table 4. *Lightweight concrete mixture design*

		Mixture proportion (by mass)					
		GG300	**GG400**	**GG500**	**S100**	**S200**	**S300**
Cement Cemex CEM I 42,5N		480	480	480	480	480	480
Limestone powder		118.8	118.8	118.8	118.8	118.8	118.8
Chemical admixtures	**Methocel 327**	0.7	0.7	0.7	0.7	0.7	0.7
	Hostapur	0.02	0.02	0.02	0.02	0.02	0.02
	Na rodanide	0.5	0.5	0.5	0.5	0.5	0.5
Expanded glass granules 0/5mm		300	400	500	400	400	400
Sand		–	–	–	100	200	300
Water		389	440	465	465	465	465
W/C ratio		0.81	0.92	0.97	0.97	0.97	0.97

table method were performed for all six concrete mixtures and was tested according to LVS EN 12350-2 and LVS EN 1015-3. Fresh concrete density was determined according to LVS EN 12350-6.

Physical properties of hardened concrete samples like density (LVS EN 12390-7:2009), water absorption and thermal conductivity were tested. For water absorption test samples were immersed into water for 72h±2h and weighted. Then samples were dried until constant dry mass was obtained. Thermal conductivity was performed with heat flow meter instrument LaserComp FOX 660 for dry lightweight samples with dimensions of 300x300x50mm.

Flexural and compressive strength were obtained according to LVS EN 1015-11.

3. Results

Lightweight concrete with increased amount of expanded glass granules

Results of fresh concrete properties for all six mixtures are given in table 5. The w/c ratio was choose according to Cone slump of lightweight concrete mixtures GG300 and GG400 was identical – 240 mm. Cone slump decreased to 210 mm for mixture GG500due to the higher amount of expanded glass granules added. Consistence of fresh mortar (by flow table method) for lightweight concrete mixture GG300 with less granules show the highest flow table result of 185 mm even with lowest W/C ratio. The consistence of mixture with increased amount of granules is reduced to 179 mm for GG400 and 148 mm for GG500. Additional amount of water did not increase workability for the chosen mixture composition. W/C ratio for compositions with constant amount of expanded glass granules and different amount of sand was constant. Fresh concrete density decreased from 809 kg/m^3 to 663 kg/m^{3}for mixtures GG300 and GG400 respectively. Density of fresh concrete decreased to 647 kg/m^3 for mixture with increased amount of expanded glass granules (GG500).

Table 5. *Fresh concrete properties*

Mixture design	Flow table, mm	Cone slump, mm	Fresh concrete density, kg/m^3
GG300	185	240	809
GG400	179	240	663
GG500	148	210	647
S100	178	240	656
S200	144	180	797
S300	137	150	837

Mechanical properties of lightweight concrete are given in Table 6. Flexural and compressive strength results indicate that the highest flexural and compressive strength was for the concrete with lowest amount of expanded glass granules (GG300).The increase of expanded glass granules in the mixture from 300 kg to 500 kg decreased the flexural strength of samples from 1.7 to 1.5MPa. Compressive strength for mixture GG300 sample was 5.8MPa and decreased to 4.1 and 4.0MPa for samples GG400 and GG500 respectively. Strength reduction between GG400 and GG500 was insignificant– only 0.1MPa.

Table 6. *Mechanical properties of hardened concrete*

Mixture design	Flexural strength, 28d, MPa	Compressive strength, 28d, MPa
GG300	1.7	5.8
GG400	1.6	4.1
GG500	1.5	4.0
S100	1.2	3.2
S200	1.6	3.8
S300	1.8	4.5

Physical properties of hardened lightweight concrete with increased amount of expanded glass granules are given in Table 7. The lightweight concrete density was measured for dry samples and water saturated samples. Samples with different expanded glass granule content provide density 685 kg/m^3 for mixture GG300, 561 kg/ m^3 for mixture GG400 and 558 kg/m^3 for mixture GG500. The density of water saturated sample was 905 mkg/m^3 for GG300; 767 kg/m^3 for GG400 and 753 kg/m^3 for GG300. The water absorption of samples increased from 30 % for GG300 to 35 % for GG500.

Thermal conductivity for samples with different expanded glass granules content decreased from 0.163 W/(m·K) for sample GG300 to 0.141 W/(m·K) for sample GG400. Further conductivity improvement was insignificant – 0.140 W/(m·K) for mixture GG500 (table 7).

Mixtures with increased amount of sand

The workability of the lightweight concrete was decreased by adding extra sand to the mixture (table 5). Flow table result for mixture S100 was 178mm, for mixture S200 – 144mm and for mixture S300 – 137mm.

The cone slump was significantly reduced by incorporation of extra sand. S100 concrete showed similar result to the samples without sand – 240mm (table 5).

The cone slump for other concrete mixtures with higher sand content (S200 and S300) decreased to 180 mm and 150 mm respectively. The fresh concrete density depends from extra incorporation of sand. Mixture S100 provided fresh concrete density 656 kg/m^3, S200 – 797kg/m^3 and S300 – 837 kg/m^3.

Lightweight concrete samples with sand incorporation in mixture provided strength increase (table 6). Mixture S100 samples provides flexural strength of 1.2MPa; S200 – 1.6MPa and S300 – 1.8MPa. In comparison to the samples without sand incorporation, the flexural strength was higher only for sample S300. Compressive strength increase was observed for mixture S100 being 3.2MPa, for mixture S200 – 3.8MPa and for mixture S300 – 4.5MPa.

The density of lightweight concrete with incorporated sand increased from 523 to 699 kg/m^3 (S100 to S300) (table 7).The density of water saturated samples was from 757 to 913 kg/m^3. The density of lightweight concrete increased due to increase of the sand content in concrete mixture. Water absorption of samples decreased from 44 to 33 %.

Due to incorporation of extra sand in the mixture of lightweight concrete thermal conductivity decreases. The thermal conductivity decreased to 0.138 W/(m·K) for mixture S100 compare with sample without sand GG400 (0.141 W/(m·K)). The further increase of sand amount in lightweight concrete mixture provides improvement of thermal conductivity to 0.161 W/(m·K) (S200) and to 0.177 W/(m·K) (S300) (table 7).

4. Discussion

Lightweight concrete made from expanded glass granules provide different mechanical and physical properties affected by chosen concrete mixture design. The chosen quantity of expanded glass granules in concrete mixture provides different material density, water absorption, strength and thermal properties of lightweight concrete. Significant difference of lightweight concrete properties between mixture GG300 and GG400 was observed. Concrete density decreased from 685 to 561 kg/m^3, thermal conductivity – from 0.163 to 0.140W/(m·K), compressive strength – from 5.8 to 4.1MPa. Further increase of expanded glass granules amount (see GG500) did not improve concrete properties considerably. It is under question, whether it is economically rentable to use increased quantity of expanded glass granules in mixture design without gaining considerable concrete properties improvement.

The different situation was observed for samples with extra sand incorporation in the lightweight concrete mixture. Due to extra incorporation of sand in the mixtures material density increased and mechanical properties improved. The density of samples increased from 523 to 651 kg/m^3 and water absorption decreased from 44 % to 30 %. Thermal conductivity increased from 0.138 to 0.177 W/(m·K) due to extra sand incorporation in the mixture (from 100 to 300 kg). Flexural and compressive strength increased from 1.2–1.8MPa and 3.2–4.5MPa respectively.

Relation between thermal and mechanical properties was identified. From the economical point of view the increase of expanded granules in the mixture (see GG400 and GG500) is not recommended due to the insignificant difference between compressive strength and thermal conductivity results of mixtures GG400 and GG500. Mixtures from S100 to S300 provide higher difference in mechanical and thermal properties. The compressive strength improvement and thermal conductivity increase was obtained by the increasing amount of sand in lightweight concrete mixture.

5. Conclusions

The identified lightweight concrete properties were affected by quantity of expanded glass granule and sand content in mixture design. By changing the quantity of expanded glass granules and the amount of incorporated sand in lightweight concrete mixture different lightweight concrete properties could be obtained.

The compressive strength of lightweight concrete with expanded glass granules could vary from 4.0 to 5.8MPa for samples with different quantity of expanded glass granules and from 3.2 to 4.5MPa for lightweight concrete with incorporated sand.

Thermal conductivity decreases with the increasing amount of expanded glass granules and increases with sand incorporation in lightweight concrete mixture.

Lightweight concrete made with expanded glass granules could be used as an insulation material with marginally low thermal conductivity and the strength of concrete could vary due to the chosen concrete mixture.

The thermal conductivity of lightweight concrete with expanded glass granules is limited by the thermal properties of cement paste and the expanded glass granule properties.

This research concludes that further increasement of expanded glass granule amount in mixture design did not provide considerably better concrete thermal conductivity what is important for producers and consumers. By increasing expanded glass amount in lightweight concrete its density could be reduced from 685 to 561 kg/m^3 and thermal conductivity – from 0.163 to 0.140 W/(m·K).

The constant amount of expanded glass granules and different amount of sand to mixture design provide increaset of concrete density as well as its strength and thermal conductivity properties. The density of lightweight concrete with sand incorporation in the mixture increases from 523 to 651 kg/m^3. The increase of thermal conductivity from 0.138 to 0.177 W/(m·K) was significant for samples with higher amount of sand. By defining concrete properties according to its application, the appropriate lightweight concrete mixture design could be chosen.

Table 7. *Physical properties of lightweight concrete with expanded glass granules*

Mixture design	Density (dry), kg/m^3	Density (water saturated), kg/m^3	Water absorption, %	Thermal conductivity, W/(m·K)
GG300	685	905	30	0.163
GG400	561	767	32	0.141
GG500	558	753	33	0.140
S100	523	757	44	0.138
S200	645	859	33	0.161
S300	699	913	30	0.177

Acknowledgment

The support of Sakret Ltd. is acknowledged.

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Received 2012 11 28

Accepted after revision 2013 03 18

Girts BUMANIS – B.SC.Ing., research assistant at Institute of Materials and Structures, Faculty of Civil Engineering, Riga Technical University. Main research area: lightweight concrete, HP concrete materials, Geopolymers.
Address: Kalku iela 1, LV 1658, Riga, Latvia.
Tel.: +371 260 62011
E-mail: *Girts.bumanis@rtu.lv*

Diana BAJARE – Dr.Sc.Ing., associated Professor at the Institute of Materials and Structures, Faculty of Civil Engineering, Riga Technical University. Main research area: HP and UHP concrete, lightweight concrete, geopolymer technology, ceramic, waste recycling in building materials, passive cooling systems, restoration of historical structures and others.
Address: Kalku iela 1, LV 1658, Riga, Latvia.
Tel.: +371 296 87085
E-mail: *Diana.bajare@rtu.lv*

Aleksandrs KORJAKINS – Dr.Sc.Ing., Professor at the Institute of Materials and Structures, Faculty of Civil Engineering, Riga Technical University. Main research area: HP and UHP concrete, lightweight concrete, geopolymer technology, ceramic, waste recycling in building materials, passive cooling systems and others.
Address: Kalku iela 1, LV 1658, Riga, Latvia.
Tel.: +371 264 22442
E-mail: *aleks@latnet.lv*