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SOCIETY FOR MATERIALS AND STRUCTURES TESTING OF SERBIA
CONTEMPORARY CLAY PRODUCTS INDUSTRY ASSOCIATION OF SERBIA

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ON RESEARCHING AND APPLICATION OF CONTEMPORARY ACHIEVEMENTS
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INVESTIGATION OF THE MECHANICAL, HYDROPHYSICAL AND THERMOTECHNICAL PROPERTIES OF POROUS LIGHTWEIGHT AGGREGATE CONCRETE

Summary: *The results of comparative testing of porous lightweight aggregate concrete made with various percentages of neutral as a partial replacement of cement are presented in this paper.* *Neutral represents non-hazardous, inert and solidified material obtained after the treatment of industrial waste materials that have further use value. Four types of prefabricated cavernous concrete flags with different percentages of cement replacement with neutral (0, 10, 20 and 30%) were tested regarding the following properties: density, compressive strength, tensile strength, frost resistance, hydraulic conductivity and thermal conductivity coefficient.*

Keywords: porous concrete, neutral, expanded clay, energy efficiency, sustainable construction

ISPITIVANJE MEHANIČKIH, HIDROFIZIČKIH I TERMOTEHNIČKIH SVOJSTAVA POROZNOG LAKOAGREGATNOG BETONA

Rezime: *U radu su prikazani rezultati komparativnih ispitivanja poroznih lakoagregatnih betona spravljenih sa različitim procentom sadržaja neutrala kao delimične zamene cementa. Neutral predstavlja neopasni, inertni i praškasti materijal – solidifikat, dobijen nakon tretmana otpadnih industrijskih materijala koji imaju dalju upotrebnu vrednost. Na četiri tipa prefabrikovanih kaveroznih behaton ploča sa različitim procentima zamene cementa neutralom (0, 10, 20 i 30%), ispitivana su sledeća svojstva: zapreminska masa, čvrstoća pri pritisku, čvrstoća pri zatezanju, otpornost na dejstvo mraza, koeficijent filtracije i koeficijent toplotne provodljivosti.*

Ključne reči: porozni beton, neutral, keramzit, energetska efikasnost, održiva gradnja

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1. INTRODUCTION

Concrete represents the world's most commonly used building material due to its low cost and numerous advantages such as durability, resistance, wide field of application, simple production, and availability of necessary raw materials. However, the biggest disadvantage of concrete is being a major environmental issue due to the high percentage of carbon dioxide (CO_2) emissions released into the atmosphere during cement production. Given that more than 20 billion tons of concrete are produced each year, this construction material accounts for approx. 7-8% of total CO_2 emissions [1]. Still, due to the price-performance ratio it provides, it is unlikely that concrete will have an alternative in the near future. Concrete plays an essential role in any successful transition to a truly sustainable society; therefore, more attention should be paid to developing sustainable and environmentally friendly concrete in manufacturing. In order to achieve that, special focus should be placed on the processing and application of recycled and waste materials, which would reduce not only the consumption of non-renewable resources but also lower CO_2 emissions and the amount of waste material at landfills. Construction waste, a product of the construction of new buildings and the demolition of existing buildings, represents one of the biggest environmental problems in the world's developed countries. It is estimated that the main construction waste (materials obtained from the demolition of buildings and infrastructure facilities) amounts to about 180 million tons per year, that is, 480 kg/per person/year only in the countries of the European Union [2,3]. The construction industry, including the concrete industry, is currently facing the transformation of the traditional design and construction process into a new approach to sustainable construction, in which the environmental aspect has a leading role [1]. The concept of sustainable construction is based on reducing energy and natural raw material consumption, reducing harmful substance emissions into the air, land, and water, reducing the area of land under landfills, increasing the durability and extending the life of structures, using secondary materials and reusing structural elements or simply put - returning used materials to the environment without endangering it.

In order to make concretes „greener“ in the manufacturing process, replacing only a part of the produced amount of cement with pozzolanic industrial waste brings significant benefits both through saving resources and through the reduction of harmful gases, leaving severe consequences for the environment [4]. Using alternative raw materials such as granulated blast furnace slag, electro filter (flying) ash from thermal power plants, silicate dust, etc., in the clinker production process or as a substitute for clinker in cement has a significant positive contribution to environmental protection. Using these alternative raw materials reduces the consumption of natural - non-renewable sources of raw materials and CO_2 emissions caused by fuel combustion. These mineral additives are used either as fillers or as materials with pozzolanic properties that can partially replace cement.

The subject of this research is energy-efficient porous light aggregate concrete, in which cement is replaced with neutral–mixed industrial waste, non-hazardous and inert powder material, with reuse value. Particular emphasis has been placed on analysing the most important hydrophysical, mechanical and thermotechincal properties of porous lightweight aggregate concrete.

2. EXPERIMENTAL RESEARCH

This research included the investigation of four types of porous lightweight concrete samples – one reference type (Type '1') and three types of samples with partial replacement of cement with inert powder filler neutral (Type '2' with 10% cement replacement with neutral, Type '3' with 20% cement replacement with neutral and Type '4' with 30% replacement of cement with neutral). Type '1' samples were made without cement replacement. As shown in Figure 1, the types of samples differ not only in cement quantity but also in their colour.

a) Type '1' sample (0% neutral) | b) Type '2' sample (10% neutral) | c) Type '3' sample (20% neutral) | d) Type '4' sample (30% neutral)

Figure 1. Types of prefabricated porous lightweight concrete samples

All samples were manufactured in the prefabrication plant „Promobet“ (Mladenovac, Serbia). The mixture receptures of all four types of lightweight porous samples are presented in Table 1. The quantities of cement variated by type: '1' (300 kg/m^3), '2' (270 kg/m^3), '3' (240 kg/m^3) and '4' (210 kg/m^3). Admixtures called Cementol SMB and Cementol A were applied. Quantities of water (80 kg/m^3), admixture I Cementol SMB (1.80 kg/m^3), and admixture II Cementol A (0.09 kg/m^3) were constant.

	Type	'1'	'2'	'3'	'4'
Mix composition	Gravity [kg/m^3]	Amount [kg/m^3]	Amount [kg/m^3]	Amount [kg/m^3]	Amount [kg/m^3]
CEM I 52.5 R	3100	300	270	240	210
Filler (Neutral)	900	0	30	60	90
Lightweight aggregate (Liapor balls of expanded clay, 1-4 mm)	900	690	670	650	630
Water	1000	80	80	80	80
Admixture I: Cementol SMB	1200	1.80	1.80	1.80	1.80
Admixture II: Cementol A	1010	0.09	0.09	0.09	0.09

Table 1. Mix design of lightweight porous concrete

This research used Portland cement CEM I 52.5R form „Moravacem“ (Popovac, Central Serbia) [5] as a binder for the porous light aggregate concrete samples. Portland cement CEM I 52.5R is a high-strength cement recommended for concrete and concrete prefabs.

As shown in Table 1, Liapor balls of expanded clay (fractions 1-4 mm) were used as a lightweight aggregate for the making of samples. Expanded clay balls produced by "Liapor GmbH" [6] have high-value construction and physical properties due to their closed pore structure.

Neutral was obtained in the plant for the treatment of various types of industrial waste of the company Yunirisk d.o.o. (Belgrade, Serbia) [7]. This product is created using a physical-chemical solidification process in which waste molecules combine with calcium-based additives. The term "solidification" refers to various processes that alter materials' physical-chemical properties. According to the EU waste categorisation, this powder is an environment-friendly and inert material with further use value as a final product. Neutral has the following properties:

- Hydraulic conductivity: $2{,}0 \cdot 10^{-7} > K > 1{,}1 \cdot 10^{-7}$ cm/s
- Specific density: 0,73 – 0,96 g/cm^3
- The water content of less than 10%
- Neutral floats on the water without reacting and mixing [7].

3. RESULTS

In this chapter, the results of experimental research conducted at the Faculty of Civil Engineering of Belgrade's Laboratory of Materials, Laboratory of Fluid Mechanics and Flow Volume Measurement, and Laboratory for Thermal Technique and Fire Protection within the Institute IMS in Belgrade are presented. In order to examine the influence of neutral on mechanical and hydrophysical properties of porous lightweight aggregate concrete, the following tests were included: density test, compressive strength test, tensile strength test, salt-frost resistance test and hydraulic conductivity test. In addition, the thermal conductivity coefficient was determined only for the reference type (type ‘1’), assuming that neutral would not affect the thermotechnical characteristics of lightweight porous concrete.

The density of porous lightweight concrete samples was determined using 8 plate samples, two of each sample type. The samples were dried for 72 hours at 105°C to a constant mass, and then the dry mass and the dimensions of the samples were measured. The outcomes are shown in Table 3.

Sample type	Dimensions [mm]	Dry mass [g]	Dry density [kg/m^3]	Average [kg/m^3]
Type ‘1’	200 x 200 x 60	2370	987.50	971
	200 x 200 x 61	2330	954.92	
Type ‘2’	200 x 200 x 58	2164	932.76	939
	200 x 200 x 58	2192	944.83	
Type ‘3’	199 x 199 x 53	1930	919.55	936
	198 x 199 x 55	2066	953.34	
Type ‘4’	199 x 199 x 54	2023	946.01	934
	199 x 200 x 56	2056	922.47	

Table 3. Dry density results

The uniaxial compressive strength investigation of porous lightweight aggregate concrete was performed on a total of 24 samples, i.e. 6 samples for each sample type (approx. dimensions: 60x40 mm). The experiment was conducted with a hydraulic press machine. The hydraulic press was used to compress the concrete samples, which were positioned in such a way that the load was applied to each sample's opposing sides and increased continuously until failure. The greatest load value at which each sample collapsed is recorded and used to calculate its compressive strength analytically. The final results of the compressive strength are shown in Table 4.

Sample type	Force [kN]	Compressive strength [MPa]	Average [MPa]
Type '1'	18.2	7.71	7.2
	17.4	7.37	
	19.0	8.05	
	19.2	8.14	
	14.4	6.00	
	13.8	5.75	
Type '2'	14.2	6.12	5.8
	12.2	5.17	
	15.4	6.64	
	13.0	5.60	
	13.6	5.76	
	13.2	5.59	
Type '3'	10.2	4.40	4.8
	10.4	4.48	
	10.8	4.58	
	9.8	4.22	
	13.6	5.86	
	12.8	5.43	
Type '4'	10.8	4.65	3.9
	8.2	3.47	
	7.2	3.05	
	11.4	4.91	
	8.2	3.47	
	9.2	3.90	

Table 4. Compressive strength results

The tensile strength of porous lightweight aggregate concrete samples was determined using the „PULL-OFF" test on three measuring places on each sample type. Three particular metal elements (stamps) were glued to the concrete surface of each sample type, and the tension force Z was applied. The steel stamp and the surrounding concrete were pulled from the structure's surface at a certain value of this force. Average tensile strength was also measured. All the data regarding mentioned test are presented in Table 5.

Samples	Tension force [kN]	Tensile strength [MPa]	Average [MPa]
	2.318	1.18	
Type '1'	1.919	0.98	1.05
	1.956	1.00	
	1.089	0.55	
Type '2'	1.688	0.86	0.83
	2.141	1.09	
	1.523	0.78	
Type '3'	1.384	0.70	0.76
	1.55	0.79	
	1.19	0.61	
Type '4'	1.057	0.54	0.55
	0.981	0.50	

Table 5. „PULL-OFF" test results

A test of the combined effect of salt and frost on porous lightweight aggregate concrete types of samples was conducted to determinate freeze-thaw and deicing salt resistance. The test was performed on a total of 12 cube samples, i.e. 3 samples for each type, which were placed in a liquid containing 97% water and 3% NaCl solutions. After immersion in 3% NaCl solution, the samples were subjected to several cycles of freezing and thawing in a saturated state. Each cycle consisted of freezing at -20°C for 18 to 20 hours and then thawing for 4 to 6 hours at a temperature of 20°C. After each sample's loss of material and total destruction, the number of obtained freeze-thaw cycles was noted. Test results are presented in Table 6.

Samples	Dimensions [mm]	Mass in the saturated state before testing [g]	Number of freeze-thaw cycles [-]
	52 x 60 x 70	306	
Type '1'	59 x 58 x71	288	14
	57 x 60 x 70	283	
	60 x 58 x 70	281	
Type '2'	58 x 60 x 70	279	12
	54 x 61 x 68	277	
	49 x 62 x 69	267	
Type '3'	58 x 60 x 70	254	9
	54 x 62 x 70	257	
	50 x 57 x 69	245	
Type '4'	52 x 60 x 67	230	3
	49 x 60 x 69	235	

Table 6. Salt-frost resistance results

The hydraulic conductivity of lightweight pervious concrete of all four sample types was determined using the standard constant head test [8]. Before starting the test, samples must be completely saturated. The scheme of the used installation is shown in Figure 2.

Water is first brought to column 1, whose role is to maintain a constant water level. Then it is brought to the specimen reservoir through a connecting pipeline. Water flows through the sample and overflows into the tank placed on the scale, which measures the change in mass per unit of time. A piezometer was set before the sample to eliminate the influence of the connecting pipeline. The results of the constant head test are shown in Table 7.

Sample type	Type '1'	Type '2'	Type '3'	Type '4'
Hydraulic conductivity K (m/s)	$1{,}18x10^{-2}$	$1{,}16x10^{-2}$	$1{,}13x10^{-2}$	$1{,}34x10^{-2}$

Table 7.Constant head test

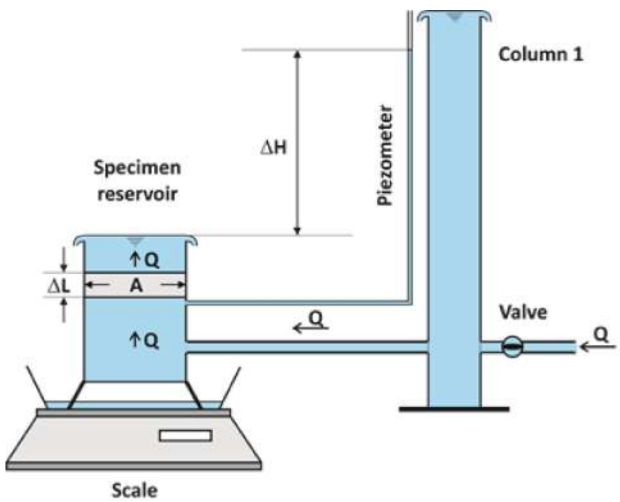


Figure 2. Scheme of the Experimental installation

The thermal conductivity test was performed in Laboratory for Thermal Technique and Fire Protection within the Institute for Materials Testing in Belgrade only on a 60 mm thick reference sample, assuming that neutral would not affect the thermotechnical characteristics of lightweight porous concrete. The average value of the obtained thermal conductivity coefficient was $\lambda = 0.299$ W/mK.

4. DISCUSSION

Based on the comparative testing results of sample types made with various percentages of neutral as a partial replacement of cement (0% - type '1', 10% - type '2', 20% - type '3'and 30% - type '4' of cement replacement), it can be concluded that:

− The average values of dry density of all four sample types are in the range of 934-971 kg/m^3. The reference samples (type '1'), in which the partial replacement of cement with neutral was not performed, have the highest dry density values among the tested samples. Figure 3 illustrates that the dry density gradually drops (type '2' has a 3.30% decrease, type '3' a 3.60% decrease, and type '4' a 3.80% decrease compared to type '1') as the content of neutral increases (10%, 20%, and 30% for types '2', '3', and '4', respectively).

– When the investigated samples' average compressive strengths are compared, the strengths range from 3.9 to 7.2 MPa. The compressive strength of the tested samples decreases almost linearly with the increase in replacement of the amount of cement with neutral, as shown in Figure 4. The reference samples have the highest strength, while type '4' have the lowest compressive strength values (a 45.8% decrease in compressive strength compared to type ‘1’). The compressive strengths of sample types ‘2’ and ‘3’ are reduced by 19.4% and 33.3%, respectively, compared to type '1'.

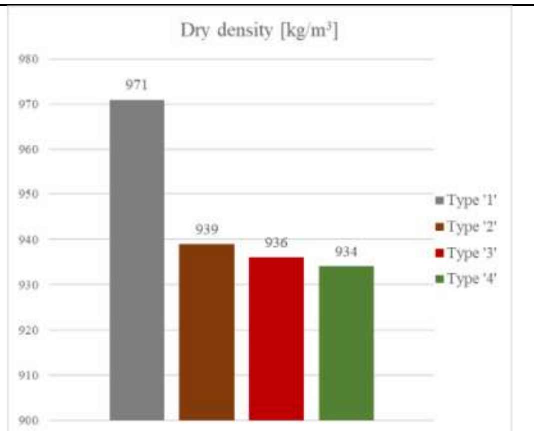


Figure 3. Dry density values

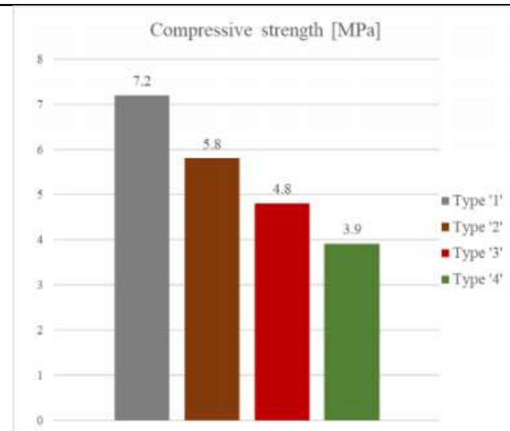


Figure 4. Compressive strength values

– The tensile strength estimated by the "PULL-OFF" test is the highest for the reference samples (type ‘1’) and lowest for sample type ‘4’ (30% of cement replacement with neutral). The tested samples' average tensile strengths range from 0.55 to 1.05 MPa and decrease almost linearly with increasing the neutral content, as seen in Figure 5.

– According to the salt-frost resistance test, none of the sample types could withstand the intended 25 cycles of freezing and thawing in the NaCl solution. The reference samples (type ‘1’) were destroyed after 14 complete freeze-thaw cycles, type ‘2’ after 12, type ‘3’ after 9, and type ‘4’ samples after 3 cycles (as shown in Figure 6). However, it should be noted that in practical use, these elements would never be subjected to such stresses because, due to their porosity, all water will travel through them and not be retained inside the material, leaving them dry in the event of freezing.

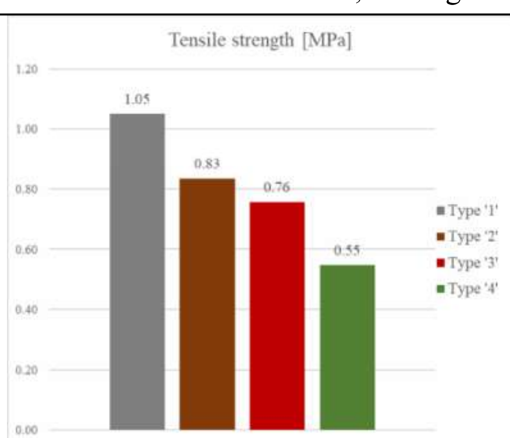


Figure 5. Tensile strength average values

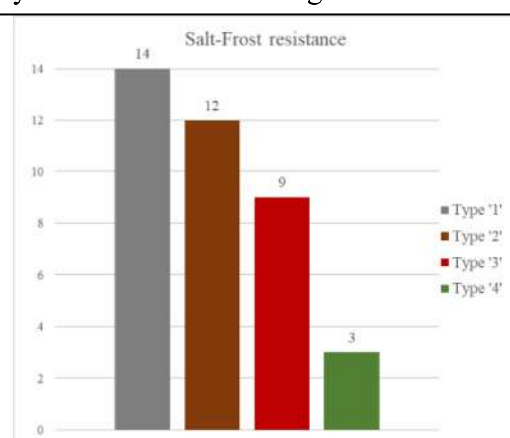
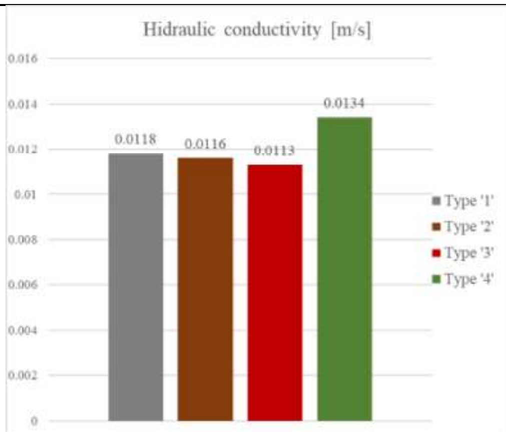


Figure 6. Salt-frost resistance values

– According to Figure 7, the hydraulic conductivity values for all sample types fall within the range of 0.0113 to 0.0134 m/s or 1.13 to 1.34 cm/s. The sample type '3' has the lowest hydraulic conductivity value, while type '4' has the highest value. The hydraulic conductivity barely varies depending on the amount of cement replacement.

– The experimentally obtained coefficient of thermal conductivity indicates (λ = 0.299 W/mK, as shown in Figure 8) excellent thermal characteristics. As such, porous lightweight aggregate energy-efficient concretes can be used as thermal insulation materials. Cavernous concrete "owes" the title of an excellent thermal insulator to its porosity.



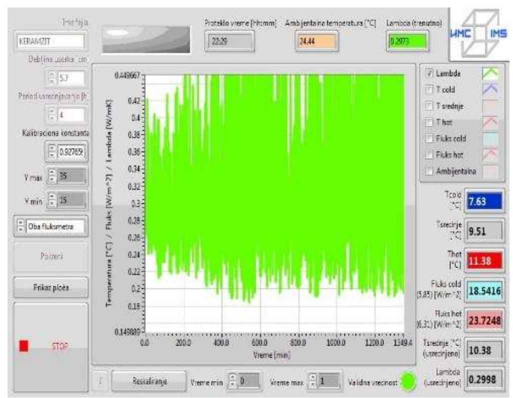


Figure 7. Hydraulic conductivity values	Figure 8. Thermal conductivity coefficient

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5. CONCLUSION

This research focuses on energy-efficient porous light aggregate concrete, in which cement is partially replaced by neutral - mixed industrial waste, non-hazardous, and inert powder material with reuse value. Using neutral as a partial replacement for cement contributes significantly to environmental preservation, the reduction of polluting gases, the preservation of non-renewable resources, the decrease of energy consumption, and also the reduction of waste in landfills.

The most important hydrophysical, mechanical, and thermotechnical properties of porous lightweight aggregate concrete have been investigated. The dry density, salt-frost resistance, compressive and tensile strength of the tested samples of light-aggregate porous concrete slabs decrease with increasing replacement of the cement content with neutral. However, the use of neutral is justifiable from an ecological standpoint. The obtained hydraulic conductivity values indicate that the amount of cement replacement barely influences this hydrophysical property. Also, it should be noted that non-standard-sized samples were used for the experimental determination of the thermal conductivity coefficient and that the results should be taken with caution.

Despite existing data, future research on the application of these porous lightweight aggregate concretes has great potential. Additional research is required to determine the pozzolanic properties of the used neutral and the possibility of using other organic or inorganic waste materials as alternative raw materials for replacing cement.

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