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Operational properties of cement-free concrete with porous aggregate

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ABSTRACT

The article presents the results of technology development and research on the operational properties of porous aggregate and cement-free concretes based on it. The purpose of the work is to study lightweight concretes containing a liquid–glass porous aggregate for resistance to various aggressive influences. The porous granular aggregate was obtained by firing a mixture of liquid glass with the ash of thermal power plants and an ash aluminosilicate microsphere. Binders based on caustic magnesite and liquid glass with the addition of thermal energy waste were used to produce coarse-pored concretes. The choice of cement-free binders is due to the high adhesion to the filler. The behavior of the developed concretes in various aggressive environments, under the influence of low and elevated temperatures, has been studied. The resistance of magnesia concrete to the effects of water and salt solutions has been revealed. The technological and operational advantages of liquid-glazed concrete are shown, featuring increased thermal insulation ability, satisfactory resistance to aggressive media and resistance to low and high-temperature fluctuations. The developed concretes can be used in the enclosing structures of objects for various purposes.

Keywords: liquid glass materials, porous granules, magnesia binders, thermal insulation concretes, water resistance, concrete corrosion.

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Introduction

Concrete is the most popular building composite material. The matrix of concrete - a composite material - is a hardened binder stone; the discrete component is the filler.

Materials of natural and artificial origin are used as filler. Filler grains are characterized by a variety of shapes and sizes, dense or porous structures. The filler makes up 70 - 80% of the mass of concrete and determines the structure and physical and mechanical properties of the composite material.

To ensure energy efficiency of construction projects, lightweight concretes with a density of 500–1600 kg/m^3 are used. Thermal and physical-mechanical properties of lightweight concrete are provided mainly by the characteristics of the porous filler. Concretes on porous fillers allow the implementation of modern technologies in construction production, expanding the range of products [[1], [2], [3], [4]].

The structure of porous fillers of artificial origin is regulated by the choice of raw materials and the method of porization. Therefore, the prospects for the development of lightweight concrete are associated with advances in the technology of porous fillers. Modern porous fillers are based on a variety of raw materials and have a wide range of properties [[5], [6], [7], [8], [9], [10], [11], [12]].

To assess the quality of new porous fillers, not only the structural and mechanical properties of the granular material are important. Lightweight concrete objects are often subject to alternating wetting and drying, freezing and thawing, and exposure to aggressive environments under operating conditions [[6], [7], [8], [9], [10], [11], [12]]. The porous structure can contribute to the destruction of concrete components under environmental influences.

When developing lightweight concrete on porous aggregate, the choice of binder is very important. The presence of amorphous silica in the composition of porous aggregates creates a risk of alkaline corrosion of cement concrete [[13], [14], [15]]. Therefore, the use of new types of porous fillers should be preceded by studies of the operational durability of lightweight concretes created on their basis.

The current article aims to study lightweight concrete containing porous liquid glass filler for resistance to various aggressive effects.

Experimental part

The porous liquid glass filler was obtained by thermal swelling of granules from a molding mixture consisting of the following components, wt.%: liquid glass – 50; thermal power plant ash (hereinafter referred to as TPP ash) – 20; ash aluminosilicate microsphere – 30 [16].

Liquid sodium glass with a silicate modulus of n = 2.7 and a density of 1350 kg/m^3 was used in the experiments.

Chemical composition of TPP ash, %: SiO_2 43 – 51; Al_2O_3 14 – 27; Fe_2O_3 4 – 9; CaO 7 – 10; MgO 2 – 4; R_2O 1 – 2; SO_3 2 – 5; loss on ignition is 4 – 15. The material composition of TPP ash is represented by aluminosilicate glass, quartz particles, mullite and unburned coal. The specific surface area of TPP ash is 280 – 300 m^2/kg.

Ash aluminosilicate microsphere is a bulk mass consisting of hollow glass-crystalline particles of spherical shape with a diameter of 50 - 250 microns. An Aluminosilicate microsphere is a light fraction of ash residue that is formed during coal combustion. Chemical composition of aluminosilicate microsphere, %: SiO_2 65 – 70; Al_2O_3 1 – 2; Fe_2O_3 2 – 4; CaO to 10. Bulk density 380 – 400 kg/m^3.

Granules from the liquid glass mixture, formed in a drum granulator, were fired at a temperature of 350^{o}C. The expanded granules had the shape of a sphere with a diameter of 5 - 10 mm. The coefficient of swelling of the granules is 1.2. The physical and mechanical properties of porous liquid glass granules, determined using standard methods, are described in Table 1.

To obtain lightweight concrete based on liquid glass granules, binders with high adhesion to the porous filler and pronounced binding capacity were used. These characteristics provide lightweight concrete with increased strength. Analysis of the results of developments [[17], [18], [19], [20], [21]] and the experience of preliminary studies by the author showed the feasibility of using caustic magnesite and liquid glass as binders for concrete mixtures.

When designing the composition of concrete mixtures, numerical modeling of the porous filler packaging in concrete was used [22]. For maximum use of the binding properties of substances, a preferred region was identified that corresponds to an average granule diameter of 6–8 mm and a binder content in the material of at least 30%. Numerical comparisons of the properties of concrete based on porous granules of different sizes indicate that, under load, large granules are more susceptible to destructive processes. It is noted that the main role in the stress-strain state of lightweight concrete is played by the binder, which causes the redistribution of forces between the elements of the large-porous structure.

Magnesia lightweight concrete was obtained on the basis of a mixed binder consisting of caustic magnesite (grade magnesite powder caustic, with a magnesium oxide content of at least 75%) and TPP ash. The concrete mixture was mixed with a magnesium chloride solution with a density of 1230 kg/m^3. Composition of magnesite concrete mix, kg/m^3: porous filler – 210 (955 l/m^3); caustic magnesite – 159; TPP ash – 106; magnesium chloride solution – 127 (103 l/m^3). The magnesite concrete mixture was prepared in the following sequence: a mixture of caustic magnesite and TPP ash, previously activated in an E-max high-speed mill, was mixed with a magnesium chloride solution and mixed for 2 minutes. Porous granules were loaded into the resulting magnesite suspension and mixed for 3 minutes to evenly distribute the magnesite paste between the aggregate grains.

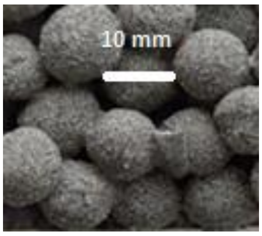
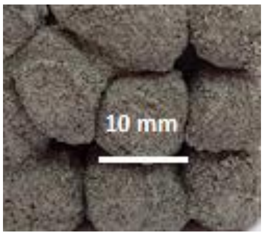
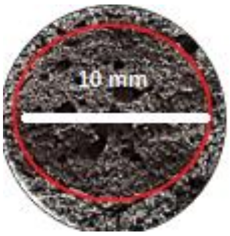
The material composition of the liquid glass binder for lightweight concrete contained components used to obtain a porous filler. Composition of the liquid glass concrete mixture, kg / m^3: porous filler - 210 (955 l / m^3); liquid glass - 200 (148 l / m^3); TPP ash - 85; ash aluminosilicate microsphere - 85. The liquid glass concrete mixture was prepared in the following order: TPP ash and aluminosilicate microsphere were poured into a liquid glass, and the mass was mixed for 2 minutes. Porous granules were loaded into the resulting liquid glass suspension and mixed for 3 minutes to uniformly coat the aggregate grains with a binder.

The mobility of concrete mixtures, assessed using an Abrams cone, corresponded to a cone settlement of 2-4 cm. Concrete mixtures were placed in metal forms measuring 100x100x100 mm and vibrated for 50 s.

Table 1 – Main properties of porous liquid glass granules

Properties	Value	Appearance of granules
Average granule density, kg/m^3	430	
Bulk density, kg/m^3	205	
Granule porosity, %	78	
Splitting strength, MPa	2.6	
Compressive strength in a cylinder, MPa	1.2	
Water absorption, %	7.5	
Softening coefficient	0.87	
Thermal conductivity coefficient, W/(m ^{0}C)	0.085	

Table 2 – Properties of lightweight concretes based on various binders

Properties	Magnesia concrete	Liquid glass concrete
Appearance		
Filler granule in concrete		
Nature of concrete destruction during strength testing		
Porosity, %	67	78
Average density, kg/m^3	515	480
Compressive strength, MPa	5.2	4.7
Thermal conductivity coefficient, W/(m ^{0}C)	0.113	0.095

After preliminary holding for 1.5 hours, the molded magnesia concrete samples were subjected to heat treatment to accelerate hardening. Drying mode: 0.5 hours – heating to a temperature of 50 °C; 3.5 hours – isothermal holding; 0.5 hours – cooling.

The molded samples of liquid glass concrete were pre-conditioned for 1 hour and then subjected to heat treatment to form water-resistant compounds in the binder. Heat treatment mode: 2 hours – heating to a temperature of 350 °C; 2.5 hours – isothermal ageing, 1 hour – cooling.

The strength of concrete samples was determined using a PGM-1000MG4 hydraulic press. The thermal conductivity coefficient of concrete was estimated using an ITP-MG4 thermal conductivity meter on samples measuring 100x100x10 mm. The results of concrete tests are presented in Table 2.

Discussion of results

The developed concretes have a large-porous structure, in which the space between the aggregate granules is free. A thin binder shell, enveloping the aggregate grains, binds them together at the points of contact. Due to the high adhesion of the binders under study, a stable structure of concretes with high porosity and heat-insulating properties is formed. The density and thermal conductivity indices characterize the developed concretes as heat-insulating materials. The nature of the destruction of concrete samples during testing indicates reliable adhesion of the aggregate to the binder stone (Table 2).

The following are accepted as aggressive operational impacts on concrete: humidity fluctuations, liquid media (water and salt solutions), and temperature differences. To enhance the impact of aggressive environments on concrete, samples with exposed ends were used. This provided open access to the inner part of the filler and made it possible to evaluate its durability in the composition of concrete. The tests used methods that are generally recognized in research practice.

Resistance to alternate water saturation and drying was determined by comparing the strength after a given test cycle with the control indicator. Test cycle: 4 hours - water saturation, 4 hours - air drying at a temperature of 20 - 22°C. Inspection and testing of samples were carried out every 10 cycles. No pronounced defects were found on the samples during the testing period. The test results confirmed the satisfactory resistance of lightweight concrete to fluctuations in ambient humidity (Table 3). The strength of concrete subjected to testing is 83 - 85% of the strength of the control samples.

Water absorption of concrete was determined taking into account the mass of the initial sample and the mass of the sample saturated with water for 1 day. The value of water absorption is significantly less than the total porosity of the materials (Tables 2 and 3), which indicates the predominance of closed pores in the structure of concrete. Water mainly fills open voids, and penetrates the pores on the sections of the samples.

The water resistance of concrete was assessed by the softening coefficient taking into account the strength of the samples after being in water for 3 days and the strength of the original samples in the air (Table 3). It is important to note that caustic magnesite and liquid glass are binders that harden and retain strength only in air conditions. However, the combination of caustic magnesite with TPP ash contributed to the formation of water-resistant hydrated formations in the magnesite binder stone. The heat treatment mode of the liquid glass binder containing waste from thermal power engineering ensured the formation of insoluble crystalline and amorphous compounds. As a result, the adopted technological solutions ensured satisfactory resistance of the studied lightweight concretes to the effects of water.

The developed concretes were tested for resistance to aggressive solutions, the composition of which is represented by salts of various compositions. Concrete samples were kept in solutions of magnesium sulfate (concentration 3%), magnesium chloride (concentration 7%) and sodium sulfate (concentration 5%). For 12 months. the samples were examined visually, and after completion of the tests, the resistance coefficient was determined (the ratio of the strength of the samples in an aggressive environment to the strength of the control samples). The results of the concrete tests are given in Table 4.

Table 3 – Indicators of resistance of lightweight concrete to the effects of humid environment and water

Properties	Magnesia concrete	Liquid glass concrete
Strength after 90 cycles of alternating wetting and drying, MPa	4.2	3.8
Water absorption, %	31	38
Softening coefficient	0.87	0.82

Table 4 – Indicators of concrete resistance to the effects of salt solutions

Type of concrete	**Coefficient of resistance of concrete in solutions**		
	magnesium sulfate (concentration 3%)	***magnesium chloride (concentration 7%)***	***sodium sulfate (concentration 5%)***
Magnesia	1.13	1.15	0.93
	Appearance of concrete after testing		
			
Liquid glass	0.81	0.84	0.47
	Appearance of concrete after testing		
			

Table 5 – Frost resistance characteristics of liquid glass concrete

Characteristic	**Before the test**	**After 50 test cycles**
Appearance of concrete		
Strength, MPa	4.7	3.7

Magnesia concrete withstood exposure to all salt environments. Exposure to solutions of magnesium chloride and sulfate contributed to the strengthening of magnesia concrete. This is due to the participation of magnesia salts in the hydration of magnesia binders.

Liquid glass concrete demonstrated resistance in the environment of magnesium salt solutions. On the surface of the samples that were in the magnesium sulfate solution, white insoluble accumulations of magnesium hydroxide formed, which are capable of compacting the structure. In the sodium sulfate solution, the strength of liquid glass concrete is reduced by almost half. The sodium salt solution contributed to the formation of soluble compounds with the participation of amorphous components of the liquid glass binder. This was accompanied by the destruction of the binder shells around the filler grains. At the final stages of testing, the destruction of the porous filler grains was observed.

Frost resistance of concrete was assessed by the number of freezing and thawing cycles. Before freezing, the samples were saturated with water. Freezing mode: freezer air, temperature "minus" 18±2°C, duration 2.5 hours. Thawing mode:

immersion of frozen samples in water with a temperature of 20±2^{o}C for 2 hours. Upon completion of each cycle, the samples were inspected to detect signs of destruction. When testing magnesia concrete, chips and small cracks were found, so after 15 cycles the tests were stopped. No obvious defects in the structure of liquid glass concrete were observed. After 25 test cycles, the strength of liquid glass samples was 92%, after 50 cycles - 78% of the strength of concrete not subjected to freezing (Table 5). The test results showed that liquid glass concrete has frost resistance that meets the requirements for wall materials.

Materials based on liquid glass are characterized by resistance to elevated temperatures [17]. The developed liquid glass concrete was tested for heat resistance and heat resistance. The heat resistance of liquid glass concrete was determined by the ability of samples to withstand sudden temperature changes. The samples were placed in a drying chamber heated to a temperature of 250^{o}C and kept for 2 hours. Then the heated samples were immersed in water (temperature 20^{o}C) for 2 hours. Thermal resistance was determined by the number of thermal changes during which the samples retained their integrity, and the mass loss did not exceed 20%. The heat resistance of liquid glass concrete was assessed by changes in appearance and residual strength after exposure to high temperatures. The samples were kept for 4 hours in a muffle furnace at a temperature of 1050^{o}C. After the furnace was turned off, the samples were cooled to a temperature of 500^{o}C for 2 hours, then again exposed to high-temperature action. For heat-resistant materials, the residual strength should be at least 80%. The test results showed that thermal effects increase the density of concrete by 6–15% (Table 6). At the same time, the strength of concrete tested for heat resistance decreased by 30% as a result of sample destruction. Concrete subjected to heat resistance testing is characterized by shrinkage of 2–3% and strengthening due to crystalline compounds formed during high-temperature treatment. Consequently, the test results indicate the thermal stability of the components of liquid glass lightweight concrete to the effects and changes in elevated temperatures.

Table 6 – Resistance of liquid glass concrete to thermal effects

Type of test	**Density, kg/m^3**		**Strength, MPa**		**Appearance after testing**
	before testing	***after 25 cycles***	***before testing***	***after 25 cycles***	
Thermal resistance	480	510	4.7	3.3	
Flame resistance		550		5.8	

Table 7 – Comparative economic indicators of concretes of different compositions

Indicators	**Costs, KAZ tenge/m^3**		
	liquid glass concrete	***magnesite concrete***	***cement expanded clay concrete***
Components of concrete mixtures	42262.26	42375.30	44716.88
Energy resources for concrete hardening	1117.29	89.96	788.12
Total	43379.55	43465.26	45505.00

The results of testing lightweight concrete on a porous aggregate show that the resistance of concrete to external influences is determined mainly by the properties of the binder, the shells of which cover, bind and protect the aggregate granules. The destruction of the binder is accompanied by a violation of the bond between the granules and the destruction of the concrete. The use of samples with exposed ends in the experiments, providing access to the aggregate, made it possible to verify the individual resistance of the aggregate of different concretes to the most aggressive influences.

A comparative analysis of the performance properties of concretes made from different binders indicates several advantages of liquid glass concrete. Firstly, with an equal volume of porous filler, concrete based on a binder made from liquid glass has a lower density and increased heat-protective capacity. Secondly, satisfactory resistance to aggressive environments and resistance to low and high-temperature changes expands the scope of the application of liquid glass concrete compared to magnesite concrete. Thirdly, the pronounced resource-saving focus of concrete made from a liquid glass binder (170 kg of man-made waste from thermal power engineering is used to obtain 1 m3 of concrete mix). Fourthly, the related composition of raw mixes for porous filler and binder of liquid glass concrete not only contributes to reliable adhesion of the components but also allows organizing a compact integrated production for the production of porous granular material and concrete based on it.

The advantages of concrete based on mixed magnesite binder are satisfactory resistance to water and high resistance to aggressive environments. The technology of the developed magnesite concrete provides for the use of a man-made component and is characterized by low energy consumption.

The main economic indicators of the developed lightweight concrete were calculated. For comparison, the base object was cement concrete containing expanded clay as a porous filler. Comparable strength indicators of different concretes are achieved provided that the density of cement expanded clay concrete is 750 kg/m^3, the thermal conductivity coefficient is 0.155 W/(m ^{o}C). Assuming that the labor intensity of technological processes does not depend on the composition of concrete mixtures, only material and energy costs for obtaining 1 m^3 of concrete were calculated. Comparative indicators of resource intensity of concretes of different compositions are given in Table 7.

The highest material costs are typical for cement concrete, which is characterized by increased density and, consequently, increased consumption of concrete mix components. The high energy intensity of liquid glass concrete is due to the adopted heat treatment mode. The total costs of material and energy resources of cement concrete are 4.48 - 4.67% higher than similar indicators of the developed concretes.

The efficiency of the developed cement-free concretes is more pronounced at the stage of application in construction. To ensure the required thermal resistance of a wall of a residential building equal to 3.279 (m^2 ^{o}C)/W, the thickness of the thermal insulation layer of different concretes, defined as the product of the thermal resistance and the thermal conductivity coefficient, will be: for liquid glass concrete 3.279 (m^2 ^{o}C)/W 0.095 W/(m ^{o}C) = 0.311 m; for magnesia concrete 3.279 (m^2 ^{o}C)/W 0.113 W/(m ^{o}C) = 0.371 m; for cement expanded clay concrete 3.279(m$^2\cdot{}^{o}$C)/W·0.155W/(m·^{o}C) = 0.508 m. Consequently, to achieve a comparable thermal effect, the consumption of cement expanded clay concrete is 1.37–1.63 times higher than the consumption of magnesia and liquid glass concrete.

Conclusions

The technology has been developed and the operational properties of porous liquid glass filler and cement-free heat-insulating concrete based on it have been studied.

The use of magnesia and liquid glass binders allows the creation of highly porous concrete structures on liquid glass filler and provides rational areas of application of lightweight concrete taking into account resistance to various operating conditions. The use of cementless binders is also aimed at developing the technology of building materials with a low carbon footprint.

The developed composition of magnesia heat-insulating concrete is characterized by a low-energy hardening process and high resistance in salt solutions and water.

The composition of the raw materials and the proposed conditions for heat treatment of concrete based on liquid glass binder provide the heat-insulating material with resistance to liquid aggressive environments, frost damage and exposure to elevated temperatures.

The developed cement-free concretes on porous liquid glass filler can be used in enclosing structures of objects for various purposes. Economic indicators demonstrate the feasibility of using the developed cement-free concrete for energy-efficient construction.

Conflict of interest: The author states that he has no conflicts of interest to disclose.

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Кеуекті толтырғышы бар цементсіз бетондардың қолданымдық қасиеттері

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Сараптамадан өтті: *25 қараша 2024*
Қабылданды: *5 желтоқсан 2024*

ТҮЙІНДЕМЕ

Мақалада кеуекті толтырғыштың және оның негізіндегі цементсіз бетондардың қолданымдық қасиеттерін зерттеу және технологияны дамыту нәтижелері келтірілген. Жұмыстың мақсаты – құрамында сұйық шыныдан тұратын кеуекті толтырғышы бар жеңіл бетондардың әртүрлі агрессивті әсерлерге төзімділігін зерттеу. Кеуекті түйіршікті толтырғыш сұйық шыны қоспасын жылу электр станцияларының күлімен және күл алюминий силикат микросферасымен күйдіру арқылы алынды. Ірі кеуекті бетондарды алу үшін каустикалық магнезит пен жылу энергетикасының қалдықтары қосылған сұйық шыныдан алынған тұтқыр заттар қолданылды. Цементсіз тұтқыр заттарды таңдау олардың толтырғышқа деген жоғары адгезиясына байланысты. Төменгі және жоғары температура әсерінен әр түрлі агрессивті ортада әзірленген бетондардың әрекеті зерттелді. Магнезиялдық бетонның су мен тұзды ерітінділердің әсеріне төзімділігі анықталды. Сұйық шыны бетонның технологиялық және пайдалану артықшылықтары көрсетілген, олар жылу оқшаулау қабілетінің жоғарылауымен, агрессивті ортаға қанағаттанарлық төзімділігімен және төмен және жоғары температураның ауытқуына төзімділігімен ерекшеленеді. Әзірленген бетондарды әртүрлі мақсаттағы объектілерді қоршайтын конструкцияларда қолдануға болады.

Түйін сөздер: сұйық шыны материалдар, кеуекті түйіршіктер, магнезиялды тұтқыр заттар, жылу оқшаулағыш бетондар, суға төзімділік, бетон коррозиясы.

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Эксплуатационные свойства бесцементных бетонов с пористым заполнителем

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АННОТАЦИЯ

В статье приведены результаты разработки технологии и исследований эксплуатационных свойств пористого заполнителя и бесцементных бетонов на его основе. Цель работы – исследование легких бетонов, содержащих жидкостекольный пористый заполнитель, на стойкость к различным агрессивным воздействиям. Пористый гранулированный заполнитель получали обжигом смеси жидкого стекла с золой тепловых электростанций и зольной алюмосиликатной микросферой. Для получения крупнопористых бетонов использовали вяжущие, полученные на основе каустического магнезита и жидкого стекла с добавлением отходов тепловой энергетики. Выбор бесцементных вяжущих обусловлен

	высокой адгезией к заполнителю. Исследовано поведение разработанных бетонов в различных агрессивных средах, при воздействии низких и повышенных температур. Выявлена стойкость магнезиального бетона к воздействию воды и солевых растворов. Показаны технологические и эксплуатационные преимущества жидкостекольного бетона, отличающего повышенной теплоизоляционной способностью, удовлетворительной стойкостью к агрессивным средам и устойчивостью к перепадам низких и высоких температур. Разработанные бетоны могут быть использованы в ограждающих конструкциях объектов различного назначения.
	Ключевые слова: жидкостекольные материалы, пористые гранулы, магнезиальные вяжущие, теплоизоляционные бетоны, водостойкость, коррозия бетона.
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