Original article
https://doi.org/10.15828/2075-8545-2024-16-3-249-256

The study of CO_2 impact on the formation of nanoscale structures and the physical and mechanical properties of concrete

Albert A. Zalyatdinov , **Renat U. Kamenov*** , **Denis S. Rechenko**
Almetyevsk State Technological University "Higher School of Oil", Almetyevsk, Russia
* Corresponding author: e-mail: renatkamenov@mail.ru

ABSTRACT

Introduction. In the context of the global fight against climate change, the reduction of CO_2 emissions and its utilization is a topical theme. One of the promising directions is the utilization of CO_2 in construction, in particular, in concrete production. The present research investigates the effect of carbon dioxide on the formation of nanoscale structure and physical and mechanical properties of concrete mixtures. **Methods and Materials.** A special unit for mixing cement, sand, water and CO_2 under pressure was developed for the research. The obtained concrete specimen were subjected to compressive and flexural strength tests using MATEST E161-03N automatic dual range testing press. The microstructure of the specimen was also analyzed using scanning electron microscope (SEM). **Discussion.** The experimental results showed that the introduction of CO_2 into the concrete mixture promotes the formation of nanoscale structure, which improves its strength properties up to a certain pressure. With further increase in pressure, deterioration of these characteristics is being observed. Additional mixing time and increase in water volume also affect the strength of concrete and its microstructure. **Conclusion.** The use of CO_2 in concrete production can significantly reduce the carbon footprint of construction materials and improve their physical and mechanical properties due to the formation of nanoscale structure. Further research and optimization of mixing parameters are necessary to create stronger and more stable concrete mixtures.

KEYWORDS: nanoscale structure, carbon dioxide utilization, concrete strength, carbonization, carbon dioxide, ecology.

FOR CITATION:
Zalyatdinov A.A., Kamenov R.U., Rechenko D.S. The study of CO_2 impact on the formation of nanoscale structures and the physical and mechanical properties of concrete. *Nanotechnologies in Construction.* 2024; 16(3): 249–256. https://doi.org/10.15828/2075-8545-2024-16-3-249-256. – EDN: DZJPZF.

INTRODUCTION

Today, one of the world trends aimed at improving the standard of living and preserving the planet is the fight against climate change and its consequences, which is also due to the great challenge of the strategy of scientific and technological development of the Russian Federation (Presidential Decree No. 642 of 01.12.2016), associated with the depletion of natural resources and environmental degradation [1]. This is directly related to the carbon neutrality of production activities and compensation of enterprise emissions through carbon-negative projects and technologies. Enterprise emissions are divided into three categories: direct emissions during production; emissions obtained due to energy consumption (coal plant, nuclear power plant, hydroelectric power plant, etc.) and emissions obtained during the life cycle of goods (purchase of raw materials, delivery, storage, use, disposal, etc.). The last two categories are indirect emissions and require serious systematic development of carbon accounting. It should be noted that the first category, which includes greenhouse gases, is the most significant and manufacturing companies are focused on reducing this category. At the same time 77.9% in the structure of emissions is energy, 11.8% – industry (production), 5.7% – agriculture and 4.6% – waste, and in the structure of emitted gases carbon dioxide (CO_2) makes 79.2%, methane (CH_4) – 14.5%, nitrogen oxide (N_2O) – 4.2%, hydrofluorocarbons (HFC) – 1.9%, perfluorocarbons (PFC) and sulfur hexafluoride (SF6) 0.1% each [2]. As can be seen carbon dioxide CO_2 or carbon dioxide in the total volume of emissions occupies a large part and this is without taking into account the minor categories, that is, the collection, storage and utilization of carbon dioxide is today an urgent task.

Modern technologies allow to effectively capture emissions and retain in any state, but the main task is their utilization and application in various industries, for example, in the manufacture of fire extinguishing agents, refrigerant, soda ash, salts, etc., but this is a very small amount of carbon dioxide processing. Therefore, the development of carbon dioxide utilization technology is an urgent task.

Concrete, as one of the most common materials in the construction industry, has strength, durability and adaptability, which makes it an essential part of modern construction [3–13]. This report takes into account both traditional concrete manufacturing methods and modern technologies, including additives and admixtures that help to improve its properties and enhance the requirements that concrete must meet.

Basic requirements in the manufacture of concrete:

1. The main objective of the concrete manufacturing process is to create a material with optimum strength and durability, capable of withstanding the stresses of service conditions;

2. The process must comply with strict standards and regulations set by the construction industry to ensure safety, reliability and quality of structures;

3. The proportioning of each component must be accurate and in accordance with established proportions to ensure optimum physical and chemical properties of the concrete mix;

4. Concrete must be subjected to certain conditions of temperature and humidity during setting and curing to ensure optimum material properties.

Adherence to the above objectives and requirements in the concrete manufacturing process is a key aspect to create a quality and reliable construction material that can meet the needs of a variety of projects and ensure their durability.

To achieve the above requirements, the concrete manufacturing process begins with carefully selected and proportioned raw materials and supplies. The quality and characteristics of each component will play a crucial role in shaping the final properties of the concrete mixture.

According to GOST 27006-86 "Concretes" selected composition of concrete components including cement, sand, crushed stone and water in the ratio of 1:1,9:3,7:0,5 respectively. This standard allows on the basis of visual control to make changes in the amount of dosed water, so for further work by experimental method was determined the following ratio of concrete mixture components 1:1,9:3,7:1.

Cement production based on the use of CO_2 as one of the components of the formulation is a new and promising technology, not yet implemented on an industrial scale, but has great potential. Carbon dioxide is captured immediately after its release, compressed into a liquid and then transported via pipeline to a storage facility right at the concrete production site [14, 15].

The hardening of concrete when CO_2 is added involves a process called carbonization. This process is a chemical reaction between carbon dioxide (CO_2) and cement hydrates formed during concrete hardening. Carbonization leads to a change in the nanoscale structure of concrete, which ultimately increases its strength and durability.

When CO_2 penetrates the concrete, it reacts with calcium oxide hydrate ($Ca(OH)_2$), which is a byproduct of cement hydration. The result of this reaction is the formation of calcium carbonate ($CaCO_3$):

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O. \quad (1)$$

Calcium carbonate is denser and less soluble than calcium oxide hydrate, which contributes to the hardening of the concrete structure.

At the nano level, carbonation leads to changes in the porous structure of concrete. Calcium oxide hydrate occupies more volume and has a looser structure, while calcium carbonate has a denser and more compact crystal lattice. Carbonization fills the pores and micro-cracks in concrete, which reduces its porosity and increases its density.

This process also affects the structure of the cement stone. Due to the formation of calcium carbonate at the nanoscale, the pore volume is reduced, which limits the access of water and other potentially harmful agents inside the concrete. This reduces the rate of degradation of the material and increases its durability.

In addition, the formation of calcium carbonate can facilitate the creation of new microstructural bonds between cement particles. These bonds improve the overall mechanical integrity of the concrete, making it more resistant to mechanical stress and deterioration.

To this day, several countries in the world are actively developing this technology. For example, the Canadian company *CarbonCure Technologies* has developed a technology that allows the production of concrete with CO_2, which is injected in controlled doses into the mixer supplying the stone-forming machine. When CO_2 is added to the concrete during mixing, it interacts with water to form carbonate ions, which rapidly interact with calcium ions released from the cement, resulting in the formation of calcium carbonate (limestone) minerals, forming a nanostructure. The conversion of CO_2 into solid calcium carbonate minerals allows it to bind in the concrete and never be released back into the atmosphere [16–21], with the nanoscale structure yielding an increase in concrete strength. A similar technology has been proposed by

American engineers from *Solidia Technologies*, but for fast-setting concrete [24].

A team of American researchers from Los Angeles is working on a unique solution, which consists in creating a closed-loop process that involves capturing carbon from power plant pipes and using it to create a new building material – carbon dioxide concrete for *3D* printing [22, 23]. Employees of the American *Purdue University* have developed a technology that allows the concrete mixture to absorb CO_2 much stronger due to titanium dioxide, which, when mixed with the concrete solution, reduces the size of calcium hydroxide molecules, which increases the volume of absorbed carbon dioxide.

In the research of scientists from a Japanese university, a process has been developed to produce concrete that affects the environment in several ways at once. The new material is made from old concrete debris that is often discarded, which extends the life of the old materials, and the process takes place at lower temperatures, while the CO_2 with which it is mixed can be obtained either from industrial exhaust or directly from the air [25–27].

Based on the research results of various scientists, it can be concluded that the capture and utilization of CO_2 in concrete production has great potential to reduce greenhouse gas emissions and create environmentally friendly building materials. New technologies, not only reduce the negative impact on the environment, but also improve the quality and durability of concrete. According to some reports, such technologies can reduce CO_2 emissions by up to 30% and increase strength by about 10–19% compared to classical technology. Increased compressive strength also allows producers to optimize their mixes by reducing the amount of cement while maintaining physical and mechanical properties. On average, ready mixed concrete producers can reduce the amount of cement by 5–8%, but the main challenge today is to set up a plant to prepare the mix with CO_2.

The effect of CO_2 application in concrete production, in particular on the change of mixture properties requires research, which is possible only if a special plant for mixing cement, water sand and carbon dioxide in liquid state is created. To date, there are no such installations, so the objectives of this work are the design and manufacture of the installation for obtaining concrete mixing mixture, obtaining concrete mixture of various formulations and research of their physical and mechanical properties.

METHODS AND MATERIALS

In the segment of concrete mixing devices there is no equipment capable of mixing the concrete mixture under pressure, so on the basis of the selected production method the design of concrete mixer according to the scheme (Fig. 1)

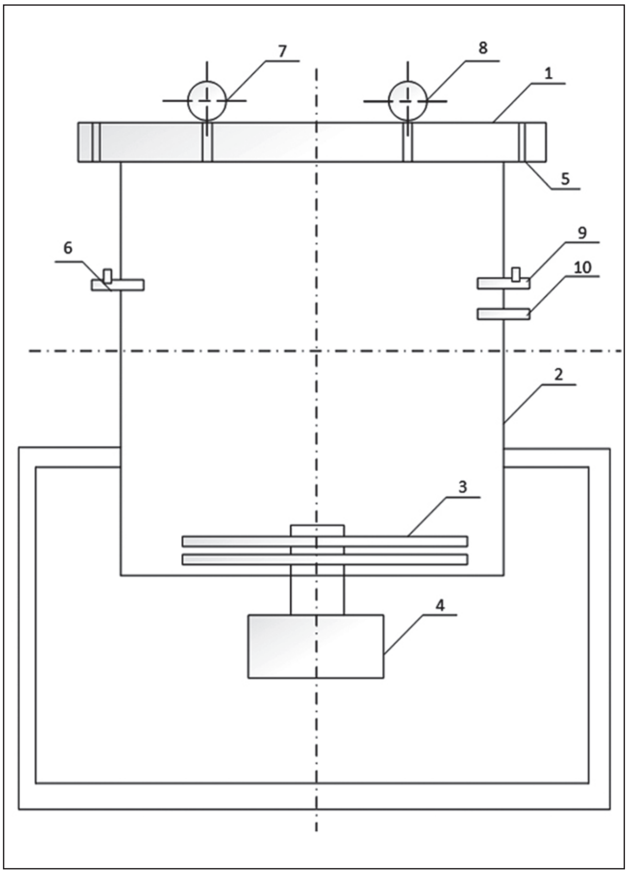

Fig. 1. **Design of concrete mixer for obtaining the mixture under pressure:** 1 – lid attached to the container with pins; 2 – cylinder-shaped container; 3 – paddles (two-level); 4 – motor; 5 – pin holes for connecting the lid and the container through the collar; 6 – tap connecting to the vacuum pump; 7 – vacuum pump; 8 – manometer; 9 – tap for supplying water saturated with CO_2; 10 – plug

The pressurized concrete mixer is a cylinder-shaped steel container with a volume of 25 liters, which is designed to operate at pressures up to 70 atm. Inside there are two-level paddles for mixing the concrete mixture, which are connected to the motor shaft. The tank is mounted on a pivoting base, which will allow this structure to be tilted together with the motor to extract the mixture. The outside of the tank has threaded holes for sensors, taps and plugs.

As a result of the design and development, a pressurized concrete mixing unit was manufactured (Fig. 2). The unit is capable of mixing concrete, in the required volume, which is 30 kg of dry mix.

Two main molds were used to make concrete test specimens for the research:

1. Square molds with sides 100×100×100 mm: These molds are designed to determine the compressive strength of concrete. This size allows the production of specimens

Fig. 2. **Concrete mixer for pressurized mix production**

that meet the test standards and ensure uniformity of results.

2. Rectangular molds with sides 70×70×280 mm: These molds are used to determine the flexural strength of concrete. Their size ensures proper distribution of stresses during testing and allows accurate determination of the strength characteristics of the material.

All molds for the specimens were selected in accordance with the requirements of GOST 10180-2012 [28], which guarantees the accuracy and comparability of the results obtained.

Sample fabrication process

The process of manufacturing the control concrete samples included several steps that ensured the accuracy of component dosing, quality mixing and proper introduction of carbon dioxide. These steps are described below:

1. Equipment preparation and inspection:

All equipment, including the concrete mixer, sample molds, and component measuring tools, was thoroughly checked to ensure that it was clean and working properly before starting. This avoids contamination of the mix and ensures accurate measurements.

2. Calculating the quantity of components:

The quantities of cement, sand, water and carbon dioxide were calculated according to predetermined proportions. This ensures that all specimens are made from the same mix, which is important for comparability of test results.

3. Loading the components into the concrete mixer:

Pre-weighed portions of cement and sand were loaded into the concrete mixer. These components were mixed for a certain time to achieve homogeneity of the dry mix.

4. Addition of calculated amount of water:

After mixing the dry components, the calculated amount of water was added to the concrete mixer. The water was added gradually to avoid lump formation and to ensure uniform distribution of liquid throughout the mix.

5. Mixing:

The mixture of cement, sand and water was mixed in the concrete mixer until a homogeneous mass was obtained. The mixing time was strictly controlled to ensure uniform distribution of all components.

6. Carbon dioxide injection:

After the homogeneity of the mixture was achieved, the calculated amount of carbon dioxide was pumped into the concrete mixer. The injection process was carried out under pressure, allowing the CO_2 to distribute evenly throughout the concrete mass and interact with the mix components.

7. Final Mixing:

After the injection of carbon dioxide, the mixture was again mixed for a certain time. This ensured complete interaction of CO_2 with the concrete components and promoted the formation of nanoscale structure.

8. Pouring the ready-mixed concrete into the molds:

The ready-mixed concrete was poured into the prepared molds. For this purpose, special tools were used to ensure uniform filling of the molds without formation of voids and air pockets.

The obtained specimens were tested on *MATEST E161-03N* (automatic dual-range test press) to measure the compressive and flexural strength of cement stone. Table 1 summarizes the results of the concrete specimens in compression and flexural tests.

It should be noted that mix 6 is a standard mix, i.e. mixing was done in air. Mixes 8, 9, 10 were mixed at different pressures of CO_2, in these mixes with increasing pressure of gas injection the mixture at the output was dry and it was decided to increase the volume of added water by 5% in mixes 11, 12 and 13. In mixes 14, 15, 16 we increased the mixing time to find out whether the mixing time will affect the strength characteristics of concrete, these mixes were also mixed at different pressures of CO_2.

The experimental results are shown in Fig. 3 and 4.

Table 1
Test results of concrete specimens in compression and bending

Batch	Water volume. l	Time. min	CO_2 pressure. atm	Average strength. Ri	
				in compression. σ_{cr}	on bending. σ_{ob}
1	3. 9	5	0	52. 40	1. 65
2	3. 9	5	10	58. 43	1. 74
3	3. 9	5	20	35. 65	1. 03
4	3. 9	5	30	51. 25	1. 18
5	4. 1	5	10	47. 66	1. 52
6	4. 1	5	20	27. 56	1. 00
7	4. 1	5	30	34. 16	1. 03
8	4. 1	10	10	25. 36	0. 86
9	4. 1	10	20	6. 95	0. 16
10	4. 1	10	30	14. 35	0. 45

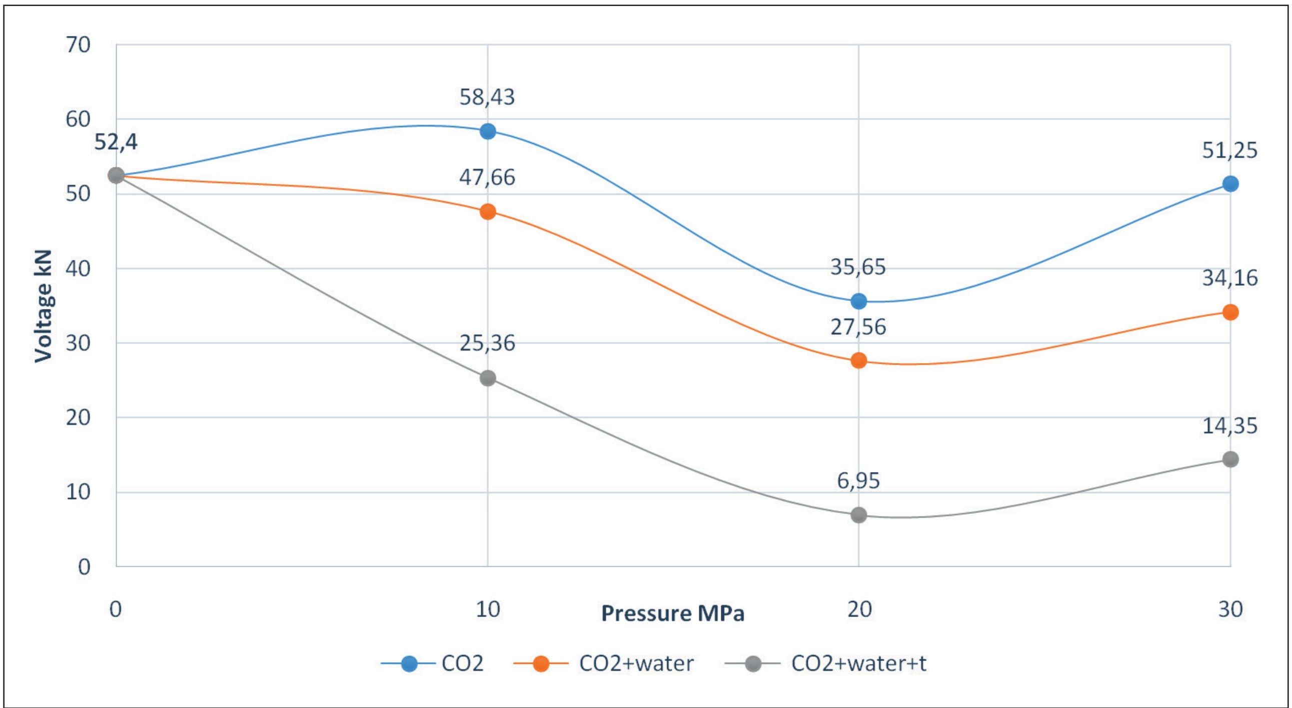

Fig. 3. **Results of compression tests on spicemens**

DISCUSSION

The experimental results showed that CO_2 pressure affects the strength characteristics of concrete mortar. Increasing the pressure up to 10 atmospheres leads to the greatest improvement in strength. However, at pressures of 20 atmospheres and above, the strength characteristics begin to deteriorate. Additionally, it was found that increasing the volume of water added by 5% in mixes 5, 6 and 7 leads to deterioration in strength characteristics. In addition, increasing the mixing time in mixes 8, 9 and 10 also shows a slight decrease in concrete strength. These results suggest that the control of CO_2 pressure, water volume and mixing time are important factors that can affect the strength properties of concrete mortar. Further investigation and optimization of these parameters may lead to a stronger and more stable concrete.

It is important to note that in this study, strength properties were evaluated based on compressive and flexural test results only. For a more complete and accurate analy-

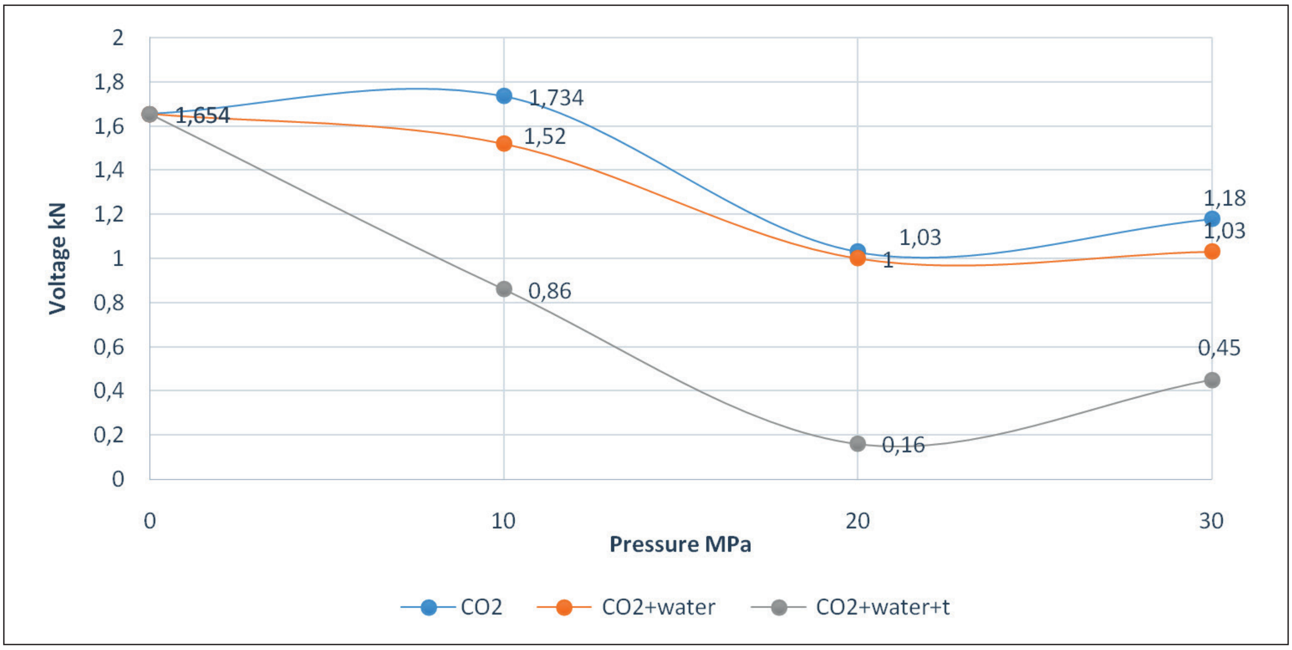

Fig. 4. **Results of bending tests of specimens**

sis, additional studies should be conducted for other types of loads such as tension and delamination, as well as increased pressure, as an increase in strength performance can be seen from Fig. 3 and 4.

In general, the results of this experiment suggest the influence of CO_2 pressure, water volume and mixing time on the strength characteristics of concrete mortar. Further research and optimization of these factors may help to develop more efficient and stronger concrete compositions, thus reducing cement costs for product production.

CONCLUSION

The international community's common goal of reducing greenhouse gas emissions is also contributing to the development of CO_2 capture and storage technologies. The joint action of many countries is aimed at reducing CO_2 emissions by 2050, which makes such innovative approaches in concrete production even more relevant. CO_2 capture and storage in the concrete production process represents a promising and important technology that can reduce the negative environmental impact of this greenhouse gas and achieve more sustainable and eco-friendly construction.

As part of the design and fabrication of the concrete mixer, a structure was developed consisting of a cylinder-shaped container, blades for mixing the concrete mixture, a motor and additional parts. All components were incorporated into drawings that served as the basis for the fabrication of the equipment.

The design and manufacture of concrete is a complex and demanding process that requires adherence to strict requirements, careful monitoring and the use of the right equipment. Optimizing the concrete manufacturing process in accordance with the specified requirements and component calculations results in a quality and reliable product.

During the testing of concrete specimens, the compressive and flexural strength of 110 specimens were measured and evaluated. The results showed that CO_2 pressure and water volume have an influence on the formation of nanoscale structure and strength characteristics of concrete mortar. Increasing the CO_2 pressure up to 10 atmospheres leads to an improvement in strength, but at 20 atmospheres the strength starts to deteriorate. At 30 atmospheres, the strength increases markedly relative to a mix at 20 atmospheres. Increasing the volume of water added by 5% did not show a noticeable increase in strength. Increasing the mixing time also showed no significant improvement in strength.

Concrete carbonization is an effective and modern technology that combines both the current needs and requirements of the concrete industry, allowing to obtain better quality products, saving cement and energy resources, and at the same time combines the utilization of waste from solid fuel combustion, taking a direct part in solving environmental problems of the planet.

The use of CO_2 in concrete production is a promising technology that can not only reduce the carbon footprint of construction materials, but also improve their physical and mechanical properties through the formation of nanoscale structure. Further research and optimization of mixing parameters will make it possible to create stronger and more stable concrete mixtures, which is important for the sustainable development of the construction industry.

REFERENCES

1. Kondratyev V.B. World cement industry. V.B. Kondratyev. Industries and sectors of the global economy: features and trends of development. Foundation for Historical Perspective Center for Research and Analysis. – Moscow : International Relations Publishing House; 2015 185-202.
2. Kline D. Designing a cement plant of the future. Part II. D. Kline. Cement and its applications. 2019; 1: 48-53.
3. Monteiro, P.J.M. Towards sustainable concrete. P.J.M. Monteiro, S.A. Miller, A. Horvath. Nature Mater. 2017;16 (7):698-699.
4. Gartner E.M. A physico-chemical basis for novel cementitious binders. E.M. Gartner, D.E. Macphee. Cement and Concrete Research. 2011; 41(7): 736-749.
5. Cement technology roadmap [Electronic resource]. Mode of access: https://www.wbcsd.org/Sector-Projects/Cement-Sustainability-Initiative/News/Cement-technology-roadmap-shows-how-the-path-to-achieve-CO2-reductions-up-to-24-by-2050. Date of access: 21.01.2024.
6. Evans L. Environmental rating of cement. L. Evans, M. Mutter. Cement and its application. 2019; 4: 24-27.
7. Meyer V. Properties of Solidia Cement and Concrete. V. Meyer, S. Sahu, A. Dunster. Proceedings of the 1st International Conference on Innovation in Lowcarbon Cement & Concrete Technology London, UK; 2019. 24-26.
8. 1st International Conference on Innovation in Low Carbon Cement and Concrete Technology. R. Mangabhai [et al]; 2019. 103
9. Boden T. Global, Regional, and National Fossil-Fuel CO2 Emissions (1751 - 2014) (V. 2017). T. Boden, R. Andres, G. Marland. 2017.
10. Cement and carbon emissions. L. Barcelo [et al.]. Mater Struct. 2014; 47(6); 1055-1065.
11. Andrew R.M. Global CO_2 emissions from cement production. R.M. Andrew. Earth Syst. Sci. Data. 2018;10(1):195-217.
12. Leber I. Some effects of carbon dioxide on mortars and concrete. I. Leber, F.A. Blakey. Mater. construcc. 2017;7 (079): 39.
13. Shmitko E.I. Chemistry of cement and binding agents. E.I. Shmitko, A.V. Krylov, V.V. Shatalov. Shatalov. Voronezh: Voronezh State University of Architecture and Civil Engineering; 2005. 164
14. Scrivener K.L. Options for the future of cement. K.L. Scrivener. 2014; (88)7:11-21.
15. Neville A.M. Properties of concrete. A.M. Neville. M.: Stroyizdat;1972. 269-271.
16. Katz A. Properties of concrete made with recycled aggregate from partially hydrated old concrete. A. Katz. Cement and Concrete Research. 2003;33(5):703-711.
17. Kosmatka S.H. Design and control of concrete mixtures. S.H. Kosmatka, B. Kerkhoff, W.C. Panarese. – Skokie, Ill: Portland Cement Association 2002. 358.
18. Neville A.M. Concrete technology. A.M. Neville, J.J. Brooks. Harlow: Prentice Hall 2010; 442.
19. Day K.W. Concrete mix design, quality control and specification. K.W. Day. London: E & FN Spon; 1999. 391.
20. Woodson R.D. Concrete structures: protection, repair and rehabilitation. Concrete structures. R.D. Woodson. Amsterdam; Boston: Butterworth-Heinemann; 2009. 255
21. Handbook of concrete engineering. ред. M. Fintel. New York: Van Nostrand Reinhold; 1985. 892
22. Mehta P.K. Concrete: microstructure, properties, and materials. Concrete. P.K. Mehta, P.J.M. Monteiro. – New York: McGraw-Hill Education; 2014. 675.
23. Palley R. Concrete: a seven-thousand-year history. Concrete. R. Palley. New York: The Quantuck Lane Press; 2010. 232.
24. Courland R. Concrete planet: the strange and fascinating story of the world's most common man-made material. Concrete planet. R. Courland. Amherst NY: Prometheus Books; 2011. 396.
25. The new concrete: visual poetry in the 21st century. The new concrete. ред. V. Bean C. McCabe, K. Goldsmith. London: Hayward Publ; 2015. 240.
26. Forty A. Concrete and culture: a material history. Concrete and culture. A. Forty. – London: Reaktion 2012.
27. Collins P. Concrete: the vision of a new architecture. Concrete. P. Collins. – Montréal: McGill-Queen's University Press; 2004. 64.
28. GOST 10180-2012 Concretes. Methods of determination of strength by control samples.

INFORMATION ABOUT THE AUTHORS

Albert A. Zalyatdinov – Cand. Sci. (Eng.), Head of Scientific and Technical Research Center, Almetyevsk State Technological University "Higher School of Oil", Almetyevsk, Russia, zalyatdinovaa@agni-rt.ru, https://orcid.org/0000-0002-8466-9013

Renat U. Kamenov – Cand. Sci. (Eng.), Head of Research Department, Almetyevsk State Technological University "Higher School of Oil", Almetyevsk, Russia, renatkamenov@mail.ru, https://orcid.org/0000-0001-9181-5704

Denis S. Rechenko – Dr. Sci. (Eng.), Associate Professor, Vice-Rector for Scientific Work, Almetyevsk State Technological University "Higher School of Oil", Almetyevsk, Russia, dsrechenko@agni-rt.ru, https://orcid.org/0000-0002-6776-6452

CONTRIBUTION OF THE AUTHORS

Albert A. Zalyatdinov – scientific guidance; final conclusions.

Renat U. Kamenov – conducting the experimental part, final design.

Denis S. Rechenko – research concept; writing the original text.

The authors declare no conflicts of interests.

The article was submitted 12.05.2024; approved after reviewing 03.06.2024; accepted for publication 07.06.2024.