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«Nanotechnologies in Construction» is a peer-reviewed journal.
The main aim of the Journal is to provide information support for the process of invention and practical application of science intensive technologies (mostly nanotechnological products) in construction, communal and housing services, joint areas (industry, power et al.).

The main tasks:
- Providing scientists and specialists from different countries with the opportunity to publish the results of their research and receive information about modern technologies and materials, high-performance equipment in construction, communal and housing services, joint areas (industry, power et al.).
- To provide information support and participate in the events (forums, conferences, symposia, workshops, exhibitions,round tables etc) devoted to nanoindustry and problems of application of nanoindustry in construction and housing and communal services, which are perspective and of great importance.

The Journal has been published since 2009. Frequency: bimonthly.

These are the topics of the papers published in the journal: creation of new functional materials; nanostructured systems strength and penetrability formation theory development; the problems of nanomaterials and nanotechnologies implementation in construction and building materials; diagnostics of building systems nanostructures and nanomaterials; technologies aimed at studying nanomaterial properties; technological principles of nanostructures creation (liquid melts, sol and gel synthesis). The topics may be different, directly or indirectly related to the areas mentioned above.

The journal publishes: original papers; reviews; discussing materials, comments, other information materials.

The language of publication: English; Russian.

The edition's readers and authors are:
- students, lecturers, post-graduates and people working for doctor's degree;
- scientists and specialists of research institutes and nanotechnological centers;
- heads and specialists of the institutions, organizations and factories from the sphere of construction and housing and communal services;
- scientists and specialists of the industries which are adjacent to construction;
- experts of the enterprise-producers manufacturing nanoindustrial output.

EDITORS

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Original article
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Low carbon footprint building materials using industrial waste

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ABSTRACT

Introduction. The possibility of producing construction materials in Vietnam based on man-made waste with a low carbon footprint and capable of absorbing carbon dioxide is being considered in order to achieve zero greenhouse gas emissions by 2050. To date, insufficient attention has been paid to the search for a solution to this problem. **Methods and materials.** Studies were conducted to assess the possibility of obtaining a "green" cement-free concrete material using local industrial and agricultural waste in the form of fly ash and bottom slag from the Green Star incineration plant, alumina sludge, ceramic waste, lime powder and coconut fiber combined with a special activating agent. an alkaline solution. The average density, compressive strength, and water absorption of the developed cement-free concrete were determined on cube samples measuring 100×100×100 mm in accordance with the requirements of current Vietnamese standards. The ability of the resulting concrete to absorb carbon dioxide was evaluated using the developed method by measuring the mass of carbon dioxide absorbed by concrete samples. Results and discussion. The average density of the developed concrete is 1950 kg/m^3; compressive strength at the age of 28 days is 7.5–11.5 MPa; water absorption is 8–10% by weight. The main advantages of using cement-free concrete of the developed composition include reducing the carbon footprint due to the abandonment of the use of Portland cement, the ability of concrete to absorb carbon dioxide and the possibility of recycling high-tonnage man-made waste during its manufacture. **Conclusion.** The results of the conducted research show that the use of the developed cement-free "green" concrete for the manufacture of building products and structures in Vietnam will allow to recycle about 1.1 tons. high-tonnage industrial waste per 1 cubic meter and absorb 10–13 kg of carbon dioxide during operation. This will contribute to the implementation of the planned course for the "green" transformation of Vietnam's economy into a sustainable closed-loop economy.

KEYWORDS: environmental protection, high-tonnage industrial waste, greenhouse gas emissions, carbon footprint reduction, "green" cement-free building materials, fly ash, finely ground bottom slag, slurry waste from alumina production, powdered ceramic waste, lime powder, coconut fiber, activating alkaline solution

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INTRODUCTION

As the urgent environmental problems of our planet become more global and require an immediate search for rational solutions, the construction industry, characterized by high levels of environmental pollution from industrial waste and significant emissions of greenhouse gases into the atmosphere, primarily CO_2, is gradually shifting to the use of environmentally friendly building materials and efficient construction technologies. with a low carbon footprint. A set of effective and economically justified measures will prevent further thinning of the ozone layer, reduce greenhouse gas emissions and stabilize their concentration in the atmosphere [1–10].

The construction sector is the world's largest consumer of raw materials, and the operation of buildings and structures for various purposes is characterized by the highest energy consumption in the world. This has allowed a stable opinion to develop and exist that one of the leading types of human activity leading to global warming and causing drastic climate change on our planet is the currently observed high global construction rate [11, 12].

Reducing greenhouse gas emissions (carbon dioxide, methane, nitrogen oxides, etc.) is currently a serious global global problem that requires effective solutions in all industrialized countries, including the Russian Federation and Vietnam.

The 26th UN Climate Change Conference, held from October 31 to November 12, 2021 in Glasgow (Great Britain) with the participation of 25,000 delegates from 200 countries, including about 120 heads of state, discussed the following three most important and pressing issues facing the world community:

1. Reducing emissions of methane, one of the most harmful greenhouse gases, which significantly contributes to climate warming. As a result of the discussion, more than 100 world leaders signed an agreement to reduce meth emissions by 30% by 2030.

2. The gradual abandonment of the use of coal during the 40s of the XXI century, since it is the most "dirty" source of fossil fuels, as a result of burning which generates and releases into the atmosphere a large amount of greenhouse gases and, first of all, carbon dioxide. More than 40 countries, including Canada, Poland, Ukraine, the Republic of Korea, Indonesia and Vietnam, have committed themselves to completely abandon coal-fired power within the specified time frame.

3. Conservation of forests on our planet, as forests play a critical role in the carbon cycle by absorbing carbon dioxide from the atmosphere. The leaders of more than 100 countries, which account for almost 85% of the world's forests, have promised to stop deforestation by 2030.

Speaking at the conference, Prime Minister of the Socialist Republic of Vietnam Pham Minh Chin made a commitment on behalf of his country to strive to achieve zero greenhouse gas emissions by 2050. The countries are the world's main consumers of coal, the Russian Federation and China have committed to achieving carbon neutrality by 2060, and India, also one of its main consumers, by 2070. In this regard, the intensification of scientific research aimed at the wider use of renewable energy sources, which include hydropower, solar energy, wind energy, geothermal energy, marine tidal energy and the use of biomass, as well as the development and implementation of low-carbon technologies in production processes, especially in industrialized countries. – The main developers of mineral deposits and consumers of fossil fuels, in particular coal and oil, and for this reason the main sources of carbon dioxide, methane and other greenhouse gases, are becoming very important areas of scientific research that can make an important contribution to the process of deflation of greenhouse gas emissions, primarily carbon dioxide into the environment (Figure 1).

Fig. 1. The annual global volume of carbon dioxide emissions into the environment is extremely high

In the context of increasing global environmental pollution caused by industrial emissions, developed countries are actively exploring various strategies to reduce them and are looking for effective ways to bury carbon dioxide in geological layers on land and under the ocean floor.

For example, the technology implemented in Japan for carbon dioxide capture at energy sector enterprises and its subsequent burial in the voids of geological layers formed as a result of the depletion of oil and natural gas deposits, the functioning scheme of which is shown in Figure 2, is one of the modern "green" technologies, the use of which potential will contribute to achieving the goal of carbon neutrality [13]. However, such burial of carbon dioxide in geological layers on land and in the coastal oceanic zone also contains a potential risk of leakage and air pollution as a result of possible fracturing of the layers due to earthquakes and man-made disasters.

Typically, concretes and mortars are made using four main raw materials: cement, aggregates obtained from natural rocks or man-made waste, water, and various additives. At the same time, the production of one cubic meter of concrete, with an annual global output of 9 billion tons, leads to emissions of about 250 kg of carbon dioxide into the environment [14]. Portland cement is the most common binder used for the production of concrete and mortar, and its annual global production is 4 billion tons. However, the production of one ton of Portland cement clinker releases about 0.8 tons of CO_2 into the environment and cement accounts for 8% of the world's annual carbon dioxide emissions [15]. Therefore, measures to reduce carbon dioxide and other greenhouse gas emissions from the production of building materials are important. To achieve this goal, methods such as changing the main ingredients and reducing the cement content in the raw material composition can be used by using finely ground multi-tonnage man-made waste in the form of fuel and metallurgical ashes and slags, as well as waste from the chemical industry, for example,

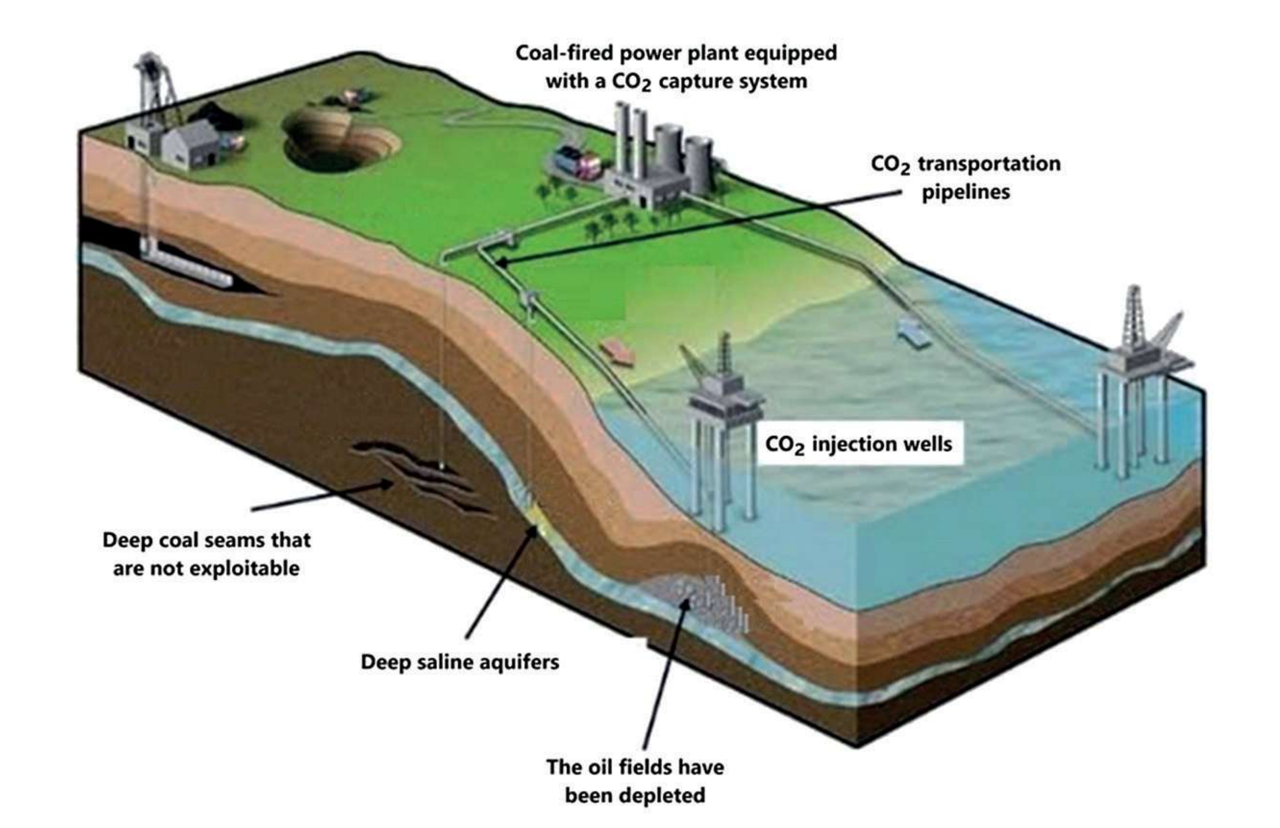

Fig. 2. Burial of carbon dioxide in Japan in the voids of geological layers [13]

electrothermophosphoric slags with a cementing effect, which are usually used as activators of binding properties alkaline solutions.

One example of the search for rational ways to dispose of high-tonnage industrial waste is the research currently being conducted jointly by the National Research University MGSU and the Institute of Building Physics of the Russian Academy of Natural Sciences to develop a technology for the production of exterior wall blocks based on carbonized steel-slag mixtures for civil engineering.

The problem of improving the environment through the rational use of high-tonnage industrial waste is very acute all over the world. For example, in the Russian Federation today, only ash and slag waste from energy complex enterprises, the annual volume of which exceeds 25 million tons, covers an area of more than 20 thousand hectares [16].

According to a report by the Ministry of Industry and Trade of Vietnam, there are currently 33 coal-fired thermal power plants in the country, emitting up to 23–25 million tons of ash and slag per year, which require landfills with a total area of about 1,000 hectares. This negatively affects the environment and causes pollution of marine and river waters. For example, the thermal power plant in the Vung Ang Industrial Park, located in the central part of Vietnam, began operating in 2012 and generates approximately 1 million tons annually. various ash and slag wastes, which, in addition to air pollution, also cause serious pollution of seawater, which in 2016 led to the mass death of fish and marine animals in the coastal waters of the South China Sea [17].

In addition, Vietnam has a significant number of metallurgical plants, such as the Thai Nguyen, Ha Tinh, Phu Mi, Hoa Phat and a number of others, which annually produce large amounts of blast furnace slag that pollute the environment. According to some data [18, 19], Vietnam's metallurgical industry produces about 45–55 million tons of slag every year. Therefore, the use of such slags to produce environmentally friendly "green" geopolymer concrete will help to increase the economic efficiency of production and minimize environmental pollution.

"Green" concrete in the broad semantic meaning of the term is concrete that meets at least one of the three criteria:

1. A variety of industrial and household waste is used to produce it.

2. The process of its manufacture does not harm the environment, since it does not require large expenditures of cement, the production of which requires a lot of energy and is accompanied by emissions of carbon dioxide into the atmosphere.

3. It has high performance and is stable throughout its entire life cycle, which is economically advantageous from the standpoint of durability and the duration of possible maintenance-free operation of concrete and reinforced concrete building products and structures, as well as their subsequent disposal.

In a narrower sense, «green» concretes are understood as low-cement concretes or cement-free binders containing, instead of cement clinker, finely dispersed mineral components with a cementing effect, which were obtained by processing high-tonnage waste from industrial plants or from waste processing of natural raw materials, as well as concretes capable of absorbing carbon dioxide from atmospheric air.

Geopolymer concretes are called environmentally friendly cement-free concretes, which include ashes and slags with pozzolanic or hydraulic activity, and slaked lime and sodium or potassium liquid glass are usually used as binders that have an activating effect on ash and slag.

Although industrial waste (fly ash, fuel and blast furnace slag) is used for the production of certain types of building materials in Vietnam, for example, baked bricks, and is also used in road construction as a leveling layer of the roadway, their use is currently very limited and amounts to only about 5-10 million tons. per year [20–22].

Industrial waste, especially fuel ash and slag, is a very serious cause of environmental problems that cause pollution of soil, water and air in all provinces of Vietnam. At the same time, the level of reuse of man-made waste is very limited and amounts to only about 2–5% of their annual amount [18, 19].

Due to the fact that the economy of the Socialist Republic of Vietnam is currently on the rise and is characterized by high rates of development, as well as due to the fact that the country is undergoing intensive processes of industrialization of the national economy, accompanied by an increase in industrial production, there are many thermal coal-fired power plants and metallurgical plants in Vietnam., As a result of which millions of tons of industrial waste are generated annually, therefore, the problem of recycling high-tonnage man-made waste and exploring the possibility of using them as local secondary raw materials for the production of building materials, including concretes for various purposes, is of great economic, environmental and social importance for Vietnam.

The implementation of these measures in Vietnam will contribute to the implementation of the policy adopted by the Communist Party of Vietnam and the Government of the Socialist Republic of Vietnam towards the development of a closed-loop economy and sustainable "green" transformation of industrial production in the country in order to achieve zero emissions of carbon dioxide and other greenhouse gases by 2050 and solve the environmental problem of protecting the environment from pollution by high-tonnage man-made waste through their rational and efficient disposal.

To contribute to the achievement of the global goal set by the Paris Climate Agreement, adopted at the end of the climate conference in December 2015, to limit warming on Earth by no more than 1.5 °C by the end of the 21st century compared to pre-industrial levels [23, 24] and to achieve the declared zero level in Vietnam by 2050. The Green Concrete research group of Hanoi Mining and Geological University is conducting research to produce a "green" cement-free concrete material., using for this purpose such high-tonnage waste from various industries in Vietnam as fly ash and slag from thermal power plants, metallurgical slags, mining and processing industry sludge, ceramic waste, lime powder in combination with a special activating solution. The article presents the results of research conducted in this area to solve the problem.

MATERIALS AND METHODS

Materials. The following raw materials were used:

Fly ash (FA) (Figure 3a), collected directly from the chimney of the Green Star incinerator power plant through a bag filter system [25, 26].

Bottom slag (BS) from the same incinerator power plant: before grinding, with porous and uneven grains, after grinding, in the form of a fine powder (Figure 3b).

The physico-mechanical properties and chemical composition of fly ash and finely ground bottom slag of the Green Star incineration power plant are presented in Tables 1 and 2.

Ceramic powder "TOTO (CP) with a particle size of 0.1–0.5 mm (Figure 4), obtained at the Hanoi TOTO Plumbing Products Plant as a result of crushing defective products and industrial waste, the monthly amount of which reaches almost 20 tons, and used as an inert mineral additive for compacting the structure of cement-free concrete.

White lime powder (LP) (Figure 5), which is slaked lime with a $Ca(OH)_2$ content of more than 90%, particle size from a few microns to 0.15 mm, true density of 2.21 g/cm^3 and partially soluble in water (0.185 g/ml).

Dried and sieved slurry waste (SW) from the Tan Rai alumina production plant with a particle size from 0.14 to 2.5 mm (Figure 6).

Coconut fiber (CF), separated from coconut shells during processing, with an average diameter of about 1.5 mm and a length of 15–20 mm, consisting of 70–90% cellulose (Figure 7).

The activating alkaline solution consisted of a mixture of two aqueous solutions: 10 M solution of sodium hydroxide (Figure 8a) and a solution of two and a half aqueous sodium silicate (Figure 8b) manufactured

Fig. 3. Fly ash and bottom finely ground slag of the Green Star incineration power plant: a – fly ash; b – finely ground bottom slag

Table 1. Physico-mechanical properties of fly ash and finely ground bottom slag

Indicators	Units of measurement	Test results	
		Fly ash	Finely ground bottom slag
Humidity	% mass.	0.5	4.5
True Density	g/см^3	2.35	2.95
Bulk density	kg/m^3	1570	1485
Specific surface area	cm^2/g	2850	3600
Average grain size	microns	7.15	4.39

Table 2. Chemical composition of fly ash and bottom slag

The content of compounds, % mass.	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	CaO	TiO_2	Other components	Lost on ignition
Fly ash	28.2	11.5	16.4	3.7	2.4	28.1	2.1	3.1	4.5
Finely ground bottom slag	54.2	23.0	8.5	2.5	2.1	1.5	0.6	3.4	4.2

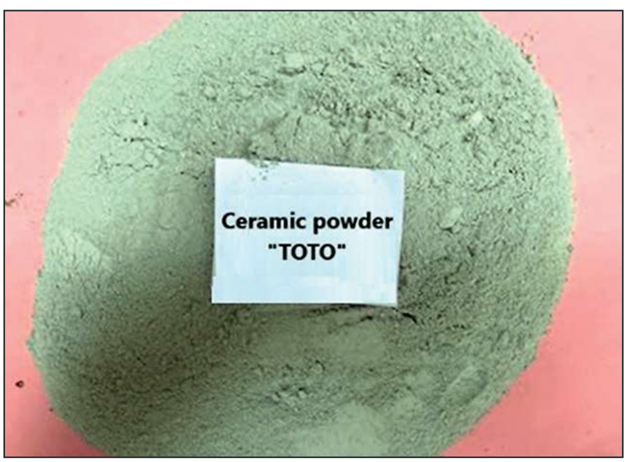

Fig. 4. Ceramic powder "TOTO"

Fig. 5. Lime powder

Fig. 6. Slurry waste from alumina production

Fig. 7. Coconut fiber

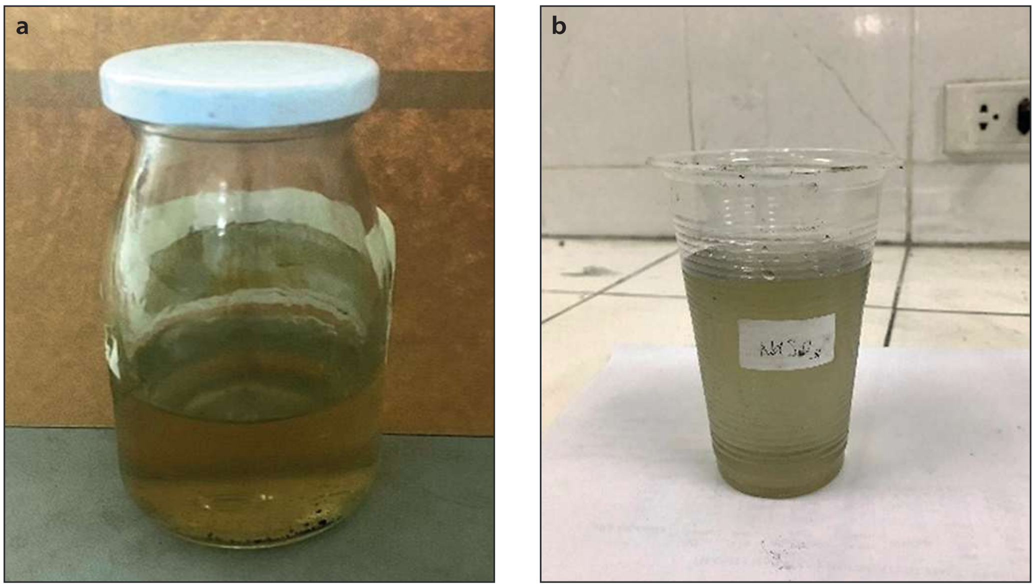

Fig. 8. Activating alkaline solution: a – 10 M sodium hydroxide solution; b – two and a half aqueous sodium silicate solution

by Viet-Nhat with a density of 1.45±0.01 g/cm^3 and 1.55±0.01 g/cm^3, respectively, in the ratio Na_2SiO_3/NaOH = 2.5 [27, 28]. Its percentage composition by weight is NaOH = 12%; Na_2SiO_3 = 30% and water = 58%.

Table 3 shows the chemical composition and physical properties of the sodium silicate solution used.

The sealing water (W) met the requirements of the Vietnamese standard TCVN 4506:2012[1].

Methods. The methodology of the work included:

The absolute volume method was used to determine the composition of the concrete mix for the production of cement-free "green" concrete.

[1] Vietnam Construction Standard TCVN 4506:2012. Water for mixing concrete and mortar. Technical requirements.

Table 3. Chemical composition and physical properties of sodium silicate solution

Chemical formula	$Na_2SiO_3 \cdot 2.5H_2O$
Na_2O	11.8%
SiO_2	29.5%
H_2O	58.7%
Color and appearance	Light yellow gel-like liquid
Color and appearance	1,55 ±0,01 g/cm^3

The experimental studies were conducted in accordance with the current Vietnamese standards:

Fig. 9. Samples-cubes measuring 100×100×100 mm made of developed cement-free "green" concrete

The average density of concrete was deermined on cube samples measuring 100x100x100 mm in accordance with TCVN 3115:2022[2];

The water absorption of concrete samples was determined on cube samples measuring 100×100×100 mm in accordance with TCVN 3113:2022[3] (Figure 9);

The compressive strength of the developed concrete was determined by testing cube samples measuring 100x100x100 mm in accordance with the requirements of TCVN 3118:2022[4] (Figure 10);

– the ability of concrete samples to absorb carbon dioxide was determined by the following method: carbon dioxide from a cylinder was supplied through a flexible hose for 10 minutes to a sealed tank containing concrete samples in the form of multi-hollow bricks (Figure 11).

Fig. 10. Compression testing of concrete samples

The mass of CO_2 absorbed by the concrete sample as a result of its forced carbonation was calculated using the formula:

$$m_{CO_2} = m_2 - m_1,$$

where: m_1 – is the mass of the concrete sample before carbonation, g; m_2 – is the mass of the concrete sample after carbonation is completed, g.

RESULTS

The composition of the concrete mix for the production of cement-free "green" concrete is shown in Table 4.

To assess the ability of the concrete of the developed composition to absorb carbon dioxide, concrete samples with dimensions of 220×110×60 mm were used, corresponding to the dimensions of the standard concrete brick used in Vietnam.5

The following test results were obtained:

- the average density of developed concrete at the age of 28 days is 1950 kg/m^3 (Figure 12);
- the compressive strength of the developed concrete at the age of 28 days is 7.5–11.5 MPa;
- water absorption by weight is 8–10% by weight;
- the mass of one sample brick of developed "green" concrete measuring 220×110×60 mm with six cylindrical voids is 1.5–2.2 kg.

An important feature is the ability of concrete bricks of the developed composition to absorb carbon dioxide during hardening due to the presence of slaked lime in their composition. According to the results obtained, each such brick sample measuring 220×110×60 mm with

[2] Vietnam Construction Standard TCVN 3115:2022. Hardened concrete. Density determination method

[3] Vietnam Construction Standard TCVN 3113:2022. Hardened concrete. Method for determining water absorption

[4] Vietnam Construction Standard TCVN 3118:2022. Hardened concrete. Method for determining compressive strength

Fig. 11. Carbonation of samples of developed concrete during their hardening

Table 4. The composition of 1 m^3 of concrete mix for the production of cement-free "green" concrete

Raw materials	FA	BS	CP	LP	SW	CF	NaOH	$Na_2SiO_3 \cdot 2.5H_2O$	W	LOI
Weight, kg	360	280	100	100	250	50	160	518	150	1968

Fig. 12. Determination of the average density of developed concrete at the age of 28 days

six voids has the ability to absorb about 15–20 g of CO_2 (Figure 13).

In addition, about 1.5 kg of industrial waste is used in the manufacture of one such sample and absolutely no natural materials are used. Thus, as a result of obtaining 1 m^3 of concrete of the developed composition, about 1.1 tons of high-tonnage industrial waste can be disposed of in the form of fly ash and bottom slags from thermal power plants, metallurgical slags, powdered ceramic waste, as well as sludge from mining and processing enterprises. Therefore, the implementation of the results of this study will contribute to the development of a sustainable "green" economy in Vietnam and minimize the risk of environmental pollution from greenhouse gas emissions and high-tonnage industrial waste.

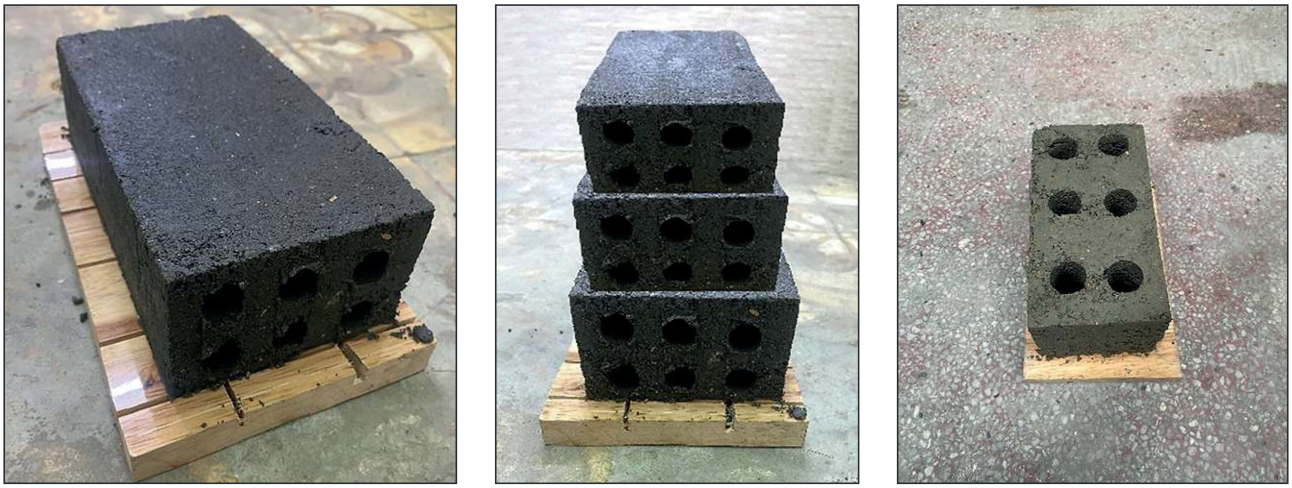

Fig. 13. Samples of developed concrete in the form of standard-sized bricks with cavities capable of absorbing carbon dioxide

The main advantages of the developed cement-free concrete, capable of absorbing carbon dioxide, include:

- Reduction of greenhouse gas emissions: it is estimated that each 1 m^3 of developed concrete is capable of absorbing about 10–13 kg of CO_2 emissions, thereby improving air quality;
- conservation of natural resources through the use of high-tonnage industrial waste and the abandonment of the use of Portland cement, the production of which requires natural raw materials and which is accompanied by significant carbon dioxide emissions;
- realization of the possibility of protecting the environment from pollution by high-tonnage industrial waste as a result of their use as the main raw material for the production of developed "green" concrete, which contributes to the development of a closed-cycle economy.

CONCLUSION

As a result of the analysis of the current state and future prospects for the development of low-carbon construction materials in Vietnam, the following conclusions can be drawn:

1. The Green Concrete Research Group of Hanoi Mining and Geological University hopes that the results of the research conducted aimed at involving high-tonnage industrial waste in the production of building materials in Vietnam can become a breakthrough solution for obtaining materials with a low carbon footprint, with the required performance properties, high consumer value and low cost. The production of such materials will contribute to the conservation of non-renewable natural resources and will have a beneficial effect in the field of environmental protection from pollution, since obtaining 1 m^3 of cement-free "green" concrete will allow the disposal of about 1.1 tons of high-tonnage industrial waste. Thus, the results of the conducted research will contribute to the implementation in Vietnam of the planned policy course for the "green" transformation of the economy into a sustainable closed-loop economy.

2. It has been established that 1 m3 of developed cement-free "green" concrete has the ability to absorb 10–13 kg of carbon dioxide. This will contribute to achieving the stated goal of achieving zero greenhouse gas emissions in Vietnam by 2050, as promised by the Prime Minister of the Socialist Republic of Vietnam at the 26th UN Climate Change Conference.

3. However, there are currently a large number of obstacles preventing the introduction of environmentally friendly, low-carbon footprint building materials into real construction projects in Vietnam. Their elimination requires further more comprehensive scientific research.

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ADDITIONAL INFORMATION

The authors declare that generative artificial intelligence technologies and technologies based on artificial intelligence were not used in the preparation of the article.

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Lam V. Tang – research concept, validation, formal analysis, resources, supervision, project administration, fundraising.

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