DOI: 10.25140/2411-5363-2024-2(36)-15-30
UDC 691.237:620.193

Maksym Bolotov[1], Hennady Bolotov[2], Iryna Prybytko[3], Mykola Korzachenko[4]

[1]PhD in Technical Sciences, Associate Professor, Associate Professor of Department of Welding Technologies and Construction
Chernihiv Polytechnic National University (Chernihiv, Ukraine)
E-mail: bolotovmg@gmail.com. **ORCID**: https://orcid.org/0000-0002-0915-4132
Scopus: 57190377278. **Researcher ID:** H-4183-2014

[2]Doctor in Technical Sciences, Doctor, Doctor of Department of welding technologies and Construction
Chernihiv Polytechnic National University (Chernihiv, Ukraine)
E-mail: bolotovgp@mail.ua. **ORCID**: https://orcid.org/0000-0003-0305-2917
Researcher ID: H-5304-2014. **Scopus:** 6506157907

[3]PhD in Technical Sciences, Associate Professor, Associate Professor of Department of welding Technologies and Constructions
Chernihiv Polytechnic National University (Chernihiv, Ukraine)
E-mail: prybytko_ira@ukr.net. **Researcher ID**: F-7325-2014
ORCID: https://orcid.org/0000-0002-8550-8318. **Scopus:** 57217181853
ORCID: https://orcid.org/0000-0003-0305-2917. **Scopus:** 6506157907

[4]PhD in Technical Sciences, Associate Professor, Associate Professor of Department of welding Technologies and Constructions
Chernihiv Polytechnic National University (Chernihiv, Ukraine)
E-mail: korzachenko_87@meta.ua. **ORCID**: https://orcid.org/0000-0002-5674-8662. **Researcher ID:** F-5177-2016

SUSTAINABLE PRACTICES OF CONCRETE MANUFACTURING

Construction using eco-friendly, recycled or bio-materials sustainably is the way to reduce carbon footprint, natural resource depletion, which is vital for our well-being and further development of humanity. It is well known, that reinforced concrete is one of the most preferable construction materials in the many areas of application. At the same time, concrete manufacturing, Portland cement specifically, turned out to be the most polluting process with enormous amounts of CO_2 emission resulting in some environmental issues known as global warming or the greenhouse effect. To go green and minimize the issues mentioned above, the shift of our habitual concrete manufacturing practices toward more sustainable and ecologically friendly is required.

The efforts of scientists all over the World to reduce CO_2 emission and resource consumption while concrete production resulted in bio- and green concrete appearance. The idea of bio-concrete (or self-healing concrete) relies on the biomimicry concept of cement manufacturing through the adaptation of natural elements, models, patterns and systems for human problem solvation. Thus, the potential of the surrounding microbiome (germs and microbes) for concrete self-healing, particularly, for $CaCO_3$ reproduction when cracking starts to accrue was established.

The idea of green concrete is quite different and mainly relies on the substitution of conventional portlandite with other supplementary cementitious material such as ground granulated blast furnace slag (GGBFS), fly ash (FA), or pozzolanic one known as silica fume (SF) as well as metakaolin (MK).

This paper provides a comprehensive overview of impact of sustainable construction materials for concrete production on its mechanical properties. It was shown, that the usage of GGBFS, FA, SF or MK incorporation as a partial replacement of ordinary Portland cement while concrete production improves its mechanical properties, particularly, compressive, tensile and flexural strength.

Key words: *Sustainability; concrete manufacturing; biomimicry; bio-concrete; self-healing concrete; green concrete.*
Fig.: 7. Table: 8. References: 45.

Urgency of the research. Currently, the consumption of concrete takes second place after water all over the globe. This is mainly due to the fact that concrete is the most versatile manmade construction material and its application is truly widespread. However, because of its outstanding mechanical properties, particularly compressive strength and durability, concrete is extensively used as a main building material for now and its consumption is quickly ramping up [1; 2].

Target setting. As far as it`s known the vast majority of modern concrete is mainly made of Portland cement as a crucial part of it, the production of which is related to the limestone baking at incredibly high temperatures [3]. The latter inevitably leads to a significant amount of CO_2 emission to the atmosphere creating an environmental warning known as global warming or greenhouse effect [4]. It is also known that almost 10 % of the total CO_2 emissions worldwide are associated with the production of concrete, as the main building material. On top of that, excessive concrete consumption has released another vital issue related to the resource depletion the water, limestone and clay in particular [5].

Actual scientific researches and issues analysis. According to [6] the Portland cement production process is as energy-intensive as the aluminum or steel manufacturing. The intention to go green and minimize natural resource consumption requires shifting our habitual concrete manufacturing practices toward the more sustainable and ecologically friendly. For these reasons, the attention of researchers all over the world is drawn to the search for innovative ways, technologies and materials for concrete production that provide a low carbon footprint, and significantly reduce energy and resource usage or waste, which is generating pollution of our ecosystem.

The research objective. The aim of this paper is to provide a deeper understanding of the peculiarities of the newest materials and practices as modern trends of concrete manufacturing in a sustainable manner. In this case, the current paper is more of an overview.

The statement of basic materials. It is well known that along with the ecological problem related to the high amount of CO_2 emission while manufacturing, reinforced concrete backfires from the environment, in particular, chlorides attack or CO_2 itself [7, 8]. This is mainly because of the penetration of aggressive chemicals such as chlorides, sulfates let alone carbon dioxide into the pores of the concrete cement stone. This leads to a dramatic reduction in pH from ~12 to the level of ~7 – 9 inside the porous moisture of a cement stone, initiating the corrosion processes in the metal rebar [9, 10]. With the corrosion exposure on reinforcement rebar, the joining of which is typically made by arc welding, the different defects of the joint`s inhomogeneity start to occur [11, 12]. The latter results in the cracking and consequent reduction in the bear capacity of the concrete structure, thus its durability [13].

For now, in order to prevent such a detrimental environmental impact on concrete by extending its lifespan along with the reduction of pollution emission during Portland cement production there are a number of highly engineered sustainable cementitious composite materials have been invented. Bio- or self-healing concrete, green concrete and ultra-high performance concrete (UHPC) should be mentioned among them.

Bio-Concrete. The search for solutions to environmental issues as well as the intention of increasing the lifespan of concrete structures forced engineers to look up to nature. This became the impetus for a new modern trend in the field of engineering, which was called biomimicry, which adopted elements of natural models, patterns and systems for regenerative solutions related to sustainable development, particularly in the construction sector [14, 15].

Biomimicry in construction, first of all, is aimed to reduce CO_2 emissions, minimize resource consumption by using recycled, bio-, or eco-materials and deep implementation of construction into nature, thereby creating a non-toxic and eco-friendly architectural environment [16].

The concept of biomimicry is not new enough, but the idea of bio-concrete as an integral part of sustainable construction refers to the early 2010s. The main idea of biomimicry relies on the fact that the surrounding microbiome such as germs and microbes forcing a fight for survival in a constantly changing and extremely harsh environment have been able to adjust to it. Thus, it has been suggested that these microorganisms, who have overcome natural selection, will be able to solve of human problems related to the sustainability in construction in a long run [17].

Bio-concrete fully corresponds to this concept, as a self-healing system. Similarly to the human organism`s natural repair system known as a vegetative one, which reacts to the appearance of tears or fractures by initiating certain chemical signals, followed by the delivery of regenerative biological agents to the site of injury. In terms of concrete healing, as a crack sealant agents there are the bacterial cultures that partake in limestone formation ($CaCO_3$) can be used. According to [18], such bacteria can be cyanobacteria, purple bacteria and methanogenic archaea that have been adapted over time and freely exist in the alkaline environment of the porous moisture of cement stone. The authors of [19] have noted, that the processes of concrete self-healing can be successful enough only in a humid environment where bacteria exists peacefully.

Since, as is known, Portland cement is mainly made up of calcium silicates, namely: Alite ($3CaO \cdot SiO_2$) ⍰ 40 ⍰ 65% and Belite ($2CaO \cdot SiO_2$) ⍰ 15 ⍰ 40%, which are products of limestone and clay processing. In the process of water saturation of cement stone from the environment, its hydration takes place. As a result, calcium hydroxide $Ca(OH)_2$ is formed, which is usually called a pore liquid or moisture:

$$3CaO\cdot SiO_2 + 2H_2O = 2CaO\cdot SiO_2\cdot H_2O\downarrow + Ca(OH)_2. \quad (1)$$

In turn, the porous moisture $Ca(OH)_2$ reacting with atmospheric CO2 results in a calcium carbonate ($CaCO_3$) formation with excess water [20]:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O. \quad (2)$$

Thus, the mechanism of concrete restoration using bacteria is carried out mainly through the transformation of CO_2 to carbonate. The reaction of concrete healing, in this case, can be explained as follows [19]:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O, \quad (3)$$

$$CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O, \quad (4)$$

$$Ca^{2+} + 2HCO_3^- \leftrightarrow CaCO_3 + CO_2 + H_2O. \quad (5)$$

Here oxygen and carbon dioxide entering the cement stone from the environment are transformed into methane (CH_4) as a result of methanogenesis, as a by-product of the archaea`s activity. Sulfates (SO_4^{2-}), that also penetrate the capillaries of cement stone from the outside, serve as a kind of chemical pulses for the activation of regenerative agents, oxidizing methane to form anaerobic bicarbonates (HCO_3, $2HCO_3$), which, in turn, reacting with calcium ions (Ca^{2+}), restores of limestone. This is exactly the way of autogenous healing of concrete. However, it should be understood that the processes of a concrete self-healing are not well-developed for now and it's mainly of a presumption.

Green concrete. Another way of environmental menace reduction while concrete production is the use of ecologically oriented materials and processes instead of conventional ones. The term "green concrete" is relatively new and mostly refers to the second half of the 2010s. The process of green concrete manufacturing is closely intertwined with the use of recycled or natural coarse aggregates as well as alternative binders are designed to reduce the carbon footprint downsizing natural resources consumption [21; 22].

The comprehensive literature overview allowed us to differentiate the next categories of environmentally enhanced materials for green concrete production: 1) Concrete with the ground granulated blast furnace slag (GGBFS); 2) Concrete with fly ash (FA); 3) Concrete with the silica fume (SF); 4) Concrete with the metakaolin (MK).

As far as it's known the slag is the side-product of cast iron smelting in a blast furnace or converters [23, 24]. It possesses incredible binding properties that make the slag so attractive as an active supplementary cementitious material for construction in a sustainable manner.

The impact of GGBFS incorporation in a cement mixture at a different percentage on the compressive strength of concrete was comprehensively studied at [25].

The studies were carried out after 7, 28 and 90 days of concrete aging with the complete number of tests of 65. The obtained results were compared with the similar, obtained for a 100% Portland cement mixture. The results of concrete compressive strength depending on w/b (water/binder) ratio for 10, 20, 40, 55, 60 and 80% of the slag replacement level are given in Fig. 1.

Analyzing the obtained results the authors have noticed that concrete compressive strength with the 10% of slag replacement after 7 days of aging was quite lower rather than conventional concrete mixture with 100% of Portland cement. The value of concrete compressive strength goes up with the increase in GGBFS replacement up to 60% for 28 and 90 days of aging exceeding such a value for conventional concrete.

The authors have also admitted the reduction in water consumption in a w/b ratio as the GGBFS percentage increases in a concrete mixture. The authors emphasize that the mixture with 60% of slag is an optimal one. Such results are in close agreement with those, obtained in [26].

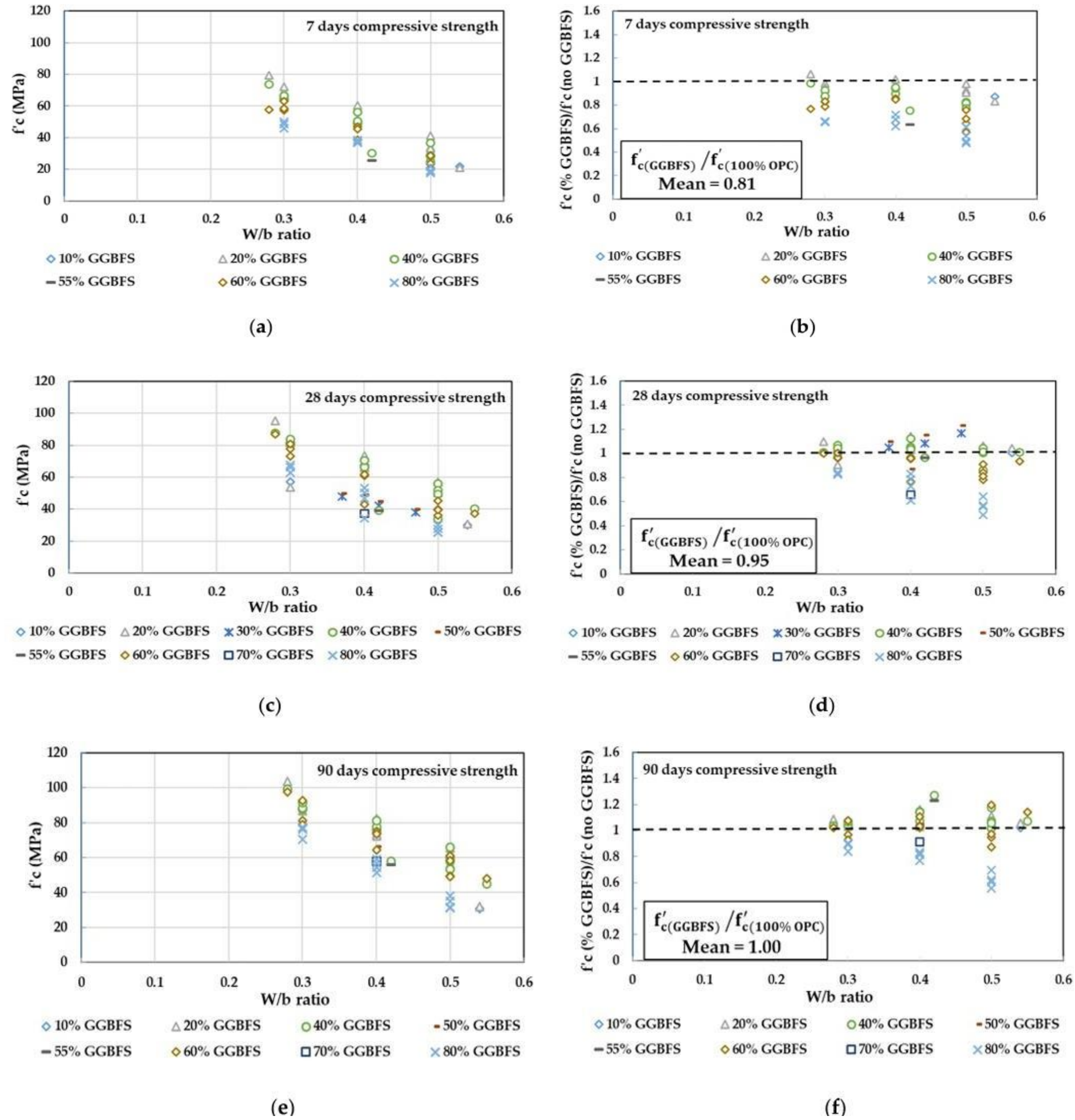

Fig. 1. GGBFS cement replaced concrete compressive strength depending on W/b ratio at: 7 days (a); 28 days (c); 90 days (e) of aging. Compressive strength of GGBFS/100% Portland cement ratio at 7 days (b); 28 days (d); 90 days (f) of aging [25]

On the other hand, the usage of pulverized fuel ash, mostly known as fly ash (FA), for Portland cement replacement while concrete manufacturing has also been known and widely applied. However, the long-term industrial application of concrete with FA replacement has shown the necessity of strict limitation of FA especially at higher replacement levels. In this case, as was shown in [27], the optimal percentage of FA in concrete is mainly revolving around 15 – 20%. In [28] was also shown that a high percentage of FA replacement in a concrete mixture (beyond 30%) leads to retardation of strength development and hence, reduced early concrete strength. In [29] it was also noticed that an excessive amount of FA (about 50 – 70%) in concrete mixture inevitably leads to compressive strength reduction compared to the reference one.

The authors of [28] have also revealed that the incorporation of FA in concrete reduces its permeability, thus increasing compressive strength. The four concrete mixes with 0% (neat concrete), 15%, 30% and 45% of FA with the same W/b ratio of 0.6 were studied. The coarse (1195 kg/m3) as well as fine aggregates (565 kg/m3) were used. The composition of concrete mixtures is given in Table 1.

Table 1 – The composition of concrete mixtures [28]

Mix	W/B	PFA %	Mix Proportions (in kg/m^3)				
			OPC	PFA	Water	CA	FA
PFA0	0.6	0	383	-	230	1195	562
PFA15	0.6	15	325.5	57.5	230	1195	562
PFA30	0.6	30	268	115	230	1195	562
PFA45	0.6	45	210.6	172.4	230	1195	562

Compressive strength tests were conducted after 3, 7, 28, 59 and 91 days of exposure according to BS EN 12390-3:2009. The results of compressive strength tests at specified ages are shown in Fig. 2 and Table 2.

Table 2 – The results of concrete compressive strength tests [28]

Mix	Age (in days)				
	3	7	28	59	91
PFA0	20.96	27.69	36.99	42.67	34.89
PFA15	16.00	21.69	32.25	43.41	38.65
PFA30	14.42	17.94	32.60	36.50	41.94
PFA45	8.53	11.20	21.27	24.54	35.95

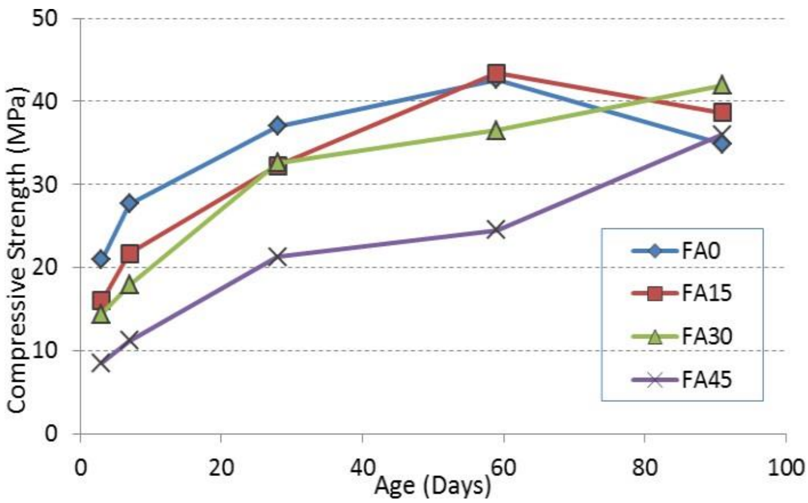

Fig. 2. Compressive strength development at different PFA replacement values [28]

Analyzing the obtained results, the authors have noticed the highest compressive strength about 20.96 MPa and 27.69 MPa for 100% Portland cement mix (PFA0) at the early age of 3 and 7 days, accordingly. This is mainly because of the higher hydration rate of pure cement at an early age. Meanwhile, the lowest values of a concrete compressive strength in the early days of aging about 8.53 MPa and 11.20 MPa for the PFA45 mix with the highest FA replacement were observed.

However, adding FA in a cement mixture of about 15 to 30% seems beneficial in the long run. Thus, in accordance with the results, the PFA15 and PFA30 concrete mixtures provide the highest level of concrete strength about 43.41 MPa for 59 days and 41.94 MPa for 91 days of aging accordingly. The authors have concluded that the incorporation of FA with the value of 15 – 30% replacement into a concrete mixture allows for reducing its permeability improving later age compressive strength.

The long-term industrial practices have set another effective way of concrete mechanical properties and dynamic behavior enhancement replacing ordinary Portland cement (OPC) with the pozzolans [30]. In [31, 32] it was shown that the use of silica fume (SF) as a substitutional material in concrete manufacturing leads to the increase of its compressive strength and flexural strength improving corrosion behavior and durability of concrete structure as a whole. On top of that, the good rheological properties of SF because of the microscopic size of its particles (about 0.1 to 0.5 μm in diameter) provide SF with an excellent filling effect that can easily fill the gaps in the cement past reducing its pore size and capillaries, contributing to a more dense and homogeneous concrete [33].

Considering the mentioned above, the practice of OPC replacement with the SF for concrete mechanical properties improvement has sparked an enormous interest of engineers and researchers all over the globe.

The impact of SF replacement on the mechanical properties of concrete, specifically its compressive and tensile strength was studied in [34]. In their research, the samples of 75 mm in diameter and 150 mm in height containing different percentages of SF, as given in Table 3, were subjected to quasi-static and dynamic loading tests. For this purpose, the MTS testing machine is equipped with a computing system, speed-regulating system as well deceleration system. The external view of specimens before testing is given in Fig. 3.

Table 3 – Mix proportion of concrete with different SF levels by weight [34]

Mass of Concrete Ingredients (kg/m^3)					
Items	**Water**	**Cement**	**SF**	**Fine Aggregate**	**Aggregate**
I	210.00	389.00	-	614.00	1141.00
II	210.00	340.80	48.20	614.00	1141.00
III	210.00	326.28	62.72	614.00	1141.00

Fig. 3. Images of the series I, II, III (according to Table 3) concrete for quasi-static and dynamic tests [34]

The experimentally obtained results the authors have shown in the form of Table 4.

Table 4 – The compressive strength and the tensile strength of tested concrete under quasi-static loading [34]

Concrete Series	Strength (MPa)	
	Compressive Strength	Tensile Strength
I	19.73	1.78
II	21.54	2.03
III	23.03	2.32

Analyzing the obtained results authors have admitted that due to the high concrete strength with the SF replacement in it, some difficulties associated with the distraction of these samples compared to the low-strength concrete containing 100% of OPC`s were observed. Thus, in their studies, the samples containing 48.2 kg/m3 (Series II) and 62.75 kg/m3 (Series III) of SF show a greater value of compressive and tensile strength of 21.54 MPa and 2.03 MPa for samples Series II and about 23.03 MPa and 2.32 MPa for samples Series III accordingly. At the same time, such a value for 100% OPC concrete doesn`t exceed 19.73 and 1.78 MPa accordingly.

Nevertheless, the prevalent majority of researchers emphasize that the percentage of SF in concrete should be strictly limited to a range of 15 – 25%, otherwise, the excessive SF incorporation leads to a dramatic decrease in concrete compressive and tensile strength [35-37].

The authors of [38] investigating of SF replacement in reinforced concrete columns have also admitted that the total strain of concrete columns goes down dramatically with an increase in SF replacement level. In their research, the amount of SF replacement was 0% (as OPC), 11%, 13%, 15% and 17%. The samples in the form of a column sized 150×150×700 mm were prepared according to the IS 10262:2009. The mechanical tests were carried out after 28 days of aging. The water/binder (cement) ratio in the concrete mixtures was set at 0.42 and 0.50. The mixture design details are presented in Table 5.

Table 5 – The details of a concrete mixture [38]

W/C – 0.42				W/C – 0.50			
Water	Cement	Fine aggregates	Coarse aggregates	Water	Cement	Fine aggregates	Coarse aggregates
197	469.04	669.04	1106.54	197	394	710.7	1123.92
0.42	1.00	1.42	2.35	0.50	1	1.80	2.85

The series of tests depending on a different content of SF replacement in a concrete at the water/cement ratio of 0.42 and 0.50 are given in Table 6.

Table 6 – The number of tests depending on a SF replacement percentage [38]

Semple`s N^o	W/C ratio	% of SF
CU1	0.42	0
CU2		11
CU3		13
CU4		15
CU5		17
CU6	0.50	0
CU7		11
CU8		13
CU9		15
CU10		17

The results of compressive strength tests for all specimens are given in Table 7 and Fig. 4.

Table 7 –The results of compressive strength tests of concrete columns incorporated with different amounts of SF [38]

W/C ratio	Series	SF, %	Load, kN	Comp. strength, N/mm²	W/C ratio	Series	SF, %	Load, kN	Comp. strength, N/mm²
0.42	C1	0	406.9	18.07	0.50	C6	0	418.74	18.61
	C2	11	495.20	22.01		C7	11	592.57	26.33
	C3	13	744.26	33.07		C8	13	799.19	35.52
	C4	15	550.48	24.44		C9	15	653.95	29.06
	C5	17	452.53	20.11		C10	17	615.95	27.37

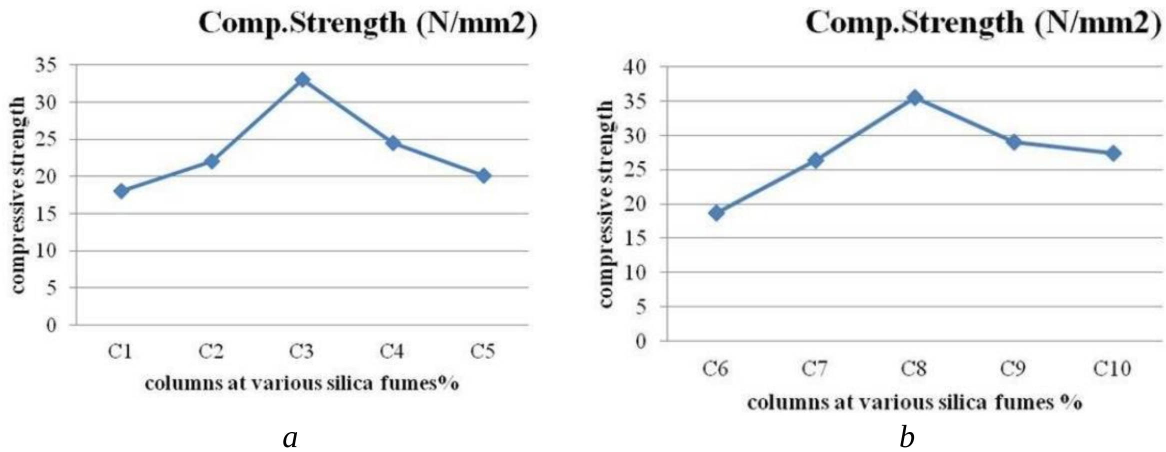

Fig. 4. The results of compressive strength tests of concrete columns with the different percentages of SF replacement for W/C ratio 0.42 (a) and 0.50 (b) [38]

The obtained results have shown that samples with 100% of OPC (without SF incorporation) series C1 and C6 failed at a lower load level of 406.9 kN and 418.74 kN accordingly. Thus, they possess a lower level of compressive strength about 18.07 N/mm² for C1 and 18.61 N/mm² for C6 respectively. The external view of column without SF under the compressive load shown in Fig. 5.

Fig. 5. Failure pattern of a concrete column with a 100% of OPC [38]

Instead, increasing the SF replacement in a concrete mixture up to 13% leads to a spike of concrete compressive strength up to 33.07 N/mm2 and 35.52 N/mm2 for C3 and C8 respectively. With the further increasing the SF percentage in concrete up to 17% the authors have observed a certain decrease in compressive strength to a level of 20.11 N/mm2 and 27.37 N/mm2 for C5 and C10 accordingly.

Thus, the authors have concluded that the concrete mix with 13% silica fumes possesses a higher compressive strength compared to the other concrete mixes with or without SF.

Metakaolin (MK) is another alternative binder, that found a widespread application in a partial cement replacement. It is held as a more reactive one compared to the FA or SF that is made MK more preferable binder material, especially in hostile chlorides marine areas [39].

Unlike GGBFS, FA and SF, metakaolin is produced mainly via the calcination (dehydration) of kaolin clay at high temperatures ranging from 650 °C up to 800 °C [40]. The reaction of kaolin clay calcination looks as follows [40]:

$$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O \rightarrow Al_2O_3 \cdot 2SiO_2 + H_2O, \quad (6)$$

Because of the endothermic kind of reaction of kaolin clay dehydration, an amorphous aluminosilicate called metakaolin has been released. Normally MK is a white to light grey colored powder with an average particle size of about 1 – 5 µm that is far less than an OPC`s particle size measuring about 10 µm [41].

Numerous studies have shown that the use of MK as a supplementary cementitious material while concrete manufacturing provides better mechanical properties and corrosion behavior improving concrete resistance to aggressive environments, in particular, to the chlorides attack [42].

In work [43], the investigation of the mechanical performance of metakaolin-based concrete, the authors have stated, that 10% MK replacement in concrete is the best way of its strength development compared to the concrete with SF replacement. Such a result is in close agreement with results, obtained in [39]. In their tests, concrete samples containing 0%, 5%, 10%, 15% and 20% of MK replacement were examined. Detailed information about testing concrete mixtures is given in Table 8.

Table 8 – Concrete mix proportions used for the experimental investigations [39]

Mix	w/b	Water (l)	Binder (kg)		Stone (kg)	Sand (kg)
			OPC	MK		
0% MK	0.54	19	35	0	101	59
5% MK	0.54	19	33	1.8	101	58
10% MK	0.57	20.5	32	4	101	60
15% MK	0.58	20.5	30	5	101	58
20% MK	0.61	21.5	28	7	101	67

The concrete samples in the form of cubes measuring 150×150×150 mm and beams of 150×150×500 mm were subjected to mechanical tests to determine their compressive and flexural strength. The investigation was carried out after 7, 28 and 56 days of aging. The results of mechanical tests have been graphically represented in Fig. 6 and Fig.7.

The experimentally obtained results have shown that MK`s incorporated concrete possesses a higher compressive and flexural strength compared to the ordinary one. The authors have attributed this to a good pozzolanic reaction of MK with Ca(OH)2 resulting in the formation of calcium silica hydrate (C-S-H) gel. The latter provides an excellent filling effect creating strong bonds with the cement particles [44]. Increasing in the exposure from 7 up to 56 days resulted in the rise of mechanical properties of examined samples. This is mainly because sufficient curing conditions were provided during 28 and 56 days. It should also be noted, that there is a small difference between values of compressive and flexural strength after 28 and 56 days of aging.

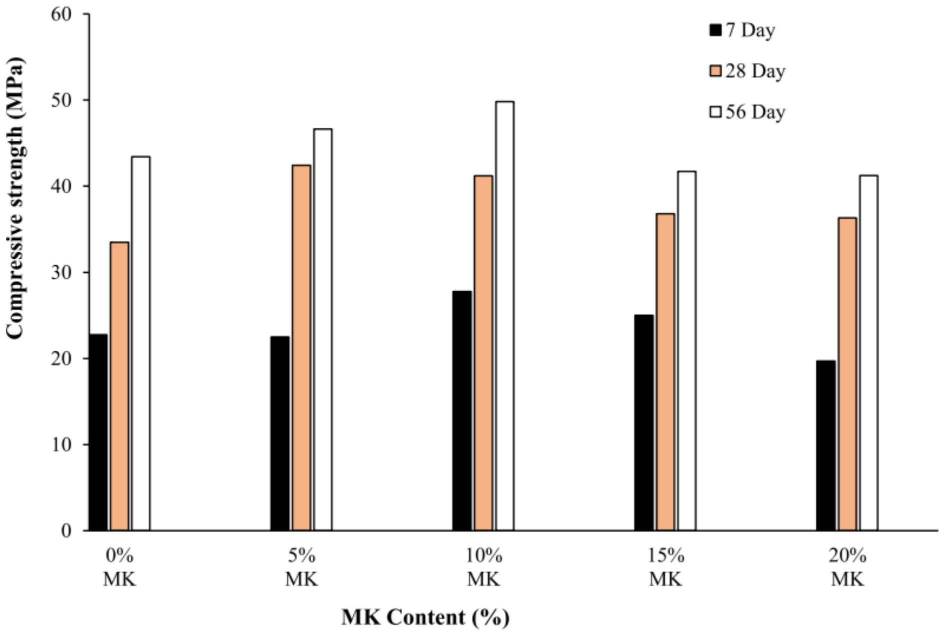

Fig. 6. Compressive strength of concrete with the different percentages of MK replacement after 7, 28 and 56 days of aging [39]

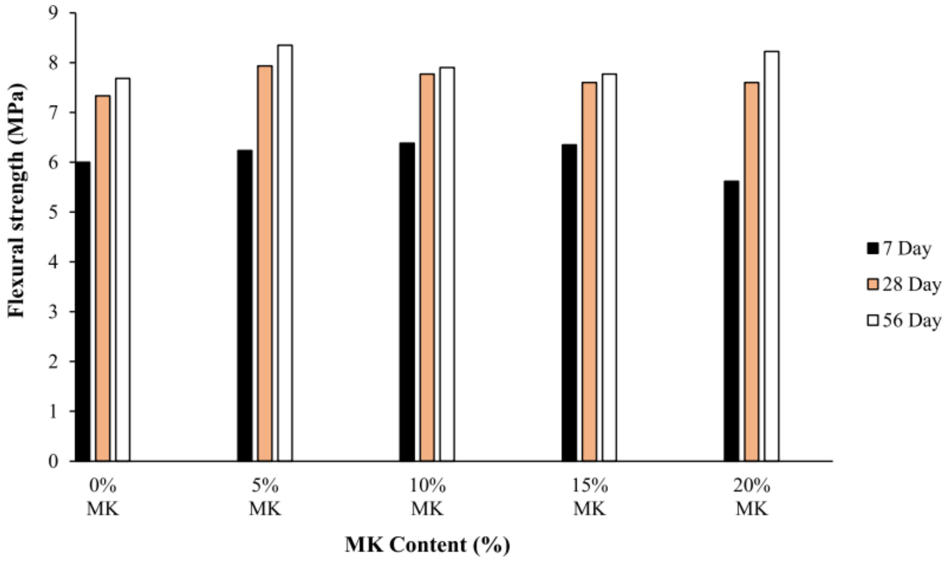

Fig. 7. Flexural strength of concrete with the different percentages of MK replacement after 7, 28 and 56 days of aging [39]

At the same time, the authors have noted a lower value of concrete compressive strength with both 5% and 20% MK replacement at an early age of 7 days. The values of compressive strength of such samples do not exceed 22.49 MPa and 19.69 MPa respectively. Instead, the authors of [45] have emphasized that nearly 10% of MK replacement, specifically at the early age of 3 days, is the best mix for a good concrete compressive strength. It is worth mentioning, that in their experiments the w/b ratio doesn`t exceed 0.3. While in [39] the w/b ratio for mixes with 5% and 20% of MK for 7 days was much higher exceeding reference one with 100% of OPCs (0.54 and 0.61 for 10% and 20% of MK`s versus 0.54 for reference sample). Thus, in their experiments, the maximum compressive strength was obtained with the mix, containing 5% and 10% of MK replacement.

The authors have also pointed out the reduction in flexural strength with the increase in w/b ratio. The minimum value of flexural strength of 5.62 MPa in their experiments was obtained after 7 days for the 20% MK mix with the highest w/b value of 0.61. However, with the aging of concrete up to 56 days its flexural properties were improved to a level of 7.68 MPa, similar to the 5% MK mix for the same days of aging.

At the same time, the authors of [25] have come to the following conclusions:

At the same time, the authors of [25] has come to the following conclusions:

1. The MK incorporation into the concrete mixture shows higher compressive strength compared to the reference one with 100% OPCs at 7 days of aging;
2. The w/b ratio as well as the percentage of MK replacement has a massive impact on concrete compressive strength;
3. The w/b ratio in the range of 0.32 – 0.5 with the 10 – 30% MK incorporation provides the concrete compressive strength on a level of 40 – 60 MPa after 7 days of curing;
4. The simultaneous reduction in w/b ratio to 0.3 – 0.36 and MK replacement to 10 – 20 % increases in concrete compressive strength up to 60 – 80 MPa respectively;
5. The higher concrete strength was obtained after 28 days with the 5% to 15% MK replacement and a w/b ratio of 0.27 – 0.3;
6. Presumably, the concrete's compressive strength with MK incorporation will further improve with the increase of its curing duration.

Conclusions. In this review, the sustainable approaches of concrete manufacturing practices based on the application of environmentally oriented binder materials were provided. It was shown, that the usage of GGBFS, FA, SF or MK incorporation as a partial replacement of ordinary Portland cement during concrete production, improves its mechanical properties, particularly, compressive, tensile and flexural strength. However, the long-term industrial application of these supplementary cementitious materials has shown the necessity of their strict limitation and the w/b ratio. Based on the mentioned above, it can be concluded that concrete with 50 – 60 % GGBFS replacement is quite effective in terms of its compressive strength enhancement after 28 and 90 days of aging with w/b ratio of 0.28.

In turn, adding 15 – 30% of FA into a concrete mix provides higher values of concrete mechanical properties, and compressive strength, particularly, about 41.94 – 43.41 MPa for 59 days of curing. Instead, the SF and MK show greater early days strength, compared to conventional concrete filled with 100% OPC.

As an optimal, the mix containing 13% SF replacement with the w/b ratio of 0.42–0.50 as one providing the highest level of concrete mechanical performances about 33.07–35.52 MPa, should be highlighted. At the same time, the 10% of MK incorporation with w/b ratio ranging 0.3 – 0.4 increases concrete compressive strength up to 40–50 MPa.

References

1. Leising, E., Quist, J., Bocken, N. (2018). Circular Economy in the building sector: Three cases and a collaboration tool. *J. Clean. Prod., 176,* 976–989.
2. Gursel, A.P., Maryman, H., Ostertag, C. (2016). A life-cycle approach to environmental, mechanical, and durability properties of "green" concrete mixes with rice husk ash. *J. Clean. Prod., 112,* 823–836.
3. Cebri´ an, G., Junyent, M., Mula, I. (2020). Competencies in education for sustainable development: emerging teaching and research developments. *Sustainability, 12(2),* 579.
4. Adesina, A., (2020). Recent advances in the concrete industry to reduce its carbon dioxide emissions. *Environ. Challenges, 1,* 100004.
5. Andrew, R.M. (2017). Global CO2 emissions from cement production. *Earth Syst. Sci. Data Discuss.,* 195–217.
6. Tarun, R., Asce, F. (2008). Sustainability of concrete construction. *Practice periodical on structural design and construction, 13(2).*
7. Chalee, W. Jaturapitakkul, C., Chindaprasirt, P. (2009). Predicting the chloride penetration of fly ash concrete in seawater. *Marine Structures, 22(3),* 341-353.

8. Broomfield, J.P. (2023). Corrosion of Steel in Concrete: Understanding, Investigation and Repair (3rd ed.). CRC Press.

9. Bolotov, M.H., Bolotov, H.P., Pribytko, I.O., Korzachenko, M.M. (2019). Ways of increasing of reinforced concrete`s corrosion strength. *Technical Sciences and Technology*, 4(18), 247–258.

10.Bolotov, M.H. (2013). Analytical report of main causes and consequences of accidents of buildings and structures on the territory of Ukraine for the past five years. *Bulletin of ChDTU,* 4, 197-204.

11.Bolotov, H.P., Bolotov, M.H., Oleksienko, S.V. (2015). Hand arc welding of builds steels by a littleamperearc with modulation of current. *Technical Sciences and Technology*, 1(1), 48-53.

12.Bolotov, M.H., Bolotov, H.P., Haneev, T.R., Korzachenko, M.M. (2017). Evaluation of the carrying capacity of reinforced concrete welded armature joints. *Technical sciences and technologies series, 1(7),* 58-67.

13.Bolotov, G., Tsybulya, S., Bolotov, M., Prybytko, I., & Yushchenko, S. (2022). Analysis of the efficiency of migrative corrosion inhibitors (MCI) usage in order to increase the exploitation duration of reinforced concrete. *Technical Sciences and Technology*, 1(27), 199–210.

14.Pacheco-Torgal, F. and Labrincha, J.A. (2013). Biotech cementitious materials: Some aspects of an innovative approach for concrete with enhanced durability. *Construction and Building Materials, 40,* 1136-1141.

15.Achal, V., Mukerjee, A. and Reddy, M. S. (2013). Biogenic treatment improves the durability and remediates the cracks of concrete structures. *Construction and Building Materials, 48,* 1-5.

16.Mattews, F. (2011). Towards a Deeper Philosophy of Biomimicry Organizations & Environment. Sage Publications (PP. 1-24).

17.Silva, F.B. et al. (2015). Industrial application of biological self-healing concrete: Challenges and economic feasibility. *Journal of Commercial Biotechnology, 21(1),* 31-38.

18.Adekunle, P., Aigbavboa, C., & Akinradewo, O. (2021). Intervention of Biomimicry for Sustainable Construction. The use of Bio-Concrete. *Journal of Agronomy, Technology and Engineering Management, 4,* 641-648.

19.Seifan, M., Samani, A.K., & Berenjian, A. (2016). Bioconcrete: next generation of self-healing concrete. *Appl Microbiol Biotechnol, 100,* 2591–2602.

20.Hearn, N. (1998). Self-sealing, autogenous healing and continued hydration: What is the difference? *Materials and Structures/Materiaux et Constructions, 31(212),* 563-567.

21.Suhendro, B. (2014). Toward green concrete for better sustainable environment. *Procedia Eng., 95,* 305–320.

22.Liew, K.M., Sojobi, A.O., Zhang, L.W. (2017). Green concrete: Prospects and challenges. *Constr. Build. Mater., 156,* 1063–1095.

23.Divsholi, B.S., Yang, T., Lim, D., Teng, S. (2014). Durability Properties and Microstructure of Ground Granulated Blast Furnace Slag Cement Concrete. *Int. J. Concr. Struct. Mater., 8,* 157–164.

24.Elchalakani, M., Aly, T., Abu-Aisheh, E. (2014). Sustainable concrete with high volume GGBFS to build Masdar City in the UAE. *Case Stud. Constr. Mater.*, 1, 10–24.

25.Al-Hamrani, A., Kucukvar, M., Alnahhal, W., Mahdi, E., Onat, N.C. (2021). Green Concrete for a Circular Economy: A Review on Sustainability, Durability, and Structural Properties. *Materials, 14,* 351.

26.Oner, A., Akyuz, S. (2007). An experimental study on optimum usage of GGBS for the compressive strength of concrete. *Cem. Concr. Compos., 29,* 505–514.

27.Bambang S., (2014). Toward Green Concrete for Better Sustainable Environment. *Procedia Engineering, 95,* 305-320.

28.Duraman, S. & Omar, M. (2019). Durability of pulverised fuel ash (PFA) concrete exposed to acidic and alkali conditions. MATEC Web of Conferences, 258. 05015. 10.1051.

29.Naik, T.R., Singh, S.S., Hossain, M.M., Fellow, P., Science, A. (1994). Permeability of concrete containing large amounts of fly ash. Cem. Concr. Res., 24, 913–922.

*30.*Shannag, M. (2000). High strength concrete containing natural pozzolan and silica fume. *Cem. Concr. Compos, 22,* 399–406.

31.Sarıdemir, M. (2014). Effect of silica fume and ground pumice on compressive strength and modulus of elasticity of high strength concrete. *Constr. Build. Mater., 49,* 484–489.

32.Duan, P., Yan, C., Zhou, W. (2017). Compressive strength and microstructure of fly ash based geopolymer blended with silica fume under thermal cycle. *Cem. Concr. Compos., 78,* 108–119.

33.Shekarchi, M., Rafiee, A., Layssi, H. (2009). Long-term chloride diffusion in silica fume concrete in harsh marine climates. *Cem. Concr. Compos., 31,* 769–775.

34.Zhao, S., Zhang, Q. (2019). Effect of Silica Fume in Concrete on Mechanical Properties and Dynamic Behaviors under Impact Loading. *Materials, 12(19),* 3263.

*35.*Khedr, S., Abou-Zeid, M. (1995). Characteristics of silica-fume concrete. *J. Mater. Civ. Eng., 6,* 357–375.

36.Mazloom, M., Ramezanianpour, A., Brooks, J.J. (2004). Effect of silica fume on mechanical properties of high-strength concrete. *Cem. Concr. Compos., 26,* 347–357.

37.Wong, H.S., Razak, H.A. (2005). Efficiency of calcined kaolin and silica fume as cement replacement material for strength performance. *Cem. Concr. Res., 35,* 696–702.

38.Iyellapogu, A., Venkata, R., Katukuri, H. (2018). Behaviour of silica fumes on reinforced concrete columns. *International Journal of Research in Engineering and Technology, 5,* 2347-4718.

39.Pillay, D. L., Olalusi, O. B., Kiliswa, M. W. (2002). Engineering performance of metakaolin based concrete. *Cleaner Engineering and Technology, 6,* 100383.

40.Khater, H. (2011). Influence of Metakaolin on Resistivity of Cement Mortar to Magnesium Chloride Solution. *Ceramics – Silikáty, 54,* 325-333.

41.Sabir, B., Wild, S., Bai, J. (2001). Metakaolin and calcined clays as pozzolans for concrete: a review. *Cement Concr. Compos.*, 23 (6), 441–454.

42.Song, H.-W., Lee, C.-H., Ann, K. Y. (2008). Factors influencing chloride transport in concrete structures exposed to marine environments. *Cement and Concrete Composites, 30(2),* 113-121.

43.Zhang, M., Malhotra, V. (1995). Characteritics of a thermally activated alumina-silicate pozzolanic material and its use in concrete. *Cem. Concr. Res., 25,* 1713–1725.

44.Wild, S., Khatib, J.M., Jones, A. (1996). Relative strength, pozzolanic activity and cement hydration in superplasticised metakaolin concrete. *Cem. Concr. Res., 26,* 1537–1544.

45.Khatib, J.M., Hibbert, J.J. (2005). Selected engineering properties of concrete incorporating slag and metakaolin. *Constr. Build. Mater., 19,* 460–472.

Список використаних джерел

1. Leising, E. Circular Economy in the building sector: Three cases and a collaboration tool / Leising E., Quist J., Bocken N. // J. Clean. Prod. – 2018. – Vol. 176. – Pp. 976–989.
2. Gursel, A.P. A life-cycle approach to environmental, mechanical, and durability properties of “green” concrete mixes with rice husk ash / Gursel A.P., Maryman H., Ostertag C. // J. Clean. Prod. – 2016. – Vol. 112. – Pp. 823–836.
3. Cebri´ an, G. Competencies in education for sustainable development: emerging teaching and research developments / Cebri´ an G., Junyent M., Mula I. // Sustainability. – 2020. – Vol. 12(2). – P. 579.
4. Adesina, A. Recent advances in the concrete industry to reduce its carbon dioxide emissions / Adesina A. // Environ. Challenges. – 2020. – Vol. 1. – P. 100004.
5. Andrew, R.M. Global CO2 emissions from cement production / Andrew, R.M. // Earth Syst. Sci. Data Discuss. – 2017. – Pp.195–217.
6. Tarun, R. Sustainability of concrete construction / Tarun R., Asce F. // Practice periodical on structural design and construction. – 2008. – Vol. 13(2).
7. Chalee, W. Predicting the chloride penetration of fly ash concrete in seawater / Chalee W., Jaturapitakkul C., Chindaprasirt P. // Marine Structures. – 2009. – Vol. 22(3). – Pp. 341-353.
8. Broomfield, J.P. Corrosion of Steel in Concrete: Understanding, Investigation and Repair (3rd ed.) / J.P. Broomfield. – 2023. – P. 304.
9. Шляхи підвищення корозійної стійкості залізобетону / М. Г. Болотов, Г. П. Болотов, І. О. Прибитько, М. М. Корзаченко // Вісник ЧНТУ. Технічні науки та технології. – 2019. – № 4(18). – Ст. 247-258.
10. Болотов, М. Г. Аналітичний огляд основних причин та наслідки аварій будівель та споруд, що сталися на території України за останні п’ять років / М. Г. Болотов // Вісник ЧДТУ. – 2013. – № 4. – С. 197-204.

11. Болотов, Г. П. Ручне дугове зварювання будівельних сталей малоамперною дугою модульованим струмом / Г. П. Болотов, М. Г. Болотов, С. В. Олексієнко // Вісник ЧНТУ. Технічні науки та технології. – 2015. – № 1(1). – С. 48-53.

12. Оцінка несучої здатності зварних з'єднань арматури залізобетону / М. Г. Болотов, Г. П. Болотов, Т. Р. Ганєєв, М. М. Корзаченко // Вісник ЧНТУ. Серія Технічні науки та технології. – 2017. – № 1(7). – С. 58-67.

13. Аналіз ефективності застосування мігруючих інгібіторів корозії (МІК) для підвищення експлуатаційної довговічності залізобетону / Г. Болотов, С. Цибуля, М. Болотов, І. Прибитько, С. Ющенко // Технічні науки та технології. – 2022. – № 1(27). – С. 199–210.

14. Pacheco-Torgal F. Biotech cementitious materials: Some aspects of an innovative approach for concrete with enhanced durability / Pacheco-Torgal, F. and J.A. Labrincha // Construction and Building Materials. – 2013. – No 40. – Pp. 1136- 1141.

15. Achal V. Biogenic treatment improves the durability and remediates the cracks of concrete structures / V. Achal, A. Mukerjee, M. Sudhakara Reddy // Construction and Building Materials. – 2013. – No 48. – Pp. 1-5.

16. Mattews F. Towards a Deeper Philosophy of Biomimicry Organizations & Environment / Mattews F. // Sage Publications, 2011. – Pp.1-24.

17. Silva, F.B. Industrial application of biological self-healing concrete: Challenges and economic feasibility / Silva F.B. et al. // Journal of Commercial Biotechnology. – 2015. – № 21(1). – Pp. 31-38.

18. Adekunle, P. Intervention of Biomimicry for Sustainable Construction: The use of Bio-Concrete / P. Adekunle, C. Aigbavboa, O. Akinradewo // Journal of Agronomy, Technology and Engineering Management. – 2021. – Vol. 4(5). – Pp. 641-648.

19. Seifan, M. Bioconcrete: next generation of self-healing concrete / M. Seifan, A.K. Samani, A. Berenjian // Appl Microbiol Biotechnol. – 2016. – Vol. 100. – Pp. 2591–2602.

20. Hearn, N. Self-sealing, autogenous healing and continued hydration: What is the difference? / N. Hearn // Materials and Structures/Materiaux et Constructions. – 1998. – Vol. 31(212). – Pp. 563-567.

21. Suhendro, B. Toward green concrete for better sustainable environment / B. Suhendro // Procedia Eng. – 2014. – Vol. 95. – Pp. 305–320.

22. Liew, K.M. Green concrete: Prospects and challenges / K.M. Liew, A.O. Sojobi, L.W. Zhang // Constr. Build. Mater. – 2017. – Vol. 156. – Pp. 1063–1095.

23. Divsholi, B.S. Durability Properties and Microstructure of Ground Granulated Blast Furnace Slag Cement Concrete / B.S. Divsholi, T. Yang, D. Lim, S. Teng // Int. J. Concr. Struct. Mater. – 2014. – Vol. 8. – Pp. 157–164.

24. Elchalakani, M. Sustainable concrete with high volume GGBFS to build Masdar City in the UAE / M. Elchalakani, T. Aly, E. Abu-Aisheh // Case Stud. Constr. Mater. – 2014. – Vol. 1. – Pp.10–24.

25. Green Concrete for a Circular Economy: A Review on Sustainability, Durability, and Structural Properties / Al-Hamrani, A., Kucukvar, M., Alnahhal, W., Mahdi, E., Onat, N.C. // Materials. – 2021. – Vol. 14. – P. 351.

26. Oner, A. An experimental study on optimum usage of GGBS for the compressive strength of concrete / A. Oner, S. Akyuz // Cem. Concr. Compos. – 2007. – Vol. 29. – Pp. 505–514.

27. Bambang, S. Toward Green Concrete for Better Sustainable Environment / S. Bambang // Procedia Engineering. – 2014. – Vol. 95. – Pp. 305-320.

28. Duraman, Saiful. Durability of pulverised fuel ash (PFA) concrete exposed to acidic and alkali conditions / Duraman Saiful, Omar Md. // MATEC Web of Conferences. – 2019. – Vol. 258, 05015. – 10.1051.

29. Permeability of concrete containing large amounts of fly ash / T.R. Naik, S.S. Singh, M.M. Hossain, P. Fellow, A. Science // Cem. Concr. Res. – 1994. – Vol. 24. – Pp. 913–922.

30. Shannag, M. High strength concrete containing natural pozzolan and silica fume / M. Shannag // Cem. Concr. Compos. – 2000. – Vol. 22. – Pp. 399–406.

31. Sarıdemir, M. Effect of silica fume and ground pumice on compressive strength and modulus of elasticity of high strength concrete / Sarıdemir, M. // Constr. Build. Mater. – 2014. – Vol. 49. – Pp. 484–489.

32. Duan, P. Compressive strength and microstructure of fly ash based geopolymer blended with silica fume under thermal cycle / P. Duan, C. Yan, W. Zhou // Cem. Concr. Compos. – 2017. – Vol. 78. – Pp. 108–119.

33. Shekarchi, M. Long-term chloride diffusion in silica fume concrete in harsh marine climates / M. Shekarchi, A. Rafiee, H. Layssi // Cem. Concr. Compos. – 2009. – Vol. 31. – Pp.769–775.
34. Zhao, S. Effect of Silica Fume in Concrete on Mechanical Properties and Dynamic Behaviors under Impact Loading / S. Zhao, Q. Zhang // Materials. – 2019. – Vol. 12(19). – P. 3263.
35. Khedr, S. Characteristics of silica-fume concrete / S. Khedr, M. Abou-Zeid // J. Mater. Civ. Eng. – 1995. – Vol. 6. – Pp. 357–375.
36. Mazloom, M. Effect of silica fume on mechanical properties of high-strength concrete / M. Mazloom, A. Ramezanianpour, J.J. Brooks // Cem. Concr. Compos. – 2004. – Vol. 26. – Pp.347–357.
37. Wong, H.S. Efficiency of calcined kaolin and silica fume as cement replacement material for strength performance / H.S. Wong, H.A. Razak // Cem. Concr. Res. – 2005. – Vol. 35. – Pp.696–702.
38. Iyellapogu, A. Behaviour of silica fumes on reinforced concrete columns / A. Iyellapogu, R. Venkata, H. Katukuri // International Journal of Research in Engineering and Technology. – 2018. – Vol. 5. – Pp. 2347–4718.
39. Pillay, D. L. Engineering performance of metakaolin based concrete / D. L. Pillay, O. B. Olalusi, M. W. Kiliswa // Cleaner Engineering and Technology. – 2002. – Vol. 6. – 100383.
40. Khater, H. Influence of Metakaolin on Resistivity of Cement Mortar to Magnesium Chloride Solution / H. Khater // Ceramics – Silikáty. – 2011. – Vol. 54. – Pp. 325-333.
41. Sabir, B. Metakaolin and calcined clays as pozzolans for concrete: a review / B. Sabir, S. Wild, J. Bai // Cement Concr. Compos. – 2001. – Vol. 23 (6). – Pp. 441–454.
42. Ha-Won Song. Factors influencing chloride transport in concrete structures exposed to marine environments / Ha-Won Song, Chang-Hong Lee, Ki Yong Ann // Cement and Concrete Composites. – 2008. – Vol. 30, Issue 2. – Pp. 113-121.
43. Zhang, M. Characteritics of a thermally activated alumina-silicate pozzolanic material and its use in concrete / M. Zhang, V. Malhotra // Cem. Concr. Res. – 1995. – Vol. 25. – Pp. 1713–1725.
44. Wild, S. Relative strength, pozzolanic activity and cement hydration in superplasticised metakaolin concrete / S. Wild, J.M. Khatib, A. Jones // Cem. Concr. Res. – 1996. – Vol. 26. – Pp.1537–1544.
45. Khatib, J.M. Selected engineering properties of concrete incorporating slag and metakaolin / J.M. Khatib, J.J. Hibbert // Constr. Build. Mater. – 2005. – Vol. 19. – Pp. 460–472.

Отримано 14.05.2024

УДК 691.237:620.193

Максим Геннадійович Болотов[1], Геннадій Павлович Болотов[2],
Ірина Олександрівна Прибитько[3], Микола Миколайович Корзаченко[4]

[1]кандидат технічних наук, доцент, кафедри технологій зварювання та будівництва,
Національний університет «Чернігівська політехніка» (Чернігів, Україна)
E-mail: bolotovmg@gmail.com. **ORCID**: https://orcid.org/0000-0002-0915-4132
Scopus: 57190377278. **Researcher ID:** H-4183-2014

[2]доктор технічних наук, професор, професор кафедри технологій зварювання та будівництва
Національний університет «Чернігівська політехніка» (Чернігів, Україна)
E-mail: bolotovgp@mail.ua. **ORCID**: https://orcid.org/0000-0003-0305-2917
Researcher ID: H-5304-2014. **Scopus:** 6506157907

[3]кандидат технічних наук, доцент, кафедри технологій зварювання та будівництва,
Національний університет «Чернігівська політехніка» (Чернігів, Україна)
E-mail: prybytko_ira@ukr.net. **Researcher ID**: F-7325-2014
ORCID: https://orcid.org/0000-0002-8550-8318. **Scopus:** 57217181853
ORCID: https://orcid.org/0000-0003-0305-2917. **Scopus:** 6506157907

[4]кандидат технічних наук, доцент, кафедри технологій зварювання та будівництва,
Національний університет «Чернігівська політехніка» (Чернігів, Україна)
E-mail: korzachenko_87@meta.ua. **ORCID**: https://orcid.org/0000-0002-5674-8662. **Researcher ID:** F-5177-2016

ЕКОЛОГІЧНО ОРІЄНТОВАНІ ПРАКТИКИ ВИРОБНИЦТВА БЕТОНУ

Будівництво з використанням екологічно чистих, перероблених або біоматеріалів – це шлях до зменшення вуглецевого сліду, виснаження природних ресурсів, що так важливо для нашого добробуту та подальшого розвитку людства. Загальновідомо, що залізобетон є одним з найбільш переважних будівельних матеріалів у багатьох сферах застосування. Водночас виробництво бетону, зокрема портландцементу, вважається найбільш забруднювальним *процесом з величезною кількістю викидів CO2, що призводить до деяких екологічних проблем, відомих як глобальне потепління або парниковий ефект. Наміри стати зеленими та мінімізувати проблеми, згадані вище, потребують зміни наших звичних методів виробництва бетону в бік більш орієнтованих на навколишнє середовище, відповідно, екологічно чистих.*

Зусилля вчених усього світу щодо зменшення викидів CO2 та споживання ресурсів під час виробництва бетону призвели до появи біо- та зеленого бетону. Ідея біобетону (або бетону, що самовідновлюється) спирається на концепцію біомімікрії виробництва цементу через адаптацію природних елементів, моделей, шаблонів і систем для вирішення проблем людини. Таким чином, було встановлено потенціал оточуючого мікробіому (мікробів і мікробів) для самовідновлення бетону, зокрема, для відтворення $CaCO_3$*, коли починають наростати тріщини.*

Ідея зеленого бетону зовсім інша і в основному базується на заміні звичайного портландиту іншим додатковим цементуючим матеріалом, таким як мелений гранульований доменний шлак, летуча зола або пуцолановий матеріал, відомий як кремнезем, а також метакаолін.

Ця стаття містить вичерпний огляд впливу стійких, екологічно орієнтованих будівельних матеріалів для виробництва бетону на його механічні властивості. Показано, що застосування доменного шлаку, летучої золи, кремнезему або метакаоліну як часткової заміни звичайного портландцементу при виготовленні бетону покращує його механічні властивості, зокрема міцність на стиск, розтяг і згин.

Ключові слова: *стійкість; виробництво бетону; біомімікрія; біобетон; самовідновлювальний бетон; зелений бетон.*
Рис.: 7. Табл.: 8. Бібл.: 45.

Bolotov, M., Bolotov, H., Prybytko, I., Korzachenko, M. (2024). Sustainable practices of concrete manufacturing. *Technical sciences and technologies*, (2(36)), 15-30.