Theory and Building Practice

Vol. 6, No.1, 2024

https://doi.org/10.23939/jtbp2024.01.086

Myroslav Sanytsky[1], Ljudmyla Kripka[2], Taras Kropyvnytskiy[1], Nataliia Slavych[1]

INFLUENCE OF TECHNOLOGICAL FACTORS ON CONCRETE EFFICIENCY INDICATORS

[1] Department of Building Production,
Lviv Polytechnic National University,
[2] Ukrcement Association,
myyroslav.a.sanytskyi@lpnu.ua

The article presents the results of studies of the influence of technological factors (clinker factor of cements, grain composition of aggregates, cement consumption in concrete, modifier additives) on technical and environmental indicators of concrete efficiency. It has been shown that in combination, the parameters of clinker and CO_2 intensities characterize the clinker efficiency of concrete, which can be improved by replacing part of the clinker in mixed cements with active mineral additives. Optimization of the granulometric composition of fine and coarse aggregates and the use of superplasticizers of the polycarboxylate type ensure the formation of a dense microstructure of the cementing matrix, which allows to increase the strength of concrete by 1–2 classes with an unchanged cement consumption and helps to reduce the CO_2 emission rate. With the correct combination of various technological factors affecting concrete mixtures, a real opportunity is created to produce modern low-carbon concrete that meets the requirements of sustainability.

Key words: clinker factor; Portland cement; polycarboxylate superplasticizer; CO_2 emission indicators; concrete efficiency; low-carbon concrete.

Introduction

According to the priority areas of the European Green Deal (Green Deal, 2020), an important issue is to ensure carbon neutrality, introduce innovations, modernize and green the industry. At the same time, at the current stage of society's development, economic growth largely determines the need to increase construction volumes, which leads to a wider use of cementing materials that ensure the manufacture of various building structures. Cement is the largest industrial product on Earth by weight, and in combination with water and various aggregates, it forms building materials such as concrete for various functional purposes. Concrete is the second most commonly used material on the planet after water. Concrete structures make up a significant part of the built environment (Borg, 2018). At the same time, over the past 65 years, the amount of cement produced in the world has increased by about 34 times, while the population has increased by less than 3 times. This indicator is much higher compared to a material such as steel (Sabbie, 2017). In 2020, the total amount of cement produced in the world was 4.6 billion tons, which corresponds to approximately 626 kg per person. This made it possible to produce about 2.1–2.3 m^3 or 4.8–5.5 tons of concrete per person. At the same time, by 2050, cement production is expected to grow to more than 6 billion tons (Feiz, 2014).

The biggest driving force for the development of cement technology has long been the requirement to reduce the specific CO_2 footprint. The European Cement Association (CEMBUREAU) has presented a strategy to reduce CO_2 emissions by 2050 at every stage of the production and technological chain – from clinker, cement and concrete production to construction. By 2030, CEMBUREAU plans to reduce CO_2 emissions from cement production at its European plants by 30 %, and from concrete production and construction by 40 %. Thus, according to the strategy, specific CO_2 emissions should be 472 kg per ton of cement produced (Promise, 2022; Javadabadi, 2019). In the advanced EU countries, CO_2 emissions have been reduced to 83.4 kg CO_2 per 1 ton of concrete, which is

19.1 % lower than the average level of 103.1 kg CO_2 per 1 ton of concrete. To reduce the E_{CO2} indicator, it is also envisaged to replace a part of pure clinker Portland cements of the CEM I type in concrete with polycomponent mineral additives, which is a relevant approach to achieve sustainable development in construction (De Grazia, 2023).

Due to the increasing requirements for modern cements to reduce CO_2 emissions, a number of environmental indicators are being introduced to assess their environmental impact (Althoey, 2023). Currently, there is an urgent need to reduce the GWP (Global Warming Potential) in cement production by 22–38 % of average emissions, which is globally 0.7–1.5 billion tons of CO_2 per year, Mt of CO_2 per year. The potential contribution of emissions to global warming GWP according to Environmental Product Declarations (EPDs) for unreinforced concrete in terms of CO_2 is 250 CO_2 eq/m^3 of concrete. It is noteworthy that these figures are significantly lower than the emissions from steel production (□1900 kg CO_2 eq./t) (Giergiczny, 2020). At the same time, it is worth noting the significant environmental impact of concrete given the huge volumes of its production.

Effective use of Portland cement clinker as the main component of cements in concrete will determine the future scenario of both low-carbon development of the construction industry and ensuring the durability of building structures. The potential for reducing CO_2 emissions in concrete is achieved by optimizing the use of binders using modern technologies that combine high aggregate content with a significant reduction in water consumption. According to the concept (Schneider, 2019; Damineli, 2010), which takes into account the technical characteristics of building materials, the efficiency of a binder or clinker in concrete (clinker intensity) in $[kg/(m^3 \cdot MPa)]$ and the intensity of CO_2 emissions (CO_2 intensity) in $[kg\ CO_2/(m^3 \cdot MPa)]$ should be calculated when producing 1 m^3 of concrete of a given strength.

An effective technological way to reduce cement consumption without reducing strength is to optimize packaging, reducing the volume of cavities between grains filled with cement dough, which is largely achieved by selecting different aggregate fractions. Reducing CO_2 intensity can also be achieved by replacing a portion of Portland cement clinker with active mineral additives of various genesis (Scrivener, 2010). At the same time, it is of practical interest to develop low-carbon concrete based on multicomponent cements using complex polyfunctional modifiers with plasticizing-accelerating effects (Sanytsky, 2021).

The design of the composition of low-carbon concrete includes a system of technological calculations to establish a ratio between the components of the concrete mix that guarantees the required strength and durability of concrete in the structure and the specified ease of its placement, taking into account the production and compaction technology, as well as the required efficiency (minimum cost of the mix) (Corinaldesi, 2012; Watari, 2022). Improving the performance of concrete is largely achieved through the use of new generation superplasticizers based on polycarboxylate ethers. At the same time, such effects of plasticizing additives on the properties of cement systems as technological, technical, economic, and environmental are achieved.

The aim of this work is to evaluate the influence of various technological factors (clinker factor of cements, grain composition of aggregates, modifiers) on the performance indicators of concretes of strength classes C16/20–C40/50.

Materials and methods

Portland cements of different types CEM I 42.5 R, CEM II/A-LL 42.5 R, CEM II/B-M 32.5R, CEM III/A 32.5R of PrJSC Ivano-Frankivskcement were used for the study. Portland cements are made on the basis of Portland cement clinker of normalized mineralogical composition (wt. %: C_3S – 60.82; C_2S – 14.62; C_3A – 6.76; C_4AF – 12.32; alkaline oxides (R_2O) content – 0.82).

For the production of heavy concrete, quartz sands from the Mykolaiv and Zhovkva deposits with a particle size modulus of M_k = 1.21 and M_k = 1.83, respectively, were used. Granite crushed stone of two fractions was used for research: 2–5 mm and 5–20 mm.

Polycarboxylate superplasticizers (PCE) were used to improve the quality of concrete mixtures and concrete.

Results and discussion

The physical and mechanical characteristics of Portland cements CEM I 42.5 R, CEM II/A-LL 42.5 R, CEM II/B-M 32.5 R, CEM III/A 32.5 R are shown in Table 1. For these mixed Portland cements, the clinker factor is 0.95, 0.88, 0.65, and 0.50, respectively, and the CO_2 emission is 865, 761, 562, and 432 kg/t of cement (Table 1).

Table 1

Physical and mechanical properties of cements according to EN-196 and CO_2 emission indicators

Cement	SSA, cm^2/g	Water demand, %	W/C	Initial setting time, min	Flow, mm	Flexural/compressive strength, MPa			Emission CO_2, kg/t kl	Relative emission CO_2, %
						2	7	28		
CEM I 42.5 R	3700	29.5	0.50	150	210	6.5/33.2	8.3/48.6	9.2/58.2	865	100.0
CEM II/A-LL42.5 R	4300	29.0	0.50	155	220	6.0/31.4	7.6 /46.6	8.7/55.0	761	87.9
CEM II/B-M 32.5 R	4560	29.4	0.50	170	190	4.3/19.3	7.1 /35.3	8.8/48.9	562	64.9
CEM III/A 32.5 R	4090	31.5	0.50	200	185	3.6/15.1	5.8 /27.4	9.1/47.9	432	49.9

To study the influence of technological factors, the effect of cement consumption of different types on the strength of concrete was determined. For the basic composition of heavy concrete with a cement consumption of 350 kg/m^3, the ratio of the components Cement: Sand : Crushed stone was 1 : 2.1 : 3.65 (C = 320 kg/m^3). At the same time, the ratio of sand : crushed stone = 1 : 1.76. In Ukraine, very fine sands with fineness modulus FM = 1.0–1.5 and coarse aggregates of 5–20 mm are often used in the manufacture of concrete mixtures. As a rule, the concrete mixture does not contain fractions from 2 to 5 mm, which leads to an increase in intergranular void in concrete and cement overconsumption. As can be seen from Fig. 1, on the diagram of the distribution of aggregate fractions according to EN 206, one should distinguish an area that refers to the granulometry of very fine sand up to 0.5 mm in size, and an area of coarse aggregate, where the vast majority of grains are characterized by sizes over 8 mm.

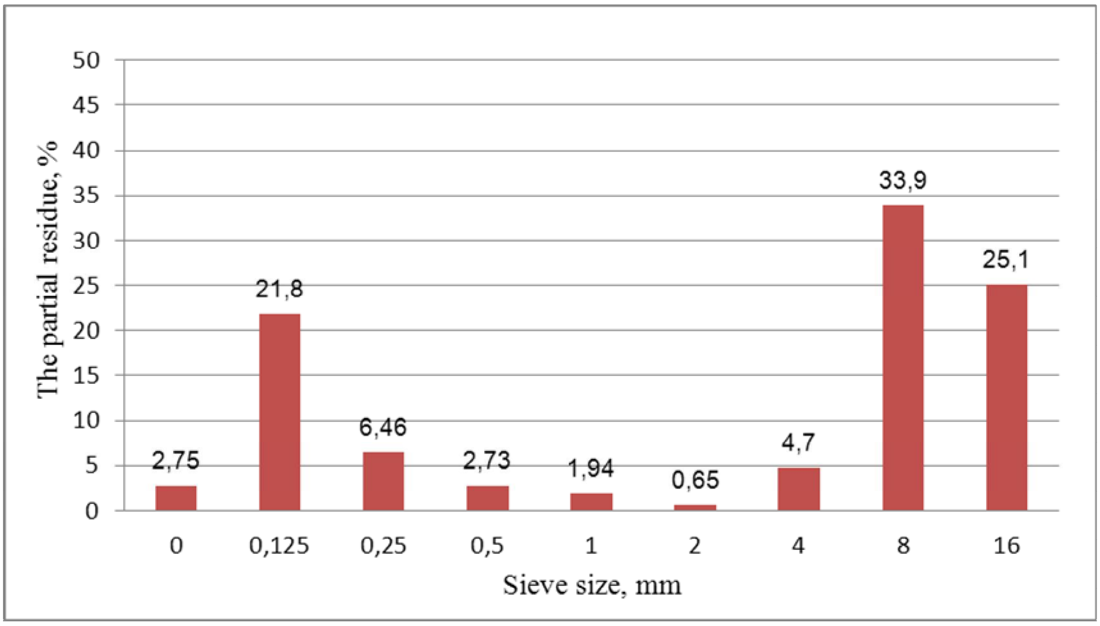

Fig. 1. Composition of the aggregate mixture Sand : Crushed stone = 1 : 1.76

It can be seen that a high content of very fine sand in the aggregate mixture leads to excessive cement and water consumption. This leads to a deterioration in the characteristics of the hardened concrete. The insufficient amount of certain grain fractions or their absence leads to an obvious deterioration in the workability parameters of the concrete mixture and a decrease in the quality of the hardened concrete. Therefore, for a number of compositions with a consumption of 420 kg of cement, aggregate mixtures with an additional fraction of granite crushed stone of 2–5 mm were designed.

The effect of the consumption of Portland cement CEM II/A-LL on the strength of concrete is shown in Table 2. At the same time, a polycarboxylate superplasticizer in the amount of 0.8 mass. % was introduced in a number of compositions. It can be seen that at a consumption of Portland cement of 320 kg/m^3 of concrete, CO_2 emissions amount to 247 kg per 1 m^3 of concrete or 104 kg per 1 ton of concrete. At the same time, the brand strength of concrete without additives is 32.4 MPa, as a result, the clinker intensity for concrete at the age of 28 days is 8.69 kg / (m^3·MPa), and the CO_2 intensity is 7.62 kg CO_2 / (m^3·MPa). At the same time, at a given cement consumption, a significant water-reducing effect (28 %) is achieved through the use of PCE-based superplasticizers. As a result of increasing the strength of the modified concretes, the clinker intensity of concretes is 4.86 kg / (m^3·MPa), respectively, the CO_2 intensity decreases to 4.26 kgCO_2 / (m^3·MPa). At the consumption of CEM II/A-LL cement at the level of 280 kg/m^3, the brand strength decreases to 27.1 MPa (concrete class C16/20), while the values of clinker and CO_2 intensities are respectively. When modifying this concrete with an additive of 0.8 mass. % PCE, the grade strength increases to 31.2 MPa, as a result, the clinker intensity decreases from 10.33 to 8.69 kg / (m^3·MPa), and the CO_2 intensity decreases from 7.86 to 6.61 kgCO_2 / (m^3·MPa).

Table 2

Influence of Portland cement and PCE consumption on the performance of concrete based on Portland limestone cement CEM II/A-LL 42.5R (S4 workability grade)

Cement consump-tion, kg/m^3	PCE, mass. %	W/C	Compressive strength, MPa, in age, days			Strength class	CO_2 emissions in concrete, kgCO_2/m^3	Clinker intensity, kg/(m^3·MPa)	CO_2-intensity , kgCO_2/ (м^3·MPa)
			2	7	28				
280	–	0.76	10.2	19.8	27.1	C16/20	213.1	10.33	7.86
280	0.8	0.68	13.6	24.8	32.2	C20/25	213.1	8.69	6.61
320	–	0.72	14.1	24.9	32.7	C20/25	243.5	9.78	7.44
320	0.8	0.60	19.4	37.8	42.7	C25/30	243.5	7.49	5.70
350	–	0.61	18.4	30.8	40.3	C25/30	266.3	8,68	6.60
350	0.8	0.51	27.4	43.7	54.4	C32/40	266.3	6.43	4.89
420	0.8	0.39	37.4	56.0	67.2	C40/50	319.6	6.25	4.72

Crushed stone fraction of 2–5 mm was additionally introduced to optimize the grain composition of aggregates for high-strength concrete with a cement consumption of 420 kg/m^3. In this case, the ratio of cement : sand : crushed stone 2–5 : crushed stone 5–20 = 1:1.3 : 0.52 : 2.48 (W/C = 0.40). Portland limestone cement CEM II/A-LL42.5 R and slag cement CEM III/A 32.5 R were used to determine the influence of the clinker factor of cements. It was established that these concretes after 28 days are characterized by compressive strength of 67.2 and 60.7 MPa, and emissions CO_2 is 319.6 and 181.4 kg per 1 m^3 of concrete. The clinker intensity for concrete based on such cements at the age of 28 days is respectively 5.50 and 3.46 kg/(m^3·MPa), and CO_2 intensity – 4.76 and 2.99 kgCO_2 / (m^3·MPa). This indicates that with a properly developed composition of the mixture of high-strength concrete using cements with a reduced clinker factor, a real possibility of manufacturing effective low-carbon concrete is created.

The results show that with an increase in concrete strength, the clinker and CO_2 intensities decrease, i. e., clinker is used more efficiently. This indicates that an increase in the clinker efficiency of concrete is characteristic of a higher strength class and is achieved to a large extent by using effective modifiers and optimizing the grain size distribution of aggregates (Sanytsky, 2023). At the same time, a monolithic structure of the cementitious matrix is observed, which leads to the density of the concrete cementitious matrix (Kropyvnytska, 2023).

Thus, with an increase in concrete strength, the values of the indicators of the intensity of the use of Portland cement clinker and CO_2 emissions decrease, i. e., clinker is used more efficiently. Taken together, the parameters of clinker and CO_2 intensities characterize the clinker efficiency of concrete, which can be increased by replacing part of the clinker in mixed cements with active mineral additives and fillers, as well as by using highly reductive polycarboxylate superplasticizers. At the same time, clinker-efficient concrete should be considered as a composite material with a multilevel structure consisting of an optimized ratio of fine and coarse aggregates bound by a dense cementitious matrix. With the right combination of various technological factors affecting concrete mixtures, a real opportunity is created to produce modern low-carbon concrete that meets the requirements of a sustainability.

Conclusions

The technical and environmental efficiency of concrete is determined by clinker and CO_2 intensity indicators and is ensured by the formation of a dense macro- and microstructure of the cementing matrix to obtain higher strength, which is achieved through the complex action of the following technological factors: compliance with the extremely low water-binder ratio due to the use of polycarboxylate superplasticizers; selection of the ratio of different components of the solid phase at different scale levels, which contributes to obtaining a particularly dense string. The use of modified high-strength concrete of class C40/50 ensures a more complete implementation of the concept of low-carbon development of the construction industry due to a significant reduction in CO_2 emissions.

Prospects for further research

Increasing the clinker efficiency of concrete is achieved by combining a number of technological factors that determine the creation of a dense packing of cementitious matrix particles. Further studies should investigate the influence of the clinker factor of the cements used and various modifiers on the performance of concrete in order to obtain modern low-carbon concrete.

References

The European Green Deal (2020). Available online: https://eur□lex.europa.eu.

Borg R. P., Hajek P., & Fernandez-Ordonez D. (2018). Sustainable Concrete: Materials and Structures. *IOP Conf. Series: Materials Science and Engineering*, 442, 011001. DOI: 10.1088/1757-899X/442/1/011001.

Sabbie A., Vanderley M., Sergio A., & Arpad H. (2017). Carbon dioxide reduction potential in the global cement industry by 2050. *Cement and Concrete Research*, 114, 115–124. https://doi.org/10.1016/j.cemconres.2017.08.026

Feiz R., Ammenberg J., Baas L., Eklund M., Helgstrand A., & Marshall R. (2014). Improving the CO_2 performance of cement, part I: utilizing life-cycle assessment and key performance indicators to assess development within the cement industry. *Journal of Cleaner Production,* 1–10. http://dx.doi.org/10.1016/j.jclepro.2014.01.083

Promise D. Nukah, Samuel J. Abbey, & Colin A. (2022). Evaluation of the Structural Performance of Low Carbon Concrete. *Sustainability*, 14, 16765. https://doi.org/10.3390/su142416765

Javadabadi M. T., Kristiansen D. de L., Redie M. B., & Baghban M. H. (2019). Sustainable Concrete: A Review. *International Journal of Structural and Civil Engineering Research.* 8, 2. DOI: 10.18178/ijscer.8.2.126-132.

De Grazia M. T., Sanchez L. F. M., & Yahia A. (2023). Towards the design of eco-efficient concrete mixtures: An overview. *Journal of Cleaner Production*, 389, 135752. https://doi.org/10.1016/j.jclepro.2022.135752

Althoey, Ansari W. S., Sufian M., & Deifalla A. F. (2023). Advancements in low-carbon concrete as a construction material for the sustainable built environment. *Developments in the Built Environment*, 16(9), 100284. https://doi.org/10.1016/j.dibe.2023.100284

Giergiczny Z., Król A., Tałaj M., & Wandoch K. (2020). Performance of Concrete with Low CO_2 Emission. *Energies*, 13, 4328. DOI: 10.3390/en13174328

Damineli B. L., Kemeid F. M., Aguiar P. S., & John V. M. (2010). Measuring the eco-efficiency of cement use. *Cem. Concr. Compos*., 32, 555–562. https://doi.org/10.1016/j.cemconcomp.2010.07.009

Scrivener K. L., & Gartner E. M. (2018). Ecoefficient cements: potential economically viable solutions for a low CO_2 cement based materials industry. *Cem. Concr. Res*., 114, 2–26. https://wedocs.unep.org/20.500.11822/25281

Sanytsky M. A., Kropyvnytska T. P., & Heviuk I. M. (2021). Rapid-hardening clinker-effective cements and concretes: monograph, 206 p. ISBN 978-617-8055-16-5

Corinaldesi V., Moriconi G. (2012). Environmentally-friendly concretes for sustainable building. *WIT transactions on ecology and the environment*, Vol. 155. https:// doi:10.2495/SC120952

Takuma Watari, Zhi Cao, Sho Hata, Keisuke Nansai (2022). Efficient use of cement and concrete to reduce reliance on supply-side technologies for net-zero emissions. *Nature communications*, 13 : 4158. https://doi.org/10.1038/s41467-022-31806-2

EN 206:2013. Concrete Specification, Performance, Production and Conformity. CEN: Brussels, Belgium. https://standards.iteh.ai/catalog/standards/cen/0e839092-9d2c-4b1c-ada2-b4d7f585e33b/en-206-2013

Sanytsky M., Kropyvnytska T., Geviuk I., Makovijchuk M., & Kripka L. (2023). Performance of concretes with a low carbon footprint containing multi-component mineral additives. XII Konferencja DNI BETONU 2023, 783–795. https://www.dnibetonu.com/wp-content/pdfs/2023/Sanytsky_i%20inni.pdf

Kropyvnytska T., Sanytsky M., Heviuk I., Kripka L. (2022). Study of the properties of low-carbon Portland-composite cements CEM II/C-M. Lecture Notes in Civil Engineering this Proceedings of EcoComfort 2022. 290, 230–237. https://doi.org/10. 10.1007/978-3-031-14141-6_22

М. А. Саницький[1], Л. І. Кріпка[2], Т. С. Кропивницький[1], Н. І. Славич[1]
[1] Національний університет “Львівська політехніка”,
кафедра будівельного виробництва
[2] Асоціація “УКРЦЕМЕНТ”

ВПЛИВ ТЕХНОЛОГІЧНИХ ФАКТОРІВ НА ІНДИКАТОРИ ЕФЕКТИВНОСТІ БЕТОНІВ

У статті наведено результати досліджень впливу технологічних чинників (клінкер-фактор цементів, зерновий склад заповнювачів, витрата цементів у складі бетонів, добавки модифікаторів) на технічні та екологічні індикатори ефективності бетонів. Показано, що для портландцементів CEM I 42,5 R, CEM II/A-LL 42,5 R, CEM II/B-M 32,5 R, CEM III/A 32,5 R з клінкер-фактором відповідно 0,95, 0,88, 0,65 та 0,50 емісія CO_2 становить 865, 761, 562 та 432 кг/т цементу. В комплексі індикатори клінкер- та CO_2-інтенсивностей характеризують ефективність використання портландцементного клінкеру в бетоні, підвищення якої можна досягти, замінивши частину клінкеру в складі змішаних цементів на активні мінеральні добавки та наповнювачі, а також використанням суперпластифікаторів полікарбоксилатного типу. Під час випробувань бетонів із витратою цементу 320 кг/м^3 встановлено, що у разі введення суперпластифікаторів на основі полікарбоксилатних етерів за рахунок значного водоредукувального ефекту (28 %) міцність модифікованих бетонів зростає на 30 %, показник клінкер-інтенсивності бетонів становить 4,86 кг/(м^3·МПа), відповідно CO_2-інтенсивність зменшується до 4,26 кг CO_2 / (м^3 ·МПа). Зі збільшенням міцності бетону показники клінкер- та CO_2-інтенсивностей зменшуються, тобто клінкер використовується ефективніше. Це свідчить, що підвищення клінкер-ефективності бетонів характерне для вищого класу міцності та досягається великою мірою за рахунок використання ефективних модифікаторів та оптимізації зернового складу заповнювачів. Показано, що за умови правильного поєднання різних технологічних факторів впливу на бетонні суміші в результаті формування щільного упакування частинок цементуючої матриці створюється реальна можливість отримання сучасних низьковуглецевих бетонів, які відповідають вимогам сталого розвитку.

Ключові слова: клінкер-фактор; цемент; полікарбоксилатний суперпластифікатор; показники емісії CO_2; ефективність бетону; низьковуглецевий бетон.