The Effect of Cement Reduction and Substitution on the Mechanical and Durability Properties of Concrete

Kiran Ram[1], *Diana* Londono-Zuluaga[2], *Marijana* Serdar[1] * and *Karen* Scrivener[2]

[1]University of Zagreb, Kaciceva 26, Zagreb, Croatia, 10000
[2]École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland, 1015

Abstract. There are now several initiatives to reduce the carbon footprint of cement production, such as the use of alternative binders for clinker. However, reducing the carbon emissions of the cement sector will only be possible when design optimization is combined with other measures. The construction industry is reluctant to reduce the cement content of concrete mixes and is not encouraged to use performance-based design for concrete. In most cases, these steps will negate the benefits of using alternative binders in concrete. The objective of this paper is to investigate the effects of lowering the cement content and additionally substituting part of the cement on the mechanical properties and durability of concrete. The reference mix was taken from a real bridge recently built in Croatia, and the alternative combination was prepared with a reduced cement content of 22%. All mixes were evaluated based on their mechanical strength and resistance to chloride penetration. The carbon footprint of each mix was also studied. The study concluded that the alternative mix with lower cement content had comparable durability and a significantly lower carbon footprint, meaning that the alternative mix proved to be a more sustainable option.

1 Introduction

In recent years, people all over the world have been attempting to maximise their efforts in order to reduce their carbon footprint on the environment. According to the United Nations Conference on Climate Change (COP26), the majority of countries have agreed to implement a number of strategies to mitigate the effects of global warming on climate change [1]. As a result, the industries that emit carbon dioxide into the atmosphere alter their action plans to reflect this current paradigm. Cement industry accounts for 7-8 percent of all major industries' carbon footprint, and this percentage is expected to rise in the coming years as a result of the high demand for cement for infrastructure development in countries such as India, China, and African countries etc [2]. There are a lot of ways that the cement industry has already tried to cut down the carbon footprint such as usage of alternative cementitious materials. Limestone calcined clay, for example, is one of the main types of composite cements, and it can cut down the clinker factor by up to 0.50 [3]. However, unless concrete mixtures are optimised, using alternative binders will not be enough to reduce carbon footprint.

The first step in optimising a mixture is to set the total binder content in place. If the binder content of concrete is too high, the total cost of cement will rise, and there will be no additional benefit to the structure's lifespan or durability. Aside from that, optimization of binder content through the use of particle packing technique results in a significant improvement in the mechanical and workability of concrete [4]. The most significant impediment to lowering the binder content has been identified in the literature as a reduction in the paste volume, which has been shown to have a negative impact on the flow characteristics of the mixture. This challenge is however nowadays targeted by chemical superplasticizers capable of providing the improved rheological parameters [5][6].

This paper is discussing the impact of reduction and substitution of the cement content on mechanical and durability properties of concrete, especially the chloride ingress. The reference mixture has been taken from a real-built bridge in Croatia. Also, the paper discusses the sustainability of these mixtures in terms of their service life, carbon footprint and mechanical strength.

2 Materials and methods

2.1 Materials

There were three mixtures used to analyse the impact of reduction in the binder content in this study, among which, two mixes were with CEM II B-S and one as alternative binder with limestone-calcined clay and CEM I 42.5R. The chemical composition and physical properties of CEM I, CEM II/B-S, clay, and limestone are given in the Table 1. The kaolinite content in used

* Corresponding author: marijana.serdar@unizg.grad.hr

calcined clay, which was collected locally, was found to be very small (about 18%).

Table 1. Oxide compositions of materials.

Oxides	CEM I	CEM II	Clay	Limestone
CaO	63.19	46.94	1.74	71.59
SiO_2	19.51	33.65	49.80	20.21
Al_2O_3	4.21	7.55	17.04	4.32
Fe_2O_3	2.85	2.38	5.80	1.43
MgO	0.85	3.39	1.42	1.69
Na_2O	0.20	0.78	0.84	0
K_2O	0.48	0.74	2.00	0.15
TiO_2	0.12	0.22	0.75	0.52
P_2O_5	0.45	0.01	0.29	0.42
SO_3	2.30	4.02	0.06	1.48

The particle size distribution of these materials was determined using Laser diffraction technique and it is illustrated in the Figure 1.

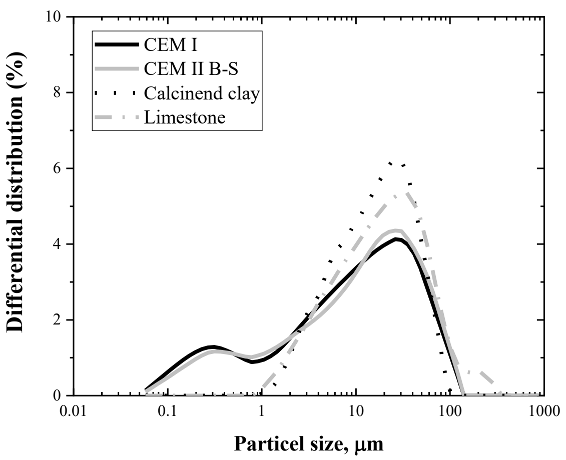

Fig. 1 Particle size distribution of all materials used in this study

Bridge mixture was taken as reference mixture (C435) for this study, while two mixtures were alternatives for the bridge design mix. The C340 mixture was made with same cement used in C435 and LC2-45 mixture was made with CEM 1 42.5R, 30% of calcined clay, and 15% limestone. The mixture compositions are given in the Table 2.

Table 2 Mixture details

Mix	w/b ratio	Binder, kg/m^3	Water, kg/m^3	Aggregate, kg/m^3		
				0-4 mm	4-8 mm	8-16 mm
C435	0.39	435	169.6	934	472	470
C340	0.40	340	136	1029	520	518
LC2-45		340	136	1001	505	504

2.2 Methods

2.2.1 Fresh properties and compressive strength

The fresh properties of all mixture were evaluated based on EN 12350. The fresh properties are given in Table 3. Three cubes of 150 mm × 150 mm× 150 mm were prepared for compressive strength and cylindrical specimen of 200 mm height and 100 mm diameter was used to evaluate the chloride migration coefficient. The compressive strength of all mixture was determined after 28 days of curing as per EN 12390-3 and chloride migration determined as per Nord test 492.

2.2.2 Determination of service life

In this study, the time required for corrosion to initiate and propagate was factored into the calculation of the reinforced structure's service life. Fick's second law of diffusion [7] was used to figure out how long it would take for the critical chloride content (Cl_{th} = 0.05% by weight of concrete) to get through a cover depth (d = 50 mm) and start corrosion of the reinforcement [8]. So, the time it takes for corrosion to start depends on the surface chloride concentration (Cl_s = 0.8% by weight of binder), the chloride diffusion coefficients (D_{cl}), and the ageing coefficients (m = 0.6). The diffusion coefficients of each mixture were evaluated based on a relation given in the Equation 1, which was established by authors' previous study[9].

$$D_{nssm} = 1.69 \times D_{cl} \quad (1)$$

2.2.3 Global Warming Potential (GWP)

The environmental impact assessment was used to evaluate the environmental impact of producing concrete ingredients from raw materials, transporting raw materials, and producing one cubic meter of concrete. In the analysis, the construction phase, service phase, and demolition phase were disregarded because they were assumed to be equivalent for all systems. Several indicators are available for measuring the impact, but the environmental impact of this work was expressed in terms of embodied carbon and energy in accordance with ISO 14040 guidelines. Embodied carbon is expressed as Global Warming Potential (GWP). Table 3 contains the conversion parameters for each material used to calculate the total embodied energy, as well as their respective references. It was assumed that Limestone Calcined Clay (LC2 blend) mixtures were pre-mixed and used as a single binder material.

Table 3 Global Warming Potential conversion factors

Material	GWP conversion factor, kg eq.CO_2/ kg	Reference
CEM I	0.803	[10]
CEM II B-S	0.646	[11]
LC2 blend	0.210	[5]
Crushed aggregate	0.00702	[12]
Superplasticizer (SP)	1.88	[13]

2.2.4 Sustainability factor (ϕ)

Muller et al. proposed a sustainability factor to evaluate the concrete mixture in terms of durability and environmental impact. The factor is determined by following relationship [14]:

$$\text{Sustainability factor, } \phi = (f_{ck} \times t_{SL}) / \text{GWP} \qquad (2)$$

where f_{ck} is 28-day compressive strength of the mixture, t_{SL} is the service life of the structure and embodied carbon is expressed as Global Warming Potential.

3 Results and discussion

3.1 Compressive strength and chloride migration coefficients

The fresh properties of each mixture are given in Table 4. The alternative mixtures needed more superplasticizer than reference mixture to reach the same workability, due to their lower amount of paste. However, all the mixture obtained the slump in between 80 mm to 120 mm.

Table 4 Fresh properties

Mix	Slump, mm	Air content, %	Wet density, kg/m^3	Super plasticizer dosage, % weight of binder
C434	105	2.4	2482	0.7
C340	105	3.1	2540	1.2
LC2-45	90	2.8	2505	1.4

Figure 2a-b illustrated the 28-day compressive strength and non-steady state chloride migration coefficients of all mixtures, calculated using the Eq 1.

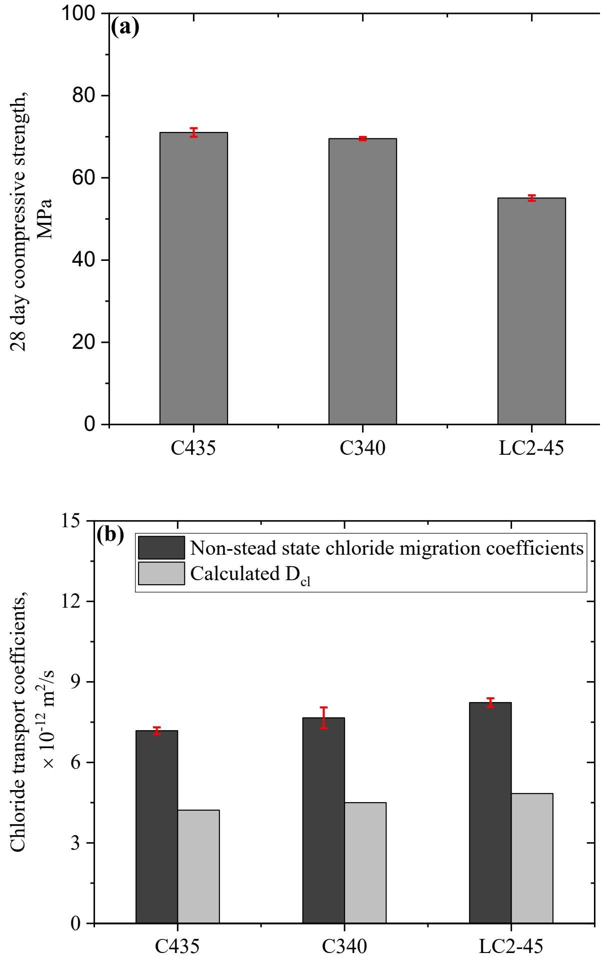

Fig. 2 a) compressive strength, and b) non-steady state chloride migration coefficients and calculated diffusion coefficients after 28 days of curing.

Compressive strengths of C435 and C340 were comparable, and an increment of 95 kg/m^3 in cement content had no discernible effect on compressive strength. In general, decreasing the cement content of concrete while maintaining the same w/b results in an increase in aggregate content, which has an adverse effect on the workability of the mixture and the performance of its compressive strength [15]. After 28 days of curing, the calcined clay mixture reached approximately 78% of the C435 strength, with 45% of the clinker replacement. Despite the lower clinker content, the alternative mixtures showed comparable values with reference mixture. In general, the chloride resistance of LC3 cements are considered to be very good; however, the clay in this study possessed a significantly lower amount of kaolinite, which is a crucial factor for chloride resistance [16]. However, the low-kaolin clay can also be a good choice for LC3 cements – especially in the region without high kaolin clay deposition.

3.2 Service life

The calculated service life is given in Table 5. The failure of the structure was determined at cumulative failure probability of 0.5 and the total life span assumed as the sum of corrosion initiation time and propagation time in years. The propagation time was taken as six years for all mixture.

Table 5 Service life of all mixtures

Mix	Service life in years
C434	94
C340	89
LC2-45	85

As visible from the Table, there was no significant reduction in the service life of mixtures with a significantly lower amount of cement. Unlike to compressive strength, the LC2-45 mix achieved 90% of service life compared to C435.

3.3 Global Warming Potential and sustainability factor

The GWP of each mixture was evaluated as per section 2.2.3. Figure 3 depicts the GWP of all mixture.

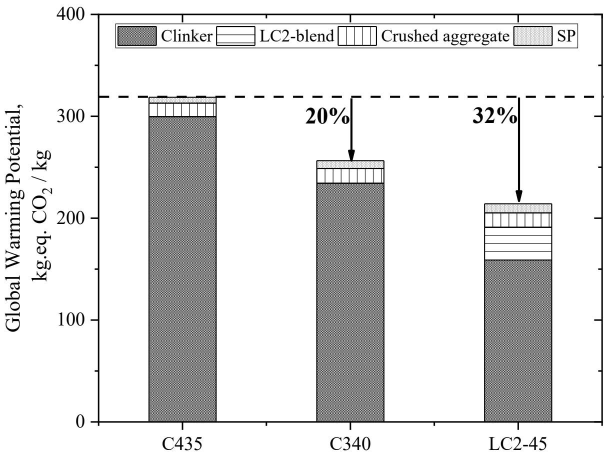

Fig. 3 Global warming potential of all mixtures

The ecological footprint considerably reduced for alternative mixture due to lower amount of clinker. The combination all these factors was expressed as sustainability factor, which is illustrated in the Figure 4.

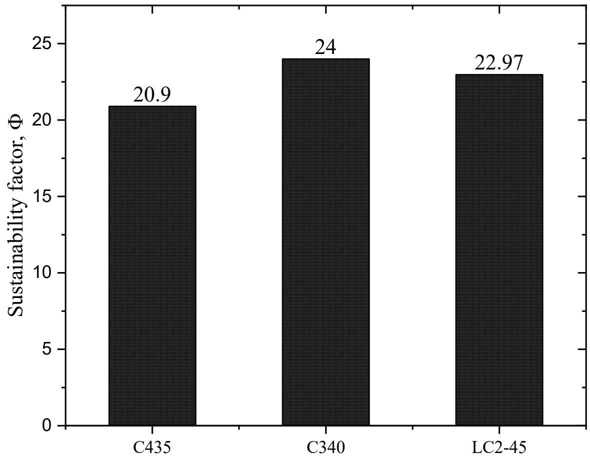

Fig. 4 Sustainability factor of all mixtures

Even with a greater amount of clinker, C435 was found to have the lowest sustainability factor. In contrast, the alternative binder performed better than C435 with a high replacement level. Moreover, since the kaolinite content of the clay plays a crucial role in the chloride penetration resistance, it could be expected to have even better sustainability factor for binders based on high kaolin clay [17], [18]. Nevertheless, present study demonstrated conclusively that the mixture could perform similarly in the sense of an overall sustainability factor even with a lower binder content and with the use of low-grade kaolin clay as a binder.

4 Conclusion

In this experimental study, concrete mixture design from a real concrete structure was compared to different approaches of lowering carbon footprint of concrete. The concrete was prepared with reduced binder contents of 340 kg/m^3 and Portland cement was replaced by 45% with calcined clay and limestone powder. Following conclusion are drawn from this study:

1. The total binder content of concrete could be reduced without compromising mechanical and durability performance. Additionally, the usage of alternative binders along with reduction in the total binder content, provides an extra pull towards sustainability.

2. The study demonstrates unequivocally that optimizing total binder content and utilizing alternative binders (particularly those that are locally available) are critical factors in ensuring sustainability of concrete

Acknowledgement

The presented research is a part of a scientific project “Advanced low CO2 cementitious materials”, ACT (grant no. IZHRZO 180590/1), financed within the Croatian–Swiss Research Program of the Croatian Science Foundation and the Swiss National Science Foundation with funds obtained from the Swiss-Croatian Cooperation Program. The first two authors also acknowledge the support of the project "Alternative binders for concrete: understanding microstructure to predict durability", ABC (grant no. HRZZ-UIP-2017-05-4767), financed by Croatian Science Foundation

References

[1] COP26, COP26 : EU helps deliver outcome to keep the Paris Agreement targets alive, no. November, pp. 2020–2021, 2021, [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/ip_21_6021.

[2] Scrivener, K. L., John, V. M., and Gartner, E. M., Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry, *Cem. Concr. Res.*, vol. 114, no. March, pp. 2–26, 2018, doi: 10.1016/j.cemconres.2018.03.015.

[3] Scrivener, K., Martirena, F., Bishnoi, S., and Maity, S., Calcined clay limestone cements (LC3), *Cem. Concr. Res.*, vol. 114, no. August 2017, pp. 49–56, 2018, doi: 10.1016/j.cemconres.2017.08.017.

[4] Fennis, S., Walraven, J., and Uijl, J. Den, The use of particle packing models to design ecological concrete, no. January, 2009.

[5] Gettu, R. *et al.*, Influence of supplementary cementitious materials on the sustainability parameters of cements and concretes in the Indian context, *Mater. Struct. Constr.*, vol. 52, no. 1, 2019, doi: 10.1617/s11527-019-1321-5.

[6] Yaphary, Y. L., Lam, R. H. W., and Lau, D., Reduction in cement content of normal strength concrete with used engine oil (UEO) as chemical admixture, *Constr. Build. Mater.*, vol. 261, p. 119967, 2020, doi: 10.1016/j.conbuildmat.2020.119967.

[7] Schiessl, P. and Concrete, T. G. M. C. for S. L. D. of C. S. I. F. for S., *Model code for service life design*. fib, CEB-FIP, 2006.

[8] Angst, U., Elsener, B., and Larsen, C. K., Vennesland (2009) Critical chloride content in reinforced concrete: a review, *Cem. Concr. Res.*, vol. 139, no. 12, p. 1122.

[9] Ram, K., Serdar, M., Londono-Zuluaga, D., and Scrivener, K., The Effect of Pore Microstructure on Strength and Chloride Ingress in Blended Cement Based on Low Kaolin Clay, *Case Stud. Constr. Mater.*, p. e01242, 2022.

[10] The European Cement Association, Environmental Product Declaration: Portland Cement (CEM I) produced in Europe, no. Cem I, 2020, [Online]. Available: https://cembureau.eu/media/3lplreko/epd-for-cement-cem-i.pdf.

[11] Holcim, 2. EPD Holcim CEMENTY.pdf. 2013.

[12] Müller, H. S., Haist, M., and Vogel, M., Assessment of the sustainability potential of concrete and concrete structures considering their environmental impact , performance and lifetime, pp. 1–17, 2014, doi: 10.1016/j.conbuildmat.2014.01.039.

[13] Federation, T. E. *et al.*, Declaration of conformity for products with Model EPDs.

[14] Müller, H. S., Haist, M., and Vogel, M., Assessment of the sustainability potential of concrete and concrete structures considering their environmental impact, performance and lifetime, *Constr. Build. Mater.*, vol. 67, no. PART C, pp. 321–337, 2014, doi: 10.1016/j.conbuildmat.2014.01.039.

[15] Seddik, M., Zitouni, S., and Belâabes, S., Effect of content and particle size distribution of coarse aggregate on the compressive strength of concrete, *Constr. Build. Mater.*, vol. 24, no. 4, pp. 505–512, 2010, doi: 10.1016/j.conbuildmat.2009.10.009.

[16] Maraghechi, H., Avet, F., Wong, H., Kamyab, H., and Scrivener, K., Performance of Limestone Calcined Clay Cement (LC3) with various kaolinite contents with respect to chloride transport, *Mater. Struct. Constr.*, vol. 51, no. 5, pp. 1–17, 2018, doi: 10.1617/s11527-018-1255-3.

[17] Fan, Y., Zhang, S., Kawashima, S., and Shah, S. P., Influence of kaolinite clay on the chloride diffusion property of cement-based materials, *Cem. Concr. Compos.*, vol. 45, pp. 117–124, 2014, doi: 10.1016/j.cemconcomp.2013.09.021.

[18] Du, H. and Pang, S. D., High-performance concrete incorporating calcined kaolin clay and limestone as cement substitute, *Constr. Build. Mater.*, vol. 264, Dec. 2020, doi: 10.1016/j.conbuildmat.2020.120152.