New cements: a look at the future of the construction sector for an ecological transition

Dott. Ing. Edoardo Runcio[1], Prof.ssa Giuliana Somma[2]

[1] *Polytechnic Department of Engineering and Architecture, Udine, Italy, edoardo.runcio@uniud.it*

[2] *Polytechnic Department of Engineering and Architecture, Udine, Italy, giuliana.somma@uniud.it*

Abstract

Concrete is the most widely used building material in the world: its fundamental component is clinker, the production of which results in the emission of 900 kg of CO_2 per ton of concrete. The impact on the environment deriving from the consumption of water to be included in the mixture and the extraction of aggregates, which are usually natural gravels of calcareous origin, is also not negligible and creates impoverishment of re-sources. The aim of this study is to promote the use of cements in concrete that are made up of a reduced percentage of clinker, replaced by more sustainable materials. Several experimental studies conducted by various re-searchers comparing traditional type I cement with type II, II/C-M, V and VI cements are taken into consideration. The comparison between the various products is carried out not only in terms of resistance at 28 days, but the entire maturation cycle is taken into account. The workability of the material obtained is also considered, wanting to guarantee the possibility of producing a concrete that can assume all the fluidity classes defined by the regulation. A further aspect that is analyzed is represented by carbon dioxide emissions: for each type of cement the release of CO_2 into the atmosphere is analyzed, defining an innovative efficiency parameter given by the ratio between the mechanical resistance and carbon dioxide emissions per m^3 of concrete. The aim of this work is to demonstrate the effectiveness of the new mixtures required by the regulation, encouraging the designer of the future to adopt them on site, in order to obtain a more sustainable construction sector. The results obtained can also be a starting point for future regulations that would introduce the concept not only of the concrete resistance, but also of the environmental efficiency.

1 Introduction

The construction industry is one of the most significant sources of carbon dioxide emissions into the atmosphere, most of which come from the production process of cement and in particular clinker: in this case we are talking about 8% of global emissions [1]. This study analyses studies carried out by university researchers in the field of replacing clinker with other materials to obtain more sustainable cements with high percentages of recycled material [2], [3]. There are various types of cement on the market in addition to the traditional CEM I Portland, but these are often not taken into consideration by designers when deciding on the type of mixture to use on site. The mechanical and environmental performance of some of the mixtures on the market is presented, highlighting their strengths and weaknesses, so as to provide designers with a scientific reference for choosing the most suitable mixtures for their work. The novelty of this study is the introduction of a coefficient β_{CO2} for the evaluation of the performance of a mixture in terms of resistance and in terms of sustainability: it is calculated as the ratio between the concrete compressive resistance [MPa] and the amount of CO_2 emitted by 1 m^3 of it.

2 Main components following UNI EN 197

Below we analyze the peculiarities of those materials that are fundamental to obtain cement intended as a binder. First of all, the presence of Portland cement clinker is fundamental, obtained by burning raw materials containing high percentages of calcium oxide (CaO), silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), iron oxide (Fe_2O_3) and negligible quantities of other elements. Alongside the clinker, which is a constant for obtaining the finished product, there are, alternatively:

- Granulated blast furnace slag, obtained by melting iron minerals in a blast furnace, composed of at least two thirds of calcium oxide, magnesium and silicon dioxide;

- Pozzolanic materials, natural substances composed mainly of silica and alumina. These, if finely ground, become reactive when placed in contact with water, determining the production of calcium silicate and calcium aluminate, guaranteeing mechanical resistance to the material;

- Fly ash, produced by electrostatic precipitation of dust contained in the exhaust gases of boilers fueled by coal dust (other ash does not comply with the requirements identified by the current legislation. It is divided into siliceous fly ash, consisting mainly of silicon oxide, and calcic fly ash, also consisting of silicon oxide, but also of reactive calcium oxide (CaO);

- Calcined shale, with hydraulic properties similar to those of clinker, obtained by combustion in a furnace at a temperature of 800°C and composed mainly of silicon dioxide;

- Limestone understood as powder of material of natural origin and with a calcium carbonate content greater than 75% [4].

In the current UNI EN 197-1 [5] regulation, the main common cements are classified into five main types as in Tab.1, characterized by a decreasing percentage of clinker, replacing it with the materials described above:

- CEM I: Portland cement;

- CEM II: Portland cement mix;

- CEM III: blast furnace cement;

- CEM IV: pozzolanic cement;

- CEM V: composite cement.

Table 1: Components of the cement following UNI EN 197-1 [5]

Main types	Notation		Clinker	Blast-furnace slag	Silica fume	Pozzolana		Fly ash		Burnt shale	Limestone		Minor additional constituents
			K	S	D	natural P	natural calcined Q	siliceous V	calcareous W	T	L	LL	
CEM I	Portland cement	CEM I	95-100	-	-	-	-	-	-	-	-	-	0-5
CEM II	Portland-slag cement	CEM II/A-S	80-94	6-20	-	-	-	-	-	-	-	-	0-5
		CEM II/B-S	65-79	21-35	-	-	-	-	-	-	-	-	0-5
	Portland-silica fume cement	CEM II/A-D	90-94	-	6-10	-	-	-	-	-	-	-	0-5
	Portland-pozzolana cement	CEM II/A-P	80-94	-	-	6-20	-	-	-	-	-	-	0-5
		CEM II/B-P	65-79	-	-	21-35	-	-	-	-	-	-	0-5
		CEM II/A-Q	80-94	-	-	-	6-20	-	-	-	-	-	0-5
		CEM II/B-Q	65-79	-	-	-	21-35	-	-	-	-	-	0-5
	Portland-fly ash cement	CEM II/A-V	80-94	-	-	-	-	6-20	-	-	-	-	0-5
		CEM II/B-V	65-79	-	-	-	-	21-35	-	-	-	-	0-5
		CEM II/A-W	80-94	-	-	-	-	-	6-20	-	-	-	0-5
		CEM II/B-W	65-79	-	-	-	-	-	21-35	-	-	-	0-5
	Portland-burnt shale cement	CEM II/A-T	80-94	-	-	-	-	-	-	6-20	-	-	0-5
		CEM II/B-T	65-79	-	-	-	-	-	-	21-35	-	-	0-5
	Portland-limestone cement	CEM II/A-L	80-94	-	-	-	-	-	-	-	6-20	-	0-5
		CEM II/B-L	65-79	-	-	-	-	-	-	-	21-35	-	0-5
		CEM II/A-LL	80-94	-	-	-	-	-	-	-	-	6-20	0-5
		CEM II/B-LL	65-79	-	-	-	-	-	-	-	-	21-35	0-5
	Portland-composite cement[c)]	CEM II/A-M	80-88	12-20									0-5
		CEM II/B-M	65-79	21-35									
CEM III	Blast furnace cement	CEM III/A	35-64	36-65	-	-	-	-	-	-	-	-	0-5
		CEM III/B	20-34	66-80	-	-	-	-	-	-	-	-	0-5
		CEM III/C	5-19	81-95	-	-	-	-	-	-	-	-	0-5
CEM IV	Pozzolanic cement[c)]	CEM IV/A	65-89	-	11-35					-	-	-	0-5
		CEM IV/B	45-64	-	36-65					-	-	-	0-5
CEM V	Composite cement[c)]	CEM V/A	40-64	18-30	-	18-30			-	-	-	-	0-5
		CEM V/B	20-38	31-49	-	31-49			-	-	-	-	0-5

Cement producers can therefore vary the composition of the mixture within the variation ranges proposed by the regulation, guaranteeing a reduction in the clinker content compared to a traditional Portland cement of up to over 90% (CEMIII/C).

With the publication of the recent UNI EN 197-5 [6] regulation, further types of mixtures have been added to the list, in particular composite ternary cements, characterized by an extension of the possible combinations of the constituents which, unlike the case of 197-1, are not two but three. With this evolution of the regulatory code, those components with pozzolanic behaviour or in any case hydraulically active are exploited to a greater extent. Through this strategy it has been possible to further reduce the clinker content and consequently the carbon dioxide emissions linked to the production process.

Table 2: Components of the cement following UNI EN 197-5 [6]

Main types	Notation		Composition (percentage by mass)										
			Main constituents										Minor additional constituents
			Clinker	Blast-furnace slag	Silica fume	Pozzolana natural	Pozzolana natural calcined	Fly ash siliceous	Fly ash calcareous	Burnt shale	Limestone		
			K	S	D[b)]	P	Q	V	W	T	L[c)]	LL[c)]	
CEM II	Composite Portland cement	CEM II/C-M	50-64	36-50									0-5
CEM IV	Composite cement	CEM VI (S-P)	35-49	31-59	-	6-20	-	-	-	-	-	-	0-5
		CEM VI (S-V)	35-49	31-59	-	-	-	6-20	-	-	-	-	0-5
		CEM VI (S-L)	35-49	31-59	-	-	-	-	-	-	6-20	-	0-5
		CEM VI (S-LL)	35-49	31-59	-	-	-	-	-	-	-	6-20	0-5

Following numerous experimental campaigns that have demonstrated good mechanical performance and durability, cements containing recycled fine material obtained from the demolition of concrete buildings have also been admitted; in this case the reference regulation is 197-6 [7]. Below is a summary table of the new mixtures:

Table 3: Components of the cement following UNI EN 197-6 [7]

Main types	Notation		Composition (percentage by mass)											
			Main constituents											Minor additional constituents
			Clinker	Fine fraction of recycled concrete	Blast-furnace slag	Silica fume	Pozzolana		Fly ash		Burnt shale	Limestone		
							natural	natural calcined	siliceous	calcareous				
			K	F	S	D [b]	P	Q	V	W	T	L [c]	LL [c]	
CEM II	Portland cement with recycled concrete	CEM II/A-F	80-94	6-20	-	-	-	-	-	-	-	-	-	0-5
		CEM II/B-F	65-79	21-35	-	-	-	-	-	-	-	-	-	0-5
	Composite Portland cement	CEM II/A-M	80-88	6-14	6-14									0-5
		CEM II/B-M	65-79	6-29	6-29									0-5
		CEM II/C-M	50-64	6-20	16-44									0-5
CEM VI	Composite cement	CEM VI	35-49	6-20	31-59	-	-	-	-	-	-	-	-	0-5

In particular, the presence of Portland cement with recycled fines, with a binary composition, and of composite cement and composite Portland, with a ternary composition, including the clinker, the recycled fines and a third component to be chosen from those permitted in UNI EN 197-1, is noted.

3 Hypothesis for the experimental tests

In order to evaluate the properties of new cements, different from those traditionally used, the results of two experimental campaigns [8] [9] involving all categories, from I to VI, in accordance with the UNI EN 197-1 standard, are reported.

In the first study, Portland cement CEM I, composed of clinker for 95%, is compared with CEM II, characterized by a clinker substitution of up to 35%, and CEM V, with a low percentage of clinker as it is replaced by slag, pozzolana and siliceous ash.

In the second study, CEM II/C-M, containing less than 50% clinker, and CEM VI, with an even lower percentage of clinker, obtained by inserting into the mixture, in addition to slag, a further constituent chosen from natural pozzolana, silica fly ash and limestone, are taken into consideration.

In the following Tabs.4-7 the components of the considered cements and concretes are indicated. It is highlighted that the water to cement ratio (w/c) is taken almost constant in a range between 0,33 and 0,41 [10], [11].

Table 4: Composition of the cements of the first study

Type of cement	Constituents (%)		
	Clinker K	Blast.furnace slag S	Fly ash V-W
CEM I	100	-	-
CEM II/B-W (65K-35W)	65	-	35
CEM II/B-M (65K-30V-5D)	65	-	30
CEM V/B (30K-40S-30V)	30	40	30
CEM V/A (40K-30S-30V)	40	30	30

Table 5: Composition of the cements of the second study

Type of cement	Constituents (%)			
	Clinker K	Blast-furnace slag S	Limestone LL	Fly ash V
CEM II/C-M (30S-10LL)	60	30	10	-
CEM II/C-M (30V-10LL)	60	-	10	30
CEM VI (35S-20LL)	45	35	20	-
CEM VI (35S-20V)	45	35	-	20

Table 6: Composition of the concretes of the first study

Study	Concrete notation	w/c	Cement content (kg/m^3)	Water (kg/m^3)	Additive PCE (kg/m^3)	Coarse aggregate (kg/m^3)
I	CEM I	0.41	445	195	-	1085
	CEM II/B-W (65K-35W)	0.33	530	175	-	1085
	CEM II/B-M (65K-30V-5D)	0.44	350	155	-	1085
	CEM V/B (30K-40S-30V)	0.35	480	170	-	1085
	CEM V/A (40K-30S-30V)	0.39	430	170	-	1085

Table 7: Composition of the concretes of the second study

Study	Concrete notation	w/c	Cement content	Water	Additive PCE	Coarse aggregate (kg/m^3)		Sand 0-2 mm
			(kg/m^3)	(kg/m^3)	(kg/m^3)	8-16 mm	2-8 mm	(kg/m^3)
II	CEM II/C-M (30S-10LL)	0.35	340	120	10.2	725	565	725
	CEM II/C-M (30V-10LL)		340	120	10.2	725	565	725
	CEM VI (35S-20LL)		340	120	10.2	725	565	725
	CEM VI (35S-20V)		340	120	10.2	725	565	725

4 Compressive strength

4.1 Comparison between CEM I – CEM II - CEM V

The evaluation of the mixtures was based on the compressive strength of cubic specimens with a side of 100 mm, considering the evolution from 3 days up to 180 days from the time of casting. It was observed that the resistance in the first days of the binary and ternary mixtures is significantly lower than that of Portland cement concrete: this is because the clinker content is reduced.

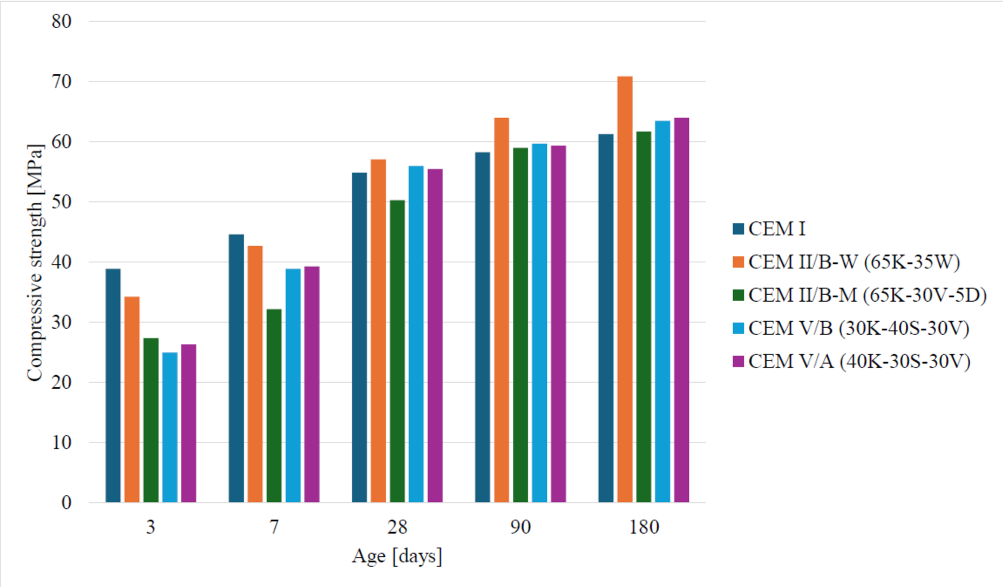

Fig. 1 Compressive strength of concrete of the first study at different times from curing

At a maturation time of 28 days, the resistances are comparable to a traditional mixture. Considering the resistance at 180 days, it is observed that Portland cement concrete is the one with the lowest resistance, while CEM II/B-W despite a low amount of clinker (65%) in the cement composition, is the one that guarantees the best performance: the resistance is 16% greater than the CEM I. This behaviour is attributable to the physical-chemical properties of the fly ashes that densify the concrete with a "microfiller" effect and promote the formation of C-S-H through the pozzolanic reaction.

4.2 Comparison between CEM II-C/M – CEM VI

The compression tests on these two classes of cement were conducted considering the resistances between 2 and 90 days of maturation. It is observed that CEM II/C-M (30S-10LL) shows a higher resistance than the others for all the time of testing, while CEM II/C-M (30V-10LL), even with the same percentage of clinker, guarantees a lower resistance. The only difference between Cem II/C-M (30S-10LL) and CEM ((/C_ (30V-10LL) is the presence of "S" (Blast furnace slag) in the first and fly ashes in the second: it is evident, as observed also in the first study, that the fly ashes have a good influence in the mechanisms increasing the compressive strength.

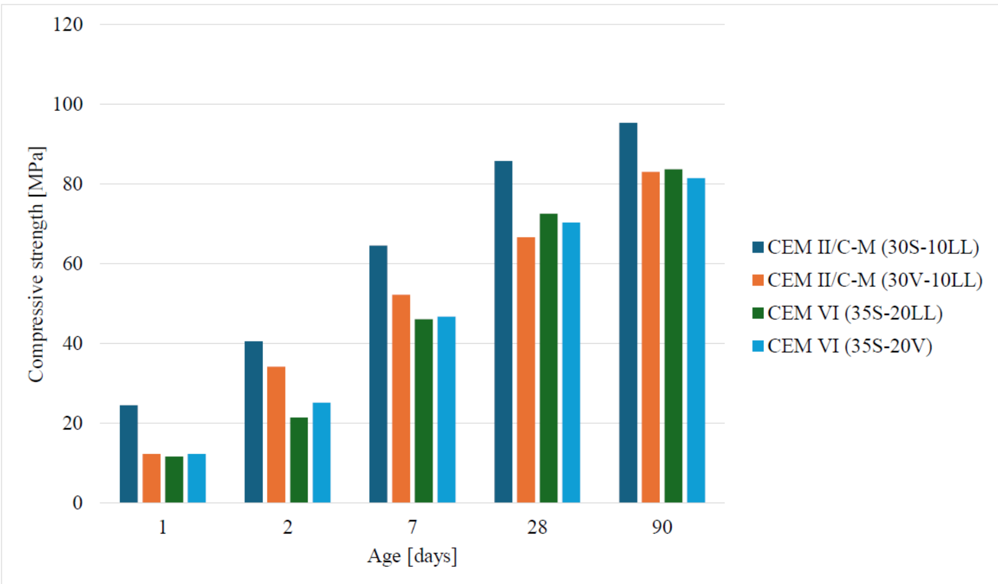

Fig. 2 Compressive strength of concrete of the second study at different times from curing

By observing the resistance after 90 days of curing, it is highlighted that CEM II/C-M(30V-10LL), CEM VI (35S-20LL) and CEM VI (35S-20V) have the same strength, despite the lower amount of clinker (45%) of the two CEM VI. It means that the addition of limestone and/or fly ash has a performing influence.

5 Durability tests: carbonation

5.1 Comparison between CEM I – CEM II - CEM V

Carbonation depth was measured on 100 mm concrete cubes exposed to a 4% CO_2 enriched environment for up to 26 weeks. Prior to exposure, the specimens were cured in water at 20 °C for 28 days and then stored at ambient conditions for at least 14 days to allow for air drying. The top, bottom and two opposite sides of the concrete specimens were coated with epoxy paint to allow CO_2 penetration only through the other two exposed sides.

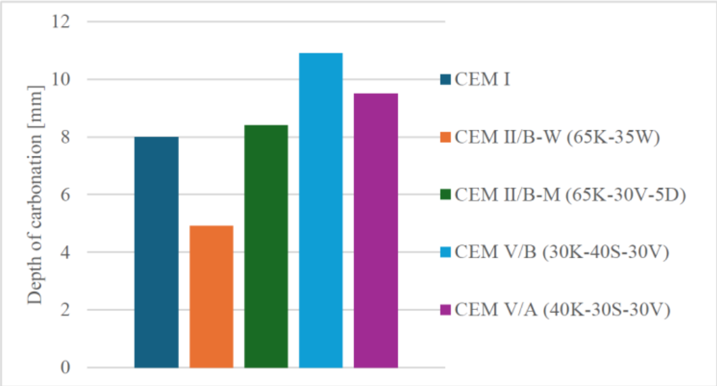

Fig. 3 Depth of carbonation at 28 days from curing for the concretes of the first study

A first evidence is that the quantity of clinker in the mix tends to decrease the carbonation depth, as in Fig. 3, since being rich in calcium hydroxide it provides a greater buffer against carbonation. An exception is made for CEM II/B-W (65K-35W), which guarantees the best behaviour in terms of durability: this trend is justified by the decrease in the water-cement ratio, which determines the formation of a denser and less permeable concrete microstructure, with a reduction of air in the mix and therefore an increase in durability. It can therefore be stated that the penetration depth of carbonation is directly proportional to the increase in the w/c ratio and the pozzolanic material content, while it is inversely proportional to the clinker content.

5.2 Comparison between CEM II-C/M – CEM VI

The carbonation susceptibility test was conducted on concretes with different cement types and under 4% accelerated CO_2 conditions for 70 days.

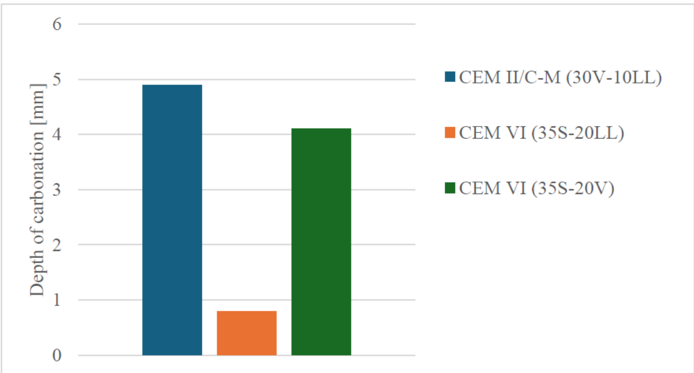

Fig. 4 Depth of carbonation at 28 days from curing for the concretes of the second study

The graph in Fig.4 shows that the CME VI (35L20LLhas the best behaviour with respect to durability, leading to low carbonation depths: this trend can be attributed to the presence of limestone in the mixture.

6 Workability

A fundamental aspect for concrete mixes is their workability: therefore, the behaviour of concretes obtained with the different types of cement analysed in this study was evaluated. Concrete production and tests on fresh concrete were carried out in accordance with UNI EN 12350:2019, parts 1 and 2 [12] [13]. Immediately after pouring, the initial subsidence was recorded, and the slump loss was monitored at 30-minute intervals up to a total of 150 minutes, by means of a compaction factor test. Concrete mixes were designed to reach the workability class S3, with a subsidence between 60 and 180 mm, in accordance with UNI EN 206:2021 [14]. To better understand the influence of the materials present in the cement mixture, the w/c ratio is considered almost constant and hence not influencing the workability.

6.1 Comparison between CEM I – CEM II - CEM V

The tests, being carried out on concretes with slightly different w/c ratios, produce results that are not exactly comparable to each other, however it is observed that comparing CEM I with CEM V/A (40K-30S-30V) (having w/c similar) the second one is much more workable.

Table 8: Slump test results on concretes of the first study

Notation of concrete	w/c ratio	Slump test [mm]
CEM I	0.41	100
CEM II/B-W (65K-35W)	0.33	120
CEM II/B-M (65K-30V-5D)	0.44	115
CEM V/B (30K-40S-30V)	0.35	145
CEM V/A (40K-30S-30V)	0.39	140

6.2 Comparison between CEM II-C/M – CEM VI

It is observed a low workability for all the samples, greatly lower with respect to the tests done in the first study.

7 Sustainability of the mixtures

As is known, clinker is the main responsible for the production of CO_2 among the materials constituting the cement. In the following Tab.9 the production of CO_2 in [kg/m^3] is indicated for every material present in the cement. The following table clearly shows how the emissions associated with clinker are one or two orders of magnitude higher than the other constituents of cement. It is therefore necessary, to make modern structures more sustainable, reducing the quantity of clinker in favour of innovative mixtures [15], [16]. It is evident that the other materials have a negligible contribution in the CO_2 emissions in comparison to clinker.

Table 9: CO_2 emissions of the concrete components

Concrete components	CO_2 [kg CO2/m^3]
Clinker	2191
Fly ash	9,6
Blast-furnace slag	160,8
Silica fume	33,6
Sand	12
Gravel	12

The CO_2 emissions have been calculated for every type of concrete considered (Tabs. 6 and 7). The results obtained show that the CO_2 released is directly proportional to the clinker content. Portland cement mixes are the most emissive in terms of carbon dioxide, while the most virtuous behaviour is guaranteed by CEM VI.

Table 10: CO_2 emissions and efficiency coefficient

Concrete notation	Cement content (kg/m^3 of concrete)	w/c ratio	CO_2 emissions (kg/m^3 of concrete)	$f_{c,28gg}$ [MPa]	β_{CO2} [MPa/(kgCO$_2$/m^3)]
CEM I	445	0,41	458,6	54,9	0,12
CEM II/B-W (65K-35W)	340	0,33	330	57,1	0,17
CEM II/B-M (65K-30V-5D)	260	0,44	265,7	50,3	0,19
CEM V/B (30K-40S-30V)	145	0,35	158,6	56	0,35
CEM V/A (40K-30S-30V)	180	0,39	180	55,5	0,31
CEM II/C-M (30S-10LL)	340.0	0.35	154,2	85,8	0,56
CEM II/C-M (30V-10LL)	340.0		154,2	66,7	0,43
CEM VI (35S-20LL)	340.0		115,7	72,6	0,63
CEM VI (35S-20V)	340.0		115,7	70,4	0,61

In order to relate the CO_2 emissions to the compressive resistance of the concrete an index of performance of the concrete, β_{CO2}, calculated as the ratio between the concrete compressive resistance [MPa] and the amount of CO_2 emitted by 1 m^3 of it [kgCO$_2$/m^3] has been introduced (Tab.10). The greater this index is the more effective is the concrete, both in terms of high resistance and low CO_2 emissions. The efficiency index of the mixtures has been calculated at 28 days. It is evident that the best efficiency is guaranteed by mixtures with low water-cement ratios and which therefore even though they contain more cement (hence more clinker, with the related CO_2 emissions), they guarantee high mechanical performance, determining a greater performance of the concrete mixture.

8 Conclusions

Until now, building design has been focused only on mechanical performance and economic savings in terms of the costs of individual materials, without giving weight to the impact that these have on the environment. In a perspective of transition towards more sustainable design practices, it is essential to take into account other factors, such as savings in terms of CO_2 emissions and in terms of consumption of water and virgin resources. This study has therefore carried out a review of the main properties of some of the cement mixtures available on the market as an alternative to traditional Portland cement; in particular, those mixtures that lead to a greater replacement of clinker with other components have been considered. An innovative concrete performance index, β_{CO2}, has been developed in this manuscript: it takes into account both mechanical resistance and the quantity of emissions, thus providing a possible tool for designers to make a responsible and reasoned choice of materials to be used on site. The hope is that in the future, regulatory bodies will include, alongside the current limit states, threshold values in the emission/performance ratio, thus starting a transition of the world of structures towards a sustainable future

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References

[1] Federbeton. 2022. “Rapporto di sostenibilità Federbeton 2022.” Accessed January 2025. https://blog.federbeton.it/wp-content/uploads/2023/10/Rapporto_di_Sostenibilita%CC%80_Federbeton_2022.pdf

[2] Schneider, Romer, Tschudin, Bolio. 2011. “Sustainable cement production - present and future”. *Cement and Concrete Research*: Volume 41 (7), 642-650.

[3] Abdul-Wahab, Al-Dhamri, Ram, Chatterjee. 2021. “An overview of alternative raw materials used in cement and clinker manufacturing”, *International Journal of Sustainable Engineering*: Volume 14 (4), 743-760.

[4] Yaşar, Erdoğan, Kılıç. 2004. “Effect of limestone aggregate type and water–cement ratio on concrete strength”. *Materials Letters*: Volume 58 (5), 772-777.

[5] UNI EN 197-1: 2011. “Cemento – Parte 1: Composizione, specificazioni e criteri di conformità per cementi comuni”.

[6] UNI EN 197-5:2021. “Cemento – Parte 5: cemento Portland composito CEM II/C-M e cemento composito CEM VI”.

[7] UNI EN 197-6: 2023. “Cemento – Parte 6: Cemento con materiali da costruzione riciclati”.

[8] Limbachiya, Bostanci, Kew. 2014. “Suitability of BS EN 197-1 CEM II and CEM V cement for production of low carbon concrete”. *Construction and Building Materials*: 71, 397-405.

[9] Krol, Giergiczny, Kuterasinka-Warwas. 2020. “Properties of Concrete Made with Low-Emission Cements CEM II/C-M and CEM VI”. *Materials* 13(10):22-57.

[10] Yiğiter, Yazıcı, Aydın. 2007. “Effects of cement type, water/cement ratio and cement content on sea water resistance of concrete”. *Building and Environment*: Volume 42 (4), 1770-1776.

[11] Singh, Munjal, Thammishetti. 2015. “Role of water/cement ratio on strength development of cement mortar”. *Journal of Building Engineering*: Volume 4, 94-100.

[12] UNI EN 12350-1:2019. “Testing fresh concrete – Part 1: Sampling and common apparatus”.

[13] UNI EN 12350-2:2019. “Testing fresh concrete – Part 2: Slump test”.

[14] UNI EN 206:2021. “Calcestruzzo – Specificazione, prestazione, produzione e conformità”.

[15] Zhang, Cheng, Lo. 2014. “Life cycle carbon footprint measurement of Portland cement and ready mix concrete for a city with local scarcity of resources like Hong Kong”. *The International Journal of Life Cycle Assessment*: Volume 19, 745-757.

[16] Mohamad, Muthusamy, Embong, Kusbiantoro, Hashim. 2022. “Environmental impact of cement production and Solutions: a review”. *Materials Today*: Proceedings, Volume 48 (4), 741-746.