Durability performance of concrete with low binder content

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Extended Abstract

MSc Dissertation in Civil Engineering

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1. Introduction

1.1. Preliminary remarks

Currently, the lifestyle practiced in industrialized societies is questionable, in part due to the large consumption of non-renewable materials without major future concerns, making it practically unaffordable, economically, socially, as well as environmentally.

Worldwide, around 3750 million tons of cement are produced annually (I.E.A., 2018). Using the ratio often referred (albeit conservative) of 1 tonne of carbon dioxide emitted for each tonne of cement produced, alarming numbers are reached, and it is foreseeable that these may currently be higher and will continue to increase in the coming years. Thus, any contribution aimed at reducing cement consumption will generate significant gains in terms of its environmental and economic impact. These increasingly demanding environmental challenges are the entire responsibility of modern day society, and it is the duty of this same society to study the best possible way to get around this issue, contributing to a sustainable future.

1.2. Scope and methodology

The main goal of this research is to evaluate the possibility of producing concrete with reduced binder content, guaranteeing acceptable levels of safety, both structural and durability-wise, as well of good workability levels. This will be able to reduce cement's environmental impact and eventually reduce the final cost of the concrete. To this end, an experimental plan was developed, involving most of the main tests characterizing the concrete, allowing the evaluation of its behaviour in the fresh- and hardened-state, and showing its durability. In total, 8 different compositions were developed, divided into two families. The first family consists of mixes with Portland cement as the only binder present, and the second one with Portland cement replaced at 30% by mass with fly ash, to investigate the influence of this mineral addition on the behaviour of concrete. The total amount of binder in both families was the same, i.e. between 180 and 260 kg/m^3 of concrete. For the different compositions, it was necessary to vary the water/binder ratio (W/B), and, in some cases, some corrections to the dosage of admixtures were necessary, in order to reach previously established levels of workability.

The methodology adopted throughout this study can be divided into phases. The first one was dedicated to research, where a survey and analysis of bibliographical references was made, both nationally and internationally, with the aim of obtaining the necessary knowledge to make the evolution of this study faster and more effective. After determining the different factors influencing the following phases, the experimental campaign was planned (phase 2), defining the composition of the mixes under study and the main tests to be carried out to characterize the aggregates and the durability of these mixes. The last phases comprise the execution of the laboratory activity as well the interpretation and discussion of the results.

1.3. Materials

For the development of this work, two different grading curve coarse aggregates were used, as well as two types of fine aggregates, with total grading curve ranging from 0.063 to 16 mm. The cement chosen for the experimental campaign was type I Portland cement of class 42.5 R (CEM I42.5R) and fly ash was also used as partial substitute of Portland cement.

1.4. Concrete composition

To design these mixes, the reference Faury curve method was used as basis. To guarantee the same comparative reference, the proportions of aggregates in the different compositions were kept constant. In each family, the amount of binder included 180, 210, 240 and 260 kg/m^3. Table 1 presents the different compositions studied. In order to compensate the water absorbed by the different aggregates, a supplementary amount of water was introduced.

Table 1 - Compositions (kg/m^3)

Compositions	Cement (kg/m^3)	Fly ash (kg/m^3)	H_2O (l/m^3)	W/B	Coarse aggregates (kg/m^3)	Fine aggregates (kg/m^3)	Superplasticizer (%)
CM180	180	-	135	0.75	939.8	1153.0	1.6
CM210	210	-	134.4	0.64	930.2	1141.2	1.12
CM240	240	-	146.4	0.61	905.1	1106.2	0.70
CM260	260	-	169	0.65	870.8	1068.4	0.24
CM180CV30	126	54	135	0.75	934.0	1145.8	1.6
CM210CV30	147	63	128.1	0.61	930.1	1141.1	1.12
CM240CV30	168	72	124.8	0.52	922.3	1131.5	0.75
CM260CV30	182	78	163.8	0.63	909.1	1115.3	0.24

1.5. Aggregates testing

To determine and characterize the aggregates' properties, several tests were performed and represented in the Table 2.

Table 2 - Aggregates tests and standards

Aggregate tests	Standards
Sieve analysis	NP EN 933-1 (2000) and NP EN 933-2 (1999)
Particle density and water absorption	NP EN 1097-6 (2003)
Sand equivalent	NP EN 933-8 (2002)
Apparent bulk density and void volume	NP EN 1097-3 (2002)

1.6. Concrete testing

Concrete was characterized in its fresh state using the slump test. This test was conducted according to the standard NP EN 12350-2 (2009). For the characterization of concrete in the hardened state, the compressive strength test was used as the main indication of mechanical performance. As for durability performance, carbonation depth, resistance to chloride penetration, water absorption by capillarity and immersion tests were performed. Table 3 presents all tests carried out in the hardened state as well the standards used.

Table 3 - Hardened concrete tests and standards

Hardened concrete tests (mechanical properties)	Standards
Compressive strength	NP EN 12390-3 (2011)
Hardened concrete tests (durability properties)	**Standards**
Capillary water absorption	LNEC E-393 (1993)
Water absorption by immersion	LNEC E-394 (1993)
Carbonation depth	LNEC E-391 (1993)
Resistance to chloride penetration	LNEC E-463 (2004)

2. Experimental results and discussion

2.1. Aggregate proprieties

The used aggregates' main physical properties are seen in Table 4. For the development of this experimental work, the coarse aggregates used were characterized by their size and mineralogical nature (quarry crushed limestone for coarse aggregates and riverbed siliceous sand for fine aggregates).

Table 4 - Properties of aggregates

Properties	Coarse aggregates		Fine aggregates	
	Limestone 1	Limestone 2	Fine sand	Coarse sand
Water absorption in 24 h (%)	1.1	1.4	0.6	0.8
Density of the impermeable material of the particles (kg/m^3)	2697	2693	2649	2607
Oven dried density (kg/m^3)	2617	2596	2649	2553
Density of particles saturated with dry surface (kg/m^3)	2647	2632	2622	2574
Bulk density in uncompressed sample (kg/m^3)	1445	1374	1686	1697

2.2. Fresh concrete properties

The slump test was done using the Abram's cone and its results are represented in Table 5. With the designed mixes' composition, it was possible to achieve slump classes between S2 and S3. The high reduction of the binding material, particularly cement, resulted in very poor workability, which led to the need of using admixtures, as well as the adjustment of the W/B ratio, in order to maintain the desired workability levels. For compositions with lower binder content (CM180 and CM210), there was a need for a longer time of vibration and concrete compaction due to the high loss of workability.

Table 5 - Slump test

Composition	CM180	CM210	CM240	CM260	CM180CV30	CM210CV30	CM240CV30	CM260CV30
Slump (mm)	55	62	96	65	105	61	50	86

2.3. Hardened concrete properties

2.3.1. Compressive strength

Most of the mixes presented mechanical properties that can be classified within the range of structural concrete, with average compressive strengths between 29 and 40 MPa (Table 6). Observing the values presented, it is noticeable that the substantial reduction of binder, namely cement, is prejudicial to the compressive strength of concrete (Figure 1).

Table 6 - Compressive strength

Composition	CM180	CM210	CM240	CM260	CM180CV30	CM210CV30	CM240CV30	CM260CV30
28 days (MPa)	18.1	28.1	28.6	28.9	12.7	22.7	31.8	22.5
91 days (MPa)	20.5	29.8	29.7	31.5	15.8	29.3	39.7	30

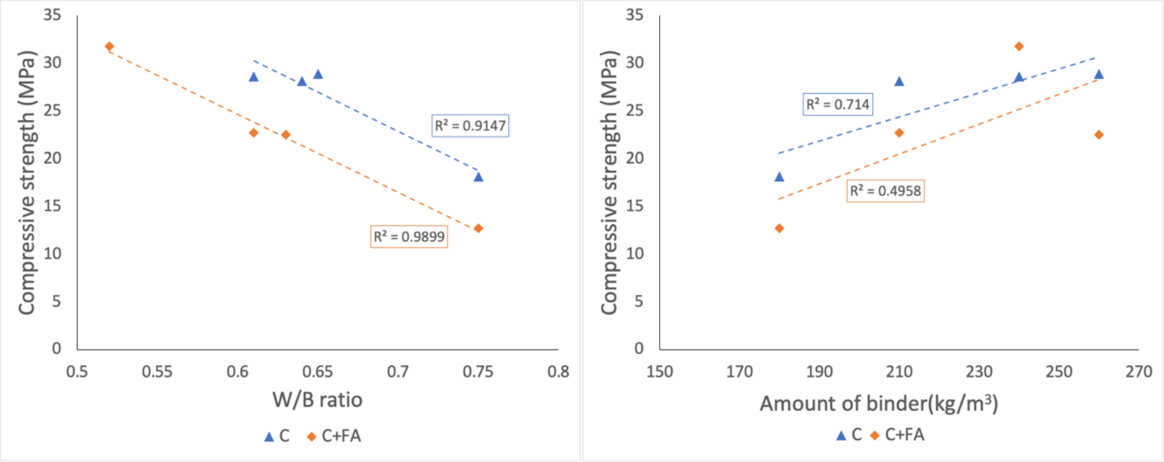


Figure 1 - Relation between compressive strength and W/B ratio (left) and the relation between compressive strength and amount of binder (right)

Replacing 30% of cement with fly ash leads to loss of strength of up to 40%, particularly at early ages. For the more advanced ages, there is a growing trend in the development of mechanical strength. For compositions without fly ash, the evolution is more evident in the early ages, while, for the more advanced ages, its evolution tends to stabilize. In compositions with less amount of binder, it was possible to increase the strength by controlling the W/B ratio (Figure 1).

2.3.2. Carbonation depth

The carbonation depth was high in most mixes. Mixes with lower binder content, namely CM180CV30, had the worst performance, with more than 5.17 mm/day$^{0.5}$, which represents an increase of more than 300% compared to the reference concrete. The evolution of the remaining compositions was proportional to the amount of binder, with the smallest depth of carbonation being related to the composition with the highest amount of binder. Figure 2 shows the carbonation coefficient of all composition.

With this study, it was possible to understand that the amount of binder had the major influence on the carbonation depth, confirming that a decrease of 20 kg/m^3 of binder material represents a 10% increase of the carbonation coefficient (Figure 2).

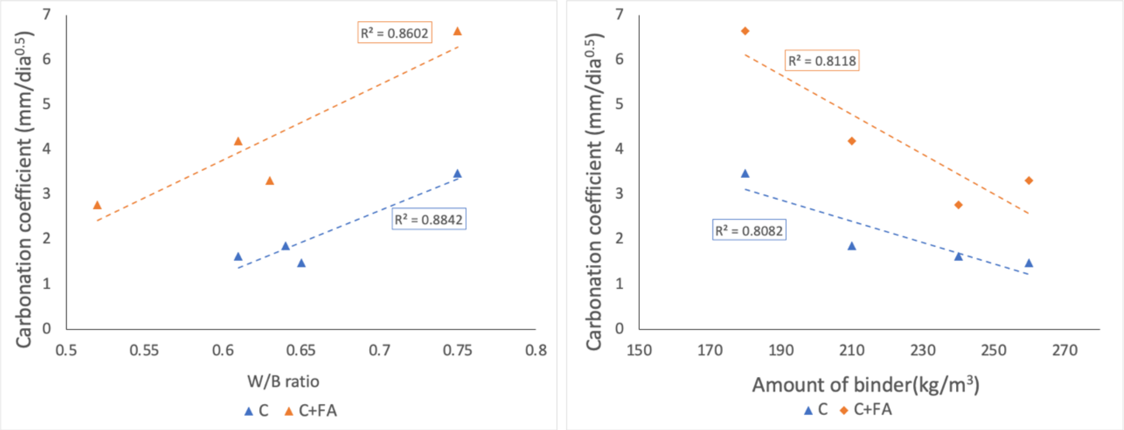
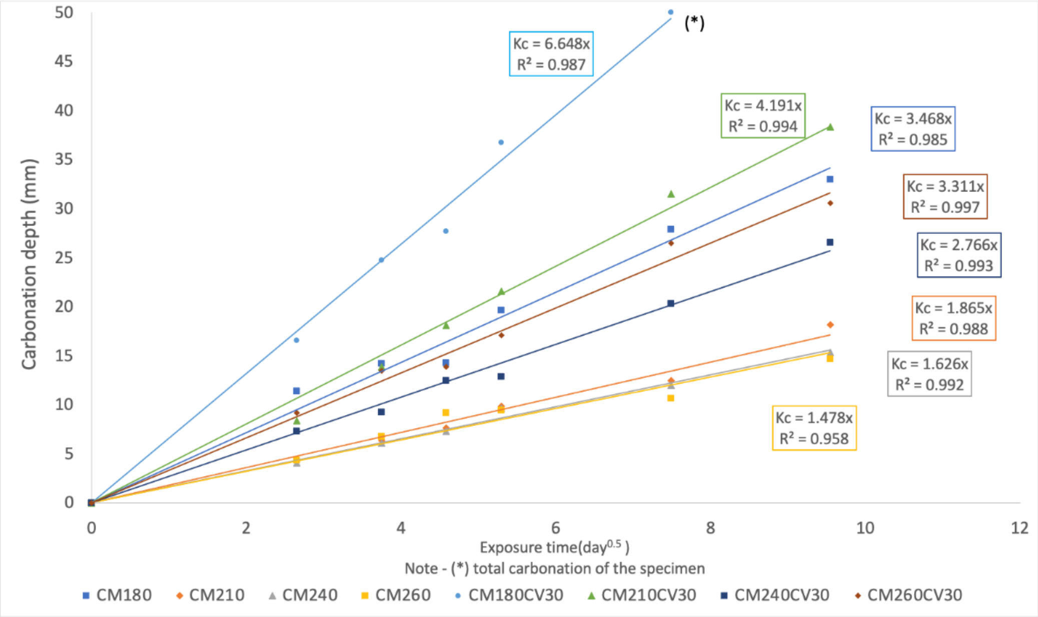


Figure 2 - Relation between the carbonation coefficient and the W/B ratio (left) and the relation between the carbonation coefficient and the amount of binder (right)



Note - (*) total carbonation of the specimen

Figure 3 - Carbonation coefficient

2.3.3. Resistance to chloride penetration

The chloride penetration coefficient results are shown in Table 7. The best result is the one to the composition with the lowest W/B ratio (0.52) and with fly ash incorporation. The incorporation of fly ash substantially increases the resistance of chlorides, by up to 50%. The evolution of the chloride diffusion coefficient was in line with that mentioned by several references, which highlight better performances at higher amounts of binder. However, this conclusion cannot be drawn for all compositions, as the mix with less 20 kg/m^3 of binder has a 25% higher performance compared to the reference mix, which can be justified by the fact that the W/B ratio is 3% lower.

Table 7 - Chloride diffusion coefficient

Composition	D_{nss} (m^2/s)x10^{-12}	
	28 days	91 days
CM180	48.91	49.61
CM210	38.66	39.66
CM240	23.64	28.48
CM260	25.44	37.48
CM180CV30	46.91	45.06
CM210CV30	24.74	22.26
CM240CV30	19.58	6.47
CM260CV30	17.52	9.47

The W/B ratio is one of the parameters that most influenced the resistance to chloride penetration in concrete. This parameter cannot be directly related to the chloride diffusion coefficient since different amounts of binder correspond to different W/B ratios. The influence of the W/B ratio and the amount of binder is shown in Figure 4.

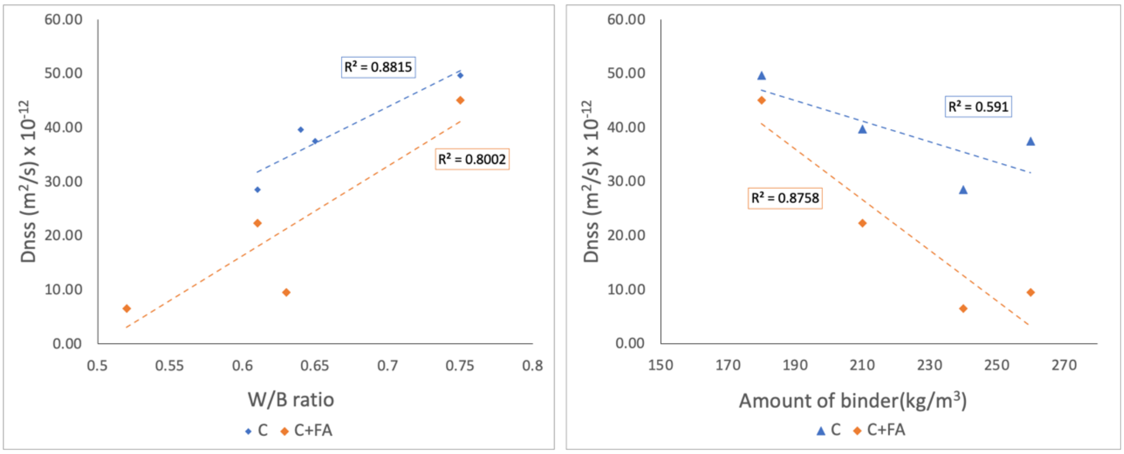


Figure 4 - Relation between the chloride diffusion coefficient and the W/B ratio (left) and the relation between the chloride diffusion coefficient and the amount of binder (right)

2.3.4. Capillary water absorption

Capillary water absorption can be expressed by the capillary absorption coefficient presented in Figure 5. Looking at mixes containing fly ash, the development of capillarity was whitin the expected range, for the amounts of binder and the W/B ratio used. The capillary absorption shows better results for greater amounts of binder and lower W/B ratio. Regarding the CM240CV30 and CM260CV30 compositions, there is a discrepancy regarding the expected trend, which can be explained by the high W/B ratio of the CM260CV30 composition.

The evolution of capillary absorption in compositions without fly ash is completely contradictory with several bibliographical sources. This discrepancy can be explained by the relationship between the difference in free water and the water required for the evolution of chemical reactions by the entire solid mass (binder, sand and gravel) (Table 8). This ratio can be directly related to the pore structure of the hardened mix and may help to understand the observed results.

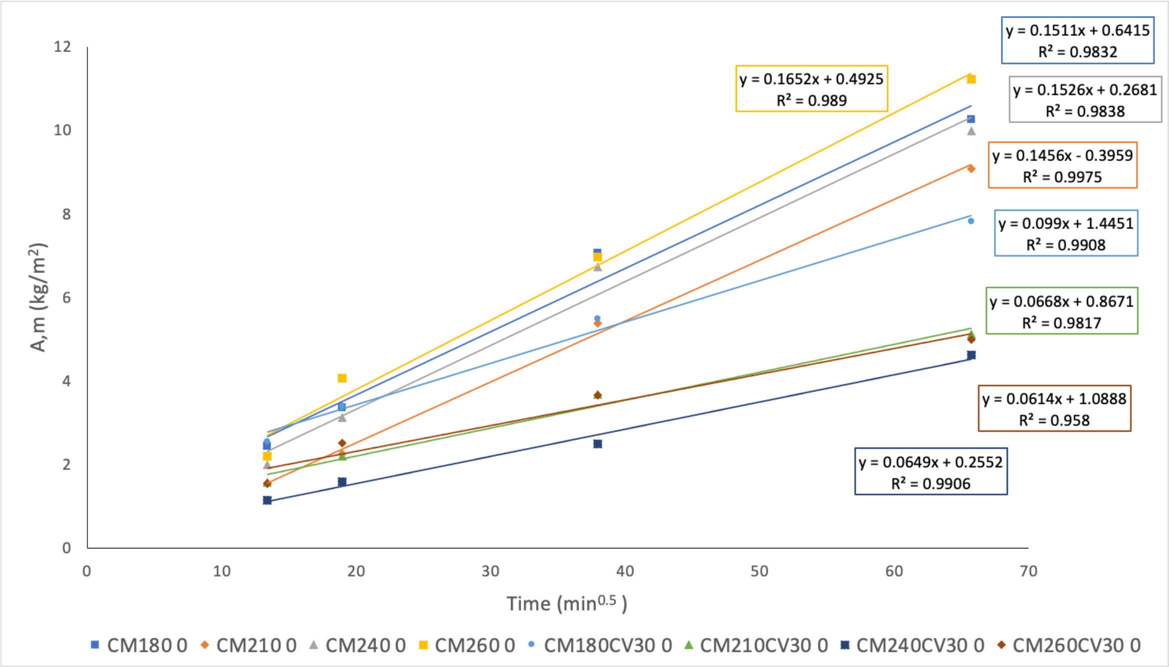


Figure 5 - Capillary absorption coefficient

Table 8 - Relation between the difference of free and necessary water over the total solid mass

Composition	W_t	W_e	W_n	m_t (kg/m^3)	$\frac{(w_e - w_n) \times l}{m_t}$
CM180	0.75	0.523	0.227	2272.9	0.0234
CM210	0.64	0.413	0.227	2281.5	0.0171
CM240	0.61	0.383	0.227	2251.3	0.0166
CM260	0.65	0.423	0.227	2199.2	0.0232
CM180CV30	0.75	0.56	0.190	2259.8	0.0211
CM210CV30	0.61	0.42	0.190	2281.2	0.0152
CM240CV30	0.52	0.33	0.190	2293.8	0.0106
CM260CV30	0.63	0.44	0.190	2284.4	0.0206

Where:

- W_t - total water content;
- W_e - evaporable water content;
- W_n - non-evaporable water content;
- m_t - total solid mass (kg/m^3);
- l - amount of binder (kg/m^3).

In fact, it appears that composition CM260 has the highest index, when compared to mixes CM210 and CM240, which may explain the difference shown in the evolution of water absorption by capillarity. It also appears that the mixes with the highest free water per solid mass rates are directly linked to the worst performances. This is visible by looking at the CM260 composition, which has the highest index when compared to the CM210 and CM240 mixes.

2.3.5. Water absorption by immersion

The results of water absorption by immersion are shown in Table 9. The evolution of water absorption by immersion between 28 and 91 days was as expected, showing a decrease in absorption by immersion with more emphasis in mixes containing cement only. For the remaining mixes, it was not possible to obtain a reliable trend for this parameter. However, the evolution of immersion absorption is identical to the development of capillary absorption. Given this, this discrepancy can be justified by the same index presented in Table 8, which tries to establish the rate of free water per solid matter content.

Table 9 - Water absorption by immersion

Composition	A,m (%)	
	28 days	91 days
CM180	12.45	10.67
CM210	11.84	10.15
CM240	13.17	11.25
CM260	14.34	12.26
CM180CV30	12.42	11.25
CM210CV30	11.38	10.18
CM240CV30	9.91	9.02
CM260CV30	13.35	12.15

3. Conclusions

In this study, it was possible to determine the influence that a significant reduction of the binder content has on the performance of concrete, focusing the research on its durability properties. The following conclusions can be draw:

- It was always possible to obtain slump classes between S2 and S3. The high reduction of the binding material, particularly cement, resulted in poor workability, which led to the use of admixtures, in order to achieve the target slump. For mixes with lower binder content (CM180 and CM210), there was a need for a longer time of vibration and concrete compaction due to the high loss of workability;
- Compressive strength in the different mixes showed promising results. Most of the concrete mixes had acceptable structural performance with average compressive strengths between 29 and 40 MPa, which makes it possible to apply in current small-scale constructions. Concrete with lower binder content showed poor performance. In general, these mixes cannot be considered structural due to their poor performance, but their use is still possible. According to CDE (2020), 75% of all the concrete used globally is non-structural, making the application of this concrete valuable at the economic and, above all, environmental level;
- The absorption of water either by immersion or by capillary showed little consistent results compared to compositions without fly ash, although the evolution was identical in both tests. Concrete with fly ash as a partial substitute for cement showed capillary absorption

coefficient values between 0.06 to 0.1 (mg/mm^{2}xmin$^{0.5}$) and absorption values between 9 and 10%. It can be concluded that these concrete mixes have some resistance to aggressive agents;

- The property most influenced by the reduction of the binding material was carbonation depth. In general, carbonation depth varied between 14 and 38 mm up to 91 days in an accelerated carbonation chamber, except one case in which the entire specimen was carbonated. The incorporation of fly ash as a partial cement substitute provided a considerable increase in the carbonation depth, which shows the negative effect that this supplementary cementing material causes;
- The resistance to the penetration of chlorides showed that the different concrete mixes show little efficiency in the penetration of this aggressive agent. The depth of penetration of chlorides evolved as expected, showing better results for compositions with higher amounts of binder and lower W/B ratios. The significant reduction in binder and the increase in the W/B ratio resulted in poor performance. The introduction of fly ash substantially improved the resistance of chlorides up to 50%. It is assumed that this gain is explained by the greater amount of aluminates, provided by the replacement of cement by fly ash.

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