D4.8: LCA analysis reports on concrete formulation

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Project coordinator: Virginie Pasquier, Project Manager Environment / Energy, ADP

Tel: +33 7 88 35 16 07

E-mail: virginie.pasquier@adp.fr

Project website address: www.olga-project.eu

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	Name	Company	Date	Visa
Coordinator	Virginie Pasquier	ADP	08/01/2026	OK
WP Leader	Laurine Feinberg	ADP	05/01/2026	OK
Task Leader	Ollivier Beghin	ADP	05/01/2026	OK
Quality Manager	Melike Riollet	LUP	22/01/2026	OK

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ADP	Aéroports de Paris	**K**	Clinker
BPE	"Béton prêt à l'emploi" or Ready To Use	**LC3**	Limestone Calcined Clay Cement
CEM	Cement	**LCA**	Life Cycle Assessment
CEM I	Portland Cement	**LL**	Limestone
CEM II	Portland-composite cement	**MBS**	Master Builders Solutions
CEM II/A-LL	Portland-composite cement, 80-94% clinker, 6-20% limestone, 0-5% minor additional constituents.	**Mk**	Metakaolin
CEM II/A-S	Portland-composite cement, 80-94% clinker, 6-20% granulated blast furnace slag, 0-5% minor additional constituents.	**NF**	French Standard
CEM II/C-M	Portland-composite cement, 50-64% clinker, 36-50% main constituent (other than clinker) (granulated blast furnace slag, silica fume, pozzolana, fly ash, calcined shale, limestone), 0-5% minor additional constituents.	**OLGA**	hOListic & Green Airports
CN	National Annex	**RILEM**	International Union of Laboratories and Experts in Construction Materials, Systems and Structures
CO2eq	Carbon Dioxide Equivalent	**WP**	Work Package
DUP	Design Working Life	**XC**	Exposure Class
Eff	Effective Water-to-Binder Ratio		
ETA	European Technical Assessment		

1 Introduction

Cerib has conducted a study on behalf of Groupe ADP on the development of a low-carbon concrete formulation based on a so-called ternary binder (K-LL-Mk) as well as the associated LCA study, as part of the hOListic & Green Airports (OLGA) project, which is part of the European Green Deal. The results presented in this report summarize this work.

1.1 Context of the study and insertion in the ADP project

Environmental concerns now play a central role in the innovation of building materials and are integrated from the earliest stages of the design of structures.

The European Commission has adopted a series of proposals under the European Green Deal, aimed at adjusting the EU's climate, energy, transport and taxation policies to reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, with the aim of making Europe the first climate-neutral continent.

The hOListic & Green Airports (OLGA) project has been selected by the European Commission with the aim of improving the environmental impact of the aviation sector in an innovative and sustainable way. These initiatives reflect Groupe ADP's commitment to various actions aimed at increasing the energy performance of its activities.

The project developed in this report concerns a study aimed at formulating concrete with a low carbon footprint and analyzing its life cycle, in the framework of WP 4 – Terminal area, led by Groupe ADP, particularly the WP.4.2.2 sub-task. "Boosting CO_2 decreases in concrete". The reduction of CO_2 emissions in the concrete used in Groupe ADP's construction projects is one of these initiatives.

1.2 Overall objective of the study

The objective is to reduce the amount of clinker in the binder, the main agent responsible for CO_2 emissions, to significantly reduce the greenhouse gas impact of the concrete products by 40%.

The study was structured around two main actions:

- develop and test a concrete formulation with a recomposed binder of cement, flash-calcined clays and limestone (LC3 type formulation);
- to produce an LCA study on this formulation.

The objective was to produce a concrete formulation that meets the following conditions:

- concrete strength class: C30/37;
- concrete exposure class: XC3;
- concrete consistency class: S4.

2 Presentation of the study

2.1 Specifications

Various constraints were formulated at the launch of the project:

- the aggregates integrated into the formulation will have to come from local power plants at the Charles De Gaulle and Orly platforms. They must be Non-Reactive (NR) with regard to the phenomena of alkali-reaction. In order to be able to clearly identify the share of calcined clays and limestone in the reduction of the carbon footprint of the formulation, it will not also include recycled concrete aggregates;
- The minimum dosage of calcined clay and cumulative calcareous filler must be 50% (percentage by mass) for the constitution of the binder. The recomposed binder must go up to the upper limit authorized by the NF EN 197-5 standard for a CEM II/C-M cement, and the final formulation must justify a target carbon impact of 40% lower than a conventional reference concrete formula based on a CEM I cement (reference concrete);
- In order to more easily meet the carbon objectives expressed above, the use of flash calcined clays rather than produced by the conventional method is to be preferred;
- it will be taken into account that there is a supplier of calcined clay at a distance of 50 km from the site;
- the wording developed will have to be based in part on the performance approach as defined in Article 8.1.1.4 of fascicle 65, particularly regarding indicators related to sustainability, and set out in the 2010 LCPC Provisional Recommendations "Control of the durability of concrete structures. Application of the performance approach".
- avoid the use of slag or a maximum incorporation of 5% in the binder with a carbon footprint of 300 kg.$CO_{2eq/ton}$;
- The performance of the classic reference formula must not make it possible to comply with exposure and resistance classes that are more penalizing than those indicated above, so as not to distort the comparison by using a reference formula that is too rich in clinker to unduly widen the gap with the low-carbon formulation.

From the outset, attention was drawn to the significant evolution of the normative context, in particular with regard to the performance approach, the new methodology of which is described in FD P 18-480 on which the new version of NF EN 206/CN revised in November 2022 is based.

It was considered appropriate to incorporate the new performance approach into the study and to conduct the tests according to the new performance approach rather than the one described in Issue 65.

The binder developed during the work can thus be more valued by such a justification, making it possible to account for a larger proportion of additions in the binder by derogating from the threshold values in relation to the prescribed quantities, as well as to go further in the recomposition than the limits of the CEM II/C-M, and thus maximize the carbon gain.

This is reflected in particular in the performance of accelerated carbonation tests, for the verification of thresholds for class XC3.

To ensure the delivery of a formulation that meets all project specifications, an initial working assumption of three test formulations was carried out for the design of the study.

2.2 Study Program

2.2.1 Development of the concrete formulation

An initial formulation work based on the work in progress at Cerib has been carried out to understand the expected properties of metakaolin concretes.

A study of the formulations of the concrete formulations already used on the Eqiom power plant supplying ADP for its current concretes and transmitted to Cerib, made it possible to define the materials and sourcing for the project.

Regarding the carbon savings objective of the formulas to be developed, a panel of three test formulas was defined and the various laboratory tests necessary for their study were carried out within the Materials and Circular Economy Department, according to the following protocols:

- Fresh concrete fabrication and characterization
    - manufacture of concrete specimens according to the developed formulation (volume of batches according to the needs of each study, assume a batch of 40 to 80 liters);
    - measurement on fresh concrete (subsidence according to the NF EN 12350-2 standard, air-entrained according to the NF EN 12350-7 standard, density according to the NF EN 12350-6 standard);
    - making and storing the specimens necessary for the tests according to the NF EN 12390-2 standard (at 20 °C, in water or in a humid room (>95% of humidity)).

- Mechanical characterization
    - determination of the compressive strength according to the NF EN 12390-3 standard on 3 (Ø11x22) cm specimens, at 7 days, 28 days and 90 days.

- Sustainability Indicators and Durability Testing
    - measurement of the water porosity and the apparent density according to the NF P 18-459 standard on Ø11x22 cm specimens, at 28 days or 90 days (series of 3 measurements);
    - accelerated carbonation rate according to the XP P18-458 standard on specimens (FD P18-480 performance approach);
    - Resistivity measurement according to XP P 18-481.

- Study on shrinkage and shrinkage associated with compression creep on concrete, based on the following reference standards, on the formula deemed most relevant at the end of the tests:
    - Shrinkage tests on 7x7x28 cm prismatic specimens:
        - measurement of endogenous shrinkage on 3 (7x7x28) cm prismatic specimens (origin of measurements: at 24 hours or date of supply of samples to the laboratory);

  - measurement of total shrinkage on 3 (7x7x28) cm prismatic specimens (origins of the measurements at 24 hours or date of supply of the samples to the laboratory);
  - Duration of the measures: 12 months.
- Creep and associated shrinkage tests on cylindrical specimens Ø9x28 cm (or other dimensions to be proposed):
  - determination of the compressive strength according to the NF EN 12390-3 standard on 3 Ø11x22 cm specimens, at the following deadlines: 7 days and 28 days (loading deadline);
  - determination of the modulus of elasticity in compression according to the NF EN 12390-13 standard on 3 Ø11x22 cm specimens, with the following deadlines: 7 days and 28 days;
  - measurement of creep and associated shrinkage under endogenous conditions on 2 Ø9x28 cm specimens (or other dimensions to be proposed) based on the NF EN 12390-16 and NF EN 12390-17 standards;
  - measurement of creep and associated shrinkage under desiccant conditions on 2 (Ø9x28) cm specimens (or other dimensions to be proposed) based on the NF EN 12390-16 and NF EN 12390-17 standards;
  - Loading deadline: 28 days (specimens are kept wet before loading is started);
  - loading rate: 33% (expected strength of concrete at 28 days: class C50/60);
  - Duration of the measures: 12 months.

2.2.2 Carrying out fire tests

For the fire qualification of the formulation developed regarding the differentials in progress to date, Cerib relies on the expertise of its Fire Test Center and proposes the following tests.

2.2.2.1 *Fire behavior test of 4 loaded slabs*

Reference document:

NF EN 1363-1 – Fire resistance tests – Part 1: general requirements. March 2013.
4 slabs were made from the different concrete formulas developed and the reference.

2.2.2.2 *Thermomechanical tests*

Reference document:

RILEM TC 129-MHT "Test methods for mechanical properties of concrete at high temperatures: Compressive strength for service and accident conditions".
RILEM TC 129-MHT "Test methods for mechanical properties of concrete at high temperatures: Modulus of elasticity for service and accident conditions".

2.2.3 Carrying out life cycle analyses

This component consists of carrying out an LCA in order to determine the environmental impact (including that of Global Warming / Carbon) of newly formulated concrete and to highlight the environmental gains achieved compared to the reference concrete, at the material level. This part was handled in coordination with the Cerib Environmental Assessment department team and the team in charge of formulation and testing to support the definition of the concrete on an ongoing basis.

The analysis is based on the environmental data available for the raw materials and possibly on internal data at Cerib. The LCA summary report presents the assumptions and results obtained on a set of selected environmental impacts but will provide all the mandatory indicators of the 15804 standards in order to allow a multi-criteria vision.

3 Concrete development

3.1 Initial assumptions

The formula developed must meet the following specifications:

- resistance class: C30/37;
- exposure class: XC3;
- for a 50-year DUP (NF EN 206/CN).

3.1.1 Prescriptive approach

The NF EN 206+A2/CN standard specifies the composition parameters to be respected and breaks them down according to the targeted exposure class, as follows:

Table 1: Extract from Table NAF.1. of NF EN 206+A2/CN

	X0	**XC1**	**XC2**	**XC3**	**XC4**
Rapport W_{eff}/B_{eq} maximal		0.65	0.65	**0.60**	0.60
Minimum strength class		C20/25	C20/25	**C25/30**	C25/30
Minimum $B_{eq\ content}$ (kg/m^3)	150	260	260	**280**	280

The prescriptive approach outlined in the standard mandates a minimum equivalent binder content of 280 kg/m^3 to comply with exposure class XC3.

The equivalent binder, defined by the equation $B_{eq} = C + k\,A$, necessitates a substantial addition of metakaolin for it to be optimally considered as a clinker substitute. However, since the calculation framework allows for only a single supplementary material, the contribution of limestone is not accounted for. Consequently, the formulation of a ternary binder under this approach would not achieve the intended reduction in carbon emissions.

In order to meet the equivalent binder requirement with a composition of 50% clinker, 30% metakaolin, and 20% limestone, the total binder content would need to reach 450 kg/m^3. This value is incompatible with the low-carbon objectives of the study.

3.1.2 Performance approach

The performance-based approach described in FD P 18-480 enables the use of a ternary binder by considering all its constituents as a whole, thereby allowing for a more flexible and optimized formulation. This approach contrasts with the prescriptive method by providing a framework in which the contributions of different supplementary cementitious materials are explicitly accounted for.

Specifically, for covered concrete, deviations from the prescriptive requirements outlined in paragraph NA.5.2.3 on aggregates and Annex F of the NF EN 206+A2/CN standard are permitted in the following aspects:

- The effective water-to-equivalent binder ratio (W_{eff}/B_{eq}) and/or the minimum equivalent binder content (B_{eq} mini);
- The nature and composition of the binder, as defined in NF EN 206/CN and FD P 18-011;
- The quality and characteristics of the aggregates, as specified in NF EN 206/CN.

Furthermore, all constituent materials must demonstrate general suitability for use in accordance with NF EN 206/CN, with the exception of those whose suitability is established solely through a European Technical Assessment (ETA).

In the context of this study, the binders considered will deviate from conventional binder compositions, as they will be formulated through a tailored recombination of clinker, metakaolin, and limestone. This approach aims to optimize performance while aligning with sustainability objectives.

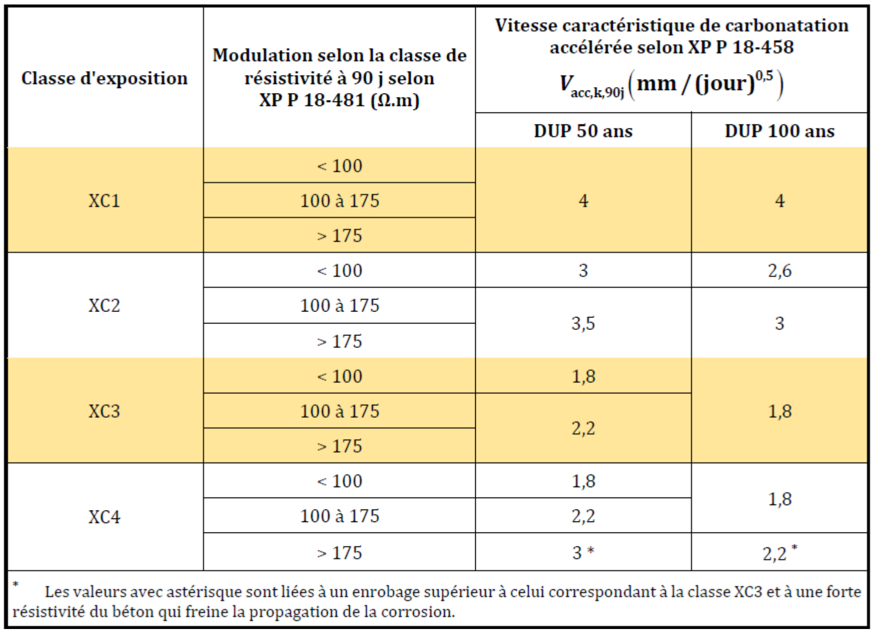
3.2 Validation by performance approach

In order for a given concrete composition to be validated by the performance approach, it must be subjected to various tests to measure its performance on the durability indicators of water-accessible porosity and electrical resistivity, as well as the quantity associated with durability related to the targeted exposure class.

The objective for this study is class XC3, related to the carbonation of concrete. The quantity associated with durability is therefore accelerated carbonation in the laboratory.

Once the properties have been measured, the results are compared, in characteristic values, with the thresholds presented in Tables 2 and 3.

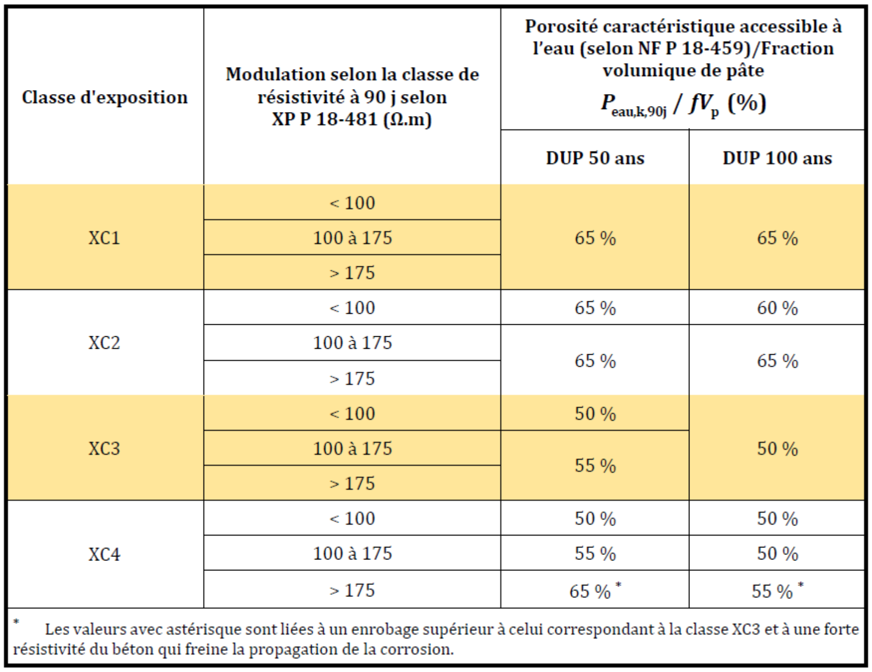
Table 2: Performance thresholds (at 50 and 100 years) based on accelerated carbonation tests (FD P 18-480)



Classe d'exposition	Modulation selon la classe de résistivité à 90 j selon XP P 18-481 (Ω.m)	Vitesse caractéristique de carbonatation accélérée selon XP P 18-458 $V_{acc,k,90j}\left(mm/(jour)^{0,5}\right)$	
		DUP 50 ans	DUP 100 ans
XC1	< 100	4	4
	100 à 175		
	> 175		
XC2	< 100	3	2,6
	100 à 175	3,5	3
	> 175		
XC3	< 100	1,8	1,8
	100 à 175	2,2	
	> 175		
XC4	< 100	1,8	1,8
	100 à 175	2,2	
	> 175	3 *	2,2 *

* Les valeurs avec astérisque sont liées à un enrobage supérieur à celui correspondant à la classe XC3 et à une forte résistivité du béton qui freine la propagation de la corrosion.

Table 3: Performance thresholds (at 50 and 100 years) for water porosity divided by the volume fraction of paste (FD P 18-480)



Classe d'exposition	Modulation selon la classe de résistivité à 90 j selon XP P 18-481 (Ω.m)	Porosité caractéristique accessible à l'eau (selon NF P 18-459)/Fraction volumique de pâte $P_{eau,k,90j} / fV_p$ (%)	
		DUP 50 ans	DUP 100 ans
XC1	< 100	65 %	65 %
	100 à 175		
	> 175		
XC2	< 100	65 %	60 %
	100 à 175	65 %	65 %
	> 175		
XC3	< 100	50 %	50 %
	100 à 175	55 %	
	> 175		
XC4	< 100	50 %	50 %
	100 à 175	55 %	50 %
	> 175	65 % *	55 % *

* Les valeurs avec astérisque sont liées à un enrobage supérieur à celui correspondant à la classe XC3 et à une forte résistivité du béton qui freine la propagation de la corrosion.

Table 4: Summary of the performances to be achieved for the concretes of the study

	NF EN 206/CN (DUP 50 years)	**FD P 18-480 (DUP 50 years)**
Resistance class	C25/30	-
W_{eff}/B_{eq}	0.60	-
Carbonation rate ($mm/d^{1/2}$)	-	2.2
Porosity/Pulp Fraction (%)	-	55

3.3 Construction of concrete formulas

The formulation of the concrete mixtures commenced with the design and characterization of the binders, ensuring their alignment with the targeted carbon reduction objectives.

3.3.1 Reference concretes

To present a comprehensive overview of the approach, various reference concretes have been defined to facilitate a well-informed comparison of CO_2 reduction outcomes:

- For the initial hypothesis work: Ref0, the class XC3 concrete used on site and supplied by Eqiom on the CDG platform, containing 320 kg/m^3 of CEM II/A-S to the blast furnace slag;
- For the rest of the study:
    - Ref1, a reference concrete based on CEM I formulated at least in table NAF1 of NF EN 206+A2/CN: 280 kg/m^3 of cement;
    - Ref2, the same concrete, but with a dosage of 300 kg/m^3 of CEM I, a classic formula encountered in concrete plants for XC3/XC4/XF1 concretes;
    - Ref3: 280 kg/m^3 of CEM II/A-LL: faced with climatic constraints, the concretes used on the day of the study hardly use any CEM I in order to reduce the impact of the BPE concretes;
    - Ref4: similarly, 300 kg/m^3 of CEM II/A-LL.

3.3.2 Working hypothesis formulas

To select the 3 formulations to be tested, a matrix of working hypotheses (Table 5) was constructed according to the composition of the binder, the binder content, the E_{eff}/L_{eq} ratio and the expected environmental gain, most of the environmental impact being carried by the latter.

Table 5: Synthesis of the initial working hypotheses of the study

Formula	Total binder	K(%)	Q(%)	LL(%)	S(%)	E_{eff}/L	CO_2/m^3 footprint of binder	Gain % Ref0	Gain % Ref1
H1_Mk15	*280*	50	15	35	0	0.45	116.6	45	48
H2_Mk15	*300*	50	15	35	0	0.45	125.0	41	45
H3_Mk15	*320*	50	15	35	0	0.45	133.3	37	41
H4_Mk20	*280*	50	20	30	0	0.45	117.8	44	48
H5_Mk20	*300*	50	20	30	0	0.45	126.2	40	44
H6_Mk20	*320*	50	20	30	0	0.45	134.6	36	40
H7_Mk30	*280*	50	30	20	0	0.45	120.1	43	47
H8_Mk30	*300*	50	30	20	0	0.45	128.7	39	43
H9_Mk30	*320*	50	30	20	0	0.50	137.3	35	39
H10_Mk30	*300*	40	30	30	0	0.45	107.8	49	52
H11_Mk20	*290*	40	20	40	0	0.45	101.8	52	55
Eqiom Concrete	*320*	75	0	0	25	/	204.5	3	9
Concrete Ref1	*280*	100	0	0	0	/	210.6	/	/
Concrete Ref2	*300*	100	0	0	0	/	225.6	/	/

The first hypotheses were able to highlight the following elements:

- remaining within the composition range of CEM II/C-M (Q) limits the carbon reduction potential to around 40% on the binder share (H7, H8 and H9);
- improving the limestone content by maintaining the clinker rate at 50% makes it possible to optimise the CO_2 gain: an assessment of the ACV block alone on block A1 alone makes it possible to estimate a 40% reduction in the LCA of the material (H1 to H6);
- Moving out of the composition range of CEM II/C-M (Q) and lowering the clinker content to 40% significantly optimizes the carbon gain beyond the initial target of 40% (H10 and H11).

To ensure satisfactory concrete performance and maintain a 40% reduction in impact, the three formulas used for the tests are assumptions H5, H8 and H10.

These formulas will be studied under the respective names of:

- C1_Mk20;
- C2_Mk30;
- C3_Mk30.

The performances obtained on these concretes, detailed in Chapter 4, made it possible to define a second batch of test concretes optimized from the point of view of the quantity of binder in order to maximize the carbon gain.

These new formulas, using the assumptions H4, H7 and H11 respectively but an increased E_{eff}/L_{eq}, are named as follows:

- C4_Mk20;
- C5_Mk30;
- C6_Mk20.

The C6_Mk20 formula has the dual advantage of lowering the clinker content to 40% and increasing the limestone content to 30%. The carbon gain estimated in the first place on this formula, for the binding part, is more than 50% compared to the Ref1 reference.

4 Results

4.1 Presentation of concrete compositions

4.1.1 First series – composition of concretes

The compositions of C1, C2 and C3 concretes are detailed in Table 6.

Table 6: Details of the compositions realized - Lot 1

		C1_Mk20	**C2_Mk30**	**C3_Mk30**
Binder	Ciment CEM II/A-LL 52,5 R Eqiom Rochefort	170	173.4	139
	Métakaolin Argicem	61	90.7	91.5
	Betocarb HP Limestone	74	43.3	76.2
Aggregates	Sable 0/4 Bocahut 0/4	887.2	934.3	930.2
	Gravel 4/10 Bocahut 4/11	206.5	218.5	216.5
	Gravel 4/20 Bocahut 11/22	766.3	805.1	803.4
Adjuvant	Master Ease 2000	7.2	8.4	9.2
	Total Binding	*305*	*307.4*	*306.7*
Water	Total water	156	158	167
	W_{eff}	137	136	144
	W_{eff} / Binder	0.45	0.44	0.47

4.1.2 Second series – composition of concretes

The compositions of C4, C5 and C6 concrete are detailed in Table 7.

Table 7: Details of the compositions manufactured - Lot 2

		C4_Mk20	C5_Mk30	C6_Mk20
Binder	Ciment CEM II/A-LL 52,5 R Eqiom Rochefort	163	163	133
	Métakaolin Argicem	57	85	58
	Betocarb HP Limestone	68	39	102
Aggregates	Sable 0/4 Bocahut 0/4	950.4	951.2	937
	Gravel 4/10 Bocahut 4/11	220.2	221.9	218
	Gravel 4/20 Bocahut 11/22	820.3	822.7	810
Adjuvant	Master Ease 2000	6.8	6.6	7
	Total Binding	*287*	*286*	*293*
Water	Total water	159	159	159
	W_{eff}	136	137	138
	W_{eff} / Binder	0.48	0.48	0.47

4.2 Fresh concrete test results

During manufacturing, various tests were carried out on fresh concrete to verify the composition parameters of the concrete as well as the rheological behavior of the latter.

The plasticizer used for the study is an MBS solution adjuvant, MasterEase 2000, which has been used at Cerib in similar studies and has the ability to achieve rheology class S4 after mixing.

The results obtained are presented in Table 8.

The Figure 1 illustrates the evolution of rheology for each concrete.

Table 8: Summary of the results and measurements obtained on the concretes

		C1_Mk20	**C2_Mk30**	**C3_Mk30**	**C4_Mk20**	**C5_Mk30**	**C6_Mk20**
Rheology	**Sagging cone T0 (cm)**	21	24	18	20	22	19
	Sagging cone T30 (cm)	17	15	18	16	15	16
	Slump cone T60 (cm)	12	9	17	12	10	15
Rheology Class (T0)		S5	S5	S4	S4	S5	S4
Concrete temperature (°C)		24	25.6	22.3	24.2	23.5	24.4
Fresh density (kg/m³)		2 369	2 425	2 460	2 438	2 443	2 412
Air content (%)		1.7	1.8	2	1,7	1.6	1.9

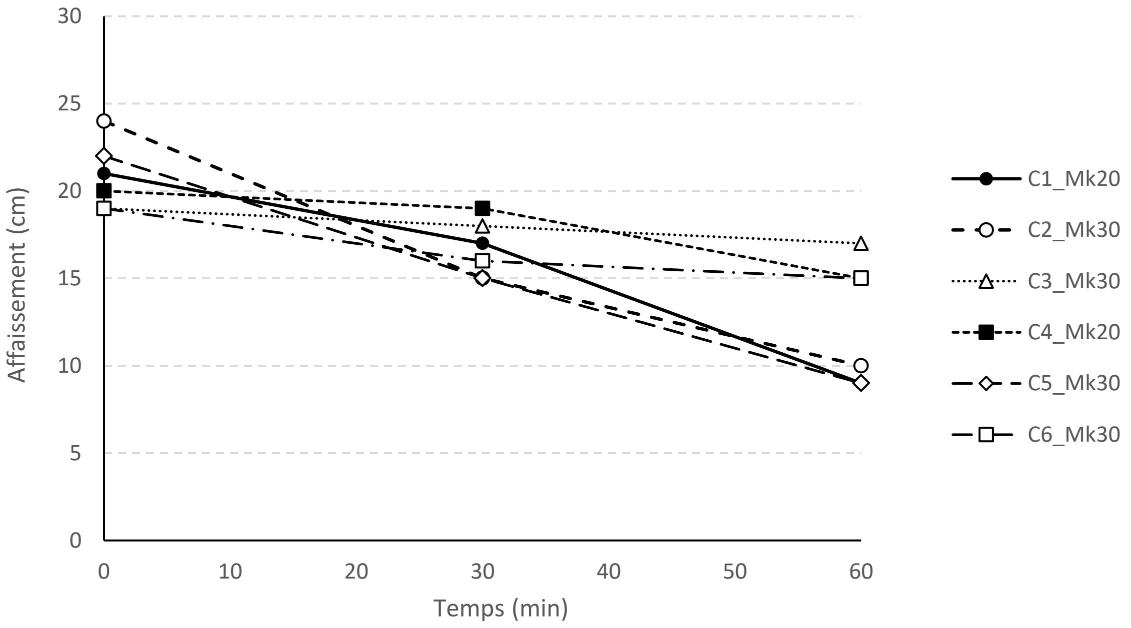


Figure 1: Evolution of concrete rheology at 60 min

4.3 Mechanical results

The compressive strength results, shown in Table 9, show that strength class C30/37 has been largely achieved for the first series of C1, C2 and C3 concretes.

The optimization of the binder quantities had a significant impact on the strengths obtained, bringing them back to a value range consistent with the target.

Table 9: Mechanical strength results in compression

	C1_Mk20	**C2_Mk30**	**C3_Mk30**	**C4_Mk20**	**C5_Mk30**	**C6_Mk20**
$f_{cm;28j}$ (MPa)	68	60	73	47	56	38
$f_{cm;90j}$ (MPa)	73	65	78	55	61	41
$f_{ck;28j}$ (MPa)	60	52	65	39	48	30

Table 9 shows that the metakaolin type additions allow access to resistances that are quite acceptable for E/L close to 0.5.

This is still a significant reduction in the E/L ratio (limited to 0.6 in Table NA. F.1 of NF EN 206+A2/CN), but acceptable to facilitate the admixture work and obtain rheology acceptable, in line with the casting problems induced by the use of metakaolin which can have been observed.

The acceptance of the concrete formulation will therefore be based on its durability performance.

4.4 Durability results

4.4.1 Durability test results

Table 9 details all the sustainability results collected on the 6 formulations studied.

For each formula, the tests for water-accessible porosity and electrical resistivity were carried out at 28 days in order to allow an evaluation of the performance before the final results.

The initial formulas C1_Mk20, C2_Mk30 and C3_Mk30 showed very strong performances, correlated with the good mechanical performance, validating the consistency of the paste optimization carried out on the following concretes.

Table 10: Summary of durability test results

	C1_Mk20	**C2_Mk30**	**C3_Mk30**	**C4_Mk20**	**C5_Mk30**	**C6_Mk20**
Porosity - 28d (%)	12.4	14.4	12.4	13.5	14.9	13.9
Resistivity - 28d (Ω.m)	136	184	279	103	165	94
Porosity - 90d (%)	12.9	13.8	11.8	13.9	14.2	14.1
Resistivity - 90d (Ω.m)	195	407	234	138	375	108
Carbonatation – 90j (mm.j$^{1/2}$)	0.92	1.14	0.81	1.40	0.93	1.68
XC3 Class Validation	OK	OK	OK	OK	OK	OK

Generally low porosity levels (less than 13%) were observed for the first 3 concretes, except C2, with an overall high resistivity from 28 days (above 130 Ω.m).

The properties of the C4 to C6 concretes were very slightly impacted at 28 days, with C6 having a resistivity below the modulation threshold of 100 Ω.m of FD P 18-480, a value that improved to 90 days to exceed it.

The 90-day values are very promising, with accelerated carbonation speeds to ensure the performance of the concrete in the XC3 class.

It is worth noting the significantly higher value of C6_Mk30, the formula with the least clinker. This result is therefore chemically consistent but shows an XC3 concrete formulation limit for the materials considered.

4.4.2 Positioning of the concretes in relation to the FD P 18-480 booklet

These results, presented in average values, must be converted into a characteristic value to be compared with the thresholds of FD P 18-480 as announced in the previous chapters.

Water porosity criterion

In the case of validation by a water porosity test (water accessible to water), it must be ensured that the measured values guarantee the achievement of an acceptable carbonation kinetics by respecting the thresholds defined in Table 3 according to the lifetime of the structure considered.

These thresholds apply to the maximum characteristic value (associated with a 90% fractile) of porosity, denoted $P_{water,k,90j}$, *divided by the paste volume fraction* f_{VP} *of the nominal concrete formula, which is conventionally defined as the following difference:*

$$f_{VP} = 1 - \text{volume of fractions of aggregate particles greater than 0.063 mm}$$

Accelerated carbonation criterion

The performance thresholds are defined on the basis of a maximum characteristic accelerated carbonation rate (associated with a fractile of 90%) denoted $V_{acc,k,90j}$.

Table 11 presents the minimum coefficients of variation to be taken into account in expressing the test result considered as a characteristic value.

Table 11: Minimum coefficients of variation for the criteria considered

	Coefficient de variation minimal admissible
Water-accessible porosity	3%
Accelerated carbonation	20%

By systematically evaluating all studied concretes against the performance thresholds outlined in FD P 18-480, it is possible to assess whether the developed formulations meet the expected performance requirements for compliance with exposure class XC3 under the performance-based approach. This validation ensures that the concrete mixtures provide adequate durability while optimizing material use.

Additionally, the standard defines criteria for adjusting concrete cover thickness based on concrete quality, allowing for a reduction of one or two structural classes. These adjustments, which complement the modulation related to compact coatings, are specified in Appendix A of the standard.

As part of the performance-based methodology, the rules governing concrete cover modulations based on mechanical strength and/or binder composition are provided in Table 4.3 NF of the national annex to NF EN 1992-1-1 (NF P 18-711-1/NA), specifically in clause 4.4.1.2(5). The permissible reductions in cover thickness are contingent upon compliance with stricter performance thresholds, reinforcing the need for high-quality formulations.

Table 12 presents the performance results of each tested concrete, expressed in characteristic values, and their positioning relative to the defined thresholds. The evaluation includes key durability indicators such as water-accessible porosity and resistance to accelerated carbonation, considering both the baseline XC3 exposure class and its two possible structural class modulations.

Table 12: Synthesis of the concrete positions for the class according to the defined criteria and possible modulations

		C1_Mk20	**C2_Mk30**	**C3_Mk30**	**C4_Mk20**	**C5_Mk30**	**C6_Mk20**
	$P_{water,k,90j}$ (%)	13.5	14.4	12.3	14.5	14.8	14.7
	$P_{water,k,90j}$ / *fVP* (%)	43	52	44	54	55	53
	$V_{acc,k,90j}$	1.20	1.48	1.05	1.82	1.21	2.18
Criterion ***Peau,k,90j / fVP***	Validation of thresholds for class XC3	Ok	Ok	Ok	Ok	Ok	Ok
	Validation of thresholds allowing the reduction of 1 structural class	Ok	Non Ok	Ok	Non Ok	Non Ok	Non Ok
	Validation of thresholds allowing the reduction of 2 structural classes	Ok	Non Ok	Ok	Non Ok	Non Ok	Non Ok
Criterion **Vacc,k,90j**	Validation of thresholds for class XC3	Ok	Ok	Ok	Ok	Ok	Ok
	Validation of thresholds allowing the reduction of 1 structural class	Ok	Non Ok	Ok	Non Ok	Ok	Non Ok
	Validation of thresholds allowing the reduction of 2 structural classes	Ok	Non Ok	Ok	Non Ok	Ok	Non Ok

All formulations comply with the thresholds established for exposure class XC3, meeting the requirements for both water porosity and accelerated carbonation rate. Formulations with a higher paste content facilitate greater structural class modulations, whereas optimized formulations ensure compliance with the required performance criteria but offer less flexibility for higher structural class adjustments.

Given that the primary objective was to maximize carbon reduction while ensuring compliance with class XC3 — without relying on structural class modulation — the formulation effort was focused on this specific requirement.

Among the tested formulations, C6 stands out as particularly promising, as it successfully meets the XC3 class requirements while achieving results very close to the performance thresholds. However, this formulation offers little margin for variation and appears to represent a limit in the study's optimization efforts. Its performance suggests that further reductions in clinker content or binder adjustments may compromise compliance with the required durability criteria.

Consequently, formulation C6 was selected for delayed strain measurements, as it provides an interesting balance between performance and carbon reduction while highlighting the constraints in further optimization.

4.4.3 Water sensitivity

The sensitivity of the latest formulas to water (variation of 10L) has been achieved, in particular C6_Mk20, a formula with the best performance/sustainability impact ratio.

The results obtained are presented in Table 13.

Table 13: Test results on concrete with water variation

	C4_Mk20+10L	**C5_Mk30+10L**	**C6_Mk20+10L**	**C6_Mk20-10L**
Rc 28 (MPa)	45.3	51.9	45.8	49.2
Rheology	S5	S4	S4	S3
Porosity (%)	14.3	14.5	13.7	12.0
Resistivity (Ω.m)	108	157	110	137

The results allow us to observe a good performance of the concretes with the addition of water. The rise in water porosity is low and the resistivity remains high above 100 Ω.m.

The C6 formula is impacted by the reduction of water for its rheology and shows a strong increase in performance on its variation at -10L.

4.5 Shrinkage and creep results

The test method used to carry out the requested measurements is based on the standards NF EN 12390-16 (2019) (shrinkage) and NF EN 12390-17 (2019) (creep). The full results can be found in the Cerib report dedicated to this trial (Re-052666-A).

The set point for the loading applied to the specimens corresponds to 33% of the average compressive strength measured on 11x22 cm specimens, i.e. 14.5 MPa.

The specimens for the measurement of creep deformations were loaded at the age of 28 days. The total duration of the monitoring of specimen deformations is one year.

The deformations of the specimens are monitored according to the deadlines recommended by the NF EN 12390-17 (2019) standard:

- during the specimen loading protocol (after a preload equal to 50% of the test load has been applied) and then immediately after the test load has been applied;
- 2 to 6 hours after the first measurement, then three times in the first week;
- once a week until the end of the first month;
- once a month thereafter.

The follow-up of shrinkage deformations was carried out at the same deadlines.

Summary of results

Figure 2 shows that C6_Mk20 concrete falls within the uncertainties of the 2005 version of the Eurocode as well as those of the future version considering a class N/class CN binder cement.

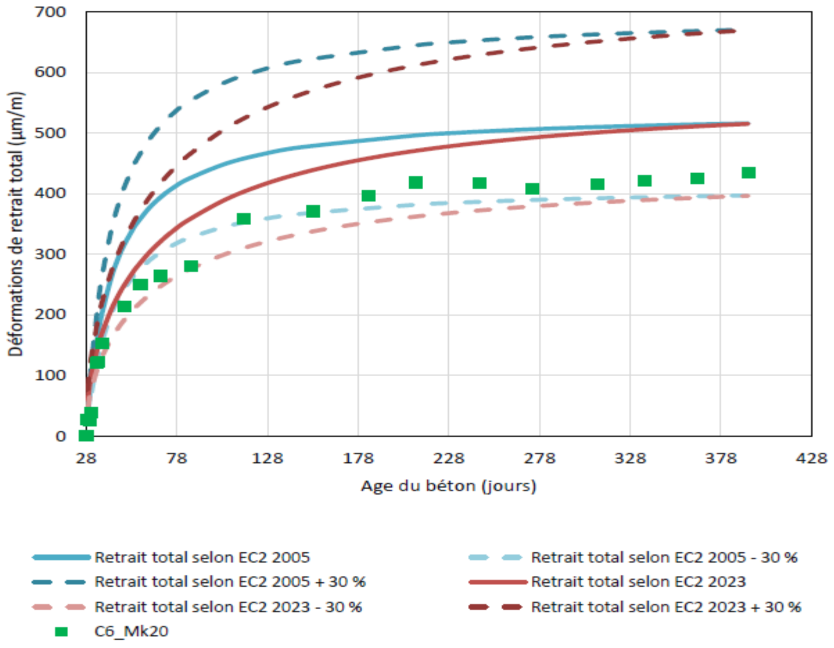


Figure 2: Comparison of the experimental results of total shrinkage and the theoretical laws of Eurocode 2 – part 1-1 (2005 version and draft future version) considering a cement/binder of type N/CN and a concrete of resistance class C30/37

The concrete presents results below the theoretical laws in comparison with concrete of strength class C30/37. Figure 3 shows the same results compared to a C/CN type cement/binder.

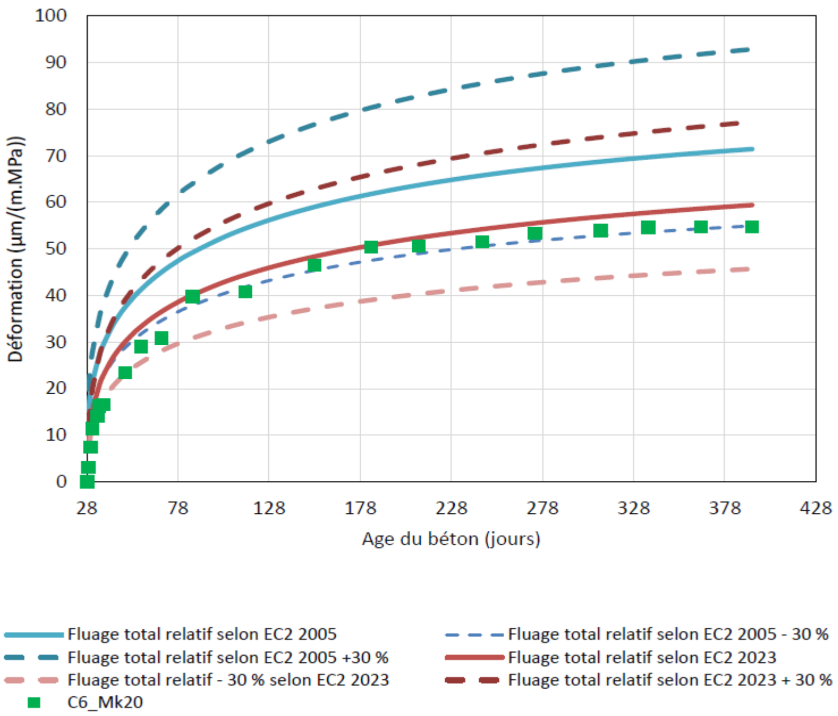


Figure 3: Comparison of the experimental results of total relative creep and the theoretical laws of Eurocode 2 – part 1-1 (2005 version and draft future version) considering a C/CN type cement/binder and a concrete of resistance class C30/37

4.6 Exploitation of the results

The concrete formulations studied in this project enable ADP to anticipate and adapt to future specifications for its infrastructure concretes, aligning with the expected ongoing development of the metakaolin supply chain in Île-de-France. By integrating these formulations, ADP can proactively address evolving regulatory and environmental requirements while optimizing material selection for enhanced sustainability.

Beyond technical validation, this study also provides ADP with a comprehensive assessment of the feasibility of these formulations in real-world applications. The results will support the adaptation of binder compositions and admixture strategies to specific project constraints, ensuring compatibility with site conditions, structural requirements, and targeted carbon reduction objectives. This approach contributes to the long-term development of low-carbon concrete solutions tailored to ADP's infrastructure needs.

A ternary diagram represents the binder composition based on the proportions of clinker, limestone, and metakaolin or slag. Positioning the studied concretes within this diagram provides a clear visualization of formulation trends, facilitating the comparison of different mixes in terms of clinker reduction and expected performance. The Figure 4 and Figure 5 illustrate the positioning of the tested formulations within this framework.

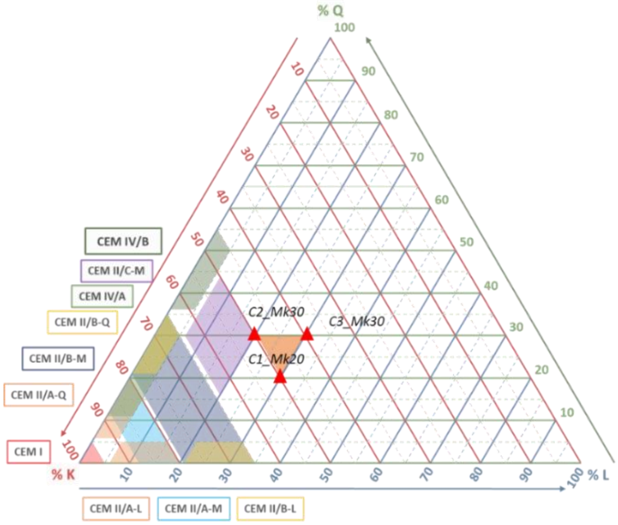


Figure 4: Ternary diagram for concrete C1 to C3

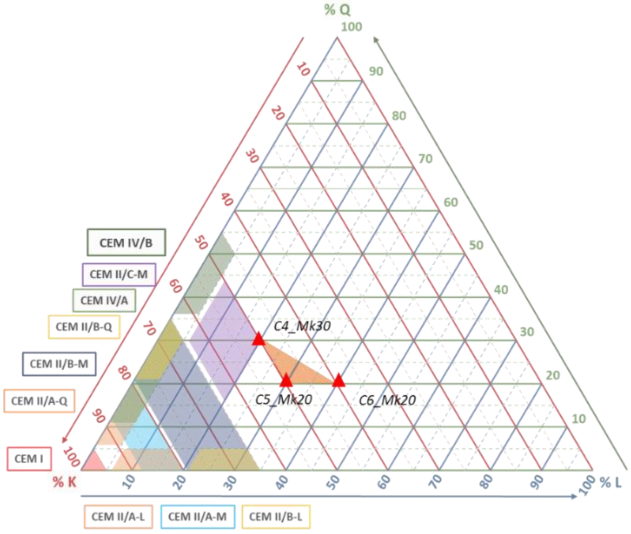


Figure 5: Ternary diagram for concrete C4 to C6

The C2_Mk30 and C4_Mk30 formulations correspond to recomposed binders similar to a CEM II/C-M-type cement, incorporating a balanced proportion of clinker, metakaolin, and limestone. These compositions remain within the framework of standardized cement classifications, ensuring a certain level of predictability in performance.

In contrast, the other tested formulations deviate significantly from conventional cement types. However, the performance-based approach adopted in this study has demonstrated their ability to achieve the required mechanical and durability properties, validating their suitability for use despite their non-standard composition.

Among these, the C6_Mk20 formulation exhibits properties that exceed the thresholds required for exposure class XC3. However, this is achieved with minimal safety margins, indicating a lack of robustness against potential variations in material properties or environmental conditions. Additionally, its increased sensitivity to water represents a factor that must be carefully considered in practical applications, particularly in environments with variable moisture exposure.

These findings suggest that, for the materials used in this study, the C6_Mk20 formulation represents a practical limit in terms of clinker reduction, durability performance, and the W_{eff}/B_{tot} ratio. Further reductions in clinker content could compromise long-term performance, particularly regarding resistance to carbonation and overall durability. Thus, while this formulation successfully meets XC3 requirements, its limited margin for adaptation highlights the constraints associated with pushing binder optimization further within the studied material system.

5 Fire tests

The purpose of the test is to evaluate the fire behavior and thermal gradient of 4 reinforced concrete slabs. The test bodies are subjected to a standardized temperature-time thermal action (standardized curve of the NF EN 1363-1 standard).

These tests are the subject of a specific referenced report: Test Report No. 041278.

Some elements will be taken up in this chapter.

5.1 Reference texts

The tests were carried out in accordance with the NF EN 1363-1 (February 2020) standard "Fire resistance tests, Part 1: General requirements".

5.2 Concrete subjected to testing

For the production of the 4 test body slabs, the following concretes were manufactured:

- Ref3 test form, for the D1 panel, on 29/08/2023;
- formula C3_Mk30, for the D2 panel, on 29/08/2023;
- formula C5-Mk30, for the D3 panel, on 30/08/2023;
- formula C6_Mk20, for the D4 panel, on 30/08/2023.

Manufacturing site: Cerib Epernon (28).

The reference chosen was the Ref3 formula, with CEM II/A-LL, which is more representative of current concrete following the gradual disappearance of CEM I.

5.3 Characteristics of test bodies

The slabs have a surface area of 1,700 mm x 980 mm and a thickness of 300 mm.

The reinforcement of the slabs is composed of 2 ST25C welded meshes on exposed and non-exposed sides and 4 HA14 and 14 HA6 frames to maintain the spacing of the meshes. The coating of welded mesh is 25 mm.

The reinforcement is set up by technicians from the Cerib Fire Test Centre.

The details of the concrete fabrications and the reinforcement plan are presented in Report No. 041278.

After acceptance at the Fire Test and Formwork Centre, the slabs and their test pieces are stored in an air-conditioned room. Details of the packaging in accordance with the first paragraph of chapter 8.1 of the NF EN 1363-1 standard: the element and its specimens are stored in an air-conditioned room with a temperature set at 23 °C and whose hygrothermal changes are measured and recorded.

Specimens for weight and water content monitoring are wrapped in aluminum foil all over their periphery and are stored close to the test body.

5.4 Trial methods

To carry out the fire tests, various measurements were carried out on the concrete subjected to the tests. Samples were made with the same tempers as those used to make the slabs.

The specimens have undergone:

- weight monitoring during the cure. These specimens have been wrapped in self-adhesive aluminum foil all over its periphery and stored horizontally, so as to have a unidirectional drying. Weight monitoring began on 15/09/2023;
- water content measurements. The cut slices are placed in an oven at 105°C and removed from the oven when the change in mass is less than 0.1% between two successive weighings spaced 24 hours apart;
- compressive strengths of concrete. The compressive strength of the concrete is determined by Cerib technicians on cylindrical specimens (Ø15 x 30 cm) (Table 14):
  - having undergone a water cure for 28 days;
  - having undergone a dry cure with peripheral aluminization (storage near the test bodies since the formwork) at 91 days.

Table 14: Compressive strength results on fire test concretes

	D1-Ref	**D2-C3-MK30**	**D3-C5_Mk30**	**D4-C6_Mk20**
Rc 28j (MPa) ***(cure humide)***	44.9	43.2	55.0	39.1
Rc 90j (MPa) ***(cure sèche)***	49.8	46.7	62.1	46.2

- measurements of water-accessible porosity and electrical resistivity, to evaluate the behaviour of the concrete in relation to the concrete of the same composition studied.

Table 15: Durability results on fire test concretes

	D1-Ref	**D2-C3-MK30**	**D3-C5_Mk30**	**D4-C6_Mk20**
Porosity - 90d (%)	13.6	13.9	12.8	13.4
Resistivity - 90d (Ω.m)	56	229	291	130

Table 14 and 15 show that the properties of the concretes obtained are within the orders of magnitude expected from the different formulas. The formulated reference concrete has the classic performance of clinker-based concrete (in particular a low electrical resistivity, less than 100 Ω.m).

The slabs are then arranged in the kiln as described in the 041278 report.

5.5 Testing and observations

An observation is made in the furnace by means of two high-temperature endoscopic cameras. A camera is placed above the furnace to observe the non-fire-exposed side of the slabs throughout the test.
The observations made during the test on the different faces of the slabs are recorded in the Table *16*.

Table 16: Camera observations over the duration of the test

Time in min	Non-fire side	Fire Exposure
0	Thermal start of the test	
7	Nothing To Report	Beginning of the spalling of the D3-C5-Mk30 panel in mark A
8		Beginning of the spalling of the D2-C3-Mk30 panel in mark B
10		Beginning of the spalling of the D4-C6-Mk20 panel in coordinate C
13		Beginning of the spalling of the D1-Ref panel in mark D
14		Appearance of the reinforcement of the D3 slab in mark E
15		Appearance of the reinforcement of the D2 slab in mark F
17		Appearance of the reinforcement of the D4 slab in mark G
18		Appearance of the reinforcement of the D1 slab in mark H
29	Penetrant testing on the D1-Ref and D3-C5-Mk30 slabs in mark 1	Continuation of the spalling of the 4 slabs
32	Penetrant testing on the D2-C3-Mk30 and D4-C6-Mk20 slabs in mark 2	Continued spalling of the 4 slabs. Flaking areas at the end of the test: - In reference I for the D1-Ref panel; - In reference J for the D2-C3-Mk30 panel; - In mark K for the D3-C5-Mk30 panel; - In L for the D4-C6-Mk20 panel.
32	End of the trial at the request of the sponsor	

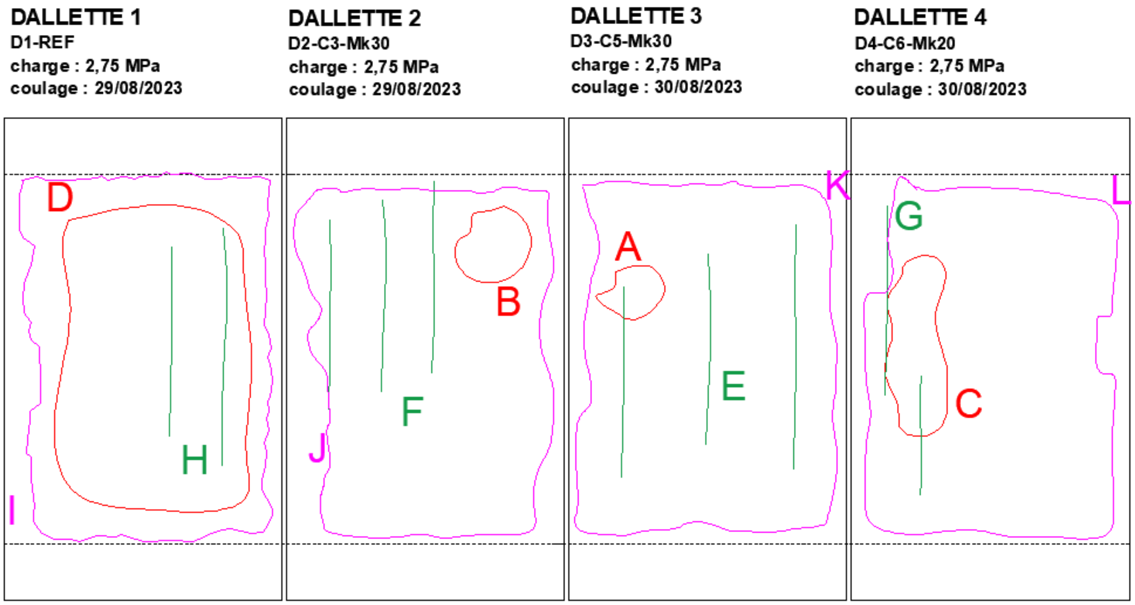


Figure 6: Location of the observations recorded on the face exposed to the fire of the slabs during the test

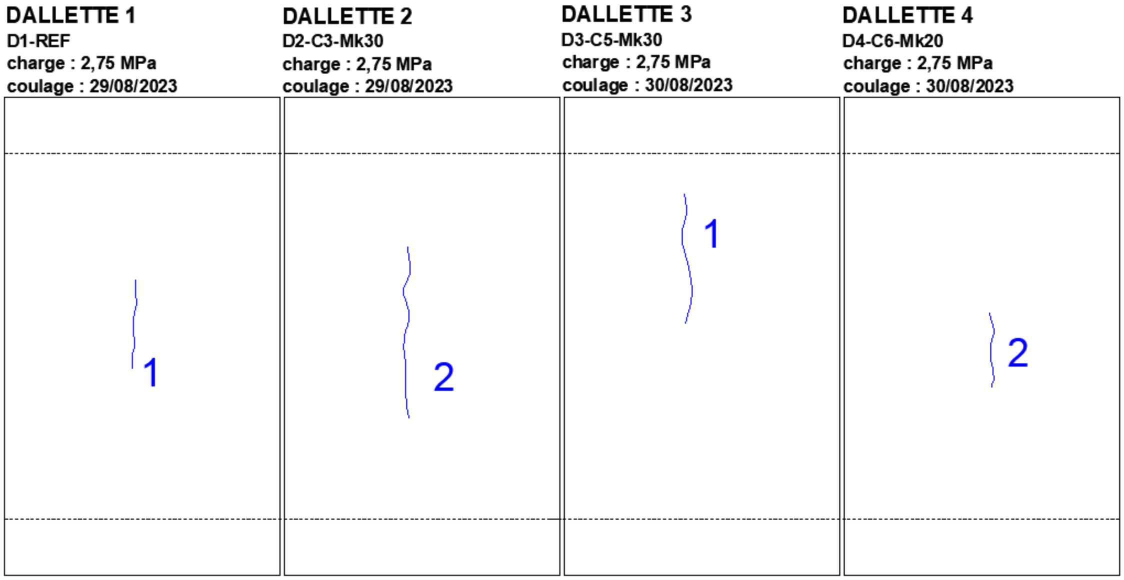


Figure 7: Location of the observations recorded on the front not exposed to the fire of the slabs during the test

Table 17: Recording of the shelling depths on the different slabs (loaded at 2.75 MPa)

Slab	**Maximum depth of the scaled area (in mm)**	**Average depth of surveys (in mm)**	**Scaled area (estimated in %)**	**Chipping onset time (in min)**
D1-Ref	100	63	95	13
D2-C3-MK30	116	89	90	8
D3- C5-Mk30	126	104	100	7
D4-C6-Mk20	100	77	95	10

The formula with the closest behavior to the reference control concrete is formula C6_Mk20.

The C5_Mk30 formula has a greater spalling that can be correlated with its higher mechanical strength, this quantity impacting the behavior of the concrete through its rigidity.

6 Life Cycle Assessments

This study was carried out in coordination with the Cerib team in charge of environmental analyses in order to support the definition of concrete on an ongoing basis and thus to determine its environmental impacts (including that of Global Warming / Carbon).

The DT DPM 2023-08 report in the appendix to this document highlights the potential environmental gains by LCA (Life Cycle Assessment), achieved compared to a reference concrete. It presents the assumptions and results obtained for the Climate Change indicator as well as a detailed analysis for this indicator. For a multi-criteria view, the other indicators of the NF EN 15804+A2 standard are presented in a dedicated file.

A summary of the results will be presented in this chapter.

6.1 Methodology

The study was carried out according to the Life Cycle Assessment (LCA) methodology, in accordance with the requirements developed in the NF EN ISO 14040 and NF EN ISO 14044 standards which provide the generic framework for the performance of an LCA.

In addition, this study is based on the requirements of the NF EN 15804+A2 standard and its national supplement NF EN 15804+A2/CN relating to "Environmental and Health Declarations for construction products", specific to construction products and following the recommendations of the RCP (Product Category Rule) for concrete and concrete elements NF EN 16757: 2022.

Due to the objective of developing low-carbon concrete, the focus is naturally on the climate change indicator (expressed in kg CO_2 eq. CO_2) which is the subject of a detailed analysis. To allow a multi-criteria view, all 38 indicators of the NF EN 15804+A2/CN standard have nevertheless been calculated and are provided in a dedicated Excel file.

6.1.1 Life cycle analysis: the steps studied

Life Cycle Assessment (LCA) is a method that assesses the environmental impacts of a product over its entire life cycle, from the extraction of raw materials to the end of its life.

Life Cycle Stages

The systems studied in a Life Cycle Assessment are subdivided into different stages according to the NF EN 15804+A2/CN standard:

- **Production (A1-A3):** all processes from the extraction of raw materials to the finished product leaving the factory;
- **Transport (A4):** from the delivery of the concrete product leaving the factory to the site for implementation;
- **Implementation (A5):** of the product and all complementary products and processes necessary for it;
- **Service life (B1-B7):** of the product during its use so that it continues to ensure the prescribed performance and carbonation of the concrete product;
- **End of life (C1-C4):** the demolition of the structure, the transport of waste and its treatment with a view to its recovery or disposal;
- **Benefits and expenses (D):** module D, end-of-life benefits and expenses related to recycling, is optional according to the NF EN 15804+A2 standard.

6.1.2 Setting References

In the case of this study, the objective is to carry out a comparative life cycle analysis of 10 concrete formulations, including 4 reference formulations and 6 containers of metakaolin and limestone. The data collected allowed us to perform an LCA to determine the relative gain observed on the indicator related to global warming for the 6 formulations.

For reference concretes, it was specified in the specifications to make a comparison with a classic class XC3 CEM I concrete according to NAF 1 of NF EN 206+A2/CN.

It was decided to enrich the comparison by modulating the references:

- Ref1: 280 kg/m^3 of CEM I, limit of the standard;
- Ref2: 300 kg/m^3 of CEM I, a classic formula encountered in concrete plants for XC3/XC4/XF1 concretes;
- Ref3: 280 kg/m^3 of CEM II/A-LL: faced with climatic constraints, the concretes used on the day of the study hardly use any CEM I in order to reduce the impact of the BPE concretes;
- Ref4: 300 kg/m^3 de CEM II/A-LL.

This modulation will allow the customer to appreciate the CO_2 savings observed both on high-impact concretes based on CEM I and on standard concretes that are a little more up-to-date.

6.2 Results

6.2.1 Results for Steps A1-A4 of the Climate Change Indicator

The life cycle analysis confirms that cement is the largest contributor to the climate change indicator. Indeed, it is responsible for more than 60% of the indicator on stages A1-A4 and more than 75% on stage A1 of the concrete life cycle, as illustrated in Figure 8.

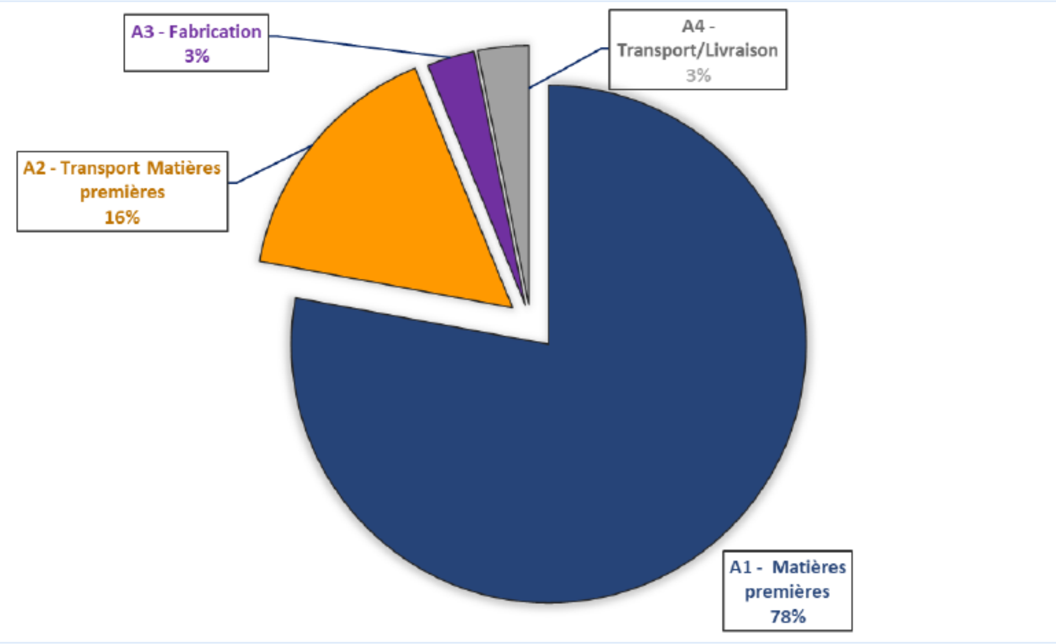


Figure 8: 99% contributors to the climate change indicator for formulation C1_Mk20

6.2.2 Relative gains of the 6 formulations compared to the 4 references

The exhaustive calculation data can be found in the DT-DPM-2023-8 report, with tables on climate change indicators in kg CO_2 eq/m^3 of concrete.

These calculations made it possible to make comparisons with the references to estimate the potential gains obtained with the different concretes in the study.

% gains on stage A1 (Commodities)

Table 18: Comparison of % gains on the climate change indicator for the 6 formulations compared to the 4 references

	C1_Mk20 (%)	C2_Mk30 (%)	C3_MK30 (%)	C4_MK20 (%)	C5_Mk30 (%)	C6_Mk30 (%)
Compared to Ref1	39	35	44	41	40	48
Compared to Ref2	43	39	48	45	44	51
Compared to Ref3	28	24	35	31	30	39
Compared to Ref4	33	29	39	36	35	43

Gains in % on stage A1-A4 (Production-Transport)

Table 19: Comparison of % gains on the climate change indicator for the 6 formulations compared to the 4 references

	C1_Mk20 (%)	C2_Mk30 (%)	C3_MK30 (%)	C4_MK20 (%)	C5_Mk30 (%)	C6_Mk30 (%)
Compared to Ref1	34	31	38	36	35	**42**
Compared to Ref2	37	35	**42**	39	39	**45**
Compared to Ref3	25	21	30	27	26	34
Compared to Ref4	29	25	34	31	30	37

The C6_Mk20 formulation using a composite binder containing 133 kg of EMF II per m^3, as well as metakaolin and limestone resulted in a gain on the global warming indicator of more than 45% compared to the reference formulation 2 composed of 300 kg of EMF I per m^3.

The formulation C3_Mk30 also composed of EMF II (139 kg of EMF II per m^3), metakaolin and limestone provides a 42% gain on the global warming indicator compared to reference formulation 2.

Figure 7 shows the preponderant impact of cement, and more particularly clinker, in the overall impact of the material.

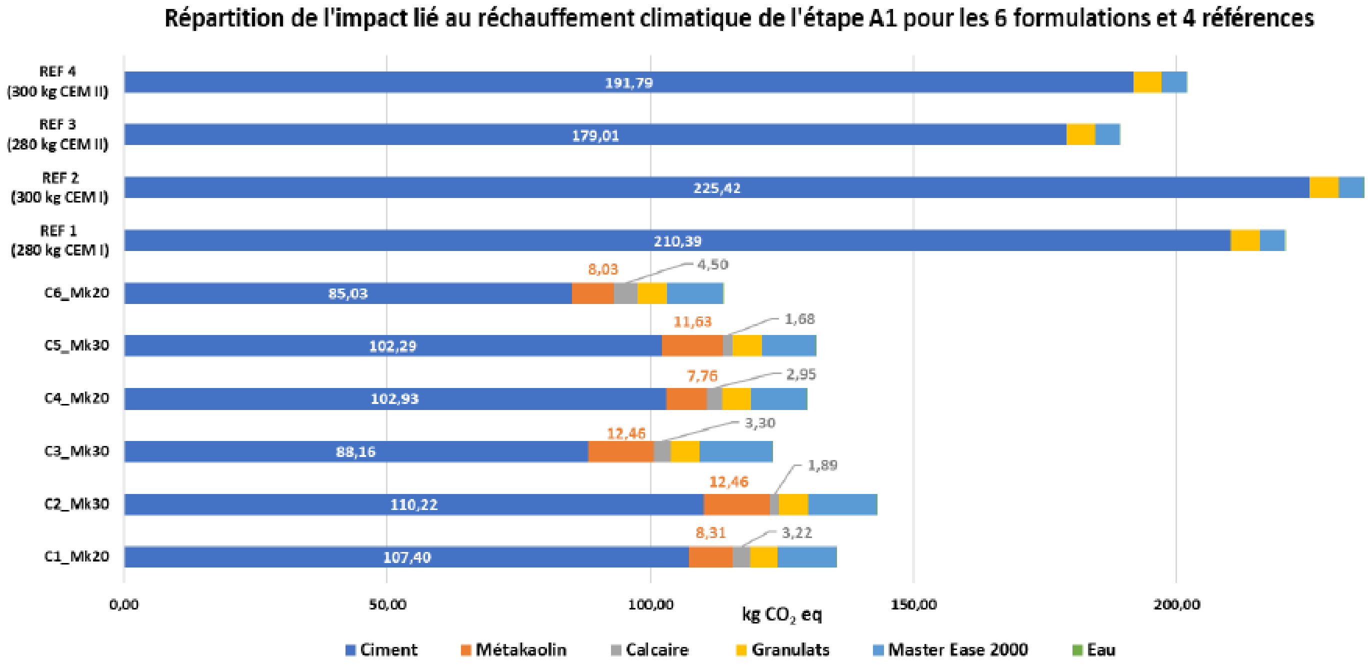


Figure 9: Contributors to the climate change indicator for step A1 of the 6 formulations and 4 references studied in kg CO_2 eq

The following LCA modules are identical for the different concretes, except for module B, which takes into account the carbonation of the concrete over the life of the structure.

To take into account the carbonation of concrete, the methodology used follows the recommendations of the NF EN 16757: 2022 RCP standard for concrete and concrete elements.

The use scenario considered for the calculations is a use of concrete in slabs.

The table below summarises the different quantities of CO_2 absorbed by the 6 formulations as well as the 4 references studied.

Formulation	Quantity of cement (kg/m^3)	Type of cement	Amount of CO_2 absorbed during the lifetime (kg CO_2)
C1_Mk20	168	CEM II	1.58
C2_Mk30	172.4	CEM II	1.62
C3_Mk30	137.9	CEM II	1.3
C4_Mk20	161	CEM II	1.51
C5_Mk30	160	CEM II	1.51
C6_Mk20	133	CEM II	1.2
REF 1	280	CEM I	3.01
REF 2	300	CEM II	3.22
REF 3	280	CEM I	2.64
REF 4	300	CEM II	2.83

As the amount of cement increases, the amount of CO_2 absorbed during the service life of the concrete product increases. The formulation C6_Mk20 containing the lowest amount of EMF II absorbs 1.2 kg of CO_2 during the product's lifetime, which represents less than 1% of the global warming indicator value for steps A1 to A4, which is 113.89 kg CO_2 eq for this formulation.

On the other hand, reference 2 using the highest amount of CEM I absorbs 3.22 kg of CO_2 during the working life of the product. This amount of CO_2 represents 1.2% of the result of the climate change indicator, which is 235.53 kg CO_2 eq for this reference on stages A1 to A4.

7 Project conclusions

The primary objective of this project was to develop a low-carbon concrete using a ternary binder composed of metakaolin and limestone, aiming to reduce the carbon footprint while maintaining sustainability performance in accordance with exposure class XC3. The results from various tests demonstrated that the **C6_Mk20** concrete formulation successfully meets sustainability requirements, achieving a notable reduction in CO_2 emissions of approximately 45%.

The key findings of this study are as follows:

1. **Mechanical and Physicochemical Properties**: The mechanical properties, including compressive strength, modulus of elasticity, and delayed deformations, were maintained at satisfactory levels despite the partial substitution of cement with supplementary materials.
2. **Durability**: The performance-based approach allowed verification that the mixtures meet the specific requirements of exposure class XC3, ensuring adequate protection of reinforcement against corrosion and long-term structural durability.
3. **Fire Behavior**: The fire performance of the most promising formulations, in terms of both performance and environmental reduction, was assessed and found to be acceptable for the intended applications.
4. **Reduced Carbon Footprint**: The partial replacement of Portland cement with metakaolin and limestone resulted in a significant decrease in CO_2 emissions associated with the production of the concrete mixtures. Specifically, **C6_Mk20** showed a reduction of over 40% in its carbon footprint, representing a substantial improvement toward the construction industry's sustainability goals.

In conclusion, the **C6_Mk20** formulation not only meets the required specifications for concrete but also offers substantial CO_2 emission reductions while maintaining performance in line with industry standards. This makes it a viable and sustainable alternative to traditional concrete mixtures. The adoption of such formulations can significantly contribute to lowering the environmental impact of the construction industry, aligning with Groupe ADP's efforts to mitigate climate change through more sustainable infrastructure practices.