Heidelberg Materials

Status Report

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Executive Summary:

Heidelberg Materials Hispania (HMH) is firmly committed to reducing the carbon footprint of its products by lowering clinker content and increasing the use of supplementary cementitious materials such as fly ash. This strategy supports Heidelberg Materials' global goal for 2030: achieving 50% of revenue from sustainable products. One of the notable developments in 2023 was the introduction of CEM II/A-V 52.5 R, replacing CEM I 52.5 R as part of the company's transition toward low-carbon solutions for the precast, prestressed and early-strength segment. This cement delivers high early and final strengths, rapid hardening, and carries the AENOR N Sustainable Mark, reducing Global Warming Potential by approximately 17% compared to the GCCA CEM I baseline.

Building on this success, HMH recently introduced CEM IV/A (V) 52.5 R-SR, an evoBuild Low Carbon Cement 30. This pozzolanic cement ensures very high mechanical strength, superior sulfate resistance, and at least 30% recycled content, achieving 30% lower CO_2 emissions.

This study evaluates the performance of CEM IV/A (V) 52.5 R-SR compared to the benchmark CEM II/A-V 52.5 R in concrete, confirming that a reduced clinker factor can deliver equal or superior performance without compromising workability, strength development or durability.

Key intermediate results:

- Both cements enabled concrete to achieve high early strength. At later ages, CEM IV/A (V) showed a more pronounced strength gain, confirming superior long-term performance due to continued pozzolanic reactions.
- Shrinkage was equivalent for both concretes stabilizing after 91 days and remaining stable after one year.
- Concrete produced with both cements demonstrated very high resistance to chloride ingress. CEM IV/A (V) exhibited slightly lower diffusion and migration coefficients than CEM II/A-V, reducing the potential risk of reinforcement corrosion.
- Tested concrete mixes fulfilled the CIF acceptance criteria, showing no internal damage or surface scaling when tested without de-icing agents.
- Accelerated carbonation depths were minimal (≈1 mm), and no carbonation was detected under natural exposure after one year, confirming excellent performance.
- Water penetration under pressure was far below Spanish Structural Code [1] limits for both mixes, ensuring excellent watertightness.

In summary, current findings confirm that CEM IV/A (V) 52.5 R-SR meets mechanical and durability requirements, making it a safe, high-performance alternative for applications requiring superior sulfate resistance, while supporting sustainable construction goals. Remaining next steps include natural carbonation testing after two years and chloride profile assessment at 180 days to further validate durability under extended exposure conditions.

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1 Introduction

1.1 Background

Heidelberg Materials Hispania (HMH) is strongly committed to reducing the carbon footprint of its products. HMH´s strategy focuses on lowering clinker content and increasing the use of fly ash in cement production. One of Heidelberg Materials' key goals for 2030 is for 50% of global revenue to come from sustainable products.

An important step toward this goal was the launch of CEM II/A-V 52.5 R in 2023, replacing CEM I 52.5 R. This transition marked a historic milestone at the Añorga and Arrigorriaga plants, where Portland cement had been produced for more than 170 years. The new CEM II/A-V 52.5 R delivers very high early and final strengths, rapid hardening, and carries the prestigious AENOR N Sustainable Mark, reducing the Global Warming Potential (GWP) by about 17% (kg CO_2 eq/t) compared to a standard GCCA CEM I (2019/20 baseline).

Building on this progress, HMH has introduced CEM IV/A (V) 52.5 R-SR, an evoBuild Low Carbon Cement 30 designed to replace CEM I 52.5 R/SR in applications requiring high sulfate resistance, while offering customers a lower-carbon alternative to CEM II/A-V 52.5 R. This pozzolanic cement complies with UNE-EN 197-1:2011, providing excellent sulfate resistance and very high mechanical strength. It achieves 30% lower CO_2 emissions and incorporates at least 30% recycled content, supporting circularity in both the precast and ready-mix sectors.

Although Spanish regulations for prestressed concrete currently allow only CEM I and CEM II/A-V— mainly due to limited market experience with other cement types. HMH aims to demonstrate that CEM IV/A (V) 52.5 R-SR is a safe and high-performance alternative when superior sulfate resistance is required in demanding precast or prestressed applications. CEM IV/A (V) 52.5 R-SR is produced at the Arrigorriaga plant and supplied in bulk.

1.2 Trial objective and scope

This study aims to assess the durability performance of CEM IV/A (V) 52.5 R-SR cement with a reduced clinker factor compared to the benchmark CEM II/A-V 52.5 R cement. The target is to ensure that these changes are implemented without loss of performance and with minimal adjustments to concrete mix design, maintaining on-site workability and durability.

The study evaluates the following properties:

- Drying shrinkage
- Carbonation resistance
- Chloride resistance
- Freeze-thaw resistance without de-icing agent
- Water penetration test

2 Experimental

2.1 Materials

Cements

In this study, two types of cement were employed. The first one, CEM II/A-V 52.5 R, is a Portland cement characterized by very high early and final mechanical strength and rapid hardening, in accordance with UNE-EN 197-1. The second cement, evoBuild LowCarbon Cement 30 – CEM IV/A (V) 52.5 R-SR, is a pozzolanic cement offering high chemical resistance to sulfates and very high early and final strength, also complying with UNE-EN 197-1:2011. Both cements are certified with the AENOR N

Sustainable Mark, which integrates European sustainability criteria into the well-established voluntary quality certification AENOR N Mark.

According to EN 197-1 and UNE 80303-1, sulfate-resistant pozzolanic cements (CEM IV SR) are characterized by a maximum C_3A content of 9% by mass of clinker. For the analyzed CEM IV/A (V) 52.5 R-SR, the estimated C_3A content in clinker is approximately 3.6%, which is well below this limit, confirming its high chemical resistance to sulfates. The reported percentages in Table A.1 (2.7%) refer to the overall cement, not the clinker fraction.

The cement composition was reassessed based on repeated XRD/Rietveld analysis, supported by thermogravimetric analysis coupled with evolved gas analysis by MS. The TG results were used to estimate the carbonate content, which was assigned mainly to limestone filler. Carbonate contents of 4.9% for CEM II/A-V 52.5 R and 2.4% for CEM IV/A (V) 52.5 R-SR were determined by TG analysis. The resulting estimated cement compositions are summarized in Table 1. Considering the expected accuracy of the analytical approach, the estimated phase contents should be interpreted with an uncertainty of approximately ±2%.

Table 1 – Estimated composition of CEM II/A-V 52.5 R and CEM IV/A (V) 52.5 R-SR cements based on XRD/Rietveld and TG analysis.

	Clinker	**Fly ash**	**Limestone filler**
CEM II/A-V 52,5 R	81.4%	13.7%	4.9%
CEM IV/A (V) 52,5 R-SR	72.9%	24.7%	2.4%

Aggregates

The aggregates used in this durability study were the same crushed limestone aggregate (0/4 sand, 4/16 and 16/22 gravel) used in daily concrete production in Bilbao RMCs Plants. They were sourced from the Mañaria quarry and delivered to Leimen in March 2025. Their basic characteristics are presented in Table 2.

Table 2 – Basic physical properties of Mañaria limestone aggregates.

Property	**Unit**	**Limestone sand 0/4 mm**	**Limestone shipping 4/11 mm**	**Limestone shipping 11/20 mm**
Density (rd)	kg/dm³	2.69	2.67	2.67
Density (ssd)	kg/dm³	2.70	2.68	2.71
Water absorption	M.-%	0.30	0.40	0.50

Admixtures

All the admixtures considered are currently used in ready-mix concrete production and are supplied by Master Builders Solutions. Master Ease 3850 is a high- range water reducer (HRWR), typically used in the RMX plant. This is combined with MasterPozzolith 7070, a mid-range water reducer (MRWR), which secondary function is a retarder. Technical data sheets of the admixtures considered are Figure A.1 and Figure A.2.

2.2 Concrete compositions

Table 3 summarizes the concrete composition used for the study. HA-35 concrete, which corresponds to a strength class (C35/45) and is widely supplied for all types of structural applications. Consistency class S3 and 22 mm maximum aggregate size are typically required.

The concrete mix design complies with the durability requirements for exposure class XD in prestressed concrete, which set a maximum water-to-cement ratio of 0.45 and a minimum cement content of 325 kg/m³, as specified in Table 43.2.1.a of the Spanish Structural Code [1].

Table 3 – Composition of tested concrete mixes.

Materials	**Unit**	**HA-35/F/20/XD- S3 Ref.**	**HA-35/F/20/XD- S3**
CEM II/A-V 52.5 R	kg/m³	325	-
CEM IV/A (V) 52.5 R-SR	kg/m³	-	325
Limestone sand 0/4 mm	kg/m³	902	899
Limestone shipping 4/11 mm	kg/m³	277	276
Limestone shipping 11/22 mm	kg/m³	777	775
Water	kg/m³	146	146
w/c ratio	-	0.45	0.45
MasterEase 3850*	% (bwoc)	2.1	2.1
Master Pozzolith 7070*	% (bwoc)	0.4	0.4

* *Additive dosage was adjusted to reach workability target.*

2.3 Analyzed properties of concrete mixes

Table 4 summarizes the tests in fresh and hardened state that have been conducted for assessing the durability of the CEM IV/A (V) 52.5 R-SR concrete mixes.

2.4 Sample preparation and storage

Concrete mixing was carried out in the GRDI laboratory under controlled conditions at 20 ± 2 °C. Fresh properties—including initial slump, wet density, and air content—were measured immediately after mixing. Specimens were cast, cured for 24 hours, then demolded and stored in water or a conditioning cabinet until testing. For each batch, 100 mm cube samples were prepared to determine compressive strength at 2 and 28 days.

Table 5 summarizes the test methods that have been conducted, together with curing regimes for each test, specimen dimensions and testing ages.

Table 4. List of fresh and hardened concrete measurements performed.

Fresh concrete	Hardened concrete
• Slump test, EN 12350-2 • Fresh concrete density, EN 12350-6 • Air content, EN 12350-7	• Compressive strength cubes and cylinders, EN 12390-3 • Dry density, EN 12390-7 • Drying shrinkage, EN 12390-16 • Natural carbonation, EN 12390-10 • Accelerated carbonation, EN 12390-12 • Chloride diffusion test, EN 12390-11. • Rapid chloride migration, NT Build 492 • Frost resistance without presence of de-icing agent, surface scaling EN 12390-9; Internal damage (CIF test), CEN/TS 12390-9 • Water penetration under pressure test, EN 12390-8

Table 5. List of durability tests, curing regimes, concrete specimens, and testing age

Durability test	Test method	Curing		Concrete specimens	Testing age
		Time	Temp. (°C) / RH (%)		
Drying shrinkage	EN 12390-16	1 day in mold, samples stored: 20°C/65%		Beams 10 x 10 x 50 cm	1, 4, 7, 14, 28, 56, 91, 182, 273 and 374 days of drying
Natural Carbonation	EN 12390-10	28 days	20°C / 65%	Beams 10 x 10 x 50 cm	1, 2, 3, 6, 12, 24 months
Accelerated Carbonation	EN 12390-12	Under water for 28 d, afterwards samples are stored in standard conditioning chamber (20 ± 2) °C, RH (57 ± 3) %		Beams 10 x 10 x 50 cm	0, 1, 4, 10 weeks
Freeze thaw resistance - CIF test	EN 12390-9 CEN/TS 12390-9	1 day in mold, 6 days under water, 21 days: 20°C/65% *		Slabs 15 x 15 x 7 cm	Scaling: 14, 28, 42, 56 cycles RDM: 0, 14, 28, 42, 56 cycles
Rapid chloride migration test	NT Build 492	until testing age	under water 20°C	Discs Ø: 10 cm; H: 5 cm	28, 90, 180 days
Natural chloride diffusion test	EN 12390-11	Under water for 28 d; vacuum saturated with Ca(OH)2, then exposed to 3% NaCl solution		cyclinders Ø: 10 cm; H: 20 cm	28, 90, 180 days
Water penetration test	UNE EN 12390-8	28 days	20°C / ≥ 95%	Cubes 15 x 15 x 15 cm	28 days

** Before starting the FT cycling, samples were exposed to water uptake in de-ionized water. The temperature during the cycles was between -20°C and 20°C.*

3 Results and interpretation

The report considers all available results up to June 2026. Natural carbonation results will be reviewed in June 2027 for two-year measurement, while the chloride profile at 180 days remains pending.

3.1 Workability and compressive strength

Figure 1 shows the consistency results for concretes produced with CEM II/A-V 52.5 R and CEM IV/A (V) 52.5 R-SR. Five trial batches were produced for each concrete type using the corresponding cement, targeting an S3 consistency class. Most mixes achieved this target, showing cohesive behavior with slight stickiness and a gradual loss of workability over time. It is important to note that the admixture was added directly into the mixer rather than being dissolved in the mixing water, which is the usual practice in ready-mix concrete plants.

Laboratory conditions were also more demanding, as dry limestone aggregates were used instead of saturated surface-dry aggregates. Fresh concrete temperatures varied across the batches: mixes prepared in May and July (Mixes 1–4) exhibited relatively high temperatures, whereas the last batch in November (Mix 5) was within the normal range of approximately 20–22 °C, which is considered optimal for fresh concrete. A clear trend was observed: higher concrete temperatures tended to result in lower initial slump for similar admixture dosages.

Additionally, for Mix 5, the Pozzolith dosage (retarding admixture) was increased from 0.4% to 0.6%, which helped maintain the target consistency under cooler conditions. Based on these findings, it is recommended to increase the retarder dosage during high-temperature periods to ensure optimal workability and consistency.

Table A.3 in the Annex summarizes the fresh properties of all studied mixes.

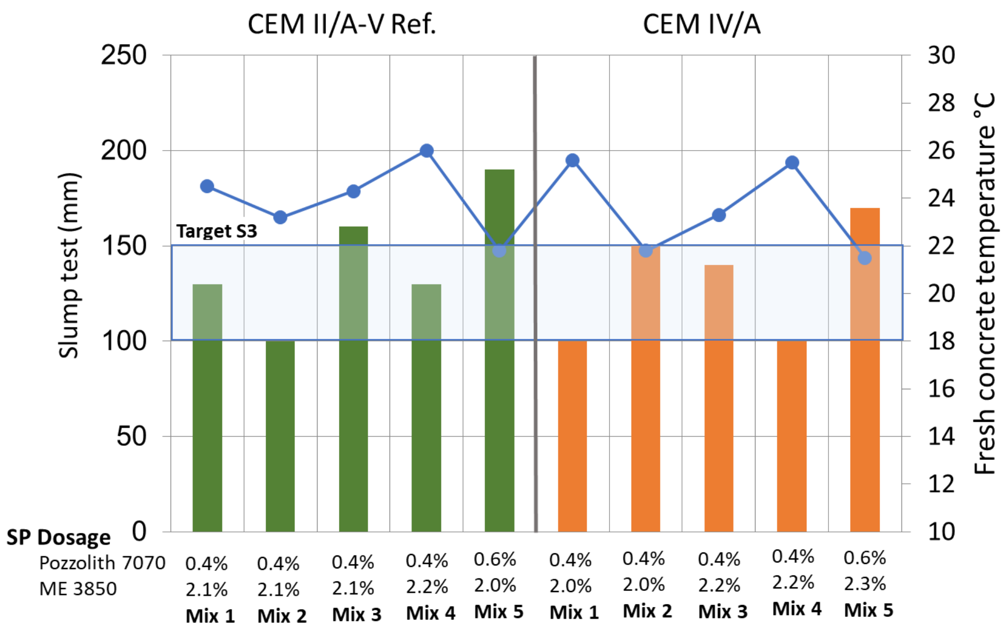
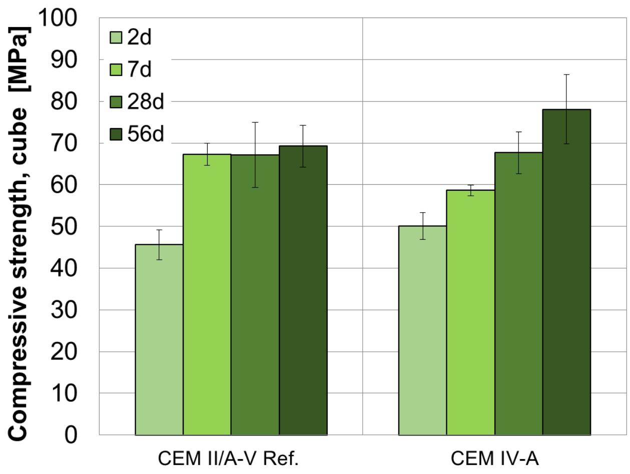


Figure 1. Consistency of CEM II/A-V 52.5 R and CEM IV/A (V) 52.5 R-SR concrete mixes.

Compressive strength results are presented in Figures 2 and 3 for cubes (100 × 100 × 100 mm³) and cylinders (h: 300 mm, Ø: 150 mm). Each data point represents the average of five different mixes, except for the 7-day cube test, which result includes value from two mixes. Both cement types achieved compressive strengths equivalent to class C35/45 within 2 days, indicating excellent early-age performance.

At 28 days, strengths were similar for both mixes, while CEM IV/A (V) demonstrated a more pronounced increase at 56 days, confirming its superior long-term strength development. This trend is attributed to the higher fly ash content in CEM IV/A (V), which promotes continued pozzolanic reactions and microstructure refinement over time.



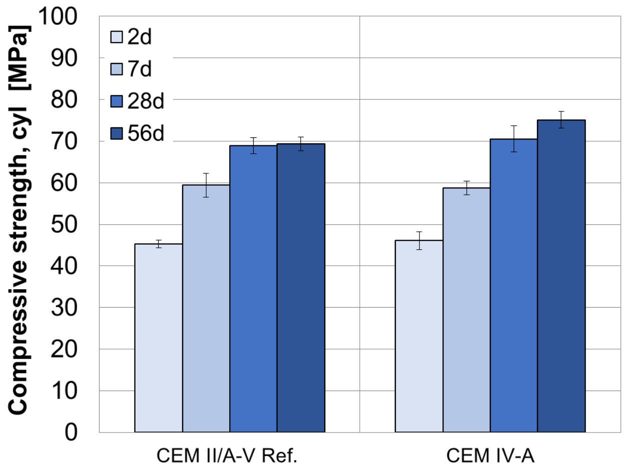


Figure 2. Compressive strength development of CEM II/A-V 52.5 R and CEM IV/A (V) 52.5 R-SR concrete mixes tested in cubes (left) and in cylinders (right) samples.

3.2 Durability tests

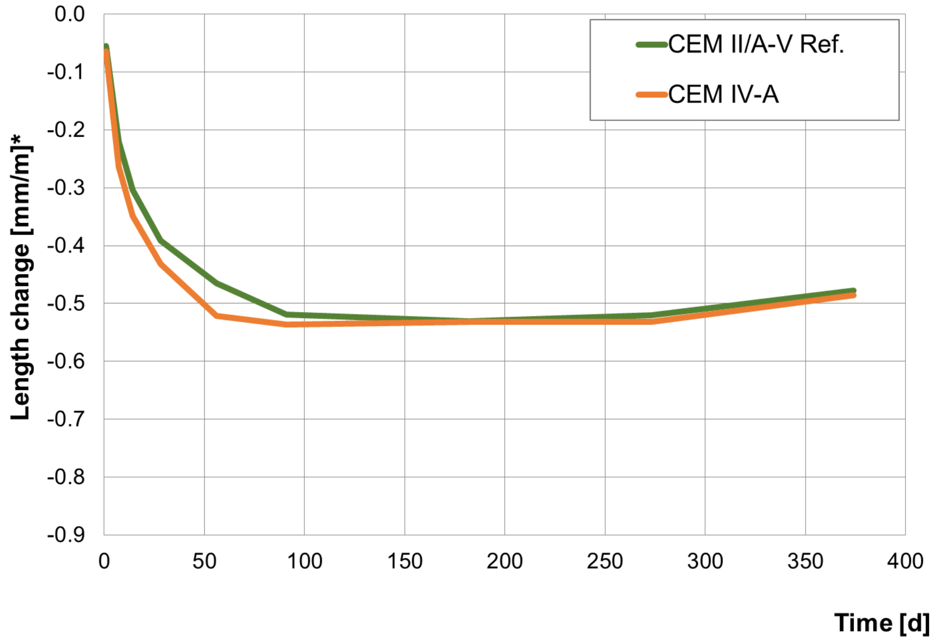
3.2.1 Drying shrinkage

Drying shrinkage in concrete is mainly caused by moisture loss under non-saturated conditions. Excessive shrinkage can lead to cracking, either as visible cracks due to restrained structural shrinkage or as microcracks within the paste caused by aggregate restraint, potentially compromising durability and aesthetics.

Neither DIN 1045-2 nor EN 1992-1-1 specify acceptance limits for drying shrinkage. However, design models such as Eurocode 2, fib Model Code 2010 and ACI 209R-92 predict ultimate shrinkage values typically in the range of 0.6–0.8 mm/m for conventional concretes. In practice, values below approximately 0.5 mm/m at 28 days are commonly considered acceptable to minimize the risk of early-age cracking.

Drying shrinkage was monitored up to 374 days for concretes produced with CEM II/A-V reference cement and CEM IV/A cement. Figure 3 shows the development over time. Both concretes exhibited a rapid increase in shrinkage during the first weeks, followed by a progressive stabilization after approximately three months. At around 90 days, shrinkage values were approximately 0.52 mm/m for the reference concrete and 0.54 mm/m for the CEM IV/A concrete. Between 90 and 274 days, only minor changes were observed, indicating that most of the drying shrinkage had already developed within the first months.

The final measurements performed at 374 days showed shrinkage values of approximately 0.48 mm/m for the reference concrete and 0.49 mm/m for the CEM IV/A concrete. These values are very close for both mixtures and remain below the typical ultimate shrinkage range predicted for conventional concretes. The results indicate that the CEM IV/A concrete exhibited a drying shrinkage behaviour comparable to that of the reference concrete over the full long-term monitoring period.



**Positive values indicate expansion, while negative values indicate shrinkage.*

Figure 3. Drying shrinkage of CEM II/A-V 52.5 R and CEM IV/A (V) 52.5 R-SR concrete mixes after 374 days of curing.

3.2.2 Chloride resistance

Chloride ingress was quantified on cores after 91 days of exposure to a sodium chloride solution. Depth-resolved chloride contents were obtained by acid digestion in accordance with EN 12390-11. By non-linear regression analysis by least squares curve fitting, the surface chloride content (C_s) and the non-steady-state diffusion coefficient (D_{nss}) are calculated by fitting Fick's second law.

Figure 4 represents the chloride profile curves for both cement types, which are comparable. However, CEM IV/A exhibits a lower chloride diffusion coefficient of 5.82×10^{-12} m²/s compared to 6.71×10^{-12} m²/s for CEM II/A-V. This reduced diffusivity in CEM IV/A is consistent with the expected pore refinement and the formation of additional C-S-H and C-A-S-H phases resulting from its higher pozzolanic content.

Chloride resistance was also evaluated using the rapid-chloride-migration (RCM) test in accordance with NT Build 492 [2].

Figure 5 shows the chloride migration coefficients measured after 28, 90, and 180 days of curing for mixes produced with CEM II/A-V 52.5 R and CEM IV/A (V) 52.5 R-SR. As expected, resistance to chloride ingress improves over time due to ongoing hydration, which progressively reduces porosity and pore connectivity. This effect is particularly pronounced in blended cements with fly ash, where hydration continues over extended periods. At later ages (90 and 180 days), CEM IV/A demonstrates higher resistance to chloride penetration compared to CEM II/A-V, consistent with its pozzolanic nature.

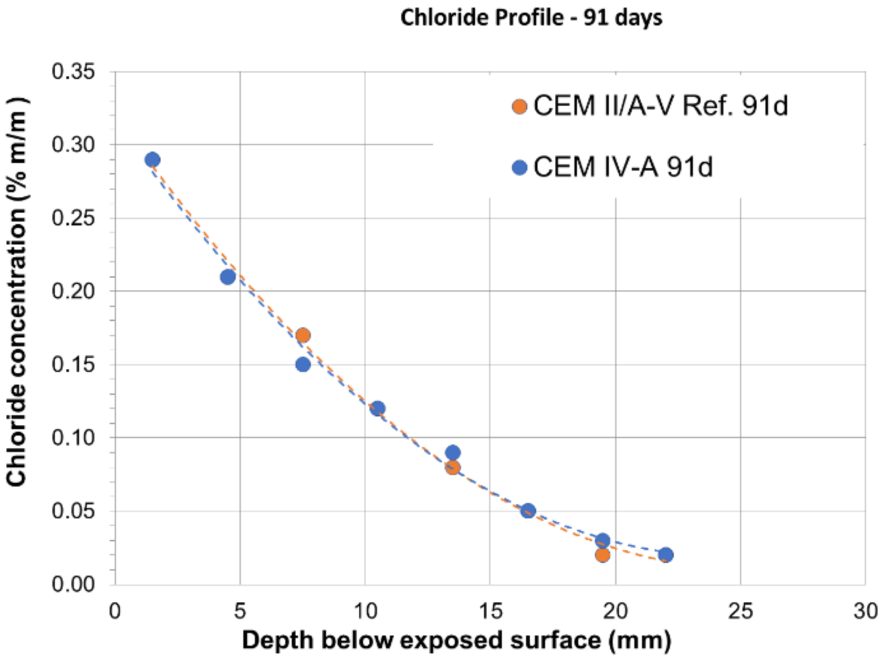


Figure 4. Chloride profile of CEM II/A-V 52.5 R and CEM IV/A (V) 52.5 R-SR concrete mixes according to EN 12390-11, exposed for 91 days in 3% NaCl solution.

These findings align with the non-steady-state diffusion coefficients obtained from chloride profiles, and both concretes fall within the category of high to very high resistance according to the classification proposed by Nilsson et al. [3].

Pictures of all samples tested are included in Figure A.3. and Figure A.4. of the Annex.

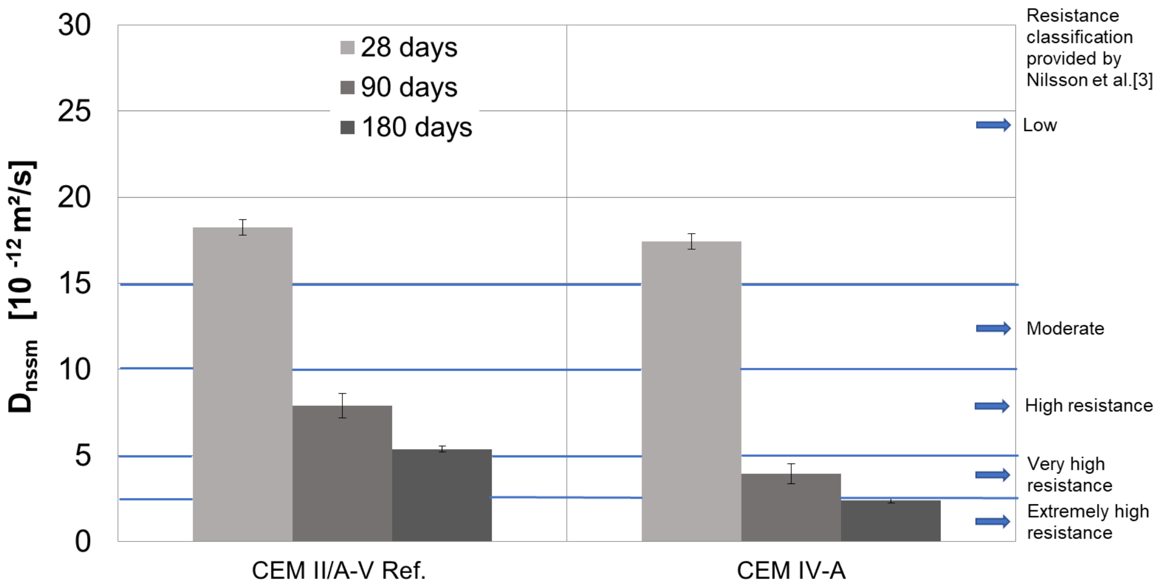


Figure 5: Average chloride migration coefficient measured by RCM test according to NT Build 492, after 28 days, 90 days and 180 days of curing for CEM II/A-V 52.5 R and CEM IV/A (V) 52.5 R-SR concrete mixes.

3.2.3 Freeze-thaw resistance without de-icing agent

The freeze-thaw resistance was evaluated using a slab test according to EN 12390-9 to assess surface scaling and a beam test according to CEN/TR 15177 to evaluate internal structural damage. Both tests were conducted without de-icing salts. Surface scaling was quantified by measuring the mass loss after brushing, while internal damage was assessed through the Relative Dynamic Modulus (RDM), determined from ultrasonic pulse velocity measurements. The results are presented in Figure 6 and Figure 7, respectively.

In the slab test, both concrete mixtures exhibited very low surface scaling, indicating excellent resistance to freeze-thaw attack. The cumulative scaling remained below 60 g/m² in both cases, which is far below the BAW (Bundesanstalt für Wasserbau) acceptance limit of 1000 g/m² [4].

In the beam test, frost resistance was evaluated according to BAW requirements using the Relative Dynamic Modulus (RDM). Concrete is considered to have failed when the RDM falls below 75%, and this limit must not be reached within the first 28 freeze-thaw cycles. As shown in Figure 7, both the CEM II/A-V Ref. and CEM IV-A mixtures maintained an RDM above 90% throughout the entire 56-cycle test, indicating only negligible deterioration. Therefore, both concretes fully comply with the German frost resistance requirements.

Figures A.5 and A.7 in the Appendix show the CEM II/A-V Ref. and CEM IV-A specimens before testing, while Figures A.6 and A.8 present the specimens after completion of the 56 freeze-thaw cycles.

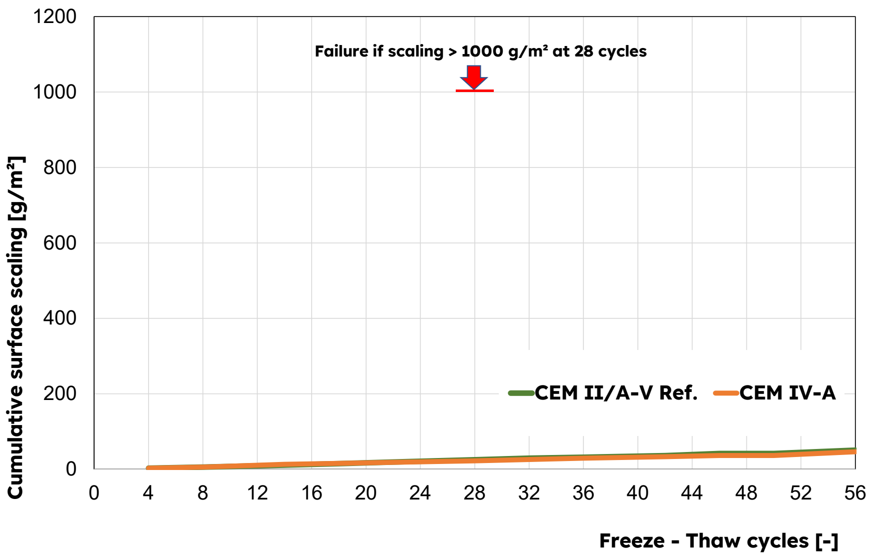


Figure 6: Cumulative surface scaling determined using the EN 12390-9 slab test method

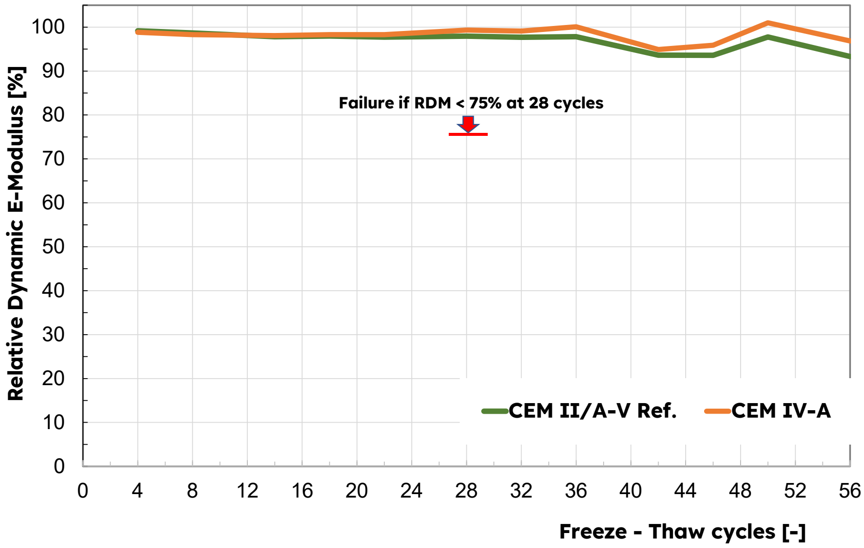


Figure 7: Relative dynamic modulus (RDM) determined using the beam test according to CEN/TR 15177.

3.2.4 Carbonation

Carbonation resistance is a key aspect of concrete durability, particularly for cements with high levels of supplementary cementitious materials and reduced clinker content. Figure 8 shows the carbonation depths obtained from accelerated testing as a function of exposure time. Both CEM II/A-V and CEM IV/A (V) mixes exhibit minimal carbonation, with depths of approximately 1 mm, indicating excellent resistance. Photographs of the specimens at 0, 28, and 70 days of testing are provided in Figures A.9, A.10, and A.11 in the Annex.

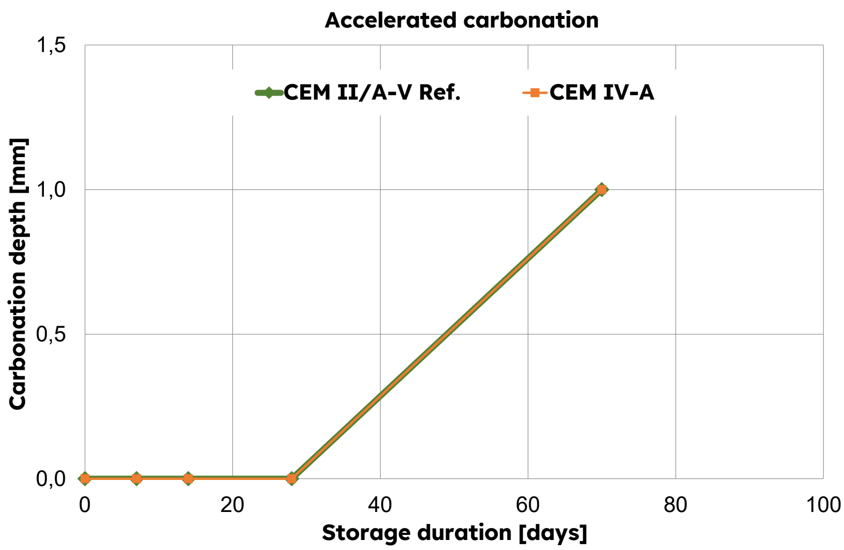


Figure 8: Accelerated carbonation of CEM II/A-V 52.5 R and CEM IV/A (V) 52.5 R-SR concrete mixes.

Figure 9 illustrates the carbonation depths measured on samples exposed to natural carbonation under laboratory conditions. After one year of exposure, no carbonation was detected in either the CEM II/A-V 52.5 R reference concrete or the CEM IV/A (V) 52.5 R-SR concrete. This confirms the high resistance of both mixes to natural carbonation under the investigated conditions. Further measurements are scheduled for June 2027, corresponding to two years of exposure.

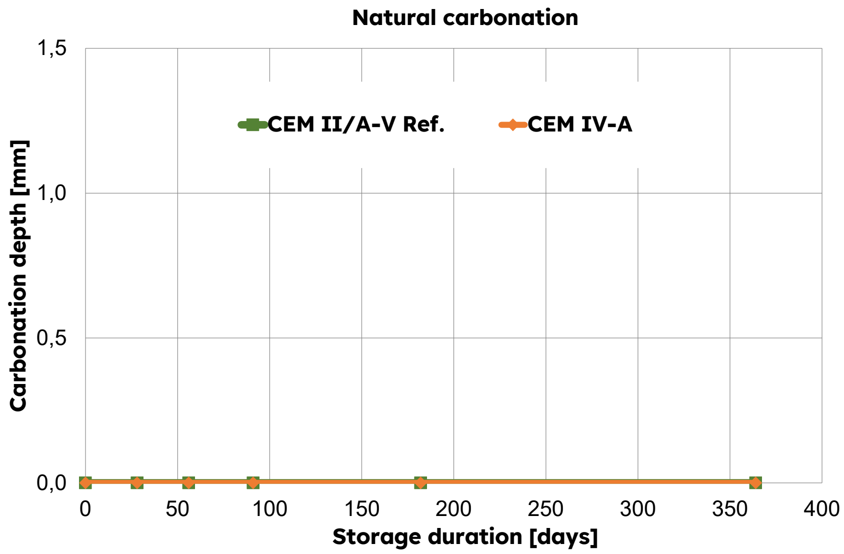


Figure 9: Carbonation depths of CEM II/A-V 52.5 R and CEM IV/A (V) 52.5 R-SR concrete mixes.

Natural carbonation: exposed to laboratory conditions 20 °C / 65% RH for 365 days.

3.2.5 Water penetration under pressure test

Water penetration under pressure was tested on three 150 mm cubic specimens in accordance with UNE-EN 12390-8. While the European Standard specifies the determination of maximum penetration depth, the Spanish Structural Code [1] extends the procedure to include the average penetration depth, providing a more comprehensive assessment of impermeability [5].

Figure 10 shows the maximum penetration depths measured on the tested concrete specimens. The CEM II/A-V 52.5 R samples reached a maximum depth of 7.3 mm, compared to 9 mm for the CEM IV/A (V) 52.5 R-SR specimens. The average penetration depth was slightly lower for CEM II/A-V (2.6 mm) than for CEM IV/A (V) (3.1 mm). A detailed summary of individual test results is provided in Table A.4 in the Annex.

According to the Spanish Structural Code [1], concrete is considered sufficiently impermeable when the maximum penetration depth is less than 30 mm and the average depth is less than 20 mm. All tested mixes meet these requirements for all exposure classes, confirming excellent watertightness [1].

Pictures of the tested specimens are provided in Figures A.12 and A.13 of the Annex.

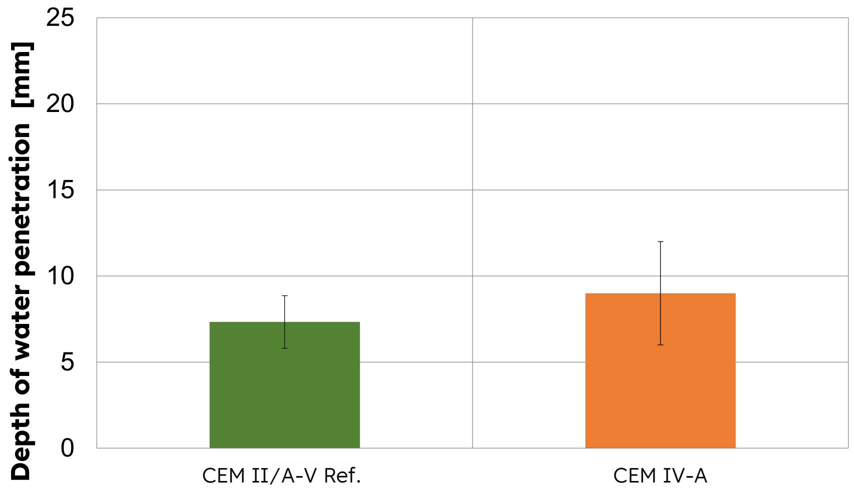


Figure 10: Water penetration depths of CEM II/A-V 52.5 R and CEM IV/A (V) 52.5 R-SR concrete mixes.

4 Conclusions

In this study, the durability performance of CEM IV/A (V) 52.5 R cement was evaluated and compared to the benchmark cement CEM II/A-V 52.5 R. The evaluation was performed in GRDI with raw materials and concrete compositions typically used in Bilbao RMCs plants.

Conclusions on the investigated concrete durability properties are as follows:

- Strength development: Both cement types achieved excellent early-age strength, meeting the C35/45 class at 2 days. At later ages, CEM IV/A (V) showed a more pronounced strength gain, confirming its superior long-term performance due to continued pozzolanic reactions and microstructure refinement.

- Drying shrinkage: CEM IV/A concrete exhibited equivalent shrinkage development compared to the reference mix over the full 374-day monitoring period. Both concretes stabilized after approximately 91 days and showed stable long-term behavior after about one year of measurements, which is favorable for durability and crack control.

- Chloride resistance: Both cements demonstrated excellent resistance to chloride ingress. Chloride profile and migration tests confirm that CEM IV/A (V) exhibits slightly lower diffusion and migration coefficients than CEM II/A-V, reflecting its denser microstructure and pozzolanic contribution. As both mixes fall within the category of high resistance to chloride penetration, the likelihood of chloride-induced reinforcement corrosion could be assumed to be negligible.

- Freeze - thaw resistance: Both concretes—CEM II/A-V and CEM IV/A (V)—demonstrated excellent freeze-thaw resistance under CIF testing without de-icing salts. This conclusion is supported by the fact that both mixes met the acceptance criteria for internal damage and surface scaling.

- Carbonation resistance: Both CEM II/A-V and CEM IV/A (V) mixes exhibited minimal accelerated carbonation, with depths of approximately 1 mm, indicating excellent resistance. In addition, no carbonation was detected in either the CEM II/A-V 52.5 R or CEM IV/A (V) 52.5 R-SR concrete samples after one year of exposure to natural carbonation.

- Water penetration under pressure test: Both concretes exhibited excellent watertightness, with maximum penetration depths far below the 30 mm limit established by the Spanish Structural Code [1], thus fully complying with impermeability requirements for all exposure classes.

In summary, CEM IV/A (V) proves to be an excellent choice for applications requiring rapid commissioning and high long-term mechanical performance. It showed outstanding durability against chloride ingress, high carbonation resistance, very low risk of freeze–thaw damage, and excellent watertightness. Overall, its performance is comparable to or superior to the benchmark cement in terms of strength and chloride resistance.

Next steps include completing the ongoing natural carbonation test after two years of exposure and the chloride profile assessment at 180 days to further validate durability under extended exposure conditions.

5 References

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Appendix

Table A. 1 – Physical, chemical properties and mineralogical analysis of cements used in this study.

Lab no.	86900-25	86899-25
Sample	CEM II/A-V 52,5 R Arrigorriaga	CEM IV/A(V) 52,5 R-SR Arrigorriaga
Chemical analysis		
SiO2-XRF (%)	21.11	25.13
Al2O3-XRF (%)	5.88	8.13
TiO2-XRF (%)	0.30	0.35
MnO-XRF (%)	0.17	0.16
Fe2O3-XRF (%)	3.65	3.97
CaO-XRF (%)	57.95	52.35
MgO-XRF (%)	2.09	2.21
K2O-XRF (%)	0.86	1.11
Na2O-XRF (%)	0.53	0.64
SO3-XRF (%)	3.17	2.66
P2O5-XRF (%)	0.30	0.27
Mineralogical analysis (Rietveld)		
C3S (%)	51.70	47.20
C2S (%)	10.30	11.30
C3A (%)	2.80	2.70
C4AF (%)	9.90	9.50
Free lime (%)	0.50	0.50
Portlandite (%)	0.80	0.80
Periclase (%)	1.30	1.20
Aphthitalite (%)	0.70	0.70
Total clinker (%)	**78.0**	**73.9**
Anhydrite (%)	1.10	0.60
Dihydrate (%)	1.00	0.50
Hemihydrate (%)	0.40	0.40
Total set regulator (%)	2.50	1.50
Quartz (%)	1.30	2.40
Calcite (%)	**4.60**	**3.00**
Dolomite (%)	1.10	0.70
Mullite 3:2 (%)	0.90	1.00
Amorphous content (%)	**11.50**	**17.60**
Physical properties		
LOI 1050 °C	2.95	2.55
Density (g/cm3)	3.06	3.00
Blaine (cm2/g)	4780	6400
BET (m2/g)	1.38	2.21

Table A. 2 – Mortar performance of CEM II/A-V (Ref.) and CEM IV/A (V) cements.

Lab no.	86900-25	86899-25
Sample	CEM II/A-V 52,5 R Arrigorriaga	CEM IV/A(V) 52,5 R-SR Arrigorriaga
water demand (%)	32.0	33.0
initial set (EN 196-3) (min)	245	180
final set (EN 196-3) (min)	290	200
spread A0 - mortar (mm)	192	180
spread A15 - mortar (mm)	185	169
spread A30 - mortar (mm)	182	164
spread A45 - mortar (mm)	178	161
spread A60 - mortar (mm)	173	160
flexural strength 1 d (MPa)	5.0	5.1
flexural strength 2 d (MPa)	6.5	6.2
flexural strength 7 d (MPa)	8.0	7.4
flexural strength 28 d (MPa)	8.9	8.1
flexural strength 90 d (MPa)	8.9	8.9
compressive strength 1d (MPa)	23.9	24.1
compressive strength 2d (MPa)	38.8	36.9
compressive strength 7d (MPa)	53.5	49.9
compressive strength 28d (MPa)	61.6	55.5
compressive strength 90d (MPa)	71.9	73.5

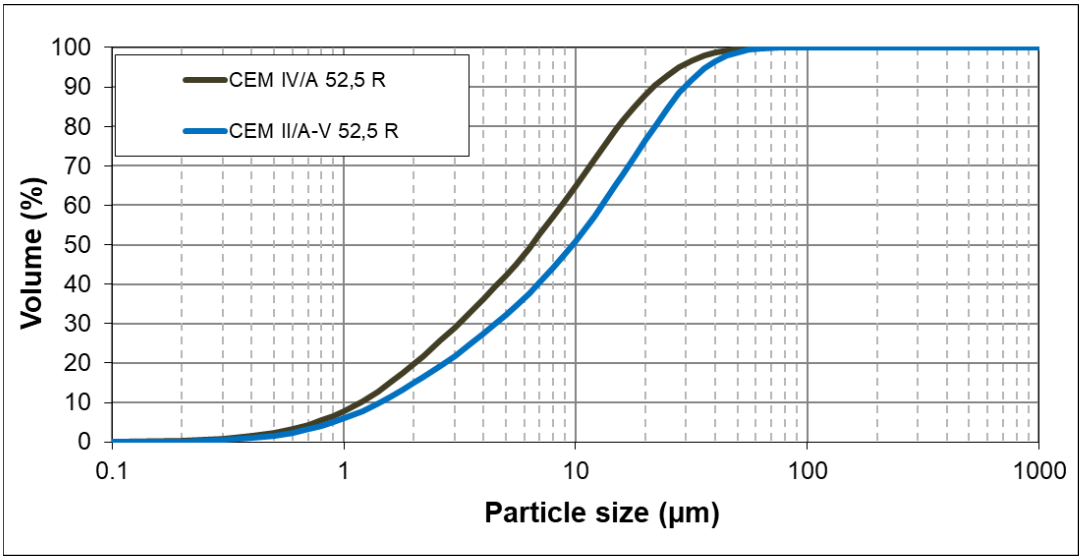

Figure A. 1 – Particle size distribution of CEM II/A-V (Ref.) and CEM IV/A (V) cements used in this study.

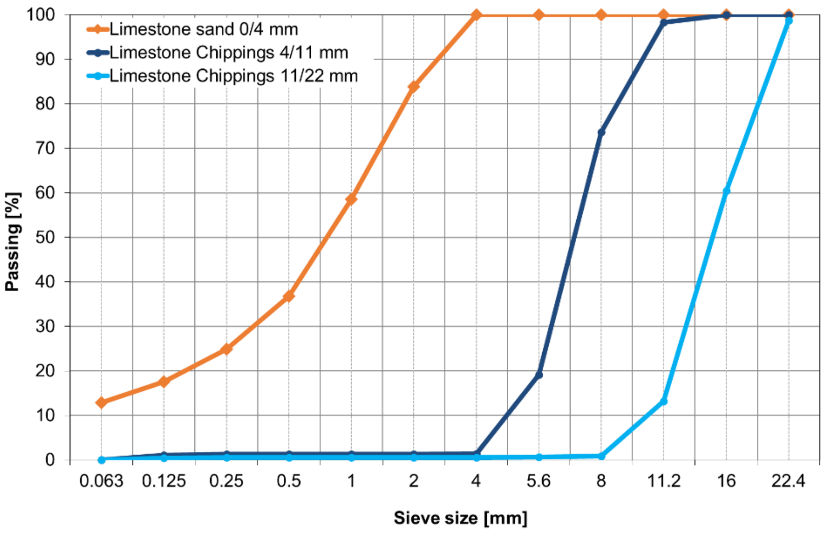

Figure A. 2 – Particle size distribution of aggregates.

Table A. 3 – Fresh properties of CEM II/A-V 52.5 R and CEM IV/A (V) 52.5 R concrete mixes.

Mix	CEM II/A-V (Ref.)	CEM IV/A (V)
Lab No.	88376-25 88387-25 88388-25 90659-25 92750-25	88393-25 88394-25 88395-25 90660-25 92751-25
Fresh concrete composition/properties*		
Fresh concrete temperature 10′ [°C]	23.5	23.5
Fresh concrete density 10′ [kg/m³]	2443	2443
Air 10′ [vol.%]	2.7	2.7
S_{10} [mm]	142	132

**Results are average of 5 mixes*

Table A. 4 – Maximum and average penetration depths of CEM II/A-V (Ref.) and CEM IV/A (V) concrete mixes.

Concrete mix	**Maximum penetration depth**				**Average penetration depth**			
	Z_1	Z_2	Z_3	Z_m	T_1	T_2	T_3	T_m
CEM II/A-V (Ref.)	7	9	6	7.3	2.7	2.2	2.8	2.6
CEM IV/A (V)	6	12	9	9	3	3.8	2.5	3.1

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Figure A. 1 – Properties of MasterPozzolith 7070.

MasterPozzolith 7070

Aditivo polifuncional de nueva generación y altas prestaciones para hormigón preparado con elevado mantenimiento de consistencia.

Hay que tener en cuenta

- Se recomienda la realización de ensayos previos a la utilización del producto.
- No emplear dosificaciones inferiores ni superiores a las recomendadas sin previa consulta con nuestro Departamento Técnico.
- Consulta la compatibilidad entre aditivos antes de su utilización.

Propiedades	
Función principal:	Plastificante / Reductor de agua.
Efecto secundario:	Retrasa el fraguado a dosis elevadas.
Aspecto físico:	Líquido turbio marrón.
pH, 20º C:	6 ± 1
Densidad, 20º C:	1,060 ± 0,02 g/cm3
Viscosidad 20º C Brookfield Sp00/100rpm:	< 15 cps.
Contenido en cloruros:	< 0,1%
Los datos técnicos reflejados son fruto de resultados estadísticos y no representan mínimos garantizados. Si se desean los datos de control, pueden solicitarse las "Especificaciones de Venta" a nuestro Departamento Técnico.	

Figure A. 2 – Properties of MasterEase 3850.

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MasterEase 3850

Aditivo superplastificante / reductor de agua de alta actividad para la producción de hormigones de baja viscosidad y reología mejorada con un buen mantenimiento de consistencia.

Manipulación y transporte

Para su manipulación deberán observarse las medidas preventivas usuales para el manejo de productos químicos por ejemplo usar gafas y guantes. No comer, beber ni fumar durante la aplicación. Lavarse las manos antes de una pausa y al término del trabajo.

La eliminación del producto y su envase debe realizarse de acuerdo con la legislación vigente y es responsabilidad del poseedor final.

Para más información, consultar la Hoja de Seguridad del producto.

Hay que tener en cuenta

- Se recomienda siempre la realización de ensayos previos a la utilización del aditivo.
- No emplear dosificaciones inferiores ni superiores a las recomendadas sin previa consulta con el Departamento Técnico.
- Consulta la compatibilidad entre aditivos

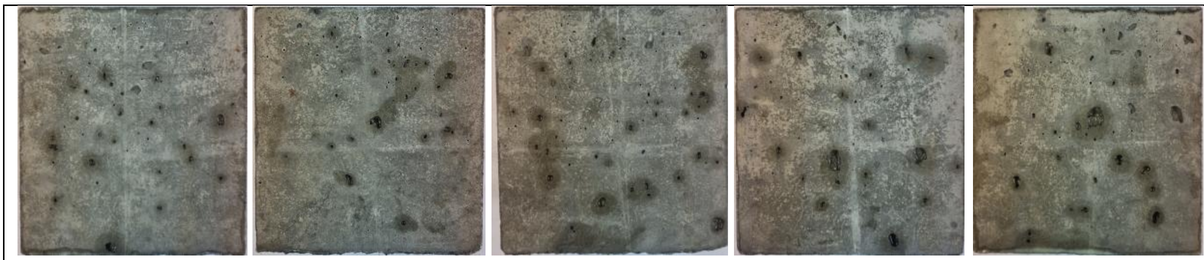
Propiedades	
Función principal:	Superplastificante / Reductor de agua de alta actividad.
Efecto secundario por sobredosificación:	Riesgo de disgregación a dosis elevadas.
Aspecto físico:	Líquido turbio amarillento.
Densidad, 20º C:	1,040 ± 0,02 g/cm3
pH, 20º C:	8 ± 1
Viscosidad Brookfield 20º C Sp00/100rpm:	< 35 cps.
Cloruros:	< 0,1%
Los datos técnicos reflejados son fruto de resultados estadísticos y no representan mínimos garantizados. Si se desean los datos de control, pueden solicitarse las "Especificaciones de Venta" a nuestro Departamento Técnico.	

(a) (b) (c)

Figure A. 3: Chloride migration front of CEM II/A-V (Ref.) individual samples after 180 days of curing

(a) (b) (c)

Figure A. 4: Chloride migration front of CEM IV/A (V) individual samples after 180 days of curing

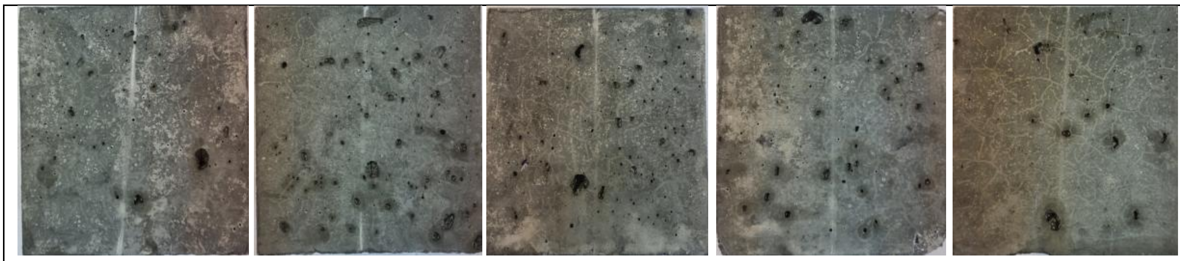


(a) (b) (c) (d) (e)

Figure A. 5: Individual samples of CEM II/A-V (Ref.) concrete before 56 cycles of freeze- thaw

(a) (b) (c) (d) (e)

Figure A. 6: Individual samples of CEM II/A-V (Ref.) concrete after freeze- thaw cycles testing



(a) (b) (c) (d) (e)

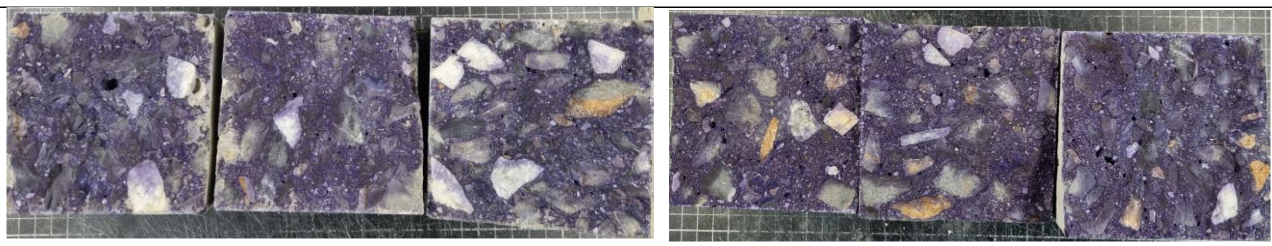
Figure A. 7: Individual samples of CEM IV/A (V) concrete before freeze- thaw cycles testing

(a) (b) (c) (d) (e)

Figure A. 8 Individual samples of CEM IV/A (V) concrete after 56 cycles of freeze- thaw

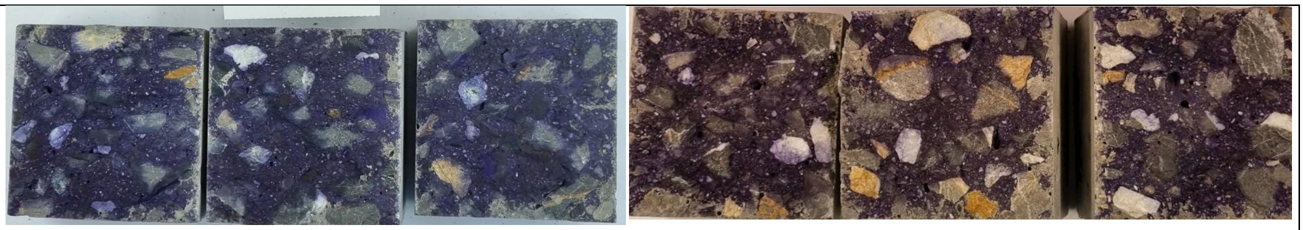
(a) (b)

Figure A. 9: Accelerated carbonation of (a) three CEM II/A-V (Ref.) and (b) three CEM IV/A (V) samples at cero measurement



(a) (b)

Figure A. 10: Accelerated carbonation of (a) three CEM II/A-V (Ref.) and (b) three CEM IV/A (V) samples after 28 days of testing

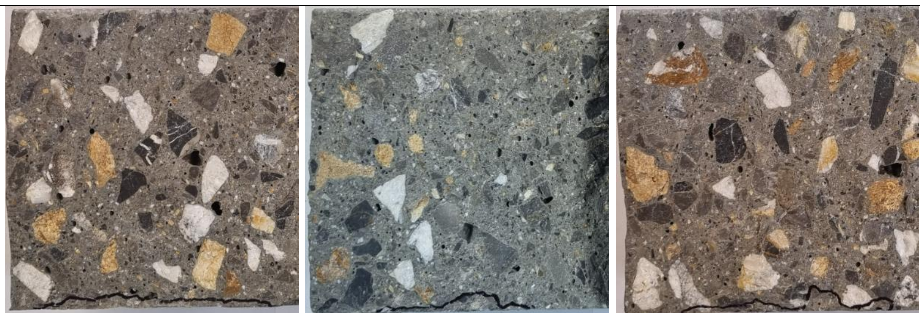


(a) (b)

Figure A. 11: Accelerated carbonation of (a) three CEM II/A-V (Ref.) and (b) three CEM IV/A (V) samples after 70 days of testing

(a) (b) (c)

Figure A. 12: Water penetration front of individual samples of CEM II/A-V (Ref.) concrete



(a) (b) (c)

Figure A. 13: Water penetration front of individual samples of CEM IV/A (V) concrete