Industrielle Gemeinschaftsforschung

Schlussbericht vom 09.02.2023

zu IGF-Vorhaben Nr. 282 EN

Thema

LeptoCalc – Recovery of fines from concrete recycling plants as cement constituent

LeptoCalc – Verwendung von Feinanteilen aus dem Betonrecycling als Zementhauptbestandteil

Berichtszeitraum

10/2020 – 12/2022

Forschungsvereinigung

VDZ Technology gGmbH

Forschungseinrichtung(en)

VDZ Technology gGmbH – Forschungsinstitut der Zementindustrie

Projektpartner (jeweils eigene nationale Förderung):

Smart Minerals GmbH – AUSTRIA

CRIC-OCCN – BELGIUM

Gefördert durch:

Bundesministerium für Wirtschaft und Klimaschutz

aufgrund eines Beschlusses des Deutschen Bundestages

AiF Forschungsnetzwerk Mittelstand

vdz

Final Project Report

LeptoCalc - Recovery of fines from concrete recycling plants as cement constituent

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Start of project	October 2020
End of project	December 2022
Date of report	09. February 2023

1 Aim of project

The main target of the project was to investigate fines from concrete recycling plants and check their sustainability as cement main constituent. In contrast to the C2CA European project, the present project focuses on an alternative recovery for the fines. The difference is the use of the fines as processed constituent in cement and not as substituent in the raw meal for the clinker production.

Fundamental prerequisites for the reutilization of the fines from concrete recycling plants as cement main constituent are the predictability of the material properties and the continuity in supply of material with constant properties. Beside the content of critical substances e.g. sulphur and chloride, the contribution to fresh concrete properties, compressive strength and durability needs to be well known. Therefore, a key part in the approach was the development of a fast testing method to estimate the properties of fines by – among others – residual hydraulic activity measurements.

Hydrated and unhydrated cement particles are concentrated in the fine fraction, independently of the specific recycling technique, thus a residual hydraulic activity should in principal occur within the fine fraction. So far, a testing method for the estimation of this residual reactivity was not available. Hence, an important goal was to develop such a method by studying chemical, mineralogical, isothermal and mechanical approaches.

Additional goals and benefits of the project were:

- Closing of material life cycles in the concrete recycling process;
- Conservation of resources;
- Exploitation of a continuously available cement main constituent;
- Positive influence on the public opinion –> production of green cements;
- CO_2-politic: possibility for cement plants to slightly reduce their CO_2-production (substitution of clinker by fines); saving of CO_2 duties;
- Saving costs for SME in the recycling-sector (cease of taxes and fees for depositing fines on landfills);
- Demonstrating technical opportunities to increase the recycling rate of CDW.

2 Overview Work packages

WP 1 Survey, Selection of plants and Sampling

- WP 1.1 Survey on the applied technologies in the recycling plants
- WP 1.2 Selection of the recycling plants and sampling protocol
- WP 1.3 Sampling of the fines in accordance with the established protocol

WP 2 Material characterization of the recycled fines

- WP 2.1 Residual Reactivity
- WP 2.2 Physico-chemical and mineralogical properties
- WP 2.3 Physico-mechanical properties

WP 3 Research and Process development

- WP 3.1 Method for the fast determination of the residual reactivity
- WP 3.2 Processing steps for increasing the residual reactivity

WP 4 Production of cements

- WP 4.1 Larger sampling of the fines
- WP 4.2 Maximum of fines and common mixing protocol
- WP 4.3 Production of cements in accordance with the established protocol

WP 5 Cement performances based on mortar production

WP 6 Cement performances based on concrete production

- WP 6.1 Evaluation of the mechanical performances
- WP 6.2 Evaluation of the durability and environmental performances

WP 7 Common performance criteria and reporting

- WP 7.1 Establishment of common performance criteria for the cements
- WP 7.2 Reporting

3 WP 1: Survey, selection of plants and sampling

<u>All partners:</u>

The most popular type of recycling plants in Austria, Belgium and Germany are mobile crushing plants. **Figure 1** shows an example of a typical building of a mobile recycling plant which represents the standard configuration also used by the participant Austrian recyclers.

These mobile plants consist of the following components:

- raw material heap
- charging hopper
- pre-sorting
- primary screening
- material feed
- crushing unit
- flue unit
- magnetic separator
- delivery belt conveyor
- sorting belt
- classification sieve
- product heap
- energy unit

Figure 1 Example of a mobile recycling plant in Austria (upper picture) and of a recycling plant in Belgium (bottom picture)

4 WP 2: Material characterization of the recycled fines

4.1 WP 2.1 Residual reactivity

4.1.1 All partners

For determination of potential residual reactivities, different methods were used in the laboratories of the project partners. All these methods were conducted on two general kinds of recycling products. As reference, artificial recycling materials were produced. Standard mortars acc. to EN 196-1 were produced using a CEM I from Germany, a CEM II/B-LL from Austria and a CEM III/A from Belgium. These mortars were crushed and ground after 28 days of standard storage.

These artificial recycling materials are in the following chapters referred to as:

Table 1 Artificial recycling fines

recycled fines from mortar with	Austria	Belgium	Germany
CEM I	Ref VDZ 7212	82931	F1
CEM II/B-LL	Ref SMG 7173	82929	F2
CEM III/A	Ref CRIC 7249	82930	F3

The second kind of materials were recycled fines from recycling plants in different regions of the partner´s countries. The origin and characterization of these materials are described in the following chapters.

4.1.2 Austria

Austria used a physical approach for the measurement of the residual reactivity in recycling fines. Since a residual reactivity in recycling material results mainly from not reacted clinker grains, a testing series with the target to determine the clinker content in hydrated fines was performed. The method was conducted using the prEN 196-4 standard and a heavy solution with a density of 3,00 g/cm³. The results are summarized in **Table 2**.

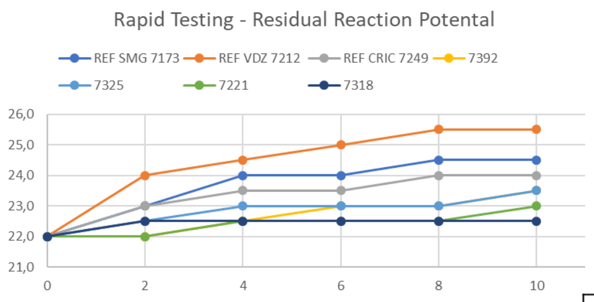
Table 2 Weight of particles with a density > 3g/m³

Sample		Residual clinker with bromoform 3,00g/cm³ [M.%]
B7173	Reference 1	0.31
B7212	Reference 2	0.38
B7249	Reference 3	0.62
B7221	Recycling 1	0.68
B7318	Recycling 2	1.61
B7325	Recycling 3	1.36
B7392	Recycling 4	0.64

The results of the density separation do not show significant values, because the weight of particles with a density > 3g/cm³ of the reference samples are lower than the recycling fines from plants. This seems not very likely since the age of the references is much lower and the hydrated samples were crushed and directly welded in vacuum. Particles from not hydrated clinker have to be higher in the laboratory samples. Summarizing that, the method seems not to be suitable for the determination of the residual reactivity.

Therefore, an additional testing series with an alternative heavy solution (sodiumpolytungstate) was conducted. It has shown, that the mixing of the recycling fine samples with the sodiumpolytungstate solution led to heat production. This phenomenon was interpreted to occur due to the hydration of the residual clinker of the recycling fines.

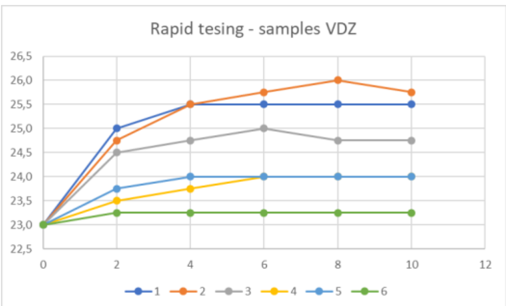
This accidental finding was used for a new, significant method for the estimation of the residual reactivity potential of fines. A rapid test method was developed which captures the heat development after mixing 10 ml sodiumpolytungstate with 1 g sample. The higher the difference of the temperature during the measurement period, the higher the expected reactivity. The results of the measurements are illustrated in **Figure 2**.



	0	2	4	6	8	10	D_0 [°C]	amunt of clinker in cement [%]	calculated value for D_0
REF SMG 7173	22,0	23,0	24,0	24,0	24,5	24,5	2,5	60	2,2
REF VDZ 7212	22,0	24,0	24,5	25,0	25,5	25,5	3,5	95	3,7
REF CRIC 7249	22,0	23,0	23,5	23,5	24,0	24,0	2,0	54	2,0

Figure 2 Results of the newly developed rapid test for the determination of the residual reactivity of recycling fines

The results of the reference samples (D_0) go conform with the original clinker content of the cements, which were used for the production of the hydrated reference samples. Furthermore, the method was validated with blind samples, which were provided by the project partners. It has shown that there is a good correlation between the developed rapid testing method and the isothermal calorimetry (TAM-AIR). The following **Figure 3** summarizes the results of the blind testing.



sample	$Delta_{max}$	comparability comparability with TAM Air H VDZ
1	2,5	good
2	3,0	good
3	2,0	no data
4	1,0	good
5	1,0	not good
6	0,3	good

Figure 3 Results of the blind samples of the project partner VDZ with the newly developed rapid test

4.1.3 Germany

In addition to the before mentioned artificial recycling fines, 4 fines from recycling plants were used in the project:

Table 3 Recycling fines from German recycling plants

Material	Plant	Description	Comment
F-03	MAV, Krefeld	pure crushed concrete, 0-3 mm	used for WP2 – WP6
F-MIX	MAV, Krefeld	crushed concrete type 1*, 0-3 mm	not used in WP 6
F-02	Feess, Kirchheim	pure crushed concrete, 0-2 mm	not used in WP 6
F-RS	BTB Recycling, Berlin	crushed railway sleepers	used for WP2 – WP6

* acc. to “DAfStb-Richtlinie Beton nach DIN EN 206-1 und DIN 1045-2 mit rezyklierten Gesteinskörnungen nach DIN EN 12620“, with up to 10 % bricks and tiles

The following methods were used for determination of residual reactivity:

- Analysis of isothermal calorimetry by TAM Air acc. to EN 196-11 with water, artificial pore solution and KOH-Solution
- Activity index of mortars acc. to EN 196-1

<u>TAM Air</u>

The recycled fines were ground to a defined fineness (see chapter 5.2.2). Three solutions were used to determine the heat of hydration using the pure recycled fines (method A). The solutions were:

- H: pure, de-ionized water
- PL: artificial pore solution with 30,2g/l KOH and 4,4g/l NaOH
- R3PL: KOH solution with 4g/l KOH and 20g/l K_2SO_4

Also, heat of hydration of cements with 10 M.% or 35 M.% recycled fines, respectively, in combination with a CEM I was measured (method B). The results are summarized in chapter 5.2.2.

<u>Activity index</u>

For determination of activity index, 20 M.% or 30 M.%, respectively, of CEM I was mixed with recycled fines. Compressive strength was measured after 2 and 28 days acc. to EN 196-1. The results are summarized in chapter 5.2.2.

4.1.4 Belgium

The idea was to use a Chemical/Mineralogical method by combining the results of specific mineralogical phases (e.g. alite, belite, etc.), acquired with XRD, with thermogravimetric measurements (TG). During the exploratory research (feasibility study), performed on crushed cement paste samples (and not on crushed mortar samples), it became clear that this method wasn't suitable for further investigation and is illustrated in **Table 4** below. No link between the mineralogical phases and TGA results is found.

Table 4 XRD and TGA results in M.% for both an untreated as a treated sample

XRD	Untreated	Treated	
	Sample 1	Sample 1 + 300°C, 1h	Sample 1 + 600°C, 1h
C_3S	14.75	18.14	16.00
C_2S	12.58	9.53	8.30
C_3A	4.01	4.43	5.38
C_4AF	5.00	5.93	5.90
Gypsum	7.01	1.14	3.96
Bassanite	1.69	1.05	0.11
Calcite	0.50	0.47	0.33
Portlandite	12.02	11.91	0.35
Lime	0.76	0.82	3.04
Quartz	1.32	0.93	0.60
Anhydrite	0.22	0.39	0.87
Vaterite	1.89	2.39	1.38
Ettringite	0.07	0.06	0.58
Amorphe	38.20	42.81	53.20
Total	100.00	99.99	99.99
Water (unbound - bound CSH and Gypsum). 0 – 275 °C	4.85	0.52	0.07
Hemihydrate, 275 – 340 °C	1.41	-	-
$Mg(OH)_2$, 340 - 420 °C	1.53	2.6	
Water Portlandite, 420 - 600 °C	4.31	4.6	2.09
CO_2, 600 - 780 °C	1.15	1.13	1.41
SO_3 and CO_2, 780 - 1008 °C	0.56	-	-
SO_3, 1008 - 1100 °C	0.21	0.77	0.72
Total	14.02	9.62	4.29
$CaCO_3$ XRD	2.39	2.86	1.71
$CaCO_3$ TGA	2.61	2.57	3
Portlandite XRD	12.02	11.91	0.35
Portlandite TGA	9.39	10.02	4.55
% Potentially still active clinker	36.34	38.03	35.58

As part of the exploratory research, the setting times and mechanical strengths were also investigated. These results, illustrated in **Figure 4** and **Figure 5**, show the positive effect of a temperature treatment on the crushed cement paste sample as the setting time decreases and the mechanical strength increases.

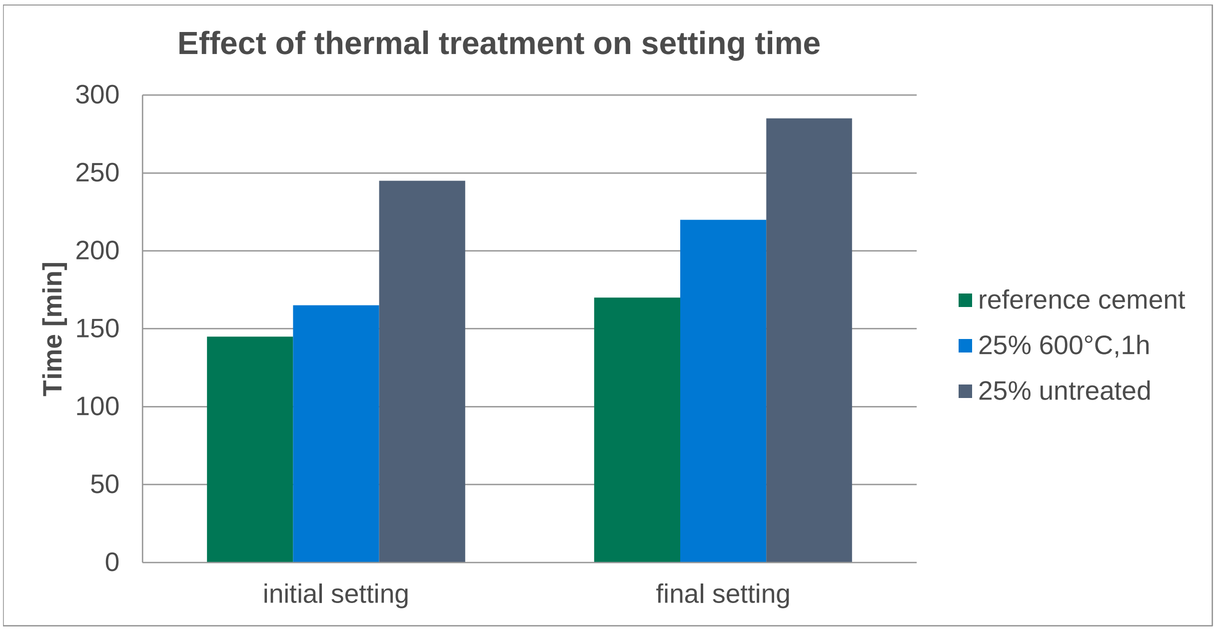


Figure 4 Effect of thermal treatment on the setting time

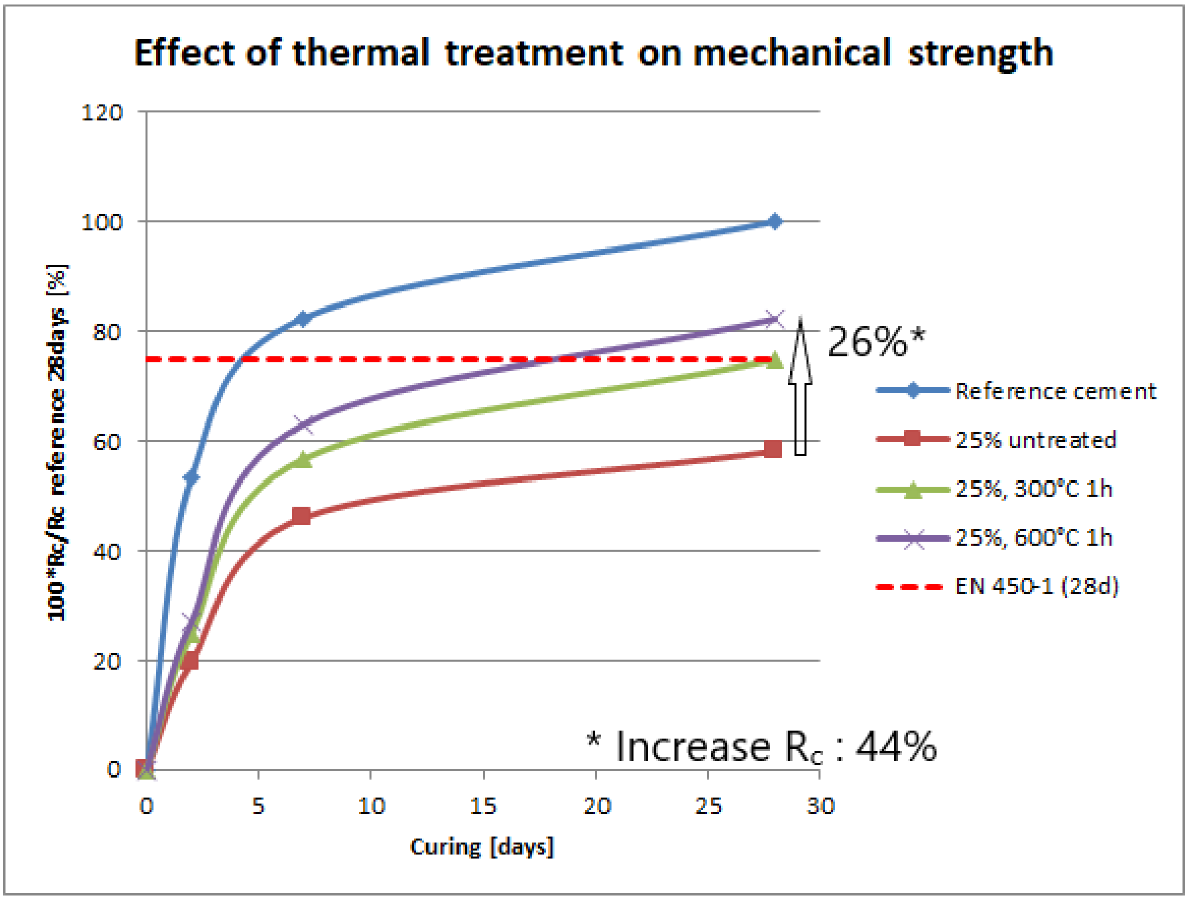


Figure 5 Effect of the thermal treatment on the mechanical strength

On the other hand, TGA results, given in **Table 5**, clearly show a decrease in the amount of water present in the newly made cement samples.

Table 5 Thermogravimetric analysis of the reference cement and the cements with 25 M.% untreated and 25 M.% treated crushed cement paste sample

Thermogravimetric analysis - Mass loss between 0°C and 600°C	**Reference cement [M.%]**	**25 M.%, Untreated [M.%]**	**25 M.%, 600°C 1h [M.%]**
Water (unbound - bound CSH and Gypsum), 0-275°C	0.28	1.39	0.25
Hemyhydrate, 275 - 340°C	0.14	0.26	0.07
$Mg(OH)_2$ + Water Portlandite, 340 - 600°C	0.33	1.41	0.83
TOTAL WATER	0.75	3.06	1.15

Combining these observations, CRIC-OCCN decided to adapt their method using the results of TGA to measure the residual reactivity. The basis for this method lies in the assumption that there is still a possible reaction with the unhydrated cement particles and using for instance a heat treatment would liberate a part of the already hydrated cement particles to increase this residual reactivity. A summary of the underlying thought is illustrated hereafter:

$$\boldsymbol{CS + H \underset{T,t}{\leftrightarrow} CSH + CH} \qquad (\mathbf{1})$$

With:

C = CaO / S = SiO_2 / H = H_2O

As the exploratory research has shown the positive effect on the mechanical strength using the temperature treatment of 600°C for 1 hour, all materials (the self-made recycled material and the recycled products from the recycling plants) were treated before considering these products as starting material. CRIC-OCCN used the thermogravimetric analysis as indicator for the residual reactivity (loss in water between 0-600°C). These results are given in **Table 6.**

Table 6 Thermogravimetric analysis of the laboratory made and industrial recycled products

Thermogravimetric analysis - Mass loss between 0°C and 600°C [%]	**Crushed mortar CEM II/B-LL**		**Crushed mortar CEM III/A**		**Crushed mortar CEM I**		**Recycled Concrete 1**		**Mix Brick - Concrete**		**Recycled Concrete 2**	
	82929	**82935**	**82930**	**82936**	**82931**	**82937**	**82932**	**82938**	**82933**	**82939**	**82934**	**82940**
	Raw	**600°C, 1h**	**Raw**	**600°C, 1h**	**Raw**	**600°C, 1h**	**Raw**	**600°C, 1h**	**Raw**	**600°C, 1h**	**Raw**	**600°C, 1h**
Water (unbound - bound CSH and Gypsum), 0-275°C	1.70	0.22	2.27	0.36	2.08	0.29	0.92	0.33	1.06	0.39	0.99	0.24
Hemyhydrate, 275 - 340°C	0.78	-	0.84	-	0.90	-	0.36	-	0.46	-	0.60	-
$Mg(OH)2$ + Water Portlandite, 340 - 600°C	0.71	0.18	1.65	0.12	1.30	0.38	0.81	-	0.81	-	0.39	-
TOTAL WATER	3.19	0.40	4.76	0.48	4.28	0.67	2.09	0.33	2.33	0.39	1.98	0.24

4.2 WP 2.2 Physico-chemical properties

4.2.1 Austria

The chemical characterization (X-ray fluorescence) is given in **Table 7**.

Table 7 Chemical composition of the reference and recycling fine samples

		7173 Ref 1	7212 Ref 2	7249 Ref 3	7221 Rec 1	7318 Rec 2	7325 Rec 3	7392 Rec 4
SiO_2	M.%	65.63	65.94	66.86	44.84	45.16	54.51	25.10
CaO	M.%	19.13	21.03	17.90	24.26	21.53	17.40	32.47
Al_2O_3	M.%	2.67	2.50	3.58	4.62	5.57	6.56	4.18
Fe_2O_3	M.%	1.17	1.15	1.30	2.21	3.10	2.81	2.22
MgO	M.%	0.99	0.44	1.26	3.64	5.29	2.69	6.44
SO_3	M.%	0.94	1.21	1.79	0.32	0.38	0.81	0.60
K_2O	M.%	0.66	0.66	0.64	0.92	1.48	1.53	0.93
Na_2O	M.%	0.20	0.18	0.20	0.55	1.01	0.70	0.36
TiO_2	M.%	0.13	0.11	0.22	0.26	0.31	0.38	0.24
P_2O_5	M.%	0.07	0.09	0.09	0.11	0.12	0.11	0.08
MnO	M.%	0.06	0.02	0.07	0.11	0.08	0.09	0.10
Cr_2O_3	M.%	0.06	0.07	0.06	0.05	0.06	0.05	0.03
Cl	M.%	0.03	0.02	0.03	0.00	0.02	0.03	0.04
SrO	M.%	0.02	0.05	0.04	0.03	0.03	0.03	0.03
CuO	M.%	0.01	0.01	0.01	0.01	0.01	0.01	0.01
LOI		8.20	6.47	5.90	18.00	15.76	12.22	27.12
ZnO	ppm	85	94	188	164	84	176	146
ZrO_2	ppm	62	187	88	82	84	176	73
WO_3	ppm	60	68	77	0	0	63	0
NiO	ppm	42	44	40	47	84	54	73
Rb_2O	ppm	21	20	20	39	59	55	40
TOTAL	**M.%**	**99.99**	**99.98**	**99.97**	**99.97**	**99.93**	**99.96**	**99.98**

The contents of acid-soluble chloride and sulphate for cements are regulated in the EN 197-1. All samples compliance the limits of the standard (**Table 8**).

Table 8 Acid-soluble sulphate and chloride (measurement according to ÖNORM EN 296-2)

sample		Cl^-	Limit chloride ÖNORM EN 197-1	SO_3	Limit sulphate ÖNORM EN 197-1
		[%]	[%]	[%]	[%]
B7173	Reference 1	0.006	≤0.10	0.49	≤3.5; ≤4.0
B7212	Reference 2	0.004	≤0.10	0.69	≤3.5; ≤4.0
B7249	Reference 3	0.011	≤0.10	0.89	≤3.5; ≤4.0
B7221	Recycling 1	0.003	≤0.10	0.10	≤3.5; ≤4.0
B7318	Recycling 2	0.015	≤0.10	0.10	≤3.5; ≤4.0
B7325	Recycling 3	0.008	≤0.10	0.34	≤3.5; ≤4.0
B7392	Recycling 4	0.024	≤0.10	0.36	≤3.5; ≤4.0

Table 9 summarizes the LOI and CO_2 content of the samples. Higher contents of CO_2 are induced by samples with higher carbonate.

Table 9 LOI (950°C) and CO_2-content

Sample		LOI	CO_2
		[%]	[%]
B7173	Reference 1	8.20	3.96
B7212	Reference 2	6.47	0.80
B7249	Reference 3	5.90	0.65
B7221	Recycling 1	18.00	15.57
B7318	Recycling 2	15.76	13.62
B7325	Recycling 3	12.22	10.36
B7392	Recycling 4	27.12	23.69

Organic carbon is undesirable in cementitious systems. All samples showed TOC contents <1 M.% and are therefore negligible. The results are summarized in **Table 10**.

Table 10 Contents of organic carbon (TOC) in M.%

samples	REF 1	REF 2	REF 3	fines	fines	fines	fines
	7173	7212	7249	7221	7318	7325	7392
TOC. [M.%]	<0.1	<0.1	<0.1	0.36	<0.1	0.43	0.56

4.2.2 Germany

The chemical compositions of the used cements and the recycling fines were determined by RFA. The results are shown for WP 2 – WP 4 in **Table 11** and for WP 5 and WP 6 in **Table 11**.

Table 11 Chemical composition of cements and recycling fines (WP 2 – WP 4)

		CEM I	CEM II/B-LL	CEM III/A	F-02	F-MIX	F-03
CO_2	M.%	1.38	14.12	1.1	8.0	5.8	4.2
H_2O		0.27	1.17	0.8	6.6	4.1	8.2
LOI		1.64	15.29	2.0	14.8	11.0	12.8
SiO_2		23.2	15.0	25.3	56.1	66.5	62.8
Al_2O_3		3.6	3.9	7.4	5.3	4.9	4.2
TiO_2		0.2	0.2	0.6	0.2	0.3	0.2
P_2O_5		0.2	0.1	0.2	0.1	0.1	0.1
Fe_2O_3		1.4	1.6	2.2	1.8	2.3	1.7
Mn_2O_3		0.0	0.2	0.2	0.0	0.2	0.1
MgO		0.8	2.4	3.5	1.3	1.7	1.0
CaO		65.7	58.7	54.3	17.2	10.6	14.1
SO_3		3.0	2.2	3.6	0.7	0.2	0.9
K_2O		0.6	0.6	0.6	1.5	1.0	1.1
Na_2O		0.2	0.2	0.3	0.7	0.6	0.6
sodium equivalent		0.6	0.6	0.7	1.7	1.3	1.3
TOC		not determined			0.2	1.1	0.4
Methylen blue	g/100g				0.1	0.2	0.1
Chloride	M.%				0.03	0.01	0.02

Table 12 Chemical composition of cements and recycling fines (WP 5 – WP 6)

		CEM I	S	LL	F-03	F-RS
CO_2	M.%	1.5	0.2	42.9	4.2	1.3
H_2O		0.3	0.3	0.1	8.2	5.4
LOI		1.8	0.5	43.1	12.8	6.7
SiO_2		22.7	36.1	0.9	62.8	63.2
Al_2O_3		3.6	10.3	0.2	4.2	8.5
TiO_2		0.2	0.7	0.0	0.2	0.4
P_2O_5		0.2	0.0	0.1	0.1	0.1
Fe_2O_3		1.4	0.6	0.2	1.7	3.5
Mn_2O_3		0.0	0.1	0.0	0.1	0.1
MgO		0.8	8.3	0.4	1.0	1.4
CaO		65.4	42.4	54.2	14.1	11.0
SO_3		3.0	0.1	0.0	0.9	0.7
K_2O		0.5	0.4	0.0	1.1	2.5
Na_2O		0.2	0.3	0.0	0.6	1.6
sodium equivalent		0.5	0.6	0.0	1.3	3.3
TOC		not determined		0.0	0.4	0.2
Methylen blue	g/100g			0.1	0.1	0.1
Chloride	M.%			n.d.	0.02	0.02

n.d.: not determined

4.2.3 Belgium

The chemical composition of the laboratory made and industrial fine samples is given below in **Table 13.** The amount of CaO is higher for the first industrial recycled concrete while the amount of SiO_2 is much higher for the second industrial recycled concrete. Another observation is the higher LOI for the industrial recycled fines compared to the laboratory made fines.

Table 13 Chemical composition of the reference and recycling fine samples.

		82935	82936	82937	82938	82939	82940
		Mortar CEM II/B-LL (1H @ 600°C)	**Mortar CEM III/A (1H @ 600°C)**	**Mortar CEM I (1H @ 600°C)**	**Recycled Concrete 1 (1H @ 600°C)**	**Recycled Mix Brick-Concrete (1H @ 600°C)**	**Recycled Concrete 2 (1H @ 600°C)**
LOI	M.%	4.23	1.56	1.73	20.73	9.28	10.2
Al_2O_3	M.%	1.87	2.67	1.84	4.23	7.00	4.75
CaO	M.%	13.81	12.94	15.10	28.29	15.43	15.93
Fe_2O_3	M.%	1.02	1.18	1.11	2.24	3.15	2.26
K_2O	M.%	0.52	0.53	0.54	0.77	1.27	0.91
MgO	M.%	0.41	0.67	0.09	1.62	1.25	1.09
MnO	M.%	0.06	0.06	0.03	0.11	0.13	0.08
Na_2O	M.%	0.15	0.17	0.15	0.28	0.51	0.36
P_2O_5	M.%	0.05	0.06	0.06	0.12	0.16	0.13
SO_3	M.%	0.07	0.65	0.27	0.2	1.03	0.12
SiO	M.%	77.65	79.25	78.91	41.04	60.23	63.81
SrO	M.%	0.04	0.05	0.06	0.04	0.06	0.05
TiO_2	M.%	0.10	0.18	0.09	0.24	0.44	0.27
Total	M.%	99.97	99.96	99.97	99.91	99.95	99.96

The contents of acid-soluble chloride and sulphate for cements are regulated in the European standard EN 197-1 and of special interest. All samples compliance the limits of the standard (**Table 14**).

Table 14 Acid-soluble sulphate and chloride (measurement according to EN 196-2)

Number	Cement	Cl^-	Limit Chloride EN 197-1	SO_3	Limit Sulphate EN 197-1
		M.%	M.%	M.%	M.%
82935	Crushed Mortar CEM II/B-LL (1H @ 600°C)	0.008	≤0.10	0.53	≤3.5; ≤4.0
82936	Crushed Mortar CEM III/A (1H @ 600°C)	0.006	≤0.10	1.05	≤3.5; ≤4.0
82937	Crushed Mortar CEM I (1H @ 600°C)	0.006	≤0.10	0.68	≤3.5; ≤4.0
82938	Recycled Concrete 1 (1H @ 600°C)	0.008	≤0.10	0.97	≤3.5; ≤4.0
82939	Recycled Mix Brick-Concrete (1H @ 600°C)	0.013	≤0.10	1.21	≤3.5; ≤4.0
82940	Recycled Concrete 2 (1H @ 600°C)	0.003	≤0.10	0.41	≤3.5; ≤4.0

Table 15 summarizes the LOI and CO_2 content of the samples. Higher contents of CO_2 are induced by samples with higher carbonate.

Table 15 LOI and CO_2-content

Number	Cement	LOI	CO2
		M.%	M.%
82935	Crushed Mortar CEM II/B-LL (1H @ 600°C)	4.23	3.83
82936	Crushed Mortar CEM III/A (1H @ 600°C)	1.56	1.09
82937	Crushed Mortar CEM I (1H @ 600°C)	1.73	1.03
82938	Recycled Concrete 1 (1H @ 600°C)	20.73	20.41
82939	Recycled Mix Brick-Concrete (1H @ 600°C)	9.28	8.89
82940	Recycled Concrete 2 (1H @ 600°C)	10.20	9.96

4.3 WP 2.3 Physico-mechanical properties

4.3.1 Austria

Beside chemical characteristic properties, physical parameters like density and grindability are as well essential factors for the potential use of recycling fines in cements.

Table 16 summarizes the measurements of the cement's density and Blaine value. The laboratory samples (Reference 1, Reference 2 and Reference 3) show a lower density than the fines from the recycling plants. The grindability on the basis of the Blaine value is significantly higher in the recycling fine samples of the real plants.

Table 16 Density and Blaine value

sample		Density [g/cm³]	Blaine [cm²/g]
B7173	Reference 1	2.57	3720
B7212	Reference 2	2.52	3990
B7249	Reference 3	2.51	3210
B7221	Recycling 1	2.66	5140
B7318	Recycling 2	2.69	3950
B7325	Recycling 3	2.67	3910
B7392	Recycling 4	2.64	5180

The distribution of the particle size is an additional criterion for the estimation of the grindability. The following **Figure 6** and **Figure 7** illustrate the average quantity-based and volume-based particle size distribution. Generally, all samples showed good grindability properties and average particle sizes of < 10 µm.

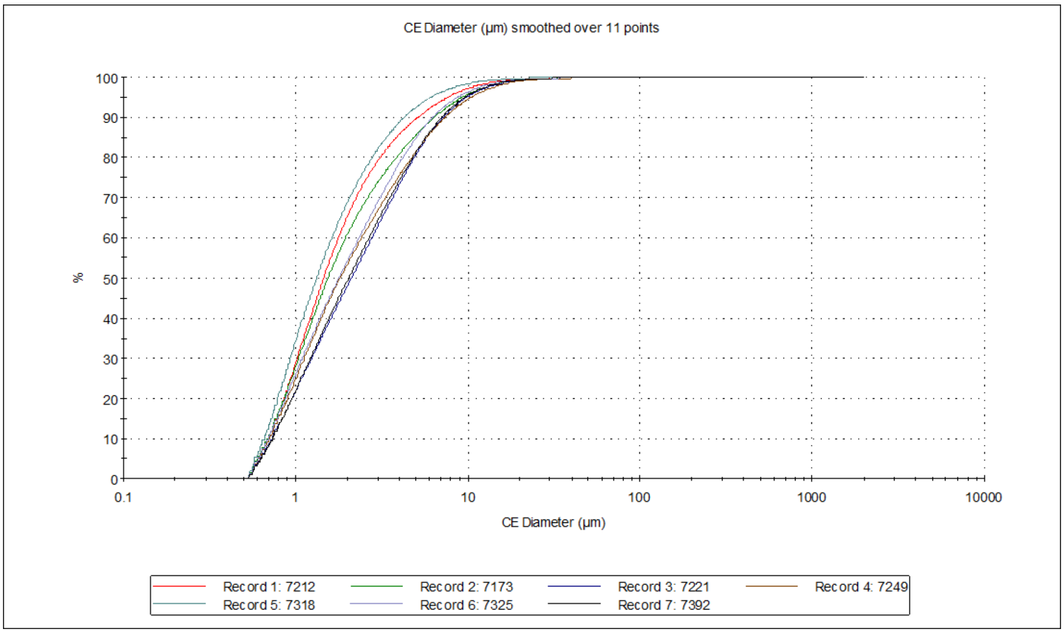


Figure 6 Quantity-based particle size distribution of the reference samples (7212, 7173, 7249) and the recycling fines (7318, 7325, 7221, 7392)

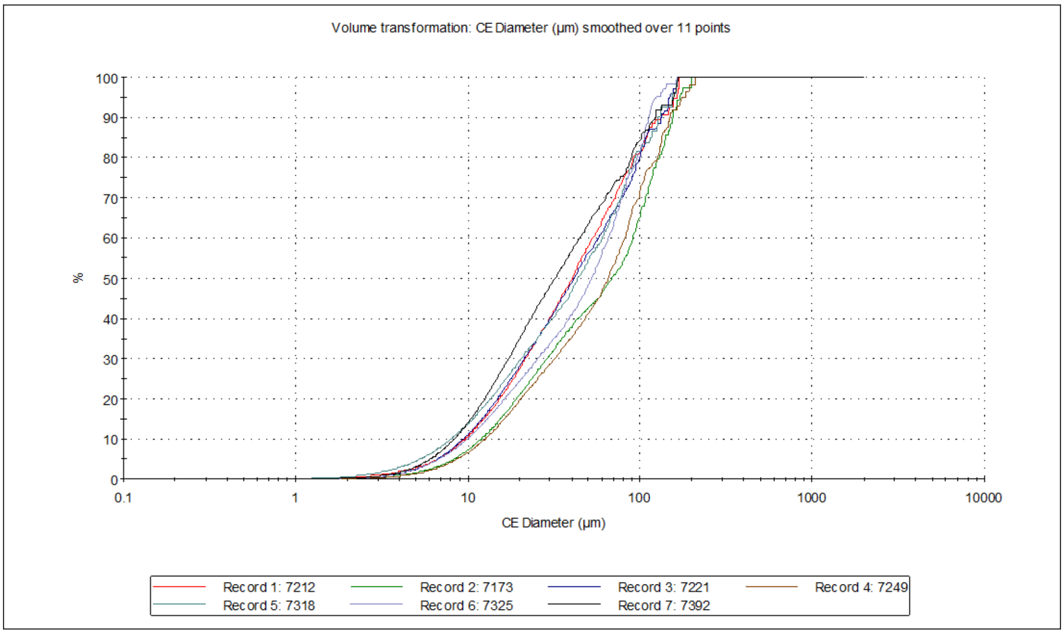


Figure 7 Volume-based particle size distribution of the reference samples (7212, 7173, 7249) and the recycling fines (7318, 7325, 7221, 7392)

4.3.2 Belgium

Table 17 summarizes the measurements of density and Blaine value. These results show no large difference in density for both the laboratory made as the industrial recycled samples. The grindability on the basis of the Blaine-value seems a bit less for the first industrial recycled concrete sample. No difference is present between the laboratory made and industrial recycled samples.

Table 17 Density and Blaine - value

Number	Cement	Density [g/cm³]	Blaine fineness [cm²/g]
82935	Crushed Mortar CEM II/B-LL (1H @ 600°C)	2.72	5135
82936	Crushed Mortar CEM III/A (1H @ 600°C)	2.66	4558
82937	Crushed Mortar CEM I (1H @ 600°C)	2.67	5197
82938	Recycled Concrete 1 (1H @ 600°C)	2.67	3976
82939	Recycled Mix Brick-Concrete (1H @ 600°C)	2.65	5103
82940	Recycled Concrete 2 (1H @ 600°C)	2.64	4337

The following **Figure 8** illustrates the average volume-based particle size distribution. Generally, all samples showed good grindability properties.

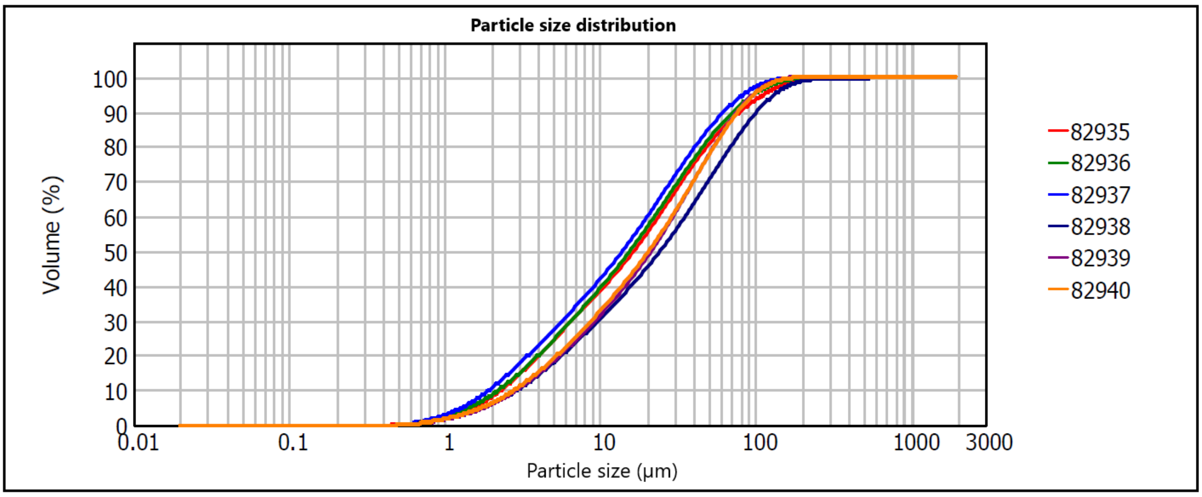


Figure 8 Volume-based particle size distribution of the laboratory made recycled samples (82935,82936,82937) and the industrial recycling fines (82938,82939,82940)

4.3.3 Germany

Blaine values are shown in chapter 5.2.2.

5 WP 3: Research and process development

5.1 WP 3.1: Method for the fast determination of the residual reactivity

5.1.1 Austria

The development of a rapid testing method for the determination of the residual reactivity is described in chapter 4.1.2.

5.1.2 Germany

The development of a rapid testing method for the determination of the residual reactivity is described in chapter 4.1.3.

5.1.3 Belgium

The development of a rapid testing method for the determination of the residual reactivity is described in chapter 4.1.4.

5.2 WP 3.2: Processing steps for increasing the residual reactivity

5.2.1 Austria

The references and recycling fines were tempered at 600°C for one hour to possibly increase the residual reactivity of the samples. After tempering, the samples were measured with the newly developed rapid test and the results have been compared with the not tempered samples. The results of the not tempered and tempered samples using the rapid test are shown in

Table 18 and **Table 19**. **Table 20** displays the comparison of the results, showing that the thermal treatment decreased the residual reactivity.

The testing procedure in the further working packages was continued with not tempered recycling fines, due to no derivable positive effect from the tempering procedure and a saving of energy, which makes the material more attractive for the market.

Table 18 Results rapid test, samples without thermal treatment

samples	0 min	2 min	4 min	6 min	8 min	10 min	$Delta_0$
REF 1	22.0	23.0	24.0	24.0	24.5	24.5	2.5
REF 2	22.0	24.0	24.5	25.0	25.5	25.5	3.5
REF 3	22.0	23.0	23.5	23.5	24.0	24.0	2.0
7392	22.0	22.0	22.5	23.0	23.0	23.5	1.5
7325	22.0	22.5	23.0	23.0	23.0	23.5	1.5
7221	22.0	22.0	22.5	22.5	22.5	23.0	1.0
7318	22.0	22.5	22.5	22.5	22.5	22.5	0.5

Table 19 Results rapid test, samples with thermal treatment

samples	0 min	2 min	4 min	6 min	8 min	10 min	$Delta_0$
REF 1	22.0	23.0	23.3	23.5	23.5	23.5	1.5
REF 2	22.0	23.5	24.0	24.5	24.5	24.5	2.5
REF 3	22.0	22.5	23.0	23.3	23.3	23.5	1.5
7392	22.0	22.0	22.3	22.5	22.5	22.3	0.3
7325	22.0	22.0	22.0	22.0	22.0	22.0	0.0
7221	22.0	22.3	22.3	22.3	22.3	22.3	0.3
7318	22.0	22.0	22.3	22.3	22.3	22.3	0.3

Table 20 Comparison of the residual reactivity of tempered and not tempered samples

	$D_{0\ not\ tempered}$	$D_{0\ tempered}$
REF 1	2.5	1.5
REF 2	3.5	2.5
REF 3	2.0	1.5
7392	1.5	0.3
7325	1.5	0.0
7221	1.0	0.3
7318	0.5	0.3

5.2.2 Germany

The artificial as well as the recycling fines from recycling plants were ground to two different finenesses (4500 cm²/g and 6000 cm²/g) using a laboratory ball mill. Additionally, as described in the Austrian part of this chapter, some of the fines were additionally tempered at 600 °C (index “T”). In total, 13 different recycling materials were produced for WP3.

Table 21 Recycling fines for WP3

Material	fineness acc. to blain in cm²/g	tempered at 600 °C
F1.4500	4730	no
F1.6000	6040	no
F1.4500-T	4340	yes
F2.4500	4414	no
F3.4500	4520	no
F3.6000	5240	no
F-02.4500	4840	no
F-02.4500-T	4910	yes
F-MIX.4500	4380	no
F-MIX.6000	6710	no
F-MIX.4500-T	4424	yes
F-03.4500	4460	no
F-03.4500-T	4280	yes

As described in chapter 4.1.3, TAM Air method A was used with three different solutions on a selection of pure recycling fines. The results are shown in **Figure 9**.

Additionally, cements were mixed with 10 M.% and 35 M.% recycling fines, respectively. Also, as a second reference beside the CEM I used for mixing these cements, a CEM II/A-LL with 10 M.% LL and a CEM II/B-LL with 35 M.% LL were produced. The heat of hydration of those cements were measured according to EN 197-11 (method B acc. to chapter 4.1.3). The results are shown in **Figure 10**. The diagram also shows the lines of dilution, representing a heat of hydration of 90% and 65%, respectively, of the CEM I.

All the cements, including the LL-cements, show a heat of hydration higher than the line of dilution, which means, that certain effects on reactivity can be observed. On the other hand, the heat of hydration of cements with different recycling fines are in the same range than the cements with LL. There is no additional effect of a higher fineness (comparison of 4500 cm²/g with 6000 cm²/g), and also no effect of tempering at 600 °C.

Also, the heat of hydration of the pure recycling fines (**Figure 10**) is not significant. So, these recycling fines do not show an own reactivity.

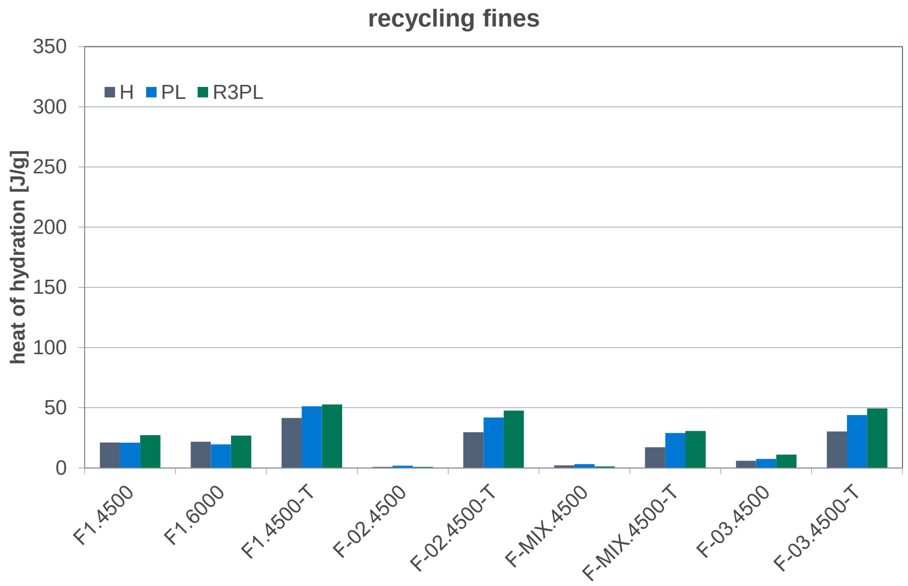


Figure 9 TAM Air on pure recycling fines, method A

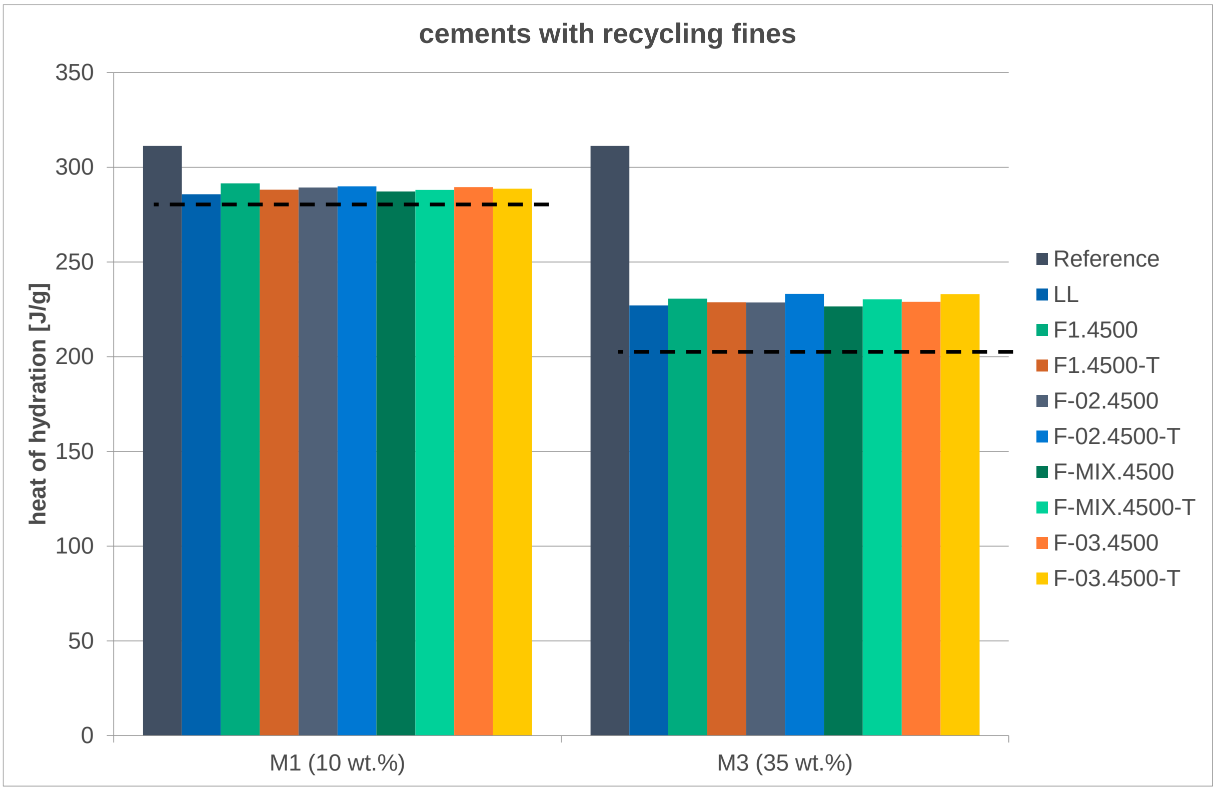


Figure 10 TAM Air on cements with recycling fines, method B

The third method to determine residual reactivities of recycling fines was measuring compressive strength acc. to EN 196-1 after 28 days and calculation of activity indices in comparison with the CEM I. Cements were produced with 20 M.% and 30 M.% recycling fines, respectively. The results are shown in **Figure 11** and **Table 22**.

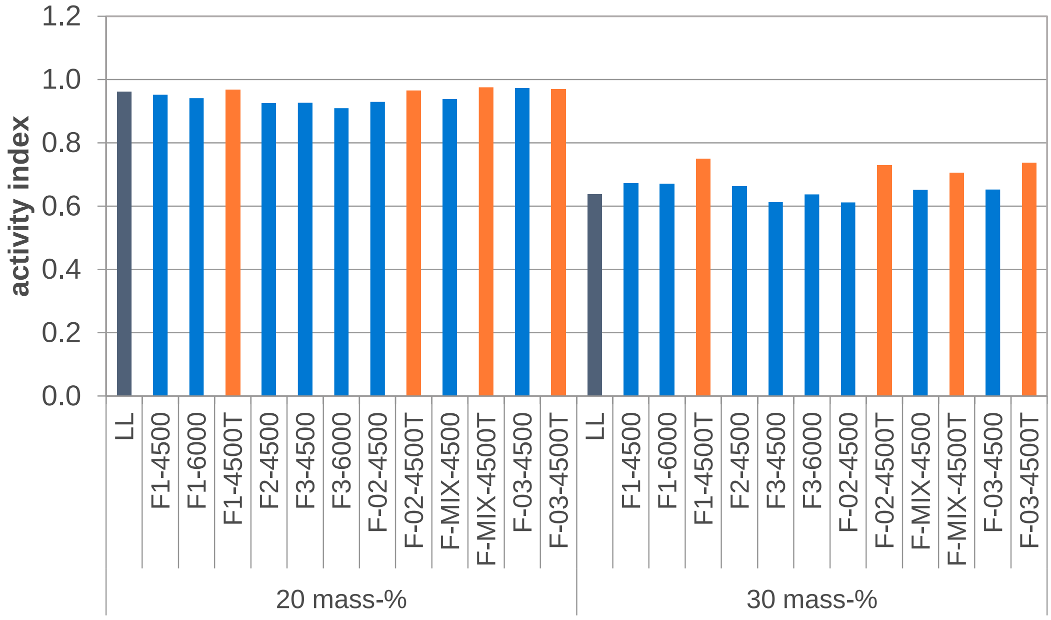


Figure 11 Activity index of mortars

Table 22 Compressive strength and activity index of mortars

mortar with	mortar compressive strength after 28 days in MPa*		activity index	
CEM I 52,5 R	69.7		100.0 %	
replacement level	**20 M.%**	**30 M.%**	**20 M.%**	**30 M.%**
LL	67.1	44.4	96.2%	63.7%
F1-4500	66.4	46.9	95.2%	67.2%
F1-6000	65.7	46.9	94.1%	67.2%
F1-4500T	67.5	52.3	96.8%	75.0%
F2-4500	64.6	46.2	92.6%	66.3%
F3-4500	64.6	42.7	92.7%	61.3%
F3-6000	63.4	44.4	90.9%	63.7%
F-02-4500	64.8	42.6	92.9%	61.1%
F-02-4500T	67.3	50.8	96.5%	72.9%
F-MIX-4500	65.5	45.4	93.9%	65.1%
F-MIX-4500T	68.0	49.2	97.6%	70.6%
F-03-4500	67.8	45.5	97.2%	65.2%
F-03-4500T	67.6	51.5	96.9%	73.8%

* mean value of 6 single values

The activity indices confirm the results of the measurement of heat of hydration: There is no significant residual reactivity of the recycled fines. In the mixtures with 30 M.% recycling fines, the tempering at 600 °C (orange columns) show little higher activity indices compared to recycling fines without tempering. But this effect is not that significant, that the thermal energy demand of the tempering process is appropriate to further use tempering for the following work packages.

5.2.3 Belgium

Like mentioned in paragraph 4.1.4, the exploratory research on crushed cement paste samples had shown promising results using a thermal treatment of 600°C for the duration of 1 hour. Hence, CRIC-OCCN has decided to temper the materials in their oven. The thermal treatment took an enormous part of time as each batch of material only had a mass of 200 g and in total around 160-180 kg had to be tempered.

6 WP 4: Production of cements

6.1 WP 4.1: Larger sampling of the fines

For the production of the cements needed in WP5 and WP6, larger amounts of selected samples from recycling plants were taken.

6.2 WP 4.2: Evaluation of the maximum amounts of fines in the produced cements and establishment of common mixing protocol

6.2.1 Austria

The necessary amount of cements for the working packages 5 and 6 was calculated. The mixing designs of the cements are documented in **Table 23**.

Table 23 Overview of the cement mix designs

cement	Cement type	CEM I [kg]	LL [kg]	Recycling fine[kg]
Ref1	CEM I 52.5 (Ref 1)	40		
Ref2	CEM II (B-L) (Ref 2)	26	14	
Z1_10	CEM II (A-fine)	4.5		0.5
Z1_20	CEM II (AB fine)	4		1
Z1_35	CEM II (B-fine)	3.25		1.75
Z2_10	CEM II (A-fine)	4.5		0.5
Z2_20	CEM II (AB fine)	4		1
Z2_35	CEM II (B-fine)	3.25		1.75
Z3_10	CEM II (A-fine)	4.5		0.5
Z3_20	CEM II (AB fine)	4		1
Z3_35	CEM II (B-fine)	3.25		1.75
Z4_10	CEM II (A-fine)	4.5		0.5
Z4_20	CEM II (AB fine)	32		8
Z4_35	CEM II (B-fine)	26		14
Z5_10	CEM II (A-fine)	4.5		0.5
Z5_20	CEM II (AB fine)	32		8
Z5_35	CEM II (B-fine)	26		14
Z6_10	CEM II (A-fine)	4.5		0.5
Z6_20	CEM II (AB fine)	32		8
Z6_35	CEM II (B-fine)	26		14

6.2.2 Germany

For determination of concrete properties in WP6, new cements were produced in larger amounts. The following materials (see **Table 24**) were used:

- new batch of CEM I (same plant)
- 2 recycled fines (F-03, same sample as in WPs before, and F-RS)
- 1 ground granulated blast furnace slag
- 1 ground limestone (LL, same sample as in WPs before)

In total, 10 cements were produced. An overview of their composition is given in **Table 24**.

Table 24 Composition of the different cements

cement	CEM I	10% F-03	10% F-RS	20% LL	20% F-03	20% F-RS	35% LL	35% F-03	35% F-RS	C-M (S-F)
CEM I	100%	90%	90%	80%	80%	80%	65%	65%	65%	50%
F-03		10%			20%			35%		20%
F-RS			10%			20%			35%	
LL				20%			35%			
S										30%

From these 10 cements, 6 were chosen for further analysis and for the concrete trials in WP6:

- CEM I
- CEM II/B-LL (35% LL)
- CEM II/A-F (20% F-03)
- CEM II/A-F (20% F-RS)
- CEM II/B-F (35% F-03)
- CEM II/C-M (S-F)

6.2.3 Belgium

The necessary amount of cements for the working packages 5 (8 kg each) and 6 (75 kg each) was calculated. The mixing designs of the cements are documented in **Table 25**.

Table 25 Overview of the cement mix designs

Sample number	Cement	cement type	CEM I [kg]	LL [kg]	Recycled fines [kg]
80336	Reference 1 : 100% CEM I	CEM I 52.5 N	83	-	-
82500	Reference 2 : 65% CEM I + 35% LL	CEM II (B-L)	53.95	29.05	-
82482	90% CEM I + 10% mortar CEM II/B-LL (1H @ 600°C)	CEM II (A-F)	7.2	-	0.8
82483	80% CEM I + 20% mortar CEM II/B-LL (1H @ 600°C)	CEM II (A-F)	7.2	-	0.8
82484	65% CEM I + 35% mortar CEM II/B-LL (1H @ 600°C)	CEM II (B-F)	7.2	-	0.8
82485	90% CEM I + 10% mortar CEM III/A (1H @ 600°C)	CEM II (A-F)	7.2	-	0.8
82486	80% CEM I + 20% mortar CEM III/A (1H @ 600°C)	CEM II (A-F)	7.2	-	0.8
82487	65% CEM I + 35% mortar CEM III/A (1H @ 600°C)	CEM II (B-F)	7.2	-	0.8
82488	90% CEM I + 10% mortar CEM I (1H @ 600°C)	CEM II (A-F)	7.2	-	0.8
82489	80% CEM I + 20% mortar CEM I (1H @ 600°C)	CEM II (A-F)	7.2	-	0.8
82490	65% CEM I + 35% mortar CEM I (1H @ 600°C)	CEM II (B-F)	7.2	-	0.8
82491	90% CEM I + 10% Recycled Concrete 1 (1H @ 600°C)	CEM II (A-F)	7.2	-	0.8
82492	80% CEM I + 20% Recycled Concrete 1 (1H @ 600°C)	CEM II (A-F)	66.4	-	16.6
82493	65% CEM I + 35% Recycled Concrete 1 (1H @ 600°C)	CEM II (B-F)	53.95	-	29.05
82494	90% CEM I + 10% Mix Brick-Concrete (1H @ 600°C)	CEM II (A-F)	7.2	-	0.8
82495	80% CEM I + 20% Mix Brick-Concrete (1H @ 600°C)	CEM II (A-F)	66.4	-	16.6
82496	65% CEM I + 35% Mix Brick-Concrete (1H @ 600°C)	CEM II (B-F)	53.95	-	29.05
82497	90% CEM I + 10% Recycled Concrete 2 (1H @ 600°C)	CEM II (A-F)	7.2	-	0.8
82498	80% CEM I + 20% Recycled Concrete 2 (1H @ 600°C)	CEM II (A-F)	66.4	-	16.6
82499	65% CEM I + 35% Recycled Concrete 2 (1H @ 600°C)	CEM II (B-F)	53.95	-	29.05

6.3 WP 4.3: Production of cements in accordance with the established protocol

The Austrian cements were mixed using the mix design summarized in **Table 23** and homogenized for 1.5 hours.

The German cements (approx. 45 kg per cement) were homogenized for 1.5 hours.

The Belgium cements for mortar and concrete evaluation were mixed separately. The amount of cement mixed were respectively 8 kg and 75 kg. These were mixed and homogenized for 1.5 hours in different batches with respectively the ratio of 3 and 2 meaning that each batch of cement for mortar included around 2.67 kg while the batches for concrete included 37.5 kg.

7 WP 5: Evaluation of the cement performances based on mortar production

7.1 General

In addition to 2 reference cements (CEM I and CEM II/B-LL), laboratory cements with recycling fines were prepared by each project partner and tested to determine their standard properties. Each project partner used the cements produced in WP4 which were produced with the fines investigated in WP2. The concentration of the fines was set at 10, 20 and 35 M.%.

7.2 Compressive strength (EN 196-1)

7.2.1 Austria

The results of the compressive strength tests according to EN 196-1 of the reference cements (Ref1 and Ref2) and of the cements produced with fines are summarized in **Table 26** and shown in **Figure 12.**

Table 26 Compressive strength after 2, 7 and 28 days

			compressive strength in MPa		
cement	**cement type**	**content fines in M.%**	**2d**	**7d**	**28d**
Ref1	CEM I 52.5	0	40.10	55.55	65.83
Ref2	CEM II (B-L)	35	21.48	30.78	36.80
Z1_10	CEM II (A-F)	10	32.18	46.13	54.98
Z1_20	CEM II (A-F)	20	23.63	35.33	43.50
Z1_35	CEM II (B-F)	35	17.58	25.48	30.73
Z2_10	CEM II (A-F)	10	31.18	43.75	55.05
Z2_20	CEM II (A-F)	20	24.65	35.70	43.55
Z2_35	CEM II (B-F)	35	17.00	25.10	31.15
Z3_10	CEM II (A-F)	10	37.58	53.45	64.00
Z3_20	CEM II (A-F)	20	40.85	55.30	63.98
Z3_35	CEM II (B-F)	35	40.65	56.80	64.90
Z4_10	CEM II (A-F)	10	33.80	47.43	58.48
Z4_20	CEM II (A-F)	20	27.78	41.20	49.10
Z4_35	CEM II (B-F)	35	20.20	30.53	35.60
Z5_10	CEM II (A-F)	10	34.20	47.58	54.68
Z5_20	CEM II (A-F)	20	29.58	41.18	48.15
Z5_35	CEM II (B-F)	35	21.40	30.25	35.05
Z6_10	CEM II (A-F)	10	33.20	47.30	56.05
Z6_20	CEM II (A-F)	20	27.23	40.78	47.20
Z6_35	CEM II (B-F)	35	19.63	29.48	35.36

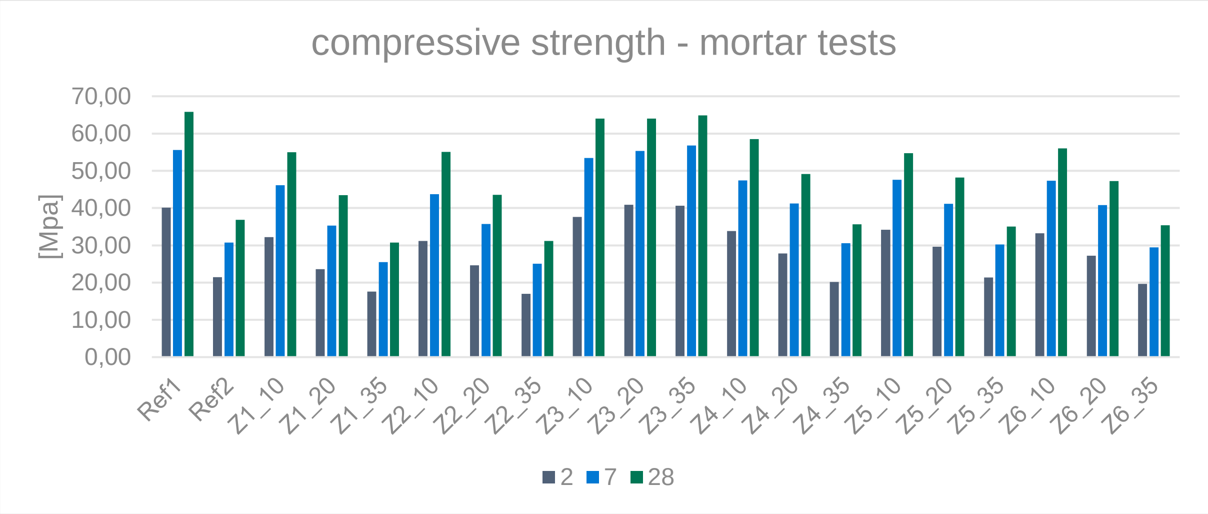


Figure 12 Illustration of the compressive strength after 2, 7 and 28 days

7.2.2 Germany

10 cements were produced and the flexural and compressive strength were determined acc. to EN 196-1. These results are given in **Table 27** and illustrated by **Figure 13**.

Table 27 Strength of cements

	CEM I	10% F-03	10% F-RS	20% LL	20% F-03	20% F-RS	35% LL	35% F-03	35% F-RS	C-M (S-F)
2d flexural strength in MPa[1)]	6.4	5.7	6.1	5.4	5.2	5.5	4.3	4.1	4.1	3.0
7d flexural strength in MPa[1)]	8.2	7.7	7.8	7.4	6.9	7.1	6.3	5.8	5.9	5.3
28d flexural strength in MPa[1)]	9.0	8.1	8.5	8.2	7.7	8.0	7.1	6.6	6.7	n.d.
2d compressive strength in MPa[2)]	39.2	33.8	33.3	28.3	27.0	28.3	20.5	21.0	20.0	13.2
7d compressive[2)] strength in MPa	60.0	52.2	55.6	47.9	45.6	46.5	36.1	35.2	35.3	32.5
28d compressive[2)] strength in MPa	73.7	61.7	64.5	59.8	55.0	56.7	43.3	42.4	41.8	46.8
activity index 28d in %	100.0	83.7	87.5	81.2	74.5	76.9	58.7	57.6	56.7	63.5

[1)] mean value of 3 single values

[2)] mean value of 6 single values

n.d.: not determined

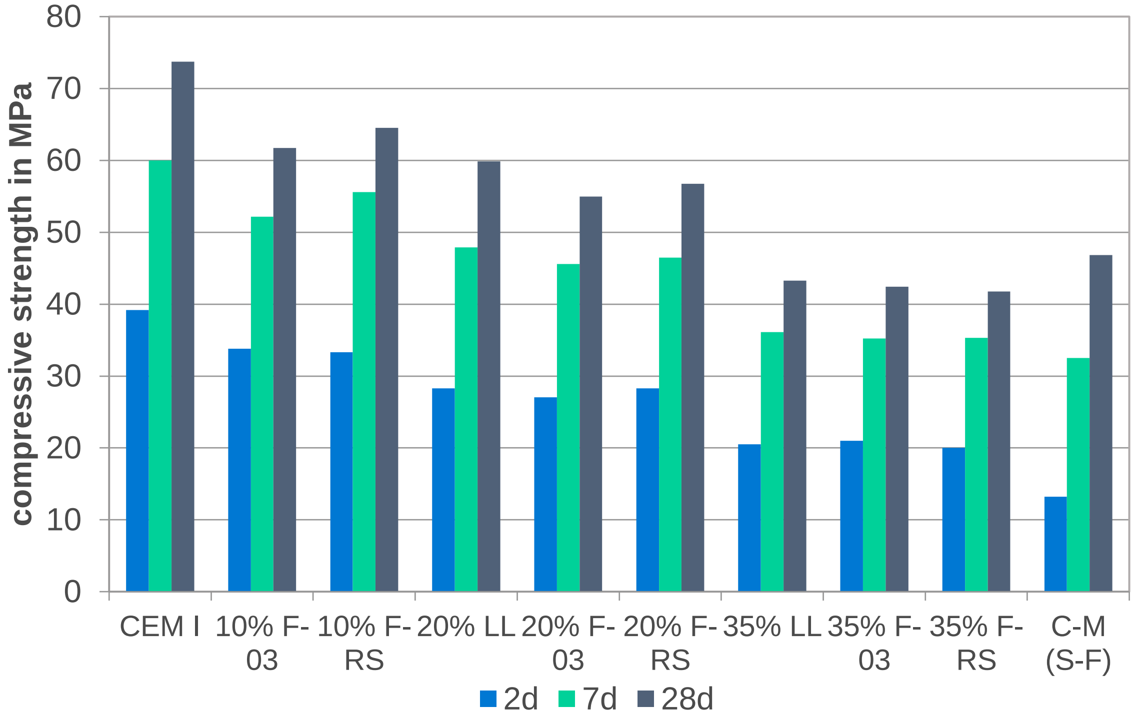


Figure 13 compressive strength of mortars

7.2.3 Belgium

The results of the compressive strength tests according to EN 196-1 of the reference cements (Ref1 and Ref2) and of the cements produced with fines are summarized in **Table 28** and shown in **Figure 14.**

Table 28 Compressive strength after 2, 7 and 28 days

				compressive strength in MPa		
Sample number	**Cement**	**cement type**	**content fines**	**2d**	**7d**	**28d**
80336	100% CEM I	CEM I 52.5 N	0	33.12	51.85	60.18
82500	65% CEM I + 35% LL	CEM II (B-L)	35	18.02	31.19	40.84
82482	90% CEM I + 10% mortar CEM II/B-LL (1H @ 600°C)	CEM II (A-F)	10	29.56	48.46	57.79
82483	80% CEM I + 20% mortar CEM II/B-LL (1H @ 600°C)	CEM II (A-F)	20	25.49	42.18	54.20
82484	65% CEM I + 35% mortar CEM II/B-LL (1H @ 600°C)	CEM II (B-F)	35	22.78	37.72	44.54
82485	90% CEM I + 10% mortar CEM III/A (1H @ 600°C)	CEM II (A-F)	10	33.46	51.13	62.11
82486	80% CEM I + 20% mortar CEM III/A (1H @ 600°C)	CEM II (A-F)	20	25.42	46.11	55.52
82487	65% CEM I + 35% mortar CEM III/A (1H @ 600°C)	CEM II (B-F)	35	22.11	36.86	47.20
82488	90% CEM I + 10% mortar CEM I (1H @ 600°C)	CEM II (A-F)	10	32.00	48.04	61.89
82489	80% CEM I + 20% mortar CEM I (1H @ 600°C)	CEM II (A-F)	20	28.95	42.01	54.46
82490	65% CEM I + 35% mortar CEM I (1H @ 600°C)	CEM II (B-F)	35	22.04	34.28	44.80
82491	90% CEM I + 10% Recycled Concrete 1 (1H @ 600°C)	CEM II (A-F)	10	28.98	44.76	58.21
82492	80% CEM I + 20% Recycled Concrete 1 (1H @ 600°C)	CEM II (A-F)	20	27.97	41.59	53.45
82493	65% CEM I + 35% Recycled Concrete 1 (1H @ 600°C)	CEM II (B-F)	35	20.09	31.67	44.52
82494	90% CEM I + 10% Mix Brick-Concrete (1H @ 600°C)	CEM II (A-F)	10	34.42	47.48	61.13
82495	80% CEM I + 20% Mix Brick-Concrete (1H @ 600°C)	CEM II (A-F)	20	28.98	41.64	54.86
82496	65% CEM I + 35% Mix Brick-Concrete (1H @ 600°C)	CEM II (B-F)	35	21.43	32.44	44.70
82497	90% CEM I + 10% Recycled Concrete 2 (1H @ 600°C)	CEM II (A-F)	10	31.60	47.81	56.97
82498	80% CEM I + 20% Recycled Concrete 2 (1H @ 600°C)	CEM II (A-F)	20	26.95	37.78	50.72
82499	65% CEM I + 35% Recycled Concrete 2 (1H @ 600°C)	CEM II (B-F)	35	19.04	29.56	40.98

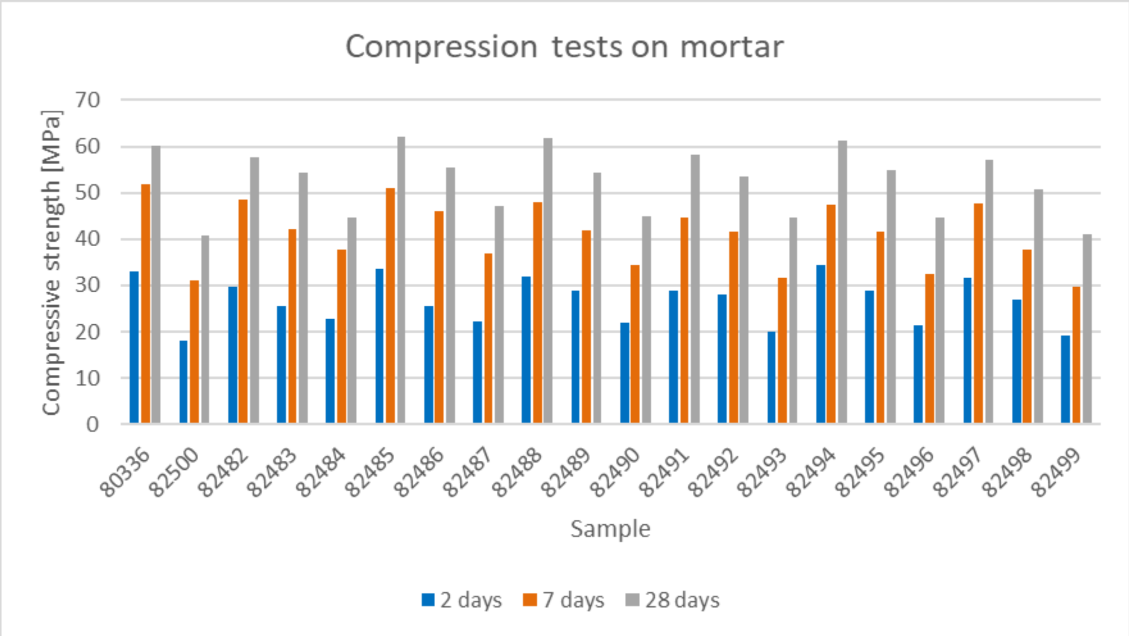


Figure 14 Illustration of the compressive strength after 2, 7 and 28 days

7.3 Langavant (EN 196-9)

7.3.1 Austria

The heat of hydration of the cements was tested by the semi-adiabatic method according to EN 196-9. The results are shown in **Table 29** and illustrated in **Figure 15**.

Table 29 Heat development according to Langavant EN 196-9

cement	cement type	content fines	Langavant (196-9), 72h
Ref1	CEM I 52,5 (Ref 1)	0	349
Ref2	CEM II (B-L) (Ref 2)	35 L	247
Z1_10	CEM II (A-F)	10	324
Z1_20	CEM II (A-F)	20	284
Z1_35	CEM II (B-F)	35	255
Z2_10	CEM II (A-F)	10	322
Z2_20	CEM II (A-F)	20	294
Z2_35	CEM II (B-F)	35	248
Z3_10	CEM II (A-F)	10	349
Z3_20	CEM II (A-F)	20	375
Z3_35	CEM II (B-F)	35	352
Z4_10	CEM II (A-F)	10	348
Z4_20	CEM II (A-F)	20	296
Z4_35	CEM II (B-F)	35	253
Z5_10	CEM II (A-F)	10	330
Z5_20	CEM II (A-F)	20	293
Z5_35	CEM II (B-F)	35	243
Z6_10	CEM II (A-F)	10	341
Z6_20	CEM II (A-F)	20	294
Z6_35	CEM II (B-F)	35	249

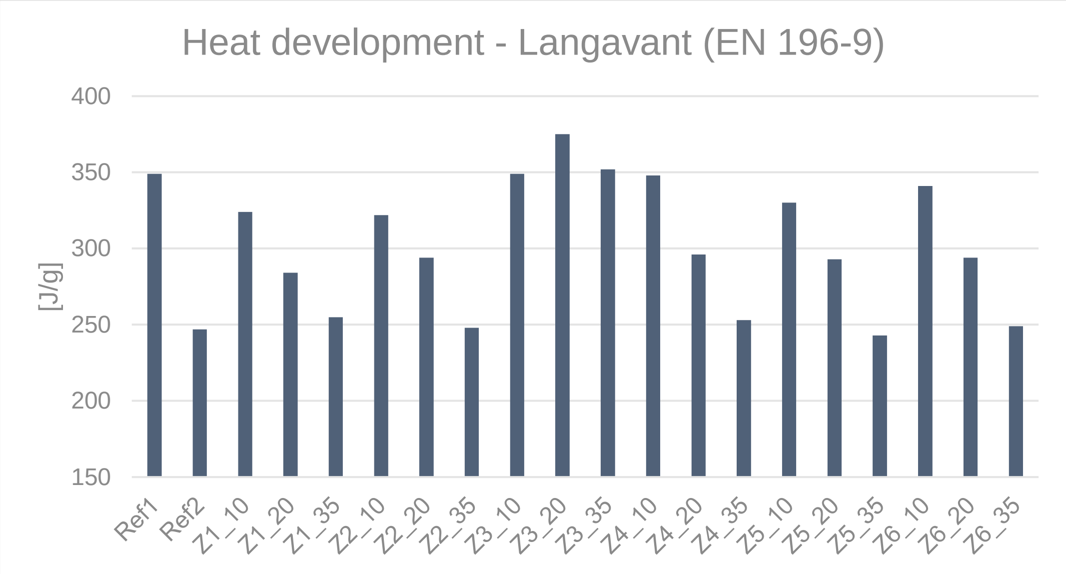


Figure 15 Comparing illustration of the heat development (EN 196-9)

7.3.2 Belgium

The heat of hydration of the cements was tested by the semi-adiabatic method EN 196-9. The results are shown in **Table 30** and illustrated in **Figure 16.** No large difference is found between the samples containing the laboratory made and industrial recycled material. Compared to the reference 2, the laboratory made samples containing a substitution rate of 35% show a little higher value for the heat of hydration while the industrial samples show a rather comparable value.

Table 30 Heat development according to Langavant EN 196-9

Sample number	Cement	cement type	content fines	Heat of Hydration at 41h [J/g]
80336	Reference 1 : 100% CEM I	CEM I 52.5 N	0	367
82500	Reference 2 : 65% CEM I + 35% LL	CEM II (B-L)	35	250
82482	90% CEM I + 10% mortar CEM II/B-LL (1H @ 600°C)	CEM II (A-F)	10	335
82483	80% CEM I + 20% mortar CEM II/B-LL (1H @ 600°C)	CEM II (A-F)	20	308
82484	65% CEM I + 35% mortar CEM II/B-LL (1H @ 600°C)	CEM II (B-F)	35	268
82485	90% CEM I + 10% mortar CEM III/A (1H @ 600°C)	CEM II (A-F)	10	336
82486	80% CEM I + 20% mortar CEM III/A (1H @ 600°C)	CEM II (A-F)	20	305
82487	65% CEM I + 35% mortar CEM III/A (1H @ 600°C)	CEM II (B-F)	35	266
82488	90% CEM I + 10% mortar CEM I (1H @ 600°C)	CEM II (A-F)	10	330
82489	80% CEM I + 20% mortar CEM I (1H @ 600°C)	CEM II (A-F)	20	300
82490	65% CEM I + 35% mortar CEM I (1H @ 600°C)	CEM II (B-F)	35	264
82491	90% CEM I + 10% Recycled Concrete 1 (1H @ 600°C)	CEM II (A-F)	10	324
82492	80% CEM I + 20% Recycled Concrete 1 (1H @ 600°C)	CEM II (A-F)	20	294
82493	65% CEM I + 35% Recycled Concrete 1 (1H @ 600°C)	CEM II (B-F)	35	261
82494	90% CEM I + 10% Mix Brick-Concrete (1H @ 600°C)	CEM II (A-F)	10	332
82495	80% CEM I + 20% Mix Brick-Concrete (1H @ 600°C)	CEM II (A-F)	20	299
82496	65% CEM I + 35% Mix Brick-Concrete (1H @ 600°C)	CEM II (B-F)	35	255
82497	90% CEM I + 10% Recycled Concrete 2 (1H @ 600°C)	CEM II (A-F)	10	327
82498	80% CEM I + 20% Recycled Concrete 2 (1H @ 600°C)	CEM II (A-F)	20	294
82499	65% CEM I + 35% Recycled Concrete 2 (1H @ 600°C)	CEM II (B-F)	35	253

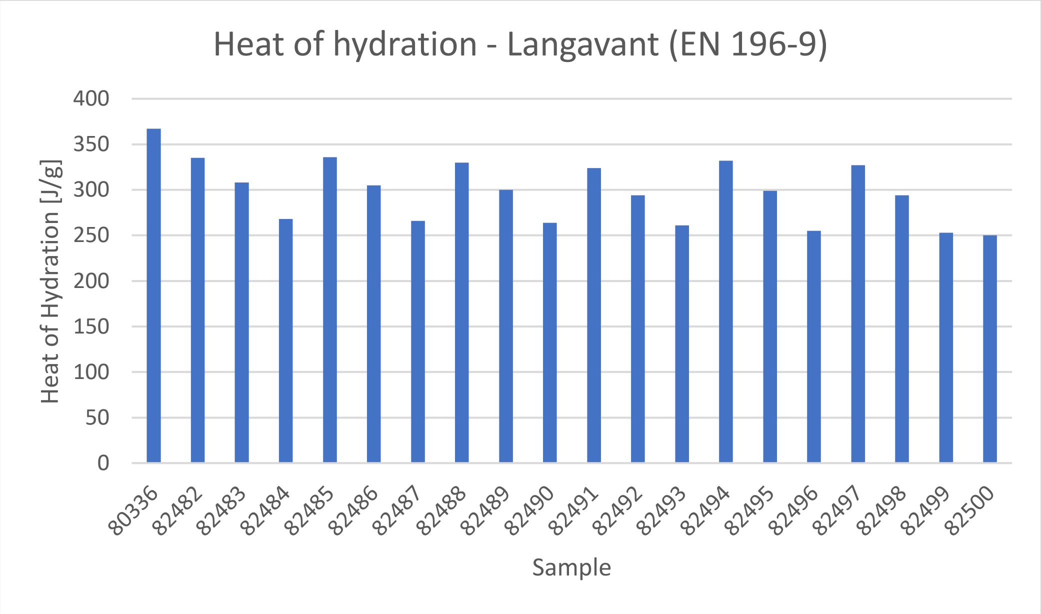


Figure 16 Comparing illustration of the heat development (EN 196-9)

7.4 Vicat (EN 196-3)

7.4.1 Austria

The results of the determination of the setting times according to EN 196-3 are summarized in **Table 31** and illustrated in **Figure 17**.

Table 31 Setting time according to EN 196-3

cement	cement type	content fines	start in min	end in min
Ref1	CEM I 52,5 (Ref 1)	0	135	180
Ref2	CEM II (B-L) (Ref 2)	35 L	140	180
Z1_10	CEM II (A-F)	10	140	195
Z1_20	CEM II (A-F)	20	150	195
Z1_35	CEM II (B-F)	35	155	195
Z2_10	CEM II (A-F)	10	145	210
Z2_20	CEM II (A-F)	20	155	210
Z2_35	CEM II (B-F)	35	155	210
Z3_10	CEM II (A-F)	10	130	180
Z3_20	CEM II (A-F)	20	130	180
Z3_35	CEM II (B-F)	35	125	180
Z4_10	CEM II (A-F)	10	130	195
Z4_20	CEM II (A-F)	20	160	225
Z4_35	CEM II (B-F)	35	180	225
Z5_10	CEM II (A-F)	10	155	255
Z5_20	CEM II (A-F)	20	160	210
Z5_35	CEM II (B-F)	35	170	225
Z6_10	CEM II (A-F)	10	145	195
Z6_20	CEM II (A-F)	20	160	225
Z6_35	CEM II (B-F)	35	160	210

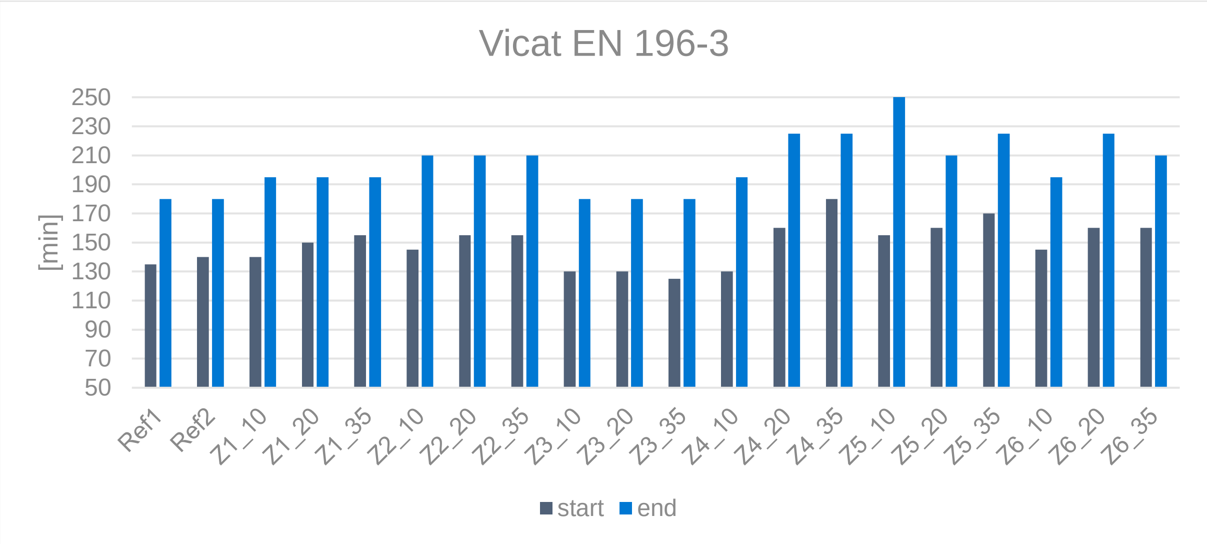


Figure 17 Start and end of the setting time according to EN 196-3

7.4.2 Belgium

The results of the determination of the setting times according to EN 196-3 are summarized in **Table 32** and illustrated in **Figure 18**. For most of the samples, a similar trend is obtained. Only the samples containing the first industrial recycled concrete fines show a difference (no change in setting times with different substitution rates). Although this result was validated with a new test sample, the test result isn't logical as the time should normally increase with increasing substitution rate.

Table 32 Setting time according to EN 196-3

Sample number	Cement	cement type	content fines	Start [min]	End [min]
80336	Reference 1: 100% CEM I	CEM I 52.5 N	0	182	235
82500	Reference 2: 65% CEM I + 35% LL	CEM II (B-L)	35	151	252
82482	90% CEM I + 10% mortar CEM II/B-LL (1H @ 600°C)	CEM II (A-F)	10	201	282
82483	80% CEM I + 20% mortar CEM II/B-LL (1H @ 600°C)	CEM II (A-F)	20	223	294
82484	65% CEM I + 35% mortar CEM II/B-LL (1H @ 600°C)	CEM II (B-F)	35	244	326
82485	90% CEM I + 10% mortar CEM III/A (1H @ 600°C)	CEM II (A-F)	10	171	272
82486	80% CEM I + 20% mortar CEM III/A (1H @ 600°C)	CEM II (A-F)	20	192	293
82487	65% CEM I + 35% mortar CEM III/A (1H @ 600°C)	CEM II (B-F)	35	211	302
82488	90% CEM I + 10% mortar CEM I (1H @ 600°C)	CEM II (A-F)	10	181	263
82489	80% CEM I + 20% mortar CEM I (1H @ 600°C)	CEM II (A-F)	20	221	302
82490	65% CEM I + 35% mortar CEM I (1H @ 600°C)	CEM II (B-F)	35	242	313
82491	90% CEM I + 10% Recycled Concrete 1 (1H @ 600°C)	CEM II (A-F)	10	181	272
82492	80% CEM I + 20% Recycled Concrete 1 (1H @ 600°C)	CEM II (A-F)	20	191	272
82493	65% CEM I + 35% Recycled Concrete 1 (1H @ 600°C)	CEM II (B-F)	35	191	272
82494	90% CEM I + 10% Mix Brick-Concrete (1H @ 600°C)	CEM II (A-F)	10	171	282
82495	80% CEM I + 20% Mix Brick-Concrete (1H @ 600°C)	CEM II (A-F)	20	181	292
82496	65% CEM I + 35% Mix Brick-Concrete (1H @ 600°C)	CEM II (B-F)	35	203	304
82497	90% CEM I + 10% Recycled Concrete 2 (1H @ 600°C)	CEM II (A-F)	10	171	262
82498	80% CEM I + 20% Recycled Concrete 2 (1H @ 600°C)	CEM II (A-F)	20	191	272
82499	65% CEM I + 35% Recycled Concrete 2 (1H @ 600°C)	CEM II (B-F)	35	210	302

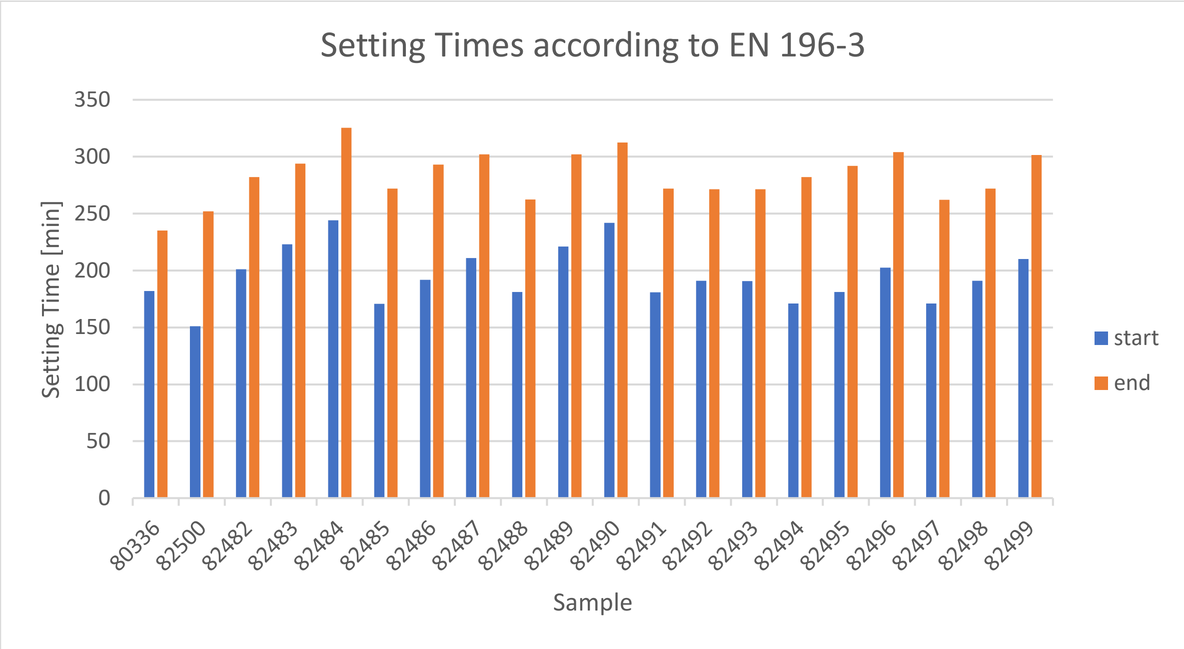


Figure 18 Start and end of the setting time according to EN 196-3

7.5 Acid-soluble chloride and sulphate (EN 196-2)

7.5.1 Austria

The results of the acid-soluble chloride and sulphate according to EN 196-2, chemical analysis of cement, are summarized in **Table 33.**

Table 33 Overview of acid-soluble chloride and sulphate contents

cement	cement type	content fines	SO_3 in M.%	Chlorid in M.%
Ref1	CEM I 52,5 (Ref 1)	0	3.11	0.067
Ref2	CEM II (B-L) (Ref 2)	35 L	2.07	0.043
Z1_10	CEM II (A-F)	10	2.82	0.046
Z1_20	CEM II (A-F)	20	2.49	0.050
Z1_35	CEM II (B-F)	35	1.91	0.041
Z2_10	CEM II (A-F)	10	2.86	0.057
Z2_20	CEM II (A-F)	20	2.66	0.040
Z2_35	CEM II (B-F)	35	2.20	0.036
Z3_10	CEM II (A-F)	10	2.32	0.060
Z3_20	CEM II (A-F)	20	2.73	0.074
Z3_35	CEM II (B-F)	35	2.62	0.050
Z4_10	CEM II (A-F)	10	2.31	0.041
Z4_20	CEM II (A-F)	20	2.51	0.046
Z4_35	CEM II (B-F)	35	1.23	0.032
Z5_10	CEM II (A-F)	10	2.71	0.044
Z5_20	CEM II (A-F)	20	1.61	0.048
Z5_35	CEM II (B-F)	35	1.69	0.050
Z6_10	CEM II (A-F)	10	1.07	0.055
Z6_20	CEM II (A-F)	20	2.61	0.060
Z6_35	CEM II (B-F)	35	2.13	0.042

7.5.2 Belgium

The results of the acid-soluble chloride and sulphate according to EN 196-2, chemical analysis of cement, are summarized in **Table 34**.

Table 34 Overview of acid-soluble chloride and sulphate contents

Sample number	Cement	cement type	content fines	SO_3 in M.%	Chloride in M.%
80336	Reference 1 : 100% CEM I	CEM I 52.5 N	0	3.09	0.065
82500	Reference 2 : 65% CEM I + 35% LL	CEM II (B-L)	35	2.06	0.039
82482	90% CEM I + 10% mortar CEM II/B-LL (1H @ 600°C)	CEM II (A-F)	10	2.96	0.056
82483	80% CEM I + 20% mortar CEM II/B-LL (1H @ 600°C)	CEM II (A-F)	20	2.72	0.048
82484	65% CEM I + 35% mortar CEM II/B-LL (1H @ 600°C)	CEM II (B-F)	35	2.28	0.041
82485	90% CEM I + 10% mortar CEM III/A (1H @ 600°C)	CEM II (A-F)	10	2.99	0.054
82486	80% CEM I + 20% mortar CEM III/A (1H @ 600°C)	CEM II (A-F)	20	2.75	0.050
82487	65% CEM I + 35% mortar CEM III/A (1H @ 600°C)	CEM II (B-F)	35	2.21	0.042
82488	90% CEM I + 10% mortar CEM I (1H @ 600°C)	CEM II (A-F)	10	2.91	0.055
82489	80% CEM I + 20% mortar CEM I (1H @ 600°C)	CEM II (A-F)	20	2.66	0.047
82490	65% CEM I + 35% mortar CEM I (1H @ 600°C)	CEM II (B-F)	35	2.27	0.039
82491	90% CEM I + 10% Recycled Concrete 1 (1H @ 600°C)	CEM II (A-F)	10	2.86	0.055
82492	80% CEM I + 20% Recycled Concrete 1 (1H @ 600°C)	CEM II (A-F)	20	2.58	0.049
82493	65% CEM I + 35% Recycled Concrete 1 (1H @ 600°C)	CEM II (B-F)	35	2.15	0.042
82494	90% CEM I + 10% Mix Brick-Concrete (1H @ 600°C)	CEM II (A-F)	10	2.97	0.056
82495	80% CEM I + 20% Mix Brick-Concrete (1H @ 600°C)	CEM II (A-F)	20	2.68	0.051
82496	65% CEM I + 35% Mix Brick-Concrete (1H @ 600°C)	CEM II (B-F)	35	2.47	0.043
82497	90% CEM I + 10% Recycled Concrete 2 (1H @ 600°C)	CEM II (A-F)	10	2.87	0.055
82498	80% CEM I + 20% Recycled Concrete 2 (1H @ 600°C)	CEM II (A-F)	20	2.57	0.049
82499	65% CEM I + 35% Recycled Concrete 2 (1H @ 600°C)	CEM II (B-F)	35	2.13	0.041

7.6 Mercury intrusion porosimetry and chemical bound water

7.6.1 Austria

The chemical bound water was determined on cement stone with a water/cement ratio of w/c = 0.40 at the age of 28 days. At the given age, the hydration was stopped by grinding the respective cement stone in acetone. After that, the sample was washed with diethyl ether 2-4 times and was dried at 60°C for 60 min to remove remaining diethyl ether.

If the determination of the chemical bound water could not be started directly, the sample was put in a sufficient container and filled with argon. The porosity of each standard mortar was determined at an age of 28 days. The results of the chemical bound water and the total porosity of mortars produced with the same cements is summarized in **Table 35**.

Table 35 Overview of the analysed chemical bound water, CO_2 and total porosity in cement stone

cement	cement type	content fines in %	CBW28 in %	CO_2 in %	total $Poro_{28d}$ in %
Ref1	CEM I 52.5	0	20.78	2.05	12.03
Ref2	CEM II (B-L)	35 L	16.41	14.13	15.67
Z1_10	CEM II (A-F)	10	19.73	2.64	12.12
Z1_20	CEM II (A-F)	20	18.23	2.38	14.52
Z1_35	CEM II (B-F)	35	17.28	2.86	18.45
Z2_10	CEM II (A-F)	10	20.06	2.02	13.23
Z2_20	CEM II (A-F)	20	21.41	1.58	15.12
Z2_35	CEM II (B-F)	35	18.04	1.56	18.44
Z3_10	CEM II (A-F)	10	19.55	2.06	11.35
Z3_20	CEM II (A-F)	20	22.85	1.71	12.63
Z3_35	CEM II (B-F)	35	19.95	2.22	12.14
Z4_10	CEM II (A-F)	10	19.92	3.17	13.5
Z4_20	CEM II (A-F)	20	19.54	4.09	14.94
Z4_35	CEM II (B-F)	35	16.94	6.03	16.42
Z5_10	CEM II (A-F)	10	20.29	3.1	9.22
Z5_20	CEM II (A-F)	20	18.71	4.07	14.22
Z5_35	CEM II (B-F)	35	18.04	5.48	16.1
Z6_10	CEM II (A-F)	10	20.86	3.59	12.36
Z6_20	CEM II (A-F)	20	18.75	5.51	13.73
Z6_35	CEM II (B-F)	35	16.42	8.94	17.89

7.6.2 Germany

The porosity of mortars acc. to EN 196-1 were determined with mercury intrusion porosimetry. The results are shown in **Figure 19**.

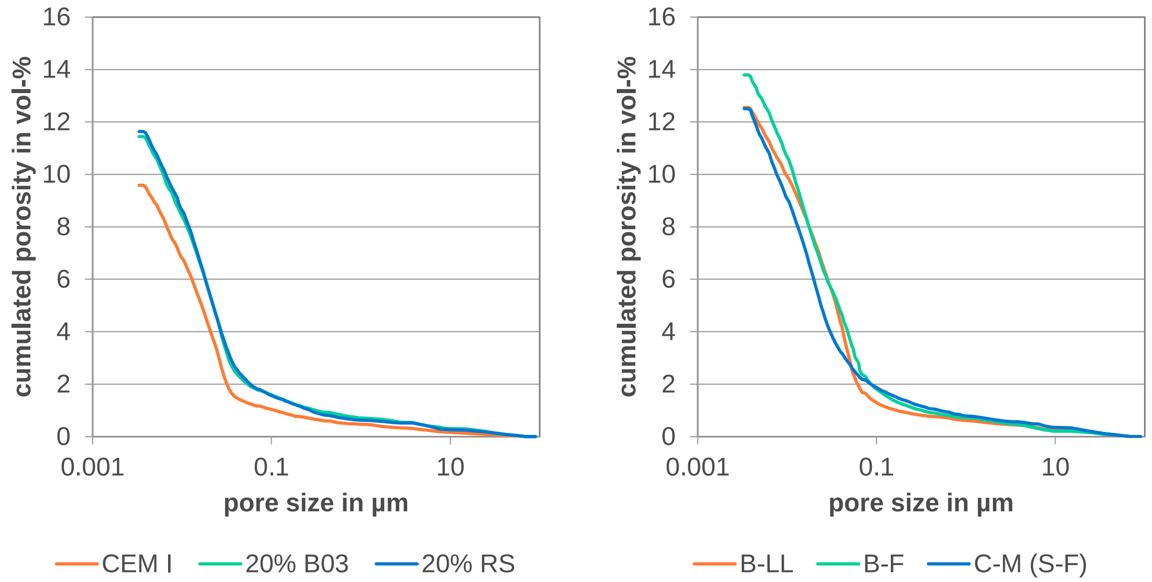


Figure 19 porosity of mortars

The chemical bound water of those 6 cements was determined on cement stone with a water/cement ratio of w/c = 0.40 at the age of 2 days, 7 days and 28 days. At each given age, the hydration was stopped by grinding the respective cement stone in acetone. After that, the sample was washed with diethylether 2-4 times and was dried at 60°C for 60 min to remove remaining diethylether. The chemical bound water was determined by CO_2 / H_2O – IR-spectroscopy. The results are shown in **Figure 20**. The functional correlation with mortar compressive strength is given in **Figure 21**.

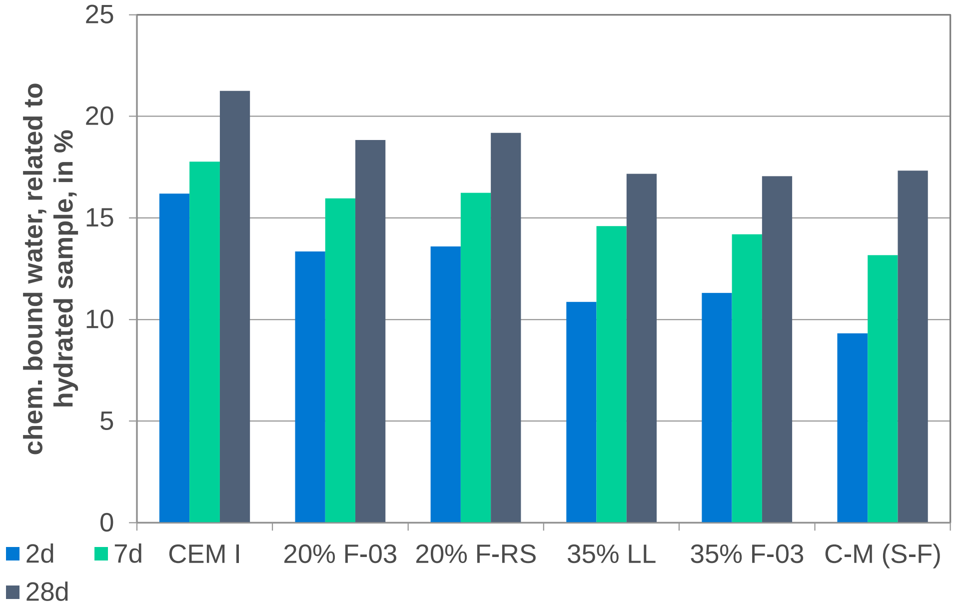


Figure 20 chemical bound water of cement stone

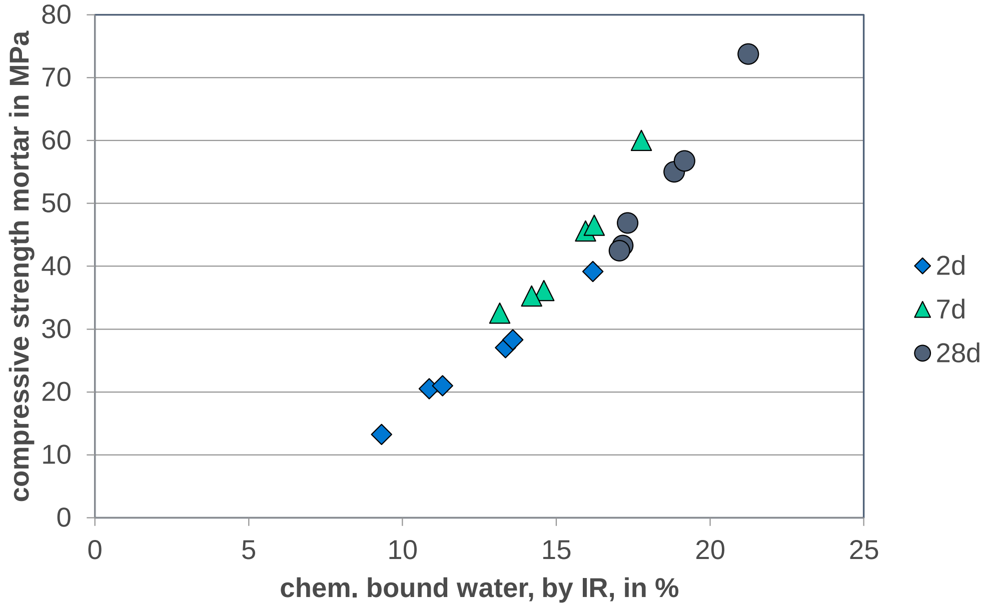


Figure 21 chemical bound water of cement stone correlated with mortar compressive strength

Table 36 Overview of the analysed chemical bound water and porosity in cement stone

cement	CBW2 in %	CBW7 in %	CBW28 in %	total $Poro_{28}$ in %	cap. $Poro_{28}$ in %[1)]
CEM I	16.2	17.8	21.3	9.58	2.28
20% F-03	13.4	16.0	18.8	11.44	3.50
20% F-RS	13.6	16.2	19.2	11.64	3.66
35% LL	10.9	14.6	17.2	12.56	5.81
35% F-03	11.3	14.2	17.1	13.79	5.80
C-M (S-F)	9.3	13.2	17.3	12.50	4.09

[1)] capillary porosity $r \geq 0.03$ µm

7.7 Blaine value (EN 196-6)

7.7.1 Austria

The Blaine value was tested according to EN 196-6 and is presented in **Table 37** and **Figure 22**.

Table 37 Overview of the Blaine value and density of the investigated cements

sample	Blaine in cm²/g	density in g/cm³
Ref 1	4875	3.15
Ref 2	4770	2.99
Z1_10	4535	3.09
Z1_20	4265	3.00
Z1_35	4095	2.92
Z2_10	4415	3.07
Z2_20	4225	3.01
Z2_35	3930	2.91
Z3_10	4785	3.13
Z3_20	4805	3.13
Z3_35	4835	3.15
Z4_10	4815	3.08
Z4_20	4960	3.02
Z4_35	5080	2.94
Z5_10	4790	3.07
Z5_20	4875	3.03
Z5_35	4995	2.96
Z6_10	4795	3.07
Z6_20	4755	3.02
Z6_35	4900	2.94

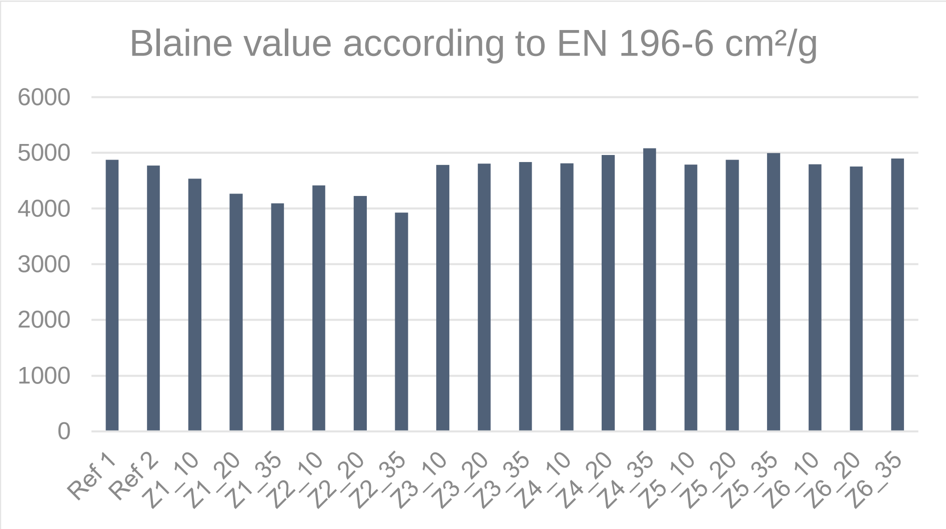


Figure 22 Blaine value of the investigated cements

7.7.2 Belgium

The Blaine value was tested according to EN 196-6 and is presented in **Table 38** and **Figure 23.** A Blaine fineness value of 4500 cm²/g was set as goal for the different cements.

Table 38 Overview of the Blaine value and density of the investigated cements

Sample number	Cement	cement type	content fines	Blaine in cm²/g	density in g/cm³
80336	Reference 1 : 100% CEM I	CEM I 52.5 N	0	3950	3,09
82500	Reference 2 : 65% CEM I + 35% LL	CEM II (B-L)	35	4684	2,95
82482	90% CEM I + 10% mortar CEM II/B-LL (1H @ 600°C)	CEM II (A-F)	10	4368	3,06
82483	80% CEM I + 20% mortar CEM II/B-LL (1H @ 600°C)	CEM II (A-F)	20	4486	3,01
82484	65% CEM I + 35% mortar CEM II/B-LL (1H @ 600°C)	CEM II (B-F)	35	4816	3,00
82485	90% CEM I + 10% mortar CEM III/A (1H @ 600°C)	CEM II (A-F)	10	4315	3,04
82486	80% CEM I + 20% mortar CEM III/A (1H @ 600°C)	CEM II (A-F)	20	4386	3,00
82487	65% CEM I + 35% mortar CEM III/A (1H @ 600°C)	CEM II (B-F)	35	4529	2,94
82488	90% CEM I + 10% mortar CEM I (1H @ 600°C)	CEM II (A-F)	10	4066	3,04
82489	80% CEM I + 20% mortar CEM I (1H @ 600°C)	CEM II (A-F)	20	3789	3,01
82490	65% CEM I + 35% mortar CEM I (1H @ 600°C)	CEM II (B-F)	35	3830	2,88
82491	90% CEM I + 10% Recycled Con-crete 1 (1H @ 600°C)	CEM II (A-F)	10	4081	3,04
82492	80% CEM I + 20% Recycled Con-crete 1 (1H @ 600°C)	CEM II (A-F)	20	4147	3,00
82493	65% CEM I + 35% Recycled Con-crete 1 (1H @ 600°C)	CEM II (B-F)	35	4305	2,97
82494	90% CEM I + 10% Mix Brick-Con-crete (1H @ 600°C)	CEM II (A-F)	10	4319	3,06
82495	80% CEM I + 20% Mix Brick-Con-crete (1H @ 600°C)	CEM II (A-F)	20	4249	2,94
82496	65% CEM I + 35% Mix Brick-Con-crete (1H @ 600°C)	CEM II (B-F)	35	4532	2,93
82497	90% CEM I + 10% Recycled Con-crete 2 (1H @ 600°C)	CEM II (A-F)	10	4235	3,06
82498	80% CEM I + 20% Recycled Con-crete 2 (1H @ 600°C)	CEM II (A-F)	20	4260	3,00
82499	65% CEM I + 35% Recycled Con-crete 2 (1H @ 600°C)	CEM II (B-F)	35	4316	2,92

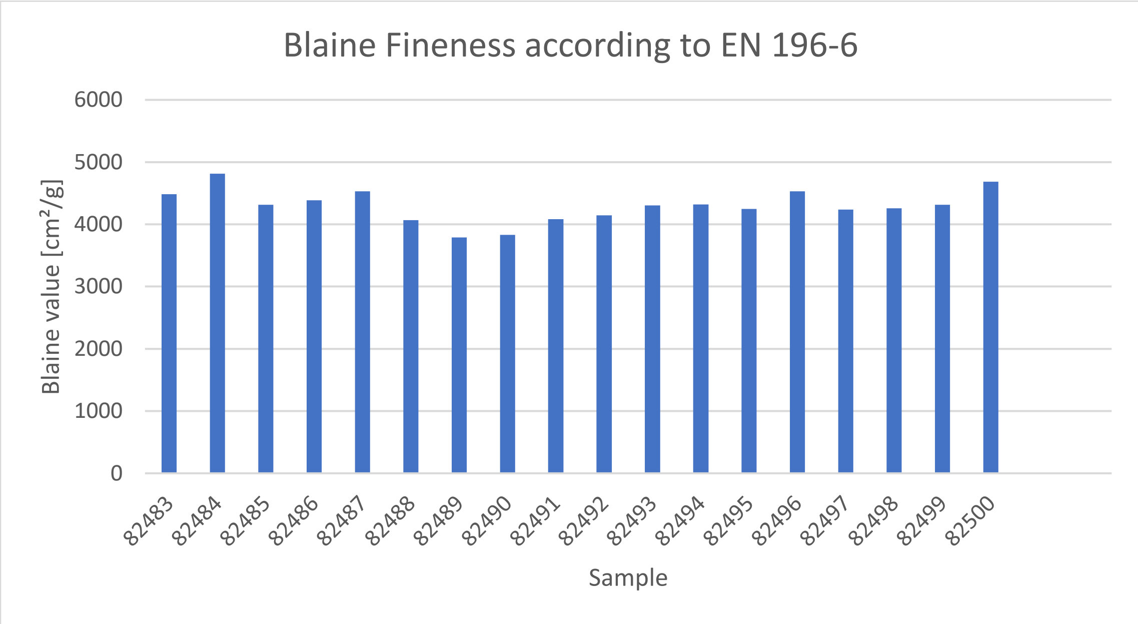


Figure 23 Illustration of the Blaine fineness value of the investigated cements

8 WP 6: Evaluation of the cement performances based on concrete production

8.1 WP 6.1: Evaluation of fresh concrete properties and the mechanical performance

8.1.1 All partners

Based on the results of the previous working packages 6 cements and two reference were chosen for the performance of concrete tests. The reference CEM I and CEM II/B-LL were used as reference material to compare with the new cements. The CEM II/B-LL was self-mixed by each project partner with a content of 35 % limestone. On the level of the mechanical performance, the following parameters were measured: compressive strength at 2,7 and 28 days, static and/or dynamic elastic modulus at 28 days and water absorption of hardened concrete.

Two different concrete recipes, summarized in **Table 39**, have been implemented for the investigations.

Table 39 Overview of the concrete recipes used in working package 6

Concrete	Cement content in kg/m³	w/c	Air content in %	Origin
C1	350	0.50	-	EAD
C2	340	0.45	5 ± 2	CEN/TR: most used

8.1.2 Austria

Fresh concrete properties

An overview of the fresh concrete properties of the concrete recipe C1 and C2 is shown in **Table 40** and **Table 41** and is illustrated in **Figure 24**, **Figure 25** and **Figure 26.**

Table 40 Overview of the C1 fresh concrete properties

	bulk density$_{10}$	flow diameter$_{10}$	air content$_{10}$	temperature$_{10}$	plasticizer
	[kg/m³]	[cm]	[%]	[°C]	[M.% cement]
MV1 - Ref1	2465	52	2.3	24.0	0.24
MV2 - Ref2	2448	53	2.3	20.7	0.22
MV3	2442	51	2.6	23.6	0.22
MV4	2424	51	2.8	22.6	0.25
MV5	2459	52	2.1	21.4	0.15
MV6	2448	52	2.2	20.5	0.12
MV7	2444	52	2.2	21.9	0.08
MV8	2444	51	2.1	20.0	0.06

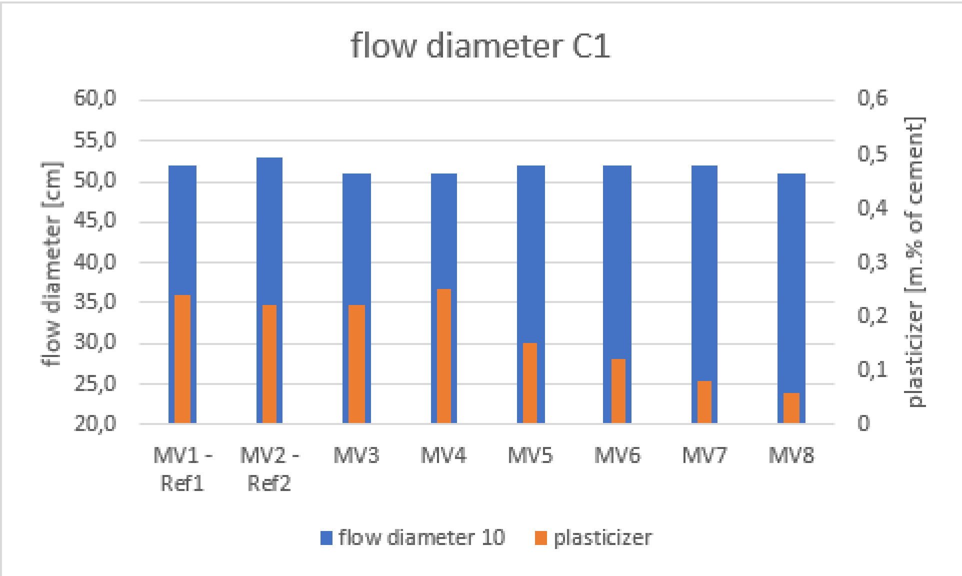


Figure 24 Flow diameter and plasticizer usage of the C1 concrete mixture

Table 41 Overview of the C2 fresh concrete properties

	bulk density$_{10}$	flow diameter$_{10}$	air content$_{10}$	temperature$_{10}$	plasticizer
	[kg/m³]	[cm]	[%]	[°C]	[M.% cement]
MV9 – Ref1	2391	52	5.5	24.4	0.40
MV10 - Ref2	2378	53	4.9	23.8	0.29
MV11	2426	52	4.7	22.7	0.76
MV12	2419	53	4.7	21.0	0.65
MV13	2435	53	4.4	21.0	0.56
MV14	2384	52	6.0	23.6	0.64
MV15	2401	53	5.5	22.3	0.74
MV16	2386	52	5.5	22.6	0.71

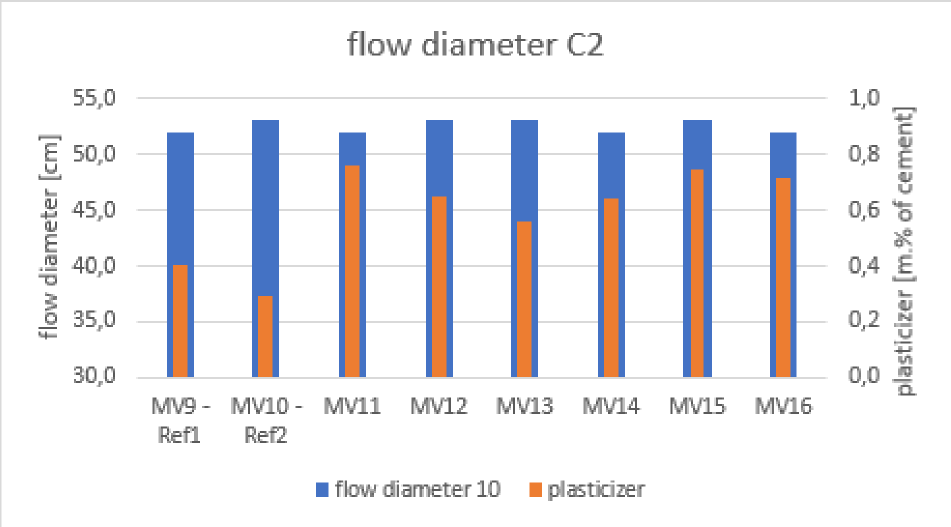


Figure 25 Flow diameter and plasticizer usage of the C2 concrete mixture

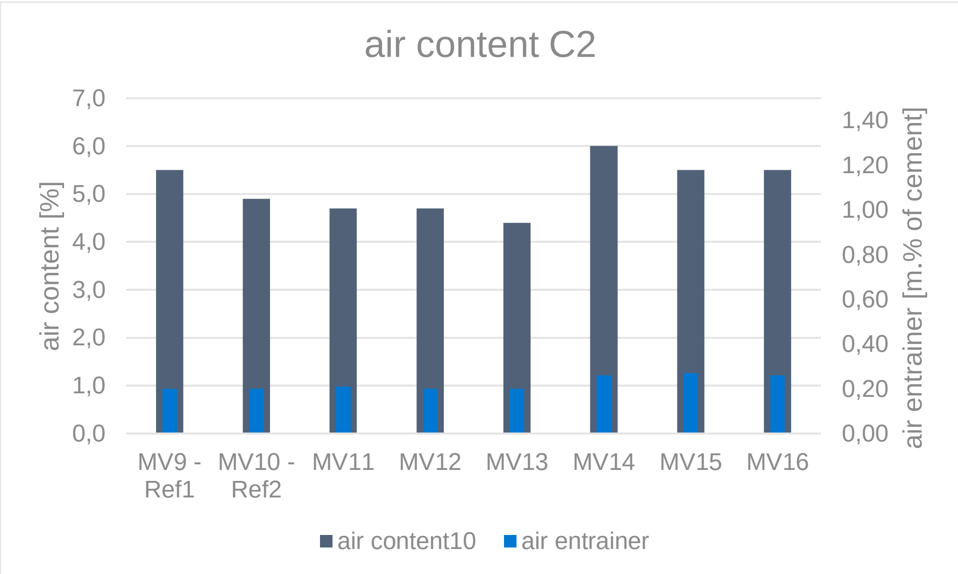


Figure 26 Air content of the C2 concrete mixture

Compressive strength and static modulus of elasticity

An overview of the compressive strength and static modulus of elasticity of concrete C1 is shown in **Table 42** and illustrated in **Figure 27** and **Figure 28** while an overview of the compressive strength of concrete C2 is shown in **Table 43** and illustrated in **Figure 29**.

Table 42 Overview of the compressive strength and static modulus of elasticity of the concrete mixture C1

		compressive strength in MPa			stat. mod. elasticity in MPa
		2d	**7d**	**28d**	**28d**
C1	MV1 - Ref1	40.2	50.0	59.9	33000
	MV2 - Ref2	23.6	29.9	41.0	27500
	MV3	30.1	39.1	52.3	30000
	MV4	23.1	30.5	40.8	28500
	MV5	30.3	39.0	51.3	31000
	MV6	19.4	28.0	38.8	28500
	MV7	27.4	35.8	46.8	29000
	MV8	20.9	28.7	39.3	27000

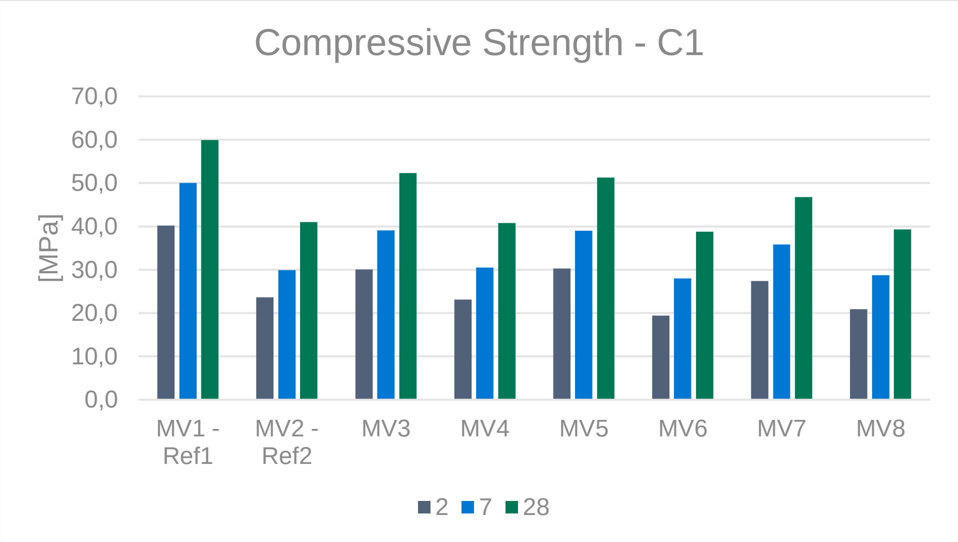


Figure 27 Illustration of the compressive strength at 2, 7 and 28 days of the concrete mixture C1

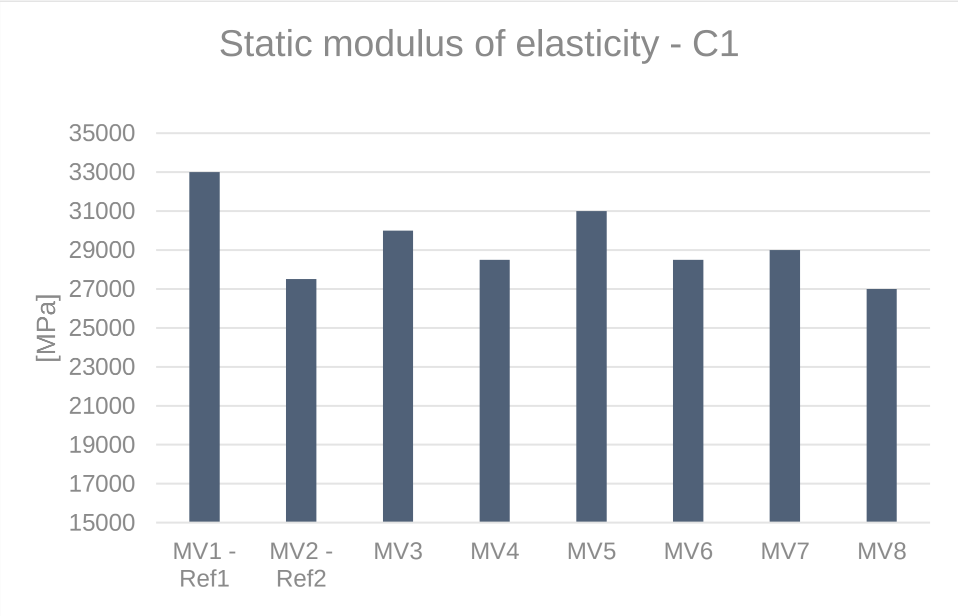


Figure 28 Illustration of the static modulus of elasticity of the C1 concrete mixture

Table 43 Overview of the compressive strength of the concrete mixture C2

		compressive strength in MPa		
		2d	7d	28d
C2	MV9 - Ref1	37.8	42.9	57.0
	MV10 - Ref2	21.6	27.2	36.5
	MV11	37.1	45.2	57.7
	MV12	27.9	35.4	46.6
	MV13	33.3	40.0	51.3
	MV14	23.3	29.1	39.5
	MV15	34.1	38.4	52.6
	MV16	24.9	31.4	41.3

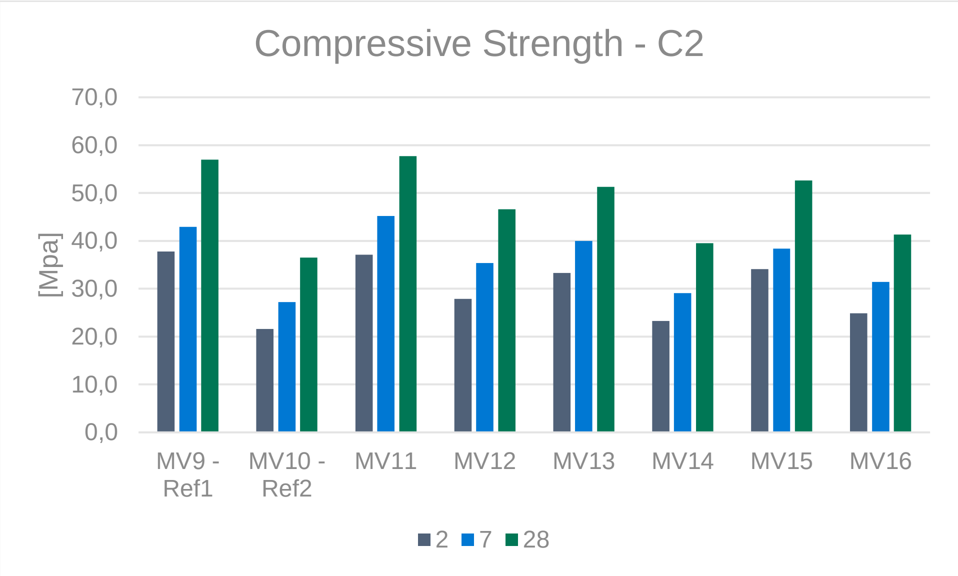


Figure 29 Illustration of the compressive strength at 2, 7 and 28 days of the concrete mixture C2

Water absorption (ONR 23303)

An overview of the water absorption of concrete C1 is shown in **Table 44** and illustrated in **Figure 30.**

Table 44 Water absorption of the C1 concrete mixtures

		water absorption in mm
		28d
C1	MV1 - Ref1	9.97
	MV2 - Ref2	19.1
	MV3	15.6
	MV4	18.25
	MV5	22.6
	MV6	12.9
	MV7	16.45
	MV8	16.1

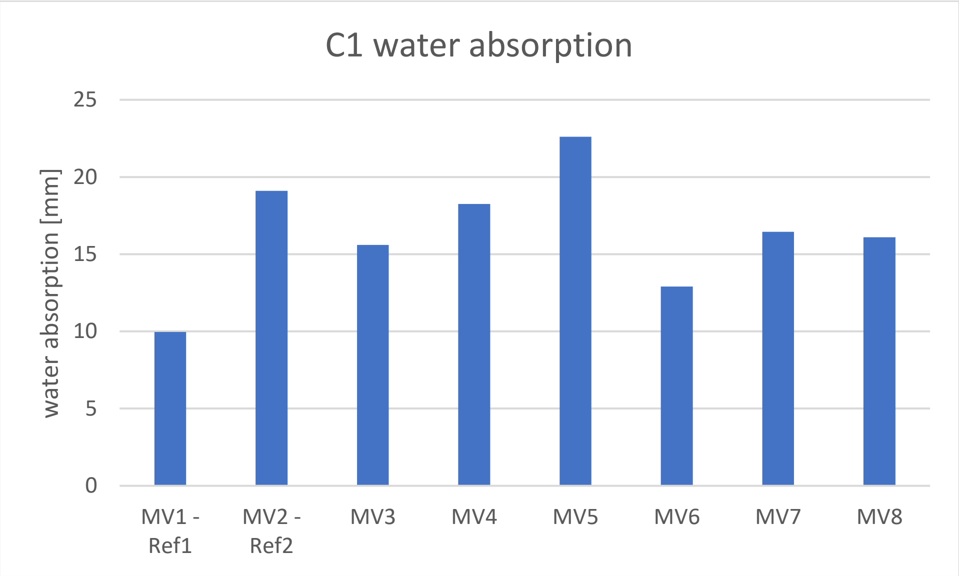


Figure 30 Illustration of the C1 concrete water absorption

8.1.3 Germany

Fresh concrete properties

The flow diameter acc. to EN 12350-5 (**Figure 31**) and the fresh concrete air content acc. to EN 12350-7 (**Figure 32**) were determined on each concrete. The results are also shown in **Table 45** and **Table 46.**

Table 45 Fresh concrete properties of C1

	CEM I	20% F-03	20% F-RS	35% F-03	C-M (S-F)	35% LL
SP content in %	0.00	0.00	0.00	0.00	0.00	0.00
AEA content in %	0.00	0.00	0.00	0.00	0.00	0.00
T (air) in °C	21.1	21.2	21.2	19.8	19.8	20.1
T (water) in °C	18.5	17.6	19.2	14.6	12.8	13.2
T (fresh concrete) in °C	22.2	20.9	22.2	19.5	19.2	19.4
flow diameter in mm	400	400	400	375	395	410
air content in %	1.0	1.2	1.2	1.4	1.8	1.2
density in g/cm³	2.38	2.37	2.35	2.35	2.35	2.36

SP: superplasticizer, AEA: air entraining agent

Table 46 Fresh concrete properties of C2

	CEM I	20% F-03	20% F-RS	35% F-03	C-M (S-F)	35% LL
SP content in %	0.10	0.15	0.15	0.00	0.10	0.00
AEA content in %	0.25	0.40	0.30	0.23	0.33	0.20
T (air) in °C	20.9	20.2	21.1	21.3	20.5	20.9
T (water) in °C	17.6	17.6	18.2	14.2	12.1	14.0
T (fresh concrete) in °C	22.1	22.0	22.0	20.2	20.7	20.6
flow diameter in mm	435	435	435	360	360	365
air content in %	5.3	5.0	5.2	4.5	4.8	5.0
density in g/cm³	2.28	2.28	2.29	2.29	2.27	2.30

SP: superplasticizer, AEA: air entraining agent

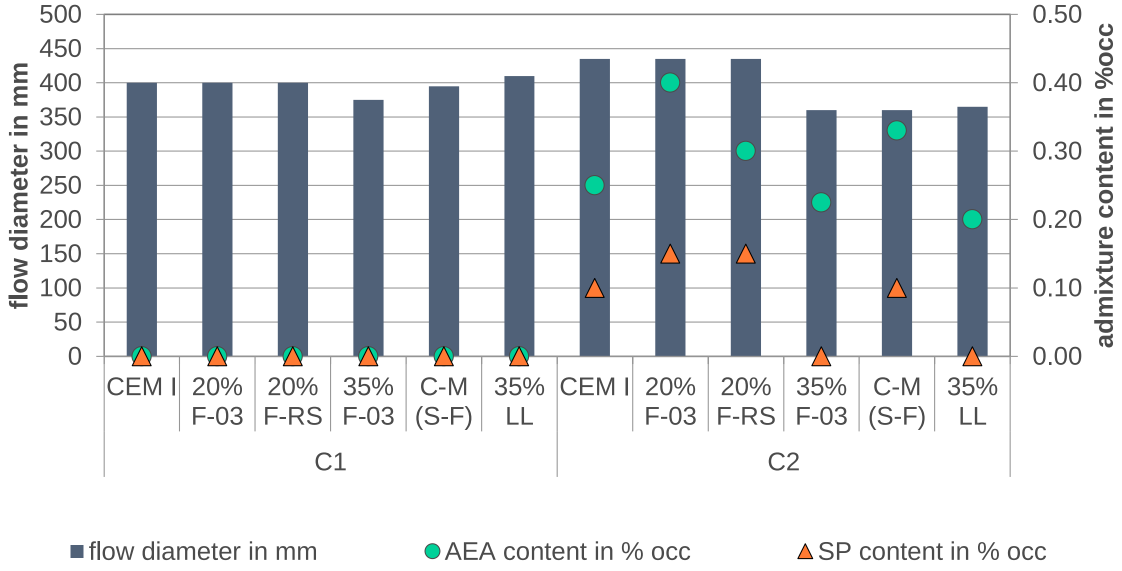


Figure 31 Flow diameters of concretes C1 and C2

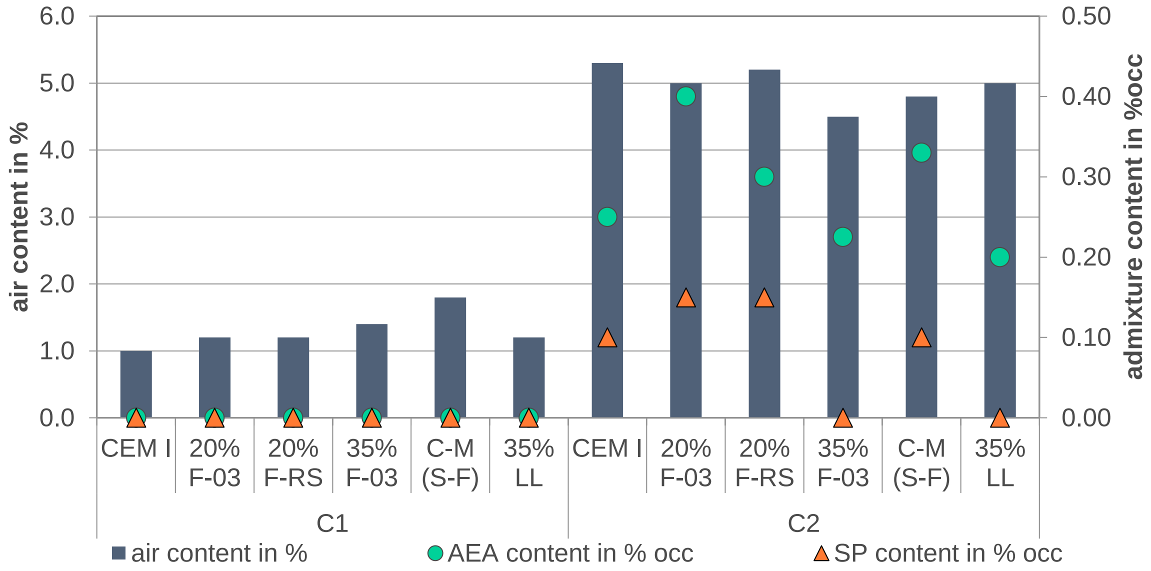


Figure 32 Fresh concrete air contents of concretes C1 and C2

Compressive strength and static modulus of elasticity

Compressive strengths were tested acc. to EN 12390-2 at the ages of 2d, 7d and 28d. The results are shown in **Figure 33.** The E-Modulus was tested acc. to EN 12390-13 after 28d on concretes C1. The results are shown in **Figure 34.** Compressive strength and E-modulus are also shown in **Table 47** and **Table 48.**

Table 47 Mean values of compressive strength and E-modulus of C1

	CEM I	20% F-03	20% F-RS	35% F-03	C-M (S-F)	35% LL
compressive strength 2d in MPa	40.2	30.7	31.1	20.3	13.8	19.1
compressive strength 7d in MPa	56.7	47.5	45.9	34.2	31.3	33.4
compressive strength 28d in MPa	72.9	60.8	60.3	43.9	48.8	42.6
E-modulus 28d in GPa	42.0	40.3	37.8	36.2	34.5	36.6

Table 48 Mean values of compressive strength of C2

	CEM I	20% F-03	20% F-RS	35% F-03	C-M (S-F)	35% LL
compressive strength 2d in MPa	30.3	27.4	25.8	22.8	15.5	19.3
compressive strength 7d in MPa	39.8	37.8	36.7	36.3	33.3	31.7
compressive strength 28d in MPa	50.2	47.7	49.5	45.8	48.3	42.7

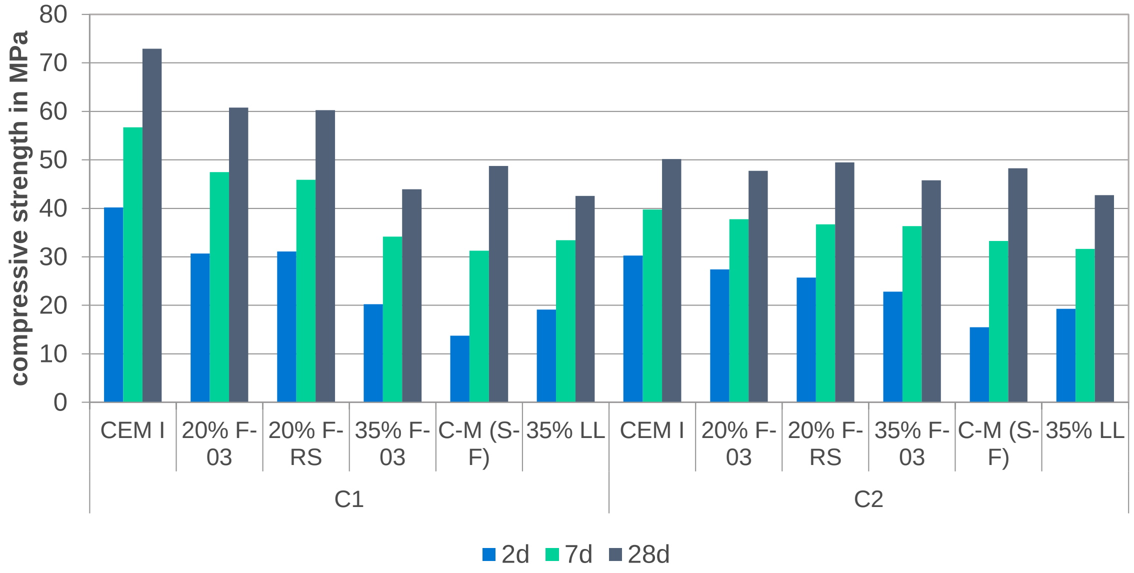


Figure 33 Compressive strength of concretes C1 and C2

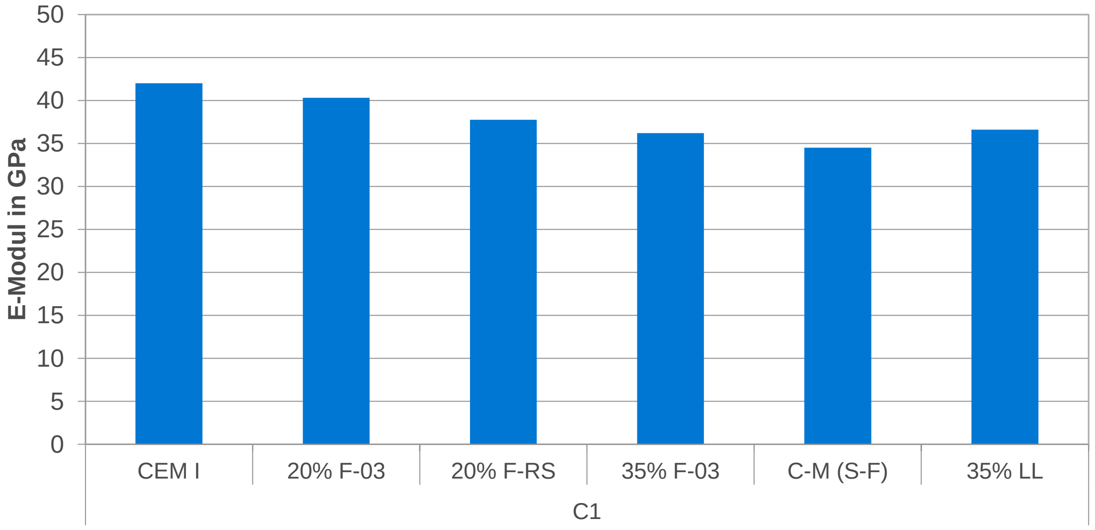


Figure 34 E-modulus of concretes C1

8.1.4 Belgium

Fresh concrete properties

An overview of the fresh concrete properties of concrete C1 and C2 is shown in **Table 49** and **Table 50** and illustrated in **Figure 35**. The Concrete ID column in these tables is made with the following identification: C_Cx_Sample where C = Concrete / x = 1 or 2 depending on which recipe / Sample = indication of reference or recycled product.

In the different concrete fabrications, there was no possibility to use a plasticizer to obtain very similar results concerning the slump values due to a limited amount of treated recycled material. As a reminder, each batch of treated sample weighed only 200 grams (very time-consuming step).

Table 49 Overview of the C1 fresh concrete properties

Concrete ID	Sample	Cement constituents	Density [kg/m³]	Slump [mm]	Air content [%]
CC1R1	Ref 1	100 % CEM I	2410	80	0.8
CC1R2	Ref 2	65% CEM I + 35% LL	2400	140	0.5
CC1Rec1_20	Rec 1 20%	80% CEM I + 20% Recycled Concrete 1 (1H @ 600°C)	2410	90	0.6
CC1Rec1_35	Rec 1 35%	65% CEM I + 35% Recycled Concrete 1 (1H @ 600°C)	2390	70	0.9
CC1Rec2_20	Rec 2 20%	80% CEM I + 20% Mix Brick-Concrete (1H @ 600°C)	2400	70	0.7
CC1Rec2_35	Rec 2 35%	65% CEM I + 35% Mix Brick-Concrete (1H @ 600°C)	2390	80	0.6
CC1Rec3_20	Rec 3 20%	80% CEM I + 20% Recycled Concrete 2 (1H @ 600°C)	2400	70	0.7
CC1Rec3_35	Rec 3 35%	65% CEM I + 35% Recycled Concrete 2 (1H @ 600°C)	2390	90	0.6

Table 50 Overview of the C2 fresh concrete properties

Concrete ID	Sample	Cement constituents	Density [kg/m³]	Slump [mm]	Air content [%]	Air entrainer [%]
CC2R1	Ref 1	100 % CEM I	2340	70	4.2	0.22
CC2R2	Ref 2	65% CEM I + 35% LL	2320	90	4.4	0.32
CC2Rec1_20	Rec 1 20%	80% CEM I + 20% Recycled Concrete 1 (1H @ 600°C)	2340	70	4.0	0.22
CC2Rec1_35	Rec 1 35%	65% CEM I + 35% Recycled Concrete 1 (1H @ 600°C)	2330	50	4.0	0.25
CC2Rec2_20	Rec 2 20%	80% CEM I + 20% Mix Brick-Concrete (1H @ 600°C)	2330	40	4.3	0.25
CC2Rec2_35	Rec 2 35%	65% CEM I + 35% Mix Brick-Concrete (1H @ 600°C)	2340	40	3.6	0.26
CC2Rec3_20	Rec 3 20%	80% CEM I + 20% Recycled Concrete 2 (1H @ 600°C)	2310	60	4.8	0.26
CC2Rec3_35	Rec 3 35%	65% CEM I + 35% Recycled Concrete 2 (1H @ 600°C)	2300	50	4.2	0.29

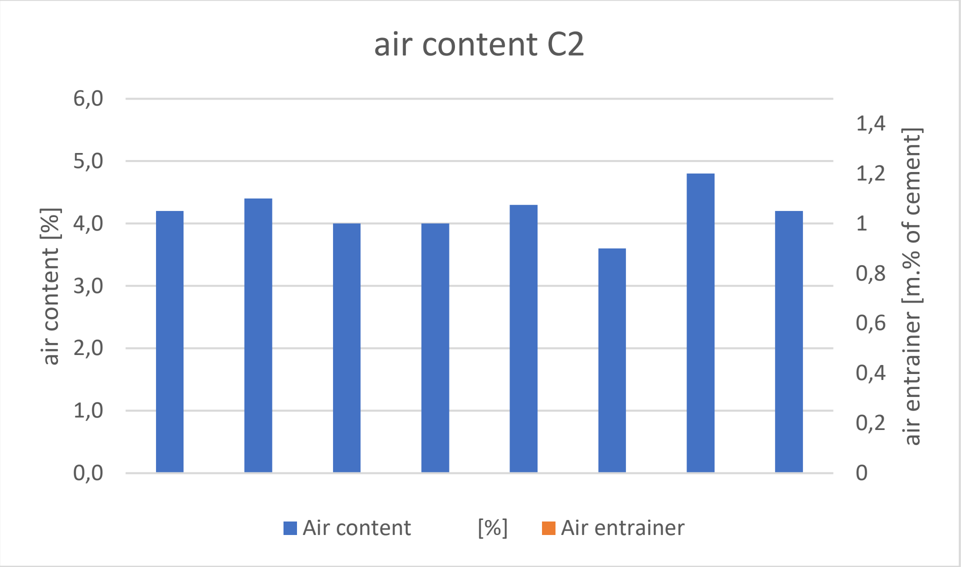


Figure 35 Air content of the C2 concrete mixture

<u>Compressive strength and static modulus of elasticity</u>

The results for the dynamic modulus of elasticity for concrete mixture C1 and compressive strengths for concrete mixtures C1 and C2 are given in **Table 51**, **Table 52** and illustrated by **Figure 36**, **Figure 37** and **Figure 38**. The dynamic modulus of elasticity and compressive strength values for the recycled samples are comparable (although a very slight increase is visible) with reference 2.

Table 51 Overview of the dynamic modulus of elasticity and compressive strength at 2, 7 and 28 days of the concrete mixture C1

		compressive strength in MPa			dyn. mod. elasticity in MPa
		2d	7d	28d	28d
C1	CC1R1	32.2	48.2	54.3	46320
	CC1R2	16.8	28.0	34.4	41091
	CC1Rec1_20	25.2	40.7	47.8	43318
	CC1Rec1_35	17.2	28.1	35.4	41421
	CC1Rec2_20	25.0	38.4	46.6	43538
	CC1Rec2_35	17.8	27.8	36.3	41715
	CC1Rec3_20	25.7	38.1	45.6	42936
	CC1Rec3_35	16.1	27.3	34.3	41457

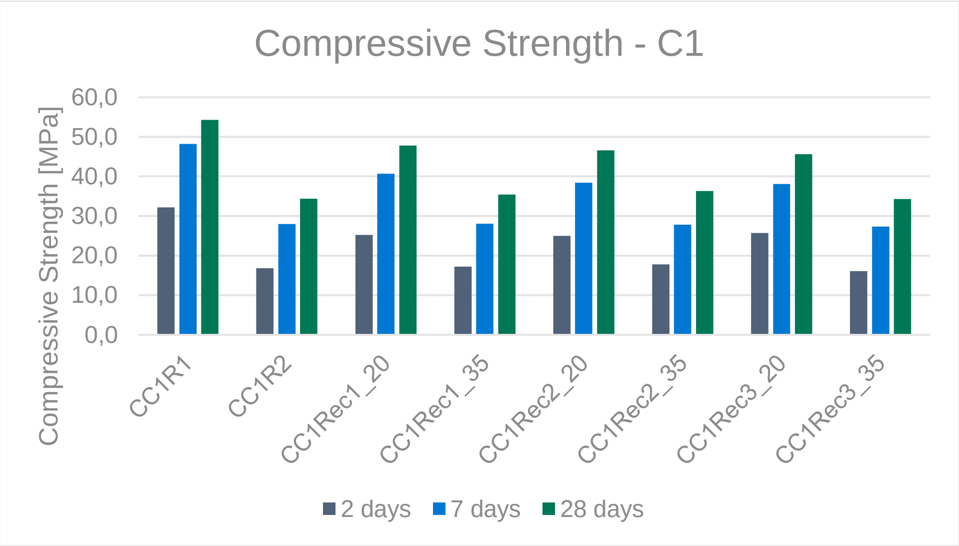


Figure 36 Illustration of the compressive strength at 2, 7 and 28 days of the concrete mixture C1

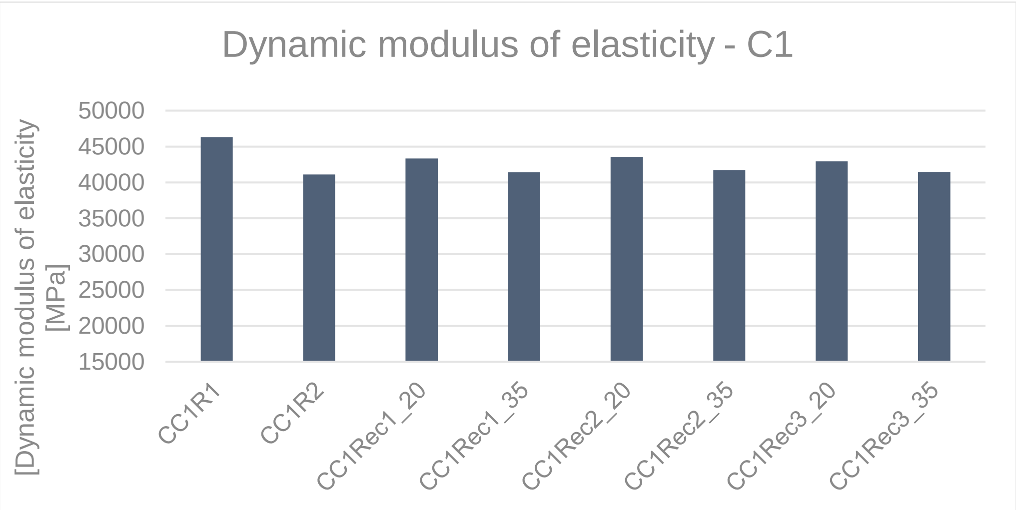


Figure 37 Illustration of the dynamic modulus of elasticity of the C1 concrete mixture

Table 52 Overview of the dynamic modulus of elasticity and compressive strength at 2, 7 and 28 days of the concrete mixture C1

		compressive strength in MPa		
		2d	**7d**	**28d**
C1	CC2R1	30.7	43.0	50.0
	CC2R2	15.8	25.1	28.3
	CC2Rec1_20	24.0	35.2	42.7
	CC2Rec1_35	16.6	25.3	32.3
	CC2Rec2_20	21.9	34.5	40.5
	CC2Rec2_35	17.0	26.0	32.1
	CC2Rec3_20	21.5	31.9	39.7
	CC2Rec3_35	15.5	23.3	29.4

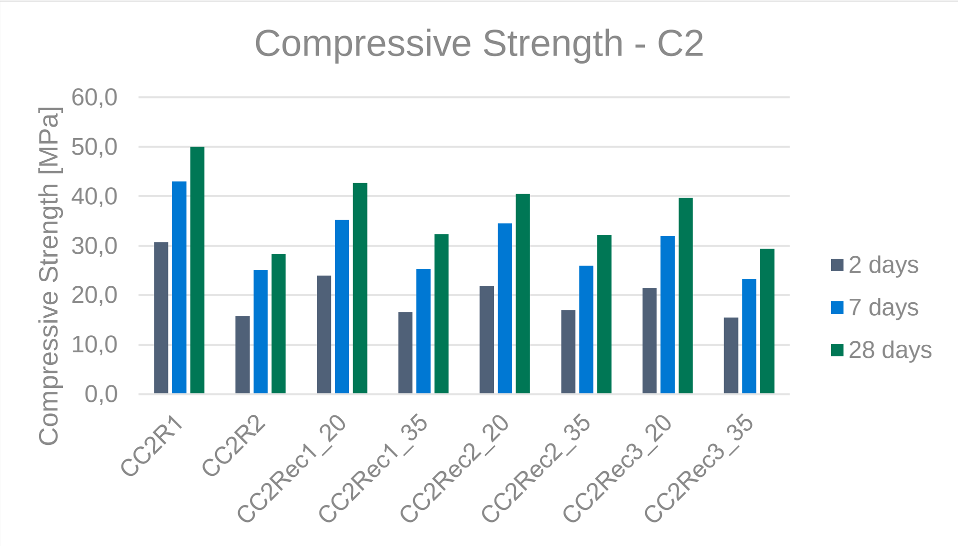


Figure 38 Illustration of the compressive strength at 2, 7 and 28 days of the concrete mixture C2

Water absorption

The water absorption of the concrete mixtures with C1-recipe is measured according to the standard NBN B 15-215. The results are given in **Table 53** and illustrated by **Figure 39**. No difference is found between the recycled samples and the reference 2.

Table 53 Water absorption of the C1 concrete mixtures

		water absorption in mm
		28d
C1	CC1R1	5.8
	CC1R2	6.1
	CC1Rec1_20	5.4
	CC1Rec1_35	6.3
	CC1Rec2_20	5.5
	CC1Rec2_35	6.1
	CC1Rec3_20	5.6
	CC1Rec3_35	5.9

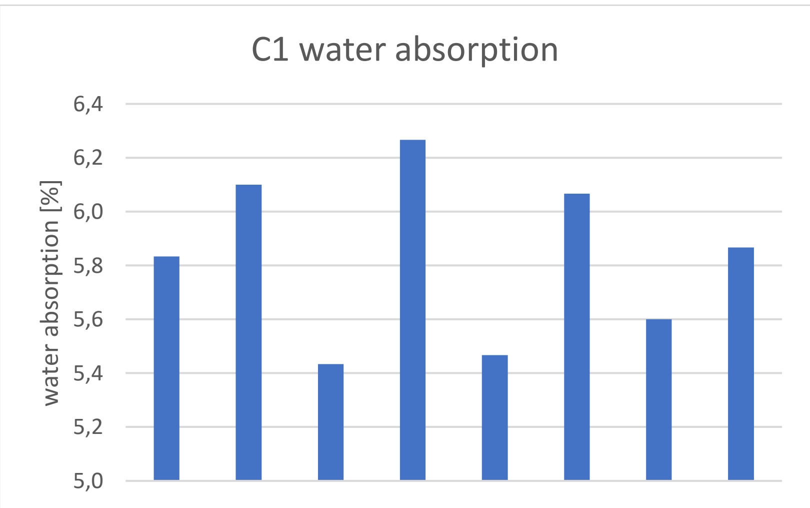


Figure 39 Illustration of the C1 concrete water absorption for the different concrete mixtures

8.2 WP 6.2: Evaluation of the durability and environmental performances

On the level of durability and environmental performances, the following tests were performed by the project partners:

- Chloride diffusion in accordance with EN 12390-11 and/or Chloride migration in accordance with NT Build 492;
- Resistance to carbonation in accordance with EN 12390-12, which currently is in formal voting (3% CO2; AT 4% CO2), or to accelerated carbonation in accordance with EN 13295 (1% CO2);
- Freeze-thaw resistance with and without de-icing salts in accordance with national Standards;
- Testing the freeze-thaw resistance of concrete - Internal structural damage CEN/TR 15177 (VDZ, CRIC-OCCN).
- Leaching tests on the concrete monoliths (selected samples) in accordance with CEN/TS 16637-2. The results of these tests were compared with the previous leaching tests, performed on the pure fines (WP2.2), in order to evaluate the environmental impact of the fines-based cements.

8.2.1 Austria

<u>Resistance to Carbonation (EN 12390-12) with 3% CO_2 storage</u>

The carbonation resistance of concretes C1 were tested acc. to EN 12390-12 with 3% CO_2. The carbonation depth was tested directly after pre-storage and before storing the specimens in the carbonation chamber and after 7, 28 and 70 days. The results are shown in **Table 54** and illustrated in **Figure 40**.

Table 54 Overview carbonation depth according to EN 12390-12

		0d	**7d**	**28d**	**70d**	**K_{AC}**
	√t	**0**	**2.6**	**5.3**	**8.4**	**slope**
C1	MV1 - Ref1	0	0.00	0.23	1.53	0.18
	MV2 - Ref2	0	3.30	8.20	13.30	1.62
	MV3	0	1.60	4.70	9.10	1.10
	MV4	0	5.00	8.50	11.80	1.39
	MV5	0	3.40	5.80	9.00	1.05
	MV6	0	4.20	8.30	12.70	1.52
	MV7	0	1.20	5.50	8.50	1.07
	MV8	0	2.70	8.90	12.90	1.61

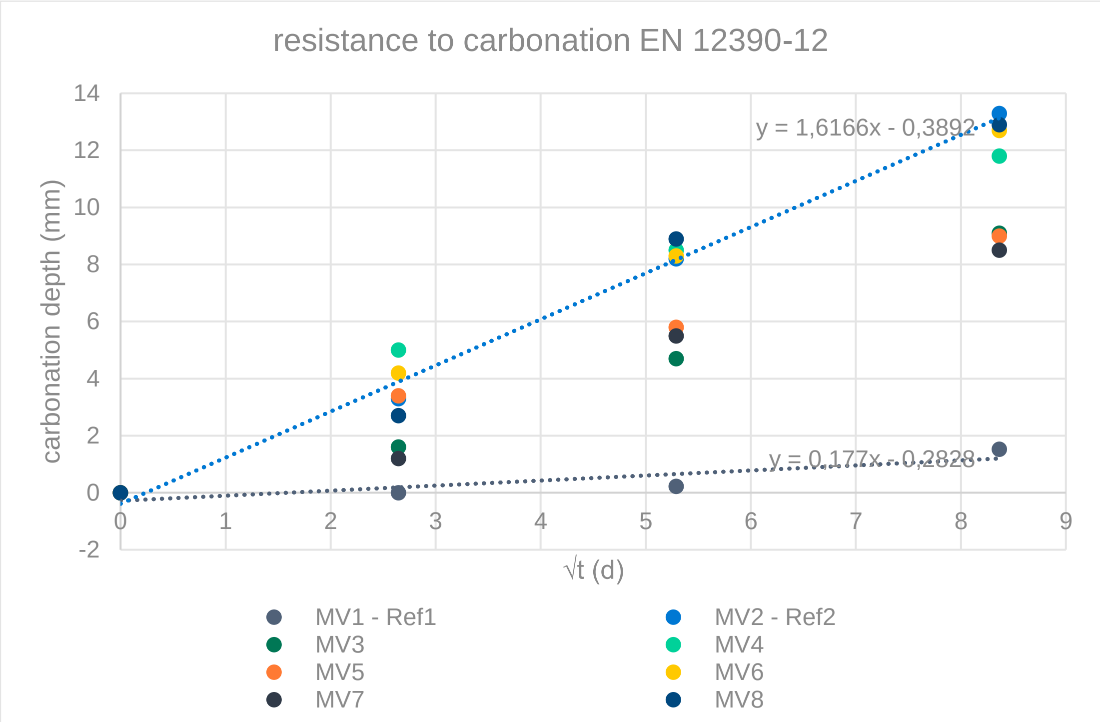


Figure 40 Illustration of the carbonation depth depending on √t

<u>Freeze thaw resistance without de-icing salt (ONR 23303)</u>

The freeze-thaw resistances of concretes C1 were tested acc. to ONR 23303. The mass change and sound propagation time are shown in **Table 55**.

Table 55 Freeze thaw resistance without de-icing salt according to the Austrian standard ÖNORM 23303

		mass change in %	sound propagation time in %	test result
C1	MV1 - Ref1	0.1	2.8	positive
	MV2 - Ref2	0.4	>76	negative
	MV3	0.2	3.7	positive
	MV4	0.4	5.0	positive
	MV5	0.1	6.0	negative
	MV6	0.1	27.8	negative
	MV7	0.3	3.2	positive
	MV8	0.3	2.8	positive

<u>Freeze thaw resistance with de-icing salt (ONR 23303)</u>

The freeze-thaw resistances with de-icing salts of concretes C2 were tested acc. to ONR 23303. The mass loss after 56 cycles is shown in **Table 56** and illustrated in **Figure 41**.

Table 56 Mass loss after 56 freeze thaw cycles with de-icing salt according to ONR 23303

		mass lost after 56 cycles in g/m²
C2	MV9 - Ref1	17
	MV10 - Ref2	205
	MV11	240
	MV12	857
	MV13	398
	MV14	440
	MV15	357
	MV16	634

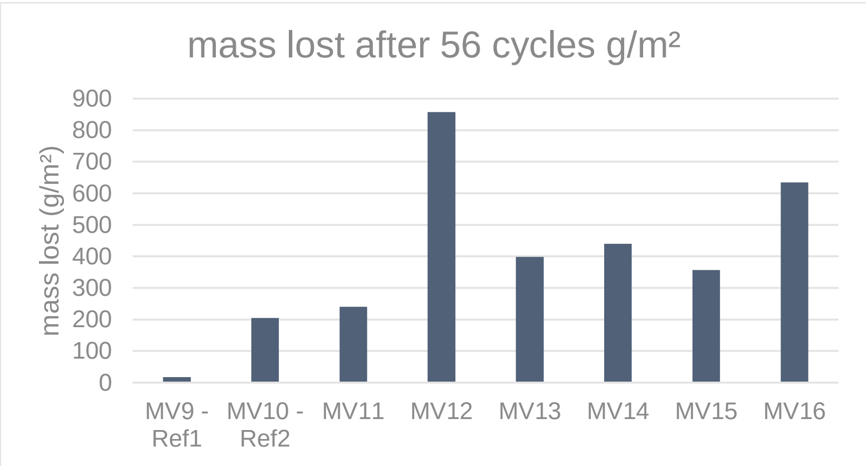


Figure 41 Graphical comparison of the mass loss after 56 freeze thaw cycles

Chloride diffusion (EN 12390-11)

Chloride diffusion is measured according to the standard EN 12390-11. The results for the concrete mixtures of C1 recipe are given in **Table 57** and illustrated in **Figure 42.**

Table 57 Overview of the C1 concrete chloride diffusion according to EN 12390-11 for the different concrete mixtures

	MV1	MV2	MV3	MV4	MV5	MV6	MV7	MV8
	Excel-Berechnung	Excel-Berechnung	Excel-Berechnung	Excel-Berechnung	Excel-Berechnung	Excel-Berechnung	Excel-Berechnung	Excel-Berechnung
C_s	0,359	0,265	0,401	0,323	0,386	0,332	0,413	0,397
D_{nss}	1,05E-11	2,42E-11	1,24E-11	1,98E-11	1,08E-11	2,58E-11	1,44E-11	1,77E-11
R^2	0,993	0,972	0,986	0,990	0,988	0,944	0,996	0,958

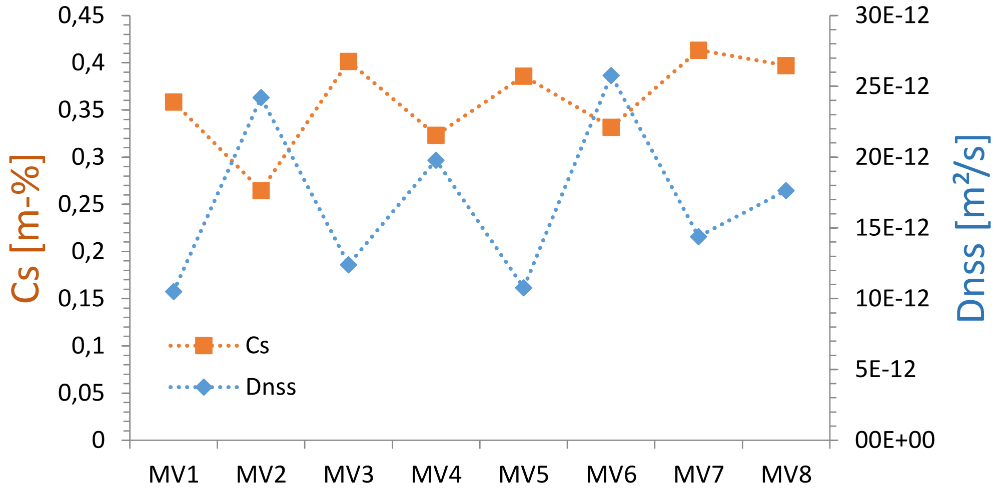


Figure 42 Illustration of the C1 concrete chloride diffusion for the different concrete mixtures

<u>Leaching tests in accordance with CEN/TS 16637-2</u>

The results of the leaching test were performed in accordance with CEN/TS 16637-2 and are summarized in **Figure 43**. The results show no significant leaching of trace elements and are in agreement with the Austrian Guideline for the use in the cement production (Technische Grundlagen für den Einsatz von Abfällen als Ersatzrohstoffe in Anlagen zur Zementerzeugung, BMLFUW 2016).

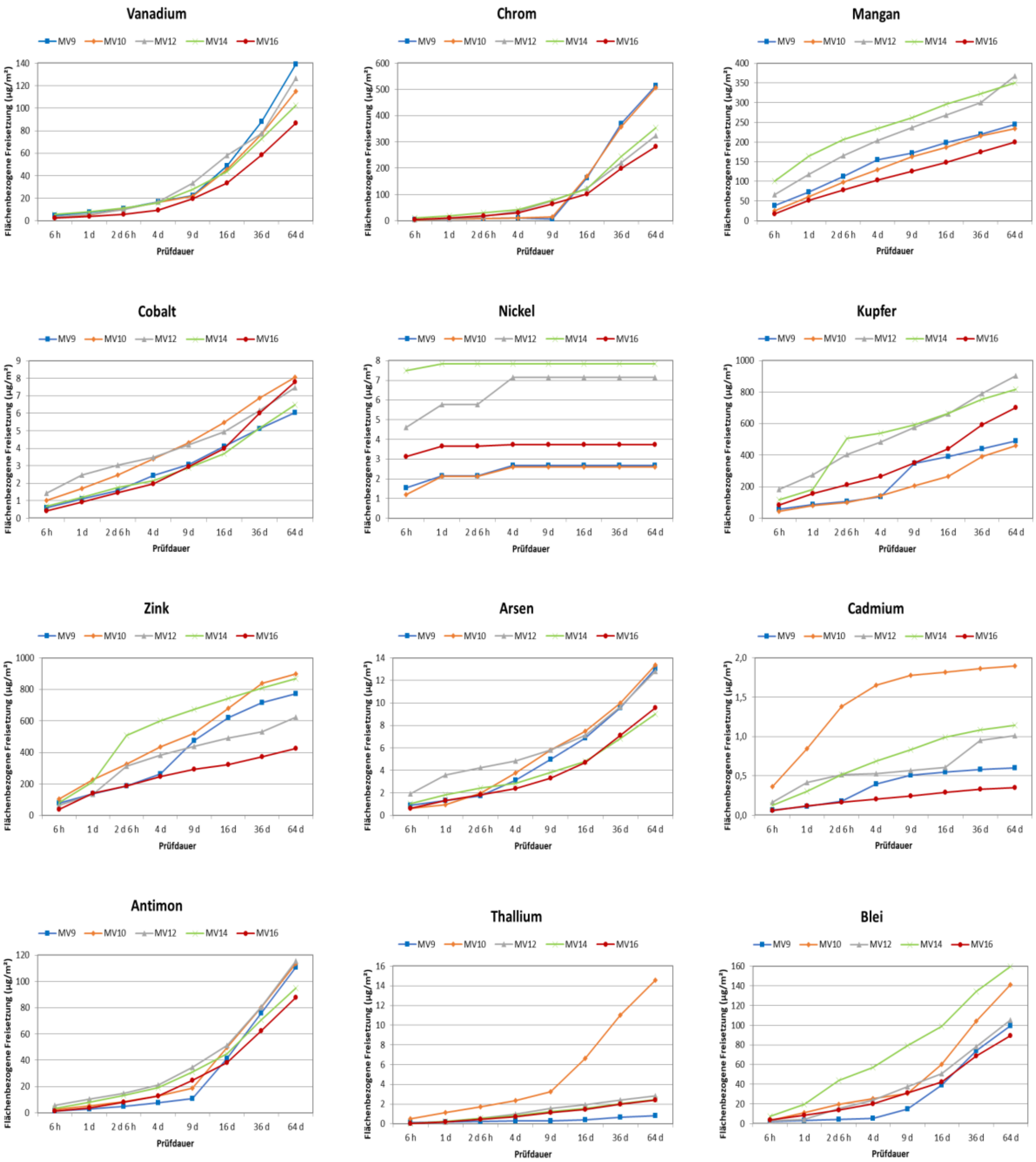


Figure 43 Cumulative leaching of trace elements of the surface (µg/m²) of the concrete C2; MV9: Reference 1 (CEMI), MV10: Reference 2 (CEMII/B-LL); MV12: CEM II/B - F (sample 1), MV14: CEM II/B – F (sample 2), MV 16: CEM II/B – F (sample 3)

8.2.2 Germany

Resistance to Carbonation (EN 12390-12) with 3% CO_2 storage

The carbonation resistance of concretes C1 were tested acc. to EN 12390-12 with 3% CO_2 on 2 specimens per concrete. The carbonation depth was tested directly after pre-storage and before storing the specimens in the carbonation chamber and after 7, 28 and 70 days. The results are shown in **Table 58** and **Figure 44.**

Table 58 Overview carbonation depth according to EN 12390-12

		0d	7d	28d	70d	K_{AC}
	√t	0	2.6	5.3	8.4	slope
C1	CEM I	0.00	0.00	0.85	1.60	0.02
	20% F-RS	0.00	2.35	4.60	6.95	0.83
	20% F-03	0.00	2.50	3.50	6.25	0.71
	C-M (S-F)	0.35	4.30	9.00	13.50	1.59
	35% F-03	0.20	3.80	8.20	13.40	1.59
	35% LL	0.20	4.30	7.70	11.95	1.39

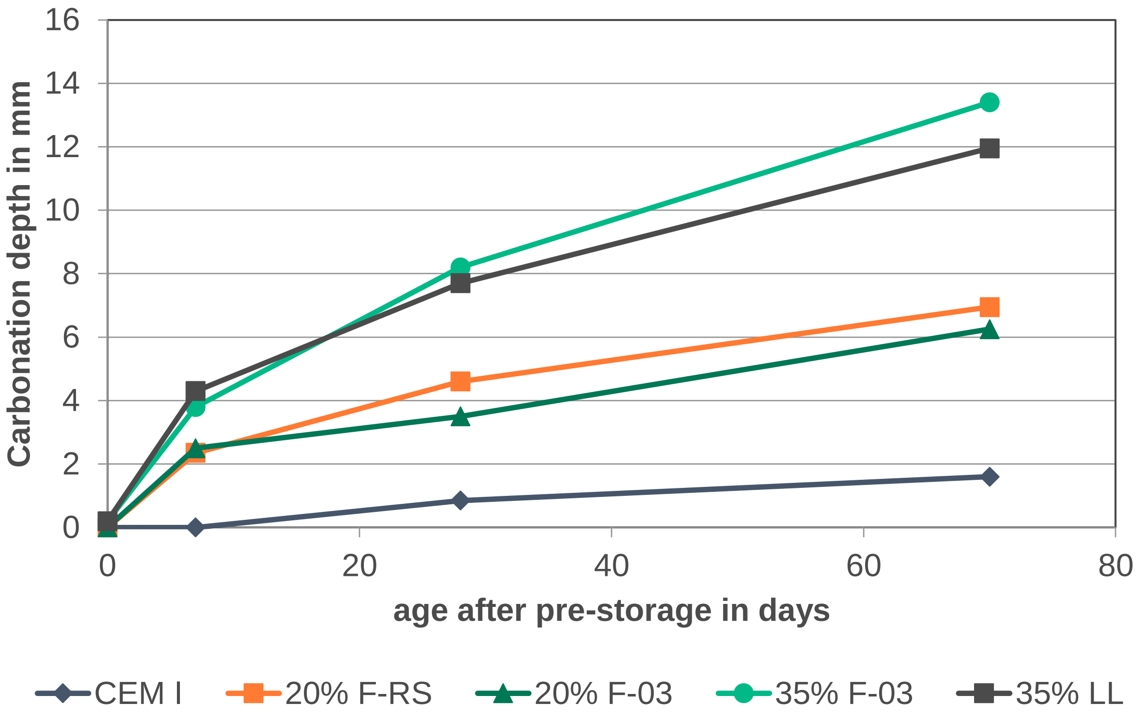


Figure 44 Carbonation depth of concretes C1

Freeze thaw resistance without de-icing salts

The freeze-thaw resistances of concretes C1 were tested with the CIF-Test (CEN/TS 12390-9 in combination with CEN/TR 15177). The scaling and the relative modulus of elasticity are shown in **Table 59** and **Figure 45**.

Table 59 Freeze-thaw results CIF of C1 (mean values)

	FTC	scaling in kg/m²	relative dyn. modulus of elasticity in %		FTC	scaling in kg/m²	relative dyn. modulus of elasticity in %
CEM I	0	0.00	100.00	C-M (S-F)	0	0.00	100.00
	4	0.02	97.42		4	0.06	95.98
	12	0.04	90.70		6	0.12	95.32
	14	0.05	87.70		14	0.28	83.04
	28	0.11	77.56		28	0.56	39.78
	42	0.21	70.42		42	0.83	33.54
	55	0.36	62.30		56	1.09	34.32
20% F-03	0	0.00	100.00	35% F-03	0	0.00	100.00
	4	0.01	98.02		4	0.02	97.62
	8	0.01	96.80		6	0.03	97.64
	16	0.01	89.10		14	0.08	94.90
	28	0.02	72.02		28	0.16	69.44
	42	0.05	63.92		42	0.37	36.16
	56	0.12	51.24		56	0.84	36.90
20% F-RS	0	0.00	100.00	35% LL	0	0.00	100.00
	4	0.01	97.20		4	0.01	97.96
	6	0.01	96.54		6	0.02	98.28
	14	0.01	87.78		14	0.03	96.10
	28	0.03	68.10		28	0.10	55.98
	42	0.04	55.90		42	0.32	35.54
	56	0.09	42.78		56	0.82	38.20

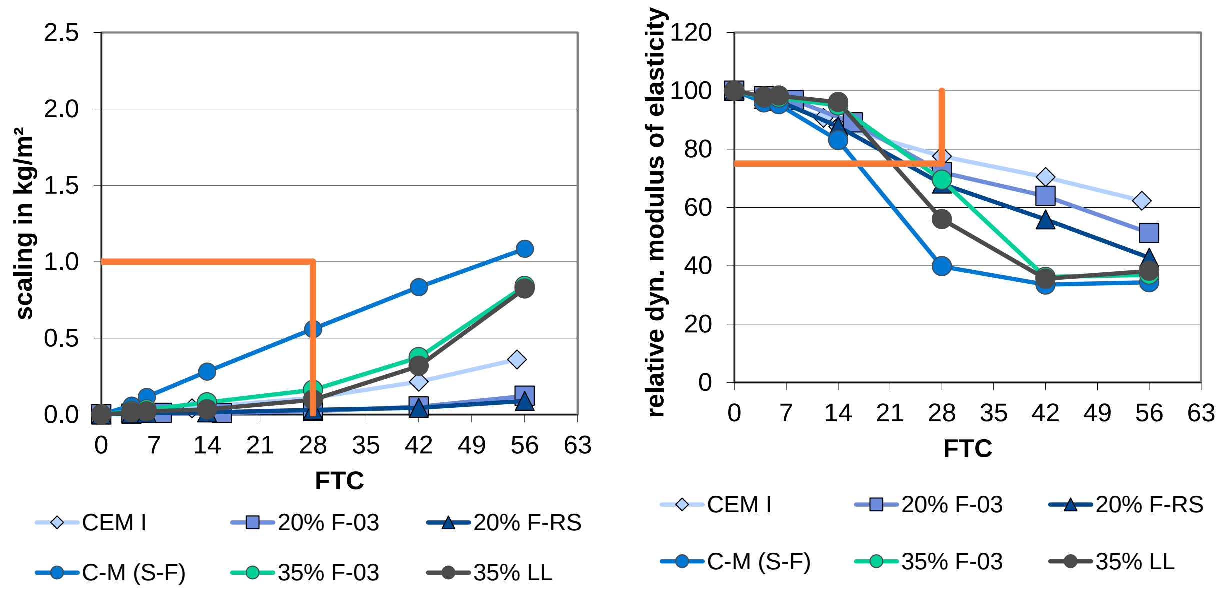


Figure 45: Scaling and the relative modulus of elasticity (CIF)

Freeze thaw resistance with de-icing salts

The freeze-thaw resistances with de-icing salts of concretes C2 were tested with the CDF test acc. to CEN/TS 12390-9. The scaling and the relative modulus of elasticity are shown in **Table 60** and **Figure 46.**

Table 60 Freeze-thaw results CDF of C2 (mean values)

	FTC	scaling in kg/m²	relative dyn. modulus of elasticity in %		FTC	scaling in kg/m²	relative dyn. modulus of elasticity in %
CEM I	0	0.00	100.00	C-M (S-F)	0	0.00	100.00
	4	0.03	98.84		4	0.31	98.54
	10	0.05	97.72		6	0.48	98.50
	14	0.06	98.30		14	0.82	98.74
	28	0.09	98.10		28	1.49	94.58
20% F-03	0	0.00	100.00	35% F-03	0	0.00	100.00
	4	0.02	99.04		4	0.05	98.04
	12	0.05	98.36		10	0.10	98.18
	14	0.06	98.90		14	0.12	97.92
	28	0.09	98.64		28	0.25	98.36
20% F-RS	0	0.00	100.00	35% LL	0	0.00	100.00
	4	0.02	98.98		4	0.05	98.00
	6	0.04	98.98		10	0.08	97.90
	14	0.08	98.96		14	0.11	97.66
	28	0.13	98.68		28	0.24	98.64

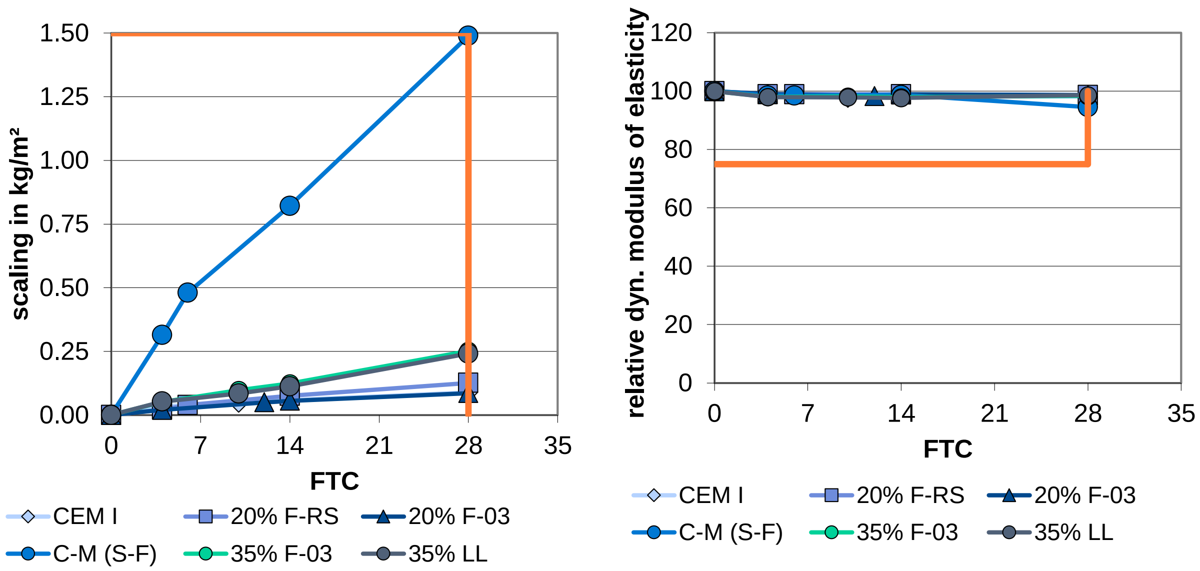


Figure 46: Scaling and the relative modulus of elasticity (CDF)

Chloride diffusion

The Chloride diffusion coefficients of concretes C1 were determined acc. to EN 12390-11. Additionally, the Chloride migration coefficients acc. to EN 12390-18 were determined. The results are shown in **Table 61** and **Figure 47**.

Table 61 Results of Chloride diffusion and migration (mean values)

	CEM I	20% F-03	20% F-RS	35% F-03	C-M (S-F)	35% LL
Initial chloride content in %	0.007	0.007	0.009	0.020	0.007	0.013
Chloride diffusion coefficient in 10^{-12} m²/s	6.56	11.16	8.60	17.80	2.74	22.78
correlation coefficient R	0.998	0.991	0.990	0.983	0.997	0.995
Chloride migration coefficient in 10^{-12} m²/s	12.1	17.9	16.6	25.8	5.6	27.0

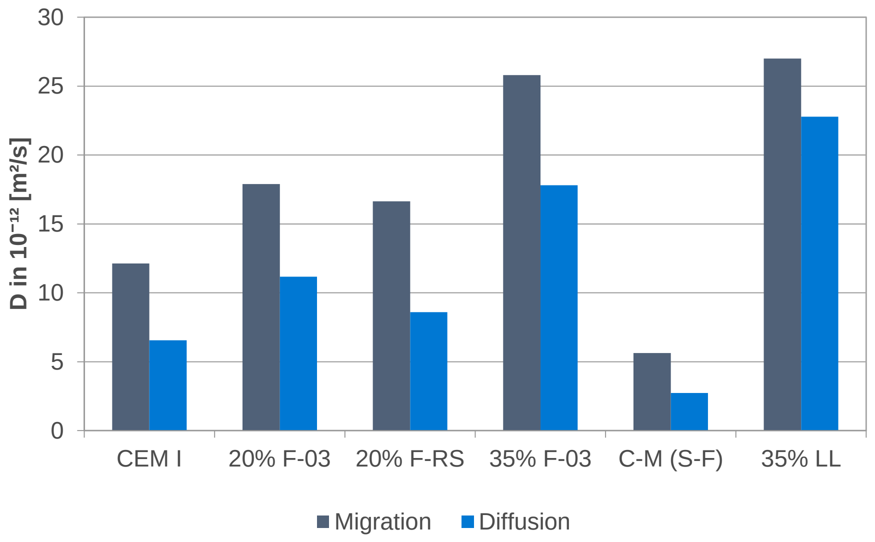


Figure 47 Chloride diffusion and migration coefficients

Content and leaching of dangerous substances

The content of dangerous substances was tested on all recycled used for WP6 of all project partners according to German Guideline “Verwendung von siliziumreicher Flugasche und Kesselsand in Betonbauteilen in Kontakt mit Boden, Grundwasser oder Niederschlag”. The results are shown in **Table 62**. All contents of dangerous substances are below the limit values given in the German guideline.

Table 62 Content of dangerous substances, results for all project partners

		requi-re-ment[1)]	VDZ		SMG			CRIC		
			F-RS	F-03	7221	7318	7392	E-21-594	E-21-595	E-21-596
total PCB	µg/g	<0.5	<0,3	<0,5	<0,5	<0,5	<0,5	<0,5	<0,5	<0,5
total PAK	µg/g	<30	<0,1	0.16	<0,1	<0,1	<0,1	0.91	0.53	0.38
total PCDD/PCDF	µg/kg	<0,1	n.d.	0.0004	0.0006	0.0006	0.0001	0.0053	0.0026	0.0023
Vanadium	µg/g	1500	42.6	30.7	24.3	32.4	27.0	56.0	71.9	51.8
Chromium	µg/g	600	135.0	102.0	121.0	197.0	102.0	165.0	214.0	247.0
Nickel	µg/g	500	15.8	17.9	12.2	53.9	19.2	19.0	27.2	16.5
Copper	µg/g	400	16.0	20.2	24.3	17.3	22.0	29.8	31.2	32.9
Zinc	µg/g	1500	45.9	131.0	53.2	39.8	93.5	143.0	224.0	113.0
Arsenic	µg/g	150	5.8	4.7	3.6	3.1	5.7	6.6	10.6	6.2
Cadmium	µg/g	10	0.1	0.3	0.2	0.1	0.2	0.4	0.5	0.2
Thallium	µg/g	7	0.5	0.3	0.194	0.307	0.193	0.335	0.4	0.234
Mercury	µg/g	5	0.0	0.0	0.037	0.019	0.043	0.04	0.082	0.072

n.d.: not determinable

[1)] according to German Guideline “Verwendung von siliziumreicher Flugasche und Kesselsand in Betonbauteilen in Kontakt mit Boden, Grundwasser oder Niederschlag“

The results of the leaching test were performed in accordance with CEN/TS 16637-2 and are summarized in **Figure 48**. The results show no significant leaching of trace elements and are in agreement with the German Guideline “Verwendung von siliziumreicher Flugasche und Kesselsand in Betonbauteilen in Kontakt mit Boden, Grundwasser oder Niederschlag”.

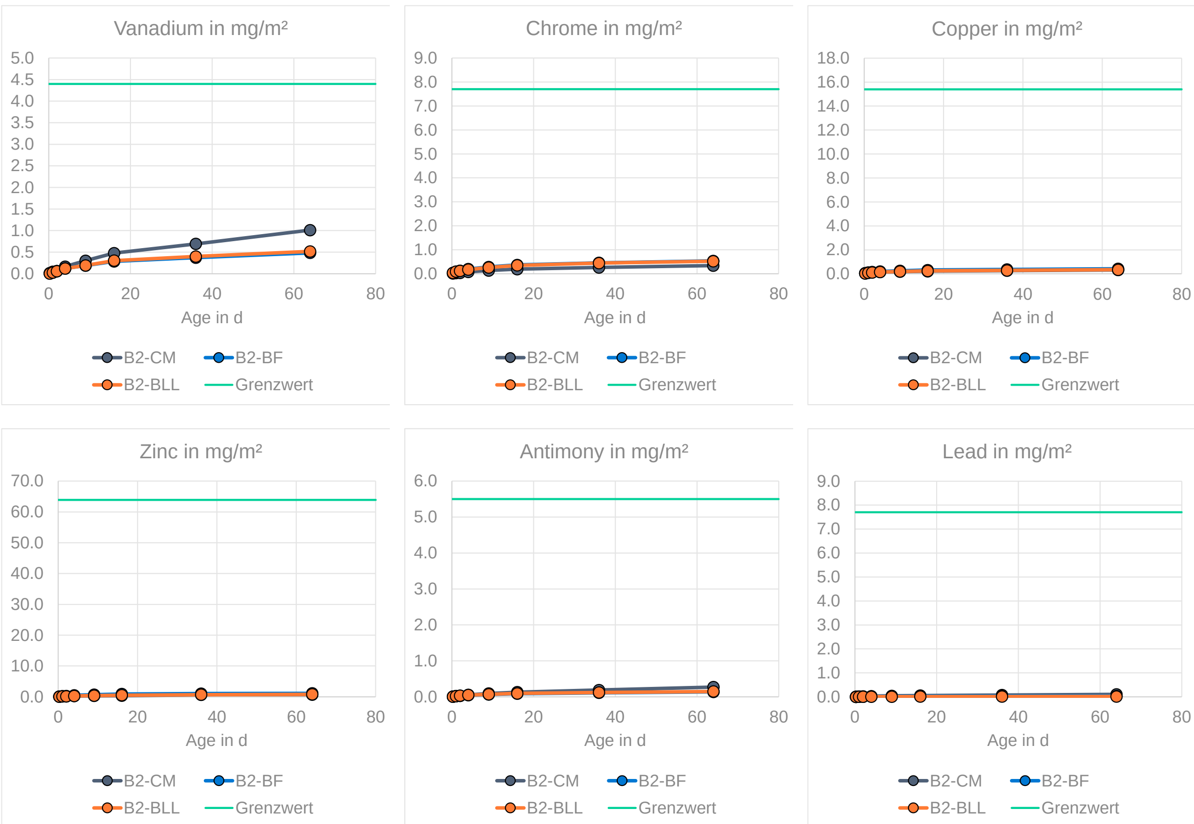


Figure 48 Leaching of dangerous substances

8.2.3 Belgium

Resistance to Carbonation (EN 13295) with 1% CO_2 storage

The resistance to carbonation is measured according to the European standard EN 13295 with 1% CO_2 storage. The results for the concrete mixtures of C1 recipe are given in **Table 63** and illustrated in **Figure 49**. The mixtures containing the industrial recycled products with 35% substitution rate are similar to reference 2.

Table 63 Resistance to carbonation according to EN 13295

		Carbonation depth [mm]		
		0d	**28d**	**56d**
C1	CC1R1	0	2.8	3.5
	CC1R2	0	6.5	9.0
	CC1Rec1_20	0	3.8	5.8
	CC1Rec1_35	0	6.2	8.5
	CC1Rec2_20	0	3.8	5.5
	CC1Rec2_35	0	6.2	8.8
	CC1Rec3_20	0	3.5	6.0
	CC1Rec3_35	0	6.5	9.8

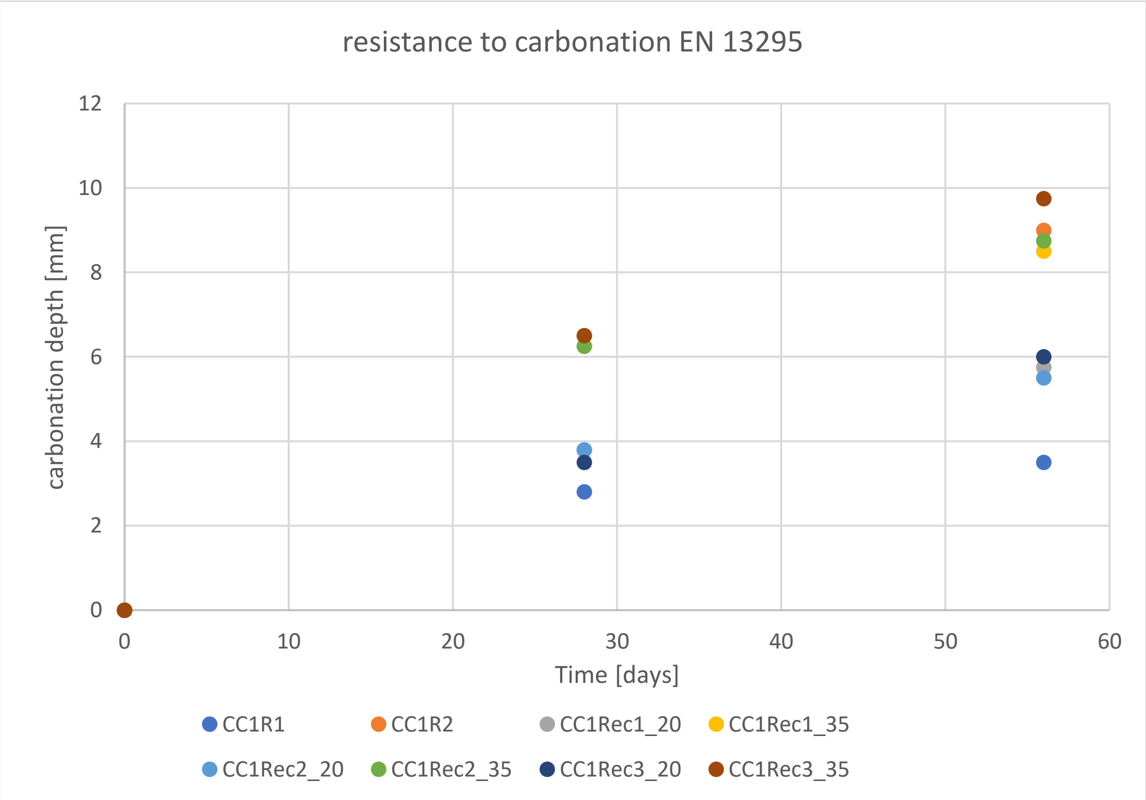


Figure 49 Illustration of the C1 concrete resistance to carbonation for the different concrete mixtures.

Freeze thaw resistance without de-icing salts

The freeze thaw resistance without de-icing salts is measured according to the standard CEN/TR 15177. The results for the concrete mixtures of C1 recipe are given in **Table 64** and illustrated in **Figure 50**. The mixtures containing the industrial recycled products with 35% substitution rate show better resistance than reference 2.

Table 64 Freeze thaw resistance without de-icing salt according to the standard CEN/TR 15177

		Relative dyn. Modulus of elasticity [%]					
		0 cycles	**7 cycles**	**14 cycles**	**28 cycles**	**42 cycles**	**56 cycles**
C1	CC1R1	100	100	100	98	76	64
	CC1R2	100	86	66	52	42	32
	CC1Rec1_20	100	99	99	99	99	96
	CC1Rec1_35	100	95	91	87	83	75
	CC1Rec2_20	100	100	99	99	99	98
	CC1Rec2_35	100	100	100	96	83	69
	CC1Rec3_20	100	99	99	99	97	90
	CC1Rec3_35	100	98	95	89	83	75

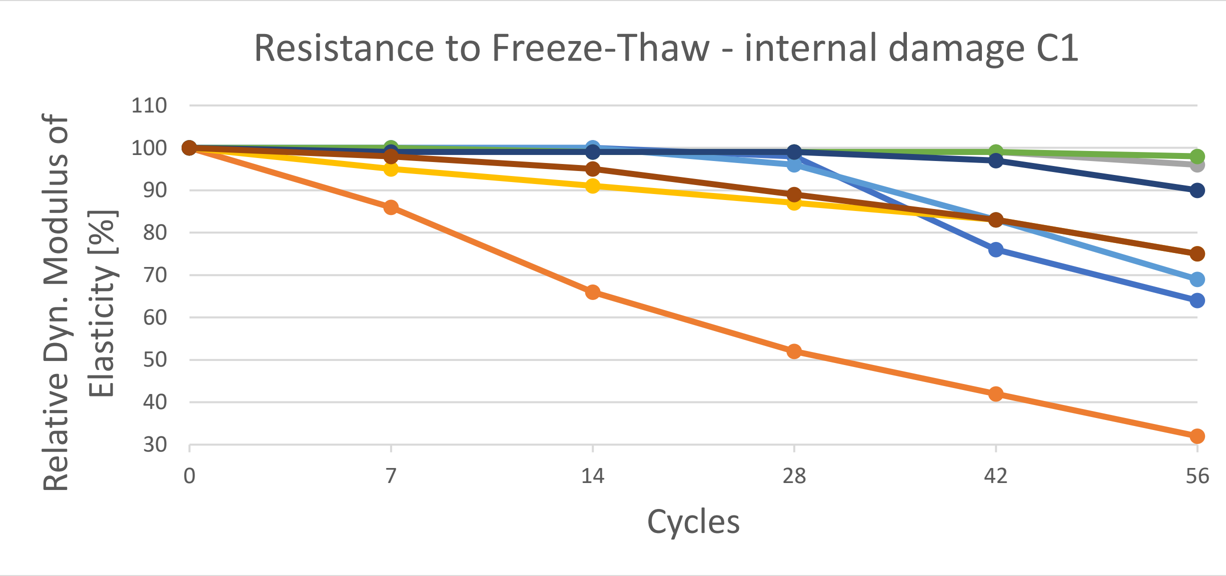


Figure 50 Illustration of the C1 concrete freeze thaw resistance without de-icing salts for the different concrete mixtures

Freeze thaw resistance with de-icing salts

The freeze thaw resistance with de-icing salts is measured according to the standard CEN 12390-9. The results for the concrete mixtures of C2 recipe are given in **Table 65** and illustrated in **Figure 51.** The mixtures containing the industrial recycled products with 35% substitution rate show similar or better performance than reference 2.

Table 65 Scaling after 56 freeze thaw cycles with de-icing salt according to CEN 12390-9

		Scaling [kg/m²]					
		0 cycles	**7 cycles**	**14 cycles**	**28 cycles**	**42 cycles**	**56 cycles**
C2	CC2R1	0	0.05	0.09	0.10	0.17	0.19
	CC2R2	0	0.58	1.11	1.50	2.75	3.24
	CC2Rec1_20	0	0.57	1.07	1.50	1.78	2.15
	CC2Rec1_35	0	0.86	1.51	2.30	2.78	3.35
	CC2Rec2_20	0	0.18	0.31	0.44	0.51	0.57
	CC2Rec2_35	0	0.23	1.16	1.87	2.20	2.38
	CC2Rec3_20	0	0.18	0.29	0.49	0.61	0.67
	CC2Rec3_35	0	0.20	0.34	0.50	0.62	0.71

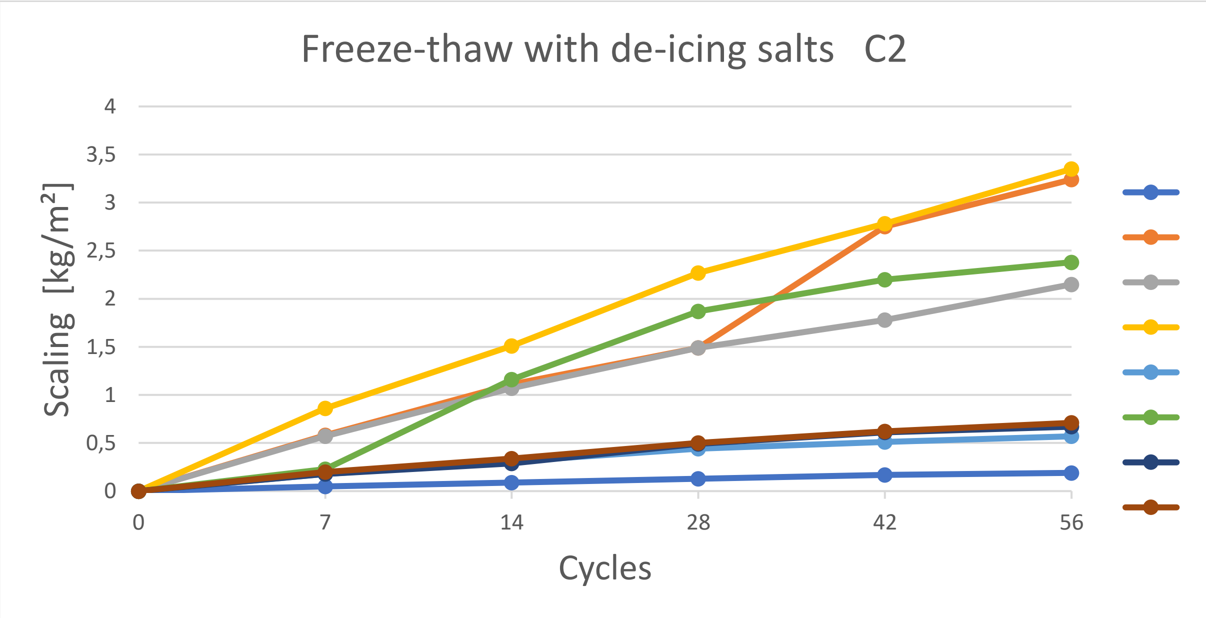


Figure 51 Illustration of the C2 concrete freeze-thaw resistance for the different concrete mixtures

Chloride diffusion

Chloride diffusion is measured according to the standard EN 12390-11. The results for the concrete mixtures of C1 recipe are given in **Table 66** and illustrated in **Figure 52.** There were difficulties in obtaining the result for the reference 2 sample and most likely the obtained result is not representative for the cement sample. Both research partners show a comparable result which is much higher. Therefore, it is better to compare the obtained result with their findings. Based on this understanding, it is found that the mixtures containing the industrial recycled products with 35% substitution rate show better performance than reference 2.

Table 66 Overview of the C1 concrete chloride diffusion according to EN 12390-11 for the different concrete mixtures

		Chloride diffusion EN 12390-11	
		D_{nss} [x10^{-12} m²/s]	C_s [M.% concrete]
C1	CC1R1	8.84	0.384
	CC1R2	12.49	0.172
	CC1Rec1_20	11.80	0.198
	CC1Rec1_35	14.12	0.123
	CC1Rec2_20	9.50	0.148
	CC1Rec2_35	10.05	0.241
	CC1Rec3_20	9.41	0.147
	CC1Rec3_35	11.50	0.182

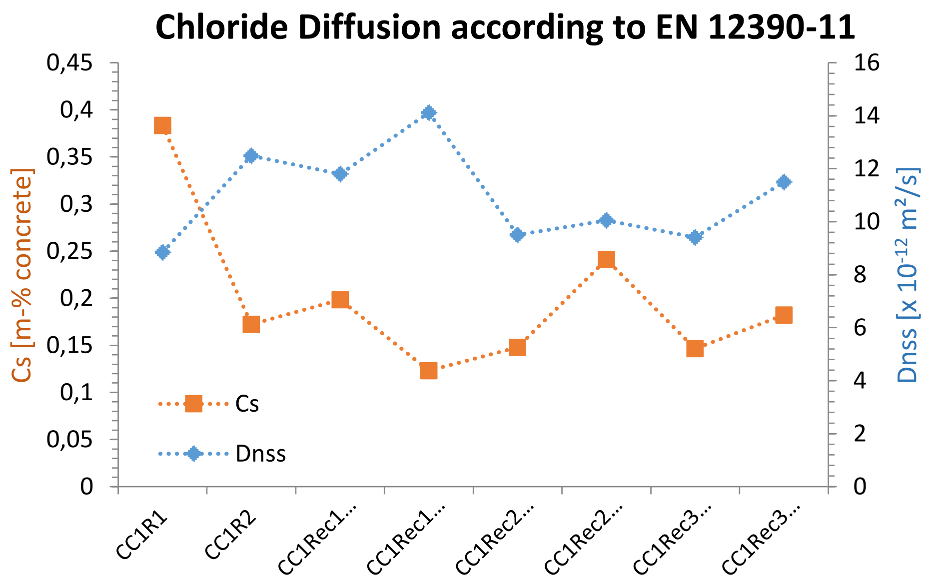


Figure 52 Illustration of the C1 concrete chloride diffusion for the different concrete mixtures

Leaching tests in accordance with CEN/TS 16637-2

Although the leaching test samples are made and available for testing, no results can be shown. The reason for this is a malfunctioning ICP device which is crucial to perform the analysis.

9 WP 7: Establishment of common performance criteria and reporting

9.1 WP 7.1: Establishment of common performance criteria for the cements

On the basis of the results of the project partners (WP5, WP6) following relevant criteria for the use of recycling fines in the cement production can be summarized:

Compressive strength:

The results of the partners established, that the compressive strength of the laboratory cements is in the same range than the reference CEM II/B-LL and/or a little higher. The cements showed constant performance and therefore are suitable for a future commercial use on the level of compressive strength.

Freeze-thaw resistance:

The results of freeze-thaw resistance of the partners, with and without de-icing salt, fluctuate depending on the test method and are therefore not easy to estimate. The freeze-thaw resistance with de-icing salt showed better fitting results were the cements with the use of recycling fines mostly do not catch the requirements of the national standards. At this point, optimizations are necessary for the future commercial use.

Resistance to carbonation:

All of the investigated cements show carbonation depths between the references CEM I and CEM II/B-LL. These results indicate little favourable properties of fines in comparison with limestone.

Resistance to chloride:

Also, the chloride diffusion coefficient (D_{nss}) of the concrete receipts C1 settles between the reference cements CEM I and CEM II/B-LL which indicates a little increase of the chloride resistance of the recycling fines in comparison to limestone.

Environmental compatibility

On the basis of the results of the leaching tests, possibly occurring contamination of the environment can be excluded.