Carinthia University of Applied Sciences

Work Package 4: Reuse Options

Cleanstone Project

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Università degli Studi di Padova

Carinthia University of Applied Sciences

Confartigianato Vicenza

E.C.O. Institut für Ökologie

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Work Package 4: Reuse options

In order to evaluate the reuse options, it is important to carry out physico-chemical analyses with the aim of defining the direction of the investigation. The materials collected from quarries are currently considered as waste by the companies. In the present document, these materials will be called 'secondary materials' considering the high potential of reuse of these by-products. The physico-chemical analysis provided by each company can be consulted in Annexes 1, 2 and 3. Annex 4 contains a scientific publication related with the reuse of secondary waste materials of quarries in Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) that was published by the Carinthia University of Applied Sciences.

Annex 1: contains the physico-chemical analysis of Diabase stone and its aggregates. The report was made by the company TPA Gesellschaft für Qualitätssicherung und Innovation GmbH. This report was provided by the company Mineral Abbau GmbH Jakoministeinbruch Bleiberg.

Annex 2: contains the physico-chemical analysis of Dolomite stone and its aggregates. The report was made by the company TPA Gesellschaft für Qualitätssicherung und Innovation GmbH. This report was provided by the company Mineral Abbau GmbH - Steinbruch Lahntal.

Annex 3: contains the physico-chemical analysis of Pietra Piasentina stone and its aggregates. The report was made by the Ceramics and Construction Material's group from the University of Udine.

Annex 4: contains the scientific publication 'REUSE OF SECONDARY MATERIALS FROM QUARRIES AS AGGREGATES IN ULTRA HIGH PERFORMANCE CONCRETE'. This document was published by the team of the Laboratory of Building Materials from the Carinthia University of Applied Sciences.

Physical and chemical test protocols of the secondary materials

In order to identify the potential reuse possibilities of quarry materials, the following test protocol is suggested:

Chemical analysis: The chemical analysis provides information about the concentration of minerals and chemical elements, pH values and a list of parameters that can be useful to define which are the suitable reuse options. These analyzes also predict the presence of toxic substances in the material. (EN 15002)

Frost resistance: this test describes the mechanical and physical properties of the natural aggregates used for unbound base courses in road construction exposed to frost action and provides information on the possible usage of the material in road construction. (ÖNORM B 4810)

Carbonate content: this test determines the concentration of carbonate present in stones. This test is important since some stones could have a weak structure and could be easily breakable under low mechanical force due to the high concentration of carbonate. (ÖNORM L 1084)

Particle size distribution analysis: the particle size distribution gives information about the range of size of the material. This information is useful to evaluate the possible reuse options, for example in concrete or other construction materials. (ÖNORM EN 933-1, ÖNORM EN ISO 17892-4)

Mineralogy and Petrography: the petrography study gives information on the origin of the stone and the geographical location including orographical data and the regional geology data. The geological data gives information about the different strata of the rock massif. Regarding mineralogy, an X-Ray diffraction analysis (XRD) is performed to identify the crystalline phases in a material and the chemical composition. This analysis provides a list of minerals present in the stone and the concentration of each one. (ÖNORM EN 932-3)

Uniaxial compression strength test of natural stone: this test gives information about how resistant to compression strength a rock is. The secondary materials from hard rocks with high compressive strength could inherit these properties resulting in hard grains and thus transferring these properties for example to concrete mixes made out of secondary materials. The harder the grains of the secondary material are, the higher will be the compression strength of the concrete made with them. (ÖNORM EN 1926)

Determination of radioactive elements: the identification of Kalium-40, Radium-226 and Thorium-232 is important to ensure that the products that could be potentially made out of secondary materials like concrete, cannot be dangerous for the human health. (ÖNORM S 5200)

Physical and chemical characterization of the secondary materials

Introduction

Fig. 1: Secondary materials collected from quarries

The materials collected from the quarries were the following: Diabase Sand and Diabase Sludge from Bad Bleiberg, Carinthia, Austria; Dolomite Sand and Dolomite Gravel from Wörgl, Tyrol, Austria and Limestone Sludge from Udine, Friuli Venezia Giulia, Italy. Some of these are considered waste due to different reasons. In the case of Diabase Sand 0/2 mm, high amounts of particles passing 0,063 mm sieve are generated during the crushing process of the stone, making this sand not suitable for road construction. Hence, the sand undergoes a washing process to remove the fine particles. As a residue of this process, Diabase Sludge is obtained. Moreover, the Diabase Sludge was dried at 90°C for 24 hours and ground to get Diabase Powder as an aggregate, the particle size of this powder was analyzed. In Fig. 3 it is possible to see the Diabase sludge in the original condition. The sludge after drying in the oven and grinding is the material named as 'Diabase powder' in Fig. 1. Regarding Dolomite Sand 0/2 mm and Gravel 2/4 mm, they are discarded since these sizes are produced in excess during the crushing process (see Fig. 1). As regards Limestone Sludge (see Fig. 2), it is obtained from the cutting process of stone blocks, where a shower of water is used to avoid heating the sawing machine blades, generating a solution of rock sawdust and water. After a sedimentation process, the sludge is obtained. For this investigation, the sludge was dried at 90°C for 24 hours and ground to get Limestone Powder as an aggregate. In Fig. 2 it is possible to see the Limestone sludge in the original condition. The sludge after drying and grinding it, the material is named as 'Limestone Powder' in Fig. 1.

Fig. 2: Limestone Sludge

Fig. 3: Diabase Sludge

Chemical and physical analysis

Regarding the chemical and physical properties, different types of analysis were performed on the different materials. The reason why not all materials were subjected to the same tests is mainly because the materials were collected at different times from the quarries, different reuse options were considered and tested throughout the project and also because the materials obtained are of different origin, chemical/mineralogical composition and different grain size distribution.

Particle size of the secondary materials

The particle size of the following secondary materials is shown in Fig. 4: Diabase Sand (0/2 mm); Diabase Powder (d10= 3.5300 µm, d90= 135.1871 µm); Dolomite Sand (0/2 mm); Dolomite Gravel (2/4 mm); Limestone Powder (d10= 0.2975 µm, d90= 21.8949 µm). Where d10 is the portion of particles with diameters smaller than this value is 10% and d90 is the portion of particles with diameters below this value is 90%.

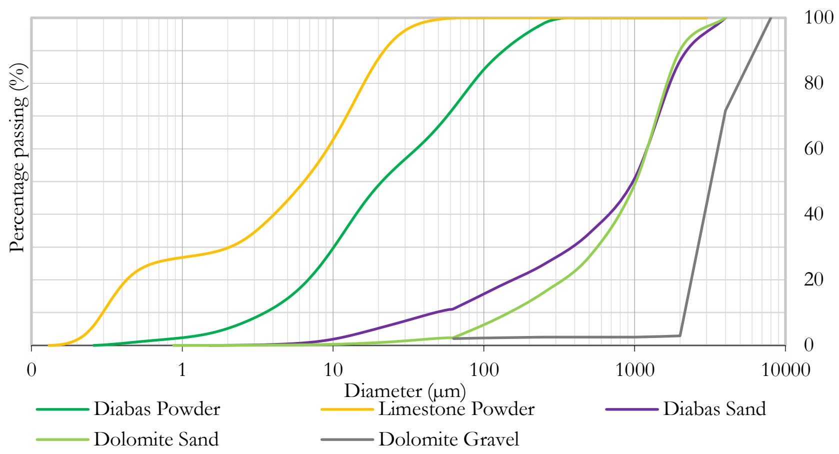


Fig. 4: Particle size distribution of the secondary materials

The particle size distribution of the Diabase Sand (0/2 mm); Dolomite Sand (0/2 mm); Dolomite Gravel (2/4 mm) was made by the procedure described by the ÖNORM EN ISO 17892-4. The serie of sieves used for this essay were the following: 4 mm; 2 mm; 1 mm; 0,5 mm; 0,250 mm; 0,125mm; 0,063mm produced according to the ISO 565 DIN ISO 3310-1 norms. The finest particles passing the sieve 0,063mm from Diabase Sand and Dolomite Sand were collected and sent to analyze with X-Ray diffraction analysis (XRD) to obtain the concentration of each size and complete the particle size distribution curve made with the sieves. The particle size of the finest materials like Diabase Powder and Limestone Powder were analyzed with X-Ray diffraction analysis (XRD). Particle size distribution (PSD) was determined by a Horiba LA950 laser scattering particle size analyzer. Analyses were made in water after 1 min sonication.

Identification of reuse options

Regarding the possible reuse options, the following chart shows an overview of in which industries, the secondary materials could be reused:

Tab. 1: Reuse options

Secondary material	Possible usage
Julia Marmi Calcium Carbonate Limestone	Paper Stone Industry and Normal Paper Industry
	Cement industry
	Production of Lime
	White Powder is used in make up products, medication (pharmacy industry), paints, toothpaste, etc
	Landscape purposes (Soil conditioner/gardening)
	Ultra High Performance Concrete (UHPC): Replacement of Fillers
	Normal Strength Concrete/Mortar: Replacement of normal sand
	Facade elements
	Concrete Bricks
	Rubber industry
Diabas Sand with high amount of fine powder/Diabas Powder	Normal Strength Concrete/Mortar: Replacement of normal sand
	Ultra High Performance Concrete (UHPC): Replacement of Fillers
	Polymer concrete
	Landscape purposes (Soil conditioner/gardening)
	Facade elements
Dolomite Magnesian Limestone gravel and sand	Normal Strength Concrete/Mortar: Replacement of normal sand/gravel
	Glass industry
	Polymer Concrete
	Cement industry
	Pulverized limestone is used as a soil conditioner to neutralize acidic soils (Agricultural lime)
	Gravel can be used for Asphalt concrete
	Fine white powder is added to toothpaste, paper, plastics, paint, tiles as both white pigment and cheap filler.
	Used for remineralizing and increasing the alkalinity of purified water to prevent pipe corrosion and to restore essential nutrient levels.
	Used in blast furnaces, limestone binds with silica and other impurities to remove them from the iron.

Diabase Sand: Mortar Samples

Diabase Sand 0/2 mm contains high amounts of particles passing 0,063 mm sieve which are generated during the crushing process of the stone, making this sand not suitable for road construction. Hence, the sand undergoes a washing process to remove the fine particles. As a residue of this process, Diabase Sludge is obtained and discarded. Currently, the quarry uses washed Diabase Sand for road construction since the particle size of it without the fine aggregates fits in the requirements of the standards. The following test was made to check the behaviour of Diabase Sand in different mortar pastes with varying ratios of replacements and water-cement ratio. For this test, the quarry provided two types of sand: washed Diabase Sand and non-washed Diabase Sand. Non-washed Diabase Sand contains higher amount of fine aggregates than washed Diabase Sand. The goal was to make a reference sample of mortar with 100% of normal sand commercialized in the Austrian market and compare the values of compressive strength and flexural strength with samples that have replacements of normal sand by the Diabase Sand in the following ratios: 0%, 25%, 50%, 75%, 100%. All mortar samples were prisms of 160 x 40 x 40 mm and were cured in water. Compressive and flexural strength tests were performed on mortar samples containing:

- Washed Diabas Sand samples without superplasticizer
- Non-washed Diabas Sand samples without superplasticizer
- Non-washed Diabas Sand samples with superplasticizer

Washed Diabase Sand mortar

Tab. 2: Washed Diabase Sand

Washed Diabas Sand Replacements without Superplasticizer					
Material	Sample 0% (REF)	Sample 25%	Sample 50%	Sample 75%	Sample 100%
Replacement Diabas (%)	0	25	50	75	100
Water/cement ratio	0.7	0.7	0.7	0.7	0.7
Cement (kg/m3)	350	350	350	350	350
Normal Sand 0/4 mm (kg/m3)	1719.30	1289.48	859.65	429.83	0.00
Washed Diabase Sand 0/2 mm (kg/m3)	0.00	429.83	859.65	1289.48	1719.30

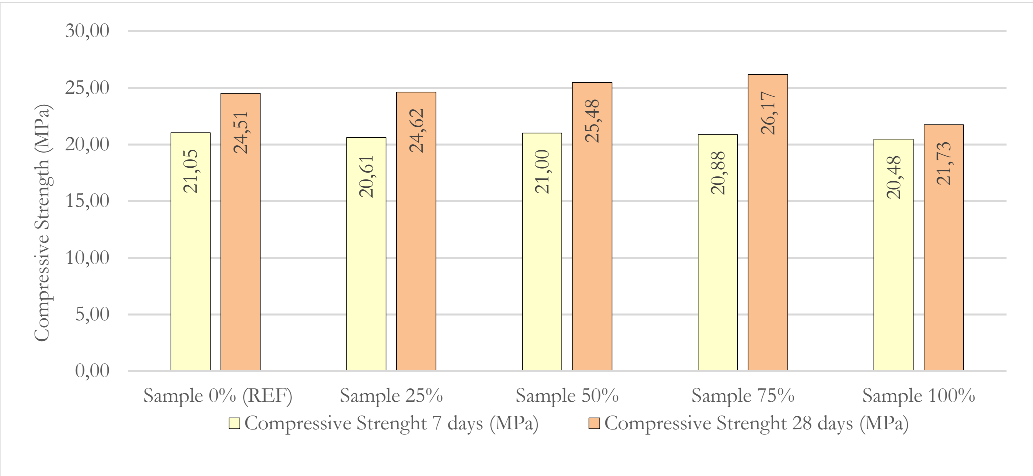


Fig. 5: Compressive strength results

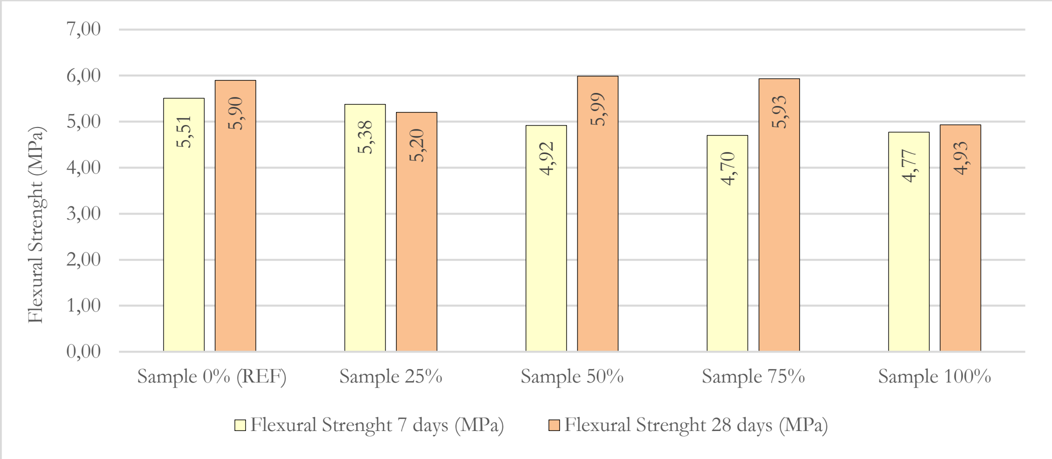


Fig. 6: Flexural strength results

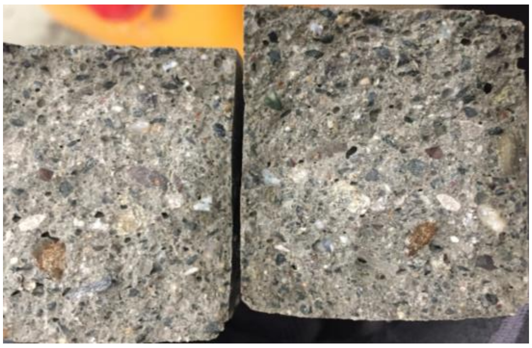


Fig. 7: 25% Sand replacement

Regarding to the compressive strength, some of the values decreased as the replacement of washed Diabase Sand increased. The values of compressive strength of samples made with normal sand are very similar to those made with washed Diabase Sand at 7 and 28 days. However, none of the values reached the compressive strength values recommended by the ÖNORM EN 197-1 in Chapter 7.1.2. Table 3 (see Fig. 8. from this report). All the values of compressive strength at 28th day are lower than the value of 42,5 MPa at 28th day according to the type of cement used. This could be due to the high water cement ratio (w/c) of 0,7. This w/c ratio was chosen in order to check how much water was necesary to mix the paste without using superplasticizer. In order to reduce the w/c and get higher compressive strength, superplasticizer was used in the batches made afterwards.

Strength class	Compressive strength MPa				Initial setting time	Soundness (expansion)
	Early strength		Standard strength			
	2 days	7 days	28 days		min	mm
32,5 L [a]	–	≥ 12,0	≥ 32,5	≤ 52,5	≥ 75	≤ 10
32,5 N	–	≥ 16,0				
32,5 R	≥ 10,0	–				
42,5 L [a]	–	≥ 16,0	≥ 42,5	≤ 62,5	≥ 60	
42,5 N	≥ 10,0	–				
42,5 R	≥ 20,0	–				
52,5 L [a]	≥ 10,0	–	≥ 52,5	–	≥ 45	
52,5 N	≥ 20,0	–				
52,5 R	≥ 30,0	–				

[a] Strength class only defined for CEM III cements.

Fig. 8: Characteristic values of cement mortars (ÖNORM EN 197-1, Chapter 7.1.2. Table 3)

Non-washed Diabase Sand mortar w/c 0,7

Tab. 3: Non-washed Diabase Sand

Non-washed Diabase Sand							
Material	Sample 0% (REF)	Sample 25%	Sample 50%	Sample 75%	Sample 100%	Sample 50% + SP	Sample 100% + SP
Replacement Diabas (%)	0	25	50	75	100	50	100
Water/cement ratio	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Cement (kg/m³)	350	350	350	350	350	350	350
Normal Sand 0/4 mm (kg/m³)	1719.30	1289.48	859.65	429.83	0.00	859.65	0.00
Non washed Diabase Sand 0/2 mm (kg/m³)	0.00	429.83	859.65	1289.48	1719.30	859.65	1719.30

The second batch was made with non-washed Diabase Sand. The main purpose of this research is to find a solution for reusing the non-washed Diabase Sand obtained primarily, since the washing process of the sand is expensive. Regarding the slump test, it was observed that as the increase of non-washed Diabase Sand replacement was made, the slump values decreased. Therefore, two of the samples (sample 50 %/100 % + SP in Table 3) were made with superplasticizer (SP) to get a better consistency of the mixture. The results showed that adding superplasticizer increases the workability, the compressive and flexural strength. The amount of superplasticizer used was 1 ml per 1 litre mixed, this is a minimum dose of superplasticizer. The superplasticizer used was Sika ViscoCrete 20 Gold High-Performance Superplasticizer produced under the ÖNORM EN 934-2. The density of this superplasticizer is: 1,06 g/cm³ and the Dosage is 0,2–2,5 % by weight of cement/binder. The values of compressive strength didn't reach 42,5 MPa at 28 days, that's why after trying the efficient behavior of the superplasticizer, it was decided to mix a new batch reducing the w/c ratio.

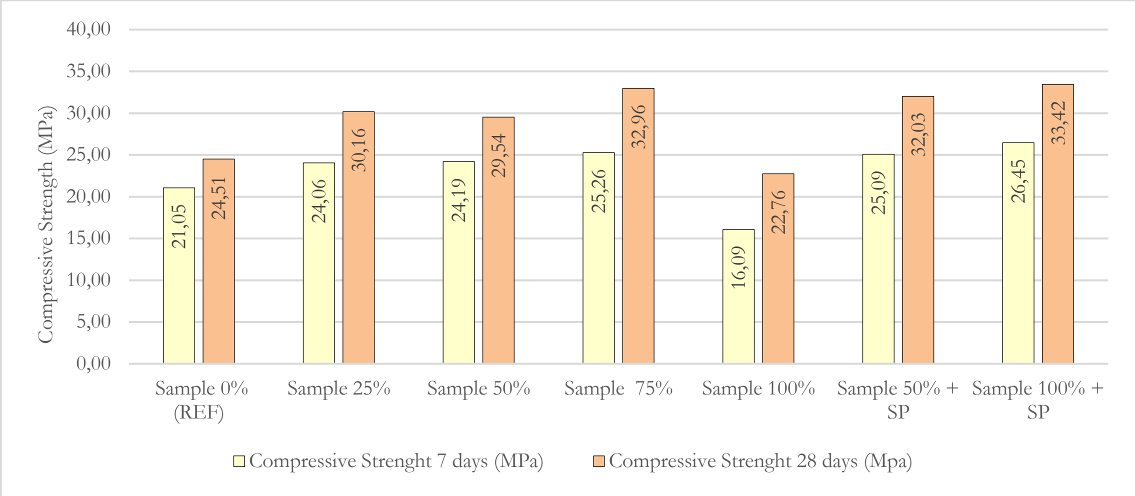


Fig. 9: Compressive strength results non-washed Diabase Sand

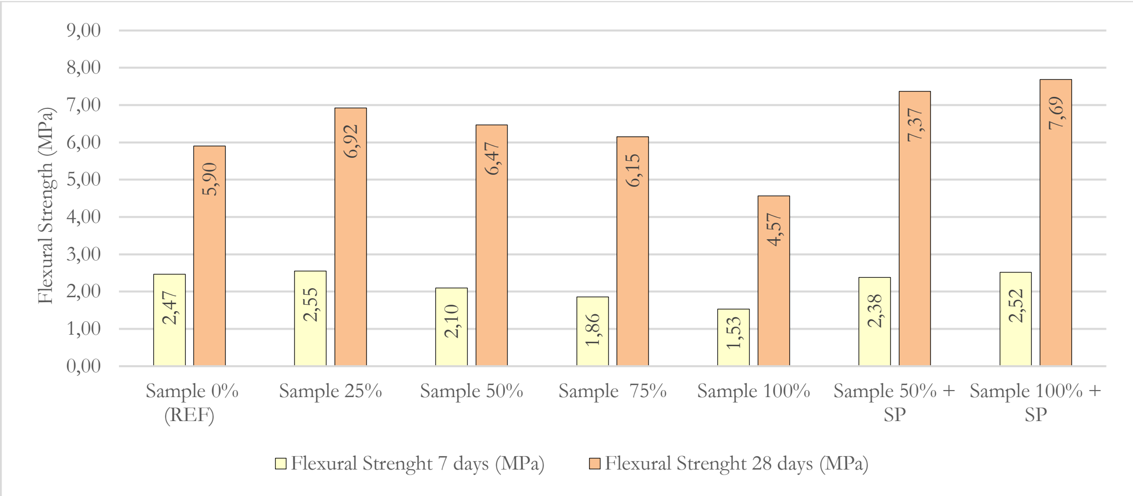


Fig. 10: Flexural strength results washed Diabase Sand

Non-washed Diabase Sand Mortar w/c 0,5

This batch was casted with a 0,5 w/c ratio. The goal was to check the behaviour of the mixture with the usage of superplasticizer while trying a lower w/c ratio.

Tab. 4: Non-washed Diabase Sand with superplasticizer and w/c 0,5

Non washed Diabase Sand				
Material	Sample 0% (REF)	Sample 50% + SP	Sample 75% + SP	Sample 100% + SP
Replacement Diabas (%)	0	50	75	100
Water/cement ratio	0.5	0.5	0.5	0.5
Cement (kg/m3)	450	450	450	450
Normal Sand 0/4 mm (kg/m3)	1350.00	675.00	337.50	0.00
Non Washed Diabase Sand 0/2 mm	0.00	675.00	1012.50	1350.00
Superplasticizer (ml/450 gr cement) (SP)	0.00	1.27	1.27	1.70

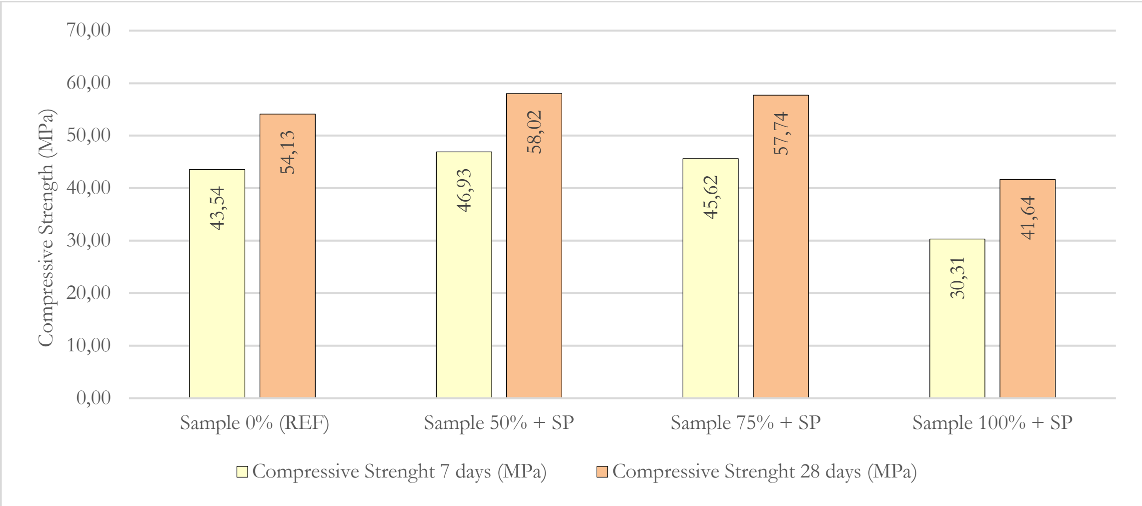


Fig. 11: Compressive strength results non-washed Diabase Sand

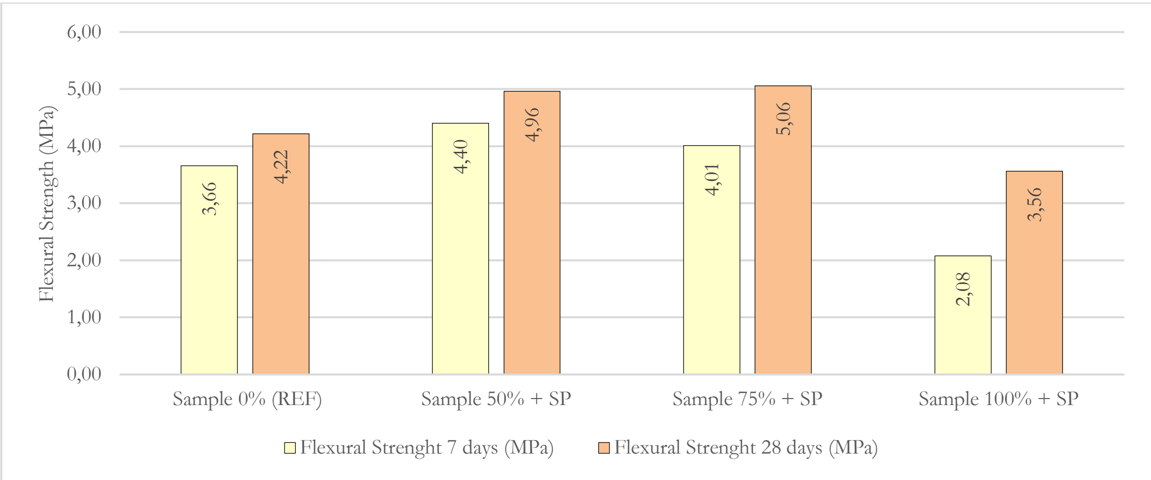


Fig. 12: Flexural strength results non-washed Diabase Sand

Mortar samples: Conclusions

The results of compression strength shown in Fig. 11 were higher than 42,5MPa at 28 days. However, the sample with 100 % replacement of non-washed Diabase Sand has a lower value of compression strength since its workability was low, as it was possible to check through the mini-slump cone test during casting. The spread diameter value was 97mm. Thus, a 100% replacement of the sand is not recommendable. The samples considered acceptable are those with 50 % and 75 % replacement since they also showed better workability and values of spread diameter above 140mm. The usage of superplasticizer made the reduction of the w/c ratio possible. This improved the workability, the compressive strength and the flexural strength.

Normal Strength Concrete

Particle size analysis for Normal Strength Concrete

Particle size analysis of non-washed Diabase Sand

With the aim to prove that non-washed Diabase Sand was suitable as a fine aggregate for Normal Strength Concrete, five particle size analysis were performed. The samples were taken from the upper, middle and bottom part of a 1 m^3 bag (see Fig. 13) that was brought by the company to check if the particle size is uniform along the different parts. The results from the sieving analysis of non-washed Diabase Sand following the procedures described by ÖNORM EN ISO 17892-4 are shown in Fig. 14.

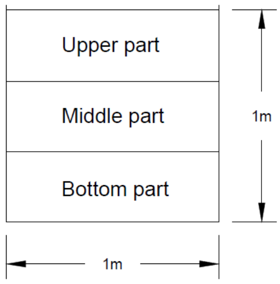
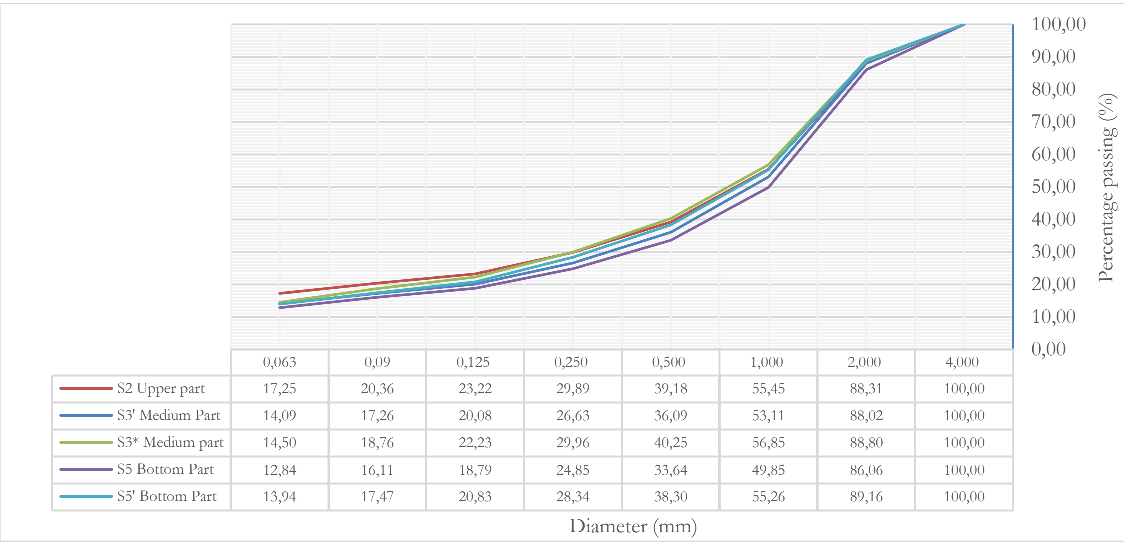


Fig. 13: Upper, middle and bottom part of the bag



	0,063	0,09	0,125	0,250	0,500	1,000	2,000	4,000
S2 Upper part	17,25	20,36	23,22	29,89	39,18	55,45	88,31	100,00
S3' Medium Part	14,09	17,26	20,08	26,63	36,09	53,11	88,02	100,00
S3* Medium part	14,50	18,76	22,23	29,96	40,25	56,85	88,80	100,00
S5 Bottom Part	12,84	16,11	18,79	24,85	33,64	49,85	86,06	100,00
S5' Bottom Part	13,94	17,47	20,83	28,34	38,30	55,26	89,16	100,00

Fig. 14: Particle Size non washed Diabase Sand

Tab. 5: Particle size non-washed Diabase Sand

S2 Upper Part		S3* Medium Part		S3' Medium Part		S5 Bottom Part		S5' Bottom Part	
Sieve size (mm)	Passing accum. (%)	Sieve size (mm)	Passing accum. (%)	Sieve size (mm)	Passing accum. (%)	Sieve size (mm)	Passing accum. (%)	Sieve size (mm)	Passing accum. (%)
4.000	100.00	4.000	100.00	4.000	100.00	4.000	100.00	4.000	100.00
2.000	88.31	2.000	88.80	2.000	88.02	2.000	86.06	2.000	89.16
1.000	55.45	1.000	56.85	1.000	53.11	1.000	49.85	1.000	55.26
0.500	39.18	0.500	40.25	0.500	36.09	0.500	33.64	0.500	38.30
0.250	29.89	0.250	29.96	0.250	26.63	0.250	24.85	0.250	28.34
0.125	23.22	0.125	22.23	0.125	20.08	0.125	18.79	0.125	20.83
0.09	20.36	0.09	18.76	0.09	17.26	0.09	16.11	0.09	17.47
0.063	17.25	0.063	14.50	0.063	14.09	0.063	12.84	0.063	13.94

After comparing the sieving curves in Fig. 14, it can be seen that there is a certain uniformity of particle size along the different places of the bag. In some parts the percentage of material passing the sieve 0,063 mm is higher than 12 %, reaching to values of 17,25 %. This means that the material has high amounts of very fine powder. In order to check if the sieving analysis of non-washed Diabas was suitable for concrete, a comparison with the recommended particle size curves of aggregates for concrete from the ÖNORM 4710-1 was made:

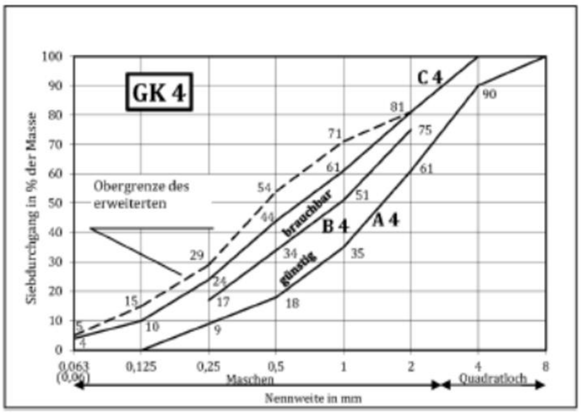


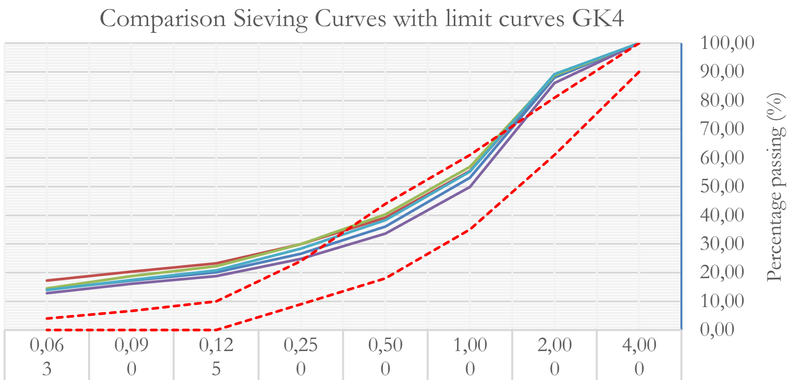
Fig. 15: Sieving curves max. grain size of 4 mm (ÖNORM 4710-1)

Tab. 6: Sieve analysis recommended in the standard: GK4 (maximum grain size 4 mm)

	Lower limit line A4	Upper limit line C4
Sieve size (mm)	Passing accum. (%)	Passing accum. (%)
4.000	90.00	100.00
2.000	61.00	81.00
1.000	35.00	61.00
0.500	18.00	44.00
0.250	9.00	24.00
0.125	0.00	10.00

0.090	0.00	6.61
0.063	0.00	4.00

The five curves of the particle size analysis made with non-washed Diabase Sand were compared with the lower limit curve and the upper limit curve recommended by the ÖNORM 4710-1 as shown in Fig. 16.



	0,063	0,090	0,125	0,250	0,500	1,000	2,000	4,000
S2 Upper part	17,25	20,36	23,22	29,89	39,18	55,45	88,31	100,00
S3' Medium Part	14,09	17,26	20,08	26,63	36,09	53,11	88,02	100,00
S3* Medium part	14,50	18,76	22,23	29,96	40,25	56,85	88,80	100,00
S5 Bottom Part	12,84	16,11	18,79	24,85	33,64	49,85	86,06	100,00
S5' Bottom Part	13,94	17,47	20,83	28,34	38,30	55,26	89,16	100,00
LOWER - Passing accum. (%)	0,00	0,00	0,00	9,00	18,00	35,00	61,00	90,00
UPPER - Passing accum. (%)	4,00	6,61	10,00	24,00	44,00	61,00	81,00	100,00

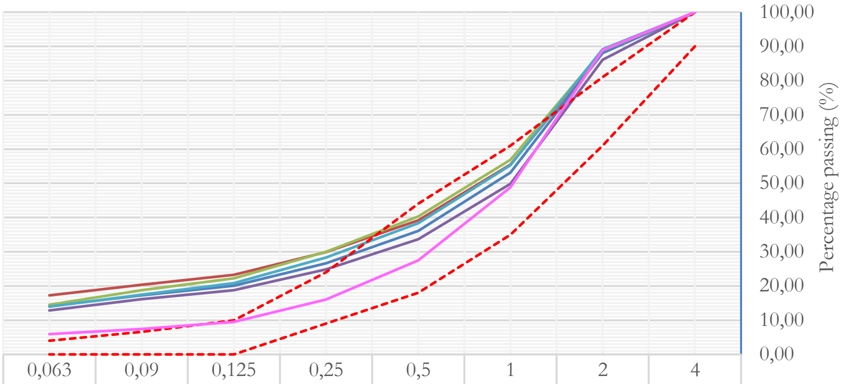
Diameter (mm)

Fig. 16: Comparison of non-washed Diabase Sand with the ÖNORM GK4

Fig. 16 shows two limit distribution curves (traced red) in which sieving curves of the materials to be tested should fit in to produce concrete. As it can be seen, non-washed Diabase Sand does not fit in completely into this limit curves due to the high percentage of fine particles.

Particle size analysis of washed Diabase Sand

Since Diabase Sand is used for road construction, the sand goes through a washing process in order to wash the fine particles out and fit into the recommended curves. The sieving curve from washed Diabase Sand was also graphed and compared with the curves from the standards. Fig. 17 shows the sieving curve of washed Diabas Sand used for road construction in magenta. It can be seen that this grain distribution fits in the recommended curves but in the upper part, around 2mm particle size, it is out of the borders.



	0,063	0,09	0,125	0,25	0,5	1	2	4
S2 Upper part	17,25	20,36	23,22	29,89	39,18	55,45	88,31	100,00
S3' Medium Part	14,09	17,26	20,08	26,63	36,09	53,11	88,02	100,00
S3* Medium part	14,50	18,76	22,23	29,96	40,25	56,85	88,80	100,00
S5 Bottom Part	12,84	16,11	18,79	24,85	33,64	49,85	86,06	100,00
S5' Bottom Part	13,94	17,47	20,83	28,34	38,30	55,26	89,16	100,00
LOWER -Passing accum.(%)	0,00	0,00	0,00	9,00	18,00	35,00	61,00	90,00
UPPER - %Passing acc	4,00	6,61	10,00	24,00	44,00	61,00	81,00	100,00
Washed Diabas 0/2	5,9	7,5	9,5	16,0	27,4	48,8	88,9	100,0

Diameter (mm)

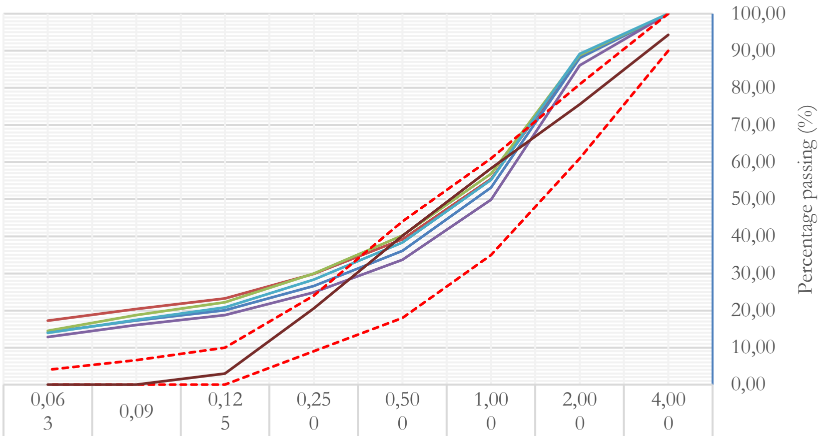
Fig. 17: Comparison of washed diabas sand with the ÖNORM GK4

Tab. 7: Sieve analysis of washed sand

Washed Diabas 0/2 mm	
Sieve size (mm)	Passing accum. (%)
4.000	100.0
2.000	88.9
1.000	48.8
0.500	27.4
0.250	16.0
0.125	9.5
0.090	7.5
0.063	5.9

Particle size analysis of normal river sand

As a comparison, a particle size analysis of the normal river sand (brown curve) commercialized for the production of concrete in Austria from Kostmann Gesmbh was performed. As it can be seen in Fig. 18, the curve fits in with the requirements of the ÖNORM limiting curves.



	0,063	0,09	0,125	0,250	0,500	1,000	2,000	4,000
S2 Upper part	17,25	20,36	23,22	29,89	39,18	55,45	88,31	100,00
S3' Medium Part	14,09	17,26	20,08	26,63	36,09	53,11	88,02	100,00
S3* Medium part	14,50	18,76	22,23	29,96	40,25	56,85	88,80	100,00
S5 Bottom Part	12,84	16,11	18,79	24,85	33,64	49,85	86,06	100,00
S5' Bottom Part	13,94	17,47	20,83	28,34	38,30	55,26	89,16	100,00
LOWER - Passing accum. (%)	0,00	0,00	0,00	9,00	18,00	35,00	61,00	90,00
UPPER - Passing accum. (%)	4,00	6,61	10,00	24,00	44,00	61,00	81,00	100,00
Normal river sand	0,00	0,00	3,00	20,60	40,10	58,30	75,60	94,30

Diameter (mm)

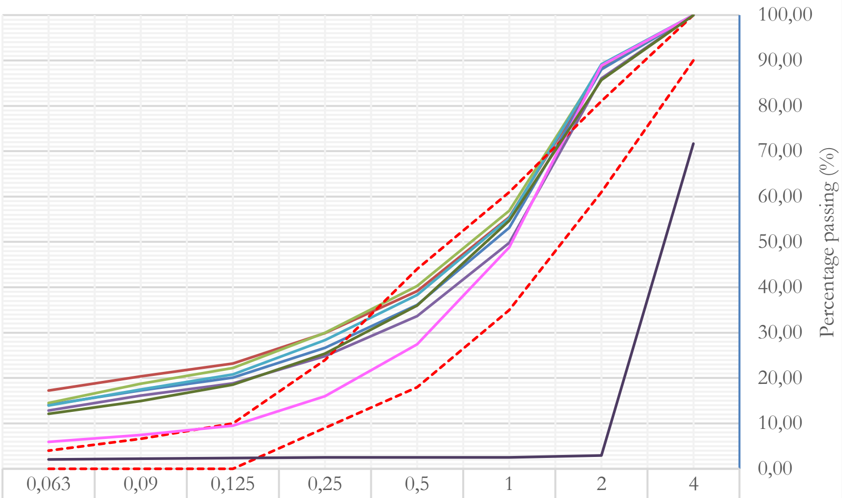
Fig. 18: Comparison of Normal river sand vs. limit curves GK4

Tab. 8: Sieve analysis of Normal river sand Kostmann GesmbH

Sieve size (mm)	Passing accum. (%)
11.2	100.00
8	100.00
4.000	94.30
2.000	75.60
1.000	58.30
0.500	40.10
0.250	20.60
0.125	3.00
0.09	0.00
0.063	0.00

Normal Strength Concrete

A mixture of Normal Strength Concrete (NSC) was designed using the Austrian Standards as a reference trying to follow the particle size recommended by this starndard even though secondary materials from quarries are not considered in this standard. The secondary materials involved in the mixture were non-washed Diabase Sand 0/2 mm, Dolomite sand 0/2 mm and Dolomite Gravel 4/8 mm. The particle size distribution of each material will be shown in the following graph in comparison with the GK4 curves that are listed in the ÖNORM as the limit particle size curves for aggregates for concrete.



	0,063	0,09	0,125	0,25	0,5	1	2	4
Diabas Sand S2 Upper part	17,25	20,36	23,22	29,89	39,18	55,45	88,31	100,00
Diabas sand S3' Medium Part	14,09	17,26	20,08	26,63	36,09	53,11	88,02	100,00
Diabas sand S3* Medium part	14,50	18,76	22,23	29,96	40,25	56,85	88,80	100,00
Diabas sand S5 Bottom Part	12,84	16,11	18,79	24,85	33,64	49,85	86,06	100,00
Diabas Sand S5' Bottom Part	13,94	17,47	20,83	28,34	38,30	55,26	89,16	100,00
LOWER - Passing accum.(%)	0,00	0,00	0,00	9,00	18,00	35,00	61,00	90,00
UPPER - Passing accum.(%)	4,00	6,61	10,00	24,00	44,00	61,00	81,00	100,00
Washed Diabase	5,9	7,5	9,5	16,0	27,4	48,8	88,9	100,0
Dolomite sand	12,12	14,93	18,52	25,39	36,00	54,72	85,73	99,98
Dolomite gravel	2,06	2,25	2,37	2,49	2,51	2,51	2,94	71,67

Fig. 19: Comparison of particle sizes of secondary materials with the ÖNORM GK4

As it can be seen in Fig. 19, the particle sizes of every material don't fit completely these curves. That is why they were mixed in different amounts so they could fit into this curve (see Table 9).

Tab. 9: Particle size distribution of every material and from the mixture

Sieve Size (mm)	Passing accum. (%)										
	Sieve curve Diabase Sand 0/2 mm	Sieve curve Dolomite gravel 4/8 mm	Sieve curve Dolomite Sand 0/2 mm	Sieve curve nomal river sand Kostmann 0/4 mm	Sieve curve Diabase Sand 0/2 mm	Sieve curve Dolomite gravel 4/8 mm	Sieve curve Dolomite Sand 0/2 mm	Sieve curve nomal river sand Kostmann 0/4 mm	**Passing accum. (%)**	Limit curves	
	100%	100%	100%	100%	**60.0%**	**30.0%**	**10.0%**	**0.0%**	**Designed Mix**	LOWER	UPPER
64	100.00	100.00	100.00	100.00	60.00	30.00	10.00	0.00	**100.00**	100	100
45	100.00	100.00	100.00	100.00	60.00	30.00	10.00	0.00	**100.00**	100	100
32	100.00	100.00	100.00	100.00	60.00	30.00	10.00	0.00	**100.00**	100	100
22	100.00	100.00	100.00	100.00	60.00	30.00	10.00	0.00	**100.00**	100	100
16	100.00	100.00	100.00	100.00	60.00	30.00	10.00	0.00	**100.00**	100	100
11	100.00	100.00	100.00	100.00	60.00	30.00	10.00	0.00	**100.00**	100	100
8	100.00	100.00	100.00	100.00	60.00	30.00	10.00	0.00	**100.00**	100	100
4	100.00	71.67	99.98	94.30	60.00	21.50	10.00	0.00	**91.50**	90	100
2	88.80	2.93	85.73	75.60	53.28	0.88	8.57	0.00	**62.73**	61	81
1	56.85	2.51	54.72	58.30	34.11	0.75	5.47	0.00	**40.34**	35	61
0.5	40.25	2.51	36.00	40.10	24.15	0.75	3.60	0.00	**28.50**	18	44
0.25	29.96	2.49	25.39	20.60	17.98	0.75	2.54	0.00	**21.26**	9	24
0.125	22.23	2.37	18.52	3.00	13.34	0.71	1.85	0.00	**15.90**	0	10
0.063	14.50	2.05	12.12	0.00	8.70	0.62	1.21	0.00	**10.53**	0	4

The mixture of the aggregates in the proportion of 60 % of non-washed Diabase Sand 0/2 mm, 10 % of Dolomite Sand 0/2 mm and 30 % Dolomite Gravel 4/8 mm fits in the curve of the GK4 recommended particle size curve for concrete. However, some points are out of these curves, as it can be seen in the Fig. 20. The mixture contains high amounts of fine powders and this is the reason why, it does not fit in every part of the curve. However, the mixture was cast and compressive strength tests were performed.

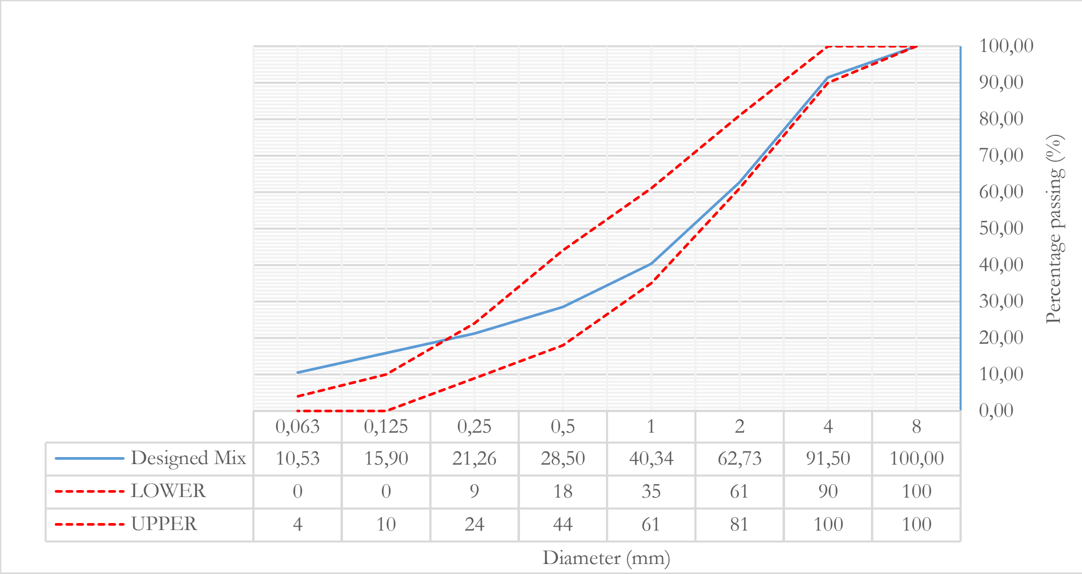


Fig. 20: Particle size of the mixture in comparison with the GK4 particle size

The mixture of concrete was designed for C50/60 and the proportions are the following:

Tab. 10: Mixing proportions

Materials	Mass (kg/m^3)
CEM I 42,5 N	550.59
Dolomite Sand 0/4 mm	157.16
Diabas Sand 0/4 mm	942.96
Dolomite Gravel 2/4 mm	471.48
Water	234.00
Superplasticizer	4.40

The samples cast were cubes of 100 x 100 x 100 mm. The average value of compression strength at 28th day was 73,95 MPa which is considered acceptable according to the values recommended by the ÖNORM B4710-1 [1] (71 MPa at 28th day for concrete class C50/60) as it can be seen in the following table:

Tab. 11: Recommended compressive strength 28 days by ÖNORM B4710-1

Festigkeitsklasse	Mindestdruckfestigkeit von 150-mm-Würfeln				
	Konformitätsprüfung		Eignungsprüfung		
	Einzelprüfung	Mittelwert von jeweils 3 Einzelprüfungen[a]	Mikroprozessorsteuerung	Massemäßige Dosierung aller Ausgangsstoffe	Massemäßige Dosierung der Ausgangsstoffe außer der Gesteinskörnung, die volumetrisch dosiert wird[b]
	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2
C8/10	7	15	17	19	23
C12/15	12	20	22	24	28
C16/20	18	26	28	30	34
C20/25	23	31	33	35	39
C25/30	29	37	39	41	–
C30/37	36	44	46	48	–
C35/45	45	53	55	57	–
C40/50	50	58	60	62	–
C45/55	56	64	66	68	–
C50/60	61	69	71	–	–
C55/67	69	77	79	–	–
C60/75	75	83	85	–	–
C70/85	85	93	95	–	–
C80/95	96	104	106	–	–
C90/105	107	115	117	–	–
C100/115	117	125	127	–	–

[a] In der Reihe (Verfahren A gemäß 8.2.1.3.2 (2)).

[b] Diese Herstellung ist nur für die Klassifikation gemäß Abschnitt 4 für X0, XC1 und XC2 zulässig.

From section 5.5.1.2 item (4) from the ÖNORM B4710-1 [1] it is possible to get the relation between the compressive strength of a cube of 100 x 100 x 100 mm and 150 x 150 x 150 mm:

ANMERKUNG 1 Für die Werte in Tabelle 32 wurden die Anforderungen der ÖNORM EN 206 auf den 150-mm-Würfel bei der Lagerung nach ONR 23303 umgerechnet. Dazu wurden die Anforderungswerte für Normalbeton bis C55/67 mit 0,92 (gerundet), und bei Normalbeton ≥ C60/75 mit 0,95 (gerundet) umgerechnet.

(4) Werden anstelle von Würfeln mit einer Kantenlänge von 150 mm solche mit 100-mm-Kantenlänge $f_{c,100\,mm}$ verwendet, dann sind die Werte nach folgender Beziehung zu berechnen:

$$f_{c,150mm} = 0{,}97 \times f_{c,100mm} \quad (1)$$

Es bedeutet:

$f_{c,150mm}$ Druckfestigkeit von würfelförmigen Probekörpern mit 150-mm-Kantenlänge bei Lagerung nach ONR 23303

$f_{c,100mm}$ Druckfestigkeit von würfelförmigen Probekörpern mit 100-mm-Kantenlänge

Fig. 21: Mathematical relation between cubes of 100 mm side and 150 mm side - ÖNORM B4710-1

Replacing the value in this formula, the compressive strength of a cube of 100 x 100 x 100 mm is 71,74 MPa.

$$f_{c,150mm} = 0{,}97 \text{ x } f_{c,100mm}$$

$$f_{c,150mm} = 0{,}97 \text{ x } 73{,}95 \text{ MPa} = 71{,}735 \text{ MPa}$$

Normal Strength Concrete: Conclusions

The result shows that the compression strength of the mixture designed fits with the optimal values recommended in the ÖNORM for C50/60 (71 MPa at 28 days) with a complete replacement of the normal aggregates by secondary materials. However, some part of the sieving curve does not fit with the optimal sieving curve for concrete in correspondence with the ÖNORM mentioned before.

Ultra High Performance Concrete (UHPC)

The goal of this investigation was to check if quarries' secondary materials were suitable for the production of Ultra High Performance Concrete (UHPC) considering that the materials collected have a high content of fine particles and UHPC has also a high content of fine powders smaller than < 250 µm (0,250 mm).

The dense microstructure of the powders present in UHPC can be optimized at low water content if there is a physical optimization, meaning a high packing density in the grain size area.

The models of optimization of particle size used were:

- Fuller and Thompson (1907) [2], q = 0.5 ,

$$P(D) = \left(\frac{D}{D_{\max}}\right)^{q} \quad \text{eq. (1)}$$

  Where:

  P = fraction that can pass the sieve with opening D

  D_{max} = maximum particle size of the mixture

- Andreasen and Andersen (1930) [3] (A&A) proposed a value of q= 0.37 for the Fuller expression in eq. 1.
- Funk and Dinger (1994) [4], q = 0,25 suggested that any real size distribution of particles must have a finite lower size limit and modified the A&A curve. This modified version of the model incorporated the minimum particle size in the mixture as

$$P(D) = \frac{D^{q} - D_{\min}^{q}}{D_{\max}^{q} - D_{\min}^{q}} \quad \text{eq. (2)}$$

  Where:

  D_{min} = minimum particle size in the mix

  In order to obtain the optimum particle packing density, the modified Andreasen and Andersen curve for particle size distribution suggested by Funk and Dinger was used. The three models are shown in the Fig. 22.

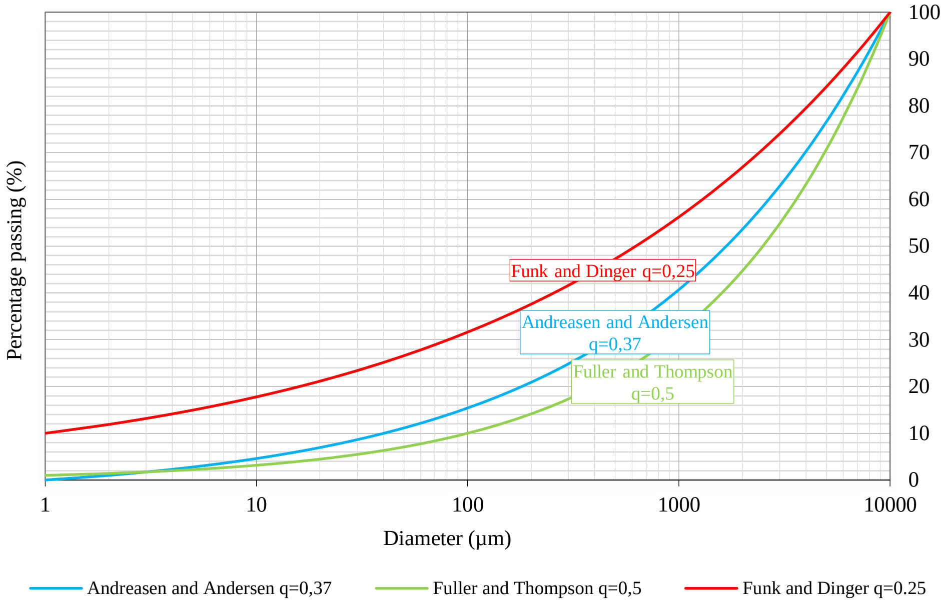


Fig. 22: Optimization models

In order to optimize the particle size distribution of UHPC, the particle size of every material present in UHPC and every secondary material was analyzed as it is shown in the following picture:

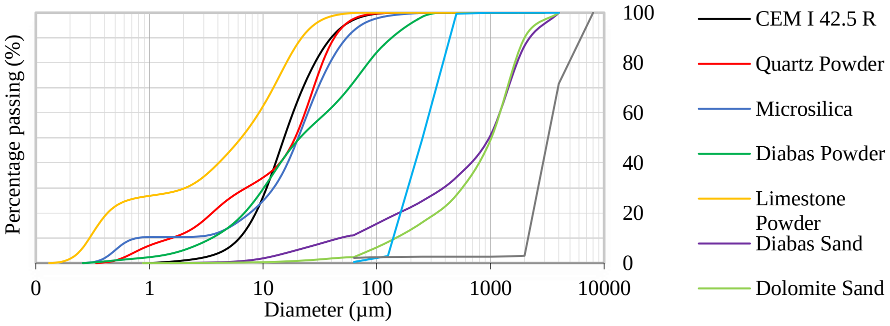


Fig. 23: Particle size distribution of each material

The materials used to mix the reference samples were the following: Cement I 42,5R (d10= 6,1732 μm, d90= 39,7122 μm); Microsilica (d10= 0,7924 μm, d90= 54,5041 μm); Quartz Powder (d10= 1.5660 μm, d90= 42.5004 μm) and Quartz Sand (0,1/0,4 mm). These materials were substituted by the following secondary materials: Diabase Sand (0/2 mm); Diabase Powder (d10= 3.5300 μm, d90= 135.1871 μm); Dolomite Sand (0/2 mm); Dolomite Gravel (2/4 mm); Limestone Powder (d10= 0.2975 μm, d90= 21.8949 μm). Additionally, samples with steel fibres of 9 mm length (Nominal Diameter= 0,15 mm, E= 210 GPa, Tensile Strength= 2600 MPa) were also cast in order to improve the mechanical properties. In order to design the mixes of UHPC containing secondary materials from quarries, the Funk and Dinger curve was considered as the 'target curve' and the 'design curve' was the curve of each mix. The design curves for each mixture were obtained by modifying the amount of each material in the mixture. The goal was to obtain uniform 'design curves' that matched the 'target curve' as closely as possible. Some of the designed curves are shown in Fig. 24. The main idea of the substitutions was to replace materials of similar grain size: Microsilica and Quartz Powder were replaced by Limestone Powder and Diabase Powder. Quartz Sand was substituted by Diabase Sand and Dolomite Sand. Moreover, Dolomite Gravel 2/4 mm was added to analyze the compression strength behaviour of coarse aggregate in the mixtures. Regarding the reference samples, three batches of reference samples REF1 A, REF2 W and REF3 HW were cast to compare the compression strength at 28 days using different curing methods. The specimens were demolded after 24 hours. REF1 A was stored at 20°C for air curing (A), REF2 W was immersed in water at 20°C for water curing (W), REF3 HW was immersed in water at 90°C for 7 days for hot water curing (HW) and the other 21 days left in water at 20°C. In order to compare the designed mixes, REF4 A was cast with conventional aggregates and stored at 20°C for air curing.

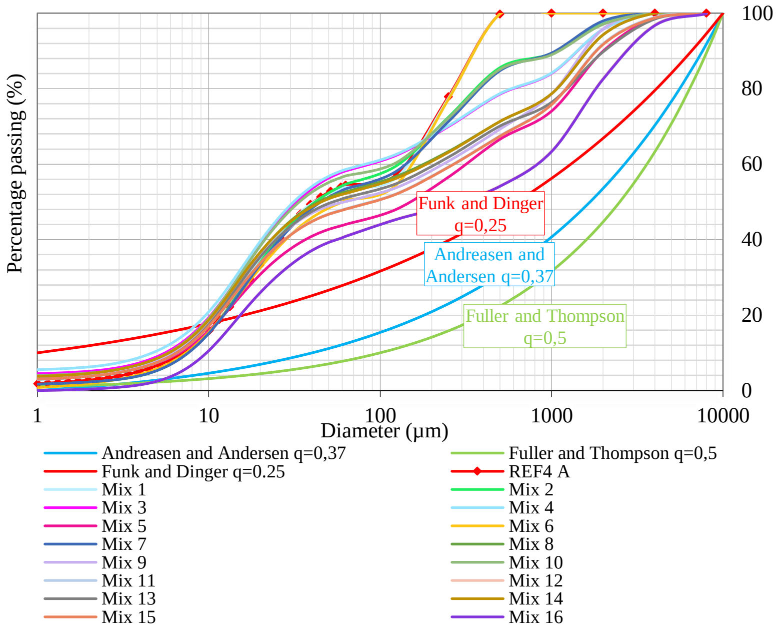


Fig. 24: Particle size of each mixture

UHPC: Conclusions

A total amount of 28 mixes were produced and compression strength tests were performed (see Table 12 and Fig. 25). The proportion of the mixes and the results of compression strength are shown in the following table and graph. As it was mentioned, UHPC has a minimum compressive strength of 120 MPa according to the Swiss Standards [5]. After testing the compressive strength of several mixes containing different combination of replacements of commercial materials by secondary materials, the maximum compressive strength value that it was possible to reach at 28 days was 143,05 MPa. This value corresponds to Mix 22. It could be seen that the replacements of Quartz Powder by Limestone Powder and Quartz Sand by Diabase Sand can be suitable for the production of Ultra High Performances Fiber Reinforced Concrete (UHPFRC). Moreover, the replacement of Quartz Sand by Diabase or Dolomite Sand could be also suitable since it shows similar compressive strength values when one or the other is substituted indistinctly. The replacement of cement by Limestone Powder was also tried and it was observed that compressive strength dropped dramatically, showing that a cement replacement with Limestone Powder is not possible. The admixture of fibers was tried to check if the compressive strength improved. Despite the compressive strength values increasing, the percentage increase was too low to be considered as an optimal improvement. The admixture of coarse aggregate 2/4 mm shows lower values of compressive strength in comparison with the other mixes. The curing methods tried with the reference samples confirm that compressive strength values are increased in the presence of water and heat during the curing process. Although not all of the mixes reached a compressive strength value of 120 MPa at 28 days, it is interesting to note that higher values than 100 MPa can be obtained at the age of 28 days only by using secondary materials as aggregates.

Tab. 12: UHPFRC Mixes

	Quantities in (kg/m³)															Compression Strength [MPa]		
Mix	Grey Cement W&P CEM I 42,5 R	White Cement CEM II A-LL 42,5 R	Microsilica RW Füller Q1	Quartz powder. Dorsilit 16900	Quarzt Sand QS ME 0.1 - 0.4	Diabas Sand	Diabas Powder	Limestone Powder	Dolomite Gravel	Dolomite Sand	Water	SUP	Fibres	w/c [-]	w/b	7 d. Air cured (MPa)	28 d. (MPa) Air cured	28 d. (MPa) Water cured
REF1 A***	850.0		143.0	245.0	891.4						195	20.0		0.25	0.21	98.40	123.70	
REF2 A***	850.0		143.0	245.0	891.4						200	37.0		0.27	0.23	96.40	123.85	
REF1A	850.0		143.0	245.0	865.0						195	20.9		0.25	0.21	105.10	138.90	
REF2W	850.0		143.0	245.0	865.0						195	20.0		0.25	0.21	—	143.00	
REF3HW	850.0		143.0	245.0	865.0						195	20.0		0.25	0.21	—	163.43	
REF4A	850.0		149.0	249.5	875.3						200	27.0		0.24	0.22	106.00	153.77	
Mix 1	850.0		122.5	143.0	891.4			122.5			200	40.2		0.27	0.23	90.30	117.80	
Mix 2	850.0		245.0		445.7	445.7		143.0			200	43.5		0.27	0.21	95.65	137.60	
Mix 3	765.0		245.0		222.9	668.6		228.0			200	46.5		0.30	0.23	90.00	128.55	
Mix 4	680.0		245.0		222.9	668.6		313.0			200	47.5		0.34	0.25	77.90	115.25	
Mix 5	641.9				222.9	860.0		241.0	90.0		200	40.0		0.36	0.36	44.55	83.35	
Mix 6	850.0			143.0	891.4		245.0				200	40.2		0.27	0.27	80.05	108.35	
Mix 7	850.0		245.0		445.7		143.0			445.7	200	46.1		0.27	0.21	72.50	108.15	
Mix 8	850.0				145.7	845.7		243.0			200	49.2		0.28	0.28	81.95	95.95	
Mix 9	850.0				145.7			243.0		845.7	200	49.7		0.28	0.28	—	99.36	
Mix 10	850.0		160.0		425.0	450.0		221.7			210	27.0		1.31	0.23	111.87	136.03	
Mix 11	850.0				160.0	196.3	50.0	225.0	85.0	665.0	195	27.0		0.23	0.25	103.93	114.47	
Mix 12	900.0					900.0			240.0	178.2	195	28.0		0.22	0.24	92.23	103.67	
Mix 13	900.0				190.0	760.0		231.9	120.0		195	27.0		0.22	0.24	98.13	112.90	
Mix 14	850.0				165.0	895.5		290.0			190	27.0		0.22	0.25	89.73	104.83	
Mix 15	850.0				162.0	198.0	52.0	228.9	87.0	667.0	190	27.0	157.00	0.22	0.25	103.03	116.27	
Mix 16	900.0					900.0			240.0	178.2	195	28.0	157.00	0.22	0.24	95.70	111.97	
Mix 17		850			165.0	895.53		290			180.0	27		0.21	0.23	Not tested	103.32	112.97
Mix 18		850	160		425	450		221.65			195	27		0.23	0.21	Not tested	141.38	139.31
Mix 19		850	160		425	450		221.65			180	27		0.21	0.20	Not tested	136.93	133.19
Mix 20		880			162	198	52	227.8	87	667	180	27		0.20	0.23	Not tested	116.38	124.42
Mix 21		880			162	198	52	200.71	87	667	190	27		0.22	0.24	Not tested	120.50	127.88
Mix 22		900	120	70	200			253.9		749.6	190	43.5		0.21	0.22	Not tested	143.05	127.90
Mix 23		900	125	90	210			253.9		753.6	175	43.5		0.19	0.20	Not tested	106.83	101.92
Mix 24		900	125	90	210			253.9		753.6	175	43.5		0.19	0.20	Not tested	128.98	109.40
Mix 25		900	219		230					975	175	43.5		0.19	0.18	Not tested	107.50	107.05
Mix 26		900	219	125		271.18				800	175	43.5		0.19	0.18	Not tested	87.01	74.28
REF 4 A	850		149	249.5	875.3						200	18.46		0.24	1.43	112.41	152.43	
Mix 27	850		160		425			221.65		450	195	18.71		0.23	0.21	119.06	142.35	
REF 4 A	850		149	249.5	875.3						200	17.75		0.24	0.21	130.35	149.59	
Mix 28	900			150		338.4		200		800	175	46.6		0.19	0.23	115.79	120.09	

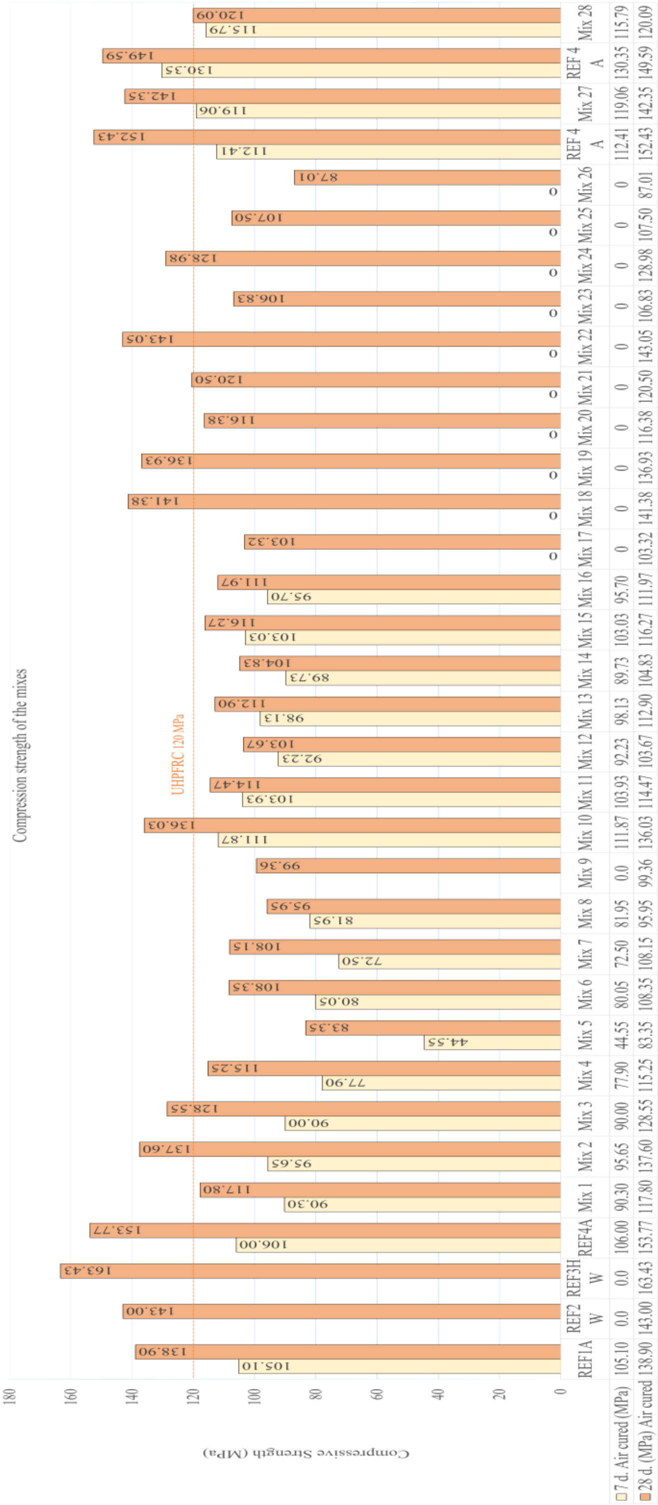


Fig. 25: Compression strength of the mixes

Life Cycle Assessment (LCA) of Ultra High Performance Concrete mixes

Concrete consists of natural raw materials like water, sand and gravel mixed with cement, additives and admixtures. Cement production is one of the most emission-intensive industrial processes. In order to make concrete more sustainable, some materials can be substituted: either concrete is replaced in principle by another building material, or the proportion of cement in the concrete is reduced, or the proportion of clinker in the cement is reduced. In the present work, concrete is not going to be replaced as a building material, since its versatility and durability make it certainly a sustainable building material. It will be analyzed how the environmental impact changes, if the proportion of cement is reduced and substituted by another material instead. To identify the potential for increasing the sustainability of concrete, an assessment of the environmental impact of each component is required. Defined characteristic values of the environmental impact represent a comparable quality feature for building materials. Decisive factors include energy requirements for production, transport and disposal, pollutant emissions during production, processing, use and disposal, use of recycled materials, service life, ease of repair or easy and environmentally friendly renewability, recyclability and regionality.

Environmental Product Declarations (EPDs) are generated for the evaluation and comparability of building materials, building products and building components. The detailed life cycle assessment data and information contained in these declarations are summarized in a standardized format. The life cycle of the product is divided into five modules, which correspond to the life cycle phases of building products according to DIN EN 15804: Product stage, Construction process stage, Use stage, End of life stage, Benefits and loads beyond the system boundary.

Product stage			Construction process stage		Use stage					End of life stage				Benefits and loads beyond the system boundary
Raw material supply	Transport	Manufacturing	Transport	Construction-installation process	Use	Maintenance	Repair	Replacement	Refurbishment	De-construction demolition	Transport	Waste processing	Disposal	Reuse- Recovery- Recycling - potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
					B6	Operational energy use								
					B7	Operational water use								

Figure 3:
Life cycle modules in accordance with EN 15804. Source: EN 15804

Indicators
EN 15804 defines a total of 24 indicators which must be included in EPDs for construction products:

Fig. 26: Life Cycle Modules [6]

In the present work, the Life Cycle Assessment (LCA) data of the different concrete mixes refer purely to this first phase, the product stage "cradle to gate" (A1 – A3), which can be explained with:

A1: raw material supply

A2: transport to the manufacturer

A3: manufacturing

In the life cycle assessment of concrete components, the greatest environmental impacts occur in the product stage. The production and extraction of concrete raw materials and cement production in particular, have the greatest influence on the life cycle assessment of concrete. Cement production accounts for around 80 % of the total greenhouse potential of concrete production, and the extraction and production of aggregates for around 5%. With increasing concrete compressive strength, the environmental impacts of concrete production increase [6].

The parameters for comparison of the concrete mixtures refer to the resource consumption:

PENRT: Primary energy input non-renewable, total, [MJ]

PERT: Primary energy renewable, total, [MJ]

and to the impact on the global and local environment:

GWP: Global warming potential, [kg CO2 eq.]

AP: Acidification potential of land and water, [kg SO2 eq.]

EP: Eutrophication potential, [kg phosphates eq.]

ODP: Ozone Depletion Potential, [kg CFC11 eq.]

POCP: Photochemical Ozone Creation Potential, [kg ethene eq.]

The following table shows the LCA values of the various materials used in the mixtures:

Tab. 13: LCA data source of the materials [8] [9] [10] [11] [12] [13] [14] [15] [16]

Material	Primary Energy Input		GWP	AP	EP	ODP	POCP	data source
	PENRT	PERT						
	[MJ/kg]	[MJ/kg]	[kg CO_2-eq/kg]	[kg SO_2-eq/kg]	[kg (PO_4)3--Eq/kg]	[kg CFC11-eq/kg]	[kg Ethene-eq/kg]	
Cement CEM I 42,5 R	2,48	0,294	0,808	0,00117	0,000402	9,27E-09	0,000106	1
CEM II A-LL 42,5 R	2,13	0,376	0,759	0,000623	0,000233	1,36E-08	0,0000822	2
Microsilica/Silica Fume *	0	0	0	0	0	0	0	-
Quartz Powder	0,82	0,0316	0,0234	0,000158	0,00000675	4,98E-09	0,00000557	3
Quartz Sand	0,539	0,0129	0,0102	0,0000754	0,000003	2,1E-09	0,00000258	3
Diabas Sand ***	0,03812	0,0121	0,002854	0,000006814	0,000001327	6,025E-17	-5,824E-07	4
Diabas Powder **	0	0	0	0	0	0	0	-
Limestone Powder **	0	0	0	0	0	0	0	-
Dolomite Gravel ***	0,1889	0,1004	0,01469	0,00002071	0,000004412	5,449E-16	6,559E-07	5
Dolomite Sand ***	0,1889	0,1004	0,01469	0,00002071	0,000004412	5,449E-16	6,559E-07	6
Water	0,001754	0,0002921	0,000128	2,063E-07	1,167E-07	1,616E-18	1,799E-08	7
SUP	31,4	1,51	1,88	0,00292	0,00103	2,3E-10	0,000312	8
Steel fibres	11	0,794	0,771	0,00105	0,000335	0,0001	0,000324	9

* Microsilica is a by-product of the production of silicon and ferrosilicon alloys. All environmental impacts were assigned to the production of the alloys.
** Mining surplus material - no consideration in VAR I and VAR II
*** Mining surplus material - no consideration in VAR I

data sources	
	1 EPD-KNT-20200209-CAA1-EN Portland Cement CEM I 42,5 R, Kunda Nordic Tsement AS
	2 EPD-HCG-20190045-CAA1-EN Portland Limestone Cement CEM II/A-LL 42.5 R, Cementa AB, HeidelbergCement Group
	3 Kromer, M et al. (eds.) 2012. Nachhaltiger Beton - Werkstoff, Konstruktion und Nutzung : 9. Symposium Baustoffe und Bauwerkserhaltung Karlsruher Institut für Technologie (KIT) ; 15. März
	4 ÖKOBAUDAT Datensatz Sand 0/2
	5 ÖKOBAUDAT Datensatz Schotter 16/32
	6 ÖKOBAUDAT Datensatz Brechsand 0/2
	7 ÖKOBAUDAT Datensatz Trinkwasser
	8 EPD-EFC-20150091-IAG1-EN Concrete admixtures - Plasticisers and Superplasticisers
	9 Environmental Product Declaration Type III ITB No. 064/2017

Concrete mixes (1 m^3 each) were designed and casted replacing normal aggregates in UHPC by the Diabase sand and Diabase Powder from Bad Bleiberg, Carinthia; Limestone Powder from Italy; Dolomite sand and Dolomite gravel from Tyrol. Steel fibers were also added. The materials from the quarries are considered mining surplus materials. The stone powder is filtered out during the processes and is normally not used further. The same applies to sand and crushed stone from quarrying operations. A part of it, is used in road construction, but the other part is surplus and has no further use. In the present consideration of the eco-indicators, the surplus materials from the quarries used in the mixtures were compared based on two variants concerning their ecological impacts:

VAR I: the impact is assumed to be zero, as the materials are secondary materials

VAR II: the impacts occurring during production are considered, with the exception of stone powder

Results of the LCA of the mixtures VAR I:

Tab. 14: LCA of all mixes, VAR I

LCA VAR I for 1 m³ concrete

Type	Mix	Primary Energy per m³		Impact on environment per m³				
		PENRT	PERT	GWP	AP	EP	ODP	POCP
		[MJ/m³]	[MJ/m³]	[kg CO_2-eq/m³]	[kg SO_2-eq/m³]	[kg $(PO_4)3-$ -Eq/m³]	[kg CFC11-eq/m³]	[kg Ethene-eq/m³]
Grey UHPC	**REF1 A*** **	3.417,707	299,398	739,250	1,159	0,367	1,098E-05	0,100
Grey UHPC	**REF2 A*** **	3.951,515	325,069	771,211	1,209	0,384	1,098E-05	0,105
Grey UHPC	**REF1A**	3.430,795	300,371	740,617	1,159	0,367	1,092E-05	0,100
Grey UHPC	**REF2W**	3.403,477	299,057	738,981	1,157	0,367	1,092E-05	0,100
Grey UHPC	**REF3HW**	3.403,477	299,057	738,981	1,157	0,367	1,092E-05	0,100
Grey UHPC	**REF4A**	3.632,528	309,904	752,352	1,179	0,374	1,097E-05	0,102
Grey UHPC	**Mix 1**	3.968,355	326,678	774,840	1,202	0,387	1,047E-05	0,106
Grey UHPC	**Mix 2**	3.714,483	321,393	773,152	1,155	0,388	8,825E-06	0,105
Grey UHPC	**Mix 3**	3.477,767	298,058	707,839	1,048	0,356	7,570E-06	0,096
Grey UHPC	**Mix 4**	3.298,367	274,578	641,039	0,951	0,323	6,783E-06	0,087
Grey UHPC	**Mix 5**	2.968,453	252,061	596,178	0,885	0,300	6,428E-06	0,081
Grey UHPC	**Mix 6**	3.968,355	326,678	774,840	1,202	0,387	1,047E-05	0,106
Grey UHPC	**Mix 7**	3.796,123	325,319	778,040	1,163	0,391	8,826E-06	0,106
Grey UHPC	**Mix 8**	3.731,763	326,130	780,808	1,149	0,393	8,197E-06	0,106
Grey UHPC	**Mix 9**	3.747,463	326,885	781,748	1,151	0,393	8,197E-06	0,106
Grey UHPC	**Mix 10**	3.185,243	296,214	741,922	1,105	0,371	8,778E-06	0,100
Grey UHPC	**Mix 11**	3.042,382	292,791	739,217	1,085	0,370	8,222E-06	0,099
Grey UHPC	**Mix 12**	3.111,542	306,937	779,865	1,135	0,391	8,349E-06	0,104
Grey UHPC	**Mix 13**	3.182,552	307,878	779,923	1,146	0,390	8,748E-06	0,104
Grey UHPC	**Mix 14**	3.045,068	292,854	739,267	1,086	0,370	8,232E-06	0,099
Grey UHPC	**Mix 15**	4.770,451	417,473	860,284	1,250	0,423	1,571E-02	0,150
Grey UHPC	**Mix 16**	4.838,542	431,595	900,912	1,300	0,443	1,571E-02	0,155
White UHPC	**Mix 17**	2.747,551	362,551	697,616	0,621	0,226	1,191E-05	0,079
White UHPC	**Mix 18**	2.887,717	365,909	700,270	0,640	0,227	1,246E-05	0,079
White UHPC	**Mix 19**	2.887,691	365,905	700,268	0,640	0,227	1,246E-05	0,079
White UHPC	**Mix 20**	2.809,834	373,792	720,355	0,639	0,233	1,231E-05	0,081
White UHPC	**Mix 21**	2.809,851	373,795	720,357	0,639	0,233	1,231E-05	0,081
White UHPC	**Mix 22**	3.448,433	408,932	768,582	0,714	0,256	1,302E-05	0,088
White UHPC	**Mix 23**	3.470,197	409,689	769,150	0,718	0,256	1,314E-05	0,089
White UHPC	**Mix 24**	3.470,197	409,689	769,150	0,718	0,256	1,314E-05	0,089
White UHPC	**Mix 25**	3.407,177	407,103	767,248	0,705	0,255	1,273E-05	0,088
White UHPC	**Mix 26**	3.385,707	408,086	767,827	0,708	0,255	1,287E-05	0,088
Grey UHPC	**REF 4 A**	3.364,372	297,009	736,297	1,154	0,365	1,096E-05	0,100
Grey UHPC	**Mix 27**	2.924,911	283,692	726,335	1,081	0,362	8,776E-06	0,097
Grey UHPC	**REF 4 A**	3.342,078	295,936	734,962	1,152	0,364	1,096E-05	0,099
White UHPC	**Mix 28**	3.818,547	339,757	818,340	1,213	0,411	9,101E-06	0,111
White UHPC	**Mix 29**	4.217,327	358,934	842,216	1,250	0,424	9,104E-06	0,115
White UHPC	**Mix 30**	3.406,207	408,876	768,412	0,711	0,256	1,300E-05	0,088
White UHPC	**Mix 31**	3.432,733	408,177	767,642	0,712	0,255	1,302E-05	0,088
White UHPC	**Mix 32**	5.729,663	520,299	906,496	0,931	0,331	1,321E-05	0,111

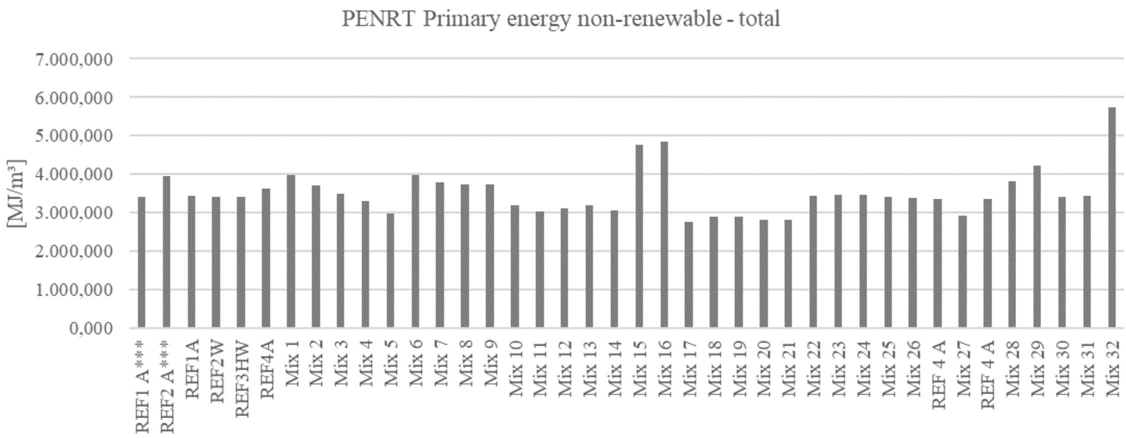


Fig. 27: PENRT of all mixes, VAR I

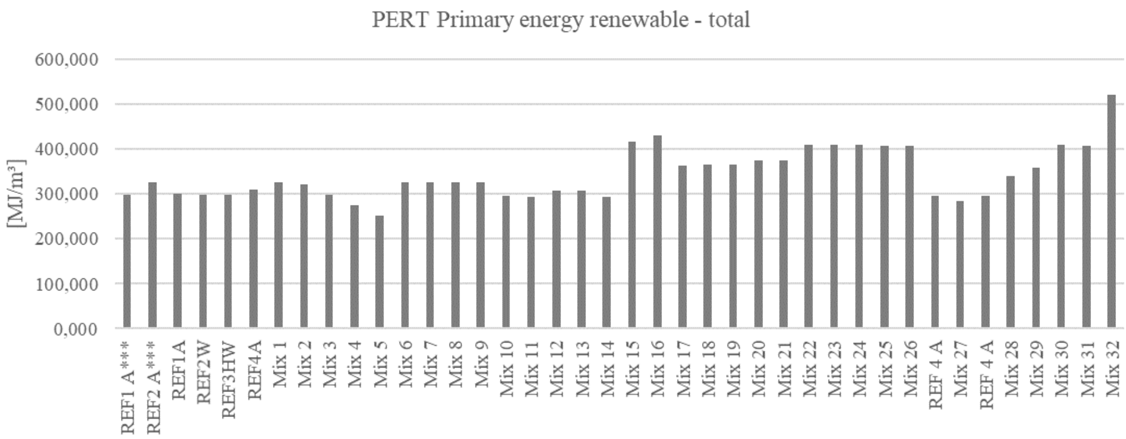


Fig. 28: PERT of all mixes, VAR I

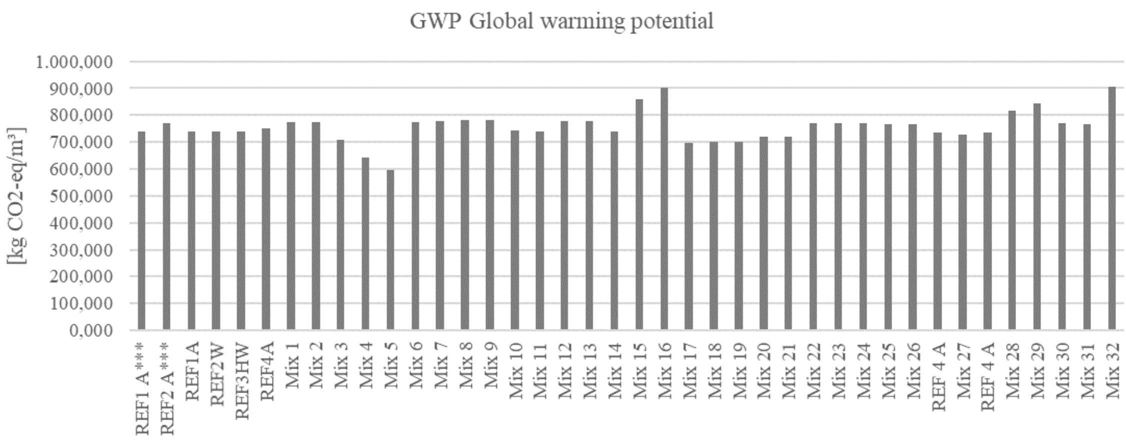


Fig. 29: GWP of all mixes, Var I

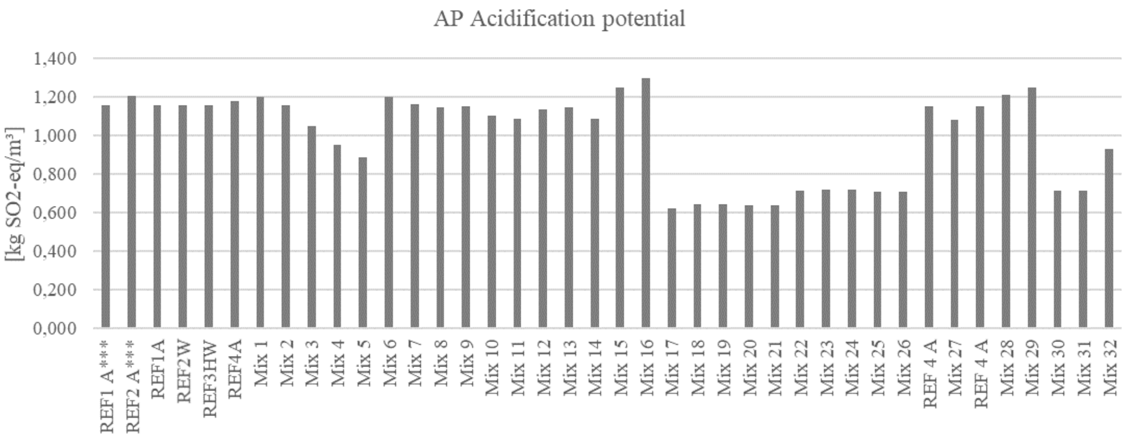


Fig. 30: AP of all mixes, Var I

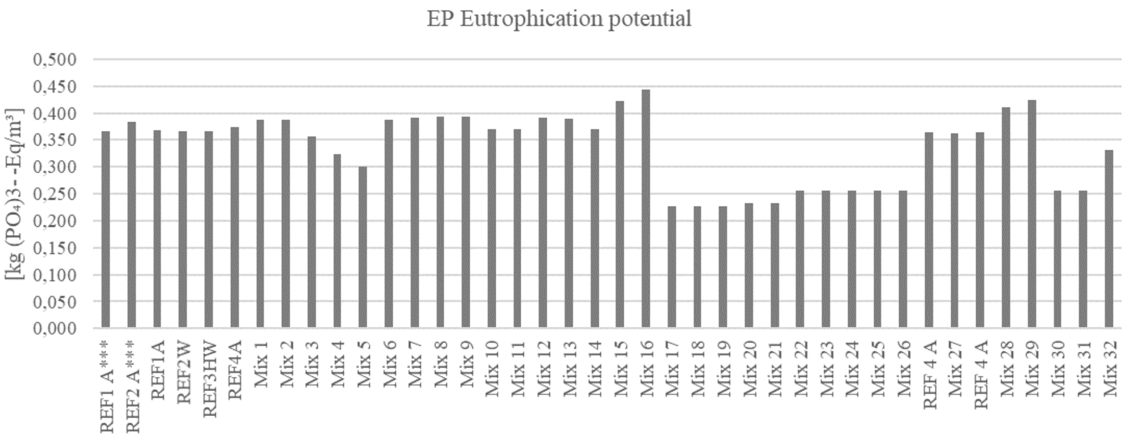


Fig. 31: EP of all mixes, Var I

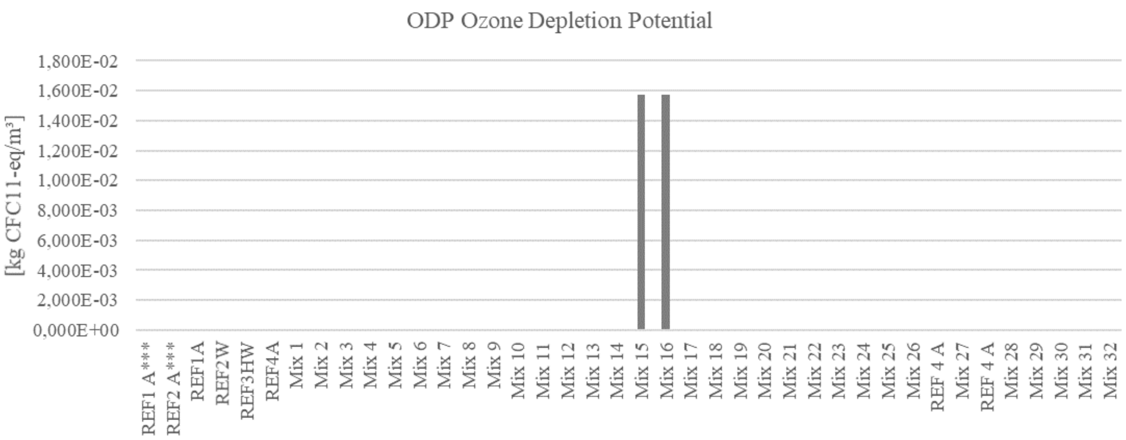


Fig. 32: ODP of all mixes, Var I

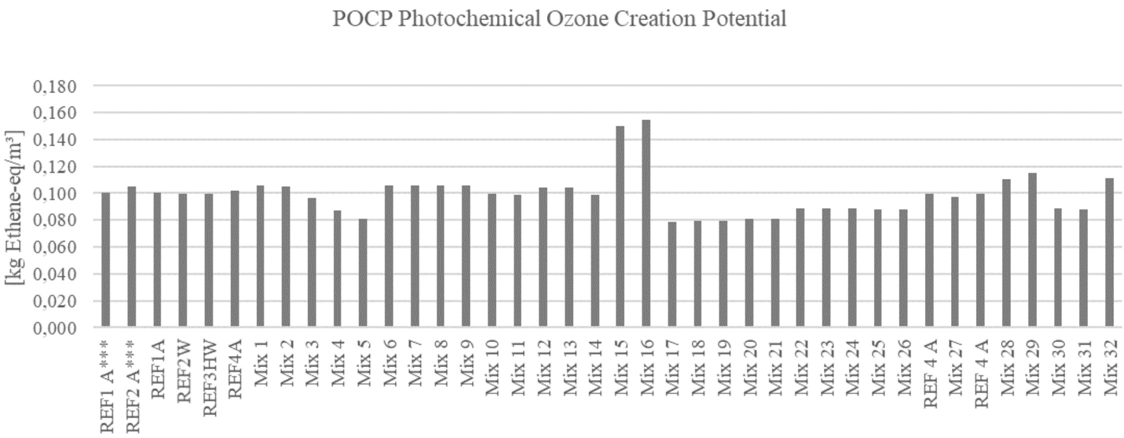


Fig. 33: POCP of all mixes, Var I

Results of the LCA of the mixtures, VAR II:

Tab. 15: LCA all mixes VAR II

LCA VAR II for 1 m³ concrete

Type	Mix	Primary Energy per m³		Impact on environment per m³				
		PENRT	PERT	GWP	AP	EP	ODP	POCP
		[MJ/m³]	[MJ/m³]	[kg CO_2-eq/m³]	[kg SO_2-eq/m³]	[kg $(PO_4)3-$ -Eq/m³]	[kg CFC11-eq/m³]	[kg Ethene-eq/m³]
Grey UHPC	**REF1 A*** **	3.417,707	299,398	739,250	1,159	0,367	1,098E-05	0,100
Grey UHPC	**REF2 A*** **	3.951,515	325,069	771,211	1,209	0,384	1,098E-05	0,105
Grey UHPC	**REF1A**	3.430,795	300,371	740,617	1,159	0,367	1,092E-05	0,100
Grey UHPC	**REF2W**	3.403,477	299,057	738,981	1,157	0,367	1,092E-05	0,100
Grey UHPC	**REF3HW**	3.403,477	299,057	738,981	1,157	0,367	1,092E-05	0,100
Grey UHPC	**REF4A**	3.632,528	309,904	752,352	1,179	0,374	1,097E-05	0,102
Grey UHPC	**Mix 1**	3.968,355	326,678	774,840	1,202	0,387	1,047E-05	0,106
Grey UHPC	**Mix 2**	3.731,473	326,786	774,424	1,158	0,388	8,825E-06	0,105
Grey UHPC	**Mix 3**	3.503,252	306,148	709,747	1,052	0,357	7,570E-06	0,096
Grey UHPC	**Mix 4**	3.323,852	282,668	642,947	0,956	0,324	6,783E-06	0,087
Grey UHPC	**Mix 5**	3.018,238	271,503	599,955	0,892	0,301	6,428E-06	0,081
Grey UHPC	**Mix 6**	3.968,355	326,678	774,840	1,202	0,387	1,047E-05	0,106
Grey UHPC	**Mix 7**	3.880,316	370,067	784,587	1,172	0,393	8,826E-06	0,106
Grey UHPC	**Mix 8**	3.764,001	336,363	783,221	1,155	0,394	8,197E-06	0,105
Grey UHPC	**Mix 9**	3.907,216	411,793	794,171	1,168	0,397	8,197E-06	0,107
Grey UHPC	**Mix 10**	3.202,397	301,659	743,206	1,108	0,371	8,778E-06	0,099
Grey UHPC	**Mix 11**	3.191,538	370,466	750,795	1,102	0,374	8,222E-06	0,099
Grey UHPC	**Mix 12**	3.224,848	359,814	788,577	1,150	0,394	8,349E-06	0,104
Grey UHPC	**Mix 13**	3.234,191	329,122	783,855	1,154	0,392	8,748E-06	0,104
Grey UHPC	**Mix 14**	3.079,206	303,690	741,823	1,092	0,371	8,232E-06	0,098
Grey UHPC	**Mix 15**	4.920,430	495,571	871,925	1,267	0,426	1,571E-02	0,150
Grey UHPC	**Mix 16**	4.951,848	484,472	909,624	1,314	0,446	1,571E-02	0,155
White UHPC	**Mix 17**	2.781,688	373,387	700,172	0,627	0,228	1,191E-05	0,078
White UHPC	**Mix 18**	2.904,871	371,354	701,554	0,644	0,228	1,246E-05	0,079
White UHPC	**Mix 19**	2.904,845	371,350	701,552	0,644	0,228	1,246E-05	0,079
White UHPC	**Mix 20**	2.959,812	451,890	731,997	0,656	0,237	1,231E-05	0,082
White UHPC	**Mix 21**	2.959,830	451,893	731,998	0,656	0,237	1,231E-05	0,082
White UHPC	**Mix 22**	3.590,033	484,192	779,594	0,729	0,259	1,302E-05	0,089
White UHPC	**Mix 23**	3.612,552	485,351	780,221	0,733	0,259	1,314E-05	0,089
White UHPC	**Mix 24**	3.612,552	485,351	780,221	0,733	0,259	1,314E-05	0,089
White UHPC	**Mix 25**	3.591,354	504,993	781,571	0,725	0,260	1,273E-05	0,089
White UHPC	**Mix 26**	3.547,164	491,687	780,353	0,726	0,259	1,287E-05	0,089
Grey UHPC	**REF 4 A**	3.364,372	297,009	736,297	1,154	0,365	1,096E-05	0,100
Grey UHPC	**Mix 27**	3.009,916	328,872	732,945	1,091	0,364	8,776E-06	0,097
Grey UHPC	**REF 4 A**	3.342,078	295,936	734,962	1,152	0,364	1,096E-05	0,099
White UHPC	**Mix 28**	3.982,567	424,172	831,058	1,232	0,415	9,101E-06	0,111
White UHPC	**Mix 29**	4.381,347	443,349	854,934	1,269	0,428	9,104E-06	0,115
White UHPC	**Mix 30**	3.570,227	493,291	781,130	0,730	0,260	1,300E-05	0,089
White UHPC	**Mix 31**	3.545,223	467,966	776,390	0,725	0,258	1,302E-05	0,089
White UHPC	**Mix 32**	5.808,246	562,065	912,607	0,939	0,333	1,321E-05	0,112

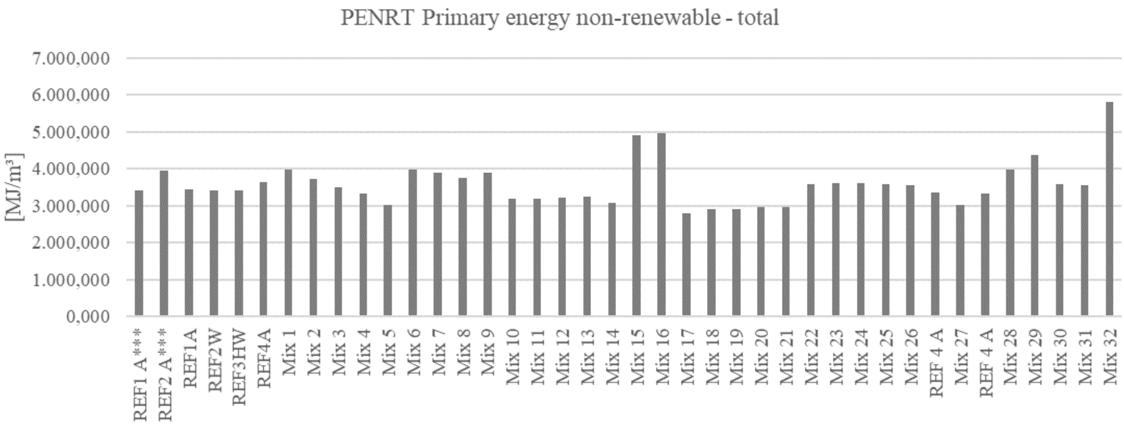


Fig. 34: PENRT of all mixes, VAR II

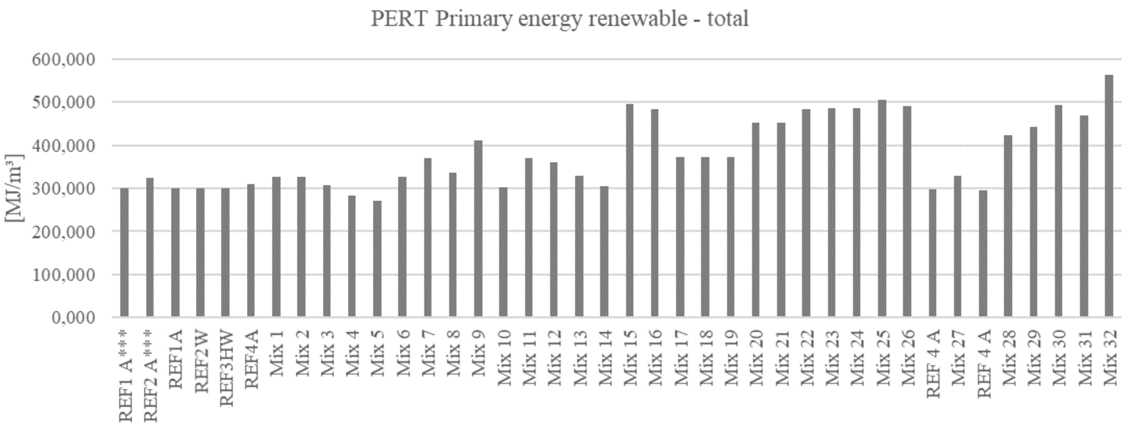


Fig. 35: PERT of all mixes, VAR II

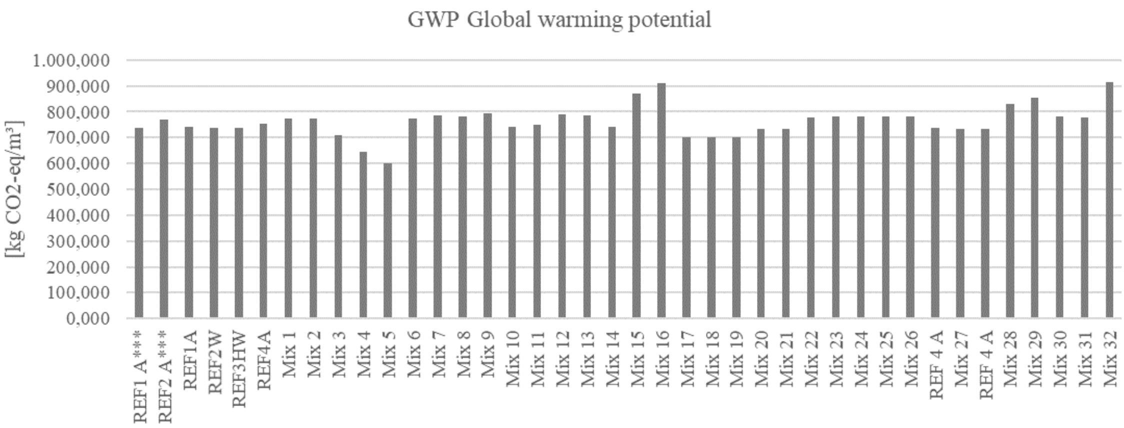


Fig. 36: GWP of all mixes, VAR II

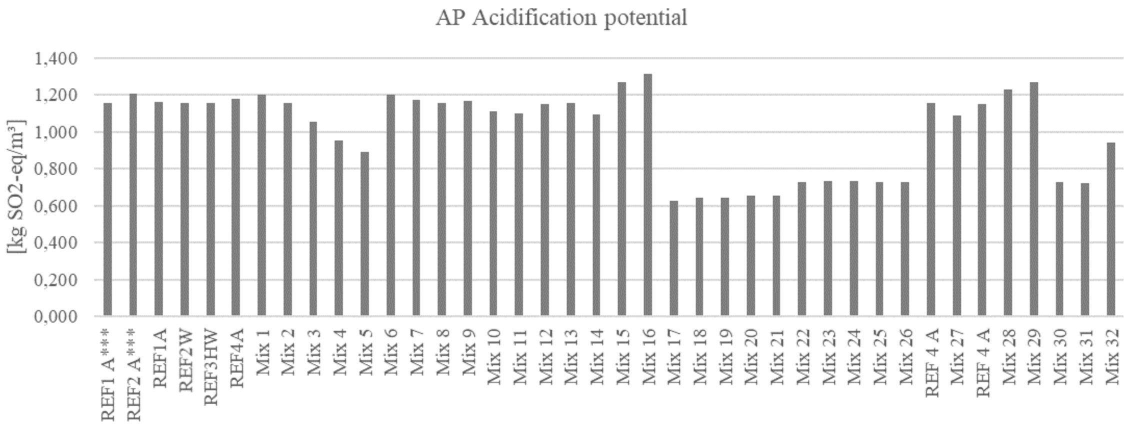


Fig. 37: AP of all mixes, VAR II

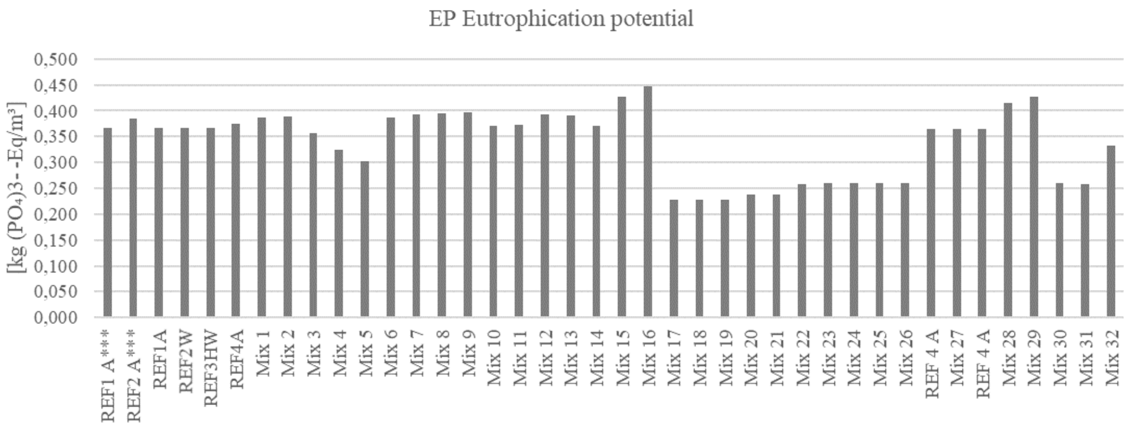


Fig. 38: EP of all mixes, VAR II

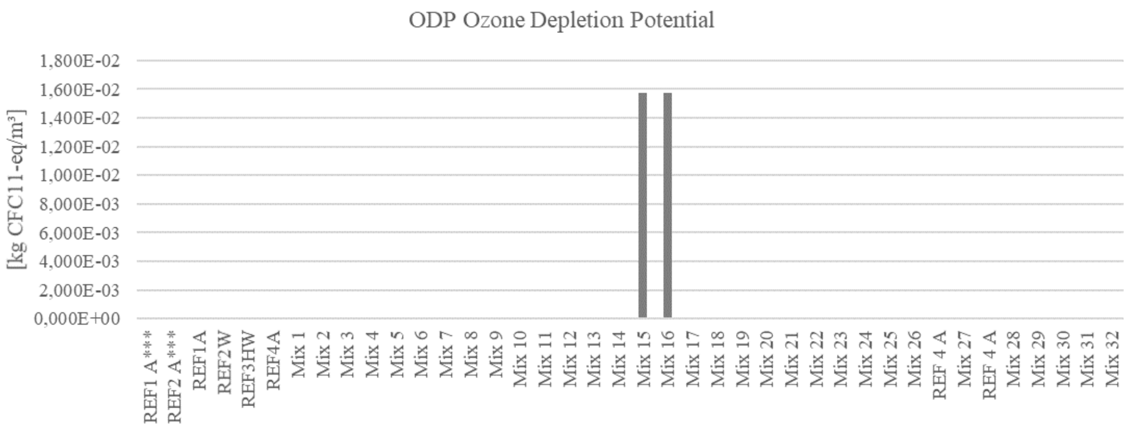


Fig. 39: ODP of all mixes, VAR II

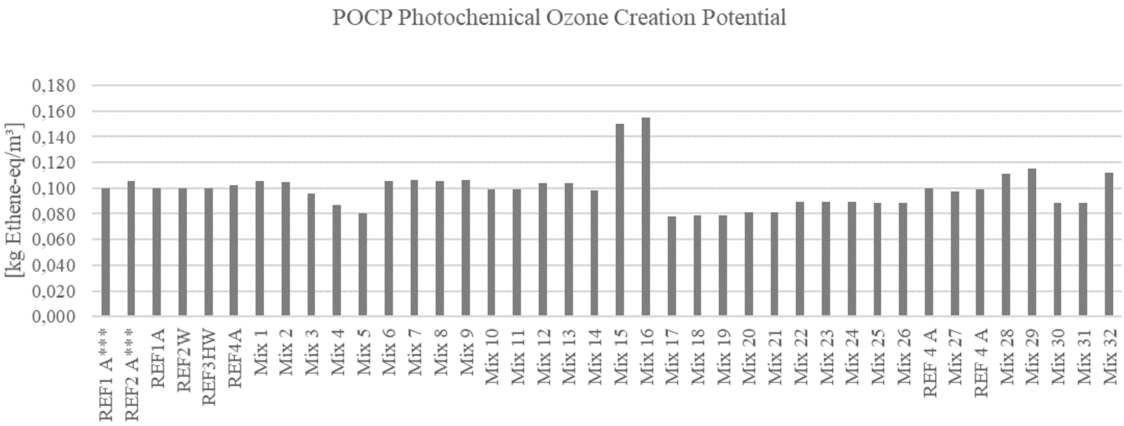


Fig. 40: POCP of all mixes

LCA of UHPC mixes: Conclusions

It is noticeable that the LCA values of Mix 5 are consistently the best. The recipe of this concrete mix has the lowest amount of cement in comparison with the others. In addition, a large amount of Diabase Sand was used, as well as other materials from the quarries, such as Limestone Powder and Dolomite Gravel.

Furthermore, mixes 17 to 21 stand out positively with regard to their Life Cycle Assessment. In these mixtures, the amount of cement (in this case white cement) was not reduced in comparison with the reference mixture. The admixture of secondary materials from quarries and a reduced amount of superplasticizer are decisive.

The worst LCA results are obtained from those mixes in which steel fibers have been added due to the influences of the steel production processes or in which the amount of superplasticizer (mix 32) is very high.

Since cement has the greatest influence on the environmental impact, those mixtures that are better from an ecological point of view, are those where more cement is substituted. The lower the cement content of the mixes is, the better the LCA results are. In conclusion, it could be said that the mixes with the lowest environmental impact are those with a low quantity of cement, no fibres and a high proportion of secondary materials replaced.

A comparison of the two variants shows that the difference in the LCA results is not very high. This can be justified by the fact that the characteristic values of the materials from the quarries are not decisive. The ecological footprint of the concrete can be decisively influenced by the cement content and the amount of superplasticizer.

The LCA results showed that the highest environmental impact occurs in the product stage A1-A3 during the process chain of steel fibers production and cement production. From an ecological point of view, the mixes with lowest environmental impact are those with a low quantity of cement, no fibers and high proportion of secondary materials.

The results of the investigations carried out regarding the reuse of secondary materials in UHPC were reported in the scientific publication “REUSE OF SECONDARY MATERIALS FROM QUARRIES AS AGGREGATES IN ULTRA HIGH PERFORMANCE CONCRETE” and presented in the SGEM Vienna Green Conference which took place on the 7th-10th December 2021.

Economical analysis of UHPC mixes made out of secondary materials

A cost estimate was made to provide an economic overview and comparison of the different mixes.

The prices of the materials are the following:

Tab. 16: Material prices [17] [18] [19] [20] [21] [22] [23] [24]

Material	price / t	price / kg
	[€]	[€]
Cement CEM I 42,5 R	129,684	0,129684
CEM II A-LL 42,5 R	122,412	0,122412
Microsilica/Silica Fume *	879,6	0,8796
Quartz Powder	559,2	0,5592
Quartz Sand	172,1	0,1721
Diabas Sand ***	4,22	0,00422
Diabas Powder **	20,82	0,02082
Limestone Powder **	10,95	0,01095
Dolomite Gravel ***	21,5	0,0215
Dolomite Sand ***	19,15	0,01915
Water	39,6	0,0396
SUP	5520	5,52
Fibers	3360	3,36

These prices were used to determine the cost of the individual mixture per m^3. Two variants were considered:

Variant a (VAR a): All material prices are included in the mixture costs.

Variant b (VAR b): The material prices for secondary materials – diabase powder and limestone powder – were set at € 0.

The results of the cost calculation of VAR a and VAR b were the following:

Tab. 17: Costs of all mixes VAR a and VAR b

VAR a - all prices included			VAR b - no costs for secondary materials		
Type	Mix	Costs [€/m³]	Type	Mix	Costs [€/m³]
Grey UHPC	REF1 A***	644,55	Grey UHPC	REF1 A***	644,55
Grey UHPC	REF2 A***	738,59	Grey UHPC	REF2 A***	738,59
Grey UHPC	REF1A	644,81	Grey UHPC	REF1A	644,81
Grey UHPC	REF2W	640,01	Grey UHPC	REF2W	640,01
Grey UHPC	REF3HW	640,01	Grey UHPC	REF3HW	640,01
Grey UHPC	REF4A	688,41	Grey UHPC	REF4A	688,41
Grey UHPC	Mix 1	682,52	Grey UHPC	Mix 1	681,18
Grey UHPC	Mix 2	653,93	Grey UHPC	Mix 2	652,36
Grey UHPC	Mix 3	622,98	Grey UHPC	Mix 3	620,48
Grey UHPC	Mix 4	618,41	Grey UHPC	Mix 4	614,98
Grey UHPC	Mix 5	358,52	Grey UHPC	Mix 5	355,88
Grey UHPC	Mix 6	578,53	Grey UHPC	Mix 6	573,43
Grey UHPC	Mix 7	676,34	Grey UHPC	Mix 7	673,37
Grey UHPC	Mix 8	421,04	Grey UHPC	Mix 8	418,38
Grey UHPC	Mix 9	436,43	Grey UHPC	Mix 9	433,77
Grey UHPC	Mix 10	485,79	Grey UHPC	Mix 10	483,36
Grey UHPC	Mix 11	313,42	Grey UHPC	Mix 11	309,92
Grey UHPC	Mix 12	291,37	Grey UHPC	Mix 12	291,37
Grey UHPC	Mix 13	314,50	Grey UHPC	Mix 13	311,96
Grey UHPC	Mix 14	302,15	Grey UHPC	Mix 14	298,97
Grey UHPC	Mix 15	841,26	Grey UHPC	Mix 15	837,67
Grey UHPC	Mix 16	818,89	Grey UHPC	Mix 16	818,89
White UHPC	Mix 17	295,57	White UHPC	Mix 17	292,39
White UHPC	Mix 18	479,02	White UHPC	Mix 18	476,59
White UHPC	Mix 19	478,42	White UHPC	Mix 19	476,00
White UHPC	Mix 20	310,83	White UHPC	Mix 20	307,25
White UHPC	Mix 21	310,93	White UHPC	Mix 21	307,65
White UHPC	Mix 22	554,07	White UHPC	Mix 22	551,29
White UHPC	Mix 23	570,85	White UHPC	Mix 23	568,07
White UHPC	Mix 24	570,85	White UHPC	Mix 24	568,07
White UHPC	Mix 25	608,11	White UHPC	Mix 25	608,11
White UHPC	Mix 26	636,22	White UHPC	Mix 26	636,22
Grey UHPC	REF 4 A	641,27	Grey UHPC	REF 4 A	641,27
Grey UHPC	Mix 27	446,16	Grey UHPC	Mix 27	443,73
Grey UHPC	REF 4 A	637,35	Grey UHPC	REF 4 A	637,35
White UHPC	Mix 28	483,70	White UHPC	Mix 28	481,51
White UHPC	Mix 29	553,80	White UHPC	Mix 29	551,61
White UHPC	Mix 30	460,04	White UHPC	Mix 30	457,85
White UHPC	Mix 31	549,95	White UHPC	Mix 31	545,57
White UHPC	Mix 32	883,47	White UHPC	Mix 32	874,71

The following graphs show an overview of the costs:

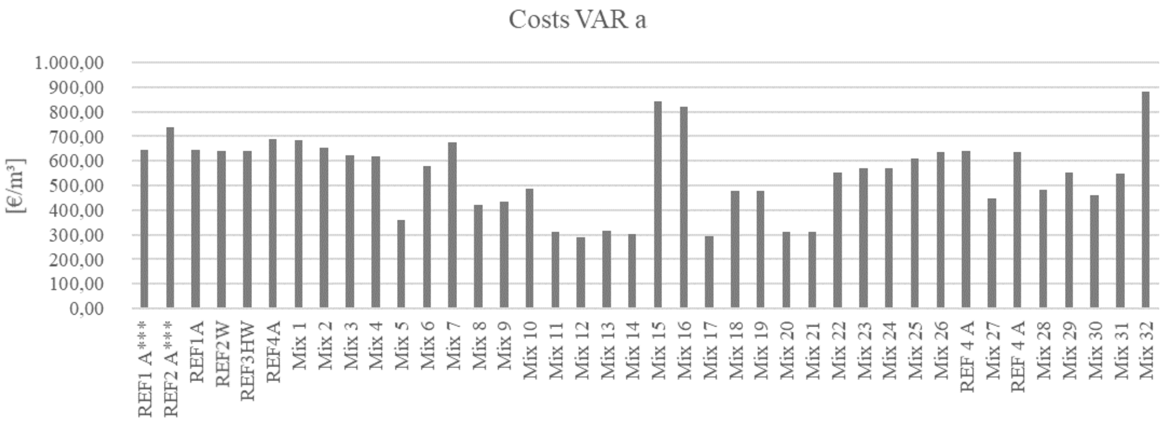


Fig. 41: Costs all mixes VAR a

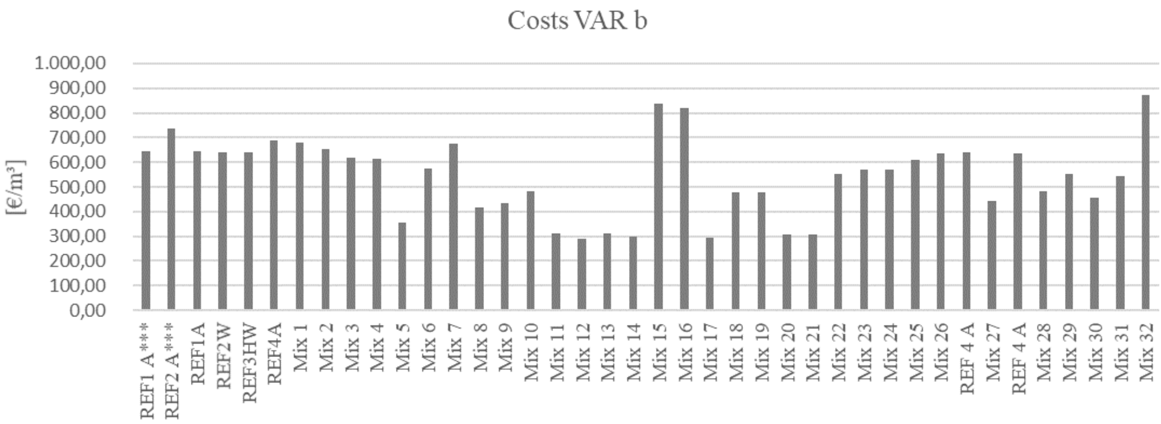


Fig. 42: Costs all mixes VAR b

Economical analysis of UHPC mixes: Conclusions

It can be concluded that the most expensive mixes are those which contain steel fibers and high amounts of superplasticizer. The most cost-efficient mixes were those with a high proportion of secondary materials or those were Quartz Sand was replaced in high amounts by secondary materials.

White Ultra High Performance Concrete

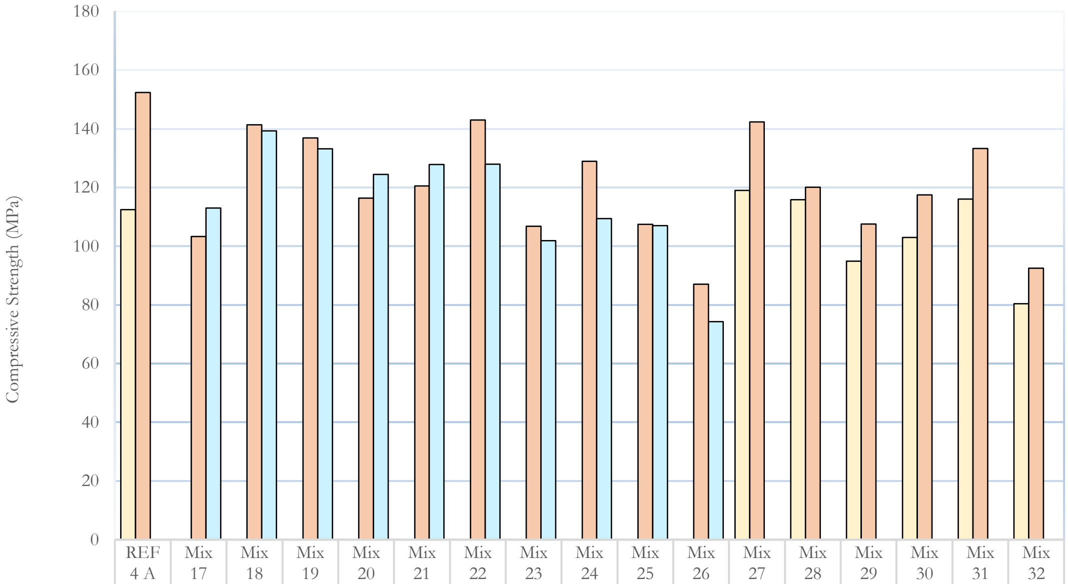
In the last section it was described the design of recipes with grey cement. As the results obtained showed good results of compression strength, it was decided to design recipes with white cement in order to get an aesthetic finishing. The main goal was to produce Façade Elements. For this experiment, the whitest secondary materials collected from quarries were used and also white cement was used in order to re-create the natural stone colour. After that, pigments were also used in combination with white cement in order to test if light colors could be obtained. Thin plates of 60 x 40 x 1 cm were cast. The recipes selected to cast the Ultra High Performance Concrete (UHPC) plates contain a high proportion of secondary materials from quarries. The normal aggregates used to mix UHPC like Cement I 42,5R (d10= 6,1732 µm, d90= 39,7122 µm); Microsilica (d10= 0,7924 µm, d90= 54,5041 µm); Quartz Powder (d10= 1.5660 µm, d90= 42.5004 µm) and Quartz Sand (0,1/0,4 mm) were replaced by secondary materials collected from quarries: These materials were substituted by the following secondary materials: Diabase Sand (0/2 mm); Diabase Powder (d10= 3.5300 µm, d90= 135.1871 µm); Dolomite Sand (0/2 mm); Dolomite Gravel (2/4 mm); Limestone Powder (d10= 0.2975 µm, d90= 21.8949 µm).

UHPC was chosen to cast Façade Elements since its high weathering resistance. The high durability of UHPC allows to make very thin plates with a longer service life reducing maintenance costs from façades. The reuse of secondary materials reduce the disponsal of waste from the quarries in the nature and consequently the environmental impact is reduced. This allows the "waste" to be considered a valuable resort and insert it again as a good quality aggregate in building construction market. Moreover, the fact of making environmental friendly UHPC based on secondary natural materials from quarries allows a healthier production of UHPC by the reduction of the usage of non sustainable, expensive and lung harmful respirable crystalline silica particles present in ultra fine powders like microsilica, quartz powder, quartz sand currently used in UHPC.

For this investigation, grey cement was replaced by white Cement CEM IIA-LL 42,5 R and small amounts of Silica aggregates like Microsilica, Quartz Powder and Quatzt Sand were used. Most of them were replaced by light coloured secondary materials from quarries like Limestone Powder (IT), Dolomite Sand and Gravel (AT). The method used for the design of the mixes was based on the principle of optimization of the particle packing density of Funk and Dinger mentioned before [4]. The performed tests were compression strength on cubes 100 x 100 x 100 mm and flexural strength on thin plates of 60 x 40 x 1 cm.

Fig. 43: Light coloured UHPC thin plates

The results of the compression strength are shown in the following table:



	REF 4 A	Mix 17	Mix 18	Mix 19	Mix 20	Mix 21	Mix 22	Mix 23	Mix 24	Mix 25	Mix 26	Mix 27	Mix 28	Mix 29	Mix 30	Mix 31	Mix 32
7 d. Air cured (MPa)	112,41											119,06	115,79	94,94	102,93	116,1	80,36
28 d. (MPa) Air cured	152,43	103,32	141,38	136,93	116,38	120,50	143,05	106,83	128,98	107,50	87,01	142,35	120,09	107,53	117,44	133,25	92,47
28 d. (MPa) Water cured		112,97	139,31	133,19	124,42	127,88	127,90	101,92	109,40	107,05	74,28						

Fig. 44: Compressive strength results

White UHPC: Conclusions

The values of compression strength for UHPC recommended by the Swiss Standards [5] are values higher than 120 MPa. The test shows that it was possible to get UHPC with a compression strength higher than 120 MPa. Mix 22 showed the highest value of air cured samples at 28 days and the value was 143,05 MPa. This value was followed by Mix 27 reaching 142,35 MPa and Mix 18 with 141,38 MPa.

Flexural strength test of UHPC plates

In order to perfom flexural strength tests on the plates described in the last sections new batches were cast. The first batch of plates were cast with UHPC without any type of reinforcement. The second batch was reinforced with glass textile and polypropylene fibres (PP fibres) to improve the mechanical and fire resistance properties of the plates (see Fig.46). The test set up and the glass textile reinforcement can be seen in Figs. 45 and 47:

Fig. 45: Flexural strength test

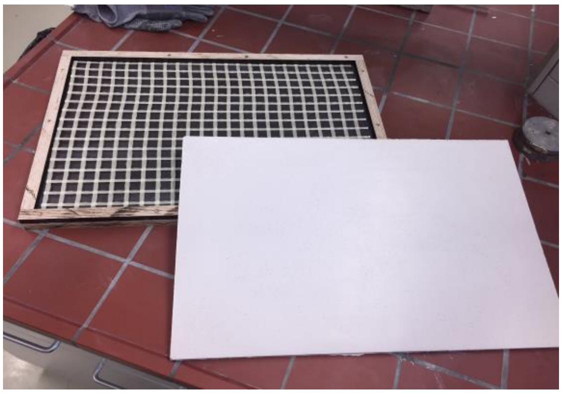


Fig. 46: Plates with glass textile in the middle of the place

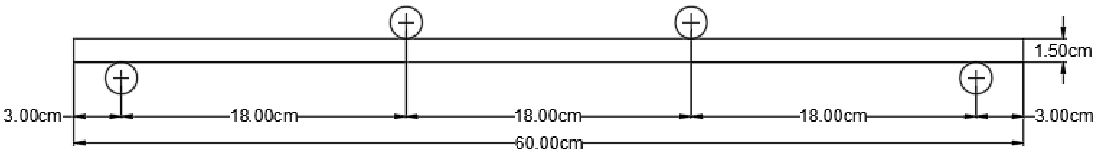


Fig. 47: Flexural test setup

In order to compare the values of flexural strength, a reference sample was cast and tested. The plates' dimensions are 40 x 60 x 1,5 cm. Two batches of four plates each were cast. One batch was UHPC made out of secondary materials from quarries adding PP fibers and glass textile reinforcement to improve the mechanical properties and another one was only UHPC made out of secondary materials from quarries without admixtures in order to compare how the mechanical properties improve. The cracking scenarios differ a lot when adding PP fibres and glass textile as it can be seen in Figs. 48-57. The curves of the samples without PP fibres and glass textile showed a brittle failure: one peak of maximum load can be seen corresponding to the moment of the failure. In contrast with this, the samples containing PP fibers and glass textile showed a ductile failure: multiple cracking peaks can be seen before the final failure due to the of the presence of glass textile reinforcement that prevented a sudden collapse. The final failure took place after considerable cracking and the failure of the grid. The following graphs show the curves of load vs. deflexion of both cases: those plates without admixtures and the plates that contain PP fibres and glass textile (this last case is named in the graphs using the format "Name of mix + F + T" where "F" is the abbreviation for the word Fibres "F" and "T" is the abbreviation for glass textile).

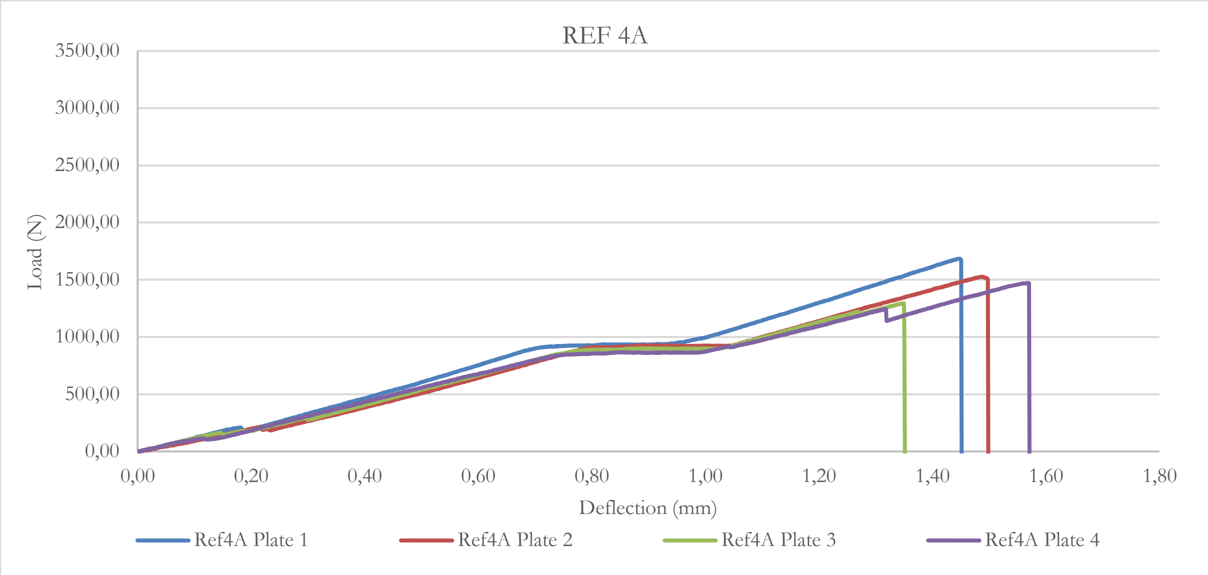


Fig. 48: Ref 4A Flexural strength test of plates without PP fibres and Glass Textile (brittle failure)

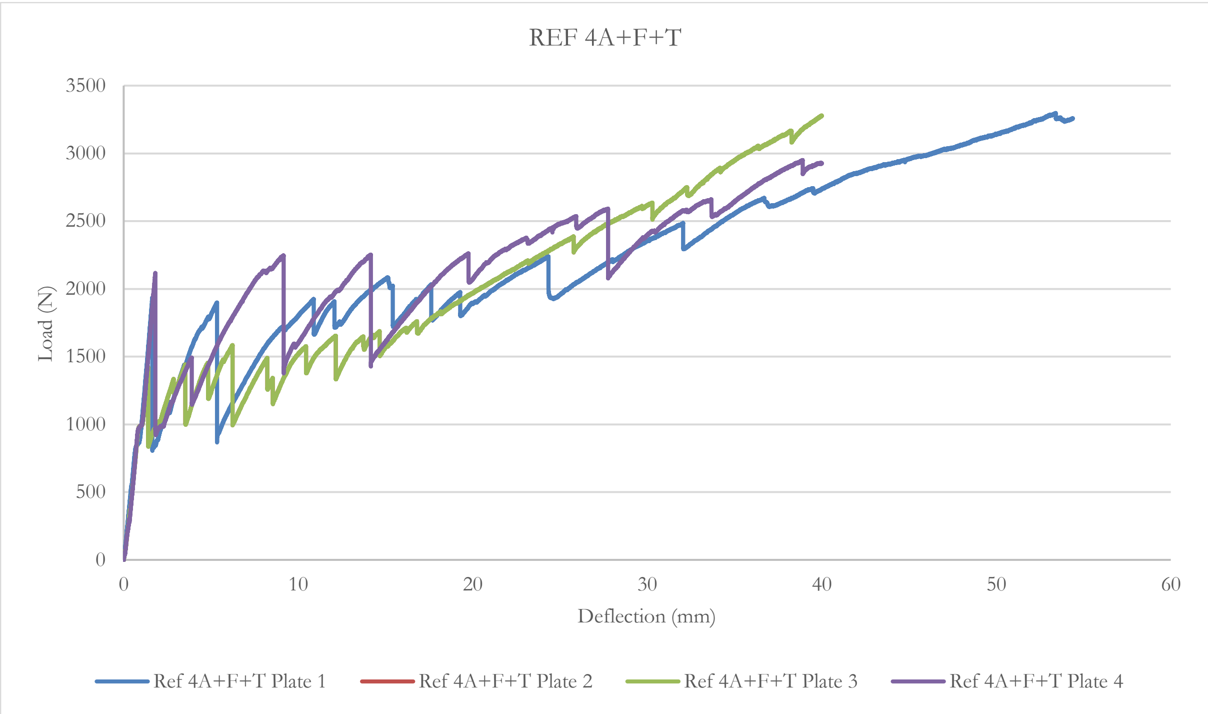


Fig. 49: Ref 4A Flexural strength test of plates with PP fibres and Glass Textile (Ductile behavior)

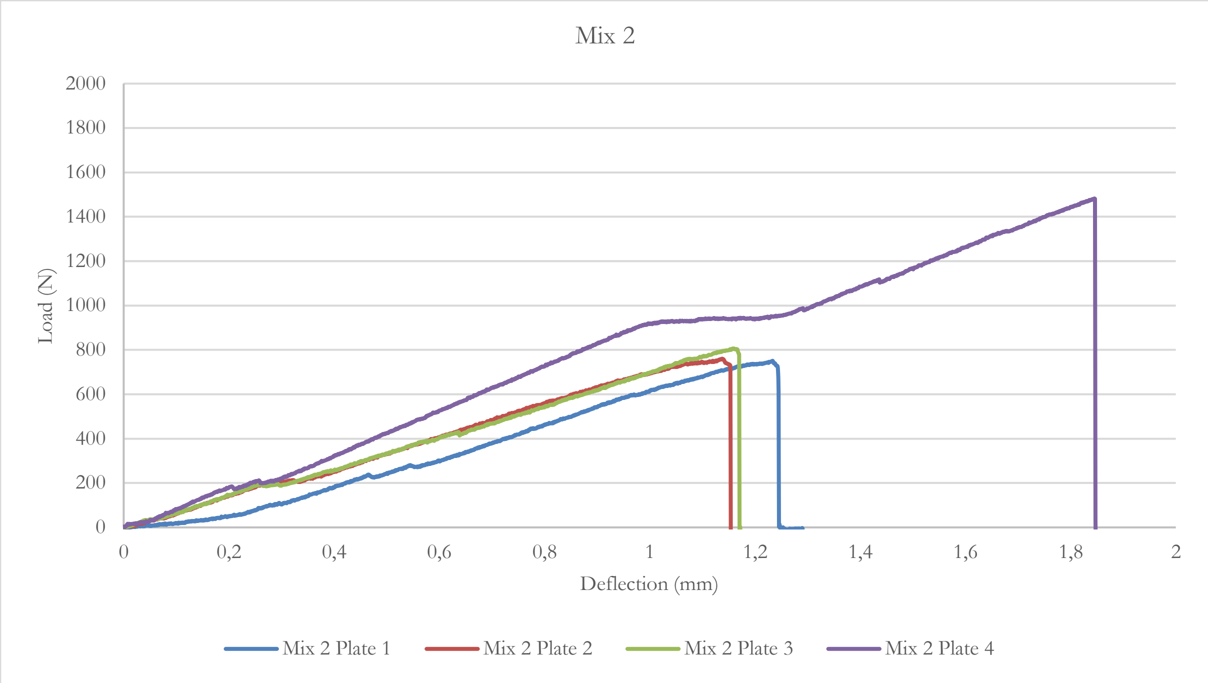


Fig. 50: Mix 2 Flexural strength test of plates without PP fibres and Glass Textile (brittle failure)

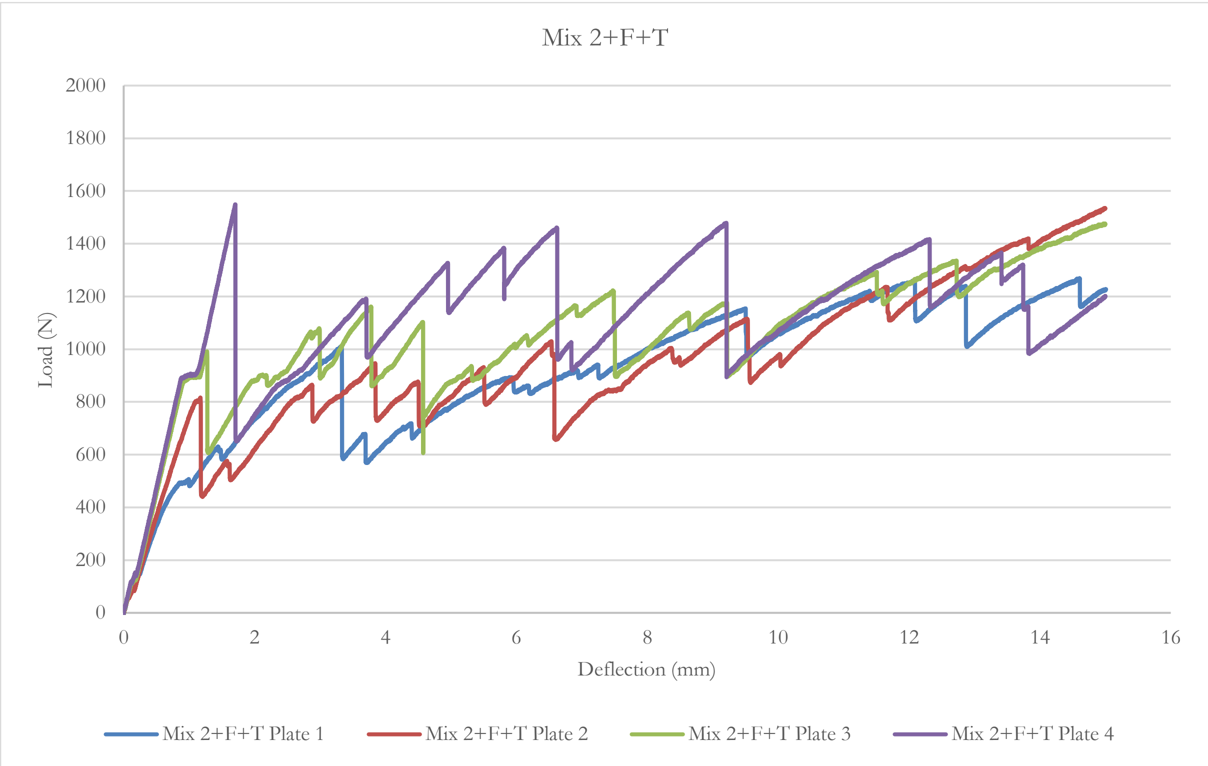


Fig. 51: Mix 2 Flexural strength test of plates with PP fibres and Glass Textile (Ductile behavior)

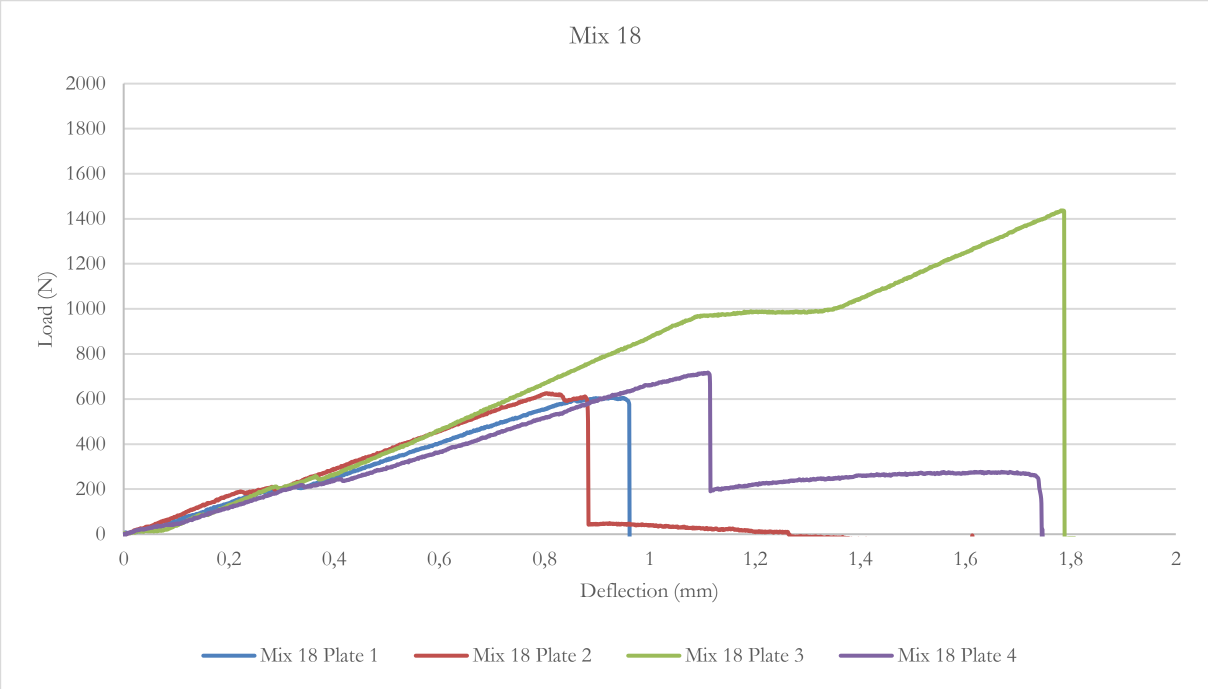


Fig. 52: Mix 18 Flexural strength test of plates without PP fibres and Glass Textile (brittle failure)

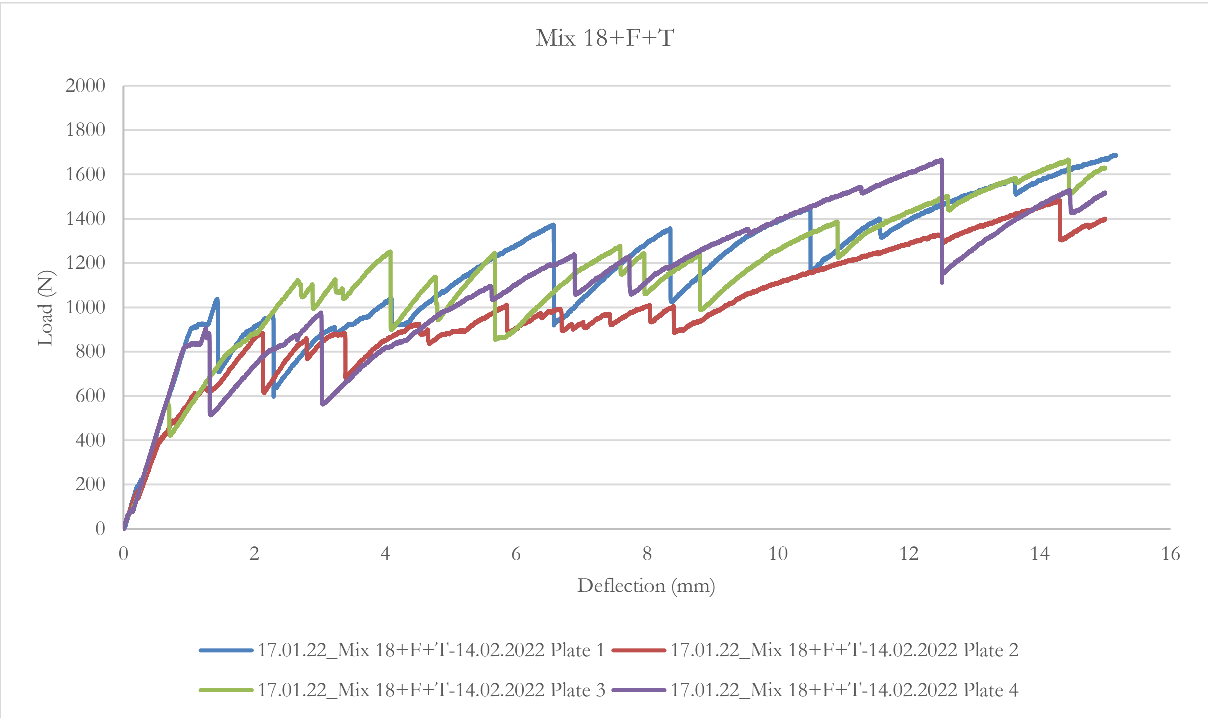


Fig. 53: Mix 18 Flexural strength test of plates with PP fibres and Glass Textile (Ductile behavior)

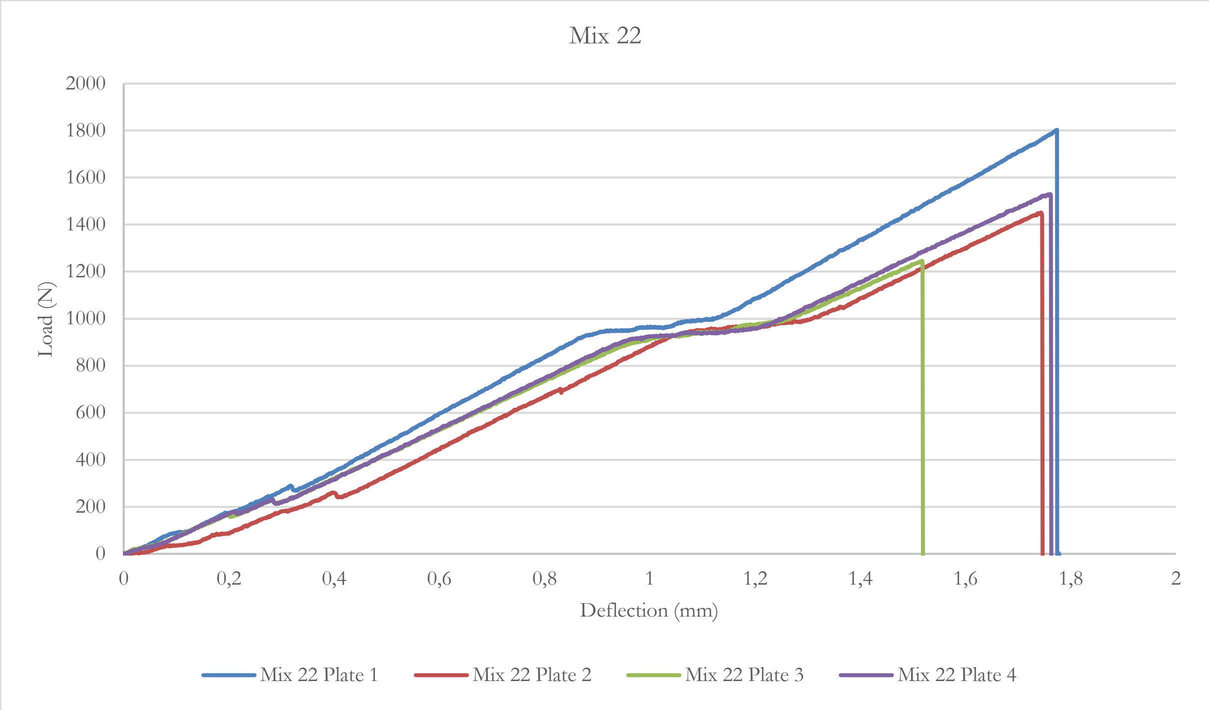


Fig. 54: Mix 22 Flexural strength test of plates without PP fibres and Glass Textile (brittle failure)

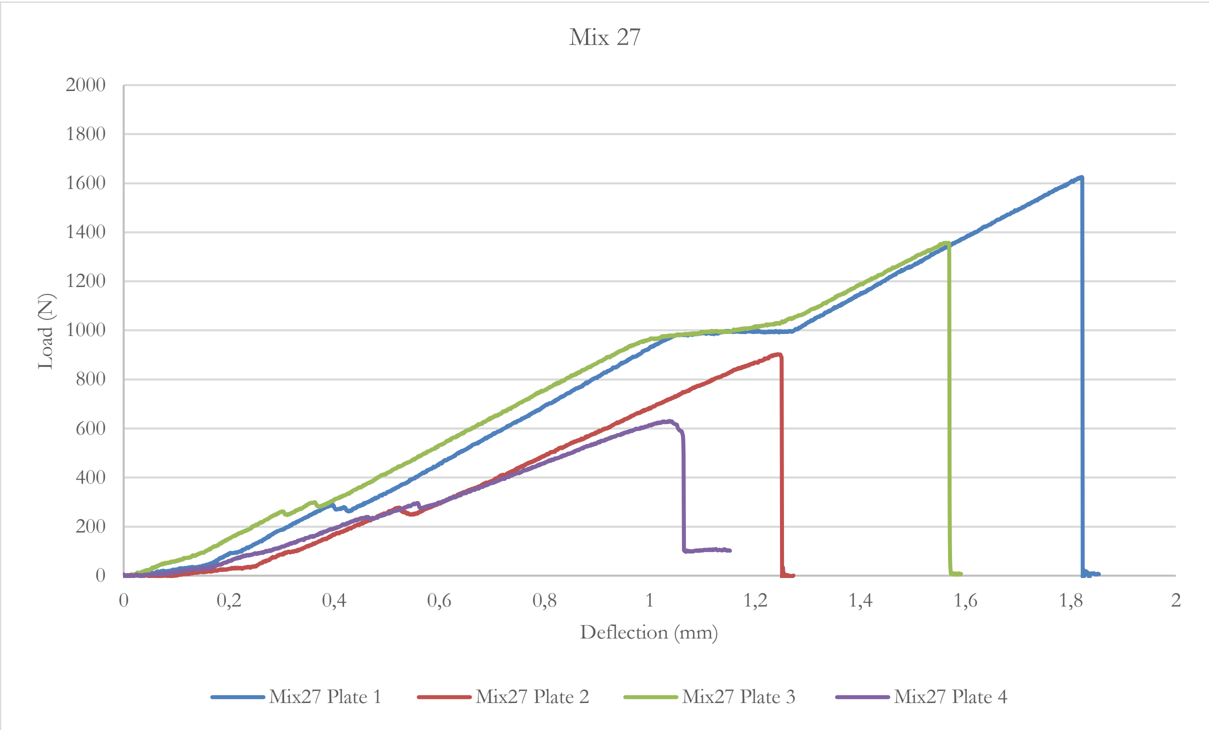


Fig. 55: Mix 27 Flexural strength test of plates without PP fibres and Glass Textile (brittle failure)

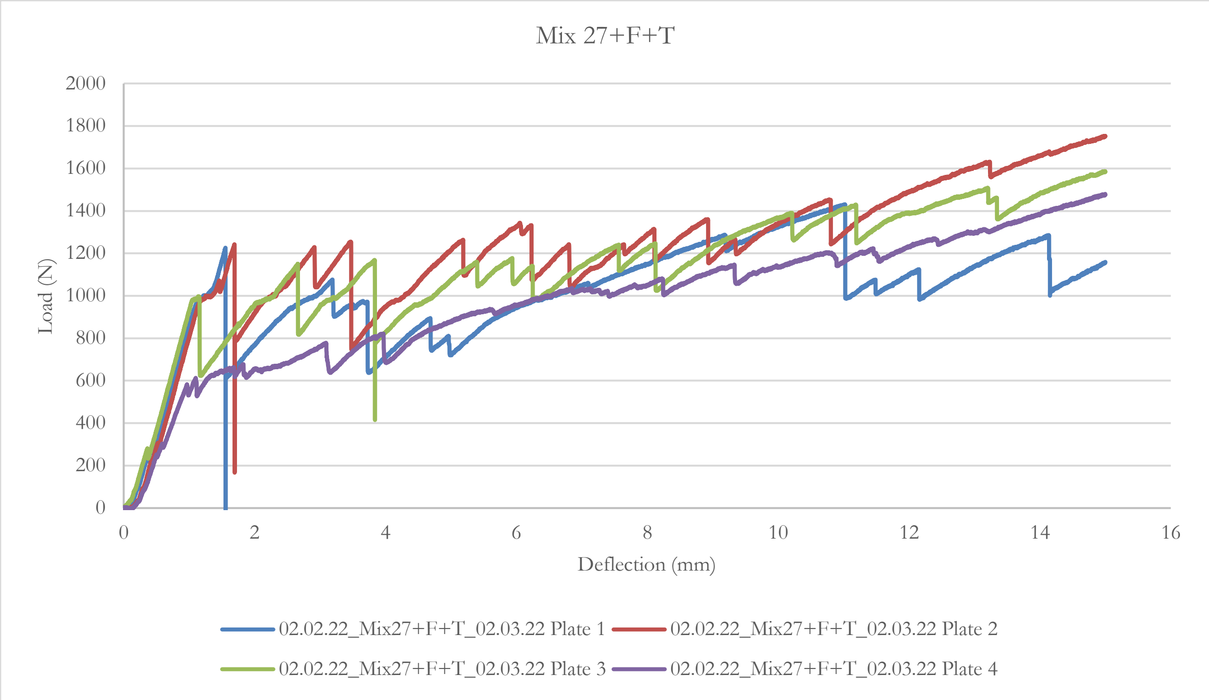


Fig. 56: Mix 27 Flexural strength test of plates with PP fibres and Glass Textile (Ductile behavior)

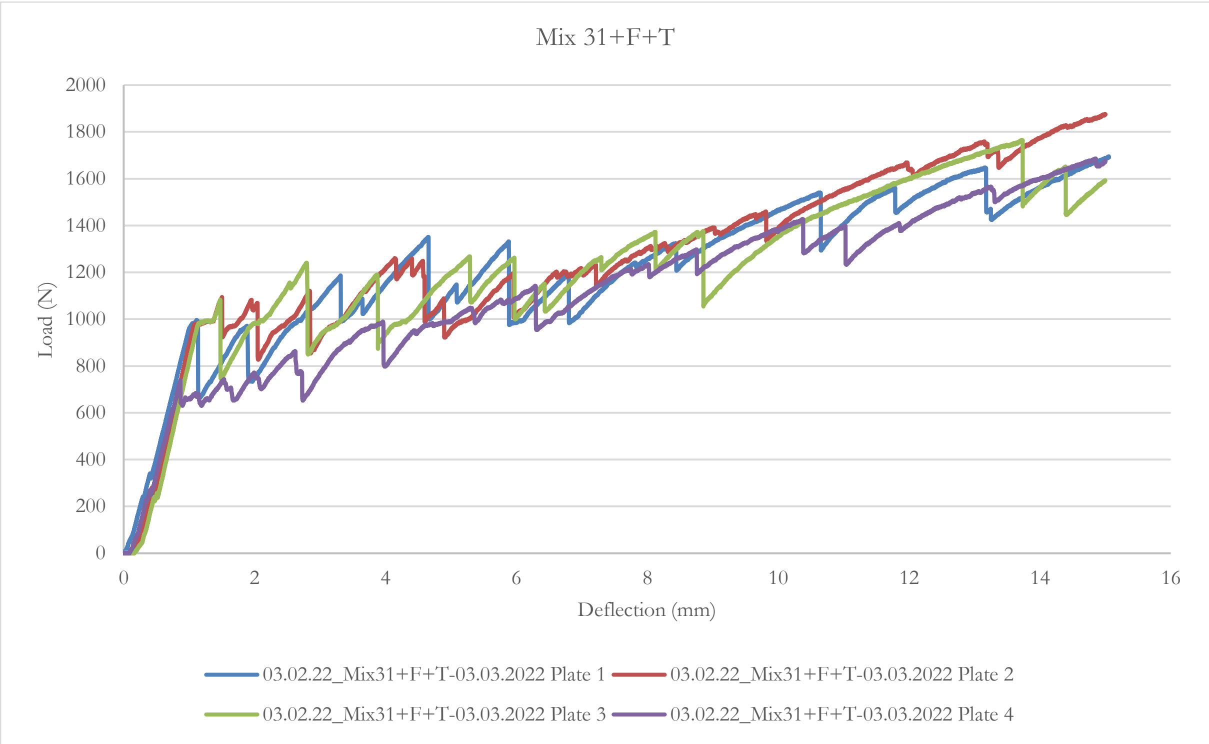


Fig. 57: Mix 31 Flexural strength test of plates with PP fibres and Glass Textile (Ductile behavior)

The mean values of flexural strength were calculated:

Tab. 18: Mean Flexural Strength values

Designation	Peak load (kN)	Deflection (mm)	Mean Flexural strength (MPa)	Increase/decrease with respect to REF 4A (%)
REF 4 A	1.68	1.45	9.64	
REF 4 A with PP fibers + Glass Textile	3.30	53.39	18.75	94.62
Mix 2	1.48	1.84	5.70	-40.85
Mix 2 with PP fibers + Glass Textile	1.54	15.00	9.21	-4.38
Mix 18	1.44	1.78	8.62	-10.51
Mix 18 with PP fibers + Glass Textile	1.69	15.16	10.04	4.24
Mix 22	1.80	1.77	10.00	3.76
Mix 27	1.63	1.82	8.95	-7.14
Mix 27 with PP fibers + Glass Textile	1.75	15.00	10.02	4.00
Mix 31 with PP fibers + Glass Textile	1.88	15.00	10.53	9.31

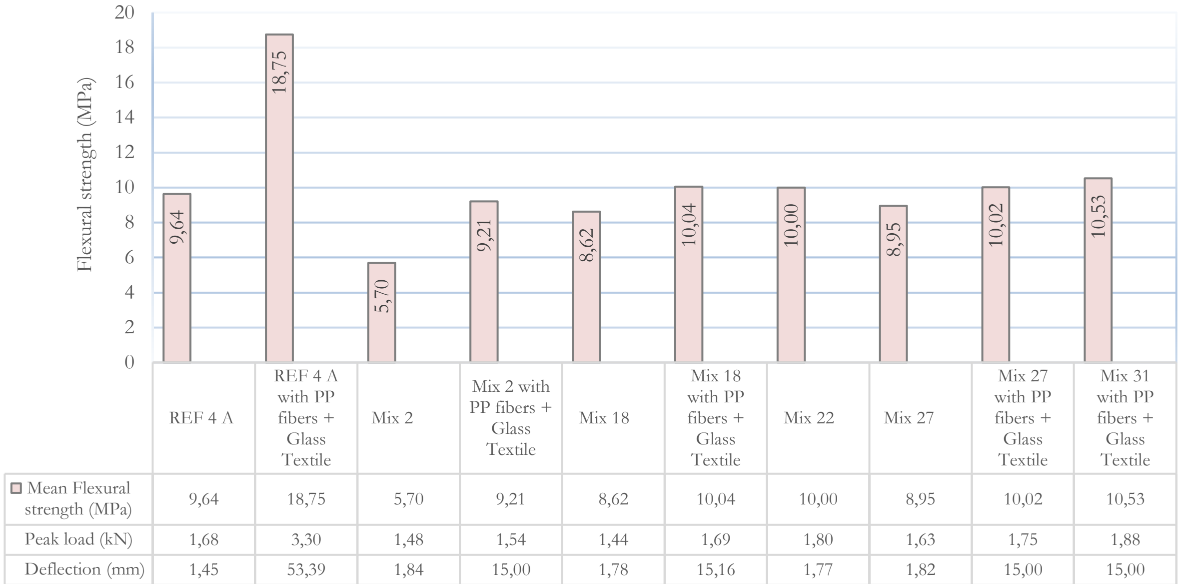


Fig. 58: Mean Flexural Strength values

Flexural strength test of UHPC plates: Conclusions

It was observed that the values of flexural strength increase when the PP fibres and the glass textile was added. The values of deflection increase by using glass textile and the plates adopted a ductile failure behavior. The highest value of flexural strength from those mixes of UHPC made out of secondary materials was mix 22 reaching 10 MPa, followed by mix 31 made with PP fibres and glass textile and which value was 10,53 MPa.

In terms of security, it can be said, that in the case that the façade element would detach from the structure and fall to the ground, the glass textile reinforcement prevents the façade element from being destroyed into several pieces that could be scattered and injure someone. By using glass textile reinforcement, the broken pieces of the façade element are held together by the mesh structure.

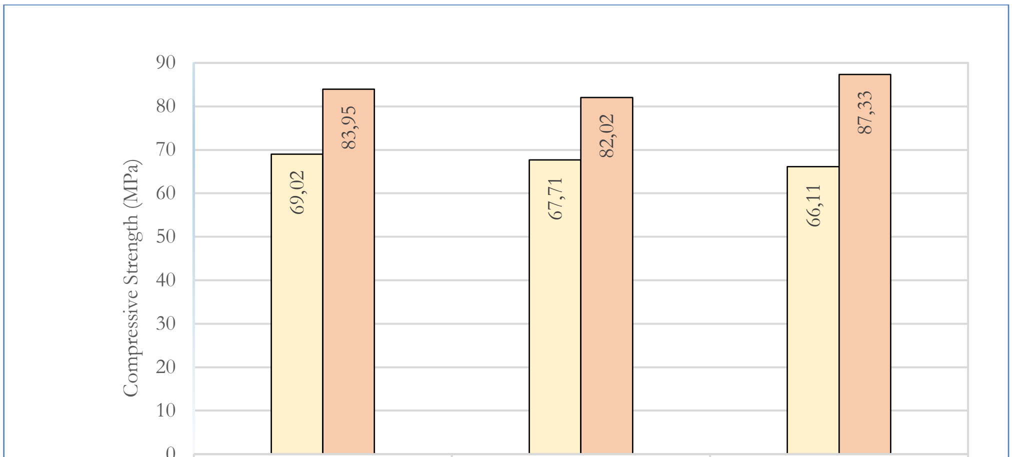
UHPC as Recycled Concrete Aggregate (RCA)

The goal of this investigation was to check if it is possible to use UHPC as a high quality RCA. The main idea was to crush old samples of UHPC made out of secondary materials from quarries to check if it is possible to reuse it as coarse aggregate in Normal Strength Concrete C50/60. The RCA mixes were the following:

Tab. 19: Designed mixes

Mix	Quantities in (kg/m³)							
	Grey Cement W&P CEM I 42,5 R	Diabas Sand 0/2mm	Dolomite Gravel 4/8mm	Dolomite Sand 0/2mm	RCA 0/8mm	Water	SUP	w/c [-]
Mix 1	500	1149.46	–	–	492.6271	225	4	0.45
Mix 2	500	–	–	1149.46	492.6271	225	4	0.45
Mix 3	500	–	82.1	985.25	574.73	225	2.3	0.45

Compression strength tests were performed on the RCA samples and the results were the following:



	Mix 1	Mix 2	Mix 3
7 days (MPa)	69,02	67,71	66,11
28 days (MPa)	83,95	82,02	87,33

Fig. 59: Compression strength values

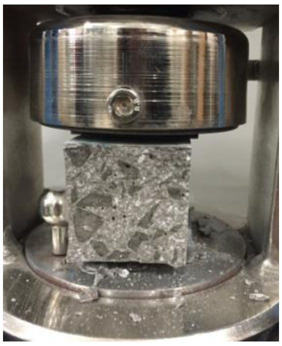


Fig. 60: Compression strength test

Fig. 61: UHPC used as RCA in Normal Strength Concrete mixes

UHPC as RCA: Conclusions

The values of compression strength at 7 and 28 days show optimal values for Normal Strength Concrete C50/60 containing RCA from UHPC according to the values recommended by the ÖNORM B4710-1 [1].

Whide Wheel Abrasion Test of UHPC

The Whide Wheel abrasion (WWA) test method described in the ÖNORM EN 14157 [7]is used to determinate the resistance of natural stone. The investigations already described about UHPC made out of secondary materials from quarries showed that is possible to obtain values higher than 120 MPa of compressive strength. This means that this material could have a long service life and a high durability. Considering that UHPC can be cast in any mould, it could be of great interest to determine whether it is possible to use this material as a floor covering, either in tile format or as a screeded concrete, for those areas with intense foot traffic. For this purpose, an abrasion test was carried out to determine if UHPC made out of secondary materials is suitable for use in flooring.

Two batches of ten specimens of 50 x 100 x 150 mm were cast and tested following the mentioned standard. The first batch cast was the reference mixture Mix REF 4A and for the second batch Mix 27 was cast since it is values of compression strength were higher than 120 MPa at 28th days. The speciments were tested for abrasion resistance after 28th days. During the test, the face of the specimen is abraded with a rotating wheel and normalized abrasive. The result of the test is given by the width of the groove in mm. The results can be seen in tables 20 and 21:

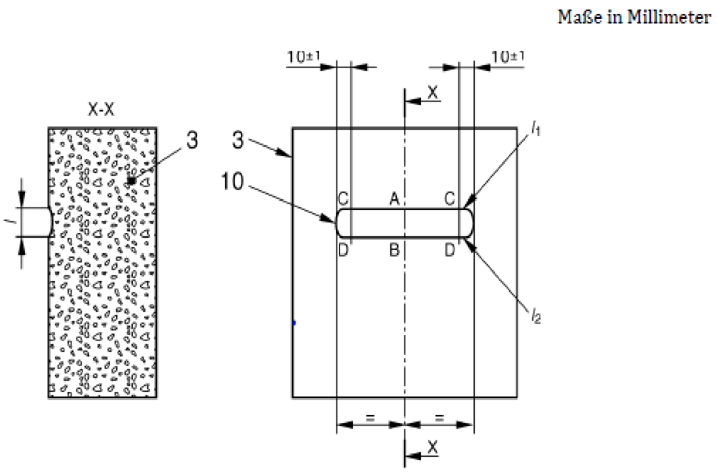


Fig. 62: Width of the groove to be measured [25]

Tab. 20: Width of the groove in mm Ref 4A

Ref 4A	A (mm)	B (mm)	C (mm)	Partial Average (mm)
Marble reference block	19.91	20.12	19.99	20.01
Versuch 1	18.77	18.71	18.29	18.59
Versuch 2	19.08	19.03	19.35	19.15
Versuch 3 (Failed)				
Versuch 4	18.67	18.65	18.98	18.77
Versuch 5	19.98	20.16	20.09	20.08
Versuch 6	19.39	19.06	18.41	18.95
Versuch 7	20.38	19.84	20.40	20.21
Versuch 8	18.65	18.77	18.75	18.72
Versuch 9	17.86	17.83	17.63	17.77
Versuch 10 (Failed)				
			Result (mm):	19.02

Tab. 21: Width of the groove in mm Mix 27

Mix 27	A (mm)	B (mm)	C (mm)	Partial Average (mm)
Marmor Referenzblock	19.91	20.12	19.99	20.01
Versuch 1	20.72	19.55	21.56	20.61
Versuch 2	20.82	21.80	19.80	20.81
Versuch 3 (Failed)				
Versuch 4	21.76	21.24	20.49	21.16
Versuch 5	19.73	20.17	18.78	19.56
Versuch 6 (Failed)				
Versuch 7	21.28	19.72	20.53	20.51
Versuch 8 (Failed)				
Versuch 9	20.03	19.00	19.33	19.45
Versuch 10	20.53	22.59	18.49	20.54
			Result (mm):	17.82

Some researchers like Marradi et al. [8] proposed a classification scheme based on the WWA test data:

- Little abradable materials: WWA < 16 mm
- Average abradable materials: WWA = 16-21 mm
- Abradable materials: WWA > 21 mm

Whide Wheel Abrasion Test of UHPC: Conclusions

The reference mixture REF 4A showed a value of abrasion resistance of 19,02 mm while the Mix 27 showed a value of 17,82 mm. These values can be classified as medium average abradable materials suitable for flooring according to the classification mentioned.

Thermal test

Thermal tests: Balls

The following research was made to check the behavior of the different types of waste material of different quarries and its ability to shape balls. As a starting point, it was decided to make a batch of samples with the aim to produce a lightweight porous material. The first batches were made with different combinations of materials: Diabase Sand, calc, clay, fly ash and sawdust. The equipment used to shape the balls was an EIRICH-Intensivemixer. The results of the different mixes are shown in the following figures:

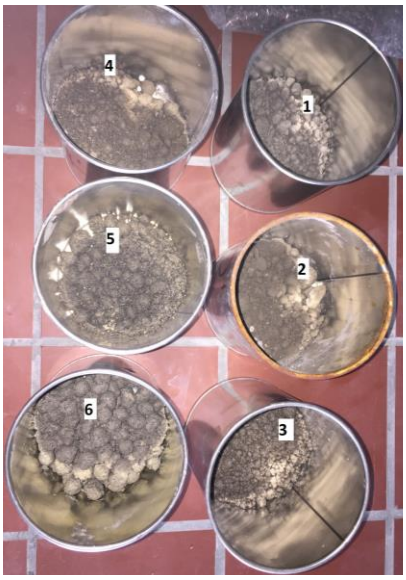


Fig. 63: Balls made out of different materials

Fig. 64: Balls in the oven

After shaping the different mixes, it possible to see that adding clay and calc was important to give plasticity to the mixtures. This allowed to shape balls in an easier and faster way compared with the usage of Diabase Sand only.

Sawdust was added in order to make ligher balls. The idea was to expose the balls to fire, burn the sawdust and obtain a porous material. However, sawdust didn't stick to the other materials in the mixture, tending to disaggregate and making it difficult to shape balls.

Regarding the admixture of fly ash, it was possible to see that it was not either a sticky material. The admixture of fly ash and sawdust was made in lower amounts since the mixture tended to disaggregate.

Moreover, the mixture containing Diabase Sand, clay, water and calc was the most suitable to shape balls in an easier and faster way presenting no disaggregation. The rest of the mixtures showed disaggregation and shaping balls was not possible.

Once that the balls were shaped, they were exposed to a thermal process. A smaller amount of balls of each mixture were put into an oven and exposed to two thermal cycles: the first cycle was 4 hours at 400°C and the second cycle was 4 hours at 800°C.

The aim was to fire the clay inside the balls in order to sinter it and get a harder and porous material. After taking out the samples out of the oven, it was observed that the balls were easily breakable with the hands. A second batch was made with another type of clay. New mixtures were designed and fired in two cycles, the first one was 4 hours at 400 °C and the second one was 4 hours at 1000 °C (see Table 22). The batches are showed in the following pictures:

Fig. 65:.Balls before firing

Fig. 66: Balls after firing

It was observed that the balls changed their colour from a grey-brown colour to a red-yellow colour. After the material cooled down, it was pressed and observed that it was more difficult to break than the other batches. It is important to say that not all of the mixtures took the same amount of water. 50 ml were needed to shape the balls. The water was added in low quantities while the rotating mixer was on. A higher amount of water could turn the dry mass into a liquid paste and cosequently it would have been not possible to shape balls. The Second Batch was also fired in two steps, the first step was 4 minutes at 400 °C and the second step was 8 minutes at 1100 °C. After the firing process only samples 10, 11, 12 were hard enough to need a hamer to break them. Samples 8 and 9 were easy to break with the hands. The clay that at first was yellow changed the color to red (see Fig. 65-66). The samples containing calc turned to have small white rocks inside and were easy breakable. In the next tables the firing process and the mixes are shown:

Tab. 22: Firing process

Firing process	Time (min)	Temperature (°C)
Step 1	4	400
Step 2	8	1100
Ramp to reach desidered temperature	40	0-400; 400-1100

Tab. 23: Mixes for the produciton of thermal balls

Samples	Materials	Mass (gr)	% w/w
Sample 8	Diabase Sand	163.77	37.71
	Calc	56.7	13.06
	Clay	163.77	37.71
	Water	50	11.51
Sample 9	Diabase Sand	327.55	56.67
	Clay	220.47	38.14
	Water	30	5.19
Sample 10	Diabase Sand	327.55	41.41
	Clay	333.47	42.16
	Fly Ash	40	5.06
	Sawdust	40	5.06
	Water	50	6.32
Sample 11	Diabase Sand	272.9	35.45
	Clay	357	46.37
	Fly Ash	80	10.39
	Sawdust	10	1.3
	Water	50	6.49
Sample 12	Diabase Sand	307.2	47.2
	Clay	247.9	38.09
	Fly Ash	35.7	5.49
	Sawdust	10	1.54
	Water	50	7.68

Thermal test: Prisms

In order to test the compression strength of the mixes designed to shape balls, prismatic samples were casted with the same mix. For getting a paste it was necessary to add more water as it is shown in Table 23-24. The mixes that showed a good behavior for shaping balls and those which were hard when exposing them to high temperature were mixed again in prismatic shapes in order to expose the samples to fire, sinter the paste and then test the specimens to compression strength.

Tab. 24: Mixes for the thermal testing

Samples	Materials	Mass (gr)	% w/w
Sample 8	Diabase Sand	163.77	33.82
	Calc	56.7	11.71
	Clay	163.77	33.82
	Water	100	20.65
Sample 9	Diabase Sand	327.55	50.55
	Clay	220.47	34.02
	Water	100	15.43
Sample 10	Diabase Sand	327.55	36.76
	Clay	333.47	37.43
	Fly Ash	40	4.49
	Sawdust	40	4.49
	Water	150	16.83
Sample 11	Diabase Sand	272.9	31.37
	Clay	357	41.04
	Fly Ash	80	9.2
	Sawdust	10	1.15
	Water	150	17.24
Sample 12	Diabase Sand	307.2	40.92
	Clay	247.9	33.02
	Fly Ash	35.7	4.75
	Sawdust	10	1.33
	Water	150	19.98

For making balls the amount of water was 50ml. For getting the consistency of a paste, it was necessary to add between 100ml and 150ml. The mixes containing sawdust needed 150ml since this material needs more water to get mixed with the other materials. Three samples of each mixture were made. The moulds were filled in in two layers and compacted by giving 30 hits with a hitting table. After that, they were left at room temperature to dry for four days and then taken out of the moulds.

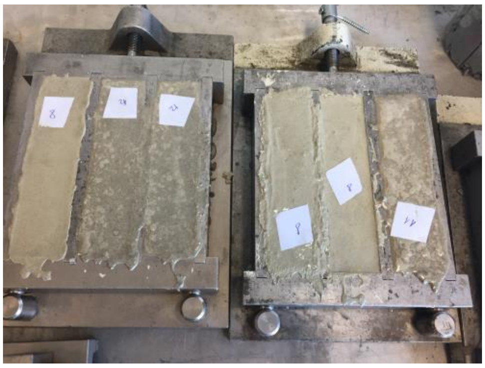


Fig. 67: Different mixture samples

Fig. 68: Firing process

The first step was drying them at 93°C in the oven. After that, the samples were pre heated for 20 minutes at 400°C to avoid cracking during the sintering process. After that, the temperature of the oven was setted up to raise up till 1200°C for another 20' for the sintering process. The heating ramp to reach every setted temperature took 40' (see Table 25). In the sintering process, it is expected that the small rocks are melted and then there would be a gain of strength in the samples. The temperature reached was 1157°C after 4 hours. The prism samples were fired in accordance to the steps mentioned before.

Tab. 25: Firing process

Firing process	Time (min)	Temperature (°C)
Step 1: Drying process	40	93
Step 2: Pre-heating process	20	400
Step 3: Sintering process	20	1200
0-400 Average heating ramp time	40	0-400
400-1157 heating ramp	40	400-1200

The aim was to reach 1200°C but only 1157°C was possible. The oven was left to cool down with the samples inside. However, one day after the material of the samples was completely melted and lost the shape. After the melting process the material cooled down and became solid again. The material showed a huge amount of porous and it looked hardened (see Fig. 69).

Fig. 69: Material after firing process

Thermal Test: Conclusions

The material showed in Fig. 69 has high hardness, assuming that this material might have high compressive strength. The aim of the experiment was to reach the correct sintering temperature of the mixture but unfortunately the material melted, the shape was lost and the compressive strength test could not be performed. The main reason why this happened is because the thermal parameters of the materials involved in this experiment are unknown. However, the goal of obtaining a porous and hard material was achieved.

Water glass and stone aggregates

The goal of this experiment was to observe the behaviour of pastes mixed with an alternative binder to cement. Sodium Silicate, also called 'water glass' was used as the main binder. Nine different mixtures were designed as an initial test, containing water glass and Dolomite Sand. The samples were mixed until the mass was homogenized. Afterwards, 2 cm thick pads were shaped in order to check if the materials were sticking each other. The amount of water glass was added empirically. The first sample made was Sample 5. As a starting point, 31,10 gr of water glass was added. As the sample crumbled, the content of binder was increased to 35,00 gr. After 24 hours, it was observed that all specimens had solidified except samples 8 and 9, which contain the highest binder content. These were still wet in the centre and were easily breakable.

Tab. 26: Mix proportions

Sample Nr.	Dolomite Sand (gr)	Water glass (gr)	w/b ratio
5	500	35.00	14.29
4	500	42.00	11.90
3	500	45.60	10.96
2	500	50.80	9.84
1	500	54.20	9.23
6	500	62.50	8.00
7	500	70.10	7.13
8	500	80.60	6.20
9	500	90.10	5.55

Fig. 70: Pad Samples

Water glass samples

In order to test the compressive strength of these mixes, prismatic samples of 40 x 40 x 160 mm were casted.

Tab. 27: Mix Proportions

Materials	Abreviation	Mass per m³ (kg/m³)	Density (Kg/l)	Volume (l)
Water glass	WG	250.0	1.37	182.48
Dolomite Sand	DOS	650.0	2.86	227.27
Dolomite Gravel	DOG	1137.2	2.86	397.62

The Dolomite Gravel and Sand were first homogenized using an Eirich Intensive mixer. Afterwards, water glass was added. After 10 minutes, the mix was taken out of the mixer and the formworks were filled and compacted with a tamper.

Fig. 71: Filled formwork

Since water glass sets best under CO_2 gassing, the filled formwork was placed in a sheet metal barrel, in which a controlled fire subsequently provided the required CO2 supply. A glass plate was placed on the opening of the barrel and glued airtight to the barrel as it can be seen in the following pictures:

Fig. 72: Test specimen in the barrel

Fig. 73: Paper towels as fuel

Fig. 74: Glass plate as protection for the test specimens

Fig. 75: Glass plate on barrel opening

The prisms were demoulded after 3 days. Despite treatment of the formwork with oil, the test specimens stuck to the formwork. Some of the prisms were damaged in the process.

Fig. 76: Samples stuck to formwork

Fig. 77: Bottom part of the samples

It was observed that the chemical setting of water glass due to the CO_2 gassing only occurred up to approx. 1,5 to 2 cm and thus, the side of the prisms at the bottom of the formwork was still not hardened. The remaining prisms, were stored in the laboratory for drying. One specimen was placed dried in the oven at 100°C. After 48 hours, it was observed that the specimen dried in the oven was harder than the specimens that were dried at room temperature.

Fig. 78: Left: specimen dried in oven; right: specimen dried at room temperature

Tab. 28: Flexural and compression results

Flexural and compression strength 7th day						
Height (mm)	Width (mm)	Length (mm)	Weight (gr)	Load (kN)	Flexural strength (MPa)	Compression strength (MPa)
35.21	39.81	159.17	476.10	1.24	6.01	4.69
41.72	39.91	159.25	520.50	1.06	3.65	3.95
42.53	39.92	158.89	499.70	1.70	5.59	8.04

Tab. 29: Flexural and Compression results

Flexural and compression strength 28th day					
Height (mm)	Width (mm)	Length (mm)	Load (kN)	Flexural Strength (MPa)	Compression strength (MPa)
40.00	40.30	160.00	2.36	8.78	14.53
40.00	40.90	160.00	2.34	8.57	15.07
40.00	40.70	160.00	2.85	10.51	15.25
40.00	40.60	160.00	2.29	8.47	16.14

Water glass samples: Conclusions

It was possible to make samples out of Dolomite Gravel and Sand using water glass as an alternative binder. The compression strength of the samples at 28th days showed values between 14,53 MPa to 16,14 MPa which are considered acceptable if they are compared with a mortar sample made with cement. According to the Austrian Standard ÖNORM EN 197-1, Chapter 7.1.2. Table 3, the standard strength of a mortar sample made with cement 32,5 L can reach values higher than 32,5 MPa at 28th day. In this case, the half of the compression strength of a normal mortar sample was gained, which is considered acceptable since water glass is only a liquid chemical product that has no solid particles that could influence the arrange of particles and the principle of filling the voids inside the paste as it happens with cement. It is also possible to see an increasement in the values of compressive and flexural strength between 7 and 28 days. This could be due to the long drying period which improves the adhesion properties of the water glass with the stone aggregates.

3D logo printing

With the aim of designing a 3D mould for casting façade elements as one of the reusing options. The logo of the Cleanstone project was drawn with Autocad 3D. Afterwards, it was printed with a 3D Printer in order to stamp the logo in fresh concrete matrices (see Fig. 79-80).

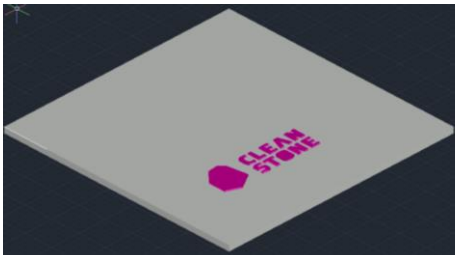


Fig. 79: 3D model designed with Autocad 3D

Fig. 80: Negative mould of the logo printed with 3D Printer

Fig. 81: Logo stamped in freshconcrete matrices

Bibliography

[1] *ÖNORM B4710-1 2018-01-01. Beton - Festlegung, Eigenschaften, Herstellung, Verwendung und Konformität - Teil 1: Regeln zur Umsetzung der ÖNORM EN 206 für Normal- und Schwerbeton.,* Austrian Standards, 2018.

[2] W. Fuller and S. Thomson, "The Laws of Proportioning Concrete," *Transactions of the American Society of Civil Engineers,* pp. LIX, pp 67-143, 1907.

[3] A. Andreasen and J. Andersen , "Über die Beziehung zwischen Kornabstufung und Zwischenraum in Produkten aus losen Körnern (mit einigen Experimenten)," *Kolloid-Zeitschrift 50,* p. pp 217–228, 1930.

[4] J. Funk and D. Dinger , "Introduction to Predictive Process Control. Predictive Process Control of Crowded Particulate Suspensions," *Springer,* pp. pp 1-6, 1994.

[5] *prSIA 2052 'Bétons fibrés Ultra-Performant: Matériaux, dimensionnement et exécution (UHPC: Material, dimensioning and construction),* Swiss Society of Engineers and Architects, 2014.

[6] A. Becke , Fachvereinigung Deutscher Betonfertigteilbau e.V., J. Reiners, VDZ Technology gGmbH and A. Tuan Phan , "Bundesverband der Deutschen Transportbetonindustrie e.V., InformationsZentrum Beton GmbH: „Umweltproduktdeklarationen – Erläuterungen zu den EPDs“," 2020. [Online]. Available: https://betonshop.de/media/wysiwyg/PDF/EPD-Begleitbroschuere-Beton-2020.pdf?utm_source=baulinks&utm_campaign=baulinks. [Accessed 2021].

[7] "ÖNORM EN 14157 2018-03-01 Prüfverfahren für Naturstein — Bestimmung des Widerstandes gegen Verschleiß," *Austrian Starndards,* 2018.

[8] A. Marradi, L. Secchiari and M. Lezzeni , "The qualifications of materials for their application in road Stone pavements," *Proceedings of the Second International Congress on Dimension Stone,* pp. 225-235, 2008.

[9] 3 H. Müller, U. Nolting, M. Haist and M. Kromer, "Nachhaltiger Beton - Werkstoff, Konstruktion und Nutzung: 9. Symposium Baustoffe und Bauwerkserhaltung Karlsruher

Institut für Technologie (KIT)," KIT Scientific Publishing, 2021. [Online]. Available: https://doi.org/10.5445/KSP/1000026526. [Accessed 2021].

[10] H. Figl, T. Brockmann , V. Huemer-Kals, O. Kusche , N. Kerz and S. Rössig , Federal Institute for Building, Urban Affairs and Spatial Development (BBSR) within the Federal Office for Building and Regional Planning (BBR), 2019. [Online]. Available: https://www.oekobaudat.de/fileadmin/downloads/0068G_en_BF_200106ms.pdf. [Accessed 2021].

[11] 1 Institut Bauen und Umwelt e.V. (IBU), "Portland Cement CEM I 42,5 R , EPD-KNT-20200209-CAA1-EN," Kunda Nordic Tsement AS, HeidelbergCement Group, 2020. [Online]. Available: https://www.knc.ee/et/system/files_force/assets/document/75/64/portland_cement_cem_i_425_r.pdf?download=1. [Accessed 2021].

[12] 2 Institut Bauen und Umwelt e.V. (IBU), "Portland Cement CEM I 42.5 N-SR3/MH/LA EPD-HCG-20190047-CAA1-EN," Cementa AB, HeidelbergCement Group, 2019. [Online]. Available: https://www.cementa.se/system/files_force/assets/document/b5/1b/portland_cement_cem_i_42.5_n-sr3mhla.pdf?download=1. [Accessed 2021].

[13] 4 ÖKOBAUDAT, " Sustainable Construction Information Portal: Datensatz Sand 0/2," Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2018. [Online]. Available: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=61655387-edd4-4800-ba3e-67bc15f2f096&version=20.19.120&stock=OBD_2021_I&lang=de. [Accessed 2021].

[14] 5 ÖKOBAUDAT, "Sustainable Construction Information Portal: Datensatz Schotter 16/32," Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2018. [Online]. Available: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=bd6aa879-e6e6-4181-afc5-1374b2f32dd1&version=20.19.120&stock=OBD_2021_I&lang=de. [Accessed 2021].

[15] 6 ÖKOBAUDAT, "Sustainable Construction Information Portal: Datensatz Brechsand 0/2," Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2018. [Online]. Available: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=a4d16918-287f-43af-831d-baf80093fe4a&version=20.19.120&stock=OBD_2021_I&lang=de. [Accessed 2021].

[16] 7 ÖKOBAUDAT, "Sustainable Construction Information Portal: Datensatz Trinkwasser," Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen, 2018. [Online]. Available: https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=ce3057d1-3371-47b4-a982-a1c42c2c6a85&version=20.19.120&stock=OBD_2021_I&lang=de. [Accessed 2021].

[17] 8 Institut Bauen und Umwelt e.V. (IBU), "Sika: Concrete admixtures - Plasticizers and Superplasticizers EPD-EFC-20150091-IAG1-EN," European Federation of Concrete Admixtures Associations Ltd. (EFCA), 2015. [Online]. Available: https://usa.sika.com/content/dam/dms/us01/0/Plasticizers%20and%20Superplasticizers%20-%20Sika%20ViscoCrete-6100-EPD.pdf. [Accessed 2021].

[18] ISO 14025 and EN 15804, "Environmental Product Declaration Type III ITB No. 064/2017," Instytut Techniki Budowlanej (ITB), 2017. [Online]. Available: https://new.itb.gitcms.pl/g/f/3469,epd-arcelormittal-sycow-wlokna-zbrojeniowe-aktualizacja-2020.pdf. [Accessed 2021].

[19] *Price of White Cement CEM II A-LL 42,5 R,* Leube Zement GmbH via telephone communication, 2022.

[20] *Price of Grey Cement W&P CEM I 42,5 R,* Leube Zement GmbH via telephone communication, 2022.

[21] *Price of Microsilica RW Füller Q1,* RW Silicium GmbH via telephone communication , 2022.

[22] *Price of Quartz powder Quarzmehl Dorsilit 16900,* Gebrüder Dorfner GmbH Co via telephone communication, 2022.

[23] *Price of Diabase Sand and Powder,* Mineral Abbau GmbH Diabas-Hartsteinwerk Jakoministeinbruch via telephone communication, 2022.

[24] Price of Limestone Powder, [Online]. Available: https://www.stoewa-kies.at/images/dateien-hp/stoewa_preisliste_2022.pdf. [Accessed 2022].

[25] Price of Dolomite Gravel and Sand, [Online]. Available: https://www.stoewa-kies.at/images/dateien-hp/stoewa_preisliste_2022.pdf. [Accessed 2022].

[26] *Price of Superplasticizer,* Sika Österreich GmbH via telephone communication.

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Annex 4: Scientific Publication