REUSE OF SECONDARY MATERIALS FROM QUARRIES AS AGGREGATES IN ULTRA HIGH PERFORMANCE CONCRETE

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ABSTRACT

The stone industry is one of the most essential industries in the Alpine region. This research aims to evaluate the possibility of reusing secondary waste materials produced by the quarry sector as aggregates in Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC). The secondary materials involved were Diabase Sand, Diabase Powder, Dolomite Sand and Dolomite Gravel from crushed stone quarries from the regions of Carinthia and Tyrol in Austria, as well as Limestone Powder from the preparation and production of stone blocks and slabs for decorative use from the Friuli Venezia Giulia region in Italy. This study aimed to compare a reference mixture with more commonly utilized aggregates in the production of UHPFRC with mixtures made out of secondary materials from quarries in terms of compressive strength. The replacements in the mixtures were made following the principle of optimizing the aggregate grading curves. Therefore, the particle size distribution of the mixtures was designed in order to follow the optimal particle packing density curves according to Andreasen and Andersen (A&A). The different concrete mixes to be compared were cast in cubes of 100x100x100 mm and the compression strength was tested at 7 and 28 days, from which mean values were calculated. Afterwards, these results were compared with the reference sample. In comparison, it could be observed that those mixtures containing replacements of Diabas Sand and Limestone Powder show compressive strength values that make them suitable for producing UHPFRC out of secondary materials. These kind of materials are otherwise considered as waste and disposed in nonoperational areas of the quarry or landfills. This offers the possibility of producing ecological friendly High-Performance Concrete with respect to a low CO_2 impact of the utilized waste materials.

Keywords: UHPFRC, compressive strength, secondary materials, quarries

INTRODUCTION

The stone industry produces high amounts of secondary materials. Substituting normal aggregates in UHPFRC with secondary materials from quarries can be an economical and environmental friendly solution. According to the Swiss Standards [1], UHPFRC is a material with a minimum compressive strength of 120 MPa. In this research, this value was used as a comparison value with respect to international standards. Researchers have already studied the behaviour of secondary materials from quarries in concrete. Safiuddin Md. et al. [2] investigated the implementation of quarry dust in high-performance concrete using dry air and water curing methods, obtaining acceptable workability and compressive strength values. Moreover, Rui Yang et al. [3] studied the effect of implementation Basalt and Limestone Powders from quarries in Ultra-High-Performance

Concrete using the modified Andreasen and Andersen model to optimize the particle packing density of the designed mixes, obtaining values of compressive strength of 140 MPa at 56 days. The goal was to investigate if the specific secondary materials collected from the quarries mentioned before, are suitable as aggregates in UHPFRC.

MATERIALS AND METHODS

Normal aggregates were substituted in UHPFRC with the following materials: Diabase Sand and Diabase Sludge from Bad Bleiberg, AT; Dolomite Sand and Dolomite Gravel from Wörgl, AT and Limestone Sludge from Udine, IT. 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. In this investigation, non washed Diabase Sand was used since the finer particles might act as a filler in the UHPFRC paste. Moreover, the Diabase Sludge was dried at 90°C for 24 hours and ground to use Diabase Powder as an aggregate. 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. As regards Limestone Sludge, 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 use Limestone Powder as an aggregate. In order to compare the compression strength behaviour of mixes containing secondary materials, reference samples were cast. 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). The particle size of the materials can be seen in Fig. 1.

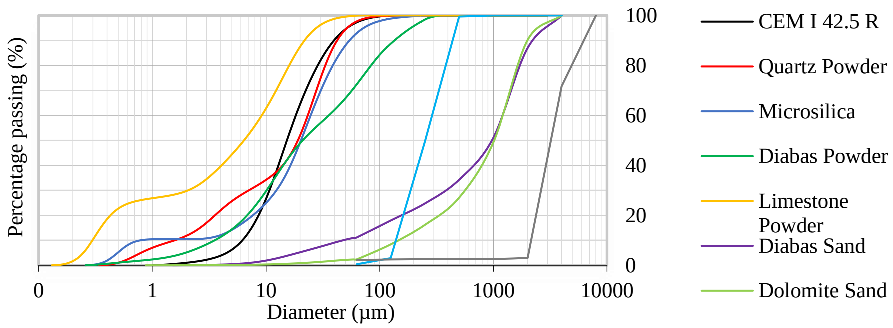


Fig. 1. Particle size of the materials

Additionally, samples with steel fibres of 9 mm length (Nominal Diameter= 0,15 mm, E= 210 GPa, Tensile Strength= 2600 MPa) were also cast. High-performance superplasticizer and water were used to control flowability. The specimens cast were cubes of 100x100x100 mm. For the design of the mixes, packing density models were followed to optimize the particle packing density of every concrete mix. The models used are based on the Fuller and Thompson [4] curve (Eq. 1):

$$(1) \qquad P(D) = \left(\frac{D}{D_{max}}\right)^q \qquad\qquad (2) \qquad P(D) = \frac{D^q - D_{min}^q}{D_{max}^q - D_{min}^q}$$

where P= fraction that can pass the sieve with opening D; q= distribution modulus (values between 0 and 1); D_{max}= max. particle size of the mix; D_{min} = min. particle size in the mixture. Different authors adopted different values for the distribution modulus: Fuller and Thompson adopted q= 0,5 for Eq. 1. Andreasen and Andersen [5] proposed q= 0,37 for Eq. 1. Funk and Dinger [6] proposed q= 0,25 and modified Eq. 1 by including 'D_{min}' to finally get Eq. 2. The three models are shown in Fig. 2. In this study, 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 and observing how the shape of the curve was changed. The goal was to obtain uniform 'design curves' that matched the 'target curve' as closely as possible with the available secondary materials collected from the quarries. The designed curves are shown in Fig. 2. 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. The proportions of every mixture can be seen in Fig 3.

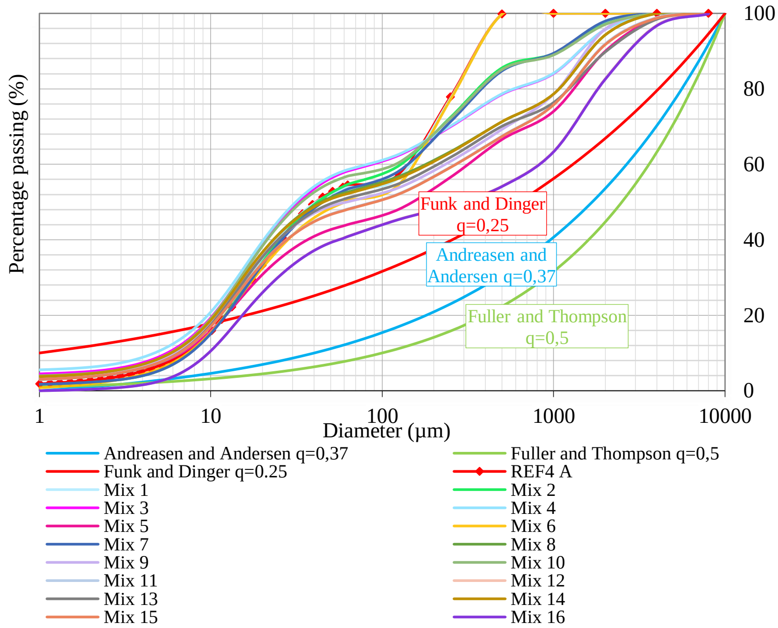


Fig. 2. Particle size distribution of the designed mixes

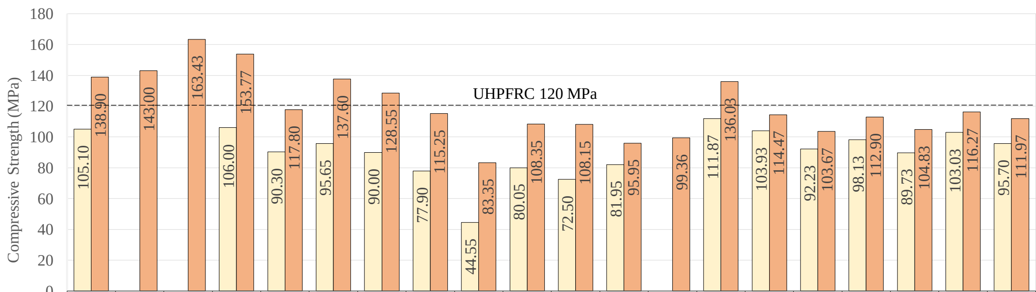
Quantities in (kg/m³)														
Mixes	Cement	Microsilica	Quartz Powder	Quartz Sand	Diabas Sand	Diabas Powder	Limestone Powder	Dolomite Gravel	Dolomite Sand	Water	SUP	Fibres	w/c [-]	w/b [-]
REF1A	850.0	143.0	245.0	865.0						195	20.9		0.25	0.21
REF2W	850.0	143.0	245.0	865.0						195	20.0		0.25	0.21
REF3HW	850.0	143.0	245.0	865.0						195	20.0		0.25	0.21
REF4A	850.0	149.0	249.5	875.3						200	27.0		0.24	0.22
Mix 1	850.0	122.5	143.0	891.4			122.5			200	40.2		0.27	0.23
Mix 2	850.0	245.0		445.7	445.7		143.0			200	43.5		0.27	0.21
Mix 3	765.0	245.0		222.9	668.6		228.0			200	46.5		0.30	0.23
Mix 4	680.0	245.0		222.9	668.6		313.0			200	47.5		0.34	0.25
Mix 5	641.9			222.9	860.0		241.0	90.0		200	40.0		0.36	0.36
Mix 6	850.0		143.0	891.4		245.0				200	40.2		0.27	0.27
Mix 7	850.0	245.0		445.7		143.0			445.7	200	46.1		0.27	0.21
Mix 8	850.0			145.7	845.7		243.0			200	49.2		0.28	0.28
Mix 9	850.0			145.7			243.0		845.7	200	49.7		0.28	0.28
Mix 10	850.0	160.0		425.0	450.0		221.7			210	27.0		1.31	0.23
Mix 11	850.0			160.0	196.3	50.0	225.0	85.0	665.0	195	27.0		0.23	0.25
Mix 12	900.0				900.0			240.0	178.2	195	28.0		0.22	0.24
Mix 13	900.0			190.0	760.0		231.9	120.0		195	27.0		0.22	0.24
Mix 14	850.0			165.0	895.5		290.0			190	27.0		0.22	0.25
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
Mix 16	900.0				900.0			240.0	178.2	195	28.0	157.00	0.22	0.24

Note: SUP: Superplasticizer; w/c: water to cement ratio; w/b: water to binder ratio

Fig. 3. Proportions of every mixture

RESULTS OF COMPRESSIVE STRENGTH INVESTIGATIONS

The graph in Fig. 4 depicts the comparison of the compressive strength results of two groups of samples. The first group of samples: REF1 A, REF2 W and REF3 HW seeks to compare the different curing methods at 28 days. The second group of samples: Mixes 1 to 16 aims to compare the replacements of secondary materials with the reference sample REF4 A. The legend 'REF1 A 28d.%' shows the increase in percentage of compressive strength values of REF2 W and REF3 HW in comparison with REF1 A at 28 days. Since the value of REF1 A was considered low, its aggregate composition was slightly modified, and REF4 A was cast. REF4 A showed an increase of 10,70 % at 28th days in comparison with REF1 A. For that reason, REF4 A was selected to compare Mixes 1 to 16. The legend 'REF4 A 7d.%' shows the decreased values in percentage of the Mixes 1 to 16 in comparison with REF4 A at 7 days. Only an increase of 5,54 % was observed in Mix 10. Mix 9 was only tested at 28 days. The legend 'REF4 A 28d.%' shows the decreased values in percentage of compressive strength of the Mixes 1 to 16 in comparison with REF4 A at 28 days. The lowest value of compressive strength at 7 and 28 days registered corresponded to Mix 5. The highest value of compression strength at 28th days corresponded to Mix 2 and it was 137,60 MPa. Its compressive strength was reduced in 9,76 % and 10,52 % at 7 and 28 days respectively, in comparison with REF4 A.



	REF1 A	REF2 W	REF3 HW	REF4 A	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12	Mix 13	Mix 14	Mix 15	Mix 16
7 d. MPa	105.10	0.0	0.0	106.00	90.30	95.65	90.00	77.90	44.55	80.05	72.50	81.95	0.0	111.87	103.93	92.23	98.13	89.73	103.03	95.70
28 d. MPa	138.90	143.00	163.43	153.77	117.80	137.60	128.55	115.25	83.35	108.35	108.15	95.95	99.36	136.03	114.47	103.67	112.90	104.83	116.27	111.97
REF1A 28d.%	0.00	2.95	17.66																	
REF4A 7d.%				0.00	-14.81	-9.76	-15.09	-26.51	-57.97	-24.48	-31.60	-22.69	0.00	5.54	-1.95	-12.99	-7.42	-15.35	-2.80	-9.72
REF4A 28d.%				0.00	-23.39	-10.52	-16.40	-25.05	-45.80	-29.54	-29.67	-37.60	-35.38	-11.54	-25.56	-32.58	-26.58	-31.82	-24.39	-27.18

Fig. 4. Compressive strength values at 7 and 28 days

LIFE CYCLE ASSESSMENT OF THE CONCRETE MIXTURES

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. Therefore Environmental Product Declarations (EPD) are generated for the evaluation and comparability of building materials, building products and building components containing detailed life cycle assessment data and information (see for example oekobaudat.de). 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. In the present work, the Life Cycle Assessment (LCA) data of the different concrete mixes refer only to the first phase, the product phase "cradle to gate" (A1 – A3), which can be explained with: A1 - raw material extraction/preparation, A2 - transport to the manufacturer, A3 - production [7]. In this stage, the highest environmental impact of concrete is generated. The following parameters were used for the comparison of the mixes (see Tab. 1):

Tab. 1. LCA data used for the comparison

Label	Description	Unit	Scaling factor*
PENRT	Primary energy input non-renewable, total	[MJ]	10^{-3}
PERT	Primary energy renewable, total	[MJ]	10^{-2}
GWP	Global warming potential	[kg CO_2 eq.]	10^{-3}
AP	Acidification potential of land and water	[kg SO_2 eq.]	1
EP	Eutrophication potential	[kg phosphates eq.]	1
ODP	Depletion potential of the stratospheric ozone layer	[kg CFC11 eq.]	1
POCP	Potential of tropospheric ozone formation	[kg ethene eq.]	1

* scaling factor is used for the graphical comparison

Tab. 2. Impact values of all components, without scaling factor

Material	Primary Energy Input		Environmental Impact					data source
	PENRT	PERT	GWP	AP	EP	ODP	POCP	
	[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 F	2,48	0,294	0,808	0,00117	0,000402	9,27E-09	0,000106	1
Microsilica *	0	0	0	0	0	0	0	-
Quartz Powder	0,82	0,0316	0,0234	0,000158	0,00000675	4,98E-09	0,00000557	2
Quartz Sand	0,539	0,0129	0,0102	0,0000754	0,000003	2,1E-09	0,00000258	2
Diabas Sand***	0,03812	0,0121	0,002854	0,000006814	0,000001327	6,025E-17	-5,824E-07	3
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	4
Dolomite Sand***	0,1889	0,1004	0,01469	0,00002071	0,000004412	5,449E-16	6,559E-07	5
Water	0,001754	0,0002921	0,000128	2,063E-07	1,167E-07	1,616E-18	1,799E-08	6
Steel fibres	11	0,794	0,771	0,00105	0,000335	0,0001	0,000324	7
SUP	31,4	1,51	1,88	0,00292	0,00103	2,3E-10	0,000312	8

* 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

1 EPD-KNT-20200209-CAA1-EN Portland Cement CEM I 42,5 R, Kunda Nordic Tsement AS

2 Kromer, M et al. (eds.) 2012. Nachhaltiger Beton - Werkstoff, Konstruktion und Nutzung : 9. Symposium Baustoffe und Bauwerkserhaltung Karlsruher Institut für Technologie (KIT) ; 15. März 2012. Karlsruhe: KIT Scientific Publishing. DOI: https://doi.org/10.5445/KSP/1000026526

3 ÖKOBAUDAT Datensatz Sand 0/2

4 ÖKOBAUDAT Datensatz Schotter 16/32

5 ÖKOBAUDAT Datensatz Brechsand 0/2

6 ÖKOBAUDAT Datensatz Trinkwasser

7 Environmental Product Declaration Type III ITB No. 064/2017

8 EPD-EFC-20150091-IAG1-EN Concrete admixtures - Plasticisers and Superplasticisers

The mixes REF1 A (mix without secondary materials), Mix 5 (mix with lowest quantity of cement, high proportion of secondary materials and best ecological characteristics in the evaluation), Mix 11 (same quantity of cement as REF1 A, low quantity of quartz sand, use of all secondary materials in this study) and Mix 16 (high quantity of cement, Diabase Sand, Dolomite Sand and Gravel, admixture of steel fibers – highest impact values) were used for the comparison of 1 m³ concrete (mix components shown in Fig. 3, LCA data of all components in Tab. 2).

The secondary materials from the quarries used in the mixtures were compared based on two variants (VAR) concerning their ecological impacts:

VAR I: The impact is assumed to be zero, as the materials are secondary materials (see Tab. 3 and Fig. 5)

VAR II: The impacts occurring during production are taken into account, with the exception of stone powder (see Tab. 4 and Fig. 5)

Tab. 3. VAR I, LCA Data for 1 m³ concrete, without scaling factor

Mixture	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]
REF1	3.009,707	285,078	717,070	1,121	0,353	2,011E-03	0,100
Mix 5	2.152,406	223,412	551,794	0,810	0,272	4,006E-03	0,082
Mix 11	2.491,582	273,459	709,274	1,035	0,351	2,708E-03	0,099
Mix 16	7.470,142	523,959	1.043,973	1,541	0,533	2,808E-03	0,153

Tab. 4. VAR II, LCA Data for 1 m³ concrete, without scaling factor

Mixture	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]
REF1	3.009,707	285,078	717,070	1,121	0,353	2,011E-03	0,100
Mix 5	2.185,189	233,818	554,249	0,816	0,273	4,006E-03	0,081
Mix 11	2.640,740	351,134	720,852	1,052	0,355	2,708E-03	0,100
Mix 16	7.583,448	576,836	1.052,685	1,556	0,536	2,808E-03	0,153

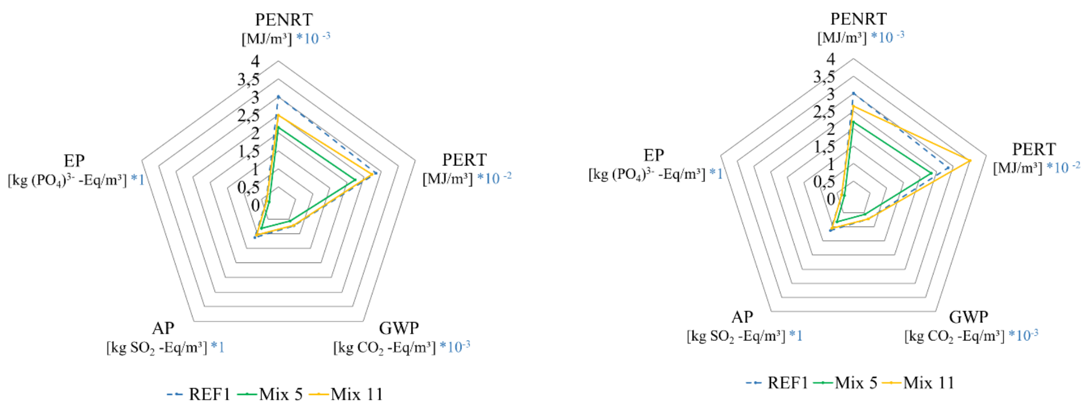


Fig. 5. Comparison of concrete mixtures: On the left: VAR I; On the right: VAR II

Tab. 3 – 4 and Fig. 5 show that it is possible to produce an ecologically more environmental friendly concrete by substituting cement and also by using secondary materials from the quarries. Since the impact values of Mix 16 are very high due to the addition of steel fibers, this mix would stand out in the graphical representation shown in Fig. 5, that's why this mix was not included in the graph.

DISCUSSION

Regarding the curing methods of REF1 A, REF2 W and REF3 HW, it was observed that REF2 W and REF3 HW, show an increase of 2,95 % and 17,66 %, respectively, compared with REF1 A. The main reason is due to the presence of water and heat. Regarding the design mixes, Mix 2 showed the highest value of compressive strength on the 28th day. This means that the increase of Microsilica, the replacement of Quartz Powder by Limestone Powder, and the Quartz Sand by Diabase Sand in the amounts shown in Fig. 3 could be suitable for producing UHPFRC.

On the other hand, 10 vol. %, 20 vol. %, and 25 vol. % of cement was reduced and replaced with Limestone Powder in mixes 3, 4, and 5 to check if possible dehydrated cement could be replaced with Limestone Powder. Moreover, in Mix 5, Quartz Powder was eliminated, Quartz Sand replaced by Diabase Sand, and Dolomite Gravel was added. The compressive strength of these mixes show a considerable drop due to the cement reduction, showing that it is not fully possible to replace non hydrated cement. In Mix 6, it can also be observed that the replacements of Microsilica made with Diabase Powder showed very low compressive strength. This indicates that Diabase Powder is less suitable as a filler material, while the replacements made with Limestone Powder show higher compressive strength values. In Mixes 8 and 9, Quartz Sand was replaced by Diabase Sand and Dolomite Sand, respectively. The compressive strength results at 28th days showed no considerable difference in compressive strength when using one sand or the other. This is probably because of the similarity between their particle size curves. Mix 15 and 11 were mixed with and without fibres, respectively, to compare how the compressive strength behaves. Mixes 12 and 16 were also mixed with the same comparison purpose. The admixture of fibers does not increase the values of compression strength at 7 and 28th days in high amounts.

CONCLUSION

The goal of this research was to evaluate if it was possible to use secondary materials from quarries from Austria and Italy as aggregates to produce UHPFRC. As it was mentioned, this type of concrete has a minimum compressive strength of 120 MPa. 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 137,60 MPa. This value corresponds to mix 2. This mix shows that the replacements of Quartz Powder by Limestone Powder and Quartz Sand by Diabase Sand can be suitable for the production of 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. However, its values are still higher than 100 MPa at 28 days. 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. Moreover, Mixes 2, 3 and 10 exceeded the value of 120 MPa.

Considering the LCA data, it becomes apparent that those mixes are more environmental friendly from an ecological point of view, the more cement is substituted. If mining secondary materials are used that have no further use otherwise, the negative environmental impact decreases. If steel fibers are added, the LCA values deteriorate considerably due to the influences of the steel production processes.

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