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PHYSICAL AND MECHANICAL PROPERTIES OF ULTRA-HIGH-PERFORMANCE CONCRETE WITH LIMESTONE

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ABSTRACT

The production of ultra-high performance concrete is one of the new ideas in modern construction, developed in the past few decades. A compressive strength higher than 150 MPa has been achieved using a relatively large amount of cement, approximately 800 kg/m^3. As the cement industry is one of the largest producers of carbon dioxide, it is clear that the cement amount in concrete should be reduced to minimize greenhouse gases emission and slow down the global warming process. One possibility for that reduction is a replacement of cement with limestone filler.

This paper shows the results of experimental testing of five ultra-high-performance concrete mixtures. A referent mixture and four mixtures with a partial replacement of cement with limestone filler were made and tested. Two types of limestone fillers varying in particle size were used: one with a mean particle size of 2.5 μm and the other one with a mean particle size of 11 μm. Two groups of concrete mixtures were made with 20% and 30% of cement replaced by limestone. All other components: silica fume, quartz sand, water and superplasticizer were kept constant in all mixtures. Limestone filler is selected based on a particle size - so that its particles are the same size or smaller compared to cement. Basic fresh and hardened concrete properties were tested for all mixtures: consistency was determined using standard flow test and 28-day compressive strength was obtained by testing 10-cm cube samples.

Based on the obtained results, it could be concluded that the replacement of cement with limestone brought improvements in compressive strength and workability. The compressive strength of all mixtures was app. 120 MPa, while the mixtures with limestone were more flowable. The economic aspect was also considered. The analysis showed that up to 25% cost reduction can be achieved without compromising the compressive strength of this type of concrete by using limestone as a filler.

Keywords: Ultra-high performance concrete; Limestone; Filler; Cement; Compressive strength.

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1. INTRODUCTION

In the past few decades, the idea of producing high-performance concrete (HPC) has been developed. Otto Graf managed to produce the first concrete with a compressive strength of 70 MPa in the early 1950s [1]. This concrete was considered as a high strength concrete [2]. During the 1980s, concrete with a strength higher than 100 MPa had been produced [1]. The precise definition of HPC has continued to change during the years [3]. More recently, there is no definition of high strength concrete in EN 1992-1-1 and EN 206-1, but the design formulas change when the strength is greater than C50/60 [2]. So, an HPC may be defined as concrete with a compressive strength higher than 60 MPa [3].

The compressive strength of concrete was limited by the compressive strength of fine and coarse aggregate (75% of concrete volume), reaching up to 120 MPa [1]. Replacing classic aggregate with finer particles of quartz sand (QS), it is possible to achieve higher strengths. Besides the usage of finer QS particles, a notable development in the production of concretes with higher compressive strength has been achieved through the use of new materials: silica fume (SF) and high range water reducer admixtures (HRWR) [1]. With the utilization of all those components, a new kind of concrete was created – ultra-high-performance concrete (UHPC). Further, the production and use of steel fibers (fiber reinforced concrete (FRC)), improved the mechanical properties of concrete. By adding steel fibers in the UHPC mixtures, ultra-high-performance fiber-reinforced concrete has been obtained.

Due to finer particle size distribution, with maximum particle size lower than one millimeter, concrete packing density is far better. Therefore, the microstructure is more homogenous, so any cracks that are formed propagate as a straight line [1]. Very high packing density and high strengths are also achieved with a small amount of water – the water-cement ratio (w/c) of UHPC is app. 0.2 [1]. When all those facts come together, the strength of these concrete types reaches 150 MPa.

High mechanical properties and excellent durability provide a wide range of UHPC use. Currently, they have application in the repair and strengthening of existing structures, in bridge constructions, facades, roofs, protective and acoustic panels. Using the UHPC enables the production of elements with significantly smaller cross-sectional dimensions and lower self-weight. The first structure made from this concrete was Sherbrook Pedestrian Overpass Quebec in Canada, built in 1997.

On the other hand, the amount of cement in UHPC is significantly higher than in ordinary Portland cement concrete (OPC). Cement is primarily used as a binding agent that reacts with water to form a solid structure. However, researches showed that a certain amount of cement in UHPC, 30% to 35%, is not activated during the hydration process [4]. Having in mind cement particle size, unreacted cement can act as a filler. This fact opens the possibility of replacing a part of cement with fine particles. This replacement can bring benefits, not only economic but also environmental, considering that the cement industry is responsible for about 10% of the overall anthropogenic CO_2 emissions in the world [5].

One possibility of cement reduction is using the limestone filler (LS). Part of cement can be replaced with this filler while maintaining mechanical properties similar to referent UHPC concrete. It is also expected that this filler will improve the consistency and workability of fresh concrete, which can be seriously disturbed by the use of a larger amount of steel fibers. Having all this in mind, the goal of this research was defined: evaluation of basic physical and mechanical properties of ultra-high-performance concrete with the addition of local limestone filler.

2. UHPC WITH LIMESTONE FILLER

UHPC is made with a specific type and amounts of component materials. Compared with HPC, it is a new class of concrete that tends to exhibit better properties such as strength and durability[6]. Its compressive strength and other properties are achieved by a micro-scale optimization of fine and ultrafine particles, as well as the inclusion of steel fibers, low water-binder ratio, and adding of superplasticizer [7]. They are also defined as concretes with a compressive strength greater than 150 MPa, micro reinforced to ensure no brittle behavior, and usage of a large amount of binder and a specific type of aggregate [6]. The cement and SF form a binder paste that fills the space between the QS particles. Cement is certainly the most common and accepted hydraulic mineral binder. According to the research review given in Table 1. [6], [7], [16], [8]–[15], and recommendations of authors given in the book "Ultra-High-Performance Concrete-Fundamentals-Design-Examples" [1] the amount of cement is 600 – 1200 kg/m^3.

SF is a waste byproduct of ferro-silicium alloys production and has a typical diameter of 0.2 μm [17]. It is the finest component in UHPC mixtures-SF medium particle is 100 times smaller than the average particle of cement [7]. However, the usage of SF is limited because variable carbon content can affect consistency [17]. One of the main disadvantages is the need for a larger amount of water due to its ultra-fine particles with a larger specific surface area. So, by adding SF the strength is increased, but the workability of concrete is reduced [18]. It is important to find the optimal quantity of SF. The amount of SF is app. 10% to 30% by mass of cement, or according to Table 1 in the range 100 – 250 kg/m^3. QS is one of the base components of UHPC mixtures. The key issue in the mixture design is to avoid the use of coarse aggregate and sand. The classic aggregate should be replaced with finely ground particles, smaller than 600 μm [19]. Due to the relatively low w/c ratio (0.13 – 0.3), the workability of fresh concrete can be disturbed. To enhance it there is a need for using HRWR.

After reviewing the relevant literature, a summary of the amounts of component materials used during the studies was given in Table 1. The amount of cement has a wide range, between 600-1200 kg/m^3. In the mixtures with the smaller amount of cement, part of it was replaced with some kind of filler, or some method for packing density was applied. With the use of QS, better mechanical properties can be achieved. Its amount is similar to the amount of aggregate in OPC. The water to binder ratio (w/b) and w/c in Table 1 show that the amount of water is lower compared to the common w/c ratio in OPC.

Table 1. Component materials amounts in UHPC according to relevant literature

Component	Cement	SF	w/c	w/b	QS
Amount [kg/m^3]	600-1200	100-180	0.13-0.30	0.14-0.22	1000-1200

As already stated, limestone filler can be used in UHPC production which improves some of its properties. For many years limestone powder has been used as an additive to cement-based materials. It is obtained by crushing and grinding natural limestone in quarries. Deniels et al. [18] showed in their research that the addition of LS increases the strength of concrete. The use of LS is encouraged primarily by its low price, homogeneous composition, abundant reserves, and relatively easy quality control [20]. In UHPC mixtures, packing density is lower when the LS particles are coarser or a size comparable to cement, the recommendation is that LS should be finer than cement [20]. Further, LS can promote cement hydration [21].

The use of fine particles requires a new approach in the concrete mixtures design, as packing density is essential. There are several methods to design mixtures according to packaging: Andreasen and Andersen particle packing model, De Larrard and Sedran [22], [23] Linear Packing Density Model, Solid Suspension Model, and Compressive Packing Model.

Many researchers investigated the use of limestone in UHPC. To summarize the main findings, concrete mix design, component materials properties, medium particle grain (D_{50}), and compressive strength results are shown in Table 2. Table 2 is focused on referent mixtures and mixtures which have a replacement of cement with LS filler.

As can be seen from Table 2, the medium particle size of LS filler is the same or smaller compared with the medium particle size of cement. The replacement of cement with limestone is usually in the range of 20% to 30%, with a critical value of 50%. For reductions greater than 50%, the compressive strength is significantly lower compared to referent mixture made without LS. The amount of cement and limestone and their particle size distribution are key parameters for an optimal mixture design. It can be concluded that the LS could be used to replace a certain amount of cement while the compressive strength is maintained.

Table 2. Components quantities in UHPC mixtures with LS filler

Paper	Mix	Cement		Water	HRWR	LS		QS		SF		Compressive strength [MPa]	
		Mass [kg/m^3]	D_{50} [μm]	Mass [kg/m^3]	Mass [kg/m^3]	Mass [kg/m^3]	D_{50} [μm]	Mass [kg/m3]	D_{50} [μm]	Mass [kg/m^3]	D_{50} [μm]	7 days	28 days
[24]	UHPC1	875	15	202	45.9	0	10	0	30	43.7	0.15	85	100
	UHPC2	612	15	202	45.9	262	10	0	30	43.7	0.15	80	85
	UHPC3	700	15	202	45.9	0	10	175	30	43.7	0.15	85	90
[25]	LP0	741	15	185	9	0	3	259	3	185	0.3	144	167
	LP25	741	15	185	9	65	3	194.25	3	185	0.3	142	159
	LP50	741	15	185	9	130	3	129.5	3	185	0.3	143	160
	LP75	741	15	185	9	194	3	64.75	3	185	0.3	138	158
	LP100	741	15	185	9	259	3	0	3	185	0.3	136	155
[21]	CSF	1251	10	201	28.2	0	8	407.8	300	291.3	0.17	120	148
	CSFLS34	826	10	201	10.5	486	8	444.4	300	192.3	0.17	140	162
	CSFLS54	576	10	201	5.1	772	8	455.7	300	134	0.17	117	155
	CSFLS74	325	10	201	5.2	1058	8	455.4	300	75.7	0.17	70	110
[26]	M0	1072	15	261	19.6	0	10			119.1		132.3	
	M20	871	15	251	17.4	215	10			96.8		125	
	M40	664	15	240	15.2	438	10			73.8		115	
	M60	448	15	234	12.8	665	10			49.8		100	
	M80	227	15	227	10.4	897	10			25.2		53.8	
[14]	LP300	600	15	200	33	300	8			200	3	87	110
	LP350	550	15	200	33	350	8			200	3	85	110
	LP400	500	15	200	33	400	8			200	3	80	110
	LP450	450	15	200	33	450	8			200	3	75	105
	LP500	400	15	200	33	500	8			200	3	75	95
	LP550	350	15	200	33	550	8			200	3	62	78
	Ref	750	15	200	33	150	8			200	3		

Ding et al. [14] made the mixtures by using the Andreasen and Andersen model. They replaced a significant amount of cement with LS filler. The greatest reduction of cement achieved was from 750 kg/m^3 to 350 kg/m^3. In mixtures they tested, 28-day compressive strength was higher than 100 MPa. Also, the slump test showed that the mixture with the greatest replacement of cement had a higher slump (better results).

The effects of cement replacement with LS have been also studied by Huang et al. [21]. In their research, the volume of LS in the binder system was 0, 34%, 54%, and 74%, binder volume and w/b were the same. The results of the slump test showed that the mixture with the greatest replacement had a better slump. They obtained 28-day compressive strengths higher than 150 MPa in all mixtures. The exception is the mixture with the smallest amount of cement. The authors [21] concluded that cement hydration increased from 39% to 66% in case of a mixture with 54% of cement reduction. They also showed that amount of emitted CO_2 is remarkably reduced when LS is in use.

3. EXPERIMENTAL TESTING

The aim of this research is to analyze the possibility of using LS filler as a partial replacement of cement in UHPC mixtures, considering the physical and mechanical properties of concrete together with economic and ecological optimization. The idea is to design a UHPC mixture with a certain filler amount, targeting improved workability and similar compressive strength as a reference mixture without LS filler.

Numerous tests of this type of concrete were done in the Laboratory for Materials at the Faculty of Civil Engineering in Belgrade. More precisely, the mixture labeled as a reference mixture in this paper, M0, was tested to find the optimal ratio of all components [27], [28]. Mechanical and physical properties testing, as well as tests related to durability, were performed. The possibility of using local LS filler in UHPC was investigated. In the M0 mixture, a certain amount of cement was replaced with LS filler to test its effect on the physical and mechanical properties.

Table 3. Concrete mix design

Component	M0	M2.5-20	M2.5-30	M11-20	M11-30
Cement CEM I 52.5R	1.00	0.80	0.70	0.80	0.70
LS filler 2.5 μm	0.00	0.20	0.30	0.00	0.00
LS filler 11 μm	0.00	0.00	0.00	0.20	0.30

Four mixtures made with various quantities of limestone were designed. Two types of LS filler varying in particle size were used: with mean particle size 2.5 μm and 11 μm. Two groups of concrete mixtures were made with cement replacement in the amount of 20% and 30%. Mixtures were named by the type of filler which is used and the amount of cement replacement M2.5-20, M11-20, M2.5-30, and M11-30. The amount of other components were kept constant: SF was 0.18 of cement mass, QS type A (0,4-0,5 mm) 1.04 of cement mass, QS type B (0.1-0.3 mm) 0.34 of cement mass, HRWR 0.05 of cement mass, and w/c ratio was 0.22. The information about cement particle size distribution was not available, but according to previous research, its medium particle size was estimated as 15 μm. The influence of filler was taken into account in two ways: by changing the quantity and by changing finesses.

All mixtures were prepared using the following mixing procedure: 1) all dry components were mixed together for five minutes; 2) water and 40% of total HRWR amount (diluted in water) were added and mixed for another two minutes; 3) remaining HRWR amount – 60% was added after seven minutes of total mixing; 4) mixing of all components continued for another 20 minutes. In this way, each mixture was mixed for 27 minutes in total. It was noticed that the moment of transition from dry to liquid state differs. Mixtures with a higher percentage of substitution turn into a liquid state earlier, after 10 minutes of mixing. Mixtures with 20% replacement go into a liquid state in 15 minutes.

Table 4. Type of testing and sample numbers

Test	Sample type	Dimensions [cm]	Number of samples	Age [days]	Standard
Compressive strength	Cube	10x10x10	6	3, 28	SRPS EN 12390-3-2014
Workability	Abrams cone	10x20x30	1	Fresh condition	SRPS EN 12350-5-2009

After mixing, concrete was cast in 10-cm cube molds and the workability tests were done (flow test). During the first 24 hours, samples were covered with wet fabric and cured in water containers. The compressive strength was tested at the age of 3 and 28 days. Workability was tested by using the Abrams cone immediately after mixtures were made. Table 4 shows all information about samples, and performed tests.

4. TESTS RESULTS

During testing, concrete density in a fresh and hardened state was measured. The results for each mixture and both states are shown in Table 5.

Table 5. Concrete density

Concrete density [kg/m^3]		
Mixture	Fresh state	Hardened state
M0	2249	2242
M2.5-20	2221	2212
M2.5-30	2247	2227
M11-20	2228	2212
M11-30	2230	2217

The results of the flow test are shown in Table 6. After the cone is lifted, the flow diameter of fresh concrete is measured. Two perpendicular diameters of fresh concrete were measured, and the mean value was calculated. Testing of flow values is shown in Figure 1.

In Tables 6, the results of compressive strength testing are also shown, after 3 and 28 days. The results are shown for each mixture and each sample, and the final result is the average value of 3 samples that were tested for each mixture. Figure 2 Shows crushed cube sample after compressive strength test. As can be seen, this type of concrete also expresses the shape of crushed sample characteristic for concrete cube samples tested in a hydraulic press.

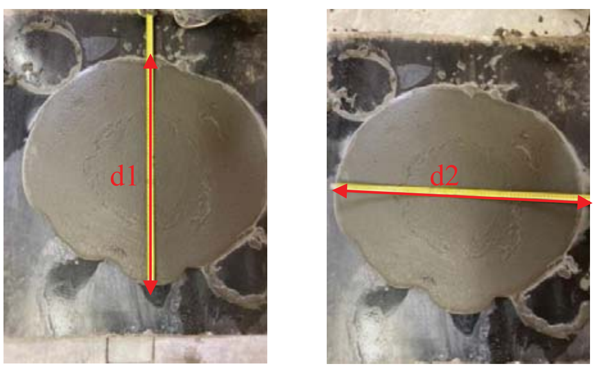


Fig. 1. Flow test-measuring the diameters

Fig. 2. Cube sample after compressive test

Table 6. Results of flow and compressive strength test

Mixture	d1	d2	d	Sample strength [MPa]			Average strength [MPa]	Sample strength [MPa]			Average strength [MPa]
	[cm]	[cm]	[cm]	1	2	3	3 days	1	2	3	28 days
M0	67	60	63.5	106	101	97	101	117	-	-	117
M2.5-20	54	59	56.5	94	97	97	96	-	-	-	-
M2.5-30	65	77	71	88	89	88	89	127	126	106	120
M11-20	65	72	68.5	82	87	83	84	113	112	115	113
M11-30	63	70	66.5	86	87	85	86	113	126	120	120

It is important to note that the test equipment malfunctioned during the testing of the mixture M0 and M2.5-20, at the age of 28 days. One cube of M0 mixture was tested successfully and this result was adopted as the mean value for M0 mixture – 117 MPa. Unfortunately, for mixture M2.5-20 there are no reliable results for compressive strength after 28 days, so the mean value for strength was predicted by the increase of the strength of other mixtures, as a value of 129 MPa.

5. ANALYSIS OF RESULTS

In two previous chapters, the method of tests and the results were presented. Observing the values obtained when determining fresh and hardened state density, it can be concluded that the values are similar, 2235 kg/m^3 and 2220 kg/m^3, respectively. The presentation of those results is shown in Figure 3. The diagram shows values for each mixture in the fresh and hardened state.

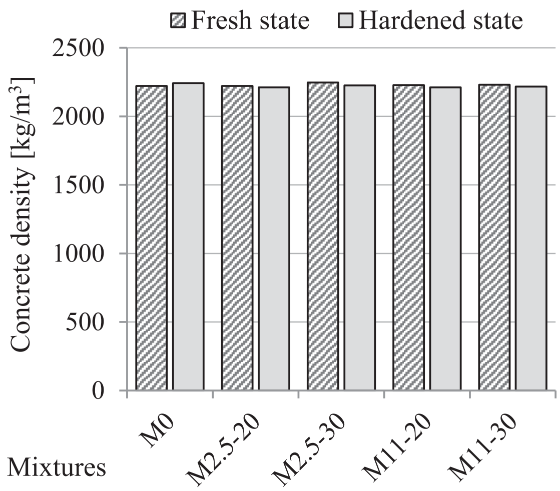


Fig. 3. Concrete density

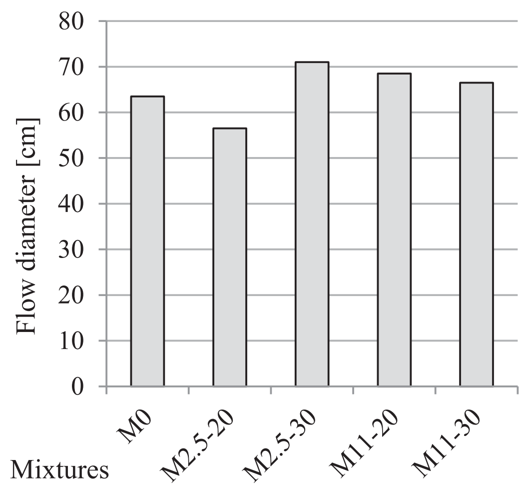
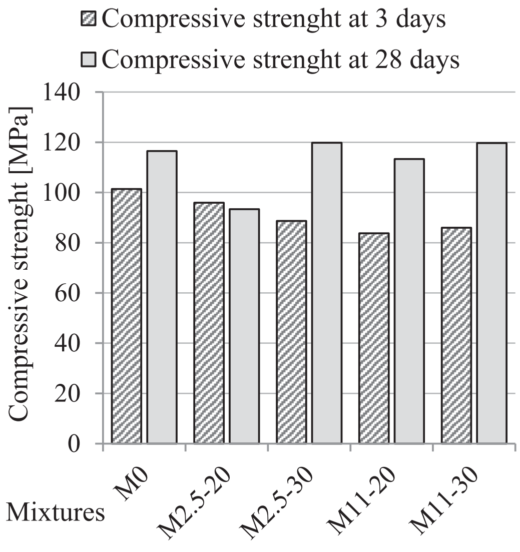


Fig. 4. Flow diameter

The results of flow diameter are also analyzed. As expected, mixtures with the addition of LS filler obtained higher flow values. The best result was noticed in the mixture with finer filler and 30% of cement replacement. All other mixtures, except the M2.5-20, had higher values in flow test (better workability) than the referent one. A possible reason is a method of measuring. For this measurement, the cone was lifted a little bit slower compared with others. In mixtures with 30% of LS filler, no difference in result can be seen, even though the fillers had different fineness. Figure 4 presents all results graphical manner.

Compressive strength was determined at two specimens' ages. It was expected that the final result would be greater than 120 MPa, without significant differences between referent and other mixtures. Also, it was expected that the mixtures with finer filler would have greater strength than the referent one. All mixtures, except the M2.5-20, had similar results as the referent one at the age of 28 days. However, the early age strength did not follow that trend. All mixtures had lower compressive strength compared with the referent one. Figure 5 shows the results of testing for both ages. Also, Figure 6 shows the results and the strength increase from 3 to 28 days. As can be seen, the mixtures with LS filler had a higher strength increase over time. A possible reason for strength increase lower than expected is partial hydration of cement which was more than a year old.

Except for experimental investigation, concrete price analysis was also done. LS filler is a local product, so the cost of each type of filler was known. Also, the market price of the cement CEM I 52.5 R was determined so, the analyze of price cost for all mixtures was done. Table 7 shows the information on the price of cement and filler and the compressive strengths obtained for all mixtures.



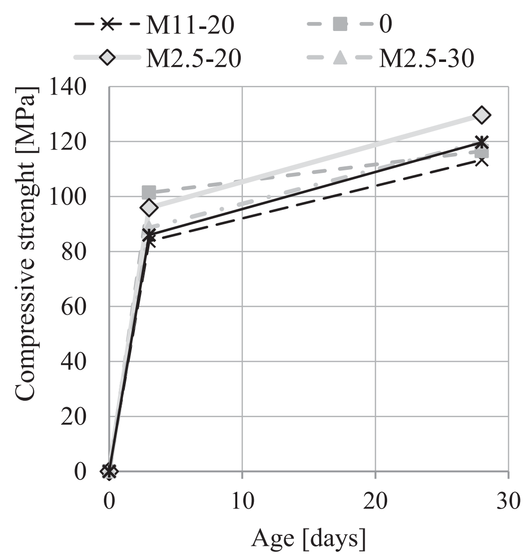


Fig. 5. Compressive strength at 3 and 28 days

Fig. 6. Compressive strength increase

The price was determined for a cubic meter of concrete. The highest price of the UHPC mixture was obtained for the referent mixture, Table 7. It can be concluded that an approximately 25% lower price can be achieved with 30% of LS filler while maintaining the same strength. The price reduction is achieved just by cement reduction.

Table 7. Cost and strength of concrete mixtures

Mixture	Type of LS filler	Cement replacement	Price of cement	Price of filler	Price cement+filler	fc
	μm	[%]	[€]	[€]	[€]	[MPa]
M0	-	0	119	0	119	117
M2.5-20	2.5	20	95	12	107	
M2.5-30	2.5	30	83	18	102	120
M11-20	11	20	95	3	98	113
M11-30	11	30	83	4	88	120

6. CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

This paper provides a review of previous research done in the field of UHPC made with LS filler. It also provides own results from conducted experimental program of four UHPC mixtures made with partial replacement of cement with LS. According to the presented results, the following conclusions can be made:

- The analysis of previous researches showed that the optimal amount of cement that can be replaced with LS is app. 50%. With greater reductions, the amount of cement paste is insufficient and cannot fill the space between QS particles.
- The flow test results, obtained from own experimental program, showed that both mixtures made with 30% of cement replacement with LS had similar workability, despite the fact that these two LS fillers had different fineness. Values of measured diameter obtained in flow test were app.

10% higher in these two mixtures compared with the referent mixture made without LS. These results can be explained by the fact that LS filler particles are spherical in shape, and in a certain way "grease" the concrete mixture and give it greater fluidity.

- Early age compressive strengths of concrete samples tested during this study are higher in the referent mixture compared to all mixtures made with LS. In concrete mixtures made with LS, the highest 3-day compressive strength was obtained in the mixture with 20% of finer LS filler. The increase in strength over time is more pronounced in mixtures made with LS filler compared with the referent one. Both mixtures with 30% of LS filler had similar (2% higher) 28-day compressive strengths compared to the referent one. The effect of filler fineness was not noticeable.
- Simple economic analysis, based on the local commercial prices of component materials, showed that the cost reductions achieved by using 20% and 30% of LS filler as a partial replacement of cement can be up to 10-25%. If we consider the fact that the reduction of cement reduces concretes' CO_2 footprint, it is clear that the use of LS filler provides benefits from both economic and environmental point of view.

The main disadvantage of LS filler is the fact that it is being made by extracting raw materials-natural stone. Therefore, it would be beneficial to explore the use of different industrial by-products (granulated blast furnace slag, fly ash etc.). or waste materials as fillers in UHPC. These fillers can be used to partially replace not only cement, but also QS. In this way, better performance of UHPC can be achieved regarding economic and environmental aspects.

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REFERENCES

[1] E. Fehling (2014), Ultra-High Performance Concrete UHPC. 2014.

[2] MPA (2021), The Concrete Centre-High Strength Concrete,2021.https://www. concretecentre.com/Specification/Special-Concrete/high-strength-concrete.aspx.

[3] R. O'Hegarty, O. Kinnane, J. Newell, и R. West (2021), „High performance, low carbon concrete for building cladding applications", J. Build. Eng., vol 43, pp. 102566,

[4] A. Korpa, T. Kowald, и R. Trettin (2009), „Phase development in normal and ultra high performance cementitious systems by quantitative X-ray analysis and thermoanalytical methods", Cem. Concr. Res., vol. 39, edition 2, pp. 69–76,

[5] K. L. Scrivener, V. M. John, и E. M. Gartner (2018), „Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry", Cem. Concr. Res., vol. 114, pp. 2–26,

[6] G. B. A. (2006), „Material Property Characterization of Ultra-High Performance Concrete", Fhwa,

[7] M. A. Bajaber и I. Y. Hakeem (2021), „UHPC evolution, development, and utilization in construction: a review", J. Mater. Res. Technol., vol. 10, pp. 1058–1074,

[8] E. Ghafari, H. Costa, и E. Júlio (2015), „Critical review on eco-efficient ultra high performance concrete enhanced with nano-materials", Constr. Build. Mater., vol. 101, pp. 201–208,

[9] Y. Shi, G. Long, X. Zen, Y. Xie, и T. Shang (2021), „Design of binder system of eco-efficient UHPC based on physical packing and chemical effect optimization", Constr. Build. Mater., vol. 274, pp. 121382,

[10] X. Ouyang, C. Shi, Z. Wu, K. Li, B. Shan, и J. Shi (2020), „Experimental investigation and prediction of elastic modulus of ultra-high performance concrete (UHPC) based on its composition", Cem. Concr. Res., vol. 138, edition April, pp. 106241,

[11] R. Yang, (2020), „Feasibility analysis of treating recycled rock dust as an environmentally friendly alternative material in Ultra-High Performance Concrete (UHPC)", J. Clean. Prod., vol. 258, pp.

120673,

[12] A. Arora, Y. Yao, B. Mobasher, и N. Neithalath (2019), „Fundamental insights into the compressive and flexural response of binder- and aggregate-optimized ultra-high performance concrete (UHPC)“, Cem. Concr. Compos., vol. 98, edition January, pp. 1–13,

[13] F. Dingqiang (2020), „Optimized design of steel fibres reinforced ultra-high performance concrete (UHPC) composites: Towards to dense structure and efficient fibre application“, Constr. Build. Mater., pp. 121698,

[14] M. Ding (2021), „Possibility and advantages of producing an ultra-high performance concrete (UHPC) with ultra-low cement content“, Constr. Build. Mater., vol 273, pp. 122023,

[15] R. Yang (2019), „The physical and chemical impact of manufactured sand as a partial replacement material in Ultra-High Performance Concrete (UHPC)“, Cem. Concr. Compos., vol. 99, edition. March, pp. 203–213,

[16] K. Jankovic, D. Nikolic, D. Bojovic, и L. Lončar (2010), „NEKA SVOJSTVA BETONA ULTRA VISOKIH Č VRSTO Ć A SOME PROPERTIES OF ULTRA-HIGH STRENGTH CONCRETE“, vol. 53, pp. 43–51,

[17] C. Shi, Z. Wu, J. Xiao, D. Wang, Z. Huang, и Z. Fang (2015), „A review on ultra high performance concrete: Part I. Raw materials and mixture design“, Constr. Build. Mater., vol. 101, pp. 741–751,

[18] A. M. Shihada S (2010), „Effects of silica fume, ultrafine and mixing sequences on properties of ultra-high performance concrete“, Asian J Mater Sci,

[19] P. Richard и M. Cheyrezy (1995), „Composition of reactive powder concretes“, Cem. Concr. Res., vol. 25, edition 7, pp. 1501–1511,

[20] D. Wang, C. Shi, N. Farzadnia, Z. Shi, H. Jia, и Z. Ou (2018), „A review on use of limestone powder in cement-based materials: Mechanism, hydration and microstructures“, Constr. Build. Mater., vol. 181, pp. 659–672,

[21] W. Huang, H. Kazemi-Kamyab, W. Sun, и K. Scrivener (2017), „Effect of cement substitution by limestone on the hydration and microstructural development of ultra-high performance concrete (UHPC)“, Cem. Concr. Compos., vol. 77, pp. 86–101,

[22] F. De Larrard и T. Sedran (2002), „Mixture-proportioning of high-performance concrete“, Cem. Concr. Res.,vol. 32, edition 11, pp. 1699–1704,

[23] F. de Larrard и T. Sedran (1994), „Optimization of ultra-high-performance concrete by the use of a packing model“, Cem. Concr. Res., vol. 24, edition. 6, pp. 997–1009,

[24] R.Yu, P.Spiesz, и H. J. H. Brouwers (2014), „Mix design and properties assessment of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC)“,Cem. Concr. Res.,vol.56, pp.29–39,

[25] S. H. Kang, Y. Jeong, K. H. Tan, и J. Moon (2018), „The use of limestone to replace physical filler of quartz powder in UHPFRC“, Cem. Concr. Compos, vol. 94,edition April, pp. 238–247,

[26] P. P. Li, H. J. H. Brouwers, W. Chen, и Q. Yu (2020), „Optimization and characterization of high-volume limestone powder in sustainable ultra-high performance concrete“, Constr. Build. Mater., vol. 242,

[27] S. Mitrović, D. Popović, M. Tepavčević, и D. Zakić (2021), „Physical-mechanical properties and durability of ultra-high performance concrete (UHPC)“, Gradjevinski Mater. i Konstr., vol. 64, edition 2, pp. 109–117,

[28] S. Mitrović, D. Popović, M. Tepavčević, и D. Zakić (2021), „Physical and mechanical properties of Ultra high performance steel fibre reinforced concrete (UHPSFRC)“, Društvo građevinskih *konstruktera Srbije*.