

Article

Influence of Aggregate Type and SCM Combinations on the Fresh and Mechanical Properties of Ultra-High Performance Concrete

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Abstract

To improve sustainability and reduce the production costs of ultra-high performance concrete (UHPC), the use of locally available aggregates is highly desirable. The combined impact of aggregate type and different supplementary cementitious materials (SCMs) on the fresh and mechanical properties of UHPC is not yet sufficiently understood. Therefore, quartz, limestone, and diabase aggregates together with different SCM combinations were used in the experimental investigation of eighteen UHPC mixtures. Laboratory tests, including flow table, compressive strength, and flexural strength tests, were performed to evaluate the performance of the mixtures. Mixtures containing limestone and fly ash (FA) generally showed higher workability compared to those containing metakaolin (MK). The highest compressive strengths were achieved in mixtures with quartz sand (average 110 MPa) containing approximately 20% MK relative to the total binder content. The mixture with optimal particle distribution and the lowest cement content (500 kg/m³) also showed extremely high mechanical performance. Based on the obtained flexural-to-compressive strength ratios (f_b/f_c), the expression $f_c \approx 7 \cdot f_b$ was proposed to estimate the compressive strength of similar fiber-free UHPC mixtures. Furthermore, heat-treated specimens exhibited a 45% higher compressive strength after 7 days compared to the reference mixture, while the addition of polyvinyl alcohol (PVA) fibers caused a slight decrease in compressive strength of approximately 4%. The obtained results contribute to the development of mechanically efficient UHPC mixtures with optimized particle packing and reduced cement consumption, which may improve the sustainability of UHPC production.



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Keywords: ultra-high performance concrete; particle packing; supplementary cementitious materials; quartz; limestone; diabase; metakaolin; fly ash; thermal treatment

1. Introduction

Ultra-High Performance Concrete (UHPC) is a new generation cement-based composite material with superior mechanical properties and durability [1]. UHPC has traditionally been described in the literature as a material with compressive strength greater than 150 MPa, a flexural strength of 25–40 MPa, and a tensile strength of 7–15 MPa [2–4]. However, there is no universally accepted definition of UHPC in terms of its strength. For example, fib Model Code 2020 (MC2020) [5] defines ultra-high-performance fiber-reinforced

concrete (UHPFRC) as a dense cementitious composite with very low permeability and a compressive strength greater than 120 MPa. Likewise, the classification of UHPC is increasingly based not only on its mechanical performance but also on its optimized particle packing, dense microstructure, and low water-to-binder ratio.

UHPC possesses considerably greater compressive strength, tensile strength, durability, fracture energy, fatigue, impact, and abrasion resistance in contrast to standard concrete. Tall buildings, rehabilitation projects, both structural and non-structural components, military constructions, and machine parts are some examples of its potential uses. UHPC enables the construction of lighter structures due to reduced cross-sectional dimensions [6]. This reduction in structural weight enables UHPC to diminish the earthquake loads that the structure will experience. Although UHPC exhibits excellent resistance to thermal cracking due to its extremely high tensile strength, it is still susceptible to microcrack formation, thermal stresses, and the thermal decomposition of hydration products when exposed to elevated temperatures [7,8]. Despite the numerous outstanding properties of UHPC, its broader application within the construction sector is constrained by its comparatively elevated initial expense [9].

Fine-grained, medium, and coarse quartz sand, Portland cement with a fineness between 0.1 and 1 mm, and silica fume with a high mass fraction of SiO_2 are typically used in UHPC production. Unlike conventional concrete, UHPC does not incorporate coarse aggregate [10,11]. Typically, the water/binder ratio varies between 0.16 and 0.22. Typically, 800–1000 kg/m³ of cementitious material is needed to prepare UHPC, which is around two–three times the quantity required to prepare normal concrete. Supplementary cementitious materials (SCMs) are essential for reducing clinker consumption while improving the mechanical and durability characteristics of cement-based materials [12]. An SCM that is crucial in the manufacturing of UHPC is silica fume (SF). Due to its extremely fine particle size, SF is capable of infiltrating the tiny pores within hardened concrete, which results in decreased porosity of the concrete matrix [13]. SF plays a crucial role in the densification of the UHPC matrix through its pozzolanic activity and its contribution to optimized particle packing [14]. The workability of UHPC can be improved by SF with a wide particle size distribution, high packing density, low void ratio, and low carbon content [15]. He et al. [16] found that the setting time and fluidity of UHPC mixture increased significantly when the SF content was 15% of the total binder. To attain a more compact arrangement of particles and enhance the strength characteristics of UHPC, it is advisable to use SF at a dosage of 20–30% of the total binder content [6,17,18]. Wu et al. [19] showed that after 28 days, the strength of UHPC increased by 10–25 MPa when the SF content was at least 15%. However, at 25% SF, an increase in porosity and a little drop in strength were observed because of the decrease in fluidity. Wu et al. [20] reported that the highest compressive strength (about 120 MPa) of UHPC specimens was achieved with 10–20% SF, while a strength reduction of 8% occurred at maximum amounts of SF of 25%. According to Xu et al. [21], a 20% dosage of SF results in a compressive strength of 170 MPa for UHPC after 3 days of thermal curing at 90 °C, which is 1.3 times higher than the strength obtained after 28 days of curing at 20 °C.

Previous studies have shown that good durability and high strength of UHPC can be achieved by using pozzolanic materials such as ground granulated blast-furnace slag and fly ash. The inclusion of fly ash (FA) will lead to a reduction in the voids within concrete, which will in turn decrease its permeability [22]. Moreover, adding FA to large-volume concrete will minimize creep and drying shrinkage as well as the heat generated due to cement hydration during mass concrete placement. According to Jing et al. [23], an FA dosage of 10–20% in UHPC is sufficient to meet the particular engineering needs of high fluidity and low viscosity. As demonstrated in [24], the application of thermal treatment

enabled UHPC-containing FA to develop its 28-day compressive strength in only three days. In addition, the porosity of UHPC specimens can be diminished by two factors: the addition of FA and increasing the duration of autoclaving [25]. Ferdosian et al. [26] demonstrated that replacing 20% of the cement with ultrafine FA with a mean particle size of 4.48 μm is justified in UHPC mixtures, as a flow diameter of 375 mm and a compressive strength of 153 MPa were achieved.

Due to its high pozzolanic reactivity, thermally activated alumino-silicate metakaolin (MK) is widely used in UHPC production. The self-compacting UHPC can be manufactured using MK and SF [27]. An increase in flexural strength and compactness is possible by adding MK due to its role in improving the interfacial transition zone (ITZ) between high-performance mortar and quartz sand [28]. An MK replacement level of 15% was reported to provide the optimum long-term compressive strength of UHPC mortars [12]. Researchers [29] concluded that substituting 10% of cement with MK enhanced the elastic modulus, flexural and compressive strengths, and resistance to water and chloride permeability, while reducing the drying shrinkage of UHPC. The replacement of SF with MK on a weight-for-weight basis enables the production of UHPC that exhibits comparable mechanical properties, regardless of the inclusion of crushed quartz, metal fibers, or heat treatment [30]. Norhasri et al. [31] showed that 1% nano-metakaolin is the optimum value for achieving the highest compressive strength, as this low dosage provides a moderate ultra-filling effect that contributes to UHPC densification. Some UHPC mix proportions are presented in Table 1.

Table 1. Summary of UHPC mix proportions from the literature.

Reference	Constituents	Quantity [kg/m^3]	Main Findings
[12]	Cement	553.4–774.8	The addition of 15% MK (by binder mass) resulted in the highest compressive and flexural strength of UHPC mortar.
	Metakaolin	0–221.4	
	Limestone	332	
	Quartz sand	1106.8	
	Superplasticizer	4.9–27.6	
	Water/binder ratio (w/b)	0.2	
[32]	Cement	788.5	Replacing SF with 10% nanosilica improved the tensile performance and compressive strength of UHPFRC, while the lowest porosity was achieved with a 20% nanosilica replacement.
	Silica flour	236.6	
	Silica sand	867.4	
	Nanosilica	19.7–98.6	
	Silica fume	98.6–197.1	
	Superplasticizer	25.0–38.0	
	Steel fiber	2%	
[22]	Water/binder ratio (w/b)	0.18–0.19	The workability of concrete improved as the FA content increased from 0% to 40%.
	Cement	394.2–657	
	Fly ash	0–262.8	
	Quarry dust	1050	
	Superplasticizer	40	
[29]	Water/binder ratio (w/b)	0.24	Replacing cement with 10% MK reduced the drying shrinkage of UHPC, while increasing its elastic modulus, compressive and flexural strength, the resistance to water and chloride penetration.
	Cement	840–1020	
	Silica fume	120	
	Metakaolin	60–240	
	Sand	780	
	Superplasticizer	37–41	
	Water/binder ratio (w/b)	0.15	

Table 1. Cont.

Reference	Constituents	Quantity [kg/m ³]	Main Findings
[33]	Cement	424–850	The combined use of glass powder and GGBS improved the workability and mechanical performance of UHPC while reducing its environmental impact.
	GGBS	0–22.5	
	Glass powder	0–538	
	Silica sand	1215	
	Silica fume	113–225	
	Superplasticizer	50–67	
	Steel fiber	157	
	Water/binder ratio (w/b)	0.18	
[34]	Cement	589–619	Increasing the steel fiber content from 0% to 2% gradually increased the compressive strength of specimens subjected to both standard and steam curing.
	Ultra-fine mineral admixture	196–206	
	Nature sand	743	
	Crushed basalt stone	782	
	Steel fiber	0–2%	
	Water/binder ratio (w/b)	0.16–0.22	
[35]	Cement	642–662	The highest flexural characteristics were achieved at the optimum plastic viscosity of UHPC mortar.
	Welan gun powder	0.18–0.27%	
	Silica fume	41–42	
	Fly ash	401–413	
	Steel fiber	1–3%	
	Water/binder ratio (w/b)	0.2	
[11]	Cement	706	Simplified equations for calculating the shrinkage strain and creep coefficient of UHPC were proposed.
	Silica fume	160	
	Coarse sand	359	
	Medium sand	717	
	Fine sand	179	
	Steel fiber	2%	
	Water/binder ratio (w/b)	0.14	
[36]	Cement	417.5–439.5	UHPC with a binder content as low as 440 kg/m ³ was successfully produced using the modified Andreassen and Andersen particle packing model.
	Limestone	263.7	
	Quartz	175.9	
	Microsand	218.7	
	Sand	1054.7	
	Nanosilica	0–22.0	
	Superplasticizer	43.9	
	Steel fiber	2.5%	
	Water/binder ratio (w/b)	0.18	
[37]	Cement	737–1005	UHPC maintained high mechanical performance up to 500 °C, while significant strength degradation occurred after exposure to 600 °C.
	Ultra-fine silica powder	0–31	
	Silica fume	0–191	
	Polypropylene fiber	0–78	
	Steel fiber	0–0.8	
	Viscous agent	1	
	Superplasticizer	25	
	Water/binder ratio (w/b)	0.195	
[38]	Cement	750	Increasing the steel fiber content from 0% to 3% resulted in a higher bending failure load of UHPC specimens.
	Sand	1000	
	Silica fume	250	
	Superplasticizer	6.0–6.3%	
	Steel fiber	0–234	
	Water/binder ratio (w/b)	0.2	

It can be seen from Table 1 that SF is the predominant SCM used in UHPC mixtures, while mixtures containing MK and FA have been investigated much less frequently. In addition, quartz sand stands out as the most frequently used aggregate in UHPC mixtures.

The amount of cement ranged from 400 to 1020 kg/m³, while the water-to-binder ratio varied between 0.14 and 0.24.

The choice of aggregate in UHPC has a considerable impact on its mechanical and durability characteristics. Similarly, for obtaining exceptional performance of cementitious systems, the particle size distribution of aggregates has a huge influence [39]. Quartz sand refers to a granular material that occurs naturally or is processed industrially, consisting mainly of quartz grains, which are crystals of silicon dioxide (SiO₂). This kind of fine aggregate is well-suited for making UHPC. However, the high cost of quartz sand prevents it from being widely used in construction [13]. A research study conducted by Mosaberpanah and Eren [40] utilized response surface modeling to examine the impact of quartz sand, quartz powder, and water curing methods on the mechanical characteristics of UHPC. Their results revealed that incorporating quartz sand up to 50% as aggregate substitution by weight significantly enhanced the 28-day compressive strength of UHPC mixtures. Employing fine aggregates such as quartz powder instead of coarse aggregates is essential for decreasing the maximum paste thickness, which results in lower porosity within the matrix, a vital aspect of UHPC mixture design [41].

Limestone offers a cost-effective solution, a homogeneous structure, significant reserves, and is readily available worldwide. The incorporation of limestone powder as a partial replacement of cement, along with a partial or total substitution of silica powder, led to a slight decrease in the mixing duration required to produce UHPC [42]. In [43], Sharma et al. demonstrated that the compressive strength of UHPC mixtures diminished as the dosage of limestone powder increased to 20%. Nevertheless, a notable decrease in the compressive strength of UHPC mixtures was not observed at a 10% limestone powder dosage. Due to its filler and dilution effects, limestone powder can accelerate hydration reaction and reduce autogenous shrinkage [44,45]. High-strength concrete incorporating basalt aggregate demonstrates superior mechanical characteristics compared to high-strength concrete using limestone, which can be ascribed to the natural strength of the basalt rock [46]. Laboratory test results regarding compressive strength, as indicated in [47], suggest that an increase in the percentage of basalt improves the strength of the mix compared to the traditional limestone mix. Szczesniak et al. [48] showed that in formulations developed for very-high-strength concrete utilizing granite or sand as natural fine aggregate, substituting the aggregate with basalt resulted in a 28% increase in compressive strength. Peng et al. [49] proposed the incorporation of coarse basalt aggregate in UHPC mixtures to enhance penetration impact resistance.

Despite the extensive body of research on UHPC, the combined influence of aggregate type and SCMs on both fresh and mechanical properties has not been sufficiently clarified. Furthermore, in fiber-free UHPC, the interaction between aggregate mineralogy, particle packing optimization, and different SCM types has not yet been sufficiently investigated. This study aims to systematically investigate how aggregate type and SCMs affect the fresh properties of UHPC, as well as its compressive and flexural strength. Additionally, the influence of thermal treatment and the addition of PVA fibers on the development of compressive strength was analyzed using a separate set of mixtures. The findings of this study are expected to contribute to the development of more sustainable and cost-effective UHPC mixtures based on locally available aggregates, while providing practical guidance for optimizing mixture design in engineering applications.

2. Experimental Program

The overall experimental program adopted in this study is summarized in Figure 1.

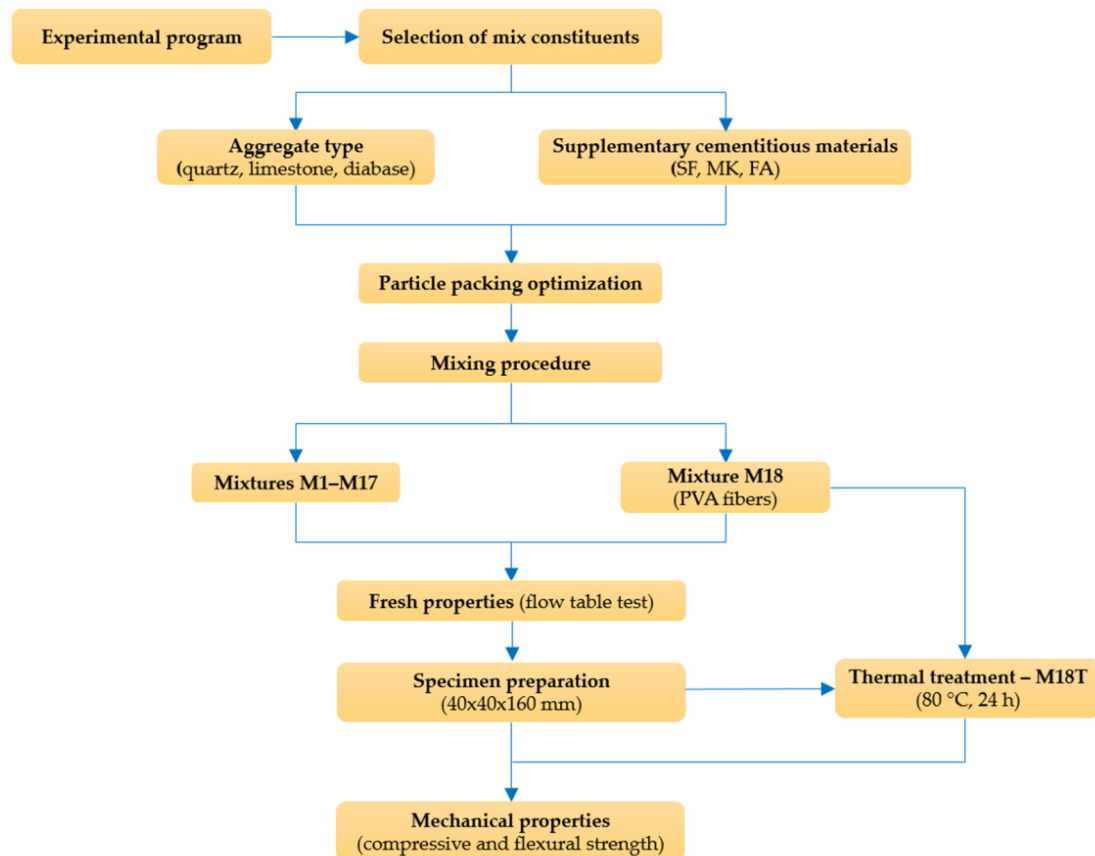


Figure 1. Flowchart of the experimental program.

2.1. Materials

Three types of aggregates were used in this experiment: quartz (0–1 mm), limestone (0–1 mm) and diabase sand (0–1 mm). Quartz sand particles were mostly isometric and rounded in shape. The remaining two aggregates were characterized by mainly angular crushed particles. According to EN 1097-6:2022 [50], the water absorption of the quartz sand and limestone aggregate was 0.57% and 1.26%, respectively. Furthermore, the content of particles passing the 0.063 mm sieve, determined in accordance with EN 933-1:2012 [51], was 1.85% for the quartz sand and 9.97% for the limestone aggregate. Diabase, which has a high density and less water absorption compared to limestone, was used for the volcanic aggregate. The diabase aggregate was characterized by a water absorption of 1.10% and an SSD particle density of 2.83 Mg/m³, indicating its dense mineral structure.

The Portland cement CEM I 52.5 N was used in the experiments. It is cement with a clinker proportion of 95%–100% and with a specific density of 3.1 g/cm³, which complies with all regulations and requirements in EN 197-1:2011 [52]. 28-day standardized compressive strength of the cement is 63 MPa. The cement content in nearly all mixtures varied between 700 and 900 kg/m³. SF, MK and FA were used as supplementary cementitious materials, while limestone powder was used as an inert filler (Figure 2).

SF called MasterRoc[®] MS 610 with specific surface area of 15,000–35,000 m²/kg was used in the experiments. Its density is 0.55–0.7 kg/L and the chloride content is less than 0.1%. The morphology of SF obtained using a scanning electron microscope (SEM) is shown in Figure 3. It can be seen that the particles have an almost perfectly spherical shape and an extremely smooth and regular surface texture, which promotes efficient particle packing and contributes to the high density of the UHPC matrix. MK called Metaver[™] N was produced by Newchem (Baden bei Wien, Austria) with specific surface area (Blaine) of 22,000 cm²/g and specific density of 2.6 g/cm³. The ability of Metaver[™] N to bind

significant amounts of free lime in the form of stable C-S-H phases is one of its important characteristics. The FA used in the experiment is Microsit[®] 20, a pozzolanic additive for high performance cement-based construction materials. Blaine value and specific density of FA are 6000 cm²/g and 2.5 g/cm³, respectively. The special particle size distribution and the spherical shaped particles of Microsit[®] 20 improve its flow properties, while amorphous particles increase the mechanical properties through their pozzolanic reaction.

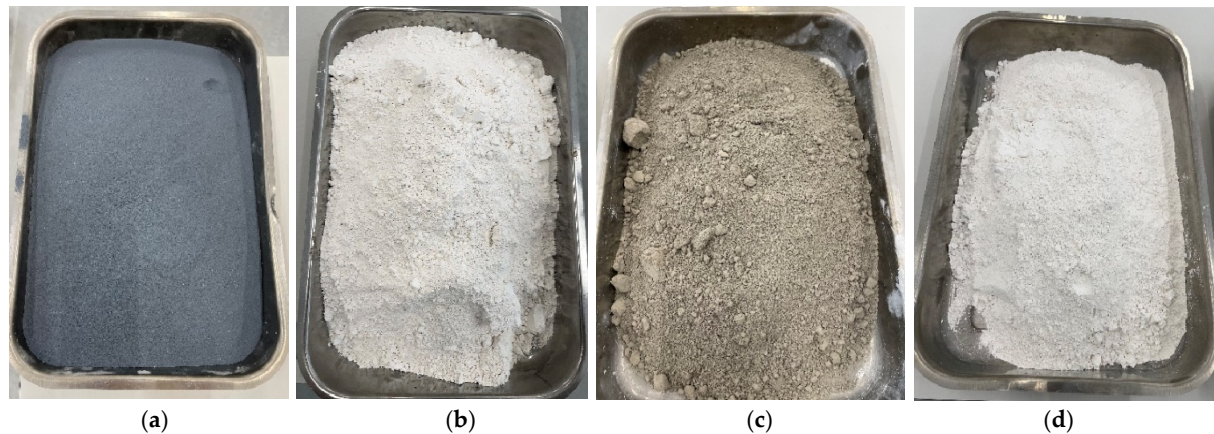


Figure 2. Supplementary cementitious materials: (a) SF; (b) MK; (c) FA; (d) limestone powder.

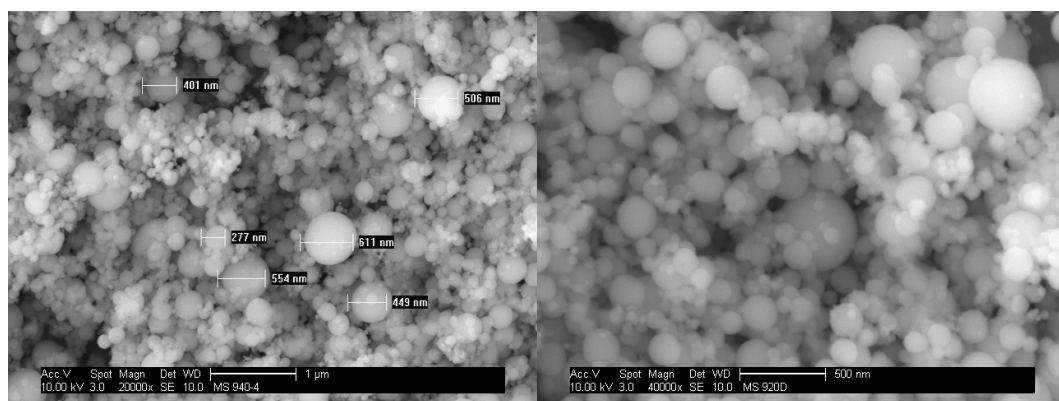


Figure 3. SEM images of the SF used in this study.

Stone powder was obtained by grinding fine limestone with a high content of calcium carbonate, which specific density is 2.7 g/cm³. The Blaine specific surface area was 5700 cm²/g. Chemical compositions of cementitious materials are summarized in Table 2.

Table 2. Chemical composition of the materials (%).

Material	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	SO ₃
Cement	19.47	4.75	3.43	63.16	1.43	0.28	0.62	2.64
SF	86–96	0.4–1	0.1–1.5	0.1–0.5	0.3–2	0.4–0.5	0.3–3	<2.0
MK	52–54	41–44	<1.5	<0.5	<0.4	<0.1	<2.0	—
FA	52	25	7	5	—	—	—	—

MasterGlenium ACE 770, a high-performance second-generation polycarboxylate ether (PCE) superplasticizer, was used in the mixtures. Polyvinyl alcohol (PVA) fibers with a diameter of 0.2 mm and a length of 6 mm were also used. These fibers have a tensile strength of 800 MPa and were added to the UHPC in the final mixing stage at a dosage of 35 kg/m³.

2.2. Mixing and Curing

Eighteen UHPC mixes were prepared in this research. Mineral admixtures of greater fineness (SF and MK) are combined with admixtures of lesser fineness (FA and limestone powder). The water-to-cement ratios (W/C) of these mixtures were selected from 0.22 to 0.27. The amount of binder used in these mixtures ranges between 1100 and 1350 kg/m³. The details of the mixtures are presented in Table 3.

Table 3. Summary of UHPC mixtures.

Materials (kg/m ³)												
Mixes	Cement	SF	MK	FA	Limestone Powder	Water	Superplasticizer	W/C	Quartz Sand	Limestone Sand	Diabase Sand	PVA Fibers
M1	790	197.5	—	—	229.1	201.7	48.6	0.25	917.9	—	—	—
M2	770	103.9	115.5	—	223.3	196.3	48.5	0.25	—	892.4	—	—
M3	770	103.9	—	115.5	223.3	192.5	48.5	0.25	—	899.8	—	—
M4	708.9	—	218	—	288.1	191.4	48.6	0.27	909	—	—	—
M5	710	—	190	50	250	184.6	48	0.26	941.5	—	—	—
M6	700	—	—	250	250	175	48	0.25	960.5	—	—	—
M7	877.5	122.5	—	—	200	204.2	48	0.23	953	—	—	—
M8	700	—	250	50	200	182	48	0.26	944.9	—	—	—
M9	800	—	200	—	300	176	52	0.22	870.2	—	—	—
M10	800	80	—	100	220	200	48	0.25	—	902.6	—	—
M11	800	80	—	100	220	190	48	0.24	—	—	955.6	—
M12	500	182.8	—	—	157.7	165	33.6	0.33	1388	—	—	—
M13	800	—	200	—	200	176	48	0.22	—	978.4	—	—
M14	810	202.5	—	—	243	191.4	49.6	0.23	909.9	—	—	—
M15	750	—	195	—	240	180	47.4	0.24	977.9	—	—	—
M16	900	225	—	—	225	181	54	0.2	811.1	—	—	—
M17	850	—	212.5	—	212.5	187	51	0.22	874	—	—	—
M18	750	—	187.5	—	187.5	172.5	39.3	0.23	1077	—	—	—
M18V	750	—	187.5	—	187.5	172.5	39.3	0.23	1077	—	—	35

Optimization of particle packing in concrete mixtures is achieved through the proper selection of particle size distribution and constituent proportions, thereby reducing the void content in the cementitious matrix. A number of components with various particle size distribution curves are mixed in the right amounts to produce an optimum curve for the dry constituents in the particle packing analysis. In this investigation, mix proportions were optimized using a modified Andreasen and Andersen model [53].

This model is most commonly applied in the design of UHPC mixtures and is described by the following equation:

$$P(D) = \frac{D^q - D_{\min}^q}{D_{\max}^q - D_{\min}^q} \quad (1)$$

in which q is the distribution modulus, $P(D)$ is a fraction of the total solids smaller than size D , D is the particle size, $D_{\min}$ is the minimum particle size and $D_{\max}$ is the maximum particle size. For UHPC, the distribution modulus q should be between 0.22 and 0.25 [54]. In this study, $q = 0.25$ was used for all mixtures (grading curve mod A&A). Laser diffraction analysis was used to determine the particle size distributions of the raw materials, and the corresponding results are presented in Figure 4.

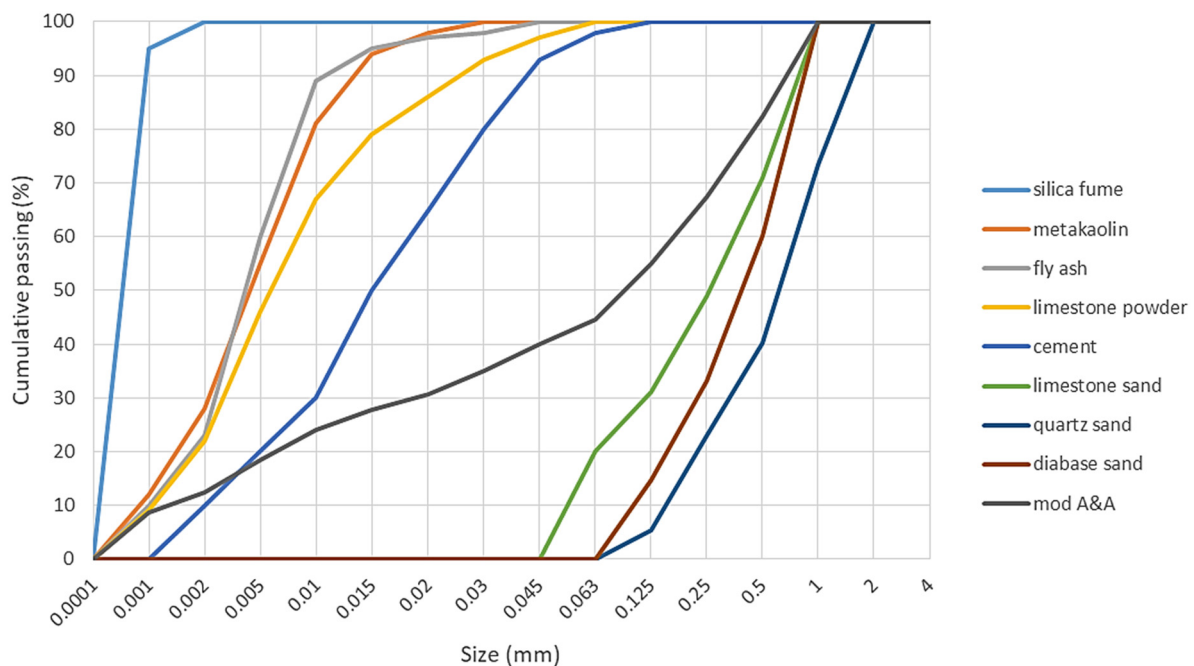


Figure 4. Particle size distribution curves of the raw materials and grading curve mod A&A.

A laboratory mortar mixer with a capacity of 5 L was used to mix UHPC mixtures. The mixing process for UHPC differs from that of ordinary concrete because of the incredibly low W/C ratio. In this study, the mixing procedure consists of three stages. In the first stage, all dry constituents (binders and aggregates) were dry-mixed for 4 min. Subsequently, 70% of the total mixing water was added, and mixing was continued for another 4 min. In the final stage, the remaining water combined with the superplasticizer was introduced, and mixing proceeded for 15 min, during which the mixer speed was gradually increased. With respect to the type of aggregate used and the combination of mineral admixtures, the consistency of fresh concrete varied from stiff to fluid.

Figure 5 shows prism specimens of mixture M2 immediately after casting and a prism cross-section after flexural strength testing. All UHPC mixtures were cast into molds with dimensions of 40 × 40 × 160 mm. After casting, the fresh UHPC specimens were compacted using a vibrating table. Each mold was filled halfway and vibrated for 60 s, after which it was completely filled and vibrated for an additional 60 s. The molds are previously coated with oil for easier separation of UHPC from molds. The specimens remained under standard curing conditions for 24 h before being demolded. Once the specimens were demolded, they were kept in the chamber until testing at a temperature of 20 ± 2 °C and a relative humidity RH ≥ 95%.

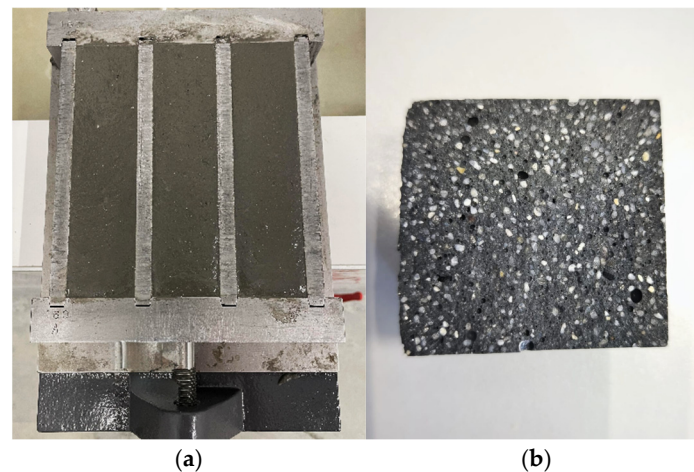


Figure 5. Representative laboratory photographs: (a) casting of UHPC prism specimens; (b) prism half after flexural testing.

For mixture M18, a selected number of specimens were subjected to thermal curing after 24 h. The specimens were immersed in water in a container, which was then placed in a temperature-controlled chamber where the temperature was incrementally increased to 80 °C, maintained for a defined period, and subsequently reduced to ambient temperature; the entire procedure lasted 24 h, after which the specimens were moved to the curing chamber until testing. The mechanical properties of UHPC were tested on these specimens.

3. Results and Discussion

3.1. Fresh UHPC Properties

Determination of consistency of fresh UHPC (by flow table) was performed according to the guidelines given by EN 1015-3 [55]. Although this method refers to testing the consistency of the mortar, it can also be applied to UHPC because it is mainly composed of aggregate grains smaller than 2 mm. A test sample's mean diameter is used for determining the flow value. The mold, which is 60 mm tall and has internal diameters of 100 mm at the base and 70 mm at the top, is placed in the middle of the flow table and filled in two layers, each of which is tamped ten times using the tamper. The mold is removed after about 15 s and the table is jolted 15 times at a rate of one jolt per second. Two orthogonal diameters of the UHPC spread are measured. Table 4 displays the UHPC mixtures' measured temperatures and flow values.

Table 4. The flow values and temperatures of UHPC mixes.

Mixes	Temperature (°C)	Diameter D_1 (mm)	Diameter D_2 (mm)	Diameter D_{mean} (mm)
M1	29.9	170	175	172.5
M2	29.6	245	240	242.5
M3	28.4	300	300	300
M4	30.6	300	300	300
M5	31.1	265	280	272.5
M6	34.6	225	230	227.5
M7	27.8	220	225	222.5

Table 4. Cont.

Mixes	Temperature (°C)	Diameter D_1 (mm)	Diameter D_2 (mm)	Diameter D_{mean} (mm)
M8	33.3	190	200	195
M9	38.3	175	180	177.5
M10	32.3	290	300	295
M11	32.8	200	205	202.5
M12	29.4	135	140	137.5
M13	35.4	240	250	245
M14	30.3	300	300	300
M15	31.6	300	300	300
M16	28.5	300	300	300
M17	34.4	300	300	300
M18	33.4	275	280	277.5
M18V	33.9	210	215	212.5

Considering the obtained results, it can be concluded that mixtures M3, M4 and M14–M17 have the highest workability. The representation of the consistency of mixtures with different types of aggregates (M12, M11 and M3) is given in Figure 6. As shown in Figure 6, the mixture containing limestone sand exhibited the highest flowability, while the mixture with quartz sand showed the lowest spread. The diabase-based mixture demonstrated intermediate workability, which can be attributed to differences in particle shape and surface texture. This observation agrees well with the findings presented in [48]. All mixtures, except M1, M8, M9 and M12, have a flow value greater than 200 mm, so they belong to the fluid consistency category.

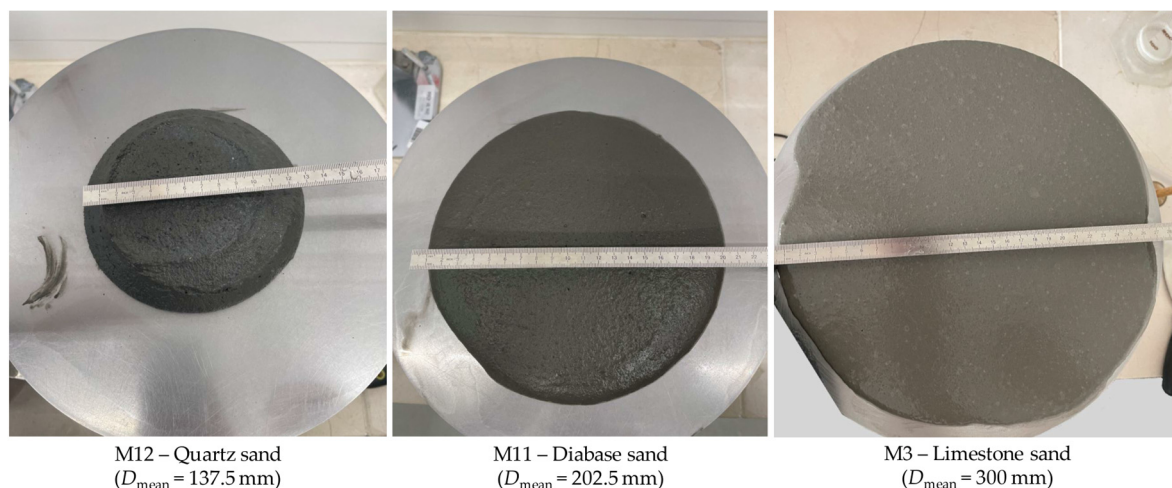


Figure 6. Representative flow test results of UHPC mixtures (M12, M11 and M3) containing different aggregate types.

Mixtures M2, M3 and M10 were prepared with limestone sand and similar binder compositions, allowing a direct assessment of the effect of SCM type on fresh properties. The combination of materials including MK (M2) showed lower flow values than mixtures containing FA (M3 and M10), despite having a similar total powder amount. The reason lies in the fact that the presence of MK increases the interparticle friction and water demand due to its angular particle morphology and larger specific surface area. Conversely, the spherical morphology of FA improves particle mobility within the fresh matrix, resulting

in enhanced workability. These results are consistent with those reported in [22], where the fluidity of UHPC mixtures increased with increasing FA dosage from 0% to 40%. Through two mechanisms SF alters the behavior of fresh UHPC: its ultrafine particles increase packing density, but their exceptionally high specific surface area raises mixture viscosity and water demand, which may reduce flowability. Mixtures M1 and M14 had considerably varied spread diameters even though their SF content and aggregate type were similar. This suggests that workability is controlled by the overall particle packing and powder balance rather than only the SF content.

Although mixture M12 exhibited a particle size distribution closely matching the Andreasen and Andersen model, its spread diameter was the lowest among all mixtures. Research results indicate that rigorous adherence to theoretical particle packing models does not necessarily lead to improved fresh performance. Although optimal packing increases density and may improve mechanical characteristics, it can also decrease workability and increase mixture viscosity. While mixture M9 had noticeably less workability (177.5 mm), mixtures M4 and M17 showed the highest spread values. The main difference was that M9 had a greater limestone powder content (300 kg/m^3), indicating that adding too much filler raises the system's total specific surface area and decreases the effective water film thickness. This suggests that there is an optimal filler content beyond which the performance of fresh UHPC declines. In mixture M18V, PVA fibers were incorporated, and as expected, they reduced the workability compared to the reference mixture M18. Increasing the content and aspect ratio of PVA fibers results in elevated yield stress and reduced flowability of the mixture. The fibers promote the development of an internal network that enhances interparticle friction and mechanical interlocking within the fresh matrix [56]. Overall, the results show that the intricate relationship between aggregate type, particle packing, SCMs, filler content, and fiber incorporation controls the fresh behavior of UHPC. This emphasizes the need for a carefully balanced mixture design to achieve sufficient workability and optimal performance.

3.2. Mechanical Properties of UHPC

Following the analysis of fresh properties, the mechanical performance of the developed UHPC mixtures was evaluated through compressive and flexural strength tests. The determination of compressive and flexural strength was carried out according to the EN 196-1 standard [57]. Mechanical testing was performed using an FORM+TEST hydraulic testing machine. The maximum load capacity of the device is 600 kN, with a maximum piston displacement of 15 mm. The load was applied at a rate of around 1.5 MPa/s, which is in accordance with EN 196-1 standard [57]. For every mixture, three prismatic specimens measuring $40 \times 40 \times 160 \text{ mm}$ were prepared. These specimens were initially tested for flexural strength (three values), and then the prism halves from the flexural test were used to assess compressive strength (six values). The final flexural strength was calculated as the mean of three test results, whereas the final compressive strength was determined as the average of six measurements obtained from the prism halves. The flexural strength of concrete f_b was determined using the following equation:

$$f_b = \frac{3 \cdot F \cdot l}{2 \cdot b \cdot h^2} \quad (2)$$

where F is the maximum applied load (N), $l = 100 \text{ mm}$ is the distance between the supports, $b = 40 \text{ mm}$ is the width of the prismatic specimen and $h = 40 \text{ mm}$ is its height.

Mechanical testing was conducted at the age of 28 days after curing under standard laboratory conditions ($20 \pm 2 \text{ }^\circ\text{C}$). The only exception is the specimens made from the M18 mixture, where tests were conducted after 7, 14 and 28 days. It should be mentioned that

specimen size effects could cause the obtained compressive strengths to vary from those evaluated on standard concrete cylinders.

3.2.1. Compressive Strength

The compressive strength values of all specimens, except M18, are presented in this section, while the results for M18 are analyzed separately with respect to the effects of thermal curing and PVA fiber incorporation. The compressive strength values for specimens M1 to M17 are shown in Figure 7. The standard deviations of the individual values are displayed by the error bars. It can be observed that the compressive strengths range from 96 to 127 MPa. Considering the absence of steel fibers and the lack of thermal curing, the obtained compressive strengths can be regarded as representative baseline values for UHPC.

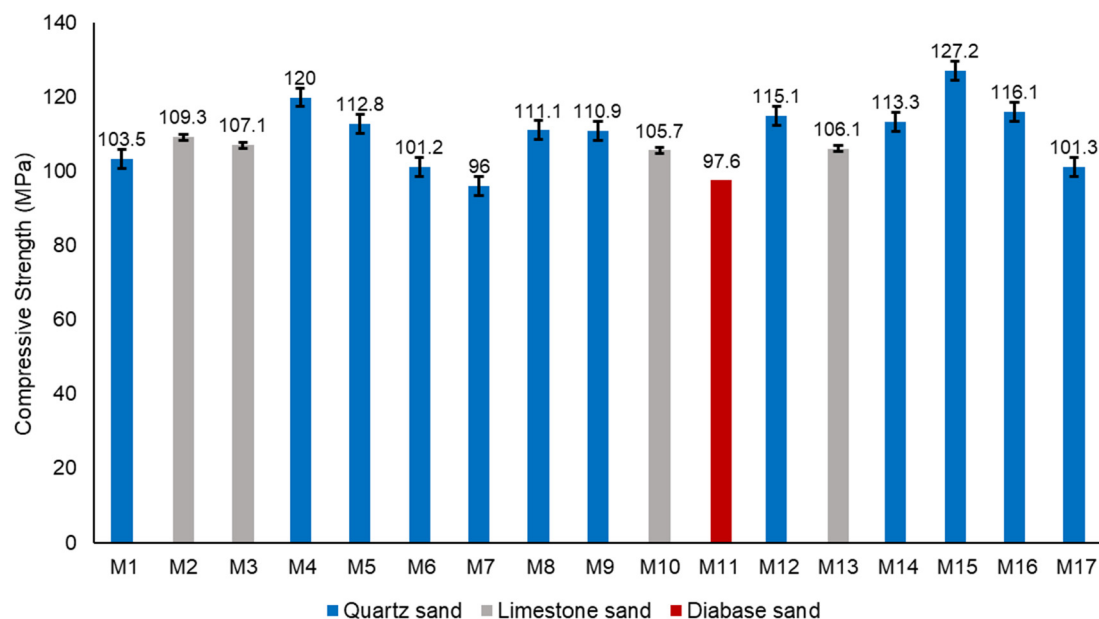


Figure 7. Comparison of compressive strength among UHPC mixtures with different aggregate types.

When grouped according to aggregate type, mixtures incorporating quartz sand exhibited the highest average compressive strength (approximately 110 MPa), followed by limestone-based mixtures (approximately 107 MPa). The compressive strength of the UHPC including diabase aggregate was lower. It should be highlighted, nevertheless, that this aggregate type was only used to create one mixture, which restricts more extensive generalization.

The slightly higher compressive strengths observed for specimens containing quartz sand may be attributed to the high stiffness and low deformability of quartz particles, which enable more efficient stress transfer within the dense UHPC matrix. Moreover, quartz's low porosity and mineralogical stability could help create a more compact ITZ [58]. On the other hand, limestone particles' possibly higher porosity and water absorption capacity may have an impact on the ITZ's local microstructure. Although limestone may contribute to filler effects and the formation of carboaluminate phases, its mechanical properties could limit the ultimate compressive strength in highly dense UHPC matrices.

The maximum compressive strengths were obtained in UHPC specimens containing MK (M15 and M4). This could be explained by the strong pozzolanic reactivity of MK, which promotes the creation of more C-S-H and C-A-S-H phases, resulting in a denser microstructure. It is worth noting that the two mixtures exhibiting the highest compressive strength values (M15 and M4) contained approximately 20–23% MK relative to the total

binder content, which may indicate a potentially favorable MK dosage in the present study. High compressive strength values were also obtained on specimens with SF (M16, M12 and M14), which further confirms the positive effect of this SCM in UHPC systems. Nevertheless, mixtures based on MK had somewhat higher maximum values in the current investigation. When compared to mixtures containing MK or SF, mixtures including FA showed somewhat lower compressive strength values. This effect was more pronounced in mixtures with higher FA content (e.g., M6 with an FA content of 26% by weight of cementitious materials). The observed trend could be explained by FA's slower reaction kinetics and reduced pozzolanic reactivity, which could restrict strength development at 28 days under standard curing conditions [59,60].

An interesting observation can be made for mixture M12, which exhibited one of the highest compressive strength values (115.15 MPa) despite containing the lowest cement content (500 kg/m^3) among all investigated mixtures. The optimal particle distribution was demonstrated by this mixture, which deviated very little from the Andreassen and Andersen particle packing curve. These findings confirm that increasing cement dosage does not always result in increased compressive strength and suggest that better packing density and reduced porosity can compensate for a lower cement content. Similar results were obtained in [36], where the modified Andreassen and Andersen model was applied to achieve a homogeneous and dense UHPC skeleton with a binder content of only 440 kg/m^3 , while the compressive and flexural strengths reached approximately 135 MPa and 25 MPa, respectively. As shown in Table 5, mixture M12 exhibited one of the lowest coefficients of variation ($\text{CV} = 3.34\%$), which implies a high degree of mixture homogeneity and consistency in particle packing.

Table 5. Statistical parameters of compressive strength of UHPC specimens.

Mixes	Aggregate	$f_{c,\text{mean}}$ (MPa)	SD (MPa)	CV (%)
M1	Quartz sand	103.50	8.08	7.81
M2	Limestone	109.32	7.08	6.48
M3	Limestone	107.15	12.85	12.00
M4	Quartz sand	120.00	7.17	5.97
M5	Quartz sand	112.86	9.89	8.76
M6	Quartz sand	101.22	8.86	8.75
M7	Quartz sand	96.04	14.96	15.58
M8	Quartz sand	111.14	18.74	16.86
M9	Quartz sand	110.94	4.20	3.79
M10	Limestone	105.73	3.51	3.32
M11	Diabase	97.65	9.67	9.90
M12	Quartz sand	115.15	3.85	3.34
M13	Limestone	106.14	9.94	9.36
M14	Quartz sand	113.30	6.31	5.57
M15	Quartz sand	127.26	3.69	2.90
M16	Quartz sand	116.14	5.90	5.08
M17	Quartz sand	101.33	16.33	16.11

The results presented in Table 5 indicate that, for most mixtures, the coefficient of variation was below 10%, implying good repeatability and a homogeneous microstructure of the specimens.

However, a few mixtures (M7, M8 and M17) showed increased variability ($CV > 15\%$), which may be associated with less uniform internal structure or suboptimal particle packing. On the other hand, mixtures like M15, M10 and M12 showed extremely low variability ($CV \approx 3\%$), indicating a consistent and uniform microstructure. Overall, the findings demonstrate that both optimal particle packing and suitable binder composition are essential for both attaining high compressive strength and providing consistent mechanical performance.

3.2.2. Flexural Strength

In order to gain even better insight into the mechanical behavior of the analyzed mixtures, the flexural strength of the UHPC specimens was also determined. The influence of aggregate type and SCMs on flexural behavior was given special consideration. Figure 8 demonstrates that flexural strength values for UHPC specimens ranged from 8.8 to 18 MPa. The lowest value was observed for mixture M9, which showed significantly lower flexural strength compared to the other mixtures. It should be emphasized that the maximum compressive and flexural strengths did not occur in the same mixtures, which is often the case with fiber-free UHPC.

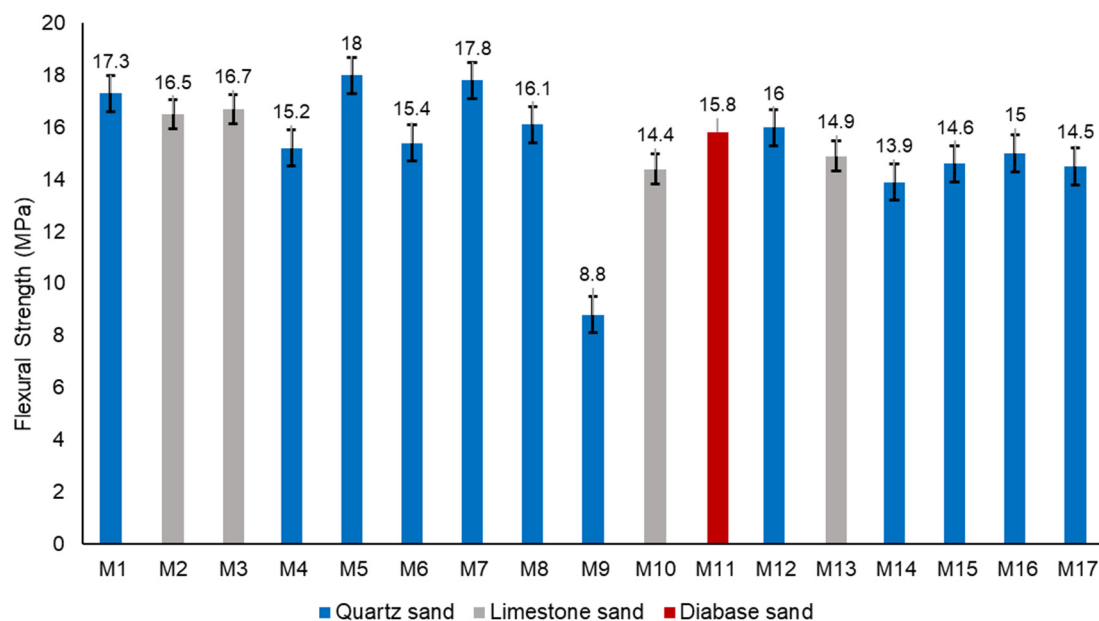


Figure 8. Flexural strength of UHPC specimens with different aggregate types.

As with the compressive strength data, mixtures including quartz sand had the highest flexural strength, whereas mixtures containing limestone sand had somewhat lower values. This may be attributed to the higher hardness and elastic modulus of quartz particles, which can improve the mechanical performance of the UHPC matrix.

The influence of SCMs on flexural strength was also analyzed. Relatively high flexural strengths were obtained in UHPC specimens with SF, where the average value is 15.9 MPa. Mixtures with MK showed similar results, but they were a bit more variable (average 14.6 MPa). Mixture M5 reached the highest recorded strength of 18 MPa. On the other hand, mixtures containing FA developed flexural strengths within a comparable range, indicating that the type of SCM had a less pronounced effect on flexural performance than aggregate type.

Table 6 shows the average flexural strengths of all mixtures as well as the corresponding statistical parameters (standard deviation and coefficient of variation). The coefficients

of variation for almost all mixtures range between 2 and 8%, confirming the good homogeneity of the mixtures. While on the one hand, the mixture M5 with the highest flexural strength showed the lowest coefficient of variation (CV = 1.76%), the mixture M9 with the lowest measured strength exhibited a significantly higher coefficient of variation (CV = 31.89%).

Table 6. Statistical parameters of flexural strength of UHPC specimens.

Mixes	Aggregate	$f_{b,mean}$ (MPa)	SD (MPa)	CV (%)
M1	Quartz sand	17.37	1.11	6.36
M2	Limestone	16.56	1.23	7.43
M3	Limestone	16.72	0.36	2.12
M4	Quartz sand	15.25	1.21	7.95
M5	Quartz sand	18.02	0.32	1.76
M6	Quartz sand	15.48	0.93	5.98
M7	Quartz sand	17.83	0.60	3.39
M8	Quartz sand	16.16	1.28	7.91
M9	Quartz sand	8.86	2.83	31.89
M10	Limestone	14.40	1.14	7.94
M11	Diabase	15.80	0.73	4.62
M12	Quartz sand	16.03	0.41	2.53
M13	Limestone	14.95	1.47	9.80
M14	Quartz sand	13.98	1.00	7.12
M15	Quartz sand	14.63	0.90	6.16
M16	Quartz sand	15.08	0.32	2.14
M17	Quartz sand	14.51	1.72	11.84

The flexural-to-compressive strength ratios (f_b/f_c) for all investigated mixtures are shown in Figure 9.

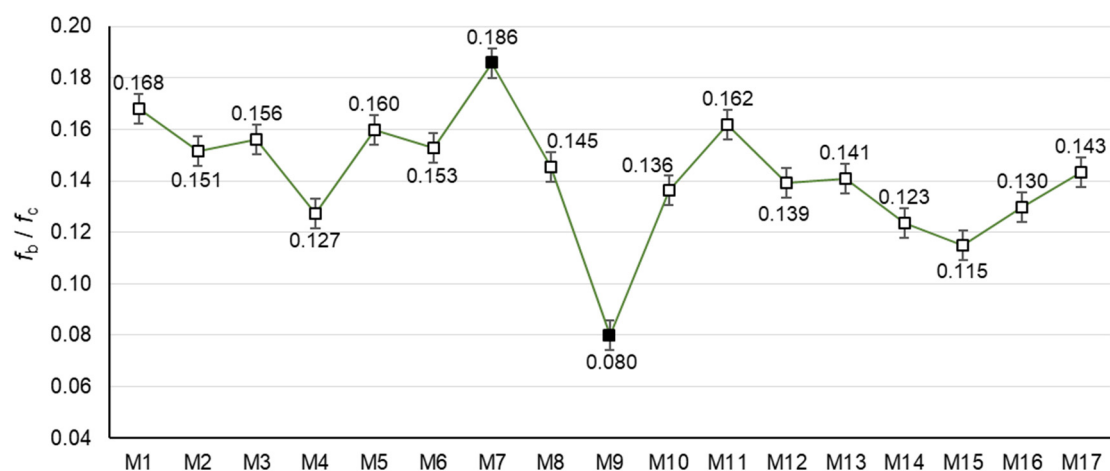


Figure 9. Flexural strength-to-compressive strength ratio (f_b/f_c) of UHPC specimens.

For most mixtures, the f_b/f_c values were in the range of 0.13 to 0.17, implying that there is a fairly stable relationship between flexural and compressive strength for the investigated UHPC mixtures. This suggests that the SCMs and aggregate type have more

influence on the absolute strength values than on their mutual relationship. The lowest f_b/f_c ratio was obtained for mixture M9, which also showed the lowest flexural strength. Considering that the average f_b/f_c ratio was approximately 0.15, the compressive strength of fiber-free UHPC may be roughly estimated as $f_c \approx 7 \cdot f_b$.

3.2.3. Effect of Thermal Treatment and PVA Fiber Addition

Three variants of M18 mixture were created to examine the impact of curing conditions and fiber reinforcement. The first group of specimens was obtained from the reference mixture M18, the specimens of the second group were thermally treated at a temperature of 80 °C for 24 h (M18T), while the third group contained PVA fibers (M18V). All mixtures had the same composition, with the only exception being M18V, which had PVA fibers added in an amount of 35 kg/m³. The compressive strength values obtained after 7, 14, and 28 days are shown in Figure 10.

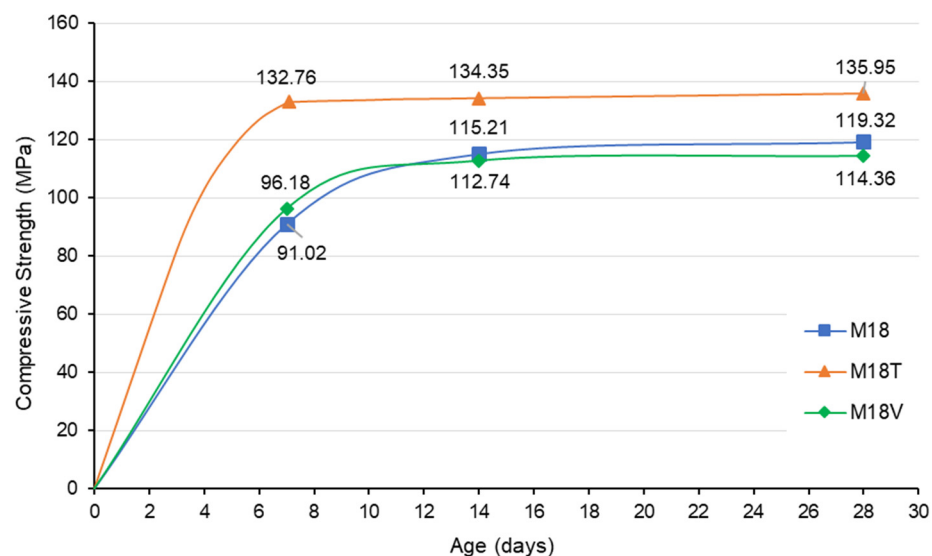


Figure 10. Compressive strength development of M18 mixtures.

The heat-treated specimens showed significantly higher compressive strength values compared to the reference mixture. This difference was particularly noticeable after 7 days, where the M18T specimens reached a compressive strength of 132.76 MPa, whereas the M18 specimens achieved 91.02 MPa, representing an increase of about 45%. After 28 days, the difference was smaller (about 14%), with M18T reaching 135.95 MPa and M18 achieving 119.32 MPa. It should be noted that the M18T specimens almost reached their maximum strength after only 7 days, which can be explained by the fact that most of the hydration and pozzolanic reactions occurred during the first few days due to curing at elevated temperatures. Thermal treatment also promotes the formation of a denser microstructure and reduces capillary porosity, which further contributes to the high early strength development of UHPC. Such rapid strength development is particularly beneficial in prefabrication processes, where thermal treatment is often applied to shorten production cycles and enable earlier demolding of UHPC elements.

The addition of PVA fibers had only a minor effect on the compressive strength. After 7 days, the M18V specimens showed slightly higher strength compared to M18, while the compressive strengths of these specimens after 28 days were 114.36 MPa and 119.32 MPa, respectively. Therefore, after 28 days, the compressive strength decreased by 4% when PVA fibers were added in comparison to the reference mixture. These findings are consistent with earlier research, which reported that the addition of this type of fiber may slightly

reduce compressive strength [61], while its primary role is to enhance the flexural and tensile performance of UHPC [62,63].

4. Conclusions

In this study, the influence of aggregate type and SCMs on the fresh properties as well as the compressive and flexural strength of UHPC was investigated. Based on the obtained experimental results, the following conclusions can be drawn.

- (1) Most mixtures exhibited spread diameters greater than 200 mm, indicating fluid consistency. Mixtures containing limestone and FA (M3 and M10) showed higher spread values compared to those with MK (mix M2), which can be attributed to the spherical shape and lower water demand of FA particles.
- (2) The M12 mixture with the highest particle packing density and the closest match to the modified Andreasen and Andersen curve had the smallest spread diameter of all the mixtures. Although optimal particle packing improves mechanical performance and density, it may reduce workability by increasing mixture viscosity.
- (3) The highest compressive strengths were obtained on specimens with quartz sand (average 110 MPa), while specimens with limestone showed slightly lower strengths (average 107 MPa). These results indicate the higher porosity of limestone while quartz is almost impermeable, which prevents water absorption from the mixture and ensures the designed water-to-cement ratio.
- (4) The highest 28-day compressive strengths were obtained in mixtures M15 and M4, which contained approximately 20% MK relative to the total binder content. This superior performance is attributed to the high pozzolanic reactivity of MK, which promotes the creation of additional C-S-H and C-A-S-H phases and contributes to the development of a denser microstructure.
- (5) The M12 mixture with optimal particle distribution and the lowest amount of cement (500 kg/m^3) showed one of the highest compressive strengths. These results demonstrate that particle packing density can be more influential than cement content, indicating that increasing cement dosage does not necessarily lead to higher compressive strength.
- (6) The results of flexural strengths followed trends similar to those observed for compressive strength, with mixtures containing quartz sand generally achieving the highest values. In addition, the mixtures that showed the highest compressive strengths did not necessarily correspond to those with the highest flexural strengths, which is a typical characteristic of fiber-free UHPC systems. Furthermore, the type of SCM had a less pronounced influence on flexural behavior than the aggregate type.
- (7) The ratio of flexural-to-compressive strength (f_b/f_c) for most mixtures was in the range of 0.13 to 0.17, so considering these values, the compressive strength of fiber-free UHPC can be approximately estimated as $f_c \approx 7 \cdot f_b$ for similar mixtures.
- (8) Thermal treatment of UHPC specimens at 80°C for 24 h significantly accelerated the development of compressive strength. After 7 days, the M18T specimens almost reached their maximum compressive strength, exhibiting a 45% higher strength compared to the reference mixture (M18). After 28 days, this difference decreased to approximately 14%. In contrast, the addition of PVA fibers (M18V) resulted in a slight reduction in compressive strength (about 4%) compared to the reference mixture, confirming that their primary role is not to enhance compressive strength.

The results obtained showed that sustainable and cost-effective UHPC mixtures can be produced using locally available aggregates while ensuring high mechanical properties. However, the application of these practical guidelines for UHPC mixture design depends on the characteristics of locally available aggregates, as the impurity content, mineralogical

composition, and water absorption may vary between different sources. Future research should investigate the use of nano-materials, such as nano-silica and nano-metakaolin, together with long-term durability assessment and microstructural characterization of UHPC mixtures produced with different locally available aggregate sources.

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References

1. Akca, K.R.; Ipek, M. Effect of different fiber combinations and optimisation of an ultra-high performance concrete (UHPC) mix applicable in structural elements. *Constr. Build. Mater.* **2022**, *315*, 125777. [\[CrossRef\]](#)
2. Ocelić, A.; Baričević, A.; Smrkić, M.F. Synergistic integration of waste fibres and supplementary cementitious materials to enhance sustainability of ultra-high-performance concrete (UHPC). *Case Stud. Constr. Mater.* **2024**, *20*, e02772. [\[CrossRef\]](#)
3. Azmee, N.M.; Shafiq, N. Ultra-high performance concrete: From fundamental to applications. *Case Stud. Constr. Mater.* **2018**, *9*, e00197. [\[CrossRef\]](#)
4. Ullah, R.; Qiang, Y.; Ahmad, J.; Vatin, N.I.; El-Shorbagy, M.A. Ultra-High-Performance Concrete (UHPC): A State-of-the-Art Review. *Materials* **2022**, *15*, 4131. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Fédération Internationale du Béton. *Fib Model Code for Concrete Structures 2020*; Ernst & Sohn: Berlin, Germany, 2023.
6. Abbas, S.; Nehdi, M.L.; Saleem, M.A. Ultra-High Performance Concrete: Mechanical Performance, Durability, Sustainability and Implementation Challenges. *Int. J. Concr. Struct. Mater.* **2016**, *10*, 271–295. [\[CrossRef\]](#)
7. Lin, H.; Jiang, Y.; Li, S.; Li, W.; Zhu, D.; Chen, J.; Teng, T.; Xue, Y.; Cao, Z. In situ study on high-temperature performance and structural deterioration mechanism of concrete. *Processes* **2026**, *14*, 1753. [\[CrossRef\]](#)
8. Yang, I.; Park, J. Mechanical and thermal properties of UHPC exposed to high-temperature thermal cycling. *Adv. Mater. Sci. Eng.* **2019**, *2019*, 1–12. [\[CrossRef\]](#)
9. Ha, N.S.; Marundrury, S.S.; Pham, T.M.; Pournasiri, E.; Shi, F.; Hao, H. Effect of grounded blast furnace slag and rice husk ash on performance of ultra-high-performance concrete (UHPC) subjected to impact loading. *Constr. Build. Mater.* **2022**, *329*, 127213. [\[CrossRef\]](#)
10. Richard, P.; Cheyrezy, M. Reactive powder concretes with high ductility and 200–800 MPa compressive strength. *ACI Spec. Publ.* **1993**, *144*, 507–518.
11. Zhu, L.; Wang, J.J.; Li, X.; Zhao, G.Y.; Huo, X.J. Experimental and numerical study on creep and shrinkage effects of ultra high performance concrete beam. *Compos. Part B Eng.* **2020**, *184*, 107713. [\[CrossRef\]](#)
12. Mo, Z.; Wang, R.; Gao, X. Hydration and mechanical properties of UHPC matrix containing limestone and different levels of metakaolin. *Constr. Build. Mater.* **2020**, *256*, 119454. [\[CrossRef\]](#)
13. Wang, S.; Wang, B.; Zhu, H.; Chen, G.; Li, Z.; Yang, L.; Zhang, Y.; Zhou, X. Ultra-high performance concrete: Mix design, raw materials and curing regimes-A review. *Mater. Today Commun.* **2023**, *35*, 105468. [\[CrossRef\]](#)
14. Xi, J.; Liu, J.; Yang, K.; Zhang, S.; Han, F.; Sha, J.; Zheng, X. Role of silica fume on hydration and strength development of ultra-high performance concrete. *Constr. Build. Mater.* **2022**, *338*, 127600. [\[CrossRef\]](#)
15. Lin, Y.; Yan, J.; Wang, Z.; Fan, F.; Zou, C. Effect of silica fumes on fluidity of UHPC: Experiments, influence mechanism and evaluation methods. *Constr. Build. Mater.* **2019**, *210*, 451–460. [\[CrossRef\]](#)
16. He, Z.; Jiang, Y.; Shi, J.; Qin, J.; Liu, D.; Yalçinkaya, Ç.; He, Y. Effect of silica fume on the performance of high-early-strength UHPC prepared with magnesium ammonium phosphate cement. *Case Stud. Constr. Mater.* **2024**, *20*, e03351. [\[CrossRef\]](#)
17. Ma, J.; Schneider, H. Properties of ultra-high performance concrete. *Leipz. Annu. Civ. Eng. Rep. (LACER)* **2002**, *7*, 25–32.

18. Chan, Y.; Chu, S. Effect of silica fume on steel fibre bond characteristics in reactive powder concrete. *Cem. Concr. Res.* **2004**, *34*, 1167–1172. [\[CrossRef\]](#)
19. Wu, Z.; Shi, C.; Khayat, K.H. Influence of silica fume content on microstructure development and bond to steel fiber in ultra-high strength cement-based materials (UHSC). *Cem. Concr. Compos.* **2016**, *71*, 97–109. [\[CrossRef\]](#)
20. Wu, Z.; Khayat, K.H.; Shi, C. Changes in rheology and mechanical properties of ultra-high performance concrete with silica fume content. *Cem. Concr. Res.* **2019**, *123*, 105786. [\[CrossRef\]](#)
21. Xu, D.; Tang, J.; Hu, X.; Zhou, Y.; Yu, C.; Han, F.; Liu, J. Influence of silica fume and thermal curing on long-term hydration, microstructure and compressive strength of ultra-high performance concrete (UHPC). *Constr. Build. Mater.* **2023**, *395*, 132370. [\[CrossRef\]](#)
22. Bahedh, M.A.; Jaafar, M.S. Ultra high-performance concrete utilizing fly ash as cement replacement under autoclaving technique. *Case Stud. Constr. Mater.* **2018**, *9*, e00202. [\[CrossRef\]](#)
23. Jing, R.; Liu, Y.; Yan, P. Uncovering the effect of fly ash cenospheres on the macroscopic properties and microstructure of ultra high-performance concrete (UHPC). *Constr. Build. Mater.* **2021**, *286*, 122977. [\[CrossRef\]](#)
24. Dong, P.S.; Tuan, N.V.; Thanh, L.T.; Thang, N.C.; Cu, V.H.; Mun, J.H. Compressive strength development of high-volume fly ash ultra-high-performance concrete under heat curing condition with time. *Appl. Sci.* **2020**, *10*, 7107. [\[CrossRef\]](#)
25. Chen, T.; Gao, X.; Ren, M. Effects of autoclave curing and fly ash on mechanical properties of ultra-high performance concrete. *Constr. Build. Mater.* **2018**, *158*, 864–872. [\[CrossRef\]](#)
26. Ferdosian, I.; Camões, A.; Ribeiro, M. High-volume fly ash paste for developing ultra-high performance concrete (UHPC). *Cienc. Tecnol. Mater.* **2017**, *29*, e157–e161. [\[CrossRef\]](#)
27. Song, Q.; Yu, R.; Wang, X.; Rao, S.; Shui, Z. A novel Self-Compacting Ultra-High Performance Fibre Reinforced Concrete (SCUHPFRC) derived from compounded high-active powders. *Constr. Build. Mater.* **2018**, *158*, 883–893. [\[CrossRef\]](#)
28. Mohamed, A.M.; Tayeh, B.A. Metakaolin in ultra-high-performance concrete: A critical review of its effectiveness as a green and sustainable admixture. *Case Stud. Constr. Mater.* **2024**, *21*, e03967. [\[CrossRef\]](#)
29. Zhan, P.; Xu, J.; Wang, J.; Jiang, C. Multi-scale study on synergistic effect of cement replacement by metakaolin and typical supplementary cementitious materials on properties of ultra-high performance concrete. *Constr. Build. Mater.* **2021**, *307*, 125082. [\[CrossRef\]](#)
30. Tafroui, A.; Escadeillas, G.; Lebaili, S.; Vidal, T. Metakaolin in the formulation of UHPC. *Constr. Build. Mater.* **2009**, *23*, 669–674. [\[CrossRef\]](#)
31. Norhasri, M.S.; Hamidah, M.S.; Fadzil, A.M.; Megawati, O. Inclusion of nano metakaolin as additive in ultra high performance concrete (UHPC). *Constr. Build. Mater.* **2016**, *127*, 167–175. [\[CrossRef\]](#)
32. Oh, T.; Chun, B.; Lee, S.K.; Kim, G.W.; Banthia, N.; Yoo, D.Y. Effect of high-volume substituted nanosilica on the hydration and mechanical properties of Ultra-High-Performance Concrete (UHPC). *Cem. Concr. Res.* **2024**, *175*, 107379. [\[CrossRef\]](#)
33. Tran, T.M.; Trinh, H.T.M.K.; Nguyen, D.; Tao, Q.; Mali, S.; Pham, T.M. Development of sustainable ultra-high-performance concrete containing ground granulated blast furnace slag and glass powder: Mix design investigation. *Constr. Build. Mater.* **2023**, *397*, 132358. [\[CrossRef\]](#)
34. Xu, Y.; Liu, J.; Liu, J.; Zhang, P.; Zhang, Q.; Jiang, L. Experimental studies and modeling of creep of UHPC. *Constr. Build. Mater.* **2018**, *175*, 643–652. [\[CrossRef\]](#)
35. Teng, L.; Meng, W.; Khayat, K.H. Rheology control of ultra-high-performance concrete made with different fiber contents. *Cem. Concr. Res.* **2020**, *138*, 106222. [\[CrossRef\]](#)
36. Yu, R.; Spiesz, P.; Brouwers, H.J.H. Effect of nano-silica on the hydration and microstructure development of Ultra-High Performance Concrete (UHPC) with a low binder amount. *Constr. Build. Mater.* **2014**, *65*, 140–150. [\[CrossRef\]](#)
37. Chen, H.J.; Yu, Y.L.; Tang, C.W. Mechanical properties of Ultra-High Performance Concrete before and after exposure to high temperatures. *Materials* **2020**, *13*, 770. [\[CrossRef\]](#) [\[PubMed\]](#)
38. Danha, L.S.; Abdul-Hussien, Z.A.; Abduljabbar, M.S.; Yassin, L.A.G. Flexural behavior of hybrid ultra-high-performance concrete. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *737*, 012008. [\[CrossRef\]](#)
39. Wang, L.; Xue, Y.; Wang, X.; Zhu, L.; Cao, X.; Ge, R. Effect of aggregate gradation on pore structure evolution and mechanical performance of coal gangue-fly ash cemented backfill: Insights from NMR. *Powder Technol.* **2026**, *482*, 122775. [\[CrossRef\]](#)
40. Mosaberpanah, M.A.; Eren, O. Effect of quartz powder, quartz sand and water curing regimes on mechanical properties of UHPC using response surface modeling. *Adv. Concr. Constr.* **2017**, *5*, 481–492. [\[CrossRef\]](#)
41. Abbas, S.; Soliman, A.M.; Nehdi, M.L. Exploring mechanical and durability properties of ultra-high performance concrete incorporating various steel fiber lengths and dosages. *Constr. Build. Mater.* **2015**, *75*, 429–441. [\[CrossRef\]](#)
42. Burroughs, J.F.; Shannon, J.; Rushing, T.S.; Yi, K.; Gutierrez, Q.B.; Harrelson, D.W. Potential of finely ground limestone powder to benefit ultra-high performance concrete mixtures. *Constr. Build. Mater.* **2017**, *141*, 335–342. [\[CrossRef\]](#)
43. Sharma, Y.; Yeluri, M.; Allena, S.; Owusu-Danquah, J. Incorporating Limestone Powder and Ground Granulated Blast Furnace Slag in Ultra-high Performance Concrete to Enhance Sustainability. *Int. J. Concr. Struct. Mater.* **2024**, *18*, 79. [\[CrossRef\]](#)

44. Du, J.; Meng, W.; Khayat, K.H.; Bao, Y.; Guo, P.; Lyu, Z.; Abu-obeidah, A.; Nassif, H.; Wang, H. New development of ultra-high-performance concrete (UHPC). *Compos. Part B Eng.* **2021**, *224*, 109220. [[CrossRef](#)]
45. Kang, S.H.; Jeong, Y.; Tan, K.H.; Moon, J. High-volume use of limestone in ultra-high performance fiber-reinforced concrete for reducing cement content and autogenous shrinkage. *Constr. Build. Mater.* **2019**, *213*, 292–305. [[CrossRef](#)]
46. Kozul, R.; Darwin, D. *Effects of Aggregate Type, Size, and Content on Concrete Strength and Fracture Energy*; SM Report No. 43; University of Kansas: Lawrence, KS, USA, 1997.
47. Kishore, I.S.; Mounika, L.; Prasad, C.M.; Krishna, B.H. Experimental study on the use of basalt aggregate in concrete mixes. *Int. J. Civ. Eng.* **2015**, *2*, 39–42. [[CrossRef](#)]
48. Szcześniak, A.; Siwiński, J.; Stolarski, A. Effect of aggregate type on properties of ultra-high-strength concrete. *Materials* **2022**, *15*, 5072. [[CrossRef](#)] [[PubMed](#)]
49. Peng, Y.; Wu, H.; Fang, Q.; Liu, J.Z.; Gong, Z.M. Impact resistance of basalt aggregated UHP-SFRC/fabric composite panel against small caliber arm. *Int. J. Impact Eng.* **2016**, *88*, 201–213. [[CrossRef](#)]
50. EN 1097-6:2022; Tests for Mechanical and Physical Properties of Aggregates—Part 6: Determination of Particle Density and Water Absorption. European Committee for Standardization: Brussels, Belgium, 2022.
51. EN 993-1:2012; Tests for Geometrical Properties of Aggregates—Part 1: Determination of Particle Size Distribution—Sieving Method. European Committee for Standardization: Brussels, Belgium, 2012.
52. EN 197-1:2011; Cement—Part 1: Composition, Specifications and Conformity Criteria for Common Cements. European Committee for Standardization: Brussels, Belgium, 2011.
53. Andreasen, A.H.M.; Andersen, J. Über die Beziehungen zwischen Kornabstufungen und Zwischenraum in Produkten aus losen Körnern (mit einigen Experimenten). *Kolloid-Zeitschrift* **1930**, *50*, 217–228. [[CrossRef](#)]
54. Wilson, W.; O’Flaherty, T. Development and localisation of ultra high performance concrete using a particle packing model. *Civ. Eng. Res. Irel.* **2020**, *4*, 131–136.
55. EN 1015-3:1999; Methods of Test for Mortar for Masonry—Part 3: Determination of Consistence of Fresh Mortar (by Flow Table). European Committee for Standardization: Brussels, Belgium, 1999.
56. Feng, Q.; Hu, W.; Liu, L.; Luo, J. State-of-art on workability and strength of ultra-high-performance fiber-reinforced concrete: Influence of fiber geometry, material type, and hybridization. *Struct. Durab. Health Monit.* **2025**, *19*, 1589–1605. [[CrossRef](#)]
57. EN 196-1:2016; Methods of Testing Cement—Part 1: Determination of Strength. European Committee for Standardization: Brussels, Belgium, 2016.
58. Shourabia, F.N.; Mirzabozorg, H.; Zhuge, Y. Optimization of UHPC based on reactive powder concrete: Box-Behnken Design, analysis of variance, components interaction effects and sensitivity analysis. *J. Build. Eng.* **2024**, *98*, 111291. [[CrossRef](#)]
59. Hassan, K.E.; Cabrera, J.G.; Maliehe, R.S. The effect of mineral admixtures on the properties of high-performance concrete. *Cem. Concr. Compos.* **2000**, *22*, 267–271. [[CrossRef](#)]
60. Papadakis, V.G. Effect of fly ash on Portland cement systems: Part I. Low-calcium fly ash. *Cem. Concr. Res.* **1999**, *29*, 1727–1736. [[CrossRef](#)]
61. Hossain, K.M.A.; Lachemi, M.; Sammour, M.; Sonebi, M. Strength and fracture energy characteristics of self-consolidating concrete incorporating polyvinyl alcohol, steel and hybrid fibres. *Constr. Build. Mater.* **2013**, *45*, 20–29. [[CrossRef](#)]
62. Afroughsabet, V.; Biolzi, L.; Ozbakkaloglu, T. High-performance fiber-reinforced concrete: A review. *J. Mater. Sci.* **2016**, *51*, 6517–6551. [[CrossRef](#)]
63. Noushini, A.; Samali, B.; Vessalas, K. Effect of polyvinyl alcohol (PVA) fibre on dynamic and material properties of fibre reinforced concrete. *Constr. Build. Mater.* **2013**, *49*, 374–383. [[CrossRef](#)]

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