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Review Paper: Ultra High Performance Concrete (UHPC) with Coarse Aggregate

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A B S T R A C T

The new generation of concrete known as Ultra High Performance Concrete (UHPC) has high compressive strength and high density. The use of local materials with coarse aggregate is one steps to replace UHPC materials that require large amounts of energy and produce carbon largely so that the cost of making UHPC can be reduced. This paper summarizes the results of previous research related to coarse aggregate used in the design of UHPC. This paper discusses the mix design analysis, mixing method, testing of fresh concrete, and curing method of UHPC design with coarse aggregate.

Keywords: UHPC, High density, Compressive strength, Coarse aggregate, Local materials

Introduction

The advancement of infrastructure proceeds to develop consistently over time. Concrete remains one of the most utilized construction materials due to its affordability and widespread availability. To enhance the longevity and efficiency of structures, efforts are being made to improve the mechanical properties and durability of concrete. One such innovation is Ultra High Performance Concrete (UHPC), which exhibits exceptional characteristics such as compressive strength exceeding 150 MPa [1], tensile strength between 5-8 MPa [2], excellent durability, and low permeability. UHPC is produced by optimizing the particle packing of the mix, increasing binder content, and reducing the water-to-binder ratio (w/b) [3]. These unique properties make UHPC a promising choice for building new infrastructure, as well as for repairing and retrofitting existing structures. Despite its advantages, the widespread use of UHPC is limited by its high production cost. This is largely due to its higher cement content compared to conventional concrete, which also leads to increased carbon emissions [4]. Moreover, the use of quartz, a non-renewable material, contributes to the depletion of natural resources [5]. Additionally, strict regulations concerning cement additives and silica fume further raise the cost of commercially available UHPC mixes. Recent developments have focused on reducing production costs by eliminating expensive components such as accelerators and ground quartz. Furthermore, curing methods play a significant role in achieving the desired compressive strength, with the FHWA [2] reported that heat curing can raise UHPC's compressive strength by 53% when compared to untreated specimens. These factors have led to the creation of sustainable UHPC materials through a variety of mixed designs that use regional ingredients.

To enhance the environmental sustainability of UHPC mixtures, local materials are increasingly being incorporated by substituting cement and aggregates with industrial waste. Various alternatives, such as fly ash, ground granulated blast furnace slag (GGBS), copper slag, and others, have been explored in recent studies [6], [7], [8], [9] and the use of coarse aggregate. along with the inclusion of coarse aggregates. However, the continuous use of waste materials at consistent substitution rates may lead to varying effects, making it difficult to replicate the same outcomes in practical applications as those reported in the literature. Consequently, designing UHPC with sustainable components presents a significant challenge. Therefore, this paper focuses on reviewing previous studies involving the use of coarse aggregates in UHPC mixtures.

ACI 239R-18 defines UHPC as a class of advanced cementitious materials that, when compared to conventional concrete or even High Performance Concrete (HPC), it have higher properties related to compression strength, tensile strength, and durability. Generally, fiber is added to meet specific needs. Under uniaxial tension, UHPC usually demonstrates elastic-plastic or strain-hardening properties and has extremely low permeability because of its dense pore structure. Furthermore, compared to conventional concrete, UHPC exhibits superior resistance to salt, frost, and carbonation, as well as better resistance to chlorides [10].

Literature Review

Previous Experimental Research of UHPC Mix Design in General

Table 1 presents a commonly used UHPC mix design found in the American Ductal® market. These commercially available UHPC formulations typically feature a high cement content, a significant amount of silica fume, and an extremely low water-cement ratio (w/c), usually below 0.2 [11]. Coarse aggregates are deliberately excluded from UHPC mixtures to allow the fine particles to densely pack within the concrete matrix, thereby achieving a high packing density [12], [13], [14], [15]. Additionally, steel fibers are incorporated to enhance the ductility of the concrete.

Table. 1 Mix Design of UHPC in marketplace [11]

Material	Total (kg/m^3)	Percentage of weight
Portland cement	712	28.5
Silica Fume	231	9.30
Fine sand	1020	40.8
Ground Quartz	211	8.40
HRWR	30.7	1.20
Accelerator	30.0	1.20
Steel fiber	156	6.20
Water	109	4.40

According to Graybeal et al.'s research [3] on FHWA [2], producing UHPC with a minimum compressive strength of 150 MPa requires that the binder makes up 40% of the total concrete volume, with silica fume accounting for 25% of that binder. Given that UHPC can be up to 20 times more expensive than conventional concrete [6], utilizing locally sourced fine aggregates, such as natural sand, presents a potential strategy to reduce costs—especially in comparison to commercially available nano fillers, which typically have particle sizes ranging from 0.15 mm to 0.6 mm. However, as the particle size of the filler increases, the compressive strength of the concrete may decrease. This occurs because fine aggregates play a crucial role in minimizing the Maximum Paste Thickness (MPT)—the distance between adjacent aggregates enveloped by a layer of paste with thickness equal to the diameter of the aggregate.

A State of the Art Report for the Bridge Community [3] suggests that UHPC mix designs should use cement with a C3A (tricalcium aluminate) content of less than 8%, such as that found in Type III cement, which typically has finer particles and lower C3A levels. Additionally, superplasticizers are incorporated to enhance the workability of the mix, especially when using a low water-to-binder (w/b) ratio of 0.22. Steel fibers, making up 2.5% of the concrete volume, are included to improve ductility, allowing the concrete to resist tensile and flexural stresses without the need for extra reinforcement. However, following the mix proportions recommended by the report can lead to higher UHPC production costs, primarily because Type III cement and nano-scale fillers are not readily available in all regions. This section summarizes and analyzes findings from previous experimental studies on UHPC that utilize locally sourced materials, such as coarse aggregates, focusing on aspects like mix design, mixing techniques, testing procedures, and curing methods for UHPC made with local materials.

Previous Experimental Research of UHPC Mix Design with Coarse Aggregate

Alsalman et al., 2017 [6] carried out a study on UHPC using locally sourced materials, specifically river sand categorized into three types: sand-1, with a natural gradation retained between sieve No. 4 (4.75 mm) and No. 200 (75 µm); sand-2, with finer particles passing through sieve No. 30 (600 µm) and retained on sieve No. 50 (300 µm); and sand-3, which passed through sieve No. 200 (75 µm). In their UHPC mix, they partially replaced Type I Portland cement with silica fume and Class C fly ash. The silica fume was used at varying levels of 0%, 5%, 10%, 15%, and 20%, while fly ash was incorporated at 0%, 20%, 30%, and 40%. The binder contents evaluated were 890 kg/m³ and 1009 kg/m³, with a constant water-to-binder ratio (w/b) of 0.2. The findings indicated that adding silica fume beyond 10% did not significantly enhance compressive strength, as mixtures with 5% and 10% silica fume produced similar results. Regardless of the sand type or silica fume percentage, compressive strength improved with higher binder content. For achieving a target compressive strength of 150 MPa at 90 days, the optimal combination was 1009 kg/m³ of binder and sand-1. In contrast, incorporating more than 20% fly ash led to reduced early-age strength, although strength gains were observed at later ages. A 20% fly ash content had minimal impact on strength, whereas a 30% fly ash content delivered the highest compressive strength at 90 days.

Miller et al., 2020 [7] conducted a study of UHPC mixtures with locally available materials in Georgia. The study was conducted on different cement types, admixture types, and Supplementary Cementitious Material (SCM) types. The cements used were Holcim type 1, argos type I/II and argos type III. The semen variables were chosen since they are easily available and inexpensive. The admixture types used were Sika Visco Crete 2100 and BASF Master Glenium 7920. These types of cement contain relatively high C3S content and have a high degree of fineness. The SCM used is fly ash with type C and F. SCM in the form of silica fume is not used in this study so that Metakaolin is used as a substitute substance for cement. The percentage of metakaolin used were 8% and 10%. The water-binder ratio (w/b) were 0.14, 0.18, 0.25, and 0.30. The aggregates used in this study were selected because their fineness values met those for the UHPC mixture and the aggregate gradation data used are listed in Table 2. From the test results, the mixture with the composition of OPC, type F fly ash, metakaolin, and BASF Master Glenium 7920 type admixture had the best results from the other mixture compositions. With a water-binder (w/b) ratio of 0.18, a compressive strength of 124 MPa was obtained.

Table. 2 Sand Gradation Data [6]

Sieve Size (mm)	Percent Passing (%)
4.75	100
2.36	99.99
1.18	95.08
0.60	63.98
0.30	17.99
0.15	1.53
0.75	0.29
FM	2.21

In the research conducted by Meng, 2017 [16] the constituent materials of UHPC include binders (type III Portland cement and SCM with silica fume 15- 30%, GGBFS 25-35%, fly ash type C 10-30%, HRWR, 13mm of steel fibers as much as 2%, sand consisting of river sand (0-4.75 mm) and stone sand (0-0.2 mm) at Saturated Surface Dry (SSD) conditions. In order to attain maximum density, the gradation of sand was improved using a modified Andreasen and Andersen gradation model. The w/c values in use ranged from 0.18 to 0.23. UHPC was treated using both conventional and heat curing techniques. The best w/c value, according to the test results, was 0.2. The ideal value of Vb/Vs was found to be 1.0 with the mixture using the same binder, such as GGBFS at 50%, silica fume at 5%, and cement at 45%, based on the flow characteristics and compressive strength at 28 days. With the standard of curing treatment method, the compressive strength counted at 28 days is 120-125 MPa while with heat curing with a maximum temperature of 900C for one day followed by seven days of moist curing, the compressive strength can reach 178 MPa. The mix design used in Meng's research is shown in Table 3.

Table. 3 Mix Design UHPC [16] (units : kg/m3)

Materials	G50SF5	G50	FAC40SF5	FAC60
Cement	548	593	663	486
SF	42	-	42	-
FAC	-	-	367	556
GGBS	535	546	-	-
Quartz sand	-	-	-	-
Fine sand	-	-	-	-
Sand A	694	698	703	715
Sand B	304	295	308	304
HRWR	16.0	12.5	12.0	5.5
Total water	167	182	171	188
Steel fiber	156	156	156	156

Hardjasaputra et al., 2011 [17] conducted research on UHPC mixtures with local materials available in Indonesia, by using high-quality quartz sand with a size smaller than 0.5 mm, marble powder, and granite. The cement used were Ordinary Portland Cement (OPC) and White Portland Cement (WPC), microsilica, and superplasticizer. The test specimens used in the study were cylinders with a size of 100 mm × 200 mm. The results showed that UHPC mixtures with local materials in Indonesia can reach 140-150 MPa with an average of elastic modulus value of 51.4 GPa. Mixtures with using WPC cement has a higher compressive strength value compared to OPC cement. The mix design shown in Table 4 is the mix design in Hardjasaputra et al., 2011's research which produces the highest compressive strength and modulus of elasticity values.

Table. 4 Mix Design of UHPC [17]

Materials	TM5 (with OPC)	TM6 (with WPC)
	Weight (kg/m^3)	Weight (kg/m^3)
Cement	800	800
Sand	977.209	935.146
Silica	230	230
Superplasticizer	39	32.89
Water	177.1	177.1
Crushed quartz	152.626	160.455
(w/b*)	0.1948	0.182
w/c	0.2214	0.208

Nasrin & Ibrahim, 2021 [18] conducted research on UHPC mixtures with local materials in the state of Idaho and applied bridge deck joints. In this research, the UHPC materials consisted of Portland cement type I-II, commercially available silica fume type sika Crete 950DP, two types of fine aggregates local sand and basalt, glass powder, steel fibers, superplasticizer type sika viscocrete-4100 with a water-cement ratio of 0.21. Although high-quality glass powder is expensive, it was used in two mix samples to discover its effect. Cubes with 50 mm on each side were the test specimens used for compressive strength. The outcomes demonstrated that silica fumes improved the concrete's strength in every instance. When compared to 10% silica fume, the strength of concrete can be increased by 47.46% when 20% silica fume is used. The effect of different fine aggregates showed that mixes containing basalt in all cases obtained higher strength than local sand. The addition of 2% steel fiber increased compressive strength. The effect of adding glass powder to the mix did not result in significant strength. So, in the application of bridge deck joints, the local UHPC mixture used as in Table 5. From the results of the UHPC mix design as in Table 4, the compressive strength of 140.31 MPa was obtained with the steam curing/heat curing method.

Table. 5 Mix Design of UHPC [19]

Material	Units	Total
Binder	kg/m^3	1112.4
Silica fume	%	20
Glass Powder	%	0
Local sand	kg/m^3	0
Basalt	kg/m^3	803.9
Steel fiber	%	2
HRWR	l/m^3	35,9
w/b	-	0,21
Flow test	mm	215.9

Oesman et al, 2022 [19] conducted research on UHPC with local materials in the form of a combination of aggregates available on the Indonesian market. The materials that make up UHPC consist of Portland Slag Cement (PSC), SCM with a silica fume type with a content of 30% by weight of the binder (PSC and silica fume), steel fiber with a content of 2%, superplasticizer with a sika viscocrete type - 8300 with a content of 1% from the cementitious materials or binder used, local aggregate with a sieve size of 4.75 mm with a composition of 45% : 55% (sand : crushed stone), w/b ratio of 0.18; 0.2; and 0.22 as in the Table 6. The mixture design results showed that on day 28, with an average flow of 235 mm and a w/b ratio of 0.22, the highest compressive strength, flexural strength, tensile strength, and modulus of elasticity were achieved. A 100 × 200 mm cylindrical test object yielded the highest compressive strength of 90.82 MPa, flexural strength of 11.41 MPa, tensile strength of 10.37 MPa, and modulus of elasticity of 49.60 GPa. Every test object underwent treatment utilizing the conventional curing procedure.

Table. 6 Mix Design of UHPC [19]

Materials	Mix 1	Mix 2	Mix 3
Cement (C) (kg/m^3)	750.4	750.4	750.4
Natural sand (kg/m^3)	454.95	454.95	454.95
Crushed Stone (kg/m^3)	556.05	556.05	556.05
Silica fume (SF) (kg/m^3)	321.6	321.6	321.6
Superplasticizer (Sp) (kg/m^3)	10.72	10.72	10.72
Steel fiber (kg/m^3)	61.198	61.198	61.198
Water (w) (kg/m^3)	225.12	203.68	182.24
Binder (b = C+SF) (kg/m^3)	1072	1072	1072
w (Sp + w) (kg/m^3)	235.84	214.4	192.96
w/b	0.22	0.20	0,18

Aulia and Yulianti, 2022 [20] conducted UHPC research with local material aggregates available on the Indonesian market. The materials that make up UHPC consist of OPC 1 cement, silica fume with levels of 10%, 15% and 20%, fly ash 15%, superplasticizer 1% of cementitious materials, steel fiber 2% of the concrete volume, w/w ratio of 0.22, and the combination of natural sand and crushed stone aggregate passes a 4.75 mm sieve. The treatment method for the test object is carried out using the standard curing method. Based on the test comes about, the most noteworthy compressive quality was gotten at 65.17 MPa with a mixture of 15% silica fume, 15% fly ash. Meanwhile, the highest tensile strength, and flexural strength were obtained by combination of a mixture of 20% silica fume and 15% fly ash at 12.12 MPa, 11.58 MPa, respectively. The results obtained by Aulia and Yulianti, 2022 show that the quality achieved does not reach the quality of UHPC in general, this is predicted due to the use of aggregate with a specific gravity below 2600 kg/m3, a simple mixer, concrete curing at room temperature, and the type of cement used. Mix design test by Aulia and Yulianti's as in Table 7.

Table. 7 Mix Design of UHPC [20]

Materials	Mix 1	Mix 2	Mix 3
Cement (C) (kg/m^3)	804	750.4	696.8
Natural sand (kg/m^3)	454.95	454.95	454.95
Crushed Stone (kg/m^3)	556.05	556.05	556.05
Silica fume (SF) (kg/m^3)	107.2	160.8	214.4
Fly ash (kg/m^3)	160.8	160.8	160.8
Superplasticizer (Sp) (kg/m^3)	10.72	10.72	10.72
Steel fiber (kg/m^3)	156	156	156
Water (w) (kg/m^3)	225.12	225.12	225.12
Binder (b = C+SF) (kg/m^3)	1072	1072	1072
w (Sp + w) (kg/m^3)	235.84	235.84	23.84
w/b	0.22	0.22	0.22

Research Method

Design Method

Meng, 2017 [16] research proposed a mix design procedure for UHPC mixes for experimental testing. There are main steps in the UHPC mix design method:

1. Determine which binder to use.

The flow characteristics were used to select the binder combination. The type of binder to be used was then limited based on the combined effects of Relative Water Demand (RWD), Minimum Water Content (MWC), and HRWR requirements. The binder combination was then finalized based on its rheological properties.

2. Determine the water-cement ratio (w/c). For the most part, the water-cement ratio (w/c) is in the range of 0.15-0.25.

3. Determine the aggregate combination.

Until the aggregate combination's gradation aligns with the desired curve, the aggregate combination is adjusted.

4. Evaluate the ratio of binder volume to sand volume (Vb/Vs).

The volume of binder (Vb) needs to be considered to fill aggregate voids and lubricate aggregate particles.

5. Optimizing steel fiber content.

Typically, UHPC uses steel fiber with a content of two to five percent. Based on the mechanical properties of UHPC mixtures made with various fibers and the properties of fresh concrete, the ideal steel fiber content is established.

6. Evaluate the results of UHPC design.

Adjustments can be made to the HRWR content and water-to-cement ratio (w/c) if the UHPC mix fails to meet the desired performance.

Mixing Method

UHPC mixing methods are generally different from conventional concrete mixing methods. This is because the materials that make up the UHPC mixture are fine-grained materials, and the addition of additives will make the resulting concrete mixture often sticky and liquid. In addition, the low water usage makes mixing require high energy to disperse the water.

In the research of Alsalman, et al.[6] mixing UHPC material in the laboratory used a Hobart 19L pan mixer with a mixing method as in Figure 1.

Figure. 1 Mixing Method Flowchart of Alsalman et al., 2017 [6] Research

In Nasrin and Ibrahim's research [18], mixing was carried out using a vertical shaft mixer which took 30-40 minutes of mixing time. The mixing method is as shown in Figure 2.

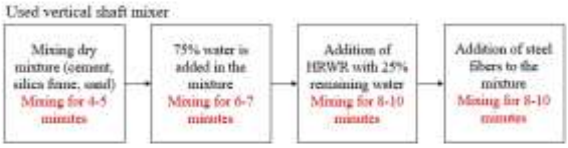

Figure. 2 Mixing Method Flowchart of Nasrin and Ibrahim's [17] Research

In Meng, et al. research [16], mixing was carried out using two types of equipment such as 12-L Hobart Mixer and 150-L EIRICH Mixer. The 12-L Hobart Mixer was used to optimize each component for UHPC, and the 150-L EIRICH Mixer to complete the UHPC mixture. The procedure for the mixing process is depicted in Figure 3.

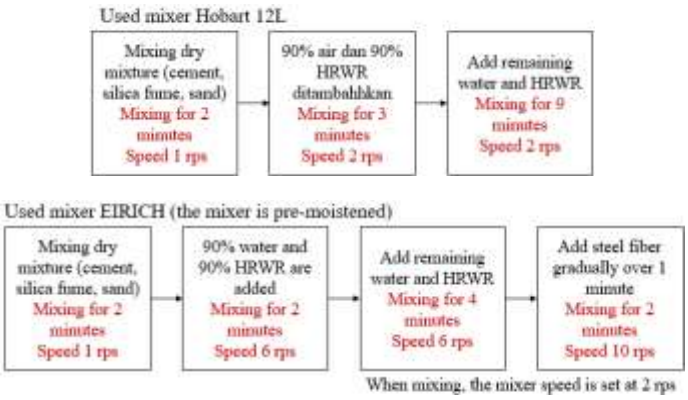

Figure 1 Mixing Method Flowchart of Meng, et al., 2017 [16]**Research**

Based on the mixing methods carried out by previous studies, principle of mixing methods are when mixing, the dry components are first stirred to ensure that they are fully mixed. After that, a mixture of water and admixture (HRWR) is introduced into the mixture. The stirring time depends on the energy of the mixer until the dry mix turns into a wet mix, then the steel fibers are introduced.

When mixing UHPC concrete, more energy is needed than when mixing conventional concrete, which means mixing time will increase [3]. The mixing time of UHPC ranges from seven to 18 minutes longer than conventional concrete. High mixer shear energy can make UHPC in a few minutes, while low mixer shear energy takes 20 minutes or more.

Properties and Testing of UHPC Fresh Concrete

Since UHPC does not contain coarse aggregates, the UHPC mixture was subjected to flow table testing to evaluate its rheology such as consistency and workability of the mixture by conducting flow table testing based on ASTM C1437 [21]. The typical consistency of UHPC mixture is Self-Consolidating Concrete (SCC). Based on ASTM C1437 the UHPC flow test value is between 200 to 250 mm. The flow diameter is measured after the flow mold is raised and the flow table is dropped up to 25 times in a 15-second period. In order to test flow tables for UHPCs with compressive strengths greater than 117.21 MPa, ASTM C1856 was utilized [22]. Fresh concrete test for UHPC mixtures with flow table testing based on ASTM C1437 as shown in Figure 4.

Figure 4 Flow Test Based on ASTM C1437

Besides flow table testing, other instruments like mini-V-Funnel [16], [23], have been utilized to assess the rheological behavior and workability of UHPC. However, because they are so scarce, their use is extremely restricted.

Curing Method

Humidity and temperature are crucial elements in the UHPC curing process. According to Graybeal et al., 2013 [2], the curing process has an impact on the mechanical characteristics of UHPC. Graybeal et al., 2013 [2] reported four distinct post-set curing techniques were used to ascertain the material properties of UHPC. The treatments included standard curing after 15 days, steam curing at 90ºC or 60ºC for 48 hours after the mold was formed and curing at standard lab temperature until test time.

Alsalman et al, 2017 [6] carried out four distinct types of curing: moist curing at 21°C until the testing day, curing at 21°C and 100% RH for the first seven days after casting, curing at 90°C and 100% RH for the first three days after casting, and heat curing at 100% RH for the first five days after casting, the first two days at 60°C, and the next three days at 90°C. The highest strength was obtained from the first two days of curing at 60°C and the final three days of curing at 90°C following casting, out of the four cures.

S. L. Yang et al, 2009 [24] performed curing one day after molding. Curing was performed at 20ºC and 90ºC. Curing with 90ºC is done by soaking in hot water at the age of one to seven days and then curing at room temperature until the testing time. Curing with a temperature of 20ºC is done by immersing the specimens in a curing tank until the day of testing. From the test results, the specimens with curing temperature of 20ºC gave 20% lower compressive strength than curing at 90ºC within one to seven days.

Nasrin and Ibrahim, 2021 [18] conducted curing in two phrases, the first after pouring and the second before testing. To stop moisture loss, specimens were cured at room temperature 23±20ºC after the concrete was poured. All specimens were taken out of the mold subsequently twenty-four hours and submerged in water that had been saturated with lime until the testing day. The test findings indicate that the compressive strength was 140.31 MPa.

The majority of UHPC mix designs recommend using heat curing to speed up the pozzolanic reaction between silica fumes and calcium hydroxide [18]. The pozzolanic reaction rate is substantially slower during moist curing than it is during heat curing [18]. If too much silica fume is used, some of it won't be hydrated and won't be able to contribute to the concrete's strength [25].

Mechanical Properties of UHPC

The mechanical properties of UHPC that need to be considered in structural design are shown in Table 6. However, achieving such high values depends on the material and technology used, the mixing procedure, the curing method, and the age of the concrete [26].

Table 7 Material Range Property of UHPC [2]

Property	Range
Compressive strength	140 - 200 MPa
Modulus of Elasticity	40 - 70 GPa
Tensile strength	6 - 10 MPa

The kind of cement used, the kind and quantity of admixtures used, and the material's temperature all affect the initial rate of UHPC. The weather has an impact on the hydration rate of conventional concrete (fast-setting or slower-setting cement). High admixture dosage and containing materials that can delay the hardening process of concrete in UHPC can significantly delay the hydration process. As a result, UHPC's capabilities and mechanical qualities differ from those of conventional concrete. Table 7 presents a comparison of the mechanical properties of UHPC and conventional concrete.

Table 8 Comparison of Conventional Concrete and UHPC

Property	Conventional Concrete	UHPC
Compressive strength	20 – 40 MPa	150 – 250 MPa
Modulus of Elasticity	25 – 30 GPa	40 – 50 GPa
Tensile strength	1 – 3 MPa	6 – 12 MPa

Conclusion

Based on the results of the review of previous research, the following conclusions can be drawn:

1. Replacement of cement used in local material UHPC mixes including fly ash, GGBS, copper slag, etc. Locally sourced aggregates such as natural sand, crushed stone, and river sand were used.
2. UHPC mixtures with local materials are very likely to be developed. Based on previous research, the use of local materials in UHPC mixtures can achieve compressive strengths of up to 150 MPa.
3. In general, the cement used in UHPC mixtures with local materials uses Portland Cement type I.
4. UHPC mixtures with high silica fume content can affect the non-hydration of the concrete mix so that the optimum strength of the concrete is not achieved. Based on previous research, the recommended silica fume content is 10-30%.
5. The use of fly ash is generally used type C and type F for UHPC research with local materials. Based on previous research, fly ash that is generally used is 10-30%.
6. Mixing UHPC using 12-L Hobart Mixer, 150-L EIRICH Mixer, and vertical shaft mixer takes ±30 minutes for one UHPC mix.
7. The recommended treatment method for UHPC is heat curing. The use of moist curing can reduce 20% lower compressive strength than heat curing.

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