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Effects of Curing Temperature and Chemical Admixture Type on Fresh Properties and Compressive Strength of Ultra High-performance Concrete

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HIGHLIGHTS

- Three types of chemical admixtures and curing regimes were used with ultra-high-performance concrete (UHPC).
- 150 MPa compressive strength is secured after 72 hours using Hyperplast PC-202 and curing at 90ºC.
- UHPC mixtures require high admixture dosages, resulting in prolonged setting time.

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ABSTRACT

The types of post-setting curing and high range water reducing (HRWR) admixture used in Ultra-High-Performance Concrete (UHPC) mixtures play significant roles in determining their rheological and mechanical properties. This study compares the performance of three types of HRWR admixtures commercially available when added to UHPC mixtures under three different curing regimes. Mixtures made with the different superplasticizers were evaluated for their flow, 45mins flow retention, and setting time as fresh mix properties. Compressive strength was also tested for each mixture after 3, 7, and 28 days of curing at the investigated various curing regimes. Sika Viscocrete 180GS produced the highest mixture flow and flow retention levels with a 241 mm flow and 93.7% flow retention. Sika Viscocrete 168-1 produced the best results of setting time with 3 hours as compared to 12 hours with Sika Viscocrete 180GS. Using Hyperplast PC-202, the required 150 MPa compressive strength was secured as early as 3 days of curing with a 48hrs-90ºC curing regime. Using the same HRWR admixture, compressive strength values slightly lower than 150 MPa were reached after 7-28 days when the 72hrs-60ºC regime was adopted. The last curing regime was recommended for producing architectural UHPC units to minimize the delayed formation of ettringite.

1. Introduction

Ultra-high performance concrete (UHPC) is distinguished with its outstanding mechanical and durability properties. Compressive strength in 150 MPa to 200 MPa is the main key for other mechanical characteristics. Tensile strength that may reach 15 MPa and flexural strength of up to 40 MPa which are unusual with a brittle material like concrete, can now be reached with UHPC [1, 2]. Due to its exceptional mechanical performance, considerably smaller section dimensions of UHPC members are expected to achieve the same structural function as members cast with normal strength concrete. This makes it an ideal material, for example, to be specifically used for long-span bridge decks, with an overall reduction of construction costs [3]. It has also been used for precast and prestressed concrete structures [4]. Furthermore, the high strength, improved ductility, and energy absorption capacity of UHP-FRC make it an ideal construction material for infrastructures intended to resist seismic, impact, and blast loads, as well as for storage halls and thin wall shell structures [5]

Extremely low water content values are usually used with UHPC compared to ordinary concrete. The water-to-binder ratio can be as low as 0.12 [6]. This results in concrete with a much finer and more homogeneous microstructure than normal concrete, and is described as almost no capillaries microstructure [5]. Mixtures with such very low levels of water contents can only be cast and used when mixed with relatively high dosages of High range water reducing admixtures (HRWR). HRWR dosages ranging up to more than 5% of cement weight have been used [7, 8].

Polycarboxylate-based HRWR admixtures are usually used with UHPC mixtures. These admixtures consist of carboxylate with oligo ethylene oxide that generates linear-form polymers [9]. The main action mechanism by which HRWR plasticizes the

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fresh mixture is by reducing the surface attraction energy of the fine particles and assisting in particle separation [10]. The result is less mixing water required to surround and lubricate the various particles of the mixture and attain the required workability. Besides elevating the flowability of the fresh UHPC mixture, superplasticizers are also expected to affect the setting time. Previous literature [11] reported that HRWR admixtures extended the dormant phase, resulting in significant delays in the initial setting. However, wide variations in the retardation of setting time were recorded due to the use of different 4 types of HRWR [12]. These variations reached more than 50% when comparing the highest value of final setting time (11.5 hrs) with the lowest one (6.5 hrs). On the other hand, these admixtures are also reported to affect the strength properties [13] marginally. Knowing that these admixtures are added to UHPC mixtures with dosages that exceed those used with normal concrete, the secondary effects of HRWR have to be considered.

On the other hand, curing is a critical stage for achieving the desirable mechanical and durability characteristics of UHPC. Due to the low levels of water contents, it is crucial to enhance the hydration reactions with the limited availability of internal water on the one hand and to take significant measures to avoid any water loss due to evaporation on the other hand. The most followed post-setting curing regime for UHPC is maintaining the concrete at 90 C with a humidity of 90% for 48 hours [14]. This thermal treatment type was reported to accelerate the pozzolanic reactions, resulting in a modified microstructure of the hydration products [15]. It was reported, however, that curing at a temperature higher than 70 C may lead to the delayed formation of Ettringite [16,17]. For this reason, UHPC precast elements cast for architectural purposes are subjected to heat treatment at 60 C for 72 hours with a relative humidity of 95% [18]. While controlled conditions can be provided at precast UHPC plants, such favorable conditions may not be available on-site, for example, when casting joints between precast UHPC units used for bridge decks. Therefore, several researchers investigated the use of normal types of curing at normal curing temperatures. Some promising results were reported for limited material properties and testing conditions. Using the so-called K-UHPC is the most significant outcome of these research efforts. In this type of UHPC, some conditions are applied to materials such as silica fume with a minimum SiO_2 content of 96%, silica sand with less than 0.5mm diameter, and a filler with an average particle size of 10µm and 96% minimum SiO2 content. Furthermore, glycol-based shrinkage reducing admixture and calcium sulfo-aluminate-based expansive agent must be added [19]. With K-UHPC, Koh et al. [20] reported 7-day compressive strength of 120-130 MPa with curing at 20 C compared to 180 MPa after steam curing at 90 C. No considerable difference between the two curing regimes was observed in compressive strength at 91 days. However, the extra cost added to the cost-intensive UHPC in terms of special materials specifications and the use of more admixtures may exceed the cost of heat curing. Furthermore, 7-day compressive strength, in some applications like bridge decks, is essential for project schedules, and attaining lower than specified strength may lead to significant delays.

The first objective of this investigation is to study the influence of HRWR admixture type on fresh properties of UHPC as well as the strength at different ages. The second objective is tracking the combined effect of HRWR admixture type and the post-setting curing regime type on the strength.

Three types of polycarboxylate-based HRWR available in the local market were selected to compare their performance in terms of the influence on flow ability, setting time, and compressive strength of UHPC. In addition, three curing regimes were performed separately for mixtures prepared with each type of superplasticizer admixtures to study and compare the fresh and hardened performance after curing with each type.

2. Materials and Methods

2.1 Materials

Cement, silica fume, and Nano silica were used as binders. The physical and chemical characteristics of the ordinary Portland cement used to comply with IOS 5-1985[21]. In addition, the silica fume is also satisfied with the pozzolanic activity index and the chemical and physical requirements of ASTM C1240-05 [22]. The physical and mechanical properties of the cement used are listed in Table 1. Table 2 illustrates the chemical compositions of cement and silica fume used in the investigation. Pozzolanic activity index and specific surface area of the silica fume are 121% and 20.5 m2/g, respectively. Nano silica in a powder form was an AEROSIL 200® product with a specific surface area of 200 m2/g, SiO2 content of 99.9%, a pH value of 4.1, and a specific gravity of 2.6.

Fine silica sand with gradation ranging from 70µm to 0.85mm was used, as shown in Figure 1. Specific gravity is 2.7, and bulk density is 1500 kg/m3. A quartz powder with an average particle size of 10 µm was used as a filler.

Three brands of polycarboxylate-based HRWR admixtures available in the local market were used. The trade name with some properties is given in Table 3. Each HRWR admixture brand is classified as to confirm with ASTM C494/ C494M-99 [23]. Steel micro-fibers coated with copper and having straight shapes were used. The average fiber diameter is 0.2mm, and fiber length ranges from 13mm to 17mm. The aspect ratio is 65 to 85. The ultimate strength is 2000 MPa.

Table 1: Physical and mechanical properties of cement

Properties	Fineness (cm^2/g)	Initial Setting time	Final Setting time (minutes)	Soundness Autoclave Expansion %	3day Comp. Strength MPa	7day Comp. Strength MPa
Measured	3170	90 minutes	255	0.04	19	24.9
IOS 5-1985	Min. 2600	Min. 45minutes	Max. 375	Max. 0.8	Min.12	Min. 19

Table 2: Chemical compositions of cement and silica fume

Substance	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	LOI	Moisture
Cement (%)	63.4	21.0	5.0	3.8	2.3	2.5	0.22	0.5	1.6	-
Silica Fume (%)	-	94.9	-	-	-	0.8	0.87 (Na_2O Eq.)		1.75	0.72

Table 3: Types and Properties of HRWR admixtures used

HRWR brand	Color	Density g/cm^3	pH	Percentage of solid content %	Chloride %	Complying with
Sika Viscocrete 180GS	Light brown	1.07	5	28.5	Nil	ASTM C494 Type F and G
Sika Viscocrete 168-1	Light brown	1.074	7	38.0		ASTM C494 Type E and F
Hyperplastic PC202	Yellow	1.052	6	40.0	Nil	ASTM C494 Type F and G

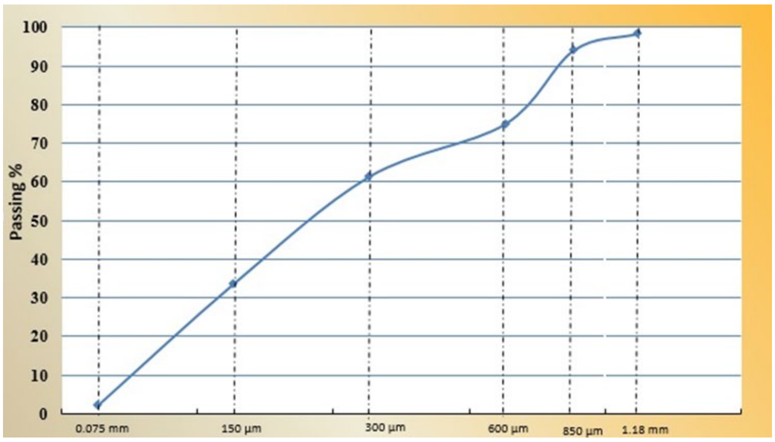

Figure 1: Gradation of the fine silica sand

2.2Mixture Proportions

Mix proportions of the main mixture were selected according to Kassel University formula M3Q_210 [24]. This formula is based on optimum particle packing and targeting a minimum of 150 MPa cylinder compressive strength. Three mixtures were prepared, each with the same mix proportions but differs from the superplasticizer type. To compare the influence of the different types, the dosage of the HRWR admixture was fixed at 1.5% of the binder weight as a percentage of the solid portion (Water is excluded from this percentage and subtracted from water content). Table 4 illustrates the mix proportion for each ingredient per cubic meter of fresh concrete, while Table 5 presents the mix proportions expressed as a ratio based on cement weight.

2.3Mixing Procedure

Mixing was performed in the following steps:

1. Cement and NS were placed together and thoroughly mixed with a manual rubbing and stirring method inside a 25 Kg capacity zipper for 30 minutes.
2. Silica fume, fine silica sand, quartz powder, and the cement-Ns mixture were mixed in a pail using a twin paddle Ingco Mixer MX218008®. The materials were mixed thoroughly at a paddle speed ranging between 300-400 rpm for a minimum of 15 minutes until a uniform dry mixture was obtained.
3. Water and half of the superplasticizer weight were added with the mixing continued at 400-500 rpm paddle speed for about 10 minutes until spherical wet particles were observed to form.
4. The remaining quantity of superplasticizer was added gradually, with the mixing continued for 5-10 minutes until a uniform fresh mixture was obtained.
5. Micro-fibers were added uniformly to the mixture, and 5 minutes of mixing was allowed to disperse the fibers in random directions throughout the fresh mixture.

A flow test is performed, and molds for the setting time test are filled with the mixture, both within five minutes after the completion of mixing. Next, the total number required of the 50mm cubes for the compressive strength test is cast and vibrated. The cube molds are then covered completely with polyethylene for 24-48 hours for initial curing at 20±2 C. Specimens are then demoulded and cured according to the curing regime of each sample group.

2.4 Curing

For each mixture with a certain superplasticizer, a group of cube specimens was stored under one of the following curing conditions:

1. 48 hours of heat curing at 90 C, then normal curing at 20 C,
2. 72 hours of heat curing at 60 C, then normal curing at 20 C,
3. Continuous normal curing at 20 C.

2.5 Flow test

UHPC fresh mixtures were tested for spread flow in accordance with ASTM C1437 [25] testing method. Flow table instruments and equipment comply with ASTM C230 [26] requirements. The mixture was placed to fill a truncated metallic cone in two layers. With every lift, the mixture was tamped 20 times. The cone was lifted upward, and the table dropped 25 times in 15 seconds. The diameter of the spread mixture was then measured in four directions. The average of the four readings was taken as the spread flow value. The flow test was performed two times for each mixture. The first flow was measured right after mixing, and the second was taken with another flow test 45 minutes after the first to evaluate the flow retention.

2.6 Setting time test

The testing procedure specified by ASTM C807-05 [27] for cement mortar was used to measure the setting time. Modified Vicat needle equipped with an electronic penetration device. The needle used in this test has a 2mm diameter cross-section. The needle is connected to a movable rod that weighs 300 g (including the needle). The fresh UHPC sample was poured in two layers with tamping into a 76mm diameter, 40mm depth mold. The device was set to zero with the needle end attached to the specimen surface. The rod was allowed to fall under its weight at fixed intervals of 5 minutes. Setting time was recorded as the first time the needle penetration is equal to or less than 10mm from the sample surface.

2.7 Compressive strength test

The test was conducted in accordance with the testing procedure specified by ASTM C109 [28] using a 3000 KN compression test machine. For each mixture, three 50 cm cube specimens were tested at 7 days, 14 days, and 28 days from each curing regime was followed to perform the test using a. Compressive strength was determined at ages 7 days and 28 days. Three cubes were tested, and the average was taken at each curing age.

Table 4: Mix proportions as kg/m^3 of concrete

Mixes	HRWR Type	Cement	Silica Fume	Fine sand	Quartz Powder	Steel microfibers	HRWR
MS180	Sika Viscocrete 180GS	825	175	975	200	157	52.60
MS168	Sika Viscocrete 168-1	825	175	975	200	157	39.47
MH202	Hyperplast PC202	825	175	975	200	157	37.5

Table 5: Mix proportions as ratios by weight of cement

Mixes	HRWR Type	Cement	Silica Fume	Fine sand	Quartz Powder	Steel microfibers	HRWR
MS180	Sika Viscocrete 180GS	1	0.212	0.818	0.217	0.190	0.063
MS168	Sika Viscocrete 168-1	1	0.212	0.818	0.217	0.190	0.048
MH202	Hyperplast PC202	1	0.212	0.818	0.217	0.190	0.045

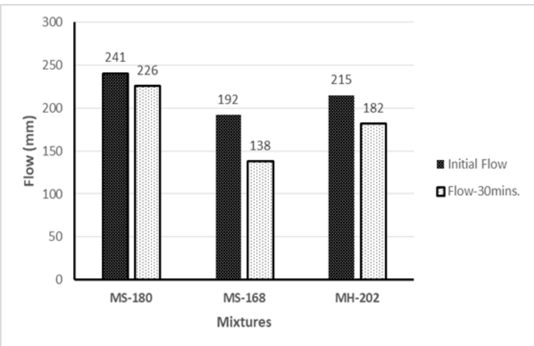

Figure 2: Flow and flow retention as affected by HRWR admixture type

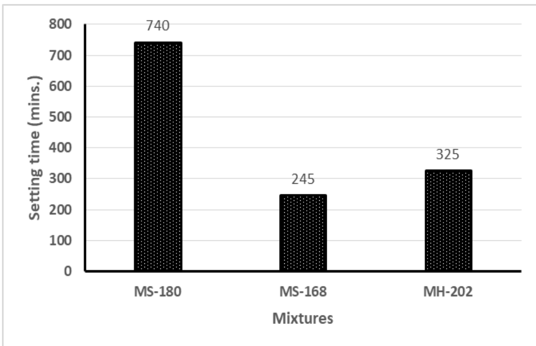

Figure 3: Influence of HRWR admixture type on setting time

3. Results and Discussion

3.1 Flow and flow retention

Figure 2 shows the results of the flow test for the three mixtures. Mixture MS-180 with Sika Viscocrete 180GS demonstrated the highest flow ability and the highest flow retention with 241 mm and 93.8% for flow measured upon the end of mixing and flow retention at 45 minutes elapsed after the end of mixing, respectively. On the contrary, the mixture MS-168 plasticized with Sika Viscocrete 168-1 showed the lowest flow and flow retention values at 192mm and 71.9%, respectively. As far as the flow and flow life are concerned, these results may indicate that using this HRWR admixture that supports high early strength and complies with ASTM C494 Type E and F is inappropriate with UHPC. Finally, moderate flow and flow retention values were recorded with a mixture of MS-202 that Hyperplast P`C202 has plasticized. The spread flow was 215mm, and flow retention was 84.7%.

3.2 Setting time

Results of the setting time test are depicted in Figure 3. Compared to fresh normal concrete, all three mixtures exhibited a considerably higher setting time duration than 4 hours. Past researchers reported similar behavior, with set times of 1 hour to 13 recorded [29, 30]. This was mainly attributed to the retardation in the early hours' hydration rate due to using relatively high amounts of HRWR admixtures.

Comparing the influence of the three admixtures, however, reflects significant differences in the contribution of these admixtures to extended setting time. Sika Viscocrete 180GS resulted in a considerably longer setting time with more than 12 hours compared to around 5.5 hours and 4 hours when Hyperplast PC202 and Sika Viscocrete 168-1 are used, respectively. Therefore, Hyperplast PC202, as an ASTM C494 type F, G compatible admixture that supports high range water reduction with strength retardation, seems to be the most appropriate as far as the fresh mix properties are concerned. Although setting time is slightly higher than Viscocrete 168-1, more convenient mix workability is attained with higher flow ability and retention, all at the same solid dosage of the admixture.

3.3 Compressive strength development

The influence of curing conditions on compressive strength development for the various HRWR admixture types used in the investigation is depicted in Figures 4 a, b, and c. The compressive strength of normally cured specimens is considerably lower than that of heat curing regimes at 60 C and 90 C. This behavior applies to all investigated HRWR types and curing periods. For example, a threshold compressive strength level of 150 MPa for UHPC was not attainable for all mixtures after up to 28 days of normal curing. However, a relatively high strength value of 139.4 MPa was reached after 28 days of normal curing for mixtures plasticized with Hyperplast PC 202 HRWR admixture.

On the other hand, mixtures with Sika Viscocrete 168-1 revealed the lowest compressive strength values over the investigated ages. It is noticeable that the superplasticizer, produced to support high early strength and is compatible with ASTM C494 types E, and F, has led to lower levels of strength starting from as early curing age as 3 days. This may be explained in terms of the period the admixture is designed to accelerate the strength gain. It enhanced the rate of hydration during the first hours, resulting in a significantly shortened interval of setting time. However, a high proportion of mixing water might have been consumed during the highly accelerated early hours of hydration, resulting in a rapid flow loss. Therefore, less remaining mixing water was available to support the subsequent hydration of the high cementitious content of the UHPC mix. This was expected to reduce the strength in the next curing stages.

The combined effect of curing temperature and HRWR admixture type on strength development demonstrated that compressive strength of 150 MPa can be secured at 3 days using a 90 C curing regime with both Sika Viscocrete 180GS and Hyperplast PC 202 HRWR admixtures. Strength development curves showed slight strength gain after 7 days of heat curing. Compressive strength values very close to 150 MPa were attainable at seven and 28 days for specimens cured at 60 C for 3 days when the mixture was plasticized using Hyperplast PC 202, as shown in Figure 5. These findings may have special significance for the production of UHPC architectural precast units where curing at 90 C may result in the delayed formation of ettringite and a subsequent deterioration that may adversely affect the aesthetic of structures' long-term integration. Curing lower than 70 C was reported to be appropriate to avoid the delayed ettringite formation problem [16,17].

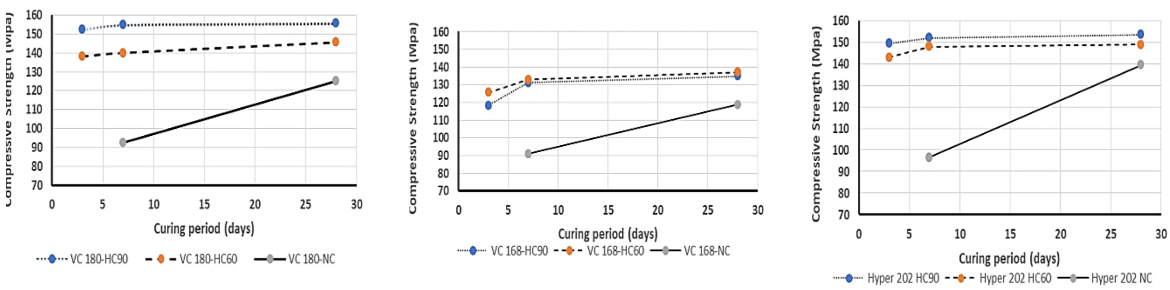

Figure 4: Strength development is affected by curing temperature and admixture type

4. Conclusions

Based on the findings of the present study, the following conclusions can be drawn:

1- The 150 MPa UHPC threshold compressive strength can be secured at an early age of 3 days using a 48 hours-90 C heat curing regime when Hyperplast PC-202 was used as an HRWR admixture.

2- Compressive strength values very close to 150 MPa were attainable at seven and 28 days using a 72 hours-60ºC heat curing regime for mixtures plasticized with Hyperplast PC-202. Therefore, this curing regime was recommended for the production of UHPC architectural precast units to avoid deterioration resulting from ettringite's delayed formation.

3- With all admixtures used, no considerable strength development was obtained after seven days of curing when both heat curing regimes were used. However, with a normal curing regime, the compressive strength increased by up to 40% at 28 days compared to 7 days.

4- The best flow and flow retention results were obtained with UHPC mixtures plasticized with the strength retarding HRWR admixture Sika Viscocrete 180GS, while the strength accelerates HRWR admixture Sika Viscocrete 168-1 produced the lowest levels of flow with impractical values of flow retention.

5- Using relatively high dosages of HRWR admixtures with UHPC mixtures resulted in a significantly extended setting time for all mixtures. However, mixtures plasticized with Sika Viscocrete 168-1 and Hyperplast PC-202 reduced the setting time by 66% and 56%, respectively, compared to the Sika Viscocrete 180GS mixture.

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Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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