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Development of an Ultra-High-Performance Fibre-Reinforced Concrete (UHPFRC) Manufacturable at Ambient Temperature

Koji Tamataki [1], Tomoaki Ito [1], Yutaka Fujino [1] and Isamu Yoshitake [2,*]

1 Mitsubishi Ube Cement Corporation, Tokyo 135-0061, Japan; koji.tamataki@mu-cc.com (K.T.); tomoaki.ito@mu-cc.com (T.I.); yutaka.fujino@mu-cc.com (Y.F.)
2 Department of Civil and Environmental Engineering, Yamaguchi University, 2-16-1 Tokiwadai, Ube 755-8611, Japan
* Correspondence: yositake@yamaguchi-u.ac.jp; Tel.: +81-836-85-9306

Abstract: Ultra-high-performance fibre-reinforced concrete (UHPFRC) manufacturing typically requires heat curing. UHPFRC production at a ready-mixed concrete (RMC) plant is often difficult because specific equipment is required for heat curing. Concerns associated with ultra-high-performance concrete (UHPC) construction include the energy costs and environmental impacts of the heat curing and transportation from the factory to the construction site. Few studies have been conducted on the manufacturing of UHPFRC under standard curing conditions. The strength properties of UHPFRC manufactured under standard curing are typically poorer than those of UHPFRC manufactured under heat curing. The materials and mixture proportions required for the UHPFRC manufacturable under ambient temperature conditions were investigated. Five types of cement and four types of powder materials were tested, as well as the fine aggregate needed to achieve proper fluidity. This paper reports that the cement having low C_3A and high C_3S is suitable for the UHPFRC manufacturable at ambient temperatures; the allowable volume of fine aggregate was 600 kg/m^3 for the UHPFRC having a proper dispersion of steel fibres; the highest water-binder ratio (W/B) of 21% was found for the UHPFRC cured under ambient temperature.

Keywords: UHPFRC; mix proportion; fluidity; strength; ambient temperature

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1. Introduction

In Japan, research on ultra-high-performance fibre-reinforced concretes (UHPFRC) has been conducted since the 1970s [1]. UHPFRCs are generally classified into three types [2]. The first type of UHPFRC is a short-fibre-reinforced concrete containing 5–10 vol% of fibres less than 10 mm long which was developed in Denmark. The second type of UHPFRC is a fibre-reinforced concrete (FRC) containing a combination of short and long fibres with a high mixing ratio (up to 11 vol%). It is noteworthy that the number of steel reinforcing bars can be reduced because the UHPFRC includes a large amount of fibres. The third type of UHPFRC is a FRC mixing long fibres. As typical UHPFRCs, DUCTAL and CERACEM, which were developed in the 1990s, are well known. UHPFRC typically contains fibres that are 13–20 mm long in an amount of 2–3 vol% to increase the tensile strength and toughness of the concrete. High-range water-reducing agents and strong fine aggregates are invariably used for UHPFRC.

The basic technology of ultra-high-performance fibre-reinforced concrete (UHPFRC) was introduced to Japan in 1999. In 2004, the Japan Society of Civil Engineers published its "Design and Construction Guidelines for Ultra-high-strength Fibre-reinforced Concrete (Draft)" [3] in reference to the SETRA/AFGC design and construction guidelines [4] of the French Society of Civil Engineers. In the Japanese guidelines, the following are shown as characteristic UHPFRC strength values ranges:

- Compressive strength: 150 MPa or higher;
- Tensile stress at cracking: 4 MPa or higher;
- Tensile strength: 5 MPa or higher.

Fine aggregates with a grain size of 2.5 mm or smaller, cement, and pozzolanic materials are used in UHPFRC, according to the guidelines. The water–binder ratio (**W/B**) for the UHPFRC should be lower than 0.24. UHPFRC manufacturing typically requires heat curing to achieve the excellent strength properties required in the guidelines [3]. If a UHPFRC is not to be heat cured, various tests of the physical properties of the UHPFRC are needed to determine the appropriate curing method and time.

The first UHPFRC in Japan was used in a prestressed concrete (PC) bridge [5]. The technologies involved have been extended to various concrete structures, and the number of UHPFRC applications is increasing. As a representative application, 22,000 m^3 of UHPFRC was employed in the construction of a runway at Haneda Airport [6].

A number of studies have been conducted to investigate the material properties and fresh and hardened characteristics of high-performance cementitious materials such as UHPC. Li et al. [7] investigated the effect of the alkali content of cement on high-performance cement mortar. They reported that the workability of the mortar decreased significantly when increasing the alkali content of the cement, delaying the setting time and decreasing the compressive strength. Chang et al. [8] examined the effect of **W/B** on the strength of UHPC. They reported that the strength is proportional to **B/W** as well as normal strength concrete. The study concluded the proper range of 17–20% for the UHPC.

Ahmed et al. [9] investigated the properties of UHPC made with the binder of low C_3A cement and blast-furnace-slag powder. They reported that the mortar without fibre achieved a compressive strength of 150 MPa without a special heat curing. Wu et al. [10] examined the properties of UHPC incorporating silica fume (SF). They reported that the viscosity of UHPC decreased in accordance with the increase in the cement-replacement rate of SF by up to 15%, and it increased the replacement rate by 15% or higher. In addition, it was observed in the study that the UHPC strength decreased with the replacement of 20% or higher because of the remaining voids owing to higher viscosity.

Yang et al. [11] conducted a comparative test using UHPC specimens cured at 20 °C and 90 °C. They reported that the compressive strength of the standard-cured UHPC was 20% lower than the strength of the heat-cured UHPC. If UHPC can be manufactured in conventional RMC plants without special curing equipment, the range of applicability of UHPC throughout the world can be expanded. Only a few studies have been conducted on how to produce UHPC at ambient temperature [12,13]. According to these studies, UHPC cured at ambient temperature is lower in strength than heat-cured UHPC, which is consistent with findings reported by Yang et al. [11]. To increase the applicability of UHPC, the strength properties of UHPC produced without heat curing must be improved.

The purpose of this study was to develop a UHPFRC manufacturable at conventional RMC factories that have strength properties comparable to those of heat-cured UHPFRC. To achieve this purpose, various materials and mixture proportions for the UHPFRC were employed, and the fresh and hardened properties of the base mortar of UHPFRC were tested. Based on test results of the base mortar, the present study examined the fresh and strength properties of UHPFRC which steel fibres were added to the base mortar. This paper reports the fundamental properties of the UHPFRC and proposes suitable materials and mixture for the UHPFRC manufacturable at ambient temperatures.

2. Experimental Program for Development of the UHPFRC

2.1. Materials

Details of the five types of cement considered in this study are given in Table 1. The applicability of five types of cement was investigated to optimise the performance of UHPFRC.

Table 1. Properties of cementitious materials.

Cement I.D.	Density (g/cm^3)	Fineness (cm^2/g)	C_3S (%)	C_2S (%)	C_3A (%)	C_4AF (%)	ig.loss (%)	SO_3 (%)	R_2O (%)
A	3.16	3280	59.6	13.8	8.9	9.6	2.28	1.98	0.437
B	3.14	4570	64.3	9.6	9.5	8.2	1.11	2.89	0.431
C	3.20	3260	50.7	26.9	2.9	12.9	1.02	2.29	0.308
D	3.21	3630	27.4	51.1	4.8	9.4	0.7	2.7	0.358
E	3.24	3560	16.0	64.0	2.9	10.0	0.76	2.68	0.335

Table 2 shows the details of the powder materials tested in this study. Powder P1 has a large specific surface area and contains a large amount of SiO_2. Powder P2 also has a relatively high SiO_2 content, 60%. Powders P3 and P4 have high CaO contents. Powder P4 has a negligible SiO_2 content.

Table 2. Properties of powder materials.

Powder I.D.	Density (g/cm^3)	Fineness (cm^2/g)	ig.loss (%)	SiO_2 (%)	CaO (%)	SO_3 (%)	R_2O (%)
P1	2.20	176,000	2.58	91.11	0.67	0.70	2.035
P2	2.20	4110	2.88	60.31	3.16	0.58	1.625
P3	2.91	4780	0.62	28.72	44.95	3.91	0.407
P4	2.70	4570	43.49	0.30	55.45	0.02	0.010

The fine aggregate used in this study (crushed sandstone; density: 2.62 g/cm^3) was commonly used in an RMC plant for UHPFRC. Figure 1 shows the particle size distribution of the fine aggregate. This fine aggregate is even used in high-strength concrete (60 MPa or higher). A high-range water-reducing agent (HRWRA) of polycarboxylic acid was used to increase the fluidity of the UHPFRC. The HRWRA has an effect of steric hindrance.

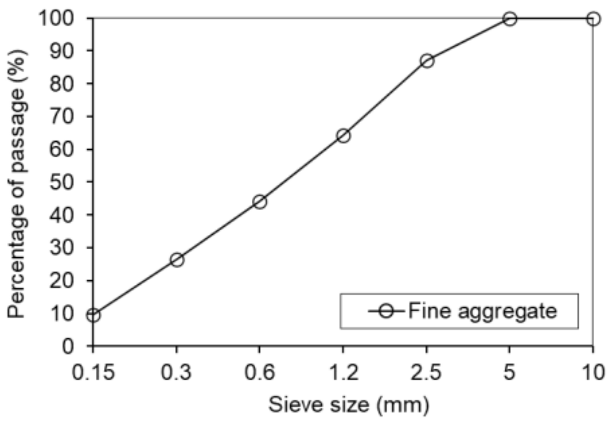


Figure 1. Particle size distribution of fine aggregate.

2.2. Mixture Proportions

Tables 3–7 show the mixture proportions of the base mortar for UHPFRC mixtures tested in the study. The text in the parentheses of each table's legend identifies the primary focuses of each set of tests. Concretes made with five types of cement (Table 1) with different chemical and mineral compositions were tested (Table 3). Note that the study employed commercial cement. As presented in Table 4, the range of W/B ratios was 14–23%, and the range of water contents of the mixtures was 180–240 kg/m^3. The mineral powder materials (Table 2) were added to the base mortar for the UHPFRC by partially replacing cement (Table 5) or fine aggregate (Table 6). When the powder material partially replaced fine aggregate, the additional amount of powder material (**P2**, **P3**, or **P4**) was varied, while the unit volume of **P1** was constant (Table 7).

Table 3. Mixture proportions of base mortar (a test for the effect of cement type).

Cement Type	W/B (%)	Unit-Weight (kg/m^3)				HRWRA (%)
		Water	Cement	P1	F-Agg.	
A	14	220	1336	236	603	2.50
	16	220	1169	206	776	1.50
B	14	220	1336	236	597	2.30
	16	220	1169	206	770	1.55
C	14	220	1336	236	616	1.50
	16	220	1169	206	789	1.20
D	14	220	1336	236	621	2.00
	16	220	1169	206	791	1.80
E	14	220	1336	236	631	2.00
	16	220	1169	206	799	2.00

Table 4. Mixture proportions of base mortar (a test for the effects of W/B and water content).

W/B (%)	Unit-Weight (kg/m^3)				HRWRA (%)
	Water	Cement [(a)]	P1	F-Agg.	
14	180	1093	193	969	1.80
	200	1214	214	796	1.65
	220	1336	236	616	1.50
	240	1457	257	440	1.35
15	180	1020	180	1045	1.80
	200	1133	200	878	1.60
	220	1247	220	707	1.40
	240	1360	240	540	1.30
16	180	956	169	1111	1.75
	200	1063	188	951	1.45
	220	1169	206	789	1.20
	240	1275	225	629	1.20
17	180	900	159	1171	1.70
	200	1000	176	1014	1.25
	220	1100	194	859	1.15
	240	1200	212	705	1.10
19	220	984	174	977	0.90
21	220	890	157	1077	0.65
23	220	813	143	1155	0.40

Note: [(a)] Cement C.

Table 5. Mixture proportions of base mortar (a test for cement replacement by powder material).

W/B (%)	Unit-Weight (kg/m^3)							HRWRA (%)
	Water	Cement [(a)]	P1	P2	P3	P4	F-Agg.	
16	220	1238	138	-	-	-	812	1.20
	220	1100	275	-	-	-	762	1.45
	220	963	413	-	-	-	710	2.50
	220	1238	-	138	-	-	812	1.50
	220	1100	-	275	-	-	762	1.40
	220	963	-	413	-	-	710	1.65
	220	1238	-	-	138	-	854	2.15
	220	1100	-	-	275	-	841	2.05
	220	963	-	-	413	-	831	1.90
	220	1238	-	-	-	138	844	0.95
	220	1100	-	-	-	275	823	0.80
	220	963	-	-	-	413	802	0.70

Note: [(a)] Cement C.

Table 6. Mixture proportions of base mortar (a test for replacement ratios by **P1** and **P4**).

W/B (%)	P1 (%)	Unit-Weight (kg/m^3)					HRWRA (%)
		Water	Cement [(a)]	P1	P4	F-Agg.	
16	5	230	1366	72	392	380	1.65
	10	230	1294	144	381	369	1.30
	15	230	1222	216	365	354	1.40
	20	230	1150	288	351	341	1.85
	25	230	1078	359	338	328	2.30
	30	230	1006	431	324	314	3.00

Note: [(a)] Cement C.

Table 7. Mixture proportions of base mortar (a test for fine aggregate replaced by powder material).

	P2, P3, P4 (vol%)	Unit-Weight (kg/m^3)							HRWRA (%)
		Water	Cement [(a)]	P1	P2	P3	P4	F-Agg.	
16	30	230	1222	216	178	-	-	495	1.30
	50				297	-	-	354	1.45
	70				416	-	-	212	1.65
	100				594	-	-	-	3.00
	30				-	236	-	495	1.35
	50				-	393	-	354	1.50
	70				-	550	-	212	1.75
	100				-	786	-	-	2.80
	30				-	-	219	495	1.30
	50				-	-	365	354	1.40
	70				-	-	510	212	1.55
	100				-	-	729	-	1.75

Note: [(a)] Cement C.

Tables 8–10 show the mixture proportions of the UHPFRC mixtures tested in the study. The steel fibre (0.16 mm diameter × 13 mm length) was mixed in the UHPFRC. Figure 2 shows steel fibres. The aspect ratio and tensile strength of steel fibre are 81.25, 2000 MPa or higher, respectively. To examine the effects of the volumes of water and fine aggregate, the mixture proportions (Table 8) were designed by varying the water content in the range of 180 to 280 kg/m^3 and that of the fine aggregate in the range of 301 to 1111 kg/m^3. The effects of mortar flow and viscosity on fibre dispersibility were examined by varying the amount of HRWRA (Table 9). In addition, the compressive and flexural strengths of the UHPFRC shown in Table 10 were examined.

Table 8. Mixture proportions of UHPFRC (a test for the effect of fine aggregate).

	Unit-Weight (kg/m^3)				SF (vol%)	HRWRA (%)
	Water	Cement.	P1	F-Agg.		
16	180	956	169	1111	2.0	1.55
	200	1063	188	951		1.35
	220	1169	206	789		1.25
	230	1222	216	707		1.25
	240	1275	225	629		1.20
	260	1381	244	464		1.20
	280	1488	263	301		1.15

Table 9. Mixture proportions of UHPFRC (a flow test for the effect of HRWRA).

W/B (%)	Unit-Weight (kg/m^3)					SF (vol%)	HRWRA (%)
	Water	Cement	P1	P4	F-Agg.		
16	220	1169	206	405	393	2.0	1.20 1.30 1.40 1.60 1.80

Table 10. Mixture proportion of UHPFRC (for the compressive and flexural strengths test).

W/B (%)	Unit-Weight (kg/m^3)					SF (vol%)	HRWRA (%)
	Water	Cement	P1	P4	F-Agg.		
16	230	1222	216	365	354	2.0	1.25

Figure 2. Steel fibres.

2.3. Test Procedures

(1) Fresh properties

A Hobart mixer with a capacity of 5 L was used for mixing the mortar. Cement, powder materials, and fine aggregate were agitated for 30 s, and subsequently, water and the HRWRA were added and mixed for 10 min. The mortar flow was tested in accordance with the Japanese Standard JIS R 5201 [14]. The time required to reach a flow of 250 mm was also measured. Hereinafter, this time is referred to as the "250 mm flow time". In addition, a Brookfield rotational viscometer was used to examine the viscosity of the mortar.

(2) Hardened properties of base mortar

The compression test was conducted in accordance with the Japanese Industrial Standard (JIS A 1108) [15] using three mortar cylinders (50 mm diameter × 100 mm long). Most RMCs in Japan use a universal loading apparatus of 1000 kN capacity for the compression test; hence, such small cylinders were used in this study to simulate the quality control in the RMC. According to the Japanese guideline [3], the cylinder of 50 mm diameter indicates equivalent strength of standard cylinder of 100 mm diameter. These strength tests were conducted after ageing for 7 and 28 days. The compressive strength was determined from averaged strength in three cylinders tests. In addition, pore size distribution in UHPFRC were measured by using Pore Master 60-GT.

(3) Hardened properties of UHPFRC

As well as the base mortar, the compression test for UHPFRC was conducted in accordance with the Japanese Industrial Standard (JIS A 1108) [15] using three mortar cylinders (50 mm diameter × 100 mm long). Furthermore, the study examined the flexural strength of the UHPFRC using three beams (100 mm × 100 mm × 400 mm long) in accordance with the Japanese Industrial Standard (JIS A 1106) [16]. These strength tests were conducted after ageing for 1, 3, 7, 14, and 28 days.

3. Results and Discussion in the Base Mortar Test

3.1. Effect of Cement

To examine the effect of cement composition, the mortar specimens listed in Table 3 were prepared and tested. Figure 3 shows relationship between the amount of C_3A in the cement and the addition ratio of HRWRA under the condition of constant mortar flow. The volume of chemical admixture was determined as the mass ratio to cement. To achieve equivalent concrete flow, the required amount of HRWRA was proportional to the volume of C_3A in the cement. The low **W/B** ratio of the concrete was notable.

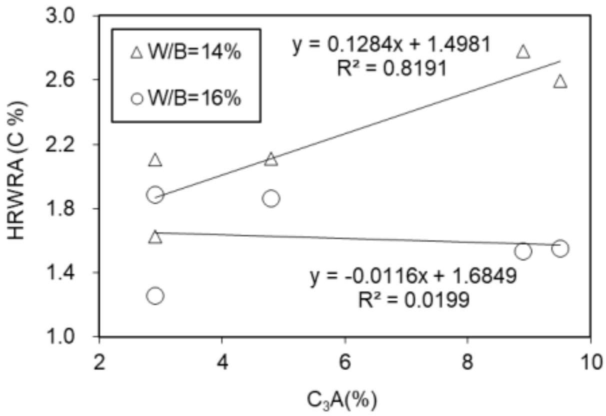


Figure 3. Relations between C_3A content and HRWRA addition ratio.

Figure 4 shows that the flow value of the mortar (**W/B** = 16%) decreased as the amount of C_3A in the cement increased. Note that the low mortar flow levels indicate relatively high viscosity. The reason for this is that the ratio of gypsum to C_3A decreases as the C_3A content increases; accordingly, the amount of ettringite, which suppresses the hydration of C_3A, decreases. Hence, mortar flow decreases with the hydration of C_3A. These test results suggest that a low C_3A cement should be used for UHPFRC manufactured at ambient temperature to maintain adequate fluidity. Li et al. [7] observed that cement with a low alkali content is suitable for use in high-performance concrete.

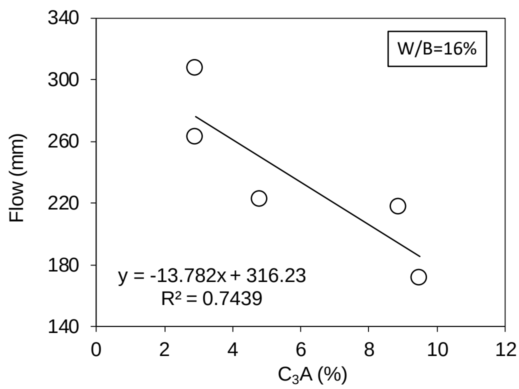
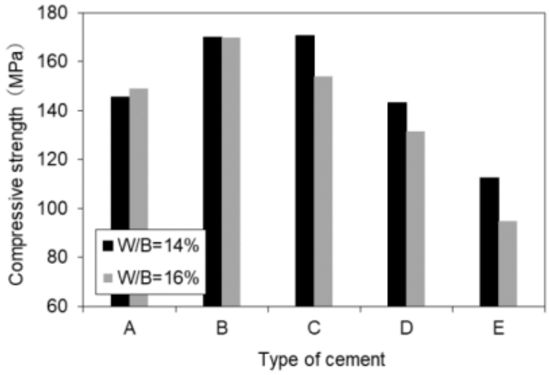


Figure 4. Relation between C_3A content and flow.

Figure 5 shows the test results of the compressive strength. The compressive strength of mortar using cement C achieved 200 MPa at 28 days. The compressive strength was almost equivalent to that of the heat-cured UHPFRC [3]. Note that the mortar having a low W/B (14%) using the cement A exhibited a lower compressive strength than that of the mortar with a high W/B (16%). This phenomenon was caused by the delayed setting due to the high addition rate of the HRWRA in the mortar having a low W/B. The HRWRA addition for the mortar of 14% using cement A was significant as shown in Figure 6a. The mortar flow is presented in Figure 6b. Even after mixing the high volume of HRWRA with the mortar having the lowest W/B of 14%, the flow was approximately 270 mm, which was lower than those of mortars using cements C, D, and E. Note that the mortar with cement having low C_3A (D, E) developed a lower strength but a greater flowability than those of mortar using the cement C. The observations imply that the cement having low C_3A and high C_3S may be suitable for manufacturing UHPFRC at ambient temperatures.



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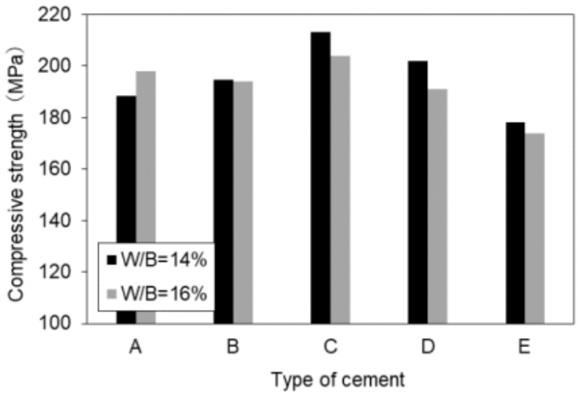

(**b**)

Figure 5. Compressive strength. (**a**) Seven days. (**b**) Twenty-eight days.

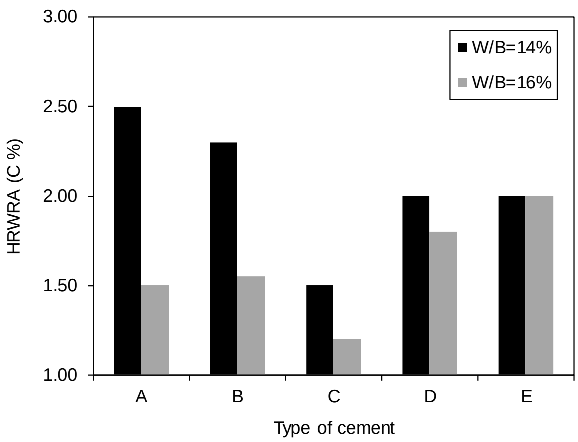

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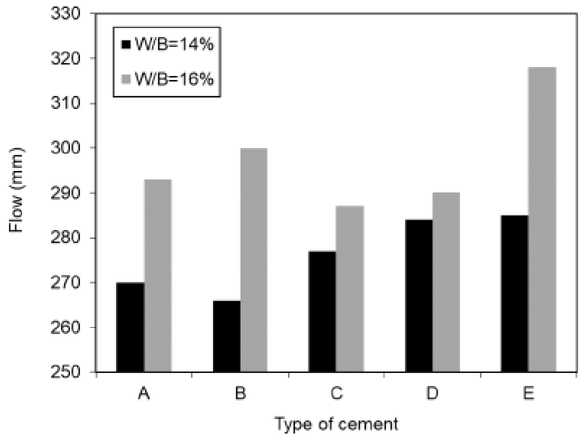
Figure 6. *Cont.*



(**b**)

Figure 6. Effect of HRWRA. (**a**) HRWRA addition ratio. (**b**) Mortar flow.

Figure 7 shows the relationship between the C_3S content in cement and compressive strength at two ageing times. The compressive strength after 7 days is seen to increase as C_3S increased. The mortar strength of cement with low C_3S was lower than the designed strength (180 MPa). It was observed that the compressive strength increased in accordance with the volume of C_3S. Note that the effect of C_3S was not obvious in higher range of 50%. The test result implies that the reaction of C_3S with cement contributes to the strength development at the early stage. It is well known that the C_3S reaction affects strength development approximately within 4 weeks; thereafter, the C_3S reaction contributes to this [17]. Yoda et al. [18] conducted a strength test of cement paste using cements having different mineral compositions. They reported that cement paste made with a high C_3S content developed a higher compressive strength after 28 days of ageing. The strength of the uncured UHPFRC was equivalent to those observed in previous studies.

Figure 8a presents the porosity in the mortar of W/B = 14%. The mortar fabricated with cement C, which had the highest compressive strength of 210 MPa after 28 days, also showed the lowest porosity. Conventional heat-cured UHPFRC [3] has a porosity of 4%, which mainly consists of pores of 3–6 nm. As shown in Figure 8a, all tested mortars fabricated under ambient temperatures had higher porosities than those of the conventional UHPFRC. Even in the mortar with cement C having the highest strength, 6–10 nm and 10–100 nm pores occupied approximately 60% of the pore-size distribution. It should be noted that the mortar has a microstructure that is denser than traditional concrete, which generally has a porosity of 9%. The low porosity of the mortar contributed to a compressive strength above 200 MPa after 28 days even under the standard curing.

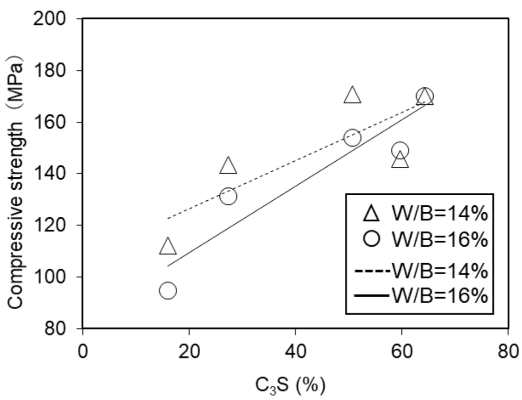


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Figure 7. *Cont.*

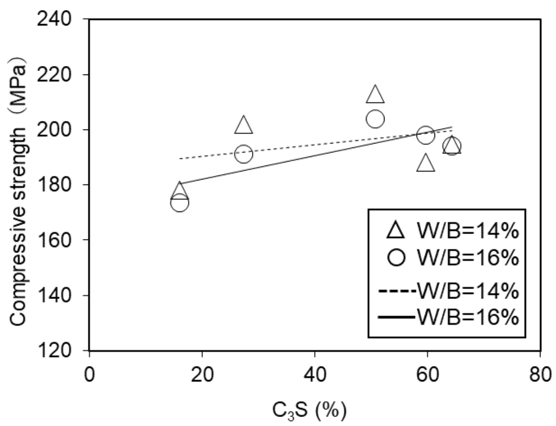

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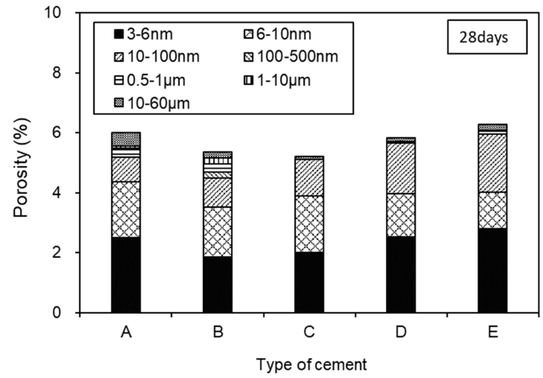
Figure 7. Relations between C_3S content and compressive strength. (**a**) Seven days. (**b**) Twenty-eight days.



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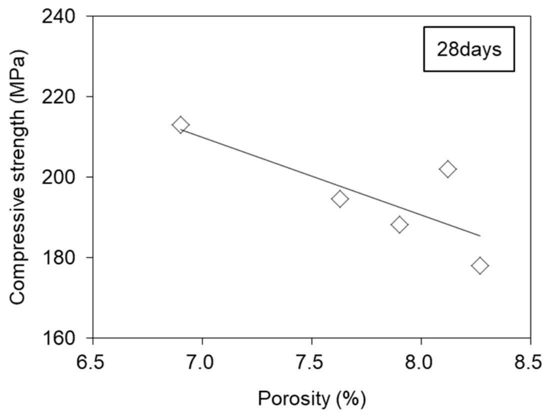


(**b**)

Figure 8. Porosity properties of mortar (W/B = 14%) made with various cement. (**a**) Porosity of mortar. (**b**) Porosity—compressive strength.

Figure 8b shows the linear relation between the porosity and compressive strength after 28 days. Even under the standard curing time, the mortar mixed with cement C having high C_3S and low C_3A achieved more than 200 MPa due to the denser structure formed.

Based on the test results concerning the effect of cement type, cement **C** was employed in the subsequent tests.

3.2. Effects of W/B and Water Content

The mixing time for UHPFRC should be kept as short as possible, within the range that meets the requirements for performance parameters such as fluidity and strength.

Figure 9 shows the liquefaction time from the start of mortar mixing. The legend for the graph shows the water contents (kg/m^3). The mixture proportions for the tested mortar are given in Table 4. The result confirms that mortars with lower **W/B** requires longer mixing times to reach fluidisation.

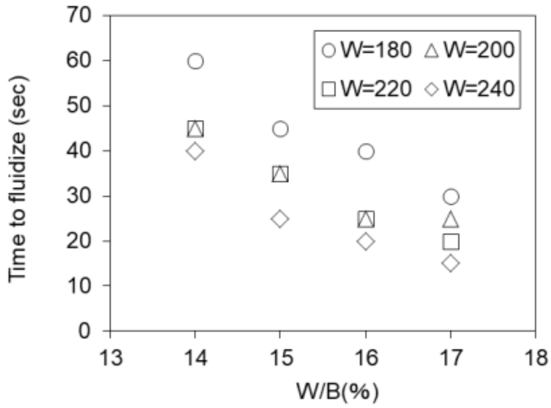
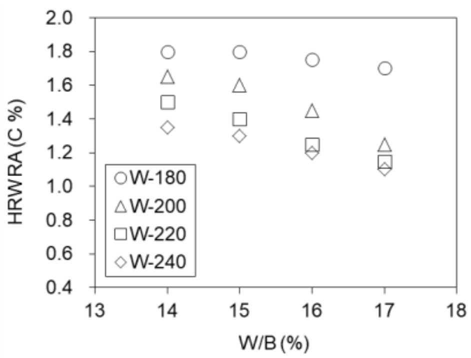
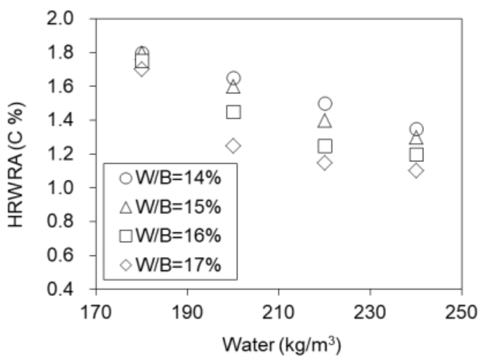


Figure 9. W/B and fluidisation time.

Figure 10a illustrates the relationship between **W/B** and the amount of the chemical admixture (HRWRA) in terms of the mass ratio to the cement content. The admixture ratios required to achieve equivalent flow of the fresh mortar were determined. The results confirm that the required HRWRA decreased with increasing **W/B** and water content of the mortar. The decrease in the HRWRA ratio is illustrated in Figure 10b. It is generally known that the setting time of increases as the mass ratio of the admixture to the binder increase. For practical use of the UHPFRC manufacturable at an RMC plant, the chemical admixture content required should be carefully determined by considering the fluidity and usable time of the UHPFRC at a construction site.



(**a**)



(**b**)

Figure 10. Chemical admixture amount. (**a**) W/B—HRWRA. (**b**) Water—HRWRA.

Figure 11a shows how the viscosity decreases with increasing flowability of the mortar. It is noteworthy that the viscosity of the mortar was inversely proportional to the flow regardless of the **W/B** in the range of 14–17%. Figure 11b shows another aspect of the relation based on the above-mentioned tests. While the viscosity decreased with increasing **W/B**, the relation between the two was not strong.

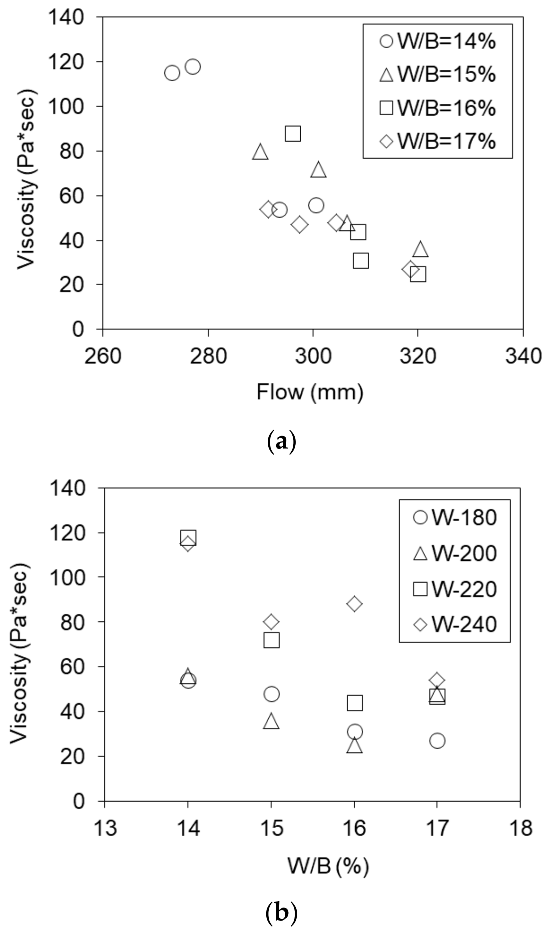


Figure 11. Mortar viscosity. (**a**) Mortar flow—viscosity. (**b**) W/B—viscosity.

Figure 12 shows the 250 mm flow time of various **W/B** and the unit-weight of water of the mortar. The result shows that the 250 mm flow time and **W/B** relations were obviously linear and had negative gradients, regardless of the water content of the mortar.

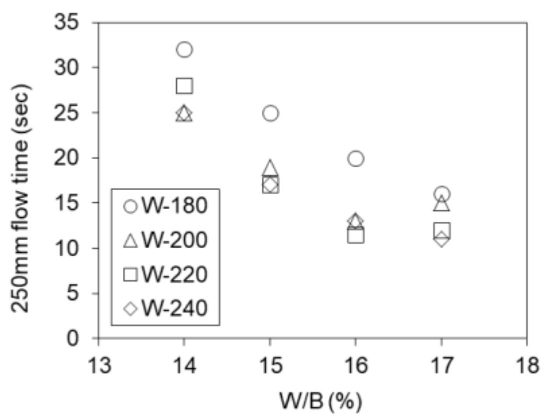
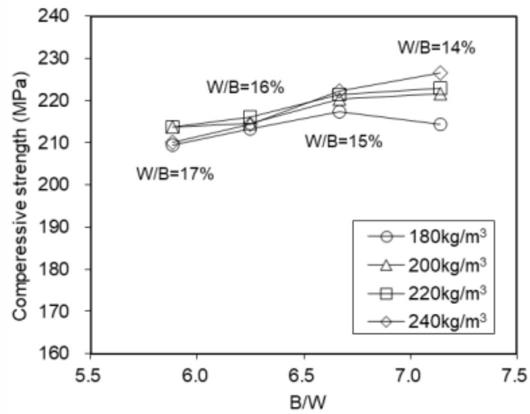


Figure 12. Relations between **W/B** and 250 mm flow time.

Based on the above-mentioned tests of fresh mortar for the UHPFRC, the recommended ranges of water and **W/B** were determined, as shown in Table 4. It should be noted that the range of **W/B** is not always appropriate for achieving the required strength of the UHPFRC. The proper range of **W/B** should be determined via strength properties; hence, the compressive strengths of the various base mortars were examined.

Figure 13 shows the variation of compressive strengths according to **B/W** and water content in the mortar. The test result confirms that the compressive strength after 28 days exceeded 200 MPa in all tested mortars. Further, it is noted that the compressive strength of the mortar mixed with water content of 180 kg/m^3 developed relatively lower strength than those of others even at the **W/B** of 14% (Figure 13a). The strength characteristic was due to the flowability of the mortar having a low water content. Figure 13b shows that compressive strength of each **W/B** mortar hardly varied due to the unit-water content, except for the mortar having **W/B** of 14%.



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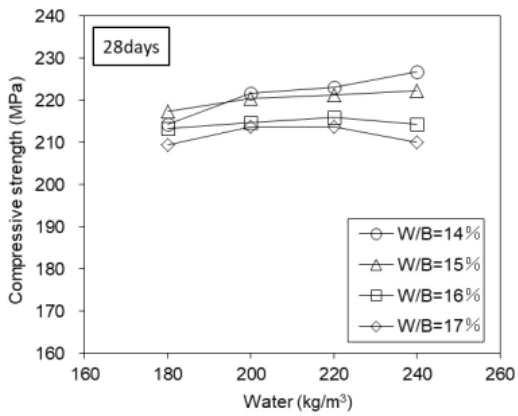


(**b**)

Figure 13. Compressive strength of mortar (cement C). (**a**) B/W—compressive strength. (**b**) Water—compressive strength.

Based on the observed results, an additional test of compressive strength was conducted by using various **W/Bs** (14–23%) of mortars having a water content of 220 kg/m^3 (see Table 4). Figure 14 shows the **B/W**-compressive strength relation. It is seen that the compressive strength is approximately proportional to the **B/W** in the **W/B** range of 14–21%. The strength of mortar of 23% **B/W** was relatively lower than the trend line. Since the mortar with **W/B** of 21% achieved the minimum target strength of 200 MPa after 28 days, this **W/B** may be the maximum for the UHPFRC cured under ambient temperatures. The applicable **W/B** for the mortar is 2% lower than the highest **W/B** of 24% for the heat-cured UHPFRC recommended in the Japanese guideline [3].

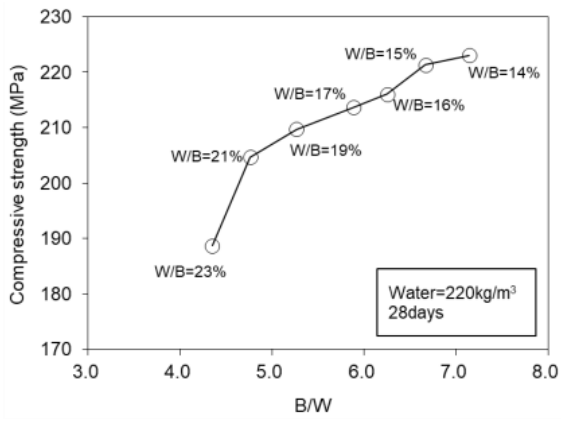


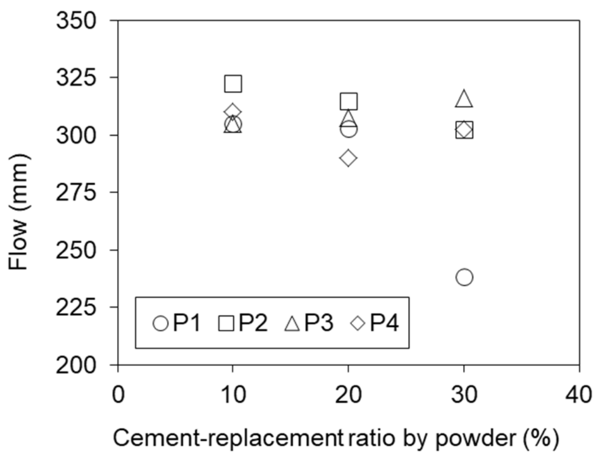
Figure 14. Compressive strengths varied by various **W/B** mortar.

3.3. *Effect of Powder Materials*

Mortars were prepared with various powder materials (**P1–P4**) to quantify the effects of aspects of the powder materials, such as the type and amount, on the properties of the fresh mortars. The powder materials were used to replace portions of the cement material by mass (Table 5). The unit weight of the fine aggregate varied because of the different volume of powder material used for each density.

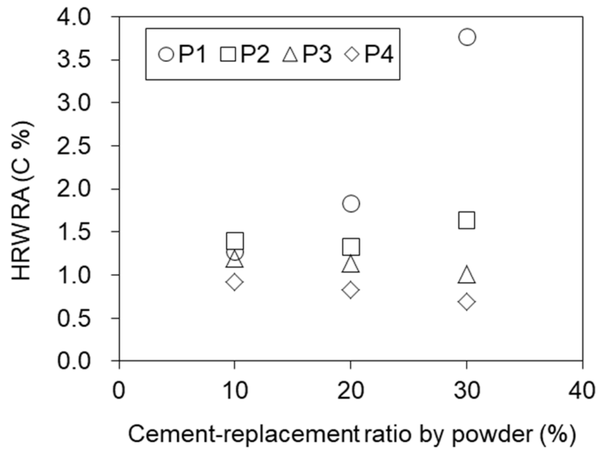
Figure 15a illustrates the flow of fresh mortars made with cement replacement ratios of 10–30% by mass. The test results show that the flow values of the tested mortars containing the powder materials **P2**, **P3**, and **P4** hardly varied with the addition ratio. The flow value of the mortars made using **P2**, **P3** and **P4** did not change because these powder materials have equivalent fineness to the cement. Of interest is that the HRWRA can be decreased in according to the increase in **P3**. It was notable that the mortar flow decreased significantly when the powder material **P1** was added at 30% by mass of cement. This was observed even though a larger amount of HRWRA was added to the mortar than to the other mortars (Figure 15b). The significant decrease in mortar flow may have been due to the fineness of the **P1** powder particles. It should be noted that the powder material **P1** was added to the UHPFRC by replacing 30% or more of the mass of cement.

Figure 15c shows the 250 mm flow time of the mortar made with each powder material. The mortars incorporating **P1** at 10–20% had significantly shorter flow times than the other mortars with other powder materials. The excellent fluidity achieved was due to the ball bearing effect of the particles and the high fineness of the powder material. The characteristics of the **P1** powder material may be noteworthy for UHPFRC.



(**a**)

Figure 15. *Cont.*



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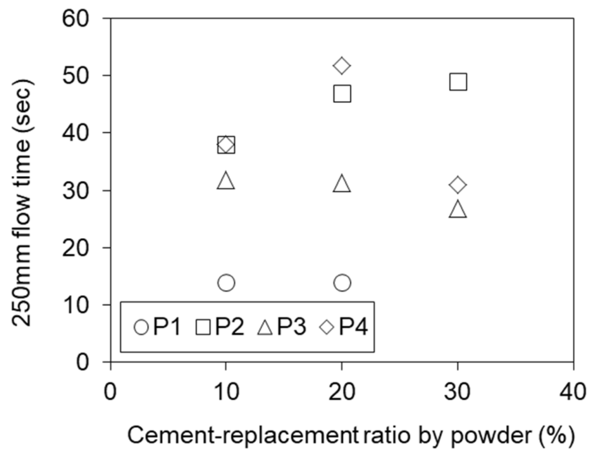


(**c**)

Figure 15. Effect of cement replacement ratio (P/B) by powder material. (**a**) P/B—mortar flow. (**b**) P/B—HRWRA. (**c**) P/B—250 mm flow time.

Figure 16a,b show the compressive strengths of mortar incorporating the powder material (**P1**, **P2**, **P3**, and **P4**) after 7 and 28 days of ageing, respectively. The **P1** mortar of **P/B** = 20% had an approximately equivalent strength as of the **P1** mortar of **P/B** = 10%. The compressive strengths of **P1** mortar after 28 days were significantly higher than those of other mortars. Note that **P1** mortar having **P/B** = 30% had a lower strength than that of mortar with other **P/B**s. The lower strength at the **P/B** of 30% was possibly due to the decrease in the cement **C** and the insufficient fluidity of fresh mortar.

Powder **P2** is a kind of pozzolanic material having an activity index of 85.3% at 28 days. The compressive strength of **P2** mortar gradually decreased in accordance with the **P/B** increase due to the relatively low pozzolanic activity of the powder material.

Powder **P3** is a material having a high activity index of 106.8% at 28 days. Note that the compressive strength of the **P3** mortar hardly varied due to the increase in **P/B**. In particular, the highest strength at 28 days in **P/B** of 30% is of interest.

The strength properties of the **P4** mortar showed a similar tendency to those of the **P2** mortar, i.e., that the strength gradually decreased with the **P/B** increase. The powder material **P4** has negligible reactivity to hydration; thus, the compressive strength decreased when the cement content decreased.

The comparative test result implies that the powder **P1** is the most effective to increase the compressive strength. Hence, an additional test of the **P1** mortars manufactured with various **P/B**s was conducted for determining an appropriate ratio in the UHPFRC. In a follow-up investigation, the proper amount of chemical admixture (HRWRA) in the mortar mixed with the **P1** was investigated. The mixture proportions of the tested mortar are given in Table 6.

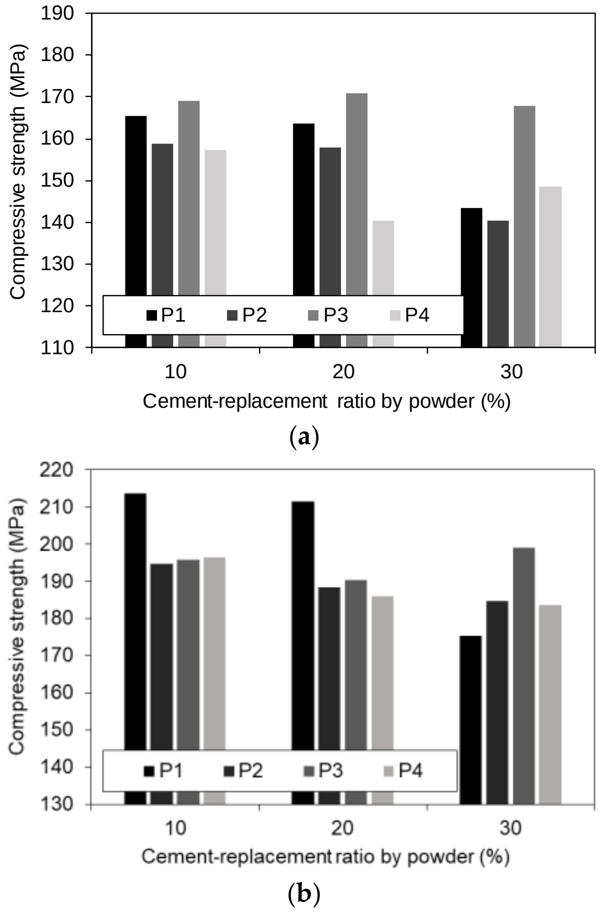
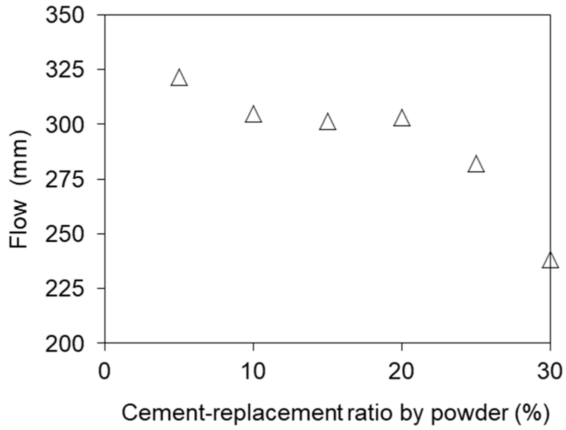


Figure 16. Effect of **P/B** on compressive strength. (**a**) Seven days. (**b**) Twenty-eight days.

Figure 17a–d show the effects of variation in the cement mass ratio on the HRWRA, mortar flow, 250 mm flow time of the mortar, and compressive strength, respectively. Figure 17a confirms the increase in dosage of the chemical admixture in accordance with the increase in the cement replacement ratio by the powder material **P1**. Note that the setting time may be significantly delayed when the HRWRA content of the mortar is 2% or higher. Figure 17b shows the decrease in the mortar flow as the powder material P1 content increases. To confirm the flowability of mortars incorporating **P1**, the 250 mm flow time was also examined, as shown in Figure 17c. The test confirms that the 250 mm flow time remains almost constant up to a replacement ratio of 20%. Based on the test results, the proper replacement ratio with **P1** should be less than 20% by mass of cement. Figure 17d shows the variation of the compressive strength with the **P/B** of powder **P1**, which confirms that the strength gradually decreased with **P/B**. A remarkable finding is that the 28-day-strength at the **P/B** of 15% was as high as the strength at the **P/B** of 5–10%. The primary reason is the decrease in cement owing to the replacement of P1 in addition to the increase in HRWRA. The effects of the other powder materials (**P2**, **P3**, and **P4**) were also examined. These materials were used as volume replacement materials for portions of the fine aggregate (Table 7). The volume replacement ratios were 30%, 50%, 70%, and 100%. A **P1** content of 216 kg/m^3 was tentatively determined to correspond to 15% of the cement mass.



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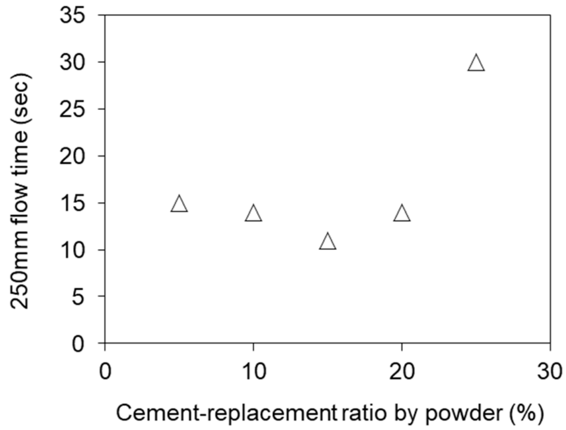

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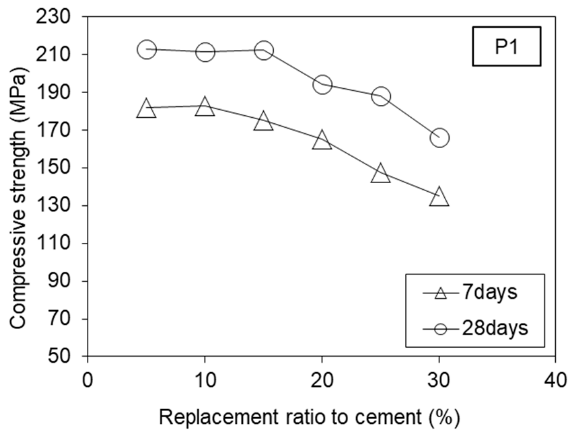


(**d**)

Figure 17. Effect of **P1** addition ratio. (**a**) HRWRA. (**b**) Mortar flow. (**c**) Two-hundred-and-fifty-millimetre flow time. (**d**) Compressive strength.

Figure 18 illustrates the variation in the powder material volume ratio with variation in the HRWRA and viscosity of the mortar, respectively. Figure 18a confirms that increasing the dosage of HRWRA corresponds to an in increase the volume replacement ratio. The required dosages for the mortar made with **P4** were relatively lower than for the other powder materials (**P2** and **P3**). Figure 18b confirms that the viscosity of the mortar made with **P4** was significantly lower than the those of the mortars made with the other powder materials (**P2** and **P3**). This effect may be related to the particle shape and chemical composition of the powder material (**P4**). With respect to the fluidity and viscosity of the mortar made with a relatively low dosage of HRWRA, the **P4** powder was found to be a suitable volume-replacement material for UHPFRC manufactured at an RMC plant.

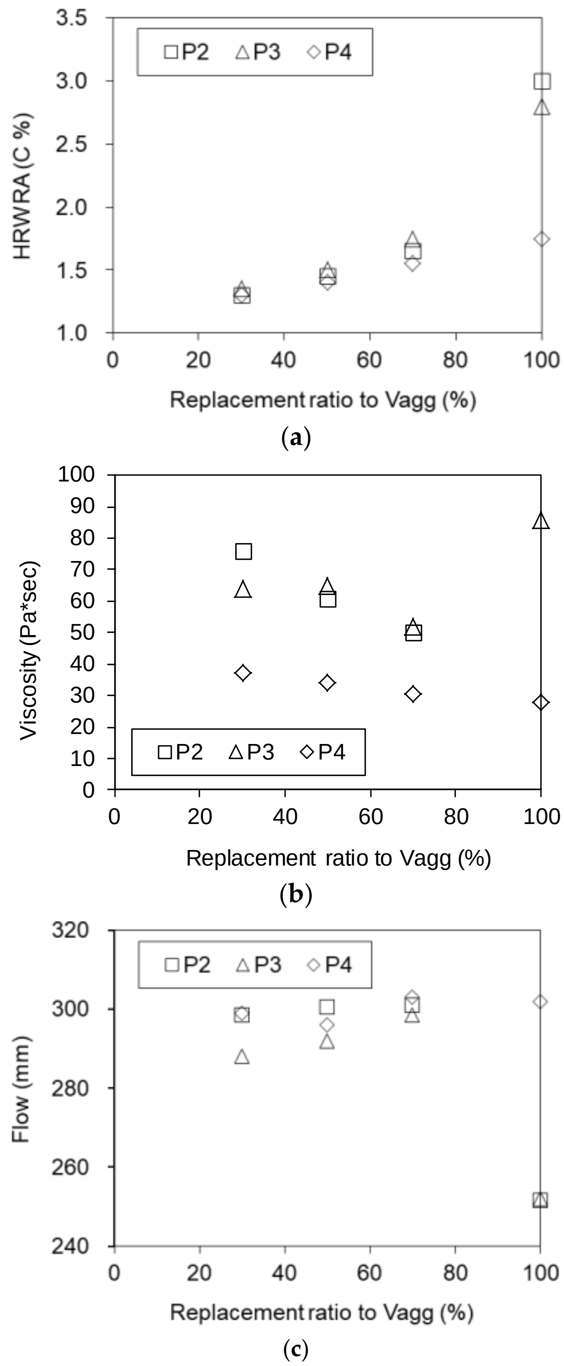
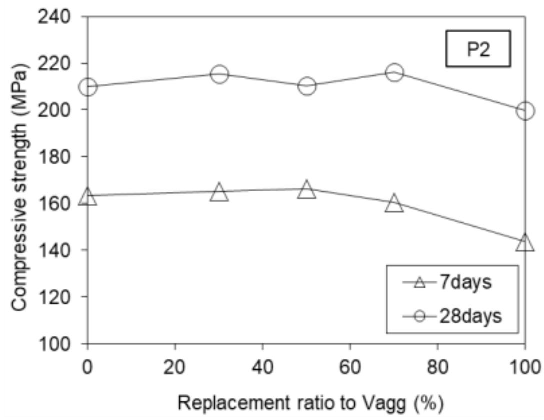


Figure 18. Effect of P2, P3, and P4 addition ratios to Vagg. (**a**) HRWRA. (**b**) Viscosity. (**c**) Mortar flow.

To confirm the effect of these powder materials (**P2**, **P3**, **P4**), compressive strengths of the base mortar were examined. Figure 19 presents the compressive strength variation of mortar mixed with powder (a) **P2**, (b) **P3**, and (c) **P4**. The strength was found to decrease when powders **P2** and **P3** were fully used as the fine aggregate because of the large amount of HRWRA (Figure 18a) and poor flowability (Figure 18c). On the other hand, the strength of mortar mixed with powder **P4** was higher than 200 MPa after 28 days when the partially or fully used fine aggregate was employed.



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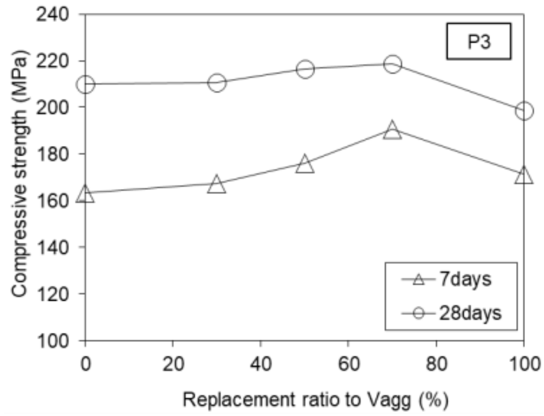

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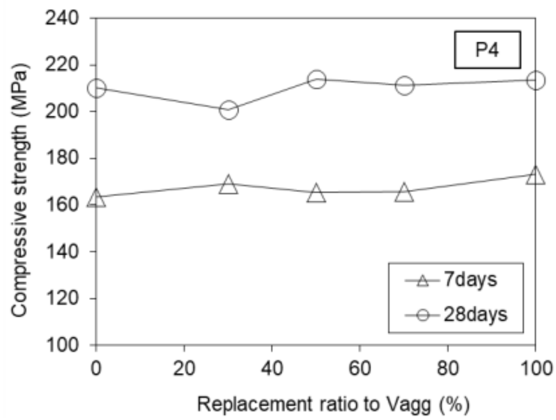


(**c**)

Figure 19. Effect of **P2**, **P3**, and **P4** addition ratios on compressive strength. (**a**) P2. (**b**) P3. (**c**) P4.

4. Results and Discussion in the UHPFRC Test

4.1. Effect of Volume of Fine Aggregate

The effect of fine aggregate was evaluated via mortar flow tests. Table 8 shows the mixture proportions of UHPFRC mixtures in which steel fibres were mixed at 2.0 vol%. Figure 20a shows that the required cement mass ratio of HRWRA increased with the increasing fine aggregate content under conditions of equivalent mortar flow. Figure 20b shows that the mortar viscosity decreased with increasing volume of fine aggregate. This is attributable to the decrease in fine powder material with increasing fine aggregate content.

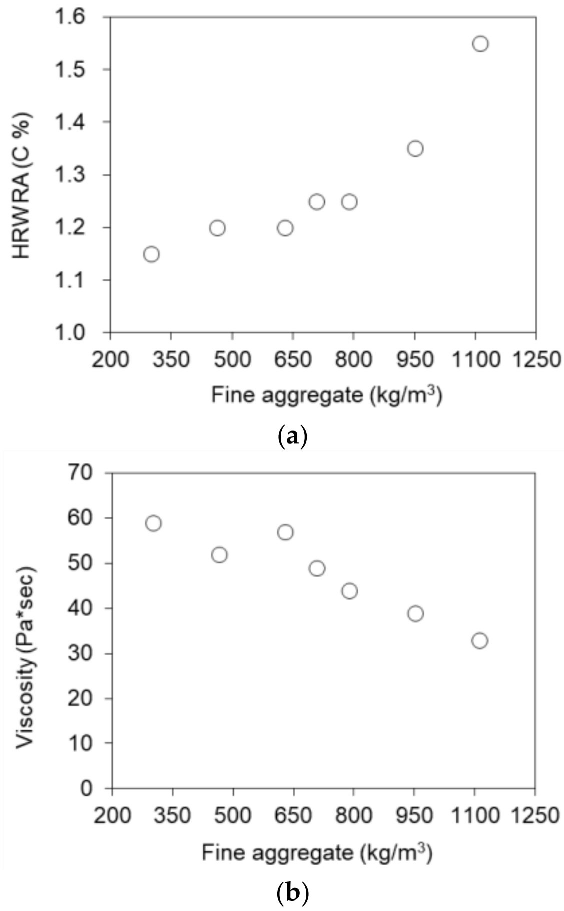


Figure 20. Effect of fine-aggregate volume. (**a**) HRWRA. (**b**) Viscosity.

Figure 21 presents the flow conditions of mortars made with various amounts of fine aggregate (Table 8). The photo shows that the dispersion of steel fibres was insufficient in UHPFRC mixtures with large volumes of fine aggregate. A comparison of the dispersions of the steel fibres in the UHPFRC mixtures suggests that the weight of fine aggregate used in typical RMC plants should be less than approximately 600 kg/m^3. Note that the volume of fine aggregate is relatively smaller than the general volume for the mortar having ultra-rich cement. The primary reason for such mixture was due to viscosity and fibre dispersion in the UHPFRC. A larger volume of fine aggregate particles, such as the powder material **P4**, is appropriate for use in UHPFRC.

Figure 22 shows the particle size distributions of all of the materials in the mortar except for the steel fibres. The legend in the graph shows the unit weight of fine aggregate in the UHPFRC. Significant differences among the UHPFRC mixtures were observed in the range of 50–100 μm of the distribution. Considering this observation and the test results of the base mortar, a mortar incorporating fine materials of which at least 70% pass the 100 μm sieve is preferable for adequate steel fibre dispersion.

Figure 23 shows the compressive strengths of the UHPFRC after the ages of 7 and 28 days. The result confirms that the compressive strength hardly varied according to the volume of fine aggregate. It implies that the general-purpose aggregate used in RMC is also suitable for such a high-strength UHPFRC. However, one concern is the dispersibility of steel fibres in UHPFRC. According to our previous investigation on fresh UHPFRC, it was observed that dispersion of steel fibres was insufficient in UHPFRC mixtures having large volumes of fine aggregate (Figure 21). The flow test using UHPFRC suggested that the unit-weight of fine aggregate used in typical RMC plants should be less than approximately 600 kg/m^3. The test implied that the powder material **P4** is appropriate for use in UHPFRC in case of a large volume of fine aggregate.

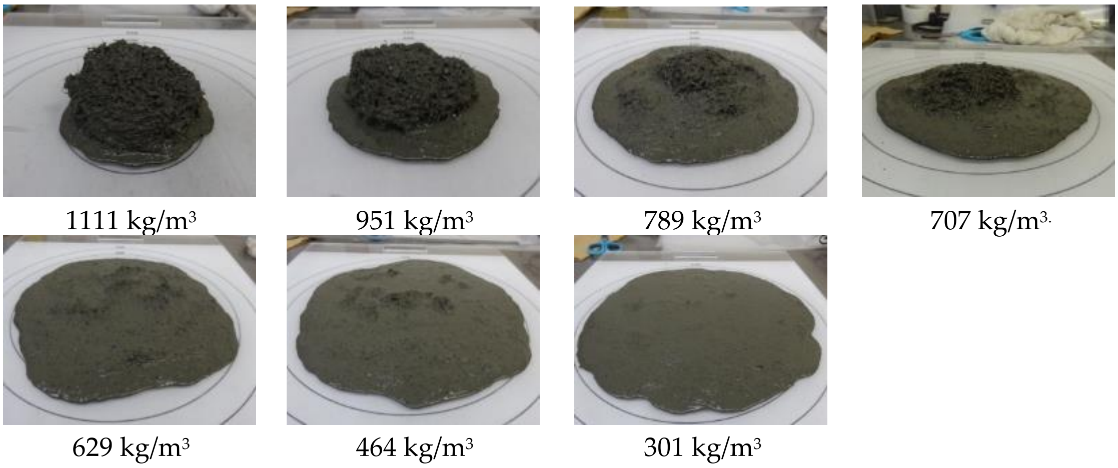


Figure 21. Mortar flow varied by volume of fine aggregate.

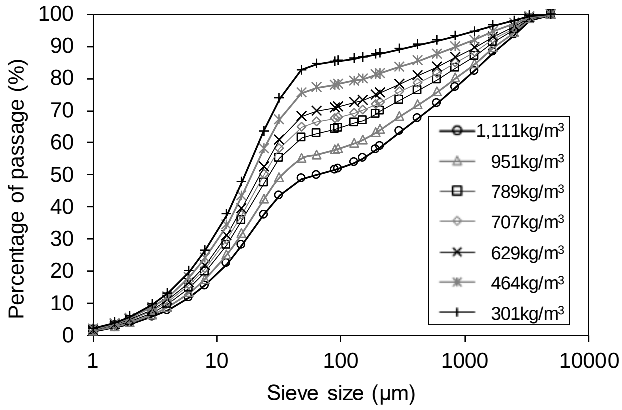


Figure 22. Size distributions of materials without steel fibres.

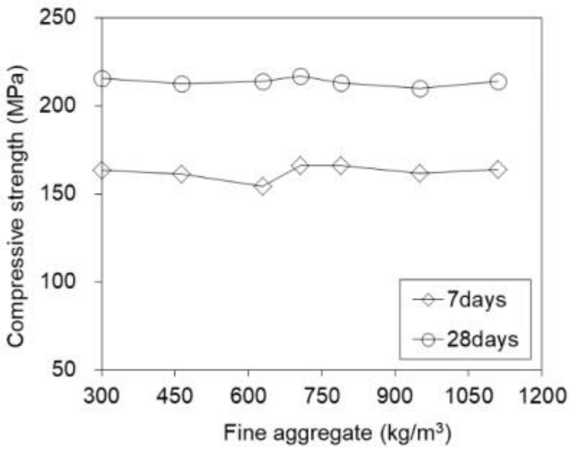
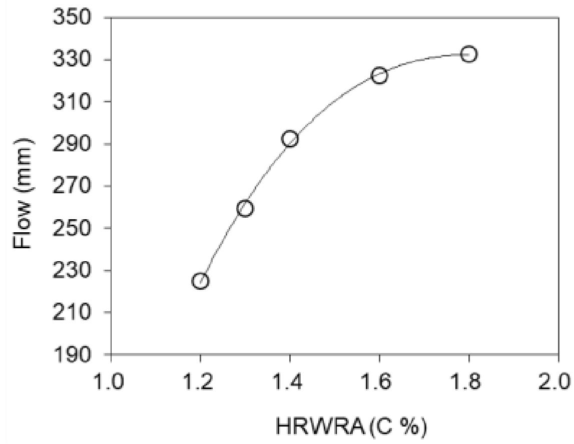


Figure 23. Compressive strength of UHPFRC with various volume of fine aggregate.

4.2. *Effects of Mortar Flow and Viscosity*

The density difference between the mortar and steel fibres should be considered in manufacturing UHPFRC. The segregation of steel fibres may occur if the mortar is of relatively low viscosity. The viscosity and flowability of fresh UHPFRC were examined in this study under test conditions involving constant volumes of water, cement, powder materials (**P1** and **P4**), and fine aggregate, as shown in Table 9. That is, the flow and viscosity were varied by the addition ratio of HRWRA alone.

Figure 24a,b show the flow and viscosity of the UHPFRC, respectively. Figure 24a confirms that the increase in flow gradually decreased around an HRWRA of 1.6% of the cement mass. Figure 24b presents the negative linear relation between the flow and the viscosity of the UHPFRC, i.e., the decrease in viscosity with increasing flow. Fresh UHPFRC materials of different viscosities were poured into cylindrical test pieces with dimensions of 52 mm (diameter) × 250 mm (height). Subsequently, the UHPFRC materials were consolidated by vibration for 60 s and were placed in a laboratory chamber at ambient temperature for 7 days.



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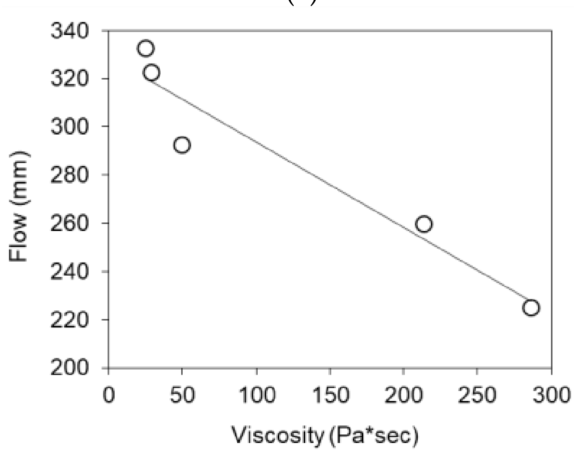


(**b**)

Figure 24. Flow of UHPFRC. (**a**) HRWRA—mortar flow. (**b**) Viscosity—flow.

To examine the segregation of steel fibres, the hardened UHPFRC specimens were cut into three parts, as shown in Figure 25, and the density of each part was examined. The results are summarised in Figure 26a. The density differences between the upper and lower parts are presented in Figure 26b. The density differences suggest the segregation of steel fibres caused by the different viscosities of the UHPFRC. Based on the observed density of each part, the volume percentages of steel fibres were calculated. Figure 26c shows the estimated volumes of steel fibres.

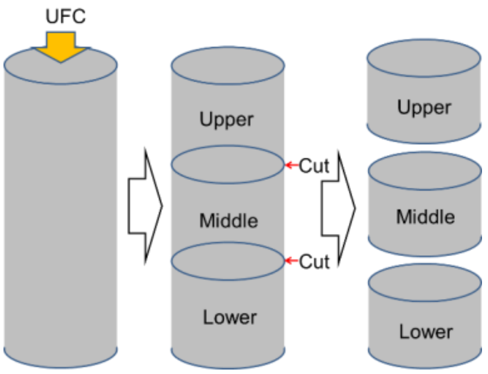
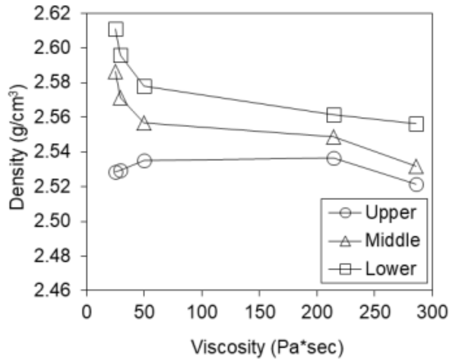


Figure 25. Examination of steel-fibre segregation.



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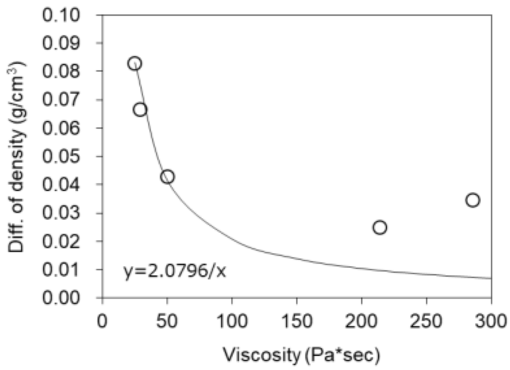

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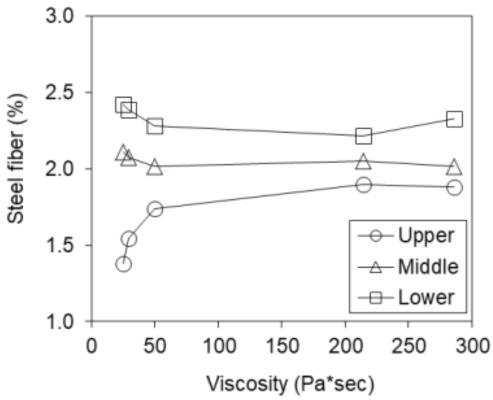


(**c**)

Figure 26. Results of steel-fibre segregation. (**a**) Densities of upper, middle, and lower parts. (**b**) Density difference. (**c**) Estimated steel fibre contents.

Figure 27a shows the relation between UHPFRC flow and compressive strength. The test result shows that the compressive strength after 7 days slightly increased in accordance with the flow and that after 28 days was almost constant in the range of 230–290 mm. It is important to note that the UHPFRC having 320 mm flow developed lower strength than those of UHPFRCs having 230–290 mm flow after 28 days.

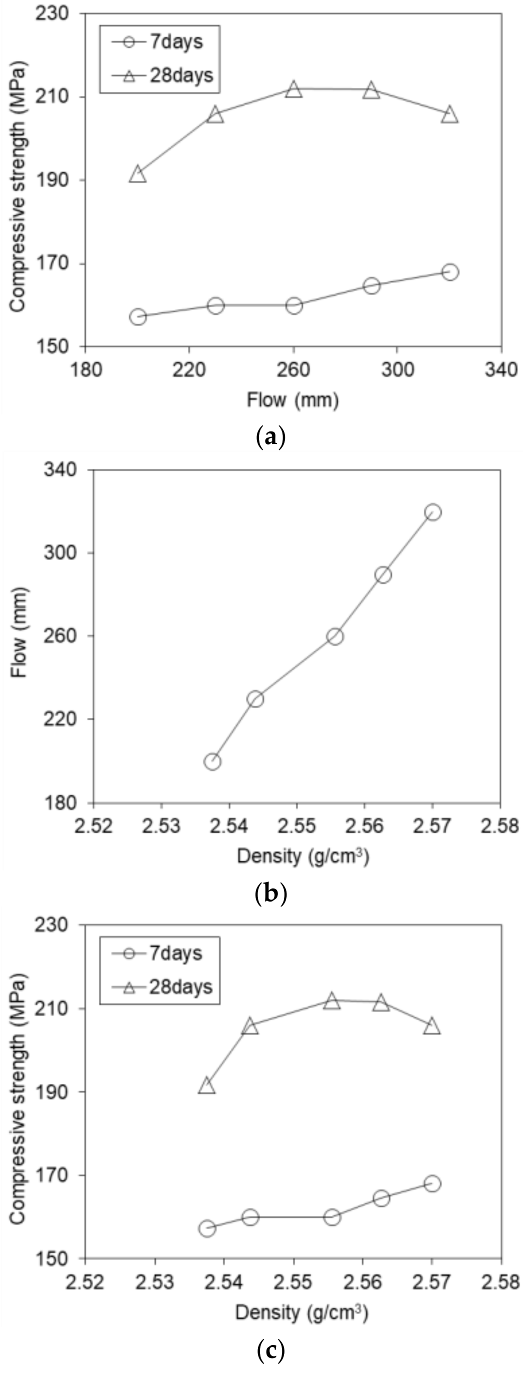


Figure 27. Compressive strength of UHPFRC having various fresh properties. (**a**) Strength—flow. (**b**) Flow—density. (**c**) Strength—density.

Air content in UHPFRC possibly decreases with the increase in flow; so, the densities of UHPFRC specimens were examined. Figure 27b,c present the relations of flow vs. density and density vs. compressive strength of the UHPFRC. The result confirmed that the density vs. strength relation was similar to that of the strength vs. flow shown in Figure 27a. These observations imply that the compressive strength of UHPFRC was possibly decreased by the segregation owing to excessive flow and insufficient viscosity. Based on results, an appropriate range of flow of 230–290 mm was determined for the UHPFRC.

This study focused on the volume of steel fibres contained in the upper part of each cylinder, which represents the segregation of various mortars of different viscosities and flows. Figure 28 presents the linear relation between flow and the volume of steel fibres in the upper parts of the cylindrical UHPFRC specimens. The results confirm that the volume of steel fibres decreased with increasing flow, i.e., with decreasing viscosity of the UHPFRC. To produce UHPFRC members that are as homogeneous as possible, the mixture design for UHPFRC manufacture under ambient temperature conditions should take the viscosity and fluidity into careful consideration.

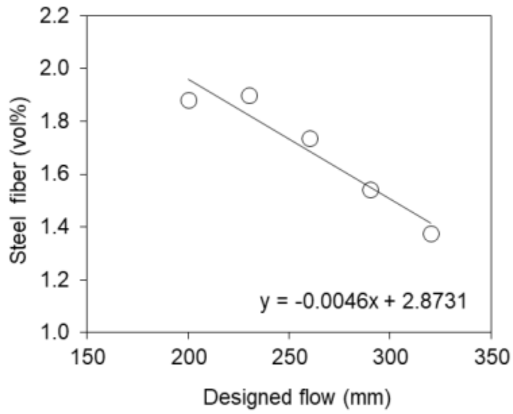


Figure 28. UHPFRC flow—steel-fibre volume.

Flexural strength testing of the UHPFRC beams made with different volume ratios of steel fibres was conducted to confirm the excellent mechanical properties. Figure 29 presents the flexural strength variation with respect to the steel fibre volume. The results confirmed that the flexural strength was almost proportional to the steel fibre content, and even the UHPFRC with a 1.0 vol% of steel fibres achieved a flexural strength greater than 20 MPa.

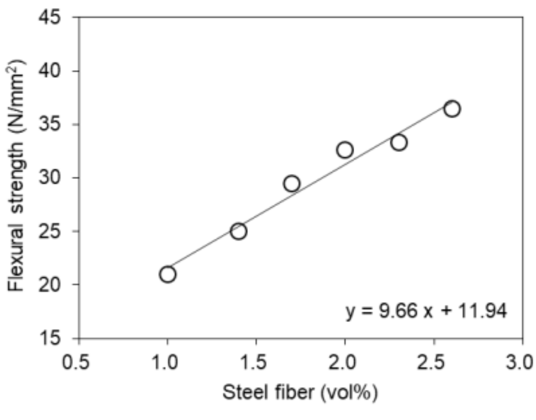


Figure 29. Steel-fibre volume—flexural strength.

To reduce the risk of material segregation, an allowable flowability for UHPFRC should be determined. The maximum flow of the UHPFRC was approximately 290 mm in this study. Note that the minimum content of steel fibres for a UHPFRC with a flowability of 290 mm was approximately 1.5 vol%, while the segregation was slightly high (a density difference of 0.07 g/cm^3). According to the test results in Figure 29, the UHPFRC incorporating steel fibres of 1.5 vol% achieved a flexural strength of approximately 25 MPa, which is significantly higher than the strength of conventional concrete. Noteworthy is that the flexural strength (25 MPa) of the UHPFRC without heat curing was equivalent to the strength of 24.4 MPa of heat-cured UHPFRC [3].

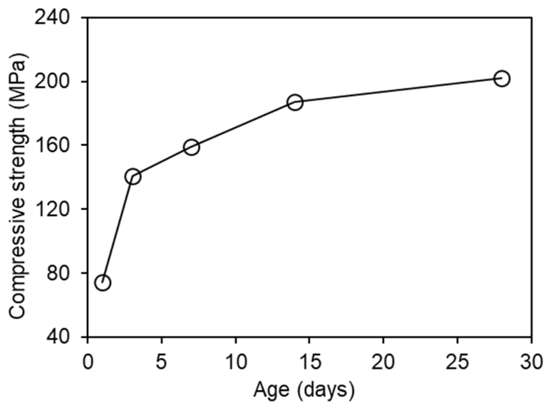
It is possible that the low flow UHPFRC indicates a relatively lower compressive strength because of the air content of UHPFRC of high viscosity. Further research should be performed to determine the relationship between the minimum flow and the compressive strength for various UHPFRC mixtures.

4.3. Relationship between Compressive and Flexural Strengths

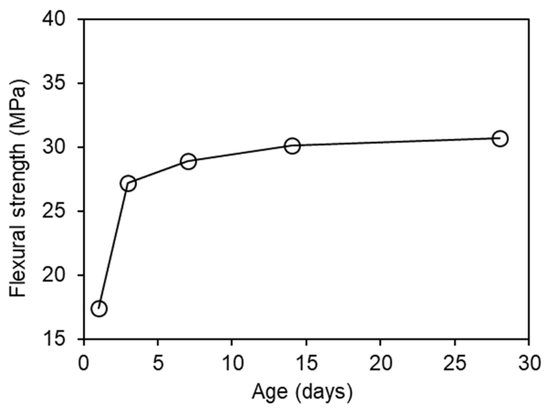
Figure 30(a), (b) show the compressive and flexural strength developments with ageing time, respectively. The tested UHPFRC was fabricated by employing the mixture of 1.4% HRWRA given in Table 10. Figure 30a confirms that the compressive strength after 28 days could reach its target of 200 MPa. Of interest is that the compressive strength (202 MPa) of the UHPFRC was slightly higher than the strength (194 MPa) of heat-cured UHPFRC [3]. Additionally, Figure 30b shows the flexural strength of the UHPFRC reached 30 MPa after 14 days. The result confirms that even the uncured UHPFRC developed an excellent flexural strength which was almost equivalent to the strength (30.4 MPa) of the conventional UHPFRC [3]. Finally, the relation between compressive and flexural strengths is represented in Figure 30c, which was almost linear until the age of 7 days, and thereafter, the flexural strength increased slightly compared to the compressive strength. The UHPFRC strength was similar to traditional concrete. The tensile strength of the UHPFRC was estimated using the previous relation between tensile and flexural strengths for the heat-cured UHPFRC, which is given in this Japanese guideline [3].

$$f_b = 2.59\, f_t + 1.54 \quad (1)$$

where f_b is the flexural strength (MPa), and f_t is the tensile strength (MPa).

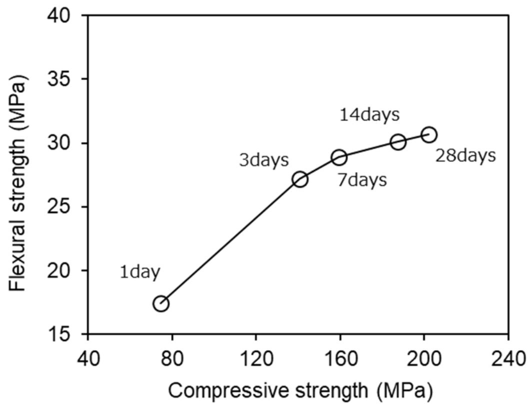


(**a**)



(**b**)

Figure 30. *Cont.*



(c)

Figure 30. Compressive and flexural strengths of UHPFRC. (**a**) Compressive strength. (**b**) Flexural strength. (**c**) Flexural strength—compressive strength.

The estimated tensile strength of 11.2 MPa was adequately higher than that of 5 MPa required for UHPFRC. Therefore, it is confirmed from the experimental study that the UHPFRC manufacturable at RMCs or similar plants can achieve the required strength.

5. Summary

The purpose of this investigation was to develop a UHPFRC that is manufacturable without special heat curing, even at RMC factories. This paper presented the suitable materials and mixture proportions of the UHPFRC. The conclusions drawn from the results of this investigation are summarised as follows:

- The mortar with **W/B** of 14% could achieve the compressive strength of 210 MPa after 28 days and had the lowest porosity. The decrease in flowability in the UHPFRC should be noted when using the cement with high C_3S. Additionally, C_3A in the cement also results in the decrease in mortar flow. To achieve the appropriate flowability and adequate strength, the cement having low C_3A and high C_3S is suitable for the UHPFRC manufacturable at ambient temperatures.
- Appropriate ranges of the water content and water–binder ratio (**W/B**) required to achieve appropriate fresh properties of the UHPFRC were identified. The mortar with **W/B** of 21% achieved 200 MPa at 28 days, so it can be designed as the maximum **W/B** for the UHPFRC.
- The reactive powder **P1** was the most effective alternative cementitious material for the UHPFRC cured under ambient temperatures. The recommendable cement-replacement ratio of the powder was 15% approximately for considering the fresh and hardened properties. Additionally, the non-reactive powder **P4** was useful for substituting fine aggregates in maintaining the adequate fluidity and compressive strength of the UHPFRC.
- The maximum volume of fine aggregate in the UHPFRC that permitted proper dispersion of steel fibres was determined to be 600 kg/m^3. Mortars made with materials with at least 70% passing the 100 μm sieve were found to be preferable for achieving adequate flowability and steel fibre dispersion.
- To reduce the risk of segregation of steel fibres, an allowable flowability for the UHPFRC was determined to be a 290 mm flow. UHPFRC incorporating steel fibres at a 1.5 vol% achieved a 290 mm flow and a flexural strength of approximately 25 MPa.

The present paper reported the fundamental properties of the UHPFRC based on the development process of the material. The UHPFRC manufacturable under ambient temperature may be suitable for various structures constructed by cast-in-place concrete, which require the ultra-high strength and durability.

For improving the material properties of the UHPFRC, the decrease in binders should be investigated to reduce the material cost and environmental impact. In addition, it must give useful information to examine the effect of fibre direction on the structural performance for the practical design.

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