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A comparison of the fluidity of spherical cement with that of broad cement and a study of the properties of fresh concrete using spherical cement

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Abstract

The fluidity of spherical cement mortar can more easily be increased without strictly controlling the size distribution and volume of the aggregate than that of broad particle size distribution cement, which is being developed for high-fluidity concrete by other researchers. Consequently, spherical cement is more practical for actual use. The changes of slump value and slump flow with the passage of time after mixing, the rate of bleeding, and the setting time of spherical cement concrete were different from those of normal portland cement concrete. These differences were due to the differences between the two kinds of cement in the activity of initial hydration and the amounts of water and water-reducing agent in their concrete. The adiabatic temperature rise of spherical cement concrete was about 6°C less than that of normal portland cement concrete as a result of the decrease in amount of cement used for same strength appearance. Spherical cement is effective for low-heat concrete.

Keywords: Spherical cement; Blended cement; Particle size distribution; Workability; Adiabatic temperature rise

Spherical cement is a cement characterized by round particles. The fundamental properties, namely fluidity, strength, and durability, of spherical cement have been previously reported. And, the possibility of utilizing spherical cement to produce high-fluidity concrete, high-strength concrete, and high-durability concrete has also been clarified [1–5]. In particular, we have made clear the mechanism for creating the high fluidity of spherical cement by examining the differences between spherical cement and normal portland cement in particle shape, size distribution, chemical surface properties, zeta potential, adsorption amount of superplasticizer, and initial hydration [6]. The high fluidity of spherical cement comes from its round shape and particle size distribution. In particular, the particle size is distributed in a narrow range and the volume of fine particles under 3 μm is less than that in normal portland cement. Generally, it has been reported that the packing ratio of powder particles increases in proportion to the increase in the range of size distribution. Similarly, the fluidity of cement paste also increases with a wider size distribution [7]. Recently, high-fluidity cement has been developed by spreading the range of particle size distribution in cement through the addition of fine particles and larger particles to ordinary cement [8].

In this paper, the comparison of fluidity between spherical cement and broad cement is examined and discussed. Here, broad cement is the cement in which particle size is controlled in a wide distribution by adding fine and coarse particles to normal portland cement. In addition, in order to make spherical cement fit for practical use in high strength concrete that which displays a compressive strength of between 60 and 100 N/mm^2 in 28 curing days, the properties of fresh concrete were investigated. That is to say, slump, slump flow, bleeding rate, setting time, and adiabatic temperature rise were examined.

1. Experiment

1.1. Material

Spherical cement, commercial normal portland cement, and broad cement were used. Spherical cement was prepared by the same method used in the previous paper [5],

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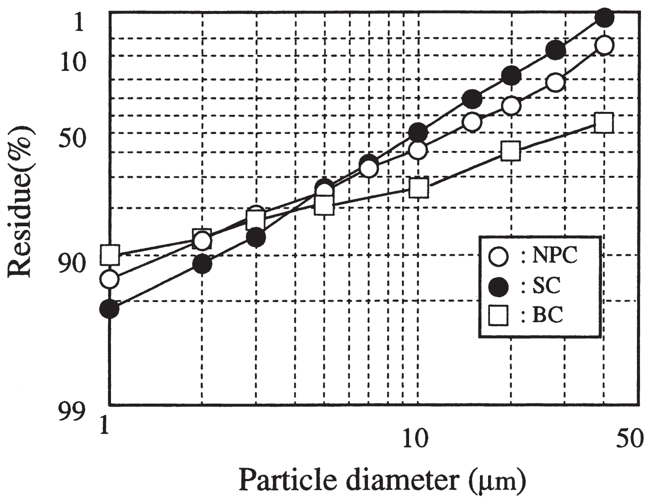

Fig. 1. Particle size distributions of cement.

Table 1
Powder properties and chemical compositions of cement

Properties	NPC	SC	BC
Degree of roundness (perfect sphere: 1)	0.67	0.87	0.67
Specific gravity	3.15	3.15	3.10
Specific surface area (cm^2/g)	3370	2700	2670
Apparent density tight packing (g/cm^3)	1.68	1.88	1.86

	Chemical composition							
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O
NPC	21.6	5.1	3.0	63.7	1.7	2.0	0.29	0.47
SC	21.1	5.0	2.9	64.4	1.4	1.9	0.22	0.42
BC	20.5	4.9	3.0	65.4	1.6	1.9	0.27	0.44

using normal portland cement as the raw material. Then, it was treated through a dry impact blending method [9]. The particle size of broad cement is controlled in a wide distribution as mentioned previously. Inorganic powder particles that are ordinarily used as additives in normal portland cement were used as fine particles and larger particles. Fig. 1 shows the particle size distributions of the three kinds of cement. Their powder properties and chemical compositions are shown in Table 1. In this paper, spherical cement is hereafter indicated as SC, normal portland cement is indicated as NPC, and broad cement is indicated as BC.

Toyoura standard sand and Ogasa land sand were used for mortar preparation. Ogasa land sand and Iwase crushed stone were used for the concrete preparation. Their properties are shown in Table 2. Naphthalene sulfonic acid-based superplasticizer (low slump-loss type) was used as a water-reducing agent. An air-entraining agent was also used as chemical admixture. The water used for mixing was tap water. To eliminate the influence of hydration on the fluidity and to examine only the influence of the particle size distribution, an organic solvent (kerosene) was also used for mixing.

1.2. Apparatus and technique

1.2.1. Estimation of fluidity

Flows of fresh cement mortar were measured by the procedure specified in JIS R 5201. The water/cement (w/c) ratio was 0.55 in the case in which Toyoura standard sand was used and the ratio was 0.51 in the case in which Ogasa land sand was used, while the cement/Toyoura standard sand mixture ratio was 0.5 and the cement/Ogasa land sand mixture ratio was 0.33. In the case of paste, the w/c ratio was 0.45, and a flow corn of ϕ5 cm × h.5 cm was used.

Table 3 presents the mix proportions of the fresh concrete. The slump value of the concrete was measured by the procedure specified in JIS A 1101. The breadth of concrete in a slump test was defined as slump flow. The rate of slump flow was determined by using Eq. (1) [10].

$$R_f = \frac{(SF-20)/2}{T_f} \qquad (1)$$

Here,

R_f = rate of slump flow (cm/second)

SF = slump flow (cm)

T_f = time till movement of slump flow stops (second)

The variation of the slump value with the passage of time after mixing was measured for 90 minutes.

1.2.2. Packing property

The packing property was determined from the apparent density measured using a 100-mL vessel in tight packing. The vessel was tapped 180 times. The cement/Ogasa sand mixture ratio was 0.33.

1.2.3. Bleeding

The rate of bleeding of fresh concrete was measured by the procedure specified in JIS A 1123.

1.2.4. Setting time

The setting time was measured using an automatic measurement apparatus (Marui Co. Ltd., Tokyo, Japan) after casting the concrete into a vessel of ϕ15 cm × h.15 cm with two layers.

1.2.5. Adiabatic temperature rise

The adiabatic temperature rise of a concrete specimen of volume of 55 L was measured through the use of an air-circulation type apparatus. The integral heat evolution of the cement paste mixed at a w/c ratio of 0.5 at 20°C was measured by a conduction calorimeter.

2. Results and discussions

2.1. Comparison of fluidity between spherical cement and broad cement

Fig. 2 shows the flow values of the paste and mortar of the three kinds of cement. In the case of paste mixed with

Table 2
Aggregate characteristics

	Test sample	Kind of aggregate	Maximum size (mm)	Specific gravity	Fineness modulus	Water absorption (%)	Solid volume (%)
Fine aggregate	Mortar	Toyoura standard sand	0.3	2.63	—	0.29	58.0
		Ogasa land sand	5.0	2.60	2.78	1.50	68.2
	Concrete	Ogasa land sand	5.0	2.60	2.78	1.50	68.2
Coarse aggregate	Concrete	Iwase crushed stone	20.0	2.65	6.70	0.70	58.9

water, the flow values of the SC and the BC were higher by about 60 and 40%, respectively, than that of the NPC. In paste mixture with organic solvent, in which the difference of hydration activity among the three kinds of cement is negligible, the flow values of the SC paste and, particularly, the BC paste were larger than that of the NPC paste. The apparent density of the SC and the BC were also higher than that of the NPC, as shown in Table 1. Therefore, the increases in the fluidity of the SC and the BC were due to the increases in their packing properties. It is believed that this remarkable effect was largely due to the increasing effect of broad particle size distribution on the fluidity of the BC paste mixed with organic solvent. However, in the case of the mortar, the flow value of the BC was smaller by about 10% than that of the NPC in combination with Toyoura standard sand. Furthermore, although in combination with Ogasa land sand, the BC mortar flow was as much as that of the NPC mortar; when mixed with organic solvent the flow value of the BC Ogasa mortar was smaller than that of the NPC. Therefore, it was concluded that the difference in the increases of fluidity between BC paste and BC mortar is not due to a difference in hydration activity. It is well known that the fluidity of cement paste, mortar, and concrete increase with the increase of the packing property based on the particle size distribution of cement or cement-aggregate mixtures [7]. Consequently, it is thought that the lack of increase in the fluidity of BC mortar mixture is because the packing ratio of BC and aggregate mixture did not increase. In fact, the apparent density of the BC and Ogasa land sand mixture was smaller by about 2% than that of the NPC and Ogasa land sand mixture (2.05 and 2.10, respectively). And by taking into account that the specific gravity of the BC was smaller by 1.6% than that of the NPC, the packing property of the BC and aggregate mixture was as much as that of the NPC and aggregate mixture. On the other hand, the flow value of the SC mortar was remarkably increased as compared with the NPC in any of the mixture conditions. Therefore, in the use of BC, the size distribution and volume of aggregate for mixing should be strictly controlled (e.g., by conducting a previous mixing test) to create high fluidity. In contrast, it is believed that the fluidity of mortar and concrete using SC can easily increase without strictly controlling the size distribution and volume of aggregate. Therefore, SC is more practical than BC.

2.2. Change of slump value and slump flow with passage of time after mixing

If the slump flow rates of two kinds of concrete are the same values, the workability based on the viscosity of these concrete is also regarded as equivalent [10]. We have reported that the unit weight of water in SC concrete can be reduced by 30% maximally and that the dosage of superplasticizer for SC concrete can be reduced by 60% maximally as compared with NPC concrete at the same level of good workability [11]. That is to say, it is possible to select the mix proportion with either as little water or superplasticizer as possible in planning mix proportion. In a previous study, we reported that limiting the slump flow rate of concrete to about 0.3–1.0 makes it possible to execute good

Table 3
Mix proportions of concrete

Mix number	Kind of cement	w/c (%)	s/a (%)	Unit weight (kg/m^3)				Admixture vs. C (%)*	Admixture vs. C (%)**	Slump (cm)	Slump flow (cm × cm)	Rate of slump flow (cm/second)	Air (%)	Strength (N/mm^2)***
				Water	Cement	Fine aggregate	Coarse aggregate							
1	NPC	35.0	43.2	175	500	715	957	1.5	0.006	21.5	37.0 × 34.0	1.11	4.0	75
2	NPC	29.0	45.8	145	500	793	957	2.6	0.006	21.0	37.0 × 37.0	0.18	2.7	95
3	SC	29.0	45.8	145	500	793	957	1.0	0.006	22.0	50.0 × 48.0	1.04	4.0	93
4	SC	25.0	47.3	125	500	845	957	1.5	0.006	22.0	46.0 × 44.0	0.34	3.2	106
5	NPC	30.0	45.4	150	500	780	957	2.4	0.005	22.0	49.0 × 46.0	0.23	3.6	90
6	SC	30.0	49.4	124	414	918	957	1.5	0.004	22.0	49.5 × 43.5	0.25	3.7	92

* Naphthalene sulfonic acid-based superplasticizer (water reducing agent).
** Air entraining agent.
*** Compressive strength in 28 curing days.

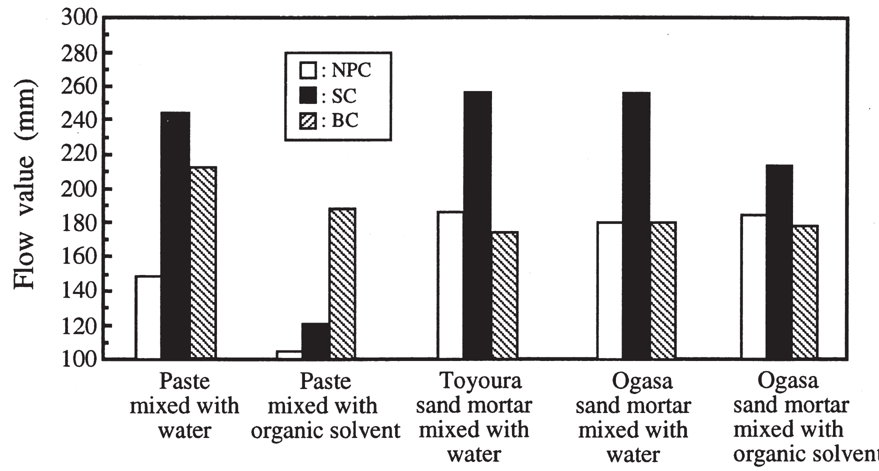

Fig. 2. Flow values of paste and mortar of three kinds of cement.

work using the concrete adequately [11]. The changes of slump value and slump flow of the SC and the NPC concrete with the passage of time after mixing were investigated. These two types of concrete reveal the same slump and slump flow rate, which is about 21 cm and 1 cm/sec, respectively, at the beginning. Fig. 3 shows the results. The changes of slump value and slump flow of the SC concrete were larger than those of the NPC concrete. It is believed that this was caused by the lower dosage (about 33% less than that in the NPC) of superplasticizer, which maintains fluidity and reduces slump loss, in SC. Therefore, in actual use, concrete mix proportion should not be determined in an effort to maximally reduce the dosage of superplasticizer. Rather, in order to depress the change of slump value and slump flow with the passage of time, it should be determined so as to adjust the proportion between water and superplasticizer for good workability. But, on the other hand, it is also thought that the properties of steep down in slump and slump flow of SC may be favorable because of the need to decrease pressure to forms after concrete casting.

2.3. Rate of bleeding

Fig. 4 shows the change of the rate of bleeding with the passage of time after mixing the SC and the NPC concrete, which reveals the same slump and slump flow rate at the beginning. Although the unit weight of water of the SC concrete was smaller than that of the NPC concrete, the rate of bleeding of the SC was higher than that of the NPC. In other words, although bleeding did not occur from the NPC concrete (w/c = 29%), bleeding occurred from the SC concrete (w/c = 25%). It is thought that this was because of the

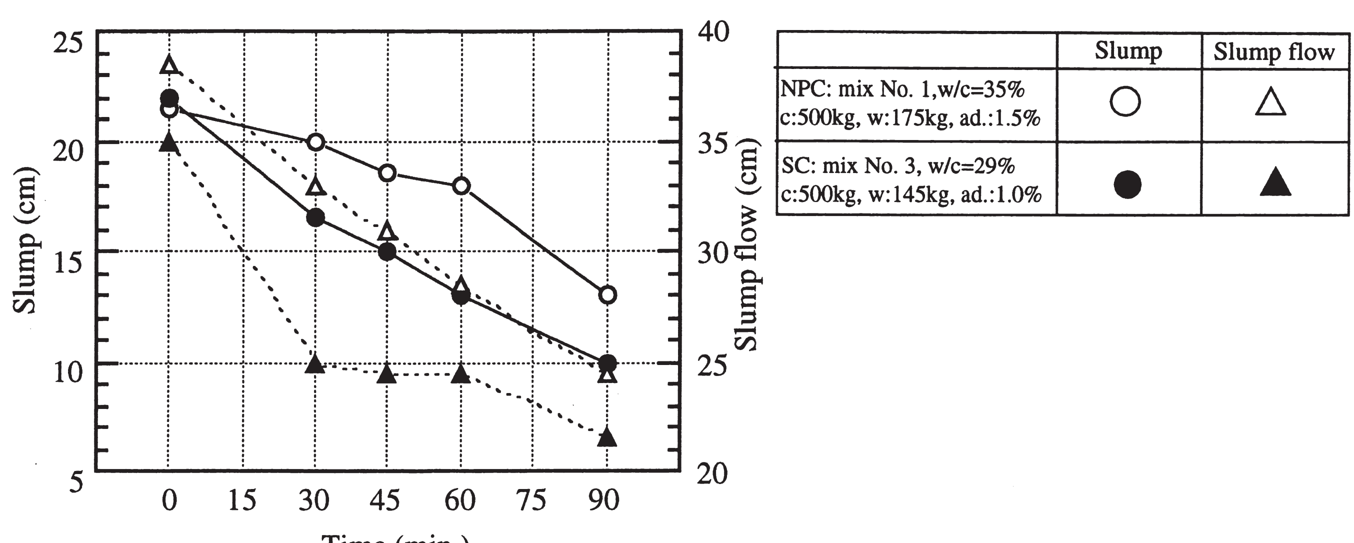

Fig. 3. Changes of slump value and slump flow with passage of time after mixing.

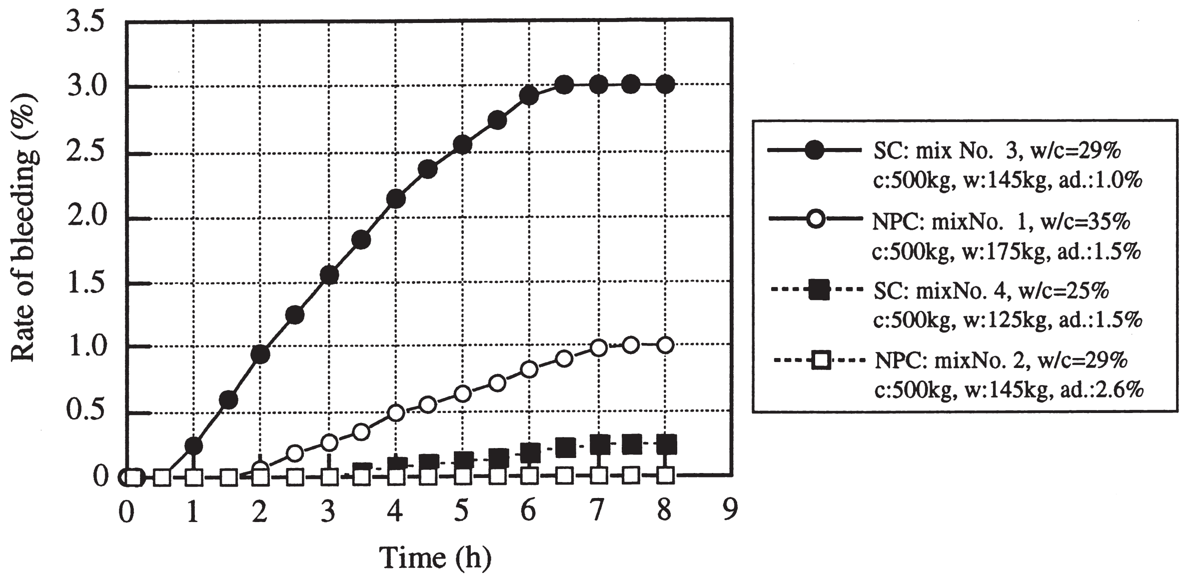

Fig. 4. Change of rate of bleeding with passage of time after mixing.

decrease of fine particles under 3 μm. Generally, it has been reported that bleeding does not occur in concrete of under w/c = 35% [12], and finish work of concrete surfaces is difficult in the case of such a low w/c. It is also thought that bleeding produced from SC concrete is effective for finish work.

2.4. Setting time

Fig. 5 shows the setting times of the SC and the NPC concrete, which reveal the same slump and slump flow rates at the beginning. The difference in setting time between the SC concrete and the NPC concrete was observed. In mix proportion with the same unit weight of water, in mix num-

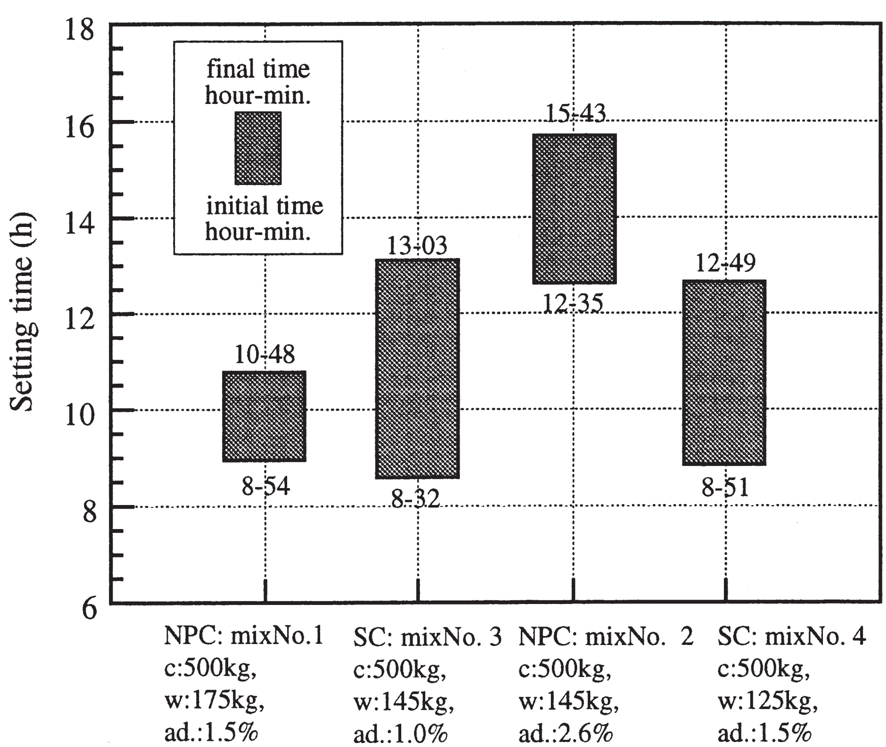

Fig. 5. Setting times of the SC and the NPC concrete.

bers 3 and 2, both the initial setting and the final setting of the SC concrete were faster than those of the NPC concrete. The dosage of superplasticizer in the SC concrete of mix number 3 was less by about 60% than that in the NPC concrete of mix number 2. Much superplasticizer causes a slower setting time [12]. Therefore, the fast setting time was because of the influence of less superplasticizer in the SC concrete. For the same reason, the setting time of the SC concrete of mix number 4 was faster than that of the NPC concrete of mix number 2. In the case of mix proportion numbers 1 and 3 that have the same workability, the initial settings were hardly different between the SC and the NPC concrete, while the final setting of the SC concrete was slower by about 2.5 hours than that of the NPC concrete. It was thought that the slow final setting time was due to the low initial hydration of SC [6]. In the case of mix proportion numbers 3 and 4, there was only a slight difference in the two kinds of SC concrete that contained different volumes of water and superplasticizer. On the other hand, it was observed that there was a large difference in setting time between NPC mix proportion numbers 1 and 2. In the case of a low w/c ratio, the dosage of superplasticizer must be increased more in NPC concrete than in SC concrete to provide good workability. Therefore, it is believed that a small dosage of superplasticizer creates the desirable property of allowing little difference between setting times of SC concrete regardless of the difference between their mix proportions.

2.5. Comparison of adiabatic temperature rise between SC and NPC concrete (effect of decrease in unit weight of cement in SC concrete)

The authors reported that the unit weight of cement in the SC concrete, which displays the compressive strength of about 90 N/mm^2 in 28 curing days, could be reduced by about 100 kg more than the NPC concrete, if it had the same strength and workability [11]. Fig. 6 shows the comparison of adiabatic temperature rise between the SC and the NPC concrete in a case where the unit weight of cement was different. The rate of temperature rise of the SC concrete initially was smaller than that of the NPC. In particular, the temperature rise for 1 or 2 curing days of the SC concrete was smaller by 23 or 11°C, respectively, than that of the NPC concrete. It was thought that this was due to both the effect of reduced cement and the low initial hydration in the SC. In other words, the height of the first and second peaks of the heat evolution rate curve of the SC paste were lower than those of the NPC, and the heat evolution amount of the SC for 72 hours was smaller by 25% than that of the NPC [6]. On the other hand, the difference in ultimate temperature rise between the SC and the NPC concrete was slight (about 6°C) in contrast with that in the initial curing for 1 or 2 days. To determine a reason, the integral heat evolution amount curve of cement paste for 7 days was examined.

Fig. 7 shows the integral heat evolution amount curves of the SC and NPC pastes. Although the difference of heat

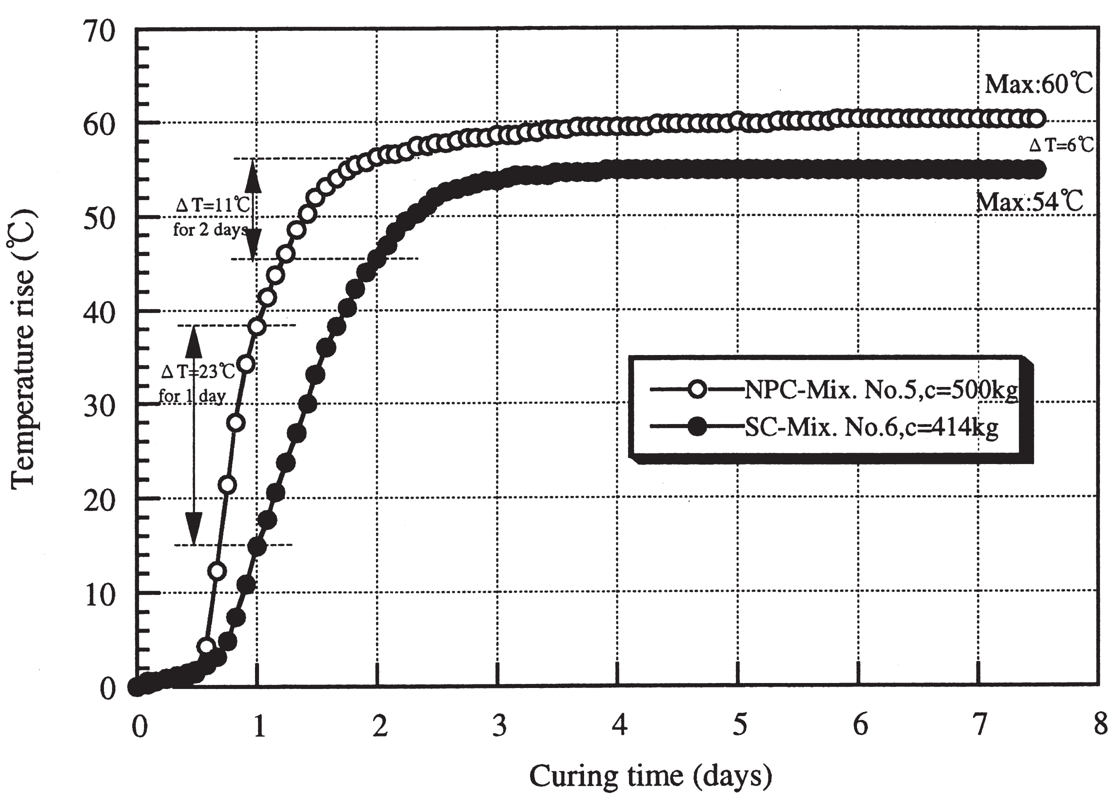

Fig. 6. Comparison of adiabatic temperature rise between the SC and the NPC concrete in a difference of unit weight of cement.

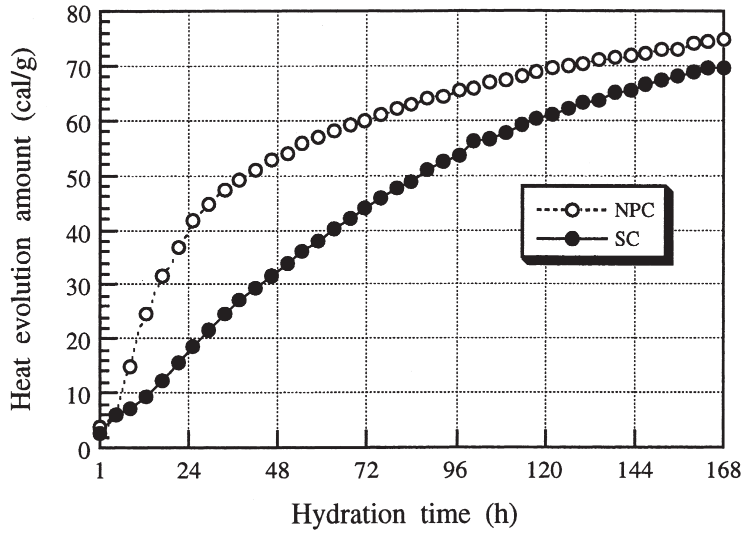

Fig. 7. Integral heat evolution amount curves of the SC and the NPC paste.

evolution amount for 3 curing days (72 hours) between the SC and NPC pastes was about 20–25% as previously reported [6], the difference for 7 days (168 hours) was smaller by about 5%. The reason for the difference in the initial curing period was the decrease of specific surface area in the SC. But, it was believed that once the hydration had started, the hydration of the SC would proceed more actively than that of the NPC. This is because SC particles are easy to contact the water because of the high dispersion in water (high fluidity [1,6]). Furthermore, the amount of the large particles over 40 μm, whose hydration dose not fully proceed on account of slow penetration of water to the cement particle core, was little as that in the SC [1]. From what is mentioned above, it is believed that the difference of heat evolution amount for 7 curing days was smaller than that for 3 days. Therefore, it was thought that the depression of the ultimate temperature rise of the SC concrete mainly resulted from the decrease in the amount of cement. Furthermore, it seemed reasonable to think that the SC is effective for low-heat concrete and massive concrete.

3. Conclusion

1. The fluidity of mortar using SC can easily be increased without strictly controlling the size distribution and volume of the aggregate. Therefore, it is believed that SC is more practical than BC for actual use.
2. The changes of slump value and slump flow of SC concrete with the passage of time after mixing were larger than those of NPC concrete. It is believed that this is caused by the decrease in the dosage of superplasticizer. Therefore, in actual use, concrete mix proportion should not be determined to maximally decrease the dosage of superplasticizer, but to adjust the proportion between water and superplasticizer to reveal good workability.
3. The rate of bleeding of SC concrete was larger than that of NPC concrete. This is due to the decrease of fine particles under 3 μm.
4. The difference in setting time between SC concrete and NPC concrete was observed. This is thought to be because of the differences in weight of water, dosage of superplasticizer, and activity of initial hydration between SC and NPC concrete.
5. The adiabatic temperature rise of the SC concrete was smaller by about 6°C than that of the NPC concrete because of the reduced amount of cement used for same strength appearance. SC is effective for low-heat concrete and massive concrete.

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