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Effect of porous ceramic coarse aggregate on strength development of high-strength fly ash concrete

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ABSTRACT

The present study aims at investigating the effect of porous ceramic coarse aggregate (PCCA) as an internal curing agent on the strength development of concrete with fly ash (FA). The cement used in this study was high early strength Portland cement and the concrete with a water to centitious material ratio of 0.30 was subjected to accelerated or sealed curing. 20% of cement in mass was replaced with FA, and 10% and 20% of coarse aggregate volume were replaced with PCCA. The results showed that the compressive strength of concrete subjected to accelerated curing with both FA and PCCA developed more than 60 N/mm^2 at the age of 1 day, which means that even the FA concrete with 20 % replacement ratio is entirely applicable to pretensioned prestressed concrete if the water to centitious material is 0.30. In addition, the PCCA contributed to developing the strength of concrete.

Keywords. fly ash, porous ceramic coarse aggregate, internal curing, accelerated curing, concrete strength

INTRODUCTION

Fly ash has been required to be utilized as a cementitious material in order to contribute to controlling environmental impact for creating a sustainable society. Fly ash is well known to produce a dense concrete and to contribute to developing the strength in the long term if sufficient wet curing is conducted. Recently, the applicability of fly ash to precast and prestressed concrete has been investigated to promote its utilization (Zachar et al.2011). Tawara investigated basic properties of concrete for pretensioned presstressed concrete containing fly ash. The study reported that fly ash was able to improve performance of concrete in terms of drying shrinkage, creep and permeability of chloride ion, and therefore fly ash could be applicable to pretensioned prestressed concrete (Tawara et al.2011). It also reported that concrete containing fly ash (hereafter, FA concrete) required lower water-to-centitious material ratio in order to apply to pretensioned prestressed concrete because the compressive strength of FA concrete is low at early age and the strength development of FA concrete subjected to high temperature at early age is not sufficient in the long term compared with that under normal temperature.

The porous ceramic aggregate, which is made of waste from porous ceramic roof tiles in the northern area of Chugoku district in western Japan, has been applied to concrete as one of internal curing agents because it has a comparatively high water absorption and a comparatively low crushing value. Suzuki et al. reported that the porous ceramic aggregate as an internal curing material was effective in reducing autogenous shrinkage and increasing compressive strength of ultra-high strength concrete (Suzuki et al. 2007, 2009). It was also reported that the porous ceramic coarse aggregate (hereafter, PCCA) was effective in improving performance of concrete made with Portland blast furnace cement type B (Sato et al. 2011).

The present study aims at investigating the effect of PCCA as an internal curing agent on strength development of FA concrete for pretensioned prestressed concrete members. For this reason, high-early-strength Portland cement is used and accelerated curing is conducted by raising the temperature of concrete specimens in early age.

EXPERIMENTS

Materials. The cement used in this study was high-early-strength Portland cement. Fly ash met the standard values of type II in JIS A 6201 (fly ash for concrete). Density, blaine specific surface area and chemical compositions are shown in Table 1. Table 2 lists the physical properties of aggregates used in this study. The minimum size of the PCCA was 5 mm and the maximum one was 15mm. The PCCA as the internal curing agent was used after 7-day immersion in water.

Table 1. Properties of cement and fly ash

	Density (g/cm^3)	Blaine specifc surface area (cm^2/g)	Chemical composition (%)								
			ig.loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O
High-early-stregth Portland cement (HC)	3.14	4490	1.28	20.15	4.8	2.71	65.32	1.15	3.08	0.16	0.4
Fly ash (FA)	2.23	3580	2.7	59.2	23.87	5.43	2.38	1.01	0.27	0.3	0.87

Table 2. Properties of aggregates

	Type	Notation	Density (SSD) (g/cm^3)	Warter absorption (%)
Fine aggregate	Quartz crushed sand	S	2.60	1.16
	Lime storne crushed sand	LS	2.65	1.22
Coarse aggregate	Quartz crushed stone	G	2.62	0.64
	Porous ceramic coarse aggregate	PCCA	2.26	8.92

Mixture proportions. Table 3 shows the mixture proportions of concretes prepared in this study together with their designations. Water to cementitious materials ratio (W/(C+F)) was 0.3 and unit water content was 165 kg/m^3 in all concrete. Replacement ratios of fly ash were 0% and 20% in mass and those of PCCA were 0%, 10% and 20% in volume, respectively.

As shown in Table 4, slump flow, air content and temperature of the fresh concretes were designed to be 600±100mm, less than 2.0% and 20.0±2.0°C, respectively. Super plasticizer and antifoaming agent were used so as to meet the design values.

Table 3. Mixture proportions

Designation	W/(C+F)	F/(C+F) (%)	PCCA replacement ratio (%)	Unit content (kg/m^3)						
				W	C	F	S	LS	G	PCCA
HC	0.3	0	0	165	550	0	469	319	88	0
HC-G10			10		550	0	469	319	800	77
HC-G20			20		550	0	469	319	711	153
HCFA20		20	0		440	110	447	304	888	0
HCFA20-G10			10		440	110	447	304	800	77
HCFA20-G20			20		440	110	447	304	711	153

Table 4. Properties of fresh concrete

	Slump flow (mm)	Air content (%)	Temperature (°C)
Designed value	600 ± 100	< 2.0	20.0 ± 2.0
HC	560	0.6	21.6
HC-G10	550	1.3	18.4
HC-G20	600	0.9	18.5
HCFA20	690	0.8	19.2
HCFA20-G10	710	0.7	19.5
HCFA20-G20	570	0.9	20.2

Curing conditions. Two curing conditions were set up in this experiment. One was accelerated curing in early age as shown in Figure 1. The temperature history adopted was the same as that of the general steam curing. Temperature of the atmosphere was raised up to 50 °C at a rate of 15 °C/hr. after a 3 hours' initial curing at 20 °C and 60% R.H.. After keeping the specimens at 50 °C for 6 hours, they were cooled down naturally to 20 °C. They were then remolded at the age of 1 day (24 hours) and stored at 20 °C and 60%R.H.. This temperature history without providing the steam was assumed to be that of the specimen where the steam could not penetrate from the upper surface. This curing condition is abbreviated as "Accelerated".

The other condition was sealed curing at 20 °C and 60% R.H.. The condition is represented as "Sealed". Some specimens in sealed curing condition were remolded at the age of 7 days and stored at 20 °C and 60% R.H. which is denoted by "Dried after 7 days". This curing condition is based on the prescription of JSCE 2007 that the wet curing period shall be longer than 7 days for blended cement concretes if average daily temperature is over 15 °C.

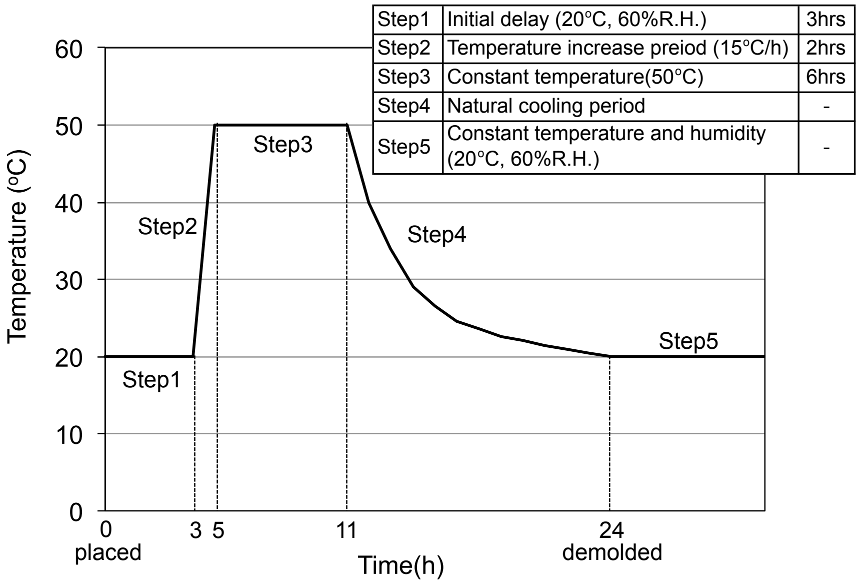


Figure 1. Temperature history of accelerated curing in early age

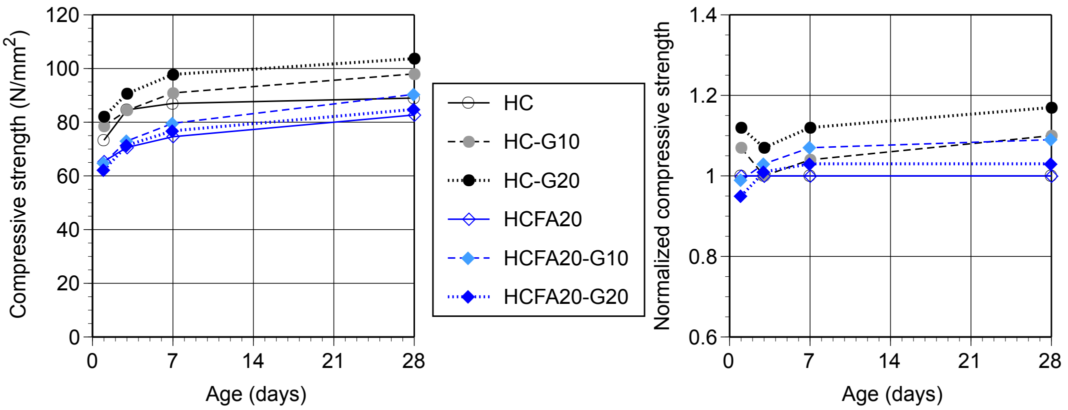
Testing procedure. Compressive strength test and Young's modulus test were carried out at the age of 1, 3, 7 and 28 days in accordance with JIS A 1108 and JIS A 1149, respectively. Specimens exposed to drying at the age of 7 days were tested only at the age of 28 days. Cylindrical specimen for compressive strength and Young's modulus tests had a diameter of 100mm and a height of 200mm. 3 specimens were tested in each condition. Length change was measured with contact strain gauge from the age of 1 day using 3 prism specimens with the dimension of 100 x 100 x 400 mm in each curing condition. Mass change was also measured at the same age when length change was measured.

RESULTS AND DISCUSSIONS

Effects of PCCA on compressive strength. Figure 2 and 3 show the effect of PCCA on compressive strength in the case of Accelerated and Sealed conditions, respectively. Compressive strength at the age of 1, 3, 7 and 28 days are shown in Figure 2 (a). "Normalized compressive strength" in Figure 2(b) means the compressive strength of FA concrete and concretes containing none of FA (hereafter, non-FA concrete), PCCA normalized by that of the companion concretes without PCCA.

As shown in Figure 2 (a), compressive strengths of all mixtures at the age of 1 day are higher than 60 N/mm^2. This result means that all the present concrete are applicable to pretensioned prestressed concrete in accordance with JSCE 2007 which provides that the compressive strength of concrete for pretensioned prestressed concrete shall meet 35 N/mm^2 when the prestressing is conducted.

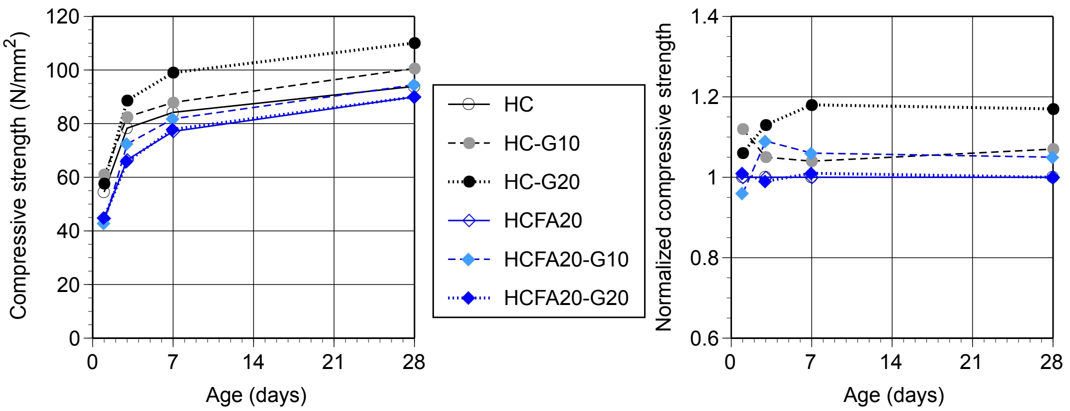
The effect of PCCA on compressive strengths of HC or HCFA20 is illustrated in Figure 2 (b). The normalized compressive strength of HC-G10 and HC-G20 are equal to or higher than that of HC and that of the latter is noticeably larger than that of the former at the each age. Furthermore, the normalized compressive strength of HC-G20 is over 10% higher than those of HC at the ages of 7 and 28 days. This result shows that the amount of internal curing water in the PCCA with 20% replacement ratio is better suited for the present non-FA concrete, the internal curing water would be supplied continually into pores of cement hydrates from PCCA, and the water supply efficiently helps the cement hydration. On the other hand, the effect of PCCA on the compressive strength of HCFA20 is observed and however, smaller than that of HC, and the PCCA of HCFA20-G10 is more effective than those in HCFA20-G20. The reason for this may be explained by the fact that as the W/C of FA concrete is higher than that of non-FA concrete, the replacement ratio of PCCA, which is higher than the natural crushed stone in terms of crushing value, is higher than necessary.



(a) Compressive strength

(b) Compressive strength normalized by that of HC or HCFA20)

Figure 2. Effect of internal curing on compressive strength of concretes (Accelerated)



(a) Compressive strength

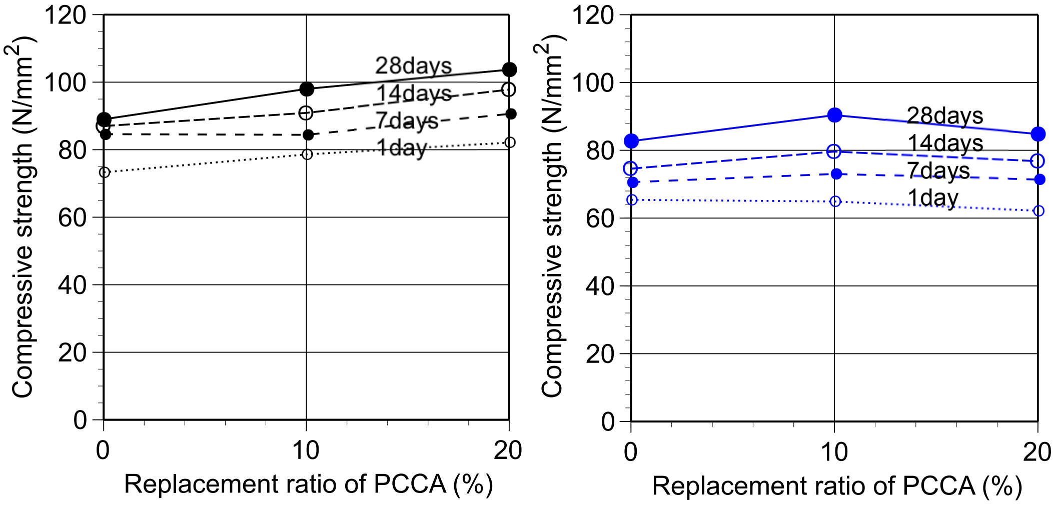
(b) Compressive strength normalized by that of HC or HCFA20)

Figure 3. Effect of internal curing on compressive strength of concretes (Sealed)

According to Figure 3, similarly to previous studies (Morimoto et al. 1995, Higginson, 1963), the compressive strengths of all the "Sealed" concretes under room temperature are lower than those of the "Accelerated" concretes at the age of 1 day, and however, the former increase more markedly and consequently become higher than the latter at the age of 28 days. The effects of PCCA in every mixture in the case of the "Sealed" except for HCFA20-G20 are roughly the same as that of the "Accelerated", while the former is not increased with age after the age of 7 days. The more effective replacement ratio of PCCA is also 20% for non-FA concrete and 10% for FA concrete like the case of "Accelerated", respectively.

The influence of the PCCA replacement ratio in Accelerated curing condition was shown in Figure 4. According to Figure 4(a), the larger the replacement ratio of PCCA is, the higher compressive strength at the each age is. This result indicates that within the age of 28 days, the internal curing water in PCCA with replacement ratio of 20% is consumed for cement hydration and the amount of the internal curing water is equal to or less than that necessary to sufficient hydration. On the other hand, as shown in Figure 4(b), the 10% replacement ratio is the most appropriate. As mentioned before, it may be due to the fact that 20% replacement ratio of PCCA, which is weaker than the natural crushed stone in terms of crushing strength, is higher than necessary replacement ratio.

The above results show that there exists the optimum replacement ratio of PCCA depending on the type of cementitious material.



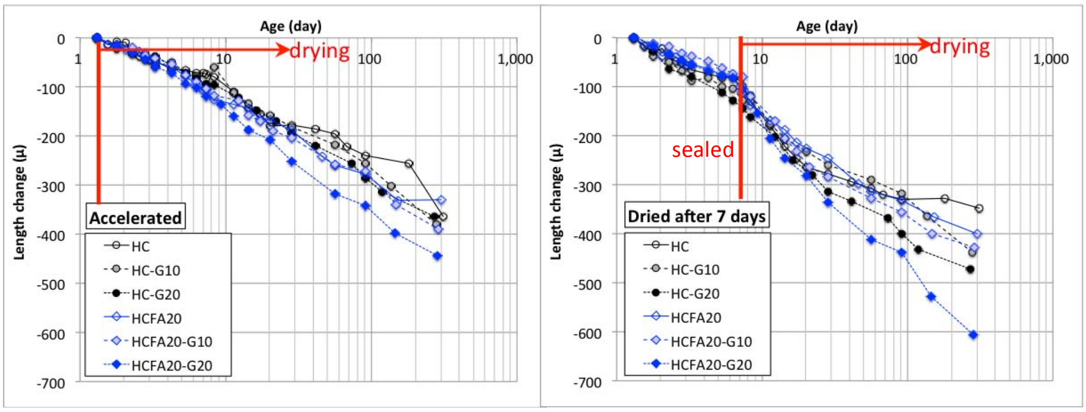
(a) HC with PCCA (b) HCFA20 with PCCA

Figure 4. Influence of PCCA replacement on internal curing effects (Accelerated)

Effects of PCCA on length change. The length changes from the age of 1day are shown in Figure 5. Figure 5 (a) and (b) show the length change under "Accelerated" and "Dried after 7 days", respectively. According to Figure 5(a), the effect of PCCA on the length change of concrete without fly ash is not observed, but the shrinkage of concrete with 20% PCCA replacement ratio is slightly larger than others in the case of FA concrete. On the other hand, as shown in Figure 5(b), in the condition of Dried after 7 days, the shrinkage tends to increase as the PCCA replacement ratio increases regardless of whether concrete contains fly ash or not.

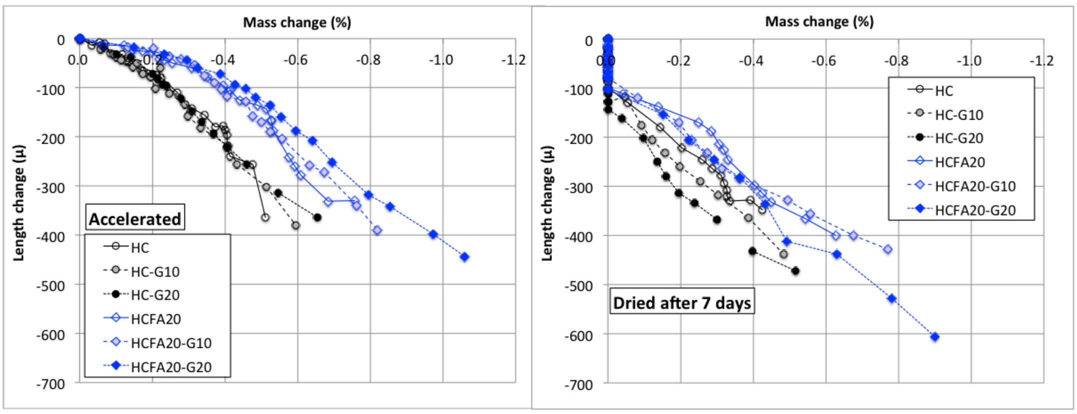
Figure 6 shows relationship between the length change and the mass change of concretes under the both curing conditions. According to Figure 6(a), non-FA concrete (HC, HC-G10 and HC-G20) shrink rapidly for the same mass change more than FA concrete (HCFA20, HCFA20-G10 and HCFA20-G20) until the length change of concrete reaches $-100x10^{-6}$. This result indicates that non-FA concrete has probably denser surface layer structure than FA concrete and the PCCA does not contribute to making the surface layer structure denser. This means that the large void in FA concrete is more numerous than that in non-FA concrete. However, exceeding the shrinkage of $-100x10^{-6}$, the shrinkage of each concrete progresses more rapidly, which may be due to the fact that the cohesive water in capillary pores began to evaporate in both concretes, while the size of capillary pores of FA concrete may increase depending on the increase of PCCA.

In case of Dried after 7 days, as shown in Figure 6(b), it is observed that the non-FA concrete shrinks more than the FA concrete in the same way as the case of "Accelerated". However, it is also observed that the shrinkage of concrete depending on mass loss becomes more effective in generating dense hydrates corresponding to increase of the PCCA for both concretes with and without FA.



(a) Accelerated (b) Dried after 7 days

Figure 5. Effect of PCCA on length change of concrete



(a) Accelerated (b) Dried after 7 days

Figure 6. Relationship between length change and mass change of concrete

CONCLUSIONS

The present study investigated the effect of porous ceramic coarse aggregate (PCCA) on the compressive strength and shrinkage of concrete with and without fly ash (FA). The concrete made with high-early cement was cured under high temperature at early age (Accelerated) and exposed to drying at the age of 7 days after sealed curing under room temperature. The following conclusions can be drawn within the limit of the study:

(1) 20% replacement ratio of PCCA as an internal curing material was suited better for non-FA concrete and 10% for FA concrete in terms of compressive strength independently of the curing condition.

(2) It was observed that when concrete made of high early strength cement is cured under high temperature similar to that of steam curing even though it contains 20% FA as a centitious material, W/B can be increased to meet the compressive strength of 35 N/mm2 at the age of 1 day required for pretensioned prestressed concrete, which is provided by JSCE.

(3) The effect of PCCA on the shrinkage of concrete without fly ash is not observed. However, in the case of concrete that with fly ash slightly increases in case with 20% PCCA replacement ratio. In the case of exposure to drying after the 7 days under room temperature, the shrinkage tends to increase as the PCCA replacement ratio increases regardless of whether concrete contains fly ash or nor.

(4) In the case of “Accelerated”, non-FA concretes shrink rapidly for the same mass change more than FA concrete until the length change of concrete reaches -100 x 10-6, probably because the large void in FA concrete is more numerous than that in non-FA concrete. However, thereafter, the shrinkage of each concrete progresses more rapidly, which may be due to the fact that the cohesive water in capillary pores began to evaporate in both concretes.

(5) In the case of “Dried after the age of 7 days”, the shrinkage of concrete depending on mass loss becomes large independent of the replacement of FA, probably because the PCCA becomes more effective in generating dense hydrates corresponding to increase of the PCCA for both concretes with and without FA.

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