ELSEVIER

Cement & Concrete Composites 22 (2000) 121–126

Cement & Concrete Composites

Expansive concrete cured in pressurized water at high temperature ☆

Ei-ichi Tazawa *, Kenji Kawai, Katsuichi Miyaguchi

Department of Civil Engineering, Hiroshima University, 401 Kagamiyama, 1 Chome, Higashi Hiroshima 739-8527, Japan

Abstract

Behaviours of expansive concretes cured in pressurized water at high temperature (TPC curing) are investigated with regard to their variations in strain, weight and strength. These behaviours are compared with those cured by autoclave curing (AC curing) at the same pressure and temperature. The experimental data show that both of these curing methods are effective in reducing autogenous shrinkage and drying shrinkage at longer age after the curing. Particularly when TPC curing is adopted, the required expansion of concrete can be attained at smaller dosage of expansive agents, and after the curing length changes due to hygrometric or hygroscopic conditions are almost eliminated for later age. Therefore, this curing method is anticipated to be effective in introducing chemical prestress in a reinforced concrete member, which is proved by loading tests of spirally reinforced pipe specimens [Ei.-i. Tazawa, K. Miyaguchi, in: Proceedings of the 25th JUCC Congress on Cement and Concrete, 1998, pp. 71–76].

Keywords: Autogenous shrinkage; Drying shrinkage; Expansive concrete; Autoclave curing; Pressurized water curing at high temperature; Expansion due to water absorption; Chemical prestress

1. Introduction

Generally, chemical shrinkage is generated during the setting and hardening process of Portland cement. Because of this shrinkage, a macroscopic volume reduction of concrete is observed after the setting at constant weight referred as autogenous shrinkage [1,2]. When concrete is subjected to drying, apparent reduction in length is measured as a sum of autogenous shrinkage and drying shrinkage. Therefore, concrete structures are vulnerable to self stresses or shrinkage crackings which might not only cause serious structural defects but also encroach durability of concrete. Expansive concrete is believed to improve these shortcomings of concrete to reduce shrinkage crackings or to increase cracking resistance of concrete members against external loads. When large expansive strain is restrained by steel or other reinforcements, compressive stress sufficient to resist tensile stresses due to external loads can be introduced as in the case of chemical prestressed concrete members. Since expansive agent is activated by hydration with water, it is expected that performances in expansion may be different for different curing conditions. In this regard, AC curing and TPC curing are experimentally compared to clarify effects of water phase and water transport during curing process on the behaviours of expansive concrete.

2. Outlines of experiments

2.1. Materials and mixture proportions

Normal portland cement (density 3.16) and three types of expansive agents, namely lime type A (density 3.14), ettringite types B (density 2.93) and C (density 3.04) are used for concrete. Expansive agent C is of newly developed type. Silica fume (density 2.20) is used as an admixture. Weathered granite type pit sand (density 2.56) is used for fine aggregate and rhyolitic crashed rock (density 2.67, max. size 20 mm) is used for coarse aggregate. Polycarbonic superplasticizer is used as a chemical admixture.

Dosage of expansive agents is so determined that free expansion after three days of normal curing or after TPC curing would become about 1000×10^{-6}. For AC curing the same dosage as that for TPC curing is adopted. Mixture proportions of concrete are shown in Table 1. Slump of concrete is 20 cm, and air content is 4%. Replacement ratio of silica fume is 10% by weight of cement.

☆ Paper presented at the Sheffield Infrastructure Conf., 1999, and reviewed according to Journal procedures.

* Corresponding author. Fax: +81-824-22-7194.

PII: S0958-9465(99)00038-4

Table 1
Mixture proportions of concrete

Curing conditions	Name	Unit content (kg/m^3)						
		W	C	E	SF	S	G	Ad
Normal	A70	173	390	70	43	684	948	6.3
	B80	173	381	80	42	684	948	6.3
	C40	173	417	40	46	684	948	6.3
AC and TPC	A20	173	435	20	48	684	948	6.3
	B50	173	408	50	45	684	948	6.3
	C20	173	435	20	48	684	948	6.3
	C15	173	445	15	50	684	948	6.3

2.2. Preparation of specimens and methods of experiments

Specimens for length change measurement are shown in Fig. 1. Specimen for restrained expansion measurement is prepared according to the prescriptions in JIS A 6202. Reinforcement ratio is 0.96% and gross extension of the bar is directly measured by attachments shown in Fig. 1.

Hollow pipe specimens are also prepared to check load carrying capacity of chemical prestressed members as shown in Fig. 2. This specimen simulates chemically prestressed Hume pipe which is commercially produced at present. In the specimen, aramid fiber reinforcement that has low modulus of elasticity is used as axial reinforcement in order to measure circumferential chemical prestress generated by spiral reinforcement.

Three curing methods are compared. As normal curing specimens are cured in water up to age 4 days at 20°C. After the curing the specimens are stored in water, sealed or dried at the same temperature 20°C. As accelerated curing two methods are used. One is AC curing and the other is TPC curing. In these methods, curing is started just after demolding at 24 h of age, by increasing temperature. Same autoclave apparatus as shown in Fig. 3 is used for both curing methods. Temperature and pressure is raised to pre-determined values (180°C, 10 atm., respectively) in 3 h at constant temperature raising speed, and then temperature is kept for 6 h before the heater is switched-off. The applied pressure is steadily reduced to normal pressure spending 7 h. Then the specimens are cooled naturally to room temperature. Natural cooling to 20°C takes 9 h. Therefore it takes 25 h in total for these accelerated curing methods. The temperature and pressure used for AC and TPC curing are the same, the only difference is that the specimens are immersed completely in liquid water in the case of TPC curing. After the accelerated curing the specimens are also stored in water, sealed or dried conditions at 20°C, and self stress variation and dimensional stability are investigated. Relative humidity during drying is 50 ± 5%.

Strain, weight and compressive strength are measured at ages, 1, 2, 4, 7, 14, 28 days (for accelerated curing, 1, 4, 28 days), bending strength of free and restrained specimens are measured at age 28 days.

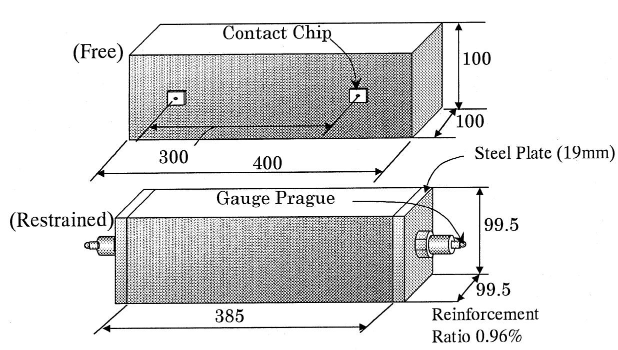

Fig. 1. Specimens for measuring strain.

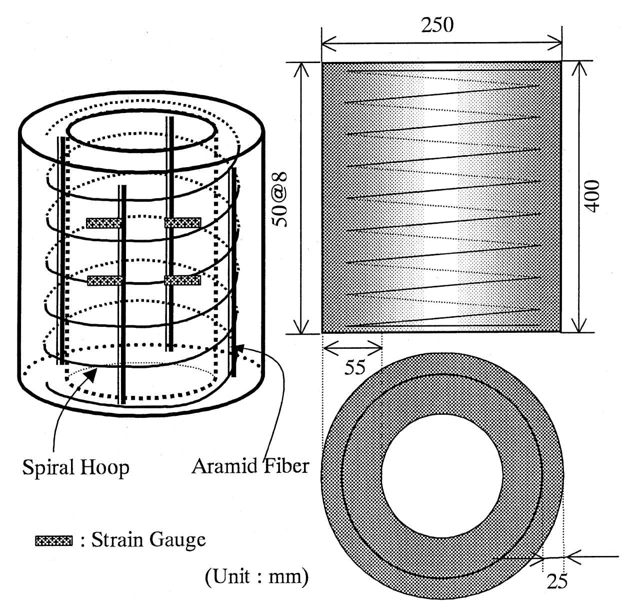

Fig. 2. Specimen for precast members.

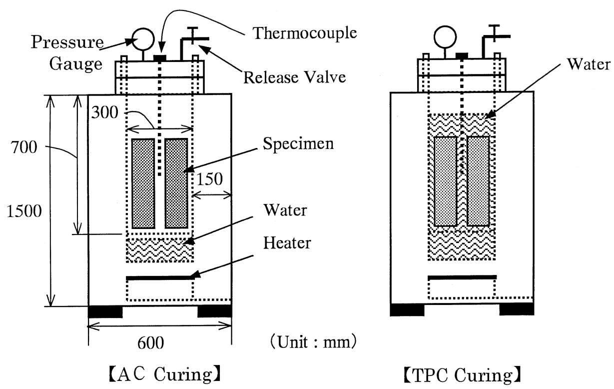

Fig. 3. AC curing and TPC curing.

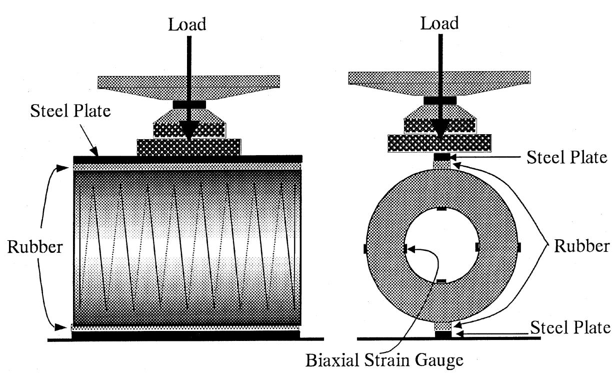

Fig. 4. Test for external pressure capacity.

Hollow pipe specimens are loaded in accordance with JIS A 5302 prescriptions, cracking load and failure load are determined by applying external line load at 28 days as shown in Fig. 4.

3. Experimental results and remarks

3.1. Dosage of expansive agents

Dosage of expansive agents required for obtaining free expansion close to 1000×10^{-6} (after 4 days of water curing for normal curing, and after accelerated curing) is shown in Table 2 for different types of agents and curing methods. For TPC curing it is observed that the required amount of expansive agents is about 1/2 of that required for normal curing. The reason is discussed later.

3.2. Variation of expansive strain after normal curing

Strain variation after normal curing up to 4 days is shown for expansive concrete prepared with W/C 0.35 in Fig. 5. Strain variations of restrained specimens stored in water, sealed and dried conditions after the curing are shown, respectively. For both dosages of expansive agents, shrinkage is observed for dried specimens from age 5 days and for immersed specimens from age 14 days. For sealed specimens behaviours are different for B 80 and C 40, but tendency similar to the above is recognized for B 80 showing 200×10^{-6} of shrinkage. This shrinkage may be either due to compressive creep caused by chemical prestress or autogenous shrinkage, or both. After the normal curing, effect of creep and autogenous shrinkage cannot be neglected for expansive concrete.

Table 2
Unit content of expansive agents and expansion

Curing condition	Items	Type of agents		
		A	B	C
Normal	Unit content (kg/m^3)	70	80	40
	Expansive strain (×10^6)	1196	1232	940
TPC	Unit content (kg/m^3)	20	50	20
	Expansive strain (×10^6)	932	858	1409

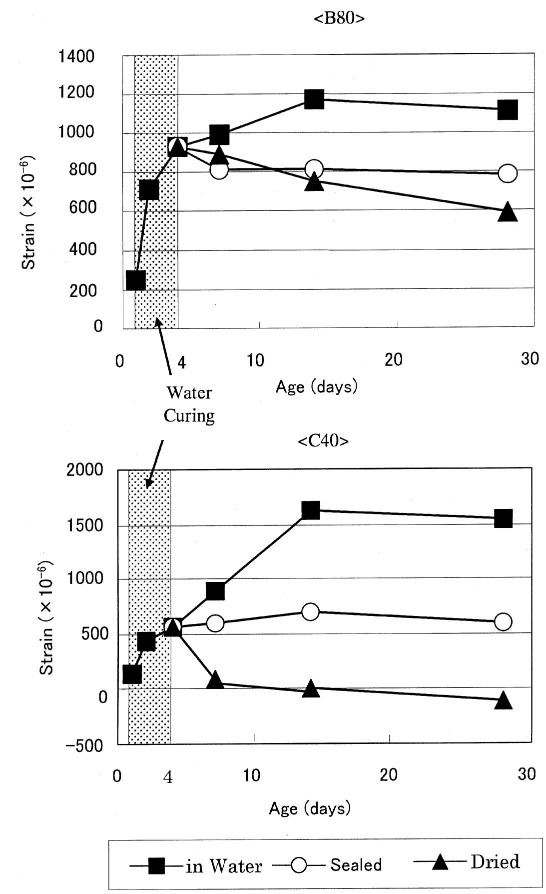

Fig. 5. Strain variation after normal curing.

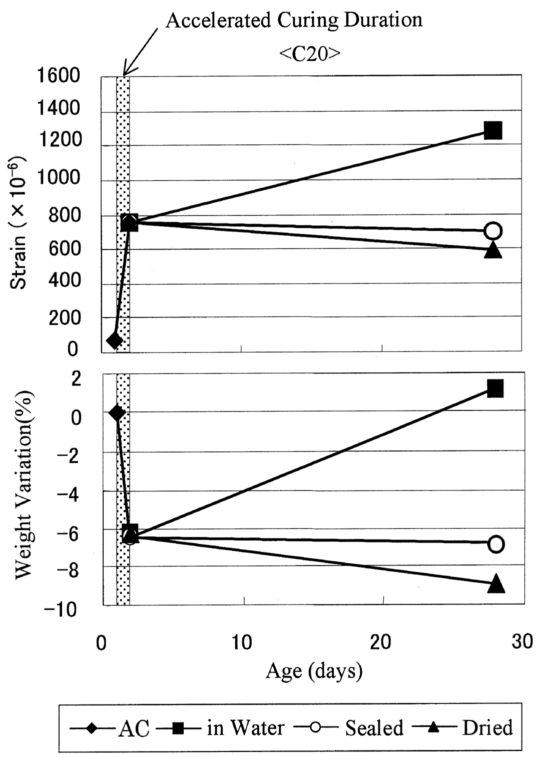

Fig. 6. Strain and weight variation after AC curing.

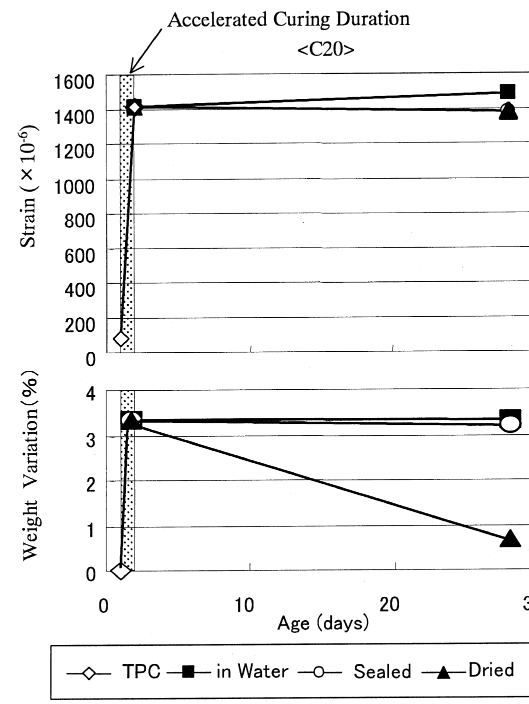

Fig. 7. Strain and weight variation after TPC curing.

3.3. Strain variation after two types of the accelerated curing

Strain variation and weight change of restrained specimen are compared for AC curing (Fig. 6) and for TPC curing (Fig. 7). The mixture proportion is the same (C 20) using the same amount of expansive agent. By comparing these data with the results shown in Fig. 5, it is clear that autogenous shrinkage and drying shrinkage after the accelerated curing are strikingly reduced for both AC curing and TPC curing. Particularly after the TPC curing length change due to hygrometric conditions is negligibly small and specimens do not show expansion nor water absorption when stored in water. For this specimen weight reduction is observed when dried, but drying shrinkage is not recognized. Resultant weight after long drying is heavier than the weight at demolding for this case. But for AC curing, expansion just after the accelerated curing is 1/2 of that observed for longer curing in water. For sealed and dried conditions shrinkage deformations are also observed for AC curing. The reason for these behaviors are considered as follows. In the case of TPC curing, space filling by hydration products takes place uniformly since pressurized water steadily permeates to the possible void space to be created, otherwise, by chemical shrinkage. In this manner the water filled space must have given the same filling possibility to the growing solids, that is, hydration products. But in the case of AC curing, considerable space in cement paste is occupied with water vapour, and this vapour occupied space is increased with progressive hydration due to chemical shrinkage. This gaseous space has given very little filling possibility to the growing new hydrates. This difference in space filling characteristics must have led to the big difference in uniformity of microstructures between the two curing methods. For AC curing it is clear that hydration process of expansive agent is not finished yet after the curing process. While for TPC curing it could be suggested that almost all the hydration of expansive agents is completed. This may explain the difference in expansion characteristics with regard to the effect of curing age.

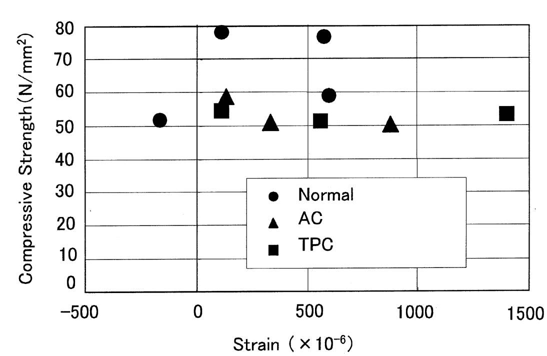

Fig. 8. Restrained expansive strain and compressive strength restrained by form.

3.4. Compressive strength

Compressive strength measured after mold-restrained curing is plotted against restrained expansion for different curing conditions. Restrained expansion in Fig. 8 is measured by the specimen shown in Fig. 1 and sample concrete for compressive strength is kept in steel mold without demolding until compressive loading. So the degree of restraint of concrete for the two sets of data is not exactly the same. For normal curing compressive strength of dried sample at 28 days and for accelerated curings compressive strength at 3 days are used, respectively. After the AC or TPC curing the strength of concrete is as high as that of normal cured concrete at 28 days. For TPC curing strength reduction due to large expansion is hardly observed.

3.5. Estimation of chemical prestress

Chemical prestress produced in prism specimens at 28 days is shown in Fig. 9. The chemical prestress was calculated from strain variation of restraining steel. From Fig. 9, it is clear that changes in chemical prestress observed for different agents and storage conditions after curing are very small for TPC curing. But for other curing methods particularly for normal curing, a large amount of relaxation of prestress is recognized in each case. This fact suggests shrinkage or creep is very small for TPC cured concrete compared to the other cases. Therefore TPC curing is ideal for introducing chemical prestress in reinforced concrete members. This is also supported by the data shown in Table 3.

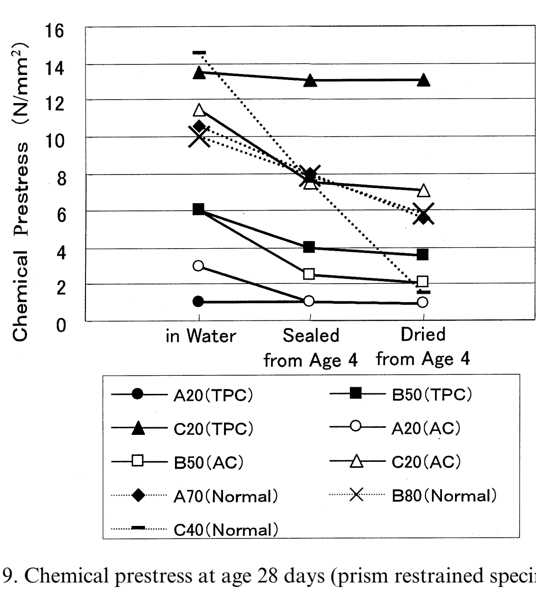

Fig. 9. Chemical prestress at age 28 days (prism restrained specimens).

Table 3
Estimation of chemical prestress (hollow slender specimens)

Type of specimen	Ratio of reinforcement (%)	Chemical prestress (N/mm^2)
C20 (TPC)	0.6	4.25×10^1
	1.2	7.61×10^1
C20 (AC)	0.6	3.14×10^1
	1.2	5.64×10^1
C40 (Water)	0.6	4.73×10^1
	1.2	8.37×10^1

3.6. Comparison of load carrying capacities

Results of external loading tests conducted at 28 days by a method shown in Fig. 4 are listed in Table 4. From Table 3 chemical prestress observed for TPC specimen is larger than that observed for AC specimen using the same amounts of expansive agent and reinforcement. Load carrying capacity of TPC specimen is superior to that of the AC specimen. This is proved by the fact that cracking load and failure load for the AC specimens are smaller than those for TPC specimens. This capacity is about the same with that of normal cured specimen for which twice amount of expansive agent is used.

3.7. Hydration model for TPC curing

Hydration model for AC and TPC curing is shown in Fig. 10. Internal voids in hydrating cement structure are filled with water vapour for AC curing, while in the case of TPC curing the voids are filled with liquid water. Since new hydrates are formed in a space occupied by liquid water phase, more uniform and dense microstructures are formed by TPC curing. In the case of AC curing a space occupied by pressurized water vapour during curing has very little possibility for cement hydrates to develop. Difference in weight variation before

Table 4
Cracking and failure load at age 28 days

Type of specimen	ratio of reinforcement (%)	Cracking load (kN)	Failure load (kN)
C15 (TPC)	0.6	67.6	100.0
	1.2	70.6	149.0
C20 (TPC)	0.6	58.8	105.8
	1.2	66.6	134.3
C20 (AC)	0.6	39.2	76.4
	1.2	58.8	103.7
C40 (Water)	0.6	63.7	76.4
	1.2	72.5	146.0

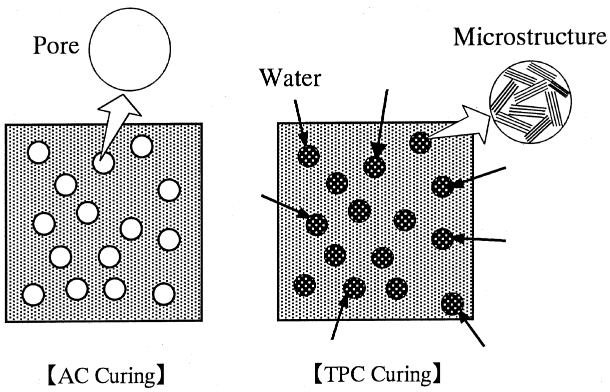

Fig. 10. Model of microstructure for AC curing and TPC curing.

and after curing will explain these situations. In the case of AC curing weight of specimen is reduced after curing because space created by chemical shrinkage is progressively occupied with pressurized vapour most of which flows back inevitably after the curing. While increased weight of sample after TPC curing suggests that permeation of water from outside into the microvoids might have occurred due to the applied pressure, and this permeated water does not flow back after the curing is finished.

4. Conclusions

Dosage of expansive agents to obtain a required amount of expansion by normal water curing can be reduced to 1/2 by TPC curing, and expansion for the same amount of agents is twice larger than that obtained by AC curing.

Once cured by TPC, expansive concrete does not show autogenous shrinkage nor drying shrinkage, and also does not show expansion due to complete hydration of expansive agent and owing to very little water absorption.

Expansive concrete suitable for chemical prestressed members can be manufactured by TPC curing, since the concrete shows high early compressive strength and large expansion sufficient to introduce high tensile stress in steel reinforcement.

References

[1] Ei Tazawa, K Miyaguchi, Properties of expansive concrete cured in high temperature and high pressure water (in Japanese). In: Proceedings of the 25th JUCC Congress on Cement and Concrete, 1998:71–6.

[2] Ei Tazawa, Autogenous Shrinkage of Concrete, E & FN SPON, 1999:393–6.