Optimization of the High-Strength Superplasticized Concrete of the 3-Gorge Dam in China

Y. Zhang, M. Collepardi, L. Coppola, W. Guan, P. Zaffaroni

Synopsis: A series of tests and analyses were conducted to optimize the mix-composition of the high-compressive strength (40-45 MPa) and erosion-resistant concrete for the 3-Gorge Dam construction. The main challenge was to choose the best binder content in this type of concrete which often, for its hydration heat, is characterized by severe shrinkage and susceptibility to cracking. In the end, a retarding superplasticizer, based on a carboxylated acrylic ester (CAE) copolymer, emerged as the best superplasticizers thanks to its high water-reduction and low slump lost. In-situ monitoring on the spillways of the 3-Gorge Dam has shown that, in addition to the high workability and better compatibility, the CAE-based superplasticizer in the C40 (40 MPa at 28 days) and C45 (45 MPa at 28 days) concretes can help to reduce the hydration heat induced a temperature rise of about 6 °C, vis-à-vis that of sulfonate naphthalene (SN) based superplasticizer. The practical significance of this improvement is to give the contractor additional means to limit the differential thermal strain below the concrete's permissible strain level, and then to allow the contractor to suppress thermal cracking by as much as 83 %. From the viewpoint of cost effectiveness, the use of the carboxylated polyacrylate superplasticizer can help the contractor to save significantly from temperature control and placing process during casting, without necessarily increasing the unit cost of the concrete.

Keywords: Heat of hydration, Mass concrete, Superplasticizer, Thermal strain

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INTRODUCTION

The "Final report on concrete proportioning tests" for the 2nd phase of the 3-Gorge Dam construction project [1] pointed out that further studies were necessary for improving the performances of erosion-resistant concrete. Relevant issues included also strength, durability, crack-prevention, air-entraining and erosion resistance.

In view of the severe working conditions (e.g. heavily grit-carrying and high velocity flow) of the water-discharging elements of the 3-Gorge Dam, past studies recommended rather high cement content for the erosion-resistant concrete. This led to the thorny challenges of volume stability, temperature control, and total alkali content. To meet these, the Construction Department of the China Three-Gorge Project Corporation (CTGPC) set a project, under which this series of tests and analyses were carried out.

This paper presents the project progress in 4 steps:

a) raw material performance in laboratory;
b) concrete performance in laboratory;
c) concrete performance at batching plant;
d) concrete performance in casting bays.

Before concluding, this paper will also briefly touch upon the cost effectiveness of a retarding superplasticizer based on a carboxylated acrylic ester (CAE) copolymer.

RAW MATERIAL PERFORMANCE IN LABORATORY

For this series of tests, as well as for much of the 2nd phase of the 3-Gorge Dam construction, a medium-heat potrlant cement of grade 525 (Jingmen Cement) was used. It was produced by Gezhouba Cement, and complied the industrial standard TGPS03-1998 (more stringent than the national standard GB 200-89 for the MgO & alkali contents).

The coarse aggregates used were crushed from coarse-grained granite excavated from the base of the 3-Gorge Dam. Their mineralogical compositions comprised feldspar, quartz, black mica, and some small amount of keraphyllite or chlorite. The dry compressive strength was about 128 MPa, while the water-saturated compressive strength was about 124 MPa.

The fine aggregates used were man-made sand crushed from a porphyritic granodiorite, having the fineness moduli controlled within the range of 2.6 ± 0.2. Their mineralogical compositions comprised quartz, anorthose, common mica and magnetite.

The fly ash used in the tests was of grade I (Pingwei) complying the industrial standard TGPS05-1998 (more stringent than the national standard GB 1596-91). The fly ash was characterised by its water reduction of more than 10 % and alkali content of less than 1.2 %.

Although the temperature of the 3-Gorge Dam site goes very rarely below the freezing point, air entraining was specified for many of the concrete types in order to ensure durability. The entraining agent was of a rosin-based product, DH9.

The initial focus of this project was to assess the market-available superplasticizers and to select the best suitable for the erosion-resistant concrete. One of the criteria was to have better performances than those products already approved and used in concreting the inner dam body, namely ZB-1A (liquid) and JG3 (powder), both based on sulfonated naphtalene polymers. Therefore, these naphthalene-based products were used as the benchmarks in the analyses.

A CAE-based superplasticizer, was examined as one of the ”third generation” superplasticizer, containing neither formaldehyde nor chloride. Thanks to its totally different water-reducing mechanism, i. e. relying on steric hindrance instead of electrostatic repulsion, this superplasticizer admixture has not only higher water reduction capability, but also very low slump loss [2]. These characteristics will be demonstrated throughout the rest of the paper.

The China Science Academy of Construction Materials conducted a comprehensive study on the combined performances of 10 retarding superplasticizers and 4 air entrainers [3]. Table 1, shows some results of this study and indicates that the CAE-based superplasticizer is better than the liquid of the sulfonated naphthalene (SN) superplasticizer in terms of high water reduction, lower bleeding, longer setting times, and lower shrinkage. However both the superplasticizers meet the requirements of GB 8076-1997 and TGPS 05-1998 Chinese standards. The amount of superplasticizers was adjusted each at its best dosage in terms of compressive strength. The best dosage was 0.7% for the SN superplasticizer (40% of polymer in the aqueous solution) and 1% for the CAE-based superplasticizer (30% of polymer in the aqueous solution).

The capability of delaying hydration process by the superplasticizers was also studies [3]. Figure 1 shows that both NS- and CAE-based superplasticizers can reduce the hydration-heat release within 24 hours; the CAE polymer effect is however more significant. After about 48 hours, the hydration-heat released by the specimen with the NS-superplasticizer already approaches that of the plain specimen without superplasticizer, while it took more than 72 hours for the specimen produced with CAE-polymer to reach the same level.

To cater for the 3-Gorge Dam requirements, 20 % of the medium-heat portland cement was substituted by the grade-I fly ash in some of the tests. The delay in the hydration-heat release in the presence of the superplasticizer was much more significant than that in the reference binder (= cement + fly ash) specimens. Figure 2 shows that it is 73 % lower in the SN specimens and 85 % lower in the CAE specimen at 12 hours; and it takes about 5 days for the SN specimens, and much longer than 7 day for the CAE one, to approach the heat level of the reference specimens. This agrees with the assumption that retarding effect of these superplasticizers is more remarkable on the portland cement-fly ash system than on the pure portland cement.

To minimise the risk of the detrimental alkali-silica reaction, the total alkali content in concrete for the 3-Gorge Dam was restricted to less than 2.5 kg/m^3. Therefore, the alkali content in the superplasticizers was also checked. Results show that the sodium oxide equivalent in SN and CAE is 6.36 % and 1.40 %, respectively.

To summarise these results, the CAE-superplasticizer has superior performance over the SN-admixture in nearly all aspects.

CONCRETE PERFORMANCE IN LABORATORY

All concrete tests were conducted in accordance with the industrial standard SD105: 82 [6]. The 3-Gorge Dam design allows dosage of grade-I fly ash to be not greater than 20 % and 10% respectively for compressive strength of 40 MPa at 28 days (C40) and 45 MPa at 28 days (C45). It also specifies the associated freezing and thawing resistance to be no worse than F150 (to successfully sustain at least 150 cycles of rapidly repeated freezing and thawing), and penetration resistance to be W10 (to successfully withstand progressively increased water pressure of no less than 11 bars). Table 2 shows some of those test results.

Comparing the water contents associated with different water-binder ratios (e.g. w/b = 0.35 for the mixes 1-2 and 2-2), the CAE concretes used 12, 13 or 15 kg less of water than the counterparts with SN. Hence, to achieve the same strength level, the CAE concretes respectively consumed 30, 37 and 50 kg less of binder. This implies lower hydration-heat release and fewer or narrower crack formation. Which in turn, especially for the mass concrete in dams, make it easier for the temperature control process in concrete production, transportation, placement, and curing.

Since the water and binder content were together reduced by 42 to 65 kg/m^3, the CAE concrete was denser, having higher aggregate content and 28-day compressive strength, and, more importantly for this particular type of concrete, having stronger erosion resistance, vis-à-vis that of the SN concrete.

In a nutshell, the CAE concretes produced in a small 150-litre drum mixer were able to further reduce water by 10.4 % (w/b = 0.40) to 12.3 % (w/b = 0.30) with respect to the SN concretes. This better performance in terms of water reduction is very important for concrete of a dam, especially for the erosion-resistant construction. The next section will show that even higher reduction of the mixing water can be realised in large-capacity batching facilities.

CONCRETE PERFORMANCE AT BATCHING PLANT

The actual construction tests were carried out on concrete mixtures produced by having 4 large batching drums of 6 m^3 capacity manufactured by Zhengzhou Hydro-Machinery. The real mixing time was only 150 seconds. It was observed that the mixing effectiveness of these super drums was much greater than that of the smaller one used in the laboratory tests: within each revolution, the CAE-based superplasticizer, together with the other concrete ingredients, absorbed many folds of shear energy with respect to the small drum. Hence, the CAE-based admixture could fully extend their long hair-like graft chains [7] and take full advantage of the steric-hindrance mechanism of water reduction and slump retention [7].

Based on the same mix proportions used for the laboratory tests, the first large batch of concrete came out with a slump of 150 mm (Table 3). Even with this high slump, the concrete samples satisfied all mechanical and durability requirements. After two more trials, the water content in C40 concrete was reduced to only 92 kg/m^3.

Being highly thixotropic in casting bays, the CAE concrete was found very easy to work and to compact with the required slopeness; so that workers reported to find some difficultiness in maintaining the spillway surface. For this reason, further optimisation was achieved by reducing the CAE dosage from 1 % to 0.8 %, DH9 from 3.0 $^{o}/_{ooo}$ to 1.0 $^{o}/_{ooo}$ for C40 and from 2.5 $^{o}/_{ooo}$ to 0.8 $^{o}/_{ooo}$ for C45, and limiting the slump at the batching plant to only about 30-50 mm.

The superiority of the CAE concrete with respect to that with the SN superplasticizer is supported by the result of the tests shown in Tables 4/A and 4/B, in which some test results of the batching plant samples are listed.

The drying shrinkage data from the batching plant samples are illustrated in Fig. 3. It shows that, at ages later than 3 days, the shrinkage of the concrete with the CAE-superplasticizer was consistently lower than that of the concrete with SN-based admixture by by 39 ~ 44 % for C40, and 14 ~ 24 % for C45.

CONCRETE PERFORMANCE IN CASTING BAY

After entering the actual construction stage, the CAE concrete was still found creeping on the rising and dropping slops of the spillways. In January 2001, further tests were carried out by the superplasticizer producer together with the project corporation (CTGPC), the contractor (Gezhouba Corp.) and the quality-control consultant (Yangtze River Commission), and finally came up with new mix proportions and slump control criterion [8]. The key points included reducing the CAE dosage to 0.6 % for the erosion-resistant C40 and C45 concretes and to 0.5 % for the spillway surface with very steep slopeness.

In the late summer of July-August, the temperature in casting bays was in a range of 25 ~ 35 °C, with a relative humidity range of 57 ~ 60%. Even under such environmental conditions, the concrete with the CAE-superplasticizer showed low loss in both slump and entrained air (Table 5) after having travelled through hundreds of metres on conveying belt and being sampled at the casting sites.

To monitor the core temperature in the dam concrete, as well as the temperature difference with respect to that of the environment, thermal-couples were embedded in C40 concretes with SN or CAE as superplasticizer. The record data plotted in Fig. 4 indicate that the core temperature of the concrete with CAE was consistently lower than that of the concrete with SN; differences of 5 ~ 7.2 °C between the two concretes were found during the first for 48 hours.

Subtracting the environmental temperature from that of the concretes core, we obtain the temperature difference between the cooler environment and the hotter core of concrete. By taking the thermal expansion coefficient to be 10×10^{-6} per °C [9], we calculated the differential thermal strains in the concretes (Fig. 5). It is observed that the CAE concrete intermittently went above the strain level of 100×10^{-6}, whereas the SN concrete continuously stayed above this value for more than 53 hours. Refer to the ultimate tensile strain values in Table 4, we should be able to appreciate the implication of the above strain level.

The reduction of 47 kg/m^3 binder in the concrete with the CAE-based superplasticizer with respect to that with the SN-based superplasticizer (Table 3) implies , at this point, no longer merely a lower material cost, but becomes a crucial mean in terms of prevention of thermal cracking.

When the naphthalene-based admixture was used for the deep-openings in the dam, the heat-increase was 46 °C and 50 °C respectively in C40 and C45 concretes, and many cracks were found afterwards. Started since October 2000, record shows that using the concrete with the CAE-based superplasticizer has reduced cracking by as much as 83% (Fig. 6).

From the viewpoint of cost effectiveness, it is worthwhile to make some economical assesments. The prices of binder and naphthalene-based superplasticizer are RMB ¥0.50/kg[*] and RMB¥8.20/kg respectively. The unit cost should then be RMB ¥221.88/m^3 for C40 concrete and RMB ¥232.44/m^3 for C45 concrete respectively (Table 3). Taking into consideration the binder saving and the 0.6% dosage of CAE, these unit costs would allow the CAE superplasticizer to be supplied competitively in a level of RMB ¥20.00/kg. In other words, even though CAE is produced in Italy, and has to bear high inter-continental transportation cost and input tax, the concrete produced with the CAE-based superplasticizer does not necessarily cost more than that of the naphthalene-based superplastcizers locally produced in China. Moreover, at least the following cost savings are for the contractors to appreciate:

a) According to the contract pricing, artificially cooling concrete down by 1 °C costs about RMB ¥2.20/m^3. Since the use of the CAE-based superplasticizer can reduce the concrete core temperature by an average of 6 °C, the total 350,000 m^3 of concrete with the CAE admixture already cast (by using SN-based admixtures) in the 3-Gorge Dam would have saved the construction cost by $2.20 \times 6 \times 350{,}000$ = RMB ¥ 4.62 Million.

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[*] 7,65 RMB¥ = 1€

b) Due to the good thixotropic property of the concrete with the CAE-based admixture, compaction in the casting bays has been reduced to one time only, and then there was no need of repeaing it as for the concretes with SN-based superplasticizers. The saving in both manpower and time was significant.

CONCLUSIONS

Through a series of tests and analyses, the CAE-based retarding superplasticizer, has been successfully used for the 3-Gorge Dam construction. The following conclusions can be drawn from the application:

(1) The CAE-based superplasticizer has high water-reduction capability and low alkali content, and is able to properly reduce the binders' hydration-heat release during the first 7 days. In comparison with many other superplasticizers based on sulfonated naphthalene, this admixture has the best overall performance. In particular, at given water-binder ratio and slump, the CAE-based admixture is able to reduce the amount of mixing water by 10.4 % to 12.3 %, with respect to SN-based superplasticizer.

(2) The high-strength concrete produced with the CAE-based superplasticizer, needs 47 kg and 40 kg less of binder for concrete with 40 MPa and 45 MPa compresive strength respectively with respect to the corresponding mixtures with the SN-based superplasticizer. This reduction produces a lower thermal peak of 6 °C, which can almost keep the differential thermal strain in the concrete below its permissible ultimate tensile strain of $100 \cdot 10^{-6}$. This is extremely important for the thermal-crack prevention for the dam structure.

(3) The concrete with the CAE-based superplasticizer has low slump loss and high thixotropy, and then it is easy to place and compact it in the casting bays. This reduces the time for the dam construction.

(4) Due to its high water-reduction capability, the concrete with the CAE-based superplasticizer contains less binder, and this improves many performances, such as compaction, lower shrinkage, higher strength, improved freeze/thaw behaviour and lower water-penetration; with less binder, the concrete has higher content of aggregates, and then stronger erosion resistance.

(5) The concrete with CAE-based superplasticizer is also very cost effective: without necessarily increasing the unit cost of the concrete, this superplasticizer can significantly reduce the cost temperature control and placing process during the construction.

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Table 1/A: Laboratory comparison of performances on fresh concretes

Superplasticizers	Dosage	Water	Reduction	Slump	Air	Bleeding	Setting time (min)	
	%	kg/m^3	%	cm	%	%	Initial	Final
Reference1	0	215	0	7.4	0.2	Reference1		
SN	0.7	173	19.5	7.2	1.7	61.8*	+562**	+480**
Reference 2	0	215	0	8.1	0.2	Reference 2		
CAE	1.0	161	25.1	8.0	0.65	30.1*	+574**	+617**
GB8076-1997: retarding superplasticizer [4]			≥ 12	—	< 4.5	≤ 100	> +90	—
TGPS05-1998: retarding superplasticizer [5]			≥ 18	—	≤ 3	≤ 100	> +360	—

*with respect to that of the corresponding refence mix.

**over the setting time of the corresponding reference mix.

Table 1/B laboratory comparison of performances on hardened concretes

Superplasticizer	Compressive Strength (MPa)			Strength (%)*			Shrinkage (%)*	
	3 d	7 d	28 d	3 d	7 d	28 d	28 d	90 d
NS	19	32.8	48.6	157	179	132	100	102
CAE	21.6	30.6	47.9	191	194	142	90	87
GB8076-1997: retarding superplasticizer [4]				≥ 125	≥ 125	≥ 120	≤ 135	—
TGPS05-1998: retarding superplasticizer [5]				≥ 125	≥ 125	≥ 120	≤ 125	—

* with respect to the corresponding reference mix.

Table 2 - Results of the laboratory concrete tests.

Mix	Water	Water/binder (w/b)	Sand content in aggregate	Fly Ash in the binder	DH9 Air Entraining	Superplasticizer Type & Dosage	Air Content	Slump	Compressive Strength at 28 days	Erosion Resistance
	kg/m^3		%	%	‱	%	%	cm	MPa	h/cm*
1-1	103	0.40	36	20	0.70	CAE @ 1.0	3.9	5.5	44.8	2.92
1-2	105	0.35	34	20	1.50	CAE@ 1.0	3.6	6.4	56.0	3.20
1-3	107	0.30	32	20	1.50	CAE @ 1.0	3.6	6.5	60.9	3.58
2-1	115	0.40	36	20	0.30	SN @ 0.9	3.5	6.0	43.0	2.67
2-2	118	0.35	34	20	0.38	SN @ 0.9	3.8	5.8	47.3	3.10
2-3	122	0.30	32	20	0.50	SN @ 0.9	3.6	6.4	60.4	3.50

*Erosion resistance, in h/cm, is the time (in h) to wear-out 1 cm of concrete according to SD105, 1982 standard [6]

Table 3 - The concrete proportions for the construction tests.

Test Code	Superplasticizer		DH9 Air Entraining	Water	Cement	Fly ash	Water/binder w/b	Sand	Aggregate 5/20	Aggregate 20/40
	Type	Dosage	$^o/_{ooo}$	kg/m^3	kg/m^3	kg/m^3		kg/m^3	kg/m^3	kg/m^3
C40	SN powder	0.6 %	0.5	121	323	81	0.30	655	568	694
	CAE	1 %	3.0	107	286	71	0.30	664	597	730
C45	SN powder	0.7%	0.45	125	375	42	0.30	635	571	698
	CAE	1 %	2.5	113	339	38	0.30	657	592	724

Table 4/A - Performance comparison of C40 concrete samples taken at the batching plant.

Super-plasticizer	Slump	Air	Erosion-Resistance Strength*	Loss of Mass (%) caused by No. of Freeze/Thaw Cycles					% of Original Modulus vs. No. of Freeze/Thaw Cycles				
	mm	%	h/(kg/m^2)	50	100	150	200	250	50	100	150	200	250
SN powder	36	2.6	1.48	0.32	0.62	0.95	1.24	1.51	92.3	93.7	93.1	91.5	89.3
CAE	65	3.0	1.52	0.13	0.17	0.18	0.25	0.33	92.3	92.6	95.2	94.8	93.2

* The erosion-resistance strength (h/kg/m^2) is the time in hour (h) to wear out 1 kg of concrete from 1 m^2 surface according to the SD 105, 1982 Standard [6].

Table 4/B – Strength and Strain performances on C40 concretes

Superplasticizer	Compressive Strength (MPa)			Split Tensile Strength (MPa)			Ultimate Tensile Strain (×10^{-6})	
	3 d	7 d	28 d	3 d	7 d	28 d	7 d	28 d
SN powder	28.1	39.0	51.3	2.07	2.28	3.00	93.4	102
CAE	35.1	43.2	56.7	2.31	2.47	3.97	93.2	110

Table 5 – Slump-loss and air-loss in the CAE concrete samples taken at the casting site.

Performance	Initial Value	Slump or Air			
		30 min	60 min	90 min	120 min
Slump (mm)	65	41	33	24	15
Air Content (%)	3.0	2.8	2.4	2.8	2.6

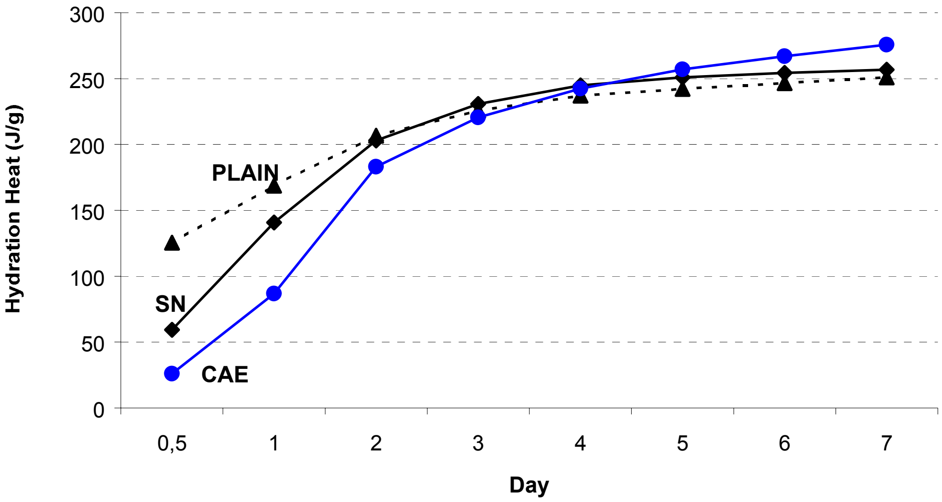

Fig. 1 - Hydration heat release from pure medium-heat portland cement specimens.

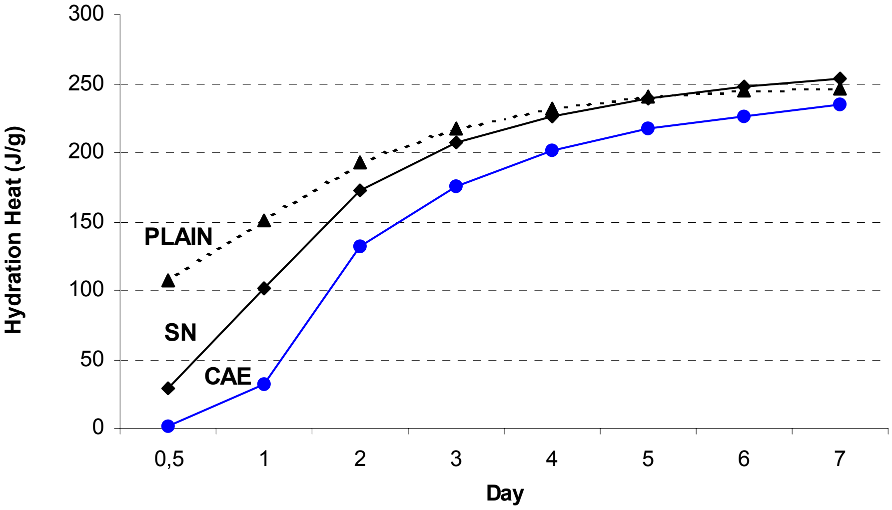

Fig. 2 - Hydration heat release from concretes with 20 % portland cement replaced by fly ash.

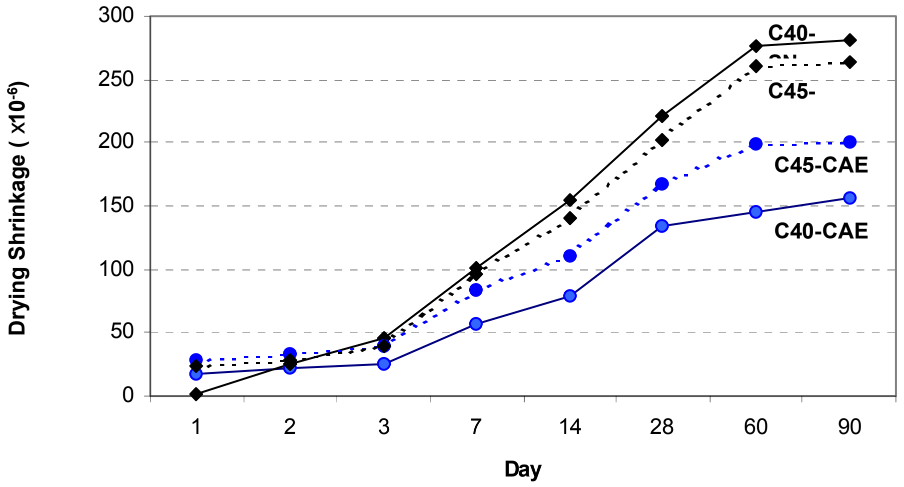

Fig. 3 - Drying shrinkage of specimens taken at the batching plant from concrete with different strength class (40 or 45 MPa) and different superplasticizer (SN vs. CAE).

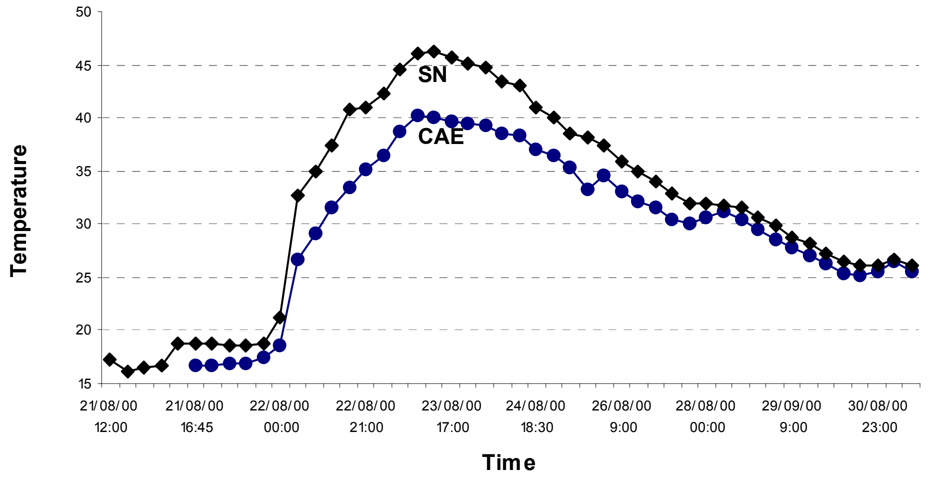

Fig. 4 - The core temperature as a function of time for concretes made with different admixtures (SN vs. CAE).

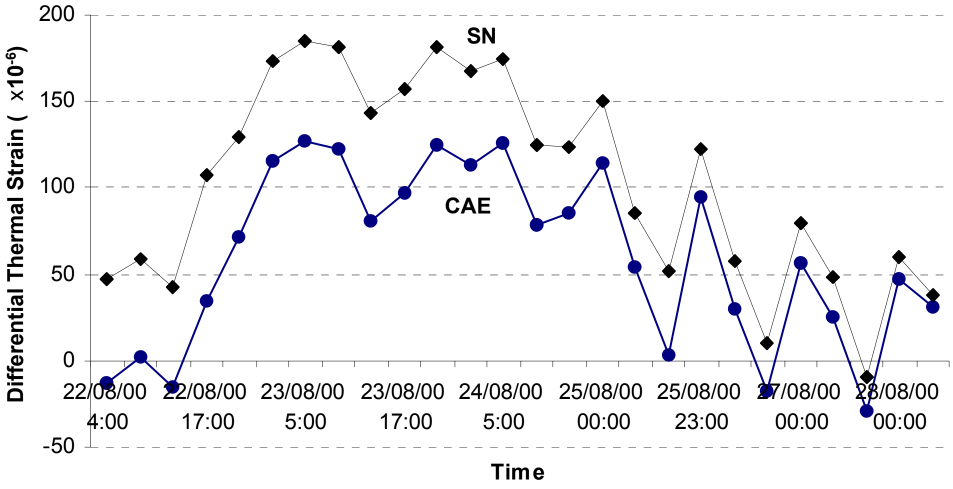

Fig. 5 - Differential thermal strain in concrete made with different admixtures.

Fig. 6 – Thermal-related cracking in the first placement with concrete combing the SN-based superplasticizer [10].