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Properties of Belite-Rich Portland Cement and Concrete in China

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Abstract: Performances of belite-rich Portland cement, or HBC (high belite cement), and the resultant concrete are introduced by comparing with that of alite based PC (Portland cement) and concrete. The comparison study of cement properties indicates that HBC possesses the properties of less water demand for normal consistency, better compatibility with water reducer, higher later age strength after 28-day under standard curing temperature of 20 °C, unique strength gain under elevated curing temperatures of 38~70 °C, lower hydration heat evolution and temperature rise, lower drying shrinkage and excellent resistance to sulphate attack. These results have been demonstrated by the comparison performance evaluation of concretes prepared by HBC and PC in terms of workability, physical mechanical properties and durability when making high performance high strength concrete and massive concrete.

Key words: Belite-rich Portland cement, Portland cement, performance comparison, lower hydration, better durability.

1. Introduction

As sustainability has become the global trend in this new century, cement, being the most commonly used fundamental building material, also faces great challenge in terms of large consumption in natural resources and energy and the emissions of greenhouse gases. This issue is of great importance especially for China due to the huge volume of cement production accounting for about 60% of the world cement production.

Great effort has been made in China to achieve high-efficient and environmental friendly cement production by restructuring the cement industry to replace the very small capacity backward vertical shaft kiln process with new dry process, by further enhanced use of clinker substitutes in Chinese cement with a low clinker factor as 0.58 in 2012 based on the statists of China Cement Association, by increased use of waste heat recovery for co-generation, and by consistently reducing the emission of SO_2, NO_x, and CO_2, etc..

Intensive research on belite (di-calcium silicate, C_2S) based cement has been conducted for decades worldwide [1-9]. The development of reactive belite based Portland cement in China since 1996 and its application in the world largest hydropower project, and the Three Gorges Dam project demonstrate that HBC (high belite cement) is not only a kind of low energy and low E (low emission) cement, but a better solution for high performance concrete making [10-14]. The revival of research on BCSA (belite based calcium sulfoaluminate) cement in the world is another example of exploring the low E clinker new binder towards cement and concrete sustainability issues [15]. This paper presents a review of the progress on the performance evaluation of HBC and the resultant concrete in China.

2. Cement Properties Evaluation

Belite-rich Portland cement (HBC) and two types of alite based Portland cement, i.e., normal PC

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(Portland cement) and MHC (moderate heat Portland cement), were used for comparison of performance evaluation of cements and the resultant concretes. All the tests unless specified were conducted on the basis of Chinese standards (GB175 and GB200). The basic characteristics of the three cements are shown in Table 1.

2.1 Water Demand and Compatibility with Water Reducers

Statistical results indicate that the water demand for normal consistency for HBC is 22.0%~25.0%, while that of PC is 24.0%~27.5%. Mortar flow test also gives higher flow of 130~140 mm for HBC compared with that of 120~130 mm for PC. These are proved by the increase of mortar flow rate and concrete slump for HBC under the same water cement ratio, especially when making high strength concrete at very low *w*/*b* (water/binder) ratio to be introduced below.

Behavior of the interaction between cement and water reducers is given in Table 2. Time-dependent flow properties of HBC and PC are also shown in Fig. 1.

As seen in Table 2 and Fig. 1, higher flowability is achieved by combination of HBC with different types of water reducers under that same *w*/*c* ratio and corresponding admixture dosage. Better compatibility has also been found in Fig. 1 by the combination of

Table 1 Typical characteristics of cement properties.

No.	Main minerals		SSA (m^2/kg)	Water demand (%)	Setting (h:min)		Mortar flow (mm)
	C_3S	C_2S			Initial	Final	
HBC	24.69	52.96	364	22.4	2:35	3:45	137
PC	52.36	24.49	367	27.4	2:05	3:05	131
MHC	52.14	22.24	295	25.3	2:48	4:32	135

SSA: specific surface area.

Table 2 Flowability of fresh paste with addition of water reducers.

Water reducers		CLS	NSP-1	NSP-2	NSP-3
Dosage (× cement%)		0.2	0.7	0.7	0.7
w/*c* ratio		0.35	0.29	0.29	0.29
Initial fresh paste flow (mm)	PC	174	172	178	108
	HBC	192	270	250	181

CLS: calcium lignosulfonate water reducer.

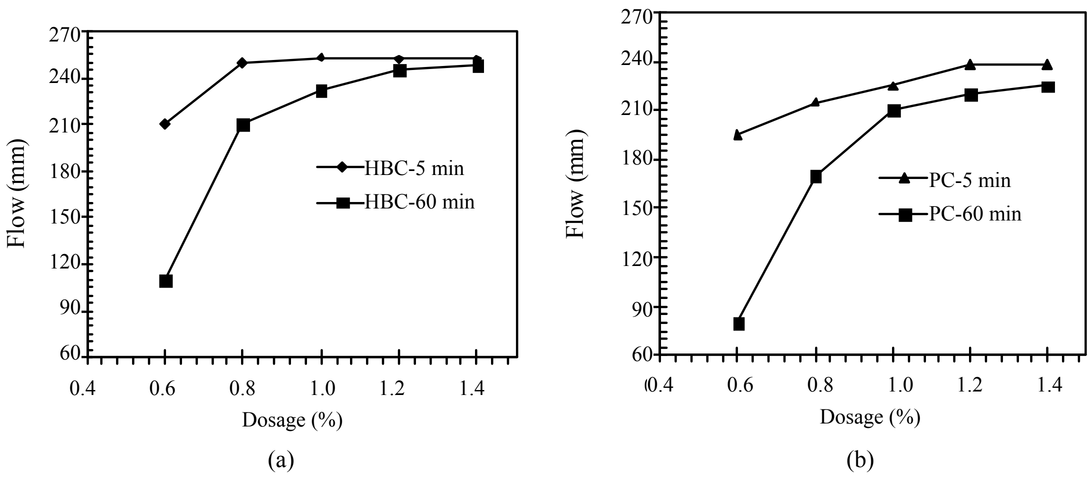


Fig. 1 Time-dependent flow of fresh pastes with different dosage of NSP for: (a) HBC; (b) PC.

HBC with NSP (naphthalene based superplasticizer). Not only the minimum dosage of NSP for achieving optimum flow for HBC pastes is lower, but also higher flow rate and flow retention time as well compared with PC pastes at related admixture dosage. The characteristics of HBC in lower water demand, higher flowability and better compatibility with reducers compared with PC can be attributed to the higher content of belite and lower content of C_3A in the clinker mineral compositions.

2.2 Mortar Strength Development

Mortar strength tests were conducted under standard curing temperature of 20 °C and elevated curing temperatures from 38 °C to 70 °C. Such comparison is worthwhile since concretes for most of the cases are subject to a temperature higher than standard curing temperature due to the heat liberation and accumulation during cement hydration. The sand/cement ratio is 2.4 and *w*/*c* ratio is 0.44.

2.2.1 Under Standard Curing Temperature

2.2.1.1 Cement without Fly Ash

Compressive strength development of HBC and PC under standard curing temperature (20 °C) is shown in Fig. 2.

It can be seen that though the early age strength of HBC (3-day and 7-day) is lower than that of PC and MHC, they have equivalent 28-day strength. The long-term strength of HBC after 3-month hydration age goes more than 10 MPa higher compared with those of PC and MHC.

2.2.1.2 Cement with Fly Ash

How HBC behaves with blending materials like slag and fly ash is often of a concern due to the lower amount of portlandite content resulting from the hydration of C_2S. The comparison test was thus carried out as shown in Fig. 3.

It can be seen that both the strength of HBC series and PC series prior to 90-day age are getting lower with the addition of fly ash. Remarkable reduction

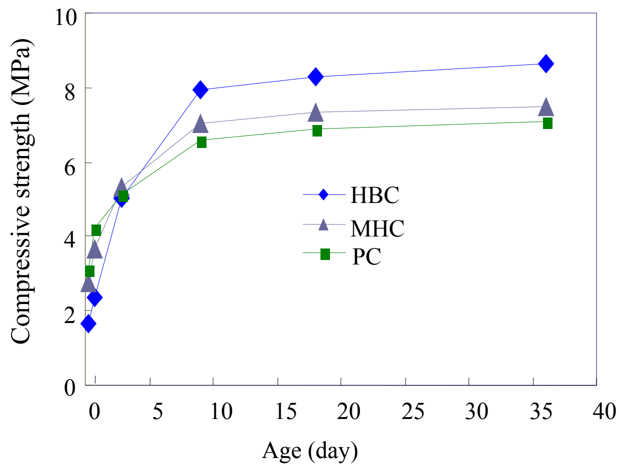


Fig. 2 Strength development of HBC, MHC and PC.

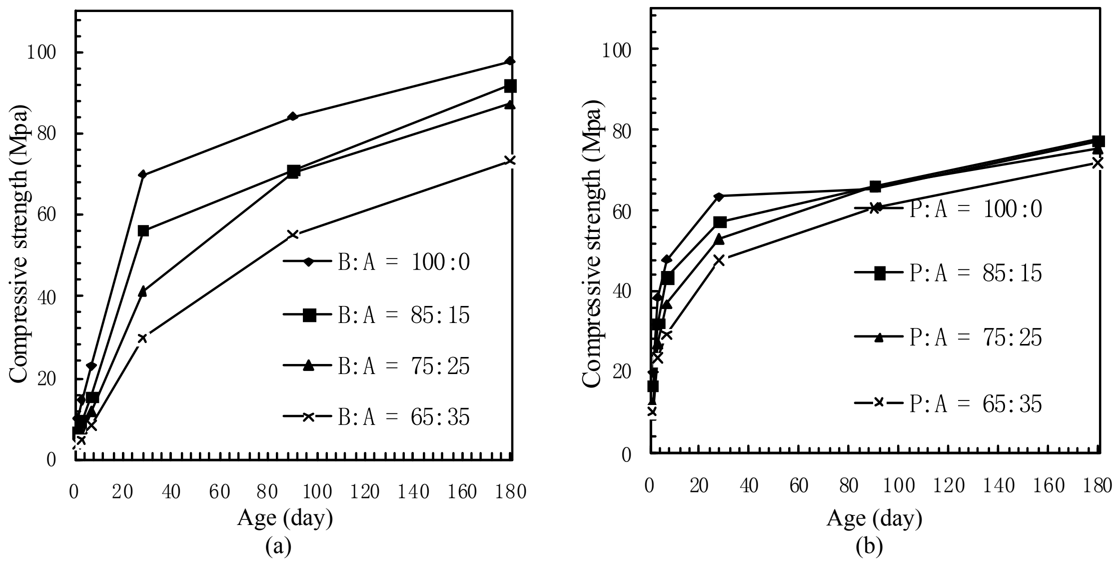


Fig. 3 Varying dosage of fly ash with: (a) HBC; (b) PC.

B:A = HBC:fly ash, P:A = PC:fly ash; water/(cement + fly ash) = 0.42; fly ash:Class I based on Chinese standard, SSA = 533 m^2/kg.

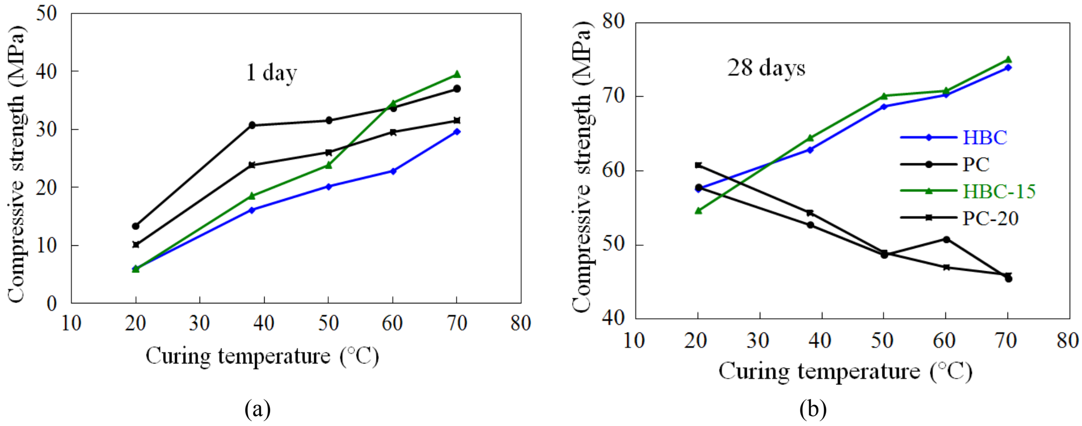


Fig. 4 Comparison of: (a) 1 day; and (b) 28 days under varying curing temperatures.

of the strength of both series is found when the addition of fly ash is 35%. A difference between HBC and PC series is that the strength of PC series with the addition of fly ash from 15% to 25% is equivalent to that of PC without fly ash at hydration age of 90-day and beyond, which can be attributed to the more content of portlandite given by the hydration of alite based PC series. It should be noticed that the 90- to 180-day strengths for HBC series are higher (except B:A (HBC:fly ash) = 65:35 at 90 days) than PC series at corresponding addition of fly ash though the decreasing rate of HBC series with addition of fly ash is higher than PC series, which means that HBC with the addition of fly ash also exerts the performance of higher later age strength.

2.2.2 Under Elevated Curing Temperature

Cement hydration is a process of exothermic reaction and can be self-accelerated by the heat evolved. Strength development of cement and concrete tested in lab is often different from that under actual working conditions due to the temperature rise inside concrete caused by the hydration heat accumulation. It is thus interesting to check the strength development of cement and concrete under elevated curing temperature.

Fig. 4 shows the comparison of HBC and PC under curing temperatures of 20, 38, 52 and 70 °C. HBC-15 and PC-20 represent HBC and PC inter-blended with 15% of slag (493 m^2/kg) and 20% of fly ash (Class I based on Chinese standard GB/T1596, SSA = 533 m^2/kg), respectively. The molding and curing of mortar samples were conducted in accordance with API (American Petroleum Institute) Spec.10A (Specification for Cements and Materials for Well Cementing).

In Fig. 4, it shows that, at 1-day age, both the strengths of HBC series (HBC and HBC-15) and PC series (PC and PC-20) increase with the increase of curing temperatures, while HBC series have higher rate of strength increase. It is interesting to mention that HBC-15 with 15% of inter-blended slag achieves a higher rate of strength increase than HBC with the increase of curing temperature. What is also worth mentioning is that it is possible to make the early age as 1-day strength of HBC equivalent to the level of PC when the curing temperature is high enough, more than 60 °C for example as indicated in Fig. 4.

The most different aspect for HBC and PC comes up later in 28-day strength development. The increase of curing temperature results in a continuous increase of the strength for HBC series, while PC series give exactly the opposite result. One main reason for the difference between alite-based and belite-based cements is that the excessively fast hydration of alite under higher curing temperature encapsulates the mineral particles and thus hinders the further hydration at following age [16]. The difference in micro-level structure of the cement pastes is also an important cause. This demonstrates the potential advantages of HBC over PC in the application of massive concrete, high temperature concreting in summer or tropical area, etc..

2.3 Heat Evolution Characteristics

It has been agreed that excess heat accumulation may be detrimental to the properties of cement and concrete because it may result in the occurrence of thermal stress and cracking and in the retrogression of later compressive strength. It is therefore very important for concrete, especially massive concrete, to control the temperature rise so as to improve long-term strength and volume stability and durability. Figs. 5a and 5b show the hydration liberation of PC and HBC with varying addition of fly ash and hydration heat evolution of the three cements, respectively. This was conducted via Chinese standards GB/T 12959 by measuring the heat of dissolution.

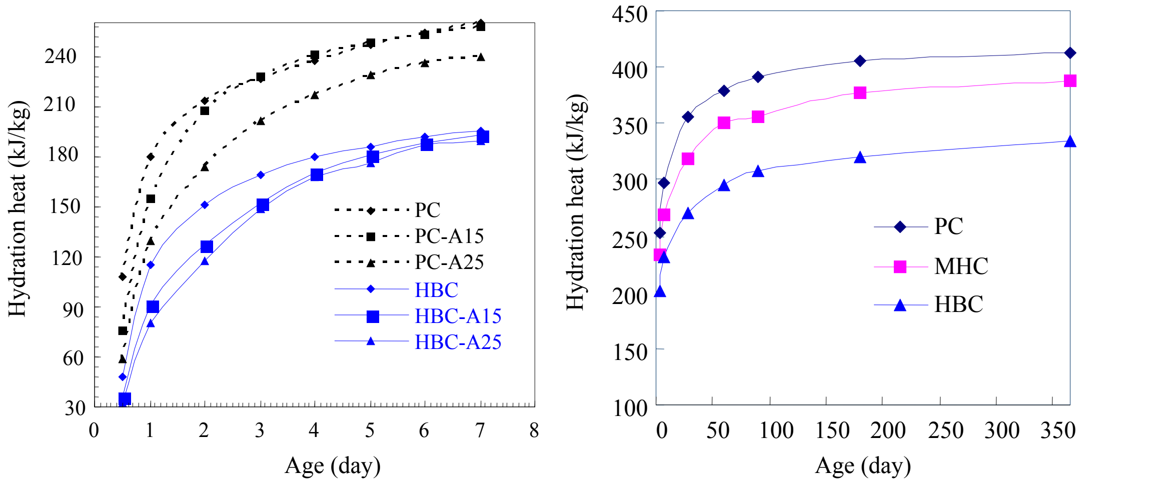
As shown in Fig. 5a, the hydration heat of PC series (PC, PC-A15 and PC-A25) is higher than that of HBC series respectively at corresponding age, and the hydration heat is getting lower with the addition of fly ash for both cements. It can also be seen from Fig. 5b that the hydration heat evolved for HBC at corresponding age decreases by more than 20% and 15% respectively compared with those for PC and MHC up to the age of 1 year. Concrete performance evaluation is in good agreement with the above-mentioned results. The adiabatic temperature rise of HBC massive concrete is 3-5 °C lower than that of the concrete for Three Gorges Dam, and the time of the appearance of peak temperature for HBC is also delayed [17].

2.4 Chemical Corrosion Resistance

Comparison on CRC (chemical corrosion resistance) of HBC and PC was conducted using the corrosive media of artificial sea water with 3 times of concentration of natural sea water (ion concentration in natural sea water used: $Cl^- = 1.93\%$, $SO_4^{2-} = 0.27\%$, $Na^+ = 1.08\%$, $Mg^{2+} = 0.13\%$, $K^+ = 0.04\%$, $Ca^{2+} = 0.04\%$, pH = 8.0), 3% of $NaSO_4$ and 5% of $MgCl_2$ solution. It can be seen from Table 3 that under 3-month age of corrosion, HBC exhibits better resistance to the corrosion of the three designated chemical solutions. In particular, excellent corrosion resistance to sodium sulfate for HBC is found mainly due to the lower content of C_3A in its clinker mineral compositions and less amount of portlandite produced during the hydration.

2.5 Drying Shrinkage

Less drying shrinkage is also found for HBC in comparison with PC. Table 4 shows that the drying



(a) (b)

Fig. 5 Hydration heat of: (a) PC and HBC with various addition of fly ash (cement/sand = 0.4, *w/c* = 0.28); (b) PC, MHC and HBC. PC-A15 = PC + 15% fly ash, so are others.

shrinkage of HBC up to 3~6 months only accounts for 50%~60% of PC at related age.

2.6 Comparison of Existing Standards for HBC

Based on the results of experimental research, industrial application and field application of the HBC, Chinese national standard was formulated in 2003. Table 5 shows technical parameters of the existing Chinese standard GB 200-2003. The 28-day compressive strength of HBC specified in Chinese standard is 20 MPa higher than that of the US and Japanese standards, which makes the HBC produced in China more reactive and much easier to be accepted by the downstream construction sector.

3. Concrete Performance

Performance of HBCC (HBC concrete) and PCC (PC concrete) was evaluated in two categories: high performance high strength concrete and massive concrete.

3.1 High Performance High Strength Concrete

HPC (high performance concrete) with strength grades of C30~C80 (equivalent to minimum requirement for 28-day compressive strength 30~80 MPa) was prepared and evaluated in terms of workability, physical mechanical properties and durability. The results for HBCC (C30~C50) as compared with PCC are very similar to the results of evaluation of cement properties. Here are only some special points acquired when making high strength HPC (C60~C80) by HBC and PC, as shown in Tables 6 and 7.

3.1.1 Workability

The results indicate that the initial slump and slump loss of HBCC behave equivalently to that of PCC

Table 3 Chemical corrosion resistance of HBC and PC.

No.	3-month, bending (MPa)/CRC coefficient (%)			
	Fresh water	3 × sea water	3% Na_2SO_4	5% $MgCl_2$
HBC	9.68/100	7.87/81	10.44/108	8.87/91
PC	9.08/100	6.67/74	5.09/56	7.21/79

Table 4 Drying shrinkage of HBC and PC (%).

Cement type	7 days	14 days	28 days	3 months	6 months
PC	0.060	0.083	0.103	0.115	0.096
HBC	0.030	0.042	0.057	0.058	0.057

Table 5 Strength parameters requirement for HBC in China, Japan and USA.

C_2S in clinker (%)		≥ 40		
Age		7 days	28 days	91 days
Compressive strength (≥ MPa)	GB 200	13.0	42.5	-
	JIS R 5210	7.5	22.5	42.5
	ASTM C150 Type IV	7.0	17.0	-

Table 6 Mix design and workability of high strength HPC with HBC and PC.

Item	Ce (kg/m^3)	A/(Ce + A)	Ce:FA:CA	NSP/Ce	Water/(Ce + A)	Slump (cm)	
						Initial	90 min
C60	414	0.2	1:1.67:2.54	1.0%	0.32	23.2	22.5
C70	440	0.2	1:1.53:2.44	1.4%	0.28	22.7	23.1
C80	510	0.15	1:1.13:2.10	1.6%	0.25	24.4	20.6
PC-C80	510	0.15	1:1.13:2.10	2.1%	0.26	18.5	16.3

Ce = cement, A = fly ash, FA = fine aggregate, CA = coarse aggregate.

Table 7 Mechanical properties of high strength HBCC and PCC (MPa).

Item	Compressive strength				Flexural strength			Splitting tensile strength		
	3 days	7 days	28 days	90 days	7 days	28 days	90 days	7 days	28 days	90 days
HBC-C60	35.2	54.6	77.6	98.5	4.0	7.2	8.9	3.81	5.37	7.44
HBC-C70	38.2	58.6	84.1	102.0	-	-	-	-	-	-
HBC-C80	52.1	68.3	95.4	116.4	4.5	8.4	10.3	4.76	6.72	8.25
PC-C60	43.7	60.3	78.5	90.2	5.2	6.7	8.2	4.45	5.16	6.36
PC-C70	52.1	69.0	86.2	94.5	-	-	-	-	-	-
PC-C80	69.0	72.5	91.0	107.5	6.2	7.9	9.1	5.28	5.94	7.35

under the water-binder ratio above 0.28. However, with the decrease of the water-binder ratio to 0.25 for making grade C80 concrete, HBC concrete still exhibits excellent fluidity while it is impossible to make flowable concrete with PC at *w*/*b* of 0.25. Therefore, more superplasticizer (2.1% of cement) and water/binder ratio (0.26) have to be used for PC-C80, which indicates that HBC is more advantageous in preparing high strength, high-performance flowing concrete at very low water/binder ratio. This is also a result of lower water demand for HBC compared with PC which is discussed in Section 2.1.

3.1.2 Strength

The strength development of HBCC and PCC is similar to that of HBC and PC mortars, as showed in Table 7. For all the mix design of HBC and OPC concretes in varying strength grade, the results of compressive strength indicate that the early strength of HBCC (3 days and 7 days) is lower than that of PCC, yet the gap is getting less to 19%~24% at 3 days and 6%~15% at 7 days for high strength concrete compared with the gap in mortar strength of 40%~45% at 3 days and 35%~40% at 7 days due to the less water demand and better compatibility of HBC with superplasticizers as proved in Section 2.1 mentioned above. Moreover, their strengths at 28 days are nearly equal, and 90-day strength of HBCC is about 6~10 MPa higher than that of PCC. The development trend of flexural strength and splitting tensile strength of HBC concrete with age is similar to that of compressive strength.

3.1.3 Durability

The results of durability of HBC concrete also show that high strength HBC concrete has equivalent or even better performance in terms of freeze-thaw resistance, permeability resistance, carbonation resistance and less shrinkage compared with PC concrete. The result was detailed elsewhere [14].

3.2 Massive Concrete

The advantage of HBC in lower hydration heat liberation and higher later age strength development enables HBC suitable for massive concrete whose temperature rise and hydration heat accumulation should be strictly controlled. The improved workability, mechanical properties, durability as well as cracking resistance of HBC massive concrete as compared with MHC massive concrete are detailed in publication [17]. Here are some results conducted on the jobsite of TGP (Three Gorges Dam Project). Both HBCC and MHCC were prepared in the same mixture proportion and up to 40% of fly ash (Class I, sieve residue of 45 μm sieve = 5.9*wt*%, *wt* means mass weight percentage) was used for concrete making.

Fig. 6 shows the on-site monitoring of the temperature rise of HBC massive concrete compared with MHC massive concrete which is used in TGP. Vibrating wire stress, strain and temperature gauge were used for monitoring the on-site massive concrete of the dam.

It is shown that the maximum temperature rise of HBCC is more than 5 °C lower than that of MHCC even at higher initial temperature. This is not only

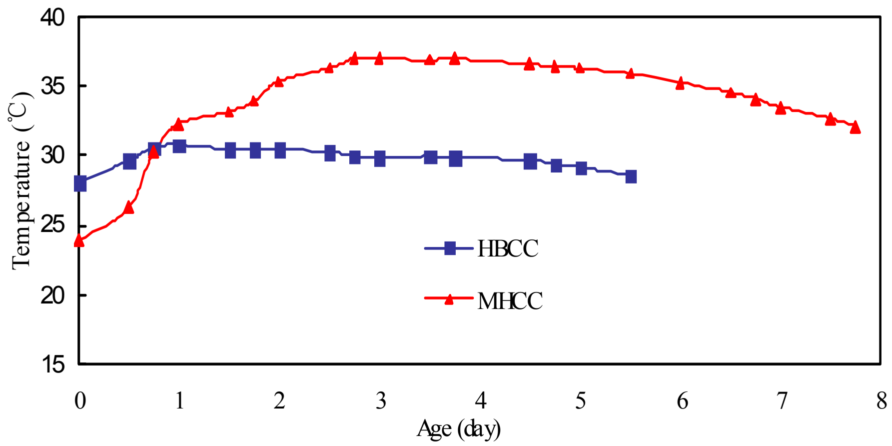


Fig. 6 On-site monitoring of maximum temperature rise of HBCC and MHCC, right bank of TGP, China.

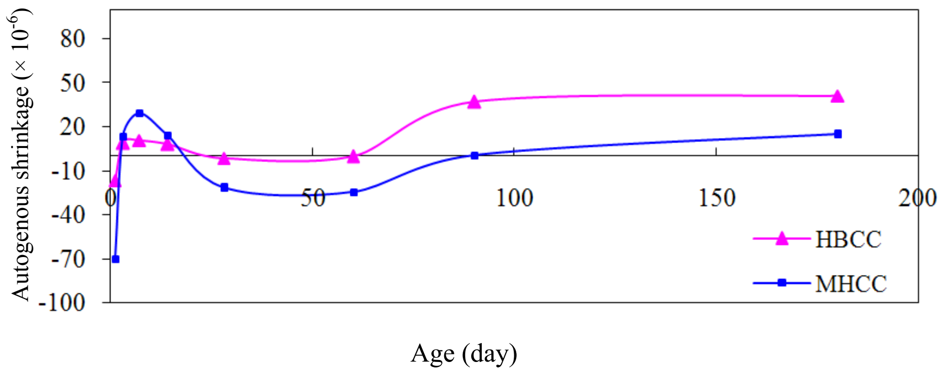


Fig. 7 On-site monitoring of autogenous shrinkage of HBCC and MHCC, right bank of TGP, China.

beneficial to the cracking resistance of the thermal stress of massive concrete, but to a big saving of direct investment for cooling the fresh concrete to 7 °C as well because the cost of MHCC for TGP is about 2.5~3USD per °C and per m^3.

Another example for HBCC performance better than MHCC is shown in Fig. 7. The expansive behavior of the autogenous deformation for HBCC means that it can better offset the shrinkage during the cooling process of the dam.

4. Conclusions

Based on laboratory study, industrial manufacturing and field application in TGP and a number of hydropower projects, HBC can be considered as a low energy and low emission cement for future solution to cement and concrete sustainability not only for energy efficient and environment friendly cement production but also for high performance concrete making as well, especially for massive concrete, high strength concrete, etc..

The outstanding characteristics of HBC as compared with PC lie in the lower hydration heat liberation and higher later age strength, and better suitability for higher temperature curing.

The advantage of lower heat generation also results in the disadvantage of HBC for its lower strength at early age prior to 7-day age, which can be tackled by finely grinding, use of superplasticizer, elevated temperature curing, etc..

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