

DEVELOPMENT AND RESEARCH OF HIGH BELITE CEMENT DAM CONCRETE WITH LOW HEAT AND HIGH CRACK RESISTANCE

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Abstract

The development and research of high belite cement (HBC) dam concrete with low heat and high crack resistance has been carried out on the basic of the state brainstorm project “HBC New Gelling Materials Research” during the “Ninth-Five.” Through the parallel tests comparing with the moderate heat cement (MHC) concrete used for Three Gorges Dam in the second stage, it is initially demonstrated that the HBC dam concrete has a good working performance, mechanical behavior and durability, and its adiabatic temperature rise is to be reduced by 3-5 degrees under same mixing proportion. The HBC dam concrete possesses good crack resistance ability, and it is a new dam concrete with low heat and high crack resistance that is expected to be popularized and applied for the mass concrete projects in water resource engineering.

The features for both low heat and high crack resistance are always the important and difficult points in dam concrete research, while the research and application in

new gelling materials have become the hotspot that the domestic and overseas cement-concrete materials science develops at present, thus it also becomes the important base for development and research of dam concrete with low heat and high crack resistance. It has successfully researched and developed one HBC mainly comprised by mineral composition of dicalcium silicate (C_2S) in the state “Ninth-Five” brainstorm project “Concrete Safety Research in Major Engineering,” which is launched by the China Institute of Building Materials Research, and participated in by both the Nanjing University of Chemical Technology and the China Institute of Water Resources and Hydropower Research. And the HBC has been listed into the state standards of low heat silicate cement, and put into production in batch mass. Cooperated with the China Institute of Building Materials Research and the China Yangtze River Three Gorges Construction Corporation General, the China Institute of Water Resources and Hydropower Research has undertaken the “Tenth-Five” brainstorm project from state science and technology department, namely the development and research of HBC low heat and high crack resistance dam concrete, and acquired a certain phase fruits.

1. Performance Analysis of High Belite Cement

1.1. HBC makeup

The main mineral composition in portland cement (PC) is the tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF), in which the mineral name for tricalcium silicate (C_3S) is also called as alite, while the dicalcium silicate (C_2S) also call as belite. The high belite cement means the belite content is large in cement composition, and the mineral and chemical compositions for portland cement (PC), moderate heat cement (MHC), and high belite cement (HBC) are shown in Table 1.

Table 1: Chemical composition and mineral makeup for HBC, PC, and MHC

Cements	Chemical composition (%)									Mineral makeup (%)			
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	K ₂ O	R ₂ O	C ₃ S	C ₂ S	C ₃ A	C ₄ AF
HBC	23.06	4.59	4.57	59.88	1.39	3.12	0.43	0.17	0.54	20.65	50.53	4.44	13.89
PC	22.66	5.31	3.29	65.75	1.21	-	-	-	-	55.10	23.40	8.50	15.80
MHC	21.22	4.68	4.13	62.95	3.95	1.06	0.50	0.18	0.62	53.50	21.64	3.85	16.67
Notes	HBC = Sichuan Jiahua Cement Factory, 525# high belite cement. MHC = Hubei Gezhouba Cement Factory, 525# moderate heat cement. PC = Silicate, 525# cement.												

As observed in Table 1, there is not much difference in chemical composition for three cements, and the CaO content in HBC is a little low. However, there are larger difference in C₃S and C₂S contents for three cements mineral compositions, namely the C₃S content in both PC and MHC is 50%, and the C₂S content only about 20%; while the C₂S content in HBC is 50%, and the C₃S content only about 20%. It is shown through the above that there is much change in cement's mineral composition, and this change is formed as a result of changes for both the formula in cement raw materials and the burning process. The highest burning temperature of PC is not less than 1400°C, but that of HBC is about 1300°C. Hence, the HBC is also regarded as one of the green energy conservation cements in present building materials, which is listed into the state low heat cement standard GB200-2002 at present, and manufactured at appointed place.

1.2. Physical mechanics performance for HBC

The physical, mechanical and thermal characteristics for HBC, PC, and MHC are listed in Tables 2–4 and Figs. 1–3.

Table 2: Physical characteristics for HBC, PC, and MHC

	Fineness (%)	Specific surf. area (m ² /kg)	Density (g/cm ³)	Water required by normal consistency (%)	Stability	Setting time (h:min)	
						Initial setting	Final setting
HBC	0.5	387	3.20	26.9	Passed	2:40	3:50
PC	1.0	367	3.19	27.3	Passed	2:33	3:34
MHC	1.4	288	3.18	25.5	Passed	3:09	4:58
GB175-1999 PC	<10	>300	–	–	Passed	0:45	<6:30
GB200-2002 MHC-LHC	–	>250	–	–	Passed	>1:00	<12:00

Table 3: Strength capabilities for HBC, PC, and MHC Gelatinovs sands

	Curing conditions	Compressive resistance (MPa)				Folding strength (MPa)			
		3d	7d	28d	90d	3d	7d	28d	90d
HBC	SCC	16.1	24.3	63.4	84.0	4.1	5.5	9.5	11.5
	38°	27.4	52.0	75.4	82.6	5.6	8.0	10.0	9.6
PC	SCC	38.4	51.3	61.5	69.6	6.4	7.6	8.3	9.0
	38°	42.1	47.9	52.7	–	–	–	–	–
MHC	SCC	32.4	43.8	63.2	75.2	6.3	7.6	9.4	11.6
	38°	40.5	50.2	65.0	68.0	6.7	8.1	9.1	9.6
Notes	SCC = Standard curing conditions. 38° = Curing conditions under water temperature 38°.								

Table 4: Hydration heat for HBC, PC, and MHC (KJ/kg)

Cement	1d	2d	3d	4d	5d	6d	7d
HBC Sichuan Jiahua cement	159	181	196	208	219	227	234
PC	–	–	247	–	–	–	289
MHC-1 Gezhouba cement-1	201	233	248	257	265	272	278
MHC-2 Gezhouba cement-2	207	238	250	262	270	276	280
MHC-3 Shimen cement	180	220	238	248	256	262	267
MHC-4 Huaxin cement-1	193	228	245	256	264	271	277
MHC-5 Huaxin cement-2	167	205	228	242	252	260	267

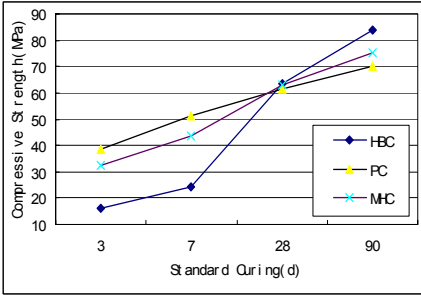


Fig. 1: Standard curing strength for different cements

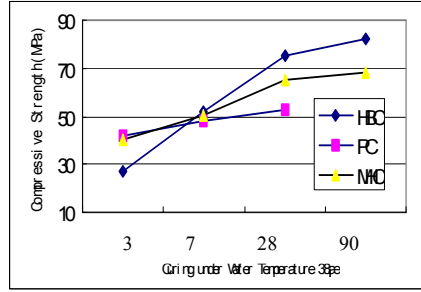


Fig. 2: Curing strength for different cements under temperature 38°

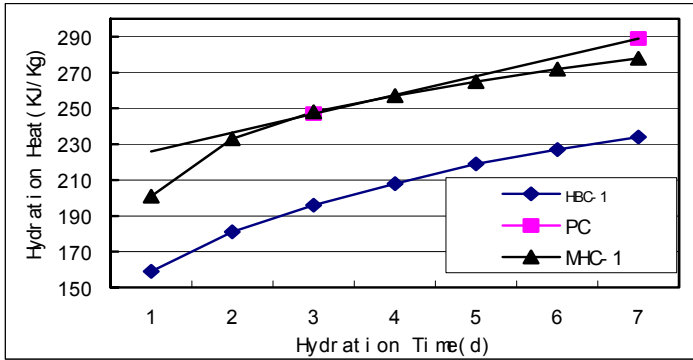


Fig. 3: Hydration heat curves for HBC, PC, and MHC

From the results in Table 2 and Figs. 1–3, we can see the following:

- The physical characteristics for HBC, PC, and MHC conform to the requirements stipulated in both GB175-1999 and GB200-2002.
- Under the same strength-grade of 42.5, and the standard curing conditions (under temperature 20°, and relative humidity of exceeding 90%) of HBC: The earlier strength prior to 7 days is low, the strength at 28 days as same as that of PC and MHC, and the strength at the 90 days is increased by 12%-20% of PC and MHC strengths.
- If raised the earlier curing temperature (e.g., the concrete within dam), then the earlier strength prior to the 7th day is similar to that of PC and

MHC, the strength at 28 days is raised by 16%-45% than that of PC and MHC, hence the higher curing temperature promotes developing the earlier strength of HBC.

- The hydration heat for HBC is obviously lower than that of PC and MHC, the hydration heat of HBC at 3 days is approximately lower for 20% than that of MHC (at about 50 KJ/kg), and the hydration heat of HBC at the 7 days lower for 15.8%-18.7% than that of MHC (at about 44-45 KJ/kg). Hence HBC belongs to the low heat silicate cement.

Through making a comparison between the cement composition and its physical mechanics performance of HBC and that of both PC with the same strength-grade (42.5) and MHC used for the dam, it can be seen that the HBC is a energy conservation cement with low heat and high performance, and it is also a new cement possible for being used for the dam concrete to raise its crack resistance and lasting quality.

2. Development and Research of HBC Dam Concrete

2.1. Research methods

The dam concrete in the Three Gorges of the Yangtze River adopts with the Moderate Heat Cement, and its design and performance for mixing proportion of dam concretes have achieved the international advanced level. This research is adopted with the raw material from the dam concretes at the Three Gorges and mixing proportion as the basic, and the varieties of cements have changed into HBC from the original MHC to compare with the characteristics of HBC dam concrete.

2.2. Working performance

The testing results of working performances on HBC and MHC dam concretes are listed in Table 5.

Table 5: Working performance of HBC and MHC concretes

Concrete	Demands of all materials in concrete (Kg/m ³)							Slump (cm)	Air content (%)
	C+F	W	S	A					
				80-150mm	40-80mm	20-40mm	5-20mm		
MHC-00	231.0+0	127.0	621.5	455.0	455.0	300.0	300.0	4.7	1.1
HBC-00	231.0+0	127.0	621.5	455.0	455.0	300.0	300.0	7.5	1.1
MHC-20	290.5+72.5	127.0	653.0	–	–	718.5	588.5	5.5	4.7
HBC-20	290.5+72.5	127.0	653.0	–	–	718.5	588.5	7.5	4.6
MHC-30	133.8+57.2	86.0	555.0	497.5	497.5	330.0	330.5	4.7	4.5
HBC-30	133.8+57.2	86.0	555.0	497.5	497.5	330.0	330.5	6.4	5.4
MHC-40	98.2+61.7	85.0	607.5	490.0	490.0	325.0	325.0	4.5	5.1
HBC-40	98.2+61.7	85.0	607.5	490.0	490.0	325.0	325.0	6.7	5.6

Notes: The serial numbers, such as -00, -20, -30 and -40, are represented for the fly ash adulterating quantity. The number 00 means the fiducial concrete has not adulterated any admixture, and other numbers represent they have been added for ZB-1A+DH.

Through the testing results, we can see that the slump and air content of HBC dam concrete are basically similar with that of MHC dam concrete whether adulterating or un-adulterating fly ash or the adulterating quantity changes between 20%-40% under the conditions of the same raw materials and mixing proportion. However, the slump for HBC dam concrete is slightly larger than that of MHC dam concrete. This shows that the HBC dam concrete can satisfy the requirements of dam construction, and its flowability is slightly better than that of MHC dam concrete.

2.3. Mechanical behavior

The testing results in mechanical behavior upon HBC and MHC dam concretes are listed in Table 6.

Table 6: Mechanical behavior upon HBC and MHC dam concretes

	Compressive strength (MPa)			Axial tension strength (MPa)		Elastic modulus ($\times 10^3$ MPa)		Limits tension ($\times 10^{-4}$)	
	7d	28d	90d	28d	90d	28d	90d	28d	90d
MHC-30	26.0/100	35.4/100	46.2/100	2.30/100	3.02/100	29.1/100	38.8/100	0.99/100	1.03/100
HBC-30	9.2/35	36.1/102	53.1/115	2.58/100	3.18/105	32.3/111	37.5/97	1.01/102	1.08/100
HBC-30*	18.7/72	38.7/109	58.1/126						

*The curing temperature is 38°, and the concrete mixing proportion is the same as in Table 5.

From Table 6, we can see the following:

- The earlier strength for HBC dam concrete is lower, the strength at 28 days equal to that of MHC dam concrete, and the later strength (at 90 days) larger than that of MHC. The compression resistant marking for HBC dam concrete is of 15%, and its axial tension marking of 5%. Therefore, HBC dam concrete processes a good latter performance.
- The limit stretching strain and elastic modulus for HBC dam concrete are basically similar to that of MHC dam concrete.

2.4. Secular distortion performance

The secular distortion performance mainly including the setting shrinkage, creepage, itself volumetric deformation, and testing results is listed as following Table 7 and Figs. 4-7.

Table 7: Secular distortions and testing results for HBC and MHC

	Dry shrinkage ($\times 10^{-6}$)				Creep degree ($\times 10^{-6}$) 28d/90d (loading time)				Volumetric deformation ($\times 10^{-6}$)			
	7d	28d	90d	180d	7d	28d	90d	180d	3d	7d	28d	60d
MHC	79.9	260.0	336.1	350.6	15.38/6.65	21.68/10.39	26.17/13.85	31.16/17.21	12.08	9.75	18.92	24.86
HBC	94.9	292.8	362.6	383.1	17.13/6.08	21.59/9.34	25.45/13.47	29.67/16.37	10.64	4.41	1.36	-14.93

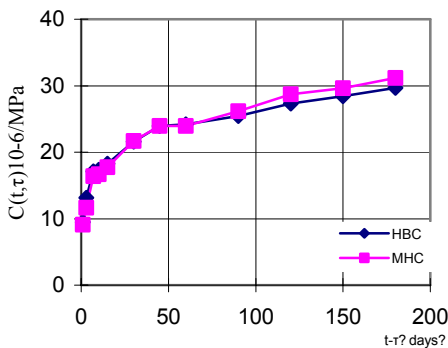


Fig. 4: Creep deformation for concrete (28 days)

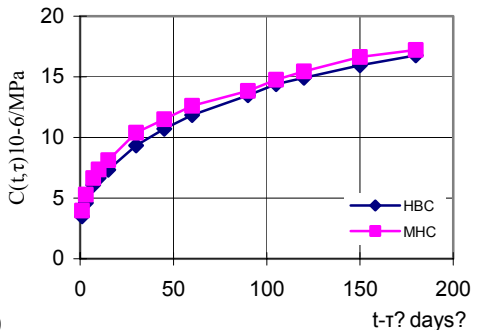


Fig. 5: Creep deformation for concrete (90 days)

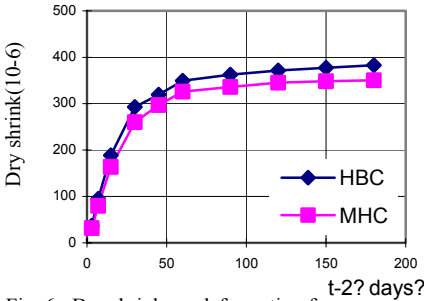


Fig. 6: Dry shrinkage deformation for concrete

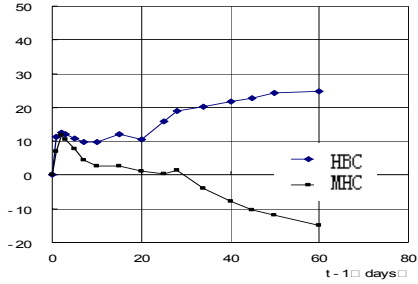


Figure 7: Self-volume deformation for concrete

The testing results show the following:

- The drying shrinkage deformation for HBC dam concrete is basically similar to that of MHC dam concrete, namely the dry shrinkage value for 180 days equal to $350\text{--}380 \times 10^{-6}$, which is further less than that of PC dam concrete. And the dry shrinkage value of PC dam concrete within 180 days will reach to approximately 500×10^{-6} .
- Whether 28 days or 90 days loading period, the creep deformation for HBC dam concrete is also similar to that of MHC dam concrete, basically. If adopted 28 days loading period, then the creep deformation for 180 days is equal to approximately 30×10^{-6} ; if adopted 90 days loading period, then the creep deformation for 180 days equal to approximately 17×10^{-6} .
- The self-volume deformation for HBC dam concrete belongs to a micro-expansion type, so its self-volume deformation in 60 days is equal to 24.86×10^{-6} . However, MHC dam concrete belongs to a micro-shrinkage type, so its self-volume deformation in 60 days is equal to -14.93×10^{-6} .

2.5. Lasting quality

The testing results upon freezing-proof and anti-filtration durability for both HBC and MHC dam concretes are listed in Table 8.

Table 8: Freezing-proof and anti-filtration results upon HBC and MHC dam concretes

	Freezing-proof test quickly froze for 300 times		Anti-filtration grade (kg/cm ²)
	Relatively moving and elastic modulus (%)	Weight loss (%)	
HBC-30	82.26	0.95	>10
MBC-30	90.49	0.85	>10

Notes: The quick-freezing evaluation standard upon concrete is understood as following: When the relatively moving and elastic modulus is less than 60%, and the weight loss not less than 5%, it is regarded that the concrete has arisen the frozen abruption.

The testing results demonstrate the following:

- In the event of adopting 30% fly ash adulterating quantity, the dam concretes for both HBC and MHC are able to satisfy the requirements to be quickly frozen for 300 times, and they are dispensed into a high freezing-proof concrete to conform with the designing requirements of concrete freezing-proof F300 at water-level changing areas of the Three Gorges Dam.
- Similar to the MHC dam concrete, the anti-infiltration grade of HBC dam concrete can achieve exceeding W10 to satisfy the design requirements of Three Gorges Dam engineering.

2.6. Analysis upon thermal characteristics and crack resistance performance

2.6.1. Adiabatic temperature rising tests for HBC and MHC dam concretes

HBC and MHC dam concretes have taken their interior concretes as an example, and the testing results upon adiabatic temperature rising from both HBC and MHC are shown in Table 9 and Fig. 8.

Table 9: Adiabatic temperature rising for HBC and MHC dam concretes

	3d	7d	14d	28d
HBC	9.1	12.4	16.4	19.2
MHC	13.1	17.8	20.7	21.2

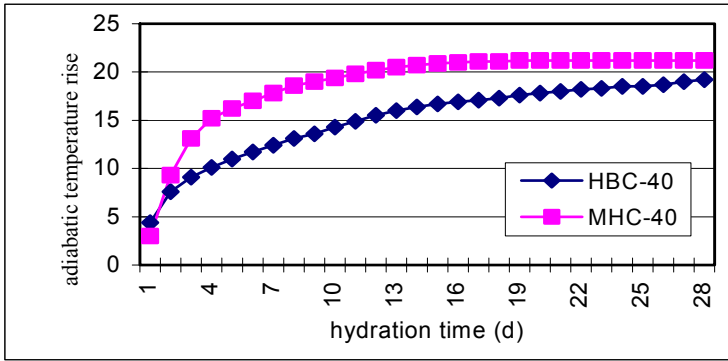


Fig. 8: Adiabatic temperature rising for HBC and MHC concretes

It can be seen through the testing results that the adiabatic temperature rising for HBC dam concrete should be lower than that of MHC dam concrete in the event of the same mixing proportion, and the descending amplitude for adiabatic temperature rising is about 3-5. This is very favourable to reduce the temperature stress from larger volume concrete, and decrease the temperature cracking.

2.6.2. Crack resistance analysis for HBC and MHC dam concretes

The crack problem in dam concrete is a pertinacious disease that is not easy to completely overcome, while the crack resistance analysis upon dam concrete is also one difficult problem in water resource engineering. So far, it has not achieved the consistently common understanding in this field. And this research carries out the crack resistance analysis on HBC and MHC dam concretes against the following three ways.

A. Limit tensile strength

In the temperature controlling design for dam, the most visual evaluation upon σ is to make the limit tensile strength in concrete as a estimation on resistibility.

$$\sigma = \epsilon_p E \tag{1}$$

where σ = limit tensile strength in concrete (MPa), ϵ_p = limit tensile deformation in concrete, and E = tensile elastic modulus in concrete (MPa).

In the limit tensile deformation for concrete (ϵ_p), it includes either the elastic deformation, or a smaller part of plastic deformation. Hence this method is also called as the elastic and plastic method. And the crack resistance abilities (σ) for HBC and MHC dam concretes are listed in Table 10.

Table 10: L crack resistance abilities for HBC and MHC concretes (σ)

Concrete	Crack resistance ability for concrete $\sigma = \epsilon_p \times E$ (MPa)	
	28d	90d
MHC-00	3.4	4.3
HBC-00	4.5	4.8
MHC-20	3.4	4.5
HBC-20	3.7	5.0
MHC-30	2.9	3.9
HBC-30	3.3	4.2
MHC-40	2.2	3.2
HBC-40	2.3	3.7

Table 10 shows that the crack resistance abilities of HBC concretes are larger than those of MHC concretes.

B. Safety factor against cracking (K)

The safety factor against cracking (K) for concrete can be represented with the formula (2):

$$\text{Safety factor against cracking } K = \text{Crack resistance } \sigma / \text{destructive force } P \quad (2)$$

where $K > 1$, the concrete can not arise a crack and $K < 1$, the concrete can arise a crack.

According to both the derivation from the concrete anti-cracking calculation of “mass concrete” against a bulky basic restricting areas in water resource engineering and the statistical data upon concrete testing at the Three Gorges Dam, the calculation results upon safety factor against cracking (K) for both HBC and MHC dam concretes are listed in Table 11.

Table 11: Safety factor against cracking (k) for both HBC and MHC concretes

Concrete	Time (d)	A ₁	A ₂	Destructive force (MPa)		Anti-cracking ability σ (MPa)	Safety factor against cracking $k = \sigma/P$
				P = $\sigma_1 + \sigma_2$			
				σ_1	σ_2		
HBC-35 basic position	7	0.597	0.500	1.03	0.02	1.1	1.05
	28	0.570	0.479	1.60	0.04	2.3	1.40
	90	0.545	0.459	2.24	0.10	3.7	1.58
MHC-35 basic position	7	0.600	0.503	1.33	-0.06	1.0	0.79
	28	0.577	0.484	1.76	-0.08	2.2	1.31
	90	0.551	0.43	2.92	-0.10	3.1	1.10

Notes: The A1 and A2 are the average constraint factor for even temperature difference in placement block and constraint factor for uneven temperature difference, respectively.

From the results in Table 11, we can see that the anti-cracking coefficients K of HBC dam concrete, whether in 7, 28, or 90 days, are more than that of MHC dam concrete, which further represents that the crack resistance of HBC dam concrete gains advantage over that of MHC dam concrete.

C. Anti-cracking coefficient during temperature deformation R

It is considered that the cracks for mass concrete are mainly caused by the temperature stress, while the temperature stress comes from the dam basic concrete or external concrete constrained by the foundation base or internal concrete during temperature drop. If the permissible stretching strain ability for concrete includes the limit tension, creep deformation, self-volume deformation and drying shrinkage deformation, and they are more than the concrete shrinkage deformation during temperature drop, then the concrete can not arise the crack. And the concrete anti-cracking coefficient R during temperature deformation is listed as following formula (3) and Table 12.

$$R = \epsilon_a / \epsilon_b \tag{3}$$

where ϵ_a = self-deformation ability for concrete (strain) and ϵ_b = shrinkage strain of concrete during temperature drop.

Table 12: Anti-cracking coefficient for HBC and MHC concretes R

Concrete	Time (d)	Anti-cracking coefficient for concrete R		
		$\varepsilon_a = k_1 \times \text{Instantaneous deformation for concrete} + k_2 \times \text{Creep deformation} - k_3 \times \text{Self-volume deformation} - k_4 \times \text{Drying shrinkage deformation} (\times 10^{-6})$	$\varepsilon_b = k_5 \times \text{Temperature deformation for concrete} (\times 10^{-6})$	Anti-cracking coefficient R
HBC-35 basic position	7	47.92	65.74	0.73
	28	73.34	97.92	0.75
	90	81.36	108.63	0.75
MHC-35 basic position	7	47.28	87.62	0.54
	28	72.59	118.58	0.61
	90	76.77	120.82	0.64

Notes: The k_1 - k_6 means the weight coefficients, and they are 0.80, 0.15, 0.04, 0.01, and 0.60, respectively.

From the results in the Table 12, we can see that the anti-cracking coefficients R of HBC dam concrete at different time are more than that of MHC concrete. This is further represented that the crack resistance of HBC dam concrete gains ascendancy over that of MHC concrete. The anti-cracking coefficient R in temperature deformation is either applicable for the dam basic concrete, or applicable for the external concrete. However, it is only a relative comparison of crack resistance in materials.

The crack resistance analysis in three ways above suggests that the anti-cracking ability of HBC dam concrete used, especially the anti-cracking ability against temperature stress, would outmatch over that of MHC dam concrete.

3. Conclusions

- This project is listed into the key task project in scientific and technological research during the “Tenth-Five.” Through existing research fruits, we can see that HBC is a environmental protection and energy conservation cement with low heat and high performance, which is expected to be popularized and applied for mass concrete in water resource engineering.
- HBC dam concrete is not only possessing a good working performance, mechanical behavior and deformability, but also possessing a high crack

resistance and durability, which is a new dam concrete with low heat and high crack resistance.

- This testing research work is to be further supplemented and perfected, which is expected to fulfil trial application in the Three Gorges engineering.

Acknowledgments

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