Pergamon

CEMENT AND CONCRETE RESEARCH

Cement and Concrete Research 31 (2001) 87–95

Influence of mixing techniques on properties of high performance concrete

Ping-Kun Chang*, Yaw-Nan Peng

Department of Civil Engineering, National Chiao Tung University, 1001, Ta Hsueh Road, Hsinchu 300, Taiwan, ROC

Received 29 March 2000; accepted 20 September 2000

Abstract

Six mixing methods were used to prepare high performance concrete (HPC) of high flowability. The properties of the fresh and hardened concrete are measured. It is found that adding all superplasticizers (SP) in water in one dose can ensure that workability can be maintained. The tested results identified a most efficient and economical method in making HPC, especially for lower binder content, which requires less mixing time and less amount of SP in producing the resulting material with higher flowability and better compressive strength than the other methods. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Superplasticizers; Water-to-binder ratio; High performance concrete; High flowability

1. Introduction

The main purpose of concrete mixing is to achieve a uniform mixture of all materials [1]. Mixing is especially important for high performance concrete (HPC) of low binder content. Poorly mixed concrete not only fails to meet the requirement of workability, but also affects its engineering properties. The following are the conventional mixing methods. ASTM C94 "Specification for Ready-Mixed Concrete" [2] contains the guidelines for traditional large-scale mixing procedures. This method comprises the following steps. First, part of the water is put into the mixer, followed by other solid materials. Liquid admixture is then added together with water, while solid admixtures is added together with other solid materials. If two or more kinds of solid admixtures are used, they should be added separately [2]. Most laboratories employ the DIN and ASTM [4,5] mixing sequence. First, part of the water and aggregate are added followed by fine aggregate and cement. Then, liquid admixtures mixed evenly with water are added followed by mineral admixtures together with cement. The mixing sequence of mortar according to ASTM C109 [3] involves blending water with cement followed by the addition of fine aggregate to produce a highly uniform paste after sufficient mixing time. Methods for mixing HPC are similar to the above-mentioned methods [5–7], but the mixing sequence varies depending on the required properties of the concrete produced. Khalaf [8] has collected and analyzed concrete mixing methods in various countries. He concluded that the method of first mixing the binder and then followed by the addition of aggregate can reduce the amount of water and cement needed in the process and at the same time lead to an increase in strength of about 10–20%. However, such is limited only to the mixing of conventional concrete. In addition, the type of mixer used also has a large influence on the mixing efficiency and uniformity of concrete. The drum type concrete mixer is most commonly used. However, whether this type of mixer is suitable for mixing HPC of low water-to-binder ratio (W/B) or of high aggregate content merits further investigation.

2. Research significance

Literature regarding the effect of mixing sequence on the properties of HPC of high flowability is scarce. Previous studies [9–13] have examined the effect of materials being added in different sequence on the strength of hardened concrete. However, the effects of the methods of adding of superplasticizers (SP) on flowability of HPC have not been given much attention. Whether SP is suitable for mixing HPC of low paste content, low W/B

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* Corresponding author. Tel.: +886-3-5712121 ext. 54901; fax: +886-3-5716257.

E-mail address: pkchang@pchome.com.tw (P.-K. Chang).

PII: S0008-8846(00)00439-7

ratio and high flowability remains unknown. The influence of changes in mixing sequence on SP dosage and HPC properties merits further exploration. This study explains the relationship between SP concentration and mixing method according to the weight of water to solid ratio (W/S) in which may shed light on the effect of SP on the flowing characteristics in accordance with the ACI mixing concept [14].

3. Materials and methods

Type I Portland Cement is used in this study. Fly ash is Type F fly ash produced from Taiwan Power Company. Slag is produced from China Steel Corporation. The chemical analysis and physical properties of the above-mentioned materials are listed in Table 1. The maximum diameter ($D_{\max}$) of the coarse aggregate is 13 mm while fine aggregate coarse sand is of fineness modulus (FM) 3.0. All aggregates comply with specifications under ASTM C33 containing no harmful substances. They were washed thoroughly and dried completely before use. The SP used complied with ASTM C494 Type G and was considered part of the water.

The design of concrete mixture followed the Densified Mixture Design Algorithm (DMDA) [7,10,12]. First, the optimal amount fly ash to fill aggregate voids is determined [13,14]. Then coarse aggregate is added to the mixture in proportion to the maximum unit weight. The ratio of fly ash to both fine and coarse aggregate of the maximum unit weight can then be obtained to calculate the void volume (V_v). When cement paste content is equal to void volume ($V_p = V_v$), it indicates that all the void space is entirely filled with cement paste. Six methods of different mixture proportions as shown in Table 2 are developed in this study. The experimental conditions are as follows. The W/B ratio is set to be 0.32 and the strength at an age of 56 days is 55 MPa. The initial slump is measured to be 230–270 mm and the slump flow is 400–600 mm. After 45 min, the slump should not be less than 230 mm while the slump flow should be no less than 400 mm. No bleeding or segregation should occur. In order to investigate the influence of paste content on HPC properties, binder content is varied to determine the optimal dosage of SP [15–18]. To understand the influence of mixing technique on the HPC properties, the mixing sequence is changed to measure the relative loss in workability for each mixture whose hardened properties were studied.

Table 1
Chemical analysis and physical properties of cement, slag and fly ash

Items		Cement	Slag	Fly ash
Chemical	SiO_2 (S)	22.0	34.9	51.2
	Al_2O_3 (A)	5.6	13.6	24.3
	Fe_2O_3 (F)	3.4	0.5	6.1
	CaO (O)	62.8	41.8	6.3
	MgO (M)	2.6	7.2	1.6
	SO_3 ($\bar{S}$)	2.1	1.7	0.6
	Free-CaO	1.1	–	–
	TiO_2 (T)	0.5	–	–
	Na_2O (N)	0.4	–	–
	K_2O (K)	0.8	–	–
	Loss on Ignition (LOI)	0.5	0.3	4.9
	Insolubility	0.1	–	–
Potential clinker	C_3S	40.1	–	–
	C_2S	32.8	–	–
	C_3A	8.9	–	–
	C_4AF	10.5	–	–
Physical properties	Fineness (cm^2/g)	2970	4350	3110
	Density (g/cm^3)	3.15	2.87	2.21
	Setting time, I.S (h: min) Vicat	4:37 (W/C = 0.47)	–	–
	Setting time, F.S (h:min) Vicat	8:22	–	–
	Retention on # 325 sieve (%)	–	–	8.0

4. Experimental procedure

Six different mixing procedures were used and the types of mixer used are summarized in Table 3. A drum type concrete mixer is generally employed to produce traditional HPC. According to ASTM C94 [2], the mixing sequence involves adding coarse and fine aggregate first, followed by cement, pozzolanic materials and half of the water. Finally, SP uniformly dissolved in the other half of the water is added. In the case of Method 1, there is a great reduction in workability after 45 min, which implies a need for the second or third addition of SP. Method 2 involves adding all SP in one dose. The mixing sequence of Method 3 is similar to that of Method 2 with two differences. First, the horizontal twin shaft concrete mixer is used [8], and second, both fine and coarse aggregates are in wet condition. For Method 4, dry aggregate with SSD water content is first added followed by cement, pozzolanic materials, fly ash and SP dissolved in water. Method 5 has the same mixing sequence as Method 4 but both Methods 5 and 6 use a horizontal twin shaft concrete mixer designed by the author [7]. The speed of this mixer can be adjusted according to the requirement. Method 6 involves first mixing the binder with a portion of SP and a part of the water. Then aggregate is added with the remaining portion of SP dissolved in the rest of the water. The amount of paste [19,20] used varies according to different mixing sequences. For Methods 2, 3 and 4, $N = 1.2–1.6$; while for Methods 5 and 6, $N = 1.2–2.0$. The mixing time for Methods 1 and 2 is 20 min while that for Methods 4, 5 and 6 ranges from 7 to 10 min. As for Method 3, the mixing time follows that specified according to the volume of the pre-mix concrete. The slump and slump flow of each mixing sequence in the

Table 2
HPC mixture proportions, kg/m^3

Mixing method	N	Water	SP	Cement	Slag	Fly ash	Aggregate		W/C	W/B	W/S (wt.%)
							Coarse	Fine			
1, 2	1.2	150	11.5	360	18	140	944	805	0.47	0.32	7.39
	1.4	172	13.4	440	22	135	888	756	0.42		8.43
	1.6	198	8.8	489	25	124	823	701	0.43		9.55
	1.4	161	11.5	436	23	80	966	709	0.4		7.76
3	1.4	161	10.2	439	23	80	966	709	0.4		7.77
	1.2	161	22.5	344	18	136	845	911	0.53		8.11
	1.4	183	13.2	431	22	125	799	851	0.45		8.87
	1.6	203	9.2	495	26	118	740	779	0.43		9.88
4	1.2	144	18.5	320	17	165	768	987	0.51		7.25
	1.4	168	15.3	389	20	151	722	930	0.48		8.34
	1.6	190	11.5	458	24	142	675	870	0.44		9.36
5	1.8	212	7.1	528	28	132	630	811	0.42		10.36
	2.0	236	3.8	601	32	122	582	755	0.4		11.54
	1.2	149	13.5	320	17	161	766	986	0.52		7.29
	1.4	173	10.2	340	15	151	930	930	0.48		8.34
6	1.6	192	9.1	460	24	142	675	869	0.44		9.35
	1.8	211	7.3	530	28	133	629	811	0.42		10.34
	2.0	236	4.0	600	32	124	582	755	0.4		11.55

beginning and after 45 min was measured. Concrete specimens were also made for the compressive strength test.

5. Results and discussion

5.1. Effect of mixing method

The conventional mixing of Method 1 involves adding portions of SP in different stages and extending the mixing time. Our results indicate that the initial slump and slump flow can meet the requirement. However, after 45 min, although there is no significant loss in the slump, the slump flow is greatly reduced. To overcome the decrease in workability, Method 2 adds all SP in one dose and maintains the same mixing time as that in Method 1. As can be seen in Table 4, the loss in workability becomes less, implying that adding all SP in water in a single dose and allowing sufficient mixing time can help to enhance the function of SP in the mixing. Upon completion of laboratory tests, large-scale mixing is conducted at the plant. Properties of fresh HPC produced by Method 3 are shown in Table 5. Note that both fine and coarse aggregates are in wet condition with the water content under rigorous control (especially for the sand). Fig. 1 shows the relationship between water content and SP dosage for various mixing sequences. Line 3 is the SP dosage recommended by the mixing plant and yet the actual amount of SP needed is only 70% of what is suggested. This indicates that large-scale mixing and appropriate sequence of SP addition can enhance the efficiency. Further additions of SP fail to restore the decrease in workability because inadequate mixing hinders SP from diffusing to the surface of the paste. This proves that adding all SP in one dose is the best way to retain workability. Among the mixing sequences developed, Method 4, which involves wetting the aggregate then followed by the addition of fly ash, proves to enhance

Table 3
Mixing procedure and mixer used

Mixing method	Mixing sequence											Mixer (Force type)
	Water					Fine aggregate		Coarse aggregate		Mineral admixture		
	Aggregate SSD water	Partial water	Rest water SP	Mixing water	Cement	Dry	Wet	Dry	Wet	Fly ash	Slag	
1		2	3		2	1		1		2	2	Pan type
2				3	2	1		1		2	2	Pan type
3				3	2		1		1	2	2	Batching type
4	1	3	5		2	1		1		4	2	Pan type
5	1	3	5		2	1		1		4	2	Horizontal twin shaft
6		1	4		2	3		3		2	2	Horizontal twin shaft

Left number represents mixing method, Right number represents mixing sequence, the same number represents materials added at the same time; N: V_p/V_v; V_v: the least void volume; V_p: the volume of paste amount; B: Binder, including cement, fly ash and slag; S: Solid materials including weight of binder and aggregate; SP: Type 1000 superplasticizer ASTM C 494 HRWRA.

Table 4
A comparison of workability of HPC mixed by Methods 1 and 2

		Mixing method 1				Mixing method 2				
		Slump (mm)		Flow (mm)		Slump (mm)		Flow (mm)		
W/B	*N*	0 min	45 min	0 min	45 min	0 min	45 min	0 min	45 min	SP (wt.%)
0.29	1.2	265	245	650	480	255	250	600	590	1.4
	1.3	260	235	625	450	265	255	650	625	4.1
	1.4	270	235	700	450	260	255	625	615	3.2
	1.6	255	245	600	420	265	245	645	625	2.3
0.32	1.2	265	230	615	420	255	240	620	600	4.1
	1.4	260	235	620	465	255	250	610	590	3.2
	1.6	245	240	510	400	250	250	595	580	1.8

the function of SP. On the other hand, allowing sufficient time for mixing the materials contributes to SP diffusion. However, for low paste volume ($V_p = 1.2V_v$), the amount of SP added reaches as high as 4.4%, implying a low mixing efficiency.

Mixing which involves high aggregate content and low W/B ratio (such as Method 4) will cause serious damage to the blades of the mixer, thus lowering the mixing efficiency. Since the initial shear force of HPC is high, it sometimes causes the mixer to stop and requires manual help to continue its operation. This will have a great influence on the uniformity and quality of HPC with low paste content. Method 5 uses the newly designed mixer with speed adjustment and involves the same mixing sequence as that of Method 4. Our results show that with the same amount of water, Method 5 reduces the paste content by about 0.8% ($N = 1.2$) and shortens the mixing time to about 7 min. This contributes greatly to decreasing the amount of SP added and energy consumption. Method 6 is developed with the objective of promoting the efficiency of the mixer and SP dosage. Binder paste is first mixed and then sand is added followed by coarse aggregate. This mixing sequence not only produces a uniform mixture, but also achieves a low paste content and low SP dosage, both similar to those of Method 5. Moreover, the lower the paste content, the less the SP is required. With the same amount of water and low paste content ($N = 1.2$), the SP dosage required by Method 6 is about 1.9% and 1% less than that of Method 4 and Method 5, respectively. Moreover, Method 6 retains the same mixing time as that of Method 5. This shows that a uniform mixture of low paste content facilitates the lubrication of coarse aggregate, thereby reducing the friction between the granular materials. As a result, the mixer blades will suffer less damage in the mixing process. In view of the above, the mixing sequence of Method 6 proves to be the most efficient in achieving uniform mixing, with economy in energy consumption and minimum damage to the equipment.

5.2. Effect of mixer type

The type and efficiency of the mixer will influence the mixing time needed, the SP dosage required and the quality of the HPC produced. Two types of concrete mixers are used in this study: the drum type and horizontal twin shaft type. Methods 1, 2 and 4 employ the drum type concrete mixer and require a mixing time of 20 min. However, in the case of low paste content ($N = 1.2$), a longer mixing time is required and this will in turn increase the load on the mixer, leading to greater wearing of the blades and more severe damage to the mixer. As a result, it is uneconomical to produce HPC by these methods. On the other hand, Methods 3, 5 and 6 employ the horizontal twin

Table 5
Properties of fresh concrete mixed by Method 3

						Flow properties (mm)						
						30 min		60 min		90 min		
Batch no.	W/B	W/C	W/S (wt.%)	*N*	SP (wt.%)	Slump	Flow	Slump	Flow	Slump	Flow	Bleeding
1	0.32	0.4	7.80	1.4	2.11	260	600	250	590	240	530	No
2					2.13	245	500	240	420	230	400	No
3					2.13	250	545	245	500	240	440	No
4					1.90	260	610	260	600	255	585	No
5	0.35	0.45	7.50	1.3	2.88	255	640	245	550	240	500	No
6			7.46		2.77	250	580	245	520	240	490	No
7			7.41		2.33	265	560	250	510	245	450	No
8			6.77	1.2	2.80	255	550	250	510	245	450	Yes
9			6.69		2.60	250	545	245	500	240	430	Yes

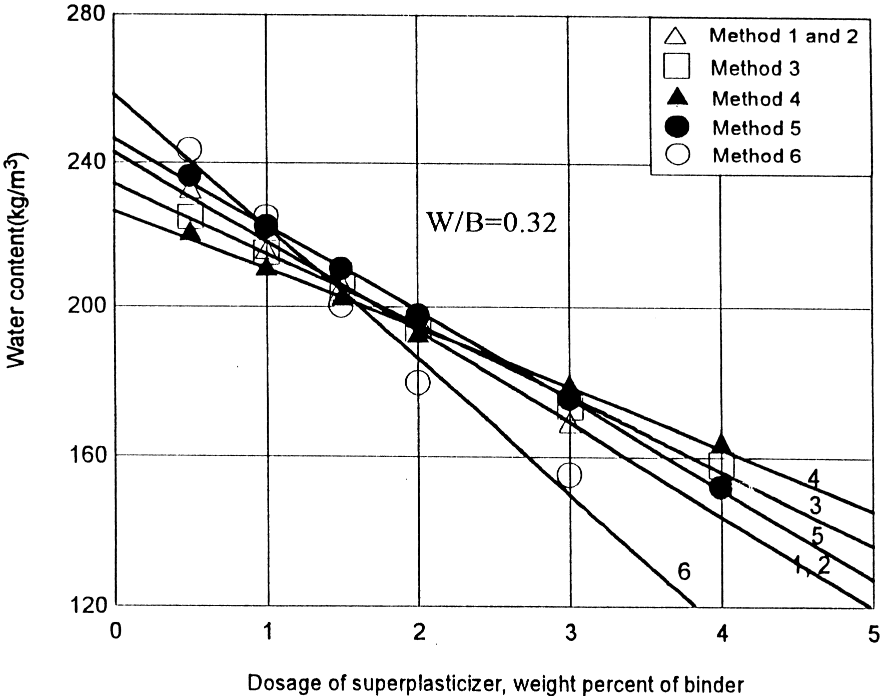


Fig. 1. The relationship between water content and SP dosage (kg/m^3).

shaft concrete mixer. For large-scale plant mixing of Method 3, a mixing time slightly longer than the normal is needed to obtain HPC of uniform quality; while laboratory mixing of Methods 5 and 6 can achieve uniform mixing within 7 min. First, a low revolution per minute is used in the initial mixing to overcome the high shear force. After various materials have been blended, mixing is performed under a high revolution per minute of the two horizontal shafts. Moreover, Method 6 is found to cause less wearing to the blades and less damage to the mixer than the other methods. This implies that the binder mixed before aggregate is added will lubricate the coarse aggregate, thereby keeping the friction between the granular materials to the minimum. As a result, this enhances mixing efficiency and reduces the mechanical damage.

5.3. Effect of binder content

The relationship between binder content and SP dosage of the different mixing methods is shown in Fig. 2. As can be seen, the SP dosage corresponding to the initial binder content in Method 6 is sufficient for achieving uniform diffusion. This produces an excellent lubricating paste in which helps to maintain high workability even after coarse aggregate is added. On the other hand, the initial step of Methods 1 through 5 all involves the addition of coarse and fine aggregate. The interlocking force between the granular materials not only increases frictional force but also requires a higher SP dosage to bind the aggregate disperse during the mixing. With the same paste content, both SP dosage and mixing time must be increased in order to obtain the necessary workability. This phenomenon is especially prominent for low binder content. On the contrary, with a fixed SP dosage and a high binder content ($N > 1.8$), workability are less influenced by the mixing sequence and mixing time, and the influence of binder content on the workability is less significant.

However, under low binder content ($N = 1.2$) and for the same workability, Method 6 can reduce the use of lubricating paste by 50–65 kg/m^3 as compared with the other methods. Fig. 2 also indicates that under fixed SP = 2.75%, Method 6 uses 13–21 kg/cm^3 of water less than the other methods. This implies that for the same workability, preparing a uniform binder first before adding coarse aggregate can reduce the interlocking effect, thus increasing the efficiency of the binder and making the production more economical. Table 4 shows the loss in workability for Methods 1 and 2. In the case of high binder content ($N > 1.8$), there is a greater reduction in slump and slump flow after 45 min. This proves that high cement content leads to more significant loss in workability due to fast hydration. The loss becomes less significant when the binder content is low because the smaller the amount of binder, the lower the cement content will be. This, together with the effect of Type G SP, contributes greatly to the retention of workability.

5.4. Effect of W/C, W/B and W/S ratios

Under low W/B ratio and low water content, addition of SP can enable HPC to meet the required uniformity and flowability. The SP dosage corresponding to the

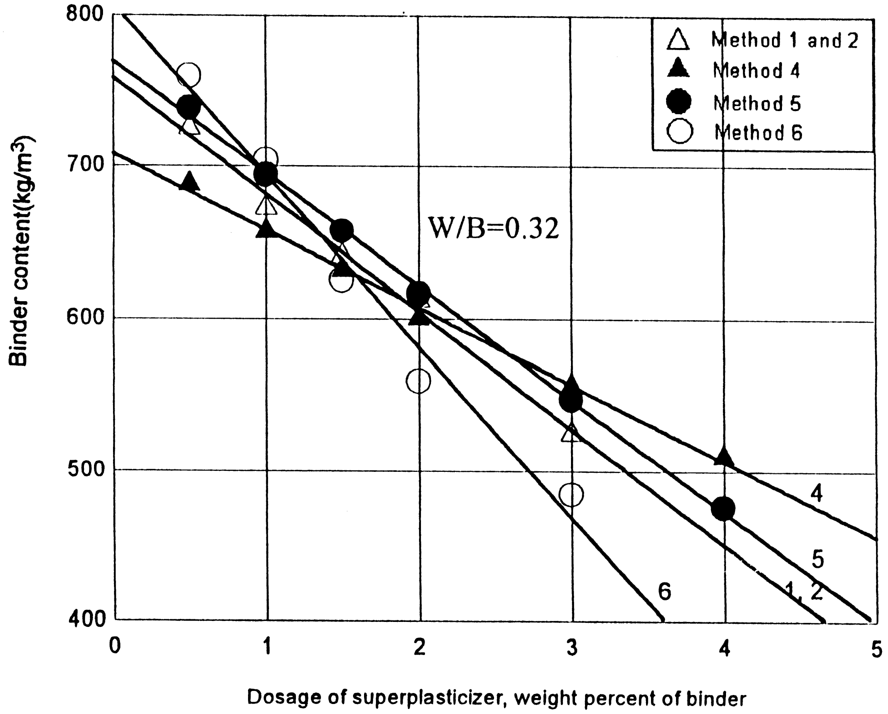


Fig. 2. The relationship between binder content and SP dosage.

concentration of binder or sand, as indicated by the W/B or W/S ratio, respectively, is quite high. Different speeds of the mixer can be adjusted to obtain a uniform HPC mixture. For concrete made up of coarse aggregate (especially crushed stones), most of the solid materials are added in the beginning. In this case, the solid material concentration corresponding to the water content and SP dosage is then converted to W/S. Fig. 4 displays the relationship between SP and W/C ratio as well as that between SP and W/S ratio. As seen in Fig. 3, a great portion of the SP is used for diffusing water, cement and pozzolanic materials; while the rest is absorbed by aggregate (especially sand), in particular, when dry aggregate is used. Under fixed W/B = 0.32, the W/C and W/S ratios are found to be directly proportional to the SP dosage, as shown in Fig. 4(a). It should

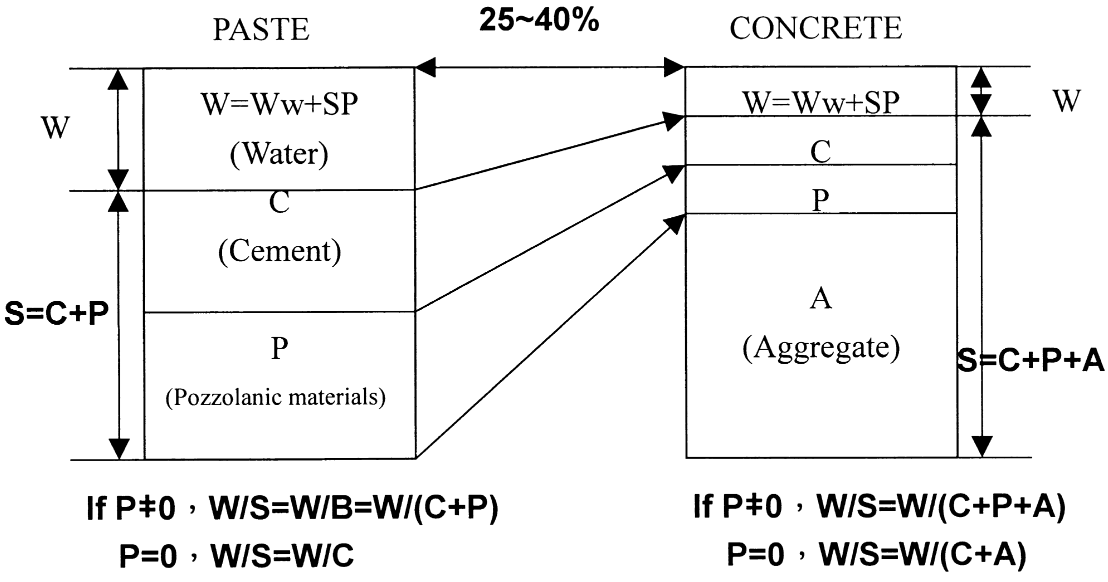
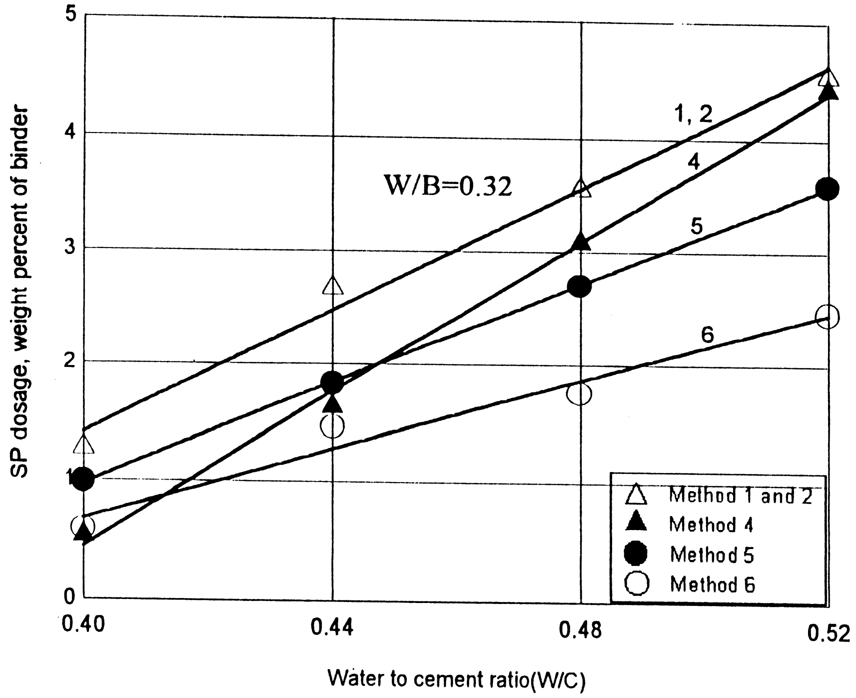
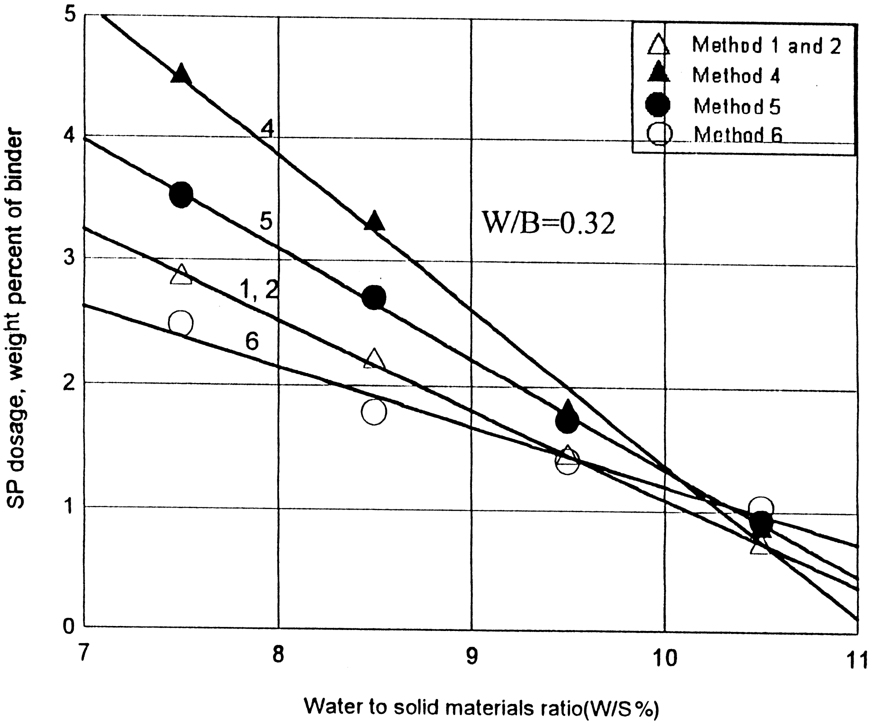


Fig. 3. The parameter of HPC added pozzolanic materials.



(a)SP & W/C



(b) SP & W/S

Fig. 4. The relationship among SP and W/C and W/S.

be noted that HPC of low binder content has a smaller W/S ratio but a larger W/C ratio. The relationship between W/C and W/S ratios is shown in Fig. 5. It indicates that under low binder content, the role of SP is not only for promoting the separation of cement particles, but also for the greater amount of pozzolanic materials and aggregate. With references to Fig. 4(b), except for Method 6, all other methods use W/S ratio to

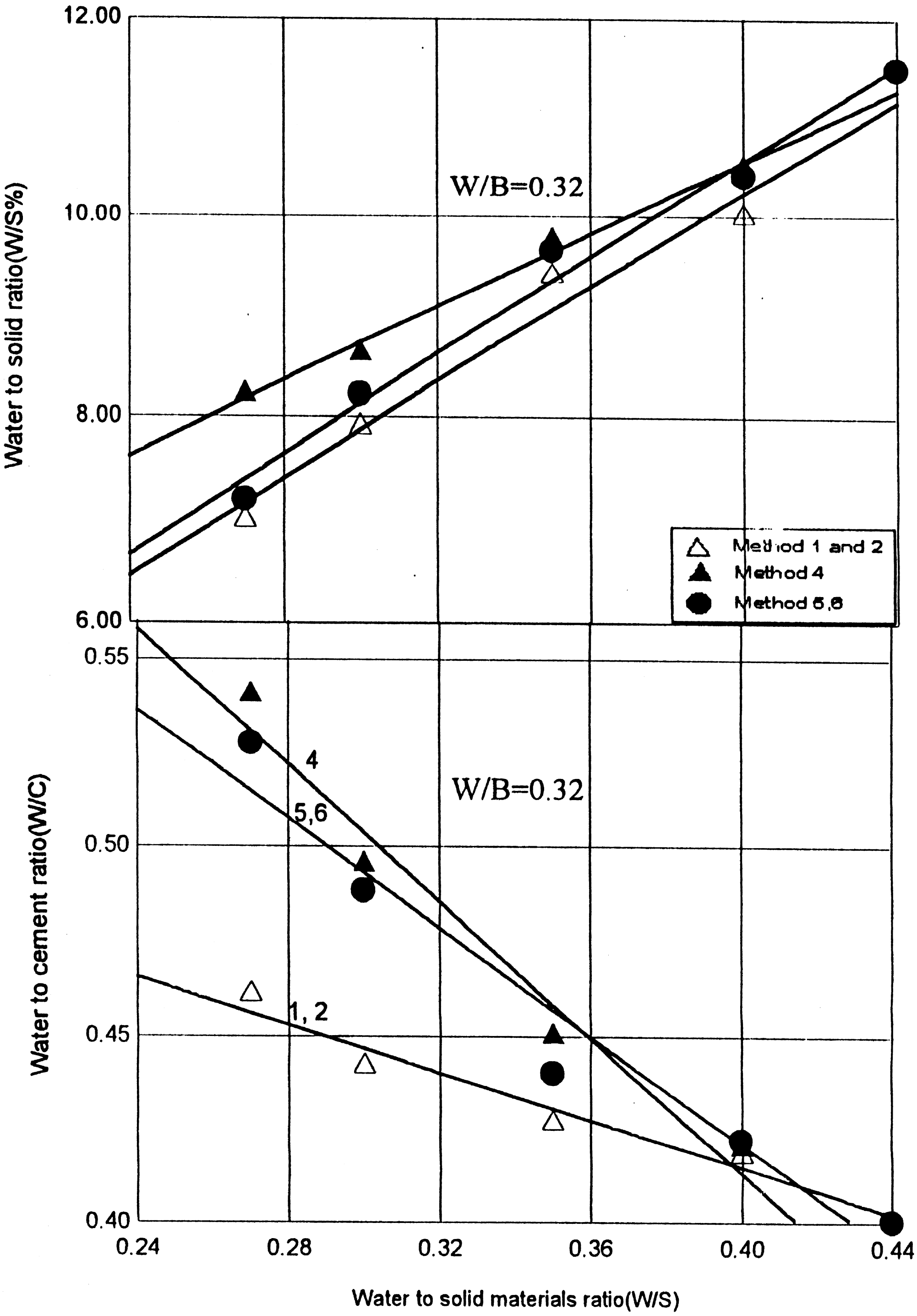


Fig. 5. The relationship among W/C and W/S and paste content of HPC mixture.

represent the water content and SP dosage corresponding to the concentration of all solid materials. Especially for Method 4, because of the low concentration and poor mixing efficiency, the low binder content fails to obtain the diffusion effect that can only be achieved by a higher SP dosage. Method 6 involves preparing a uniformly mixed binder that is advantageous to the blending of cement and water. When aggregate is added, a uniform paste will produce lubrication, thus reducing the frictional force between the granular materials. Though both Methods 5 and 6 retain the same W/S ratio, no extra addition of SP is required in Method 6 in which achieves greater economy and higher mixing efficiency, as evidenced by the effect of the mixing sequence.

Table 6
Compressive strength, MPa

		Age (days)			
Mixing method	*N*	3	7	28	56
2	1.2	27	33	66	71
	1.4	32	41	65	68
	1.6	27	35	59	65
3	1.4	37	54	60	64
	1.4	35	50	55	58
4	1.2	30	29	47	58
	1.4	42	45	65	67
	1.6	41	56	64	67
5	1.2	31	37	44	59
	1.4	33	41	55	59
	1.6	37	47	53	56
	1.8	40	48	59	63
	2.0	43	44	53	58
6	1.2	36	43	67	72
	1.4	39	50	67	72
	1.6	39	49	62	65
	1.8	40	50	60	65
	2.0	42	51	55	62

The compressive strength of concrete samples made by Mixing Method 1 was not measured.

5.5. Compressive strength of concrete

The compressive strength of concrete at different age of Methods 2 through 6 is shown in Table 6. As can be seen, under W/B = 0.32, all mixing methods obtain the required strength. This suggests that uniformly mixed HPC will have good performance in both its fresh and hardened states.

6. Conclusions

Given sufficient mixing time, the mixing sequence and type of mixer used have less influence on the uniformity of HPC under high binder content ($N > 1.8$). This is particularly true when the water content is about 200 kg/m^3. However, under low binder amount ($N < 1.6$), the effect of mixing sequence and type of mixer on the mixing efficiency of HPC becomes more significant. The horizontal twin shaft concrete mixer is found to perform better than the drum type mixer in terms of less mixing time required, implying greater economy in operation. Method 6 is also found to be the most efficient and economical. It involves first the preparation of the lubricating binder that enables SP to be sufficiently mixed. Since there is only water and binder, the high concentration of SP will ensure a highly unformed paste to be obtained. On the contrary, other methods are not effective in coating aggregate uniformly with cement paste. In addition, the cement particles are also not dispersed well in the paste. Under low binder content, initial binder mixing only needs a smaller SP dosage and may lower both the paste and water content. A shorter mixing time is required to obtain the fresh properties, thus reducing the damage to the mixing blades. In addition, higher strength is achieved which proves to be particularly important for HPC of low binder content and high flowability.

Acknowledgments

The authors thank the National Science Council of the Republic of China for the financial support. We are also grateful to Professor C.L. Hwang for his assistance on this subject to help finish this research.

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