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Properties of Self-Compacting Concrete with Machine-Made Sand and High-Volume Mineral Admixtures

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Abstract: Based on appropriate assessment methods and indexes of self-compacting concrete proposed, properties of concrete made with river-sand and machine-made sand was firstly compared in different mix proportions. The techniques such as basic parameters optimization of mix proportion, admixture composition, large-volume mineral admixtures addition for preparing machine-made sand self-compacting concrete (MSCC) were proposed, and effect of different factors on workability and compressive strength of MSCC was studied. The results indicate that requirements on parameters of mix proportion for MSCC are different from those of river-sand self-compacting concrete. Applying the techniques such as basic parameters optimization of mixture, admixture composition, high-volume mineral admixtures addition, MSCC with initial slump above 24cm, slump flow over 60cm, delivery time of inverted slump cone (DTIS) between 5s and 15s, compressive strength above 60MPa at 28 days was prepared.

Keywords: Machine-made sand; self-compacting; concrete; mineral admixture; workability

INTRODUCTION

Concrete is the largest consuming construction material for buildings at present [1, 2]. Being one of main components of concrete, sand generally includes natural sand and machine-made sand. However, natural sand, river sand as its largest portion, could not meet with the increasing demand for concrete production in some countries and regions, especially in southwest China. Meanwhile, over quarrying natural sand will undoubtedly damage the natural environment. Thus, the substitution of machine-made sand to river sand for preparing concrete has becoming a steady tendency in concrete industry [3, 4]. Application research on machine-made sand for preparing concrete has carried out for so many years in several countries and regions. At present, machine-made sand has been applied in mortar, concrete and masonry blocks in some regions in China, particularly in places such as Yunnan and Guizhou provinces in southwest China, where river sand are scarce [3-7].

Due to excellent workability, mechanical property and durability, self-compacting concrete is extensively applied in concreting projects recently. Meanwhile, self-compacting concrete has become an important research and application aspect of high-performance concrete. In recent years, a number of research and application on self-compacting concrete have been carried out [8-11]. In addition, mineral admixtures, such as fly ash, slag powder and silica fume have become indispensable components for preparing high-performance concrete [12, 13]. As to areas where are shortage of river sand, research on machine-made sand used in self-compacting concrete also becomes critical and important. MSCC has unique characteristics and requirements and differentiates from normal concrete in terms of materials, composition, mix proportion design, quality control and testing methods. Since sand is one of main components of self-compacting concrete in volume, it affects properties of self-compacting concrete certainly. As compared with river sand, machine-made sand features in poor gradation and texture, rough particles concentrated on two ends of graduation and high volume of rock powder. MSCC has its own distinctive properties. Therefore, research on preparation techniques and properties of machine-made sand self-compacting concrete with large-volume mineral admixtures is very significant to promote application of MSCC according to material properties of mineral admixtures and machine-made sand.

In this paper, properties of concrete made with river-sand and machine-made sand was compared in different mix proportions in the first study phase based on appropriate assessment methods. In the second study phase, effects of basic parameters of concrete mix proportion admixture type and dosage, mineral admixtures on workability and mechanical properties of MSCC. Then key technical parameters for machine-made sand self-compacting concrete with large-volume mineral admixtures are proposed.

RAW MATERIALS

In this experiment, An ordinary Portland cement corresponding to ASTM type 1 was used. Fly ash Class II with burning loss of 6.8% and specific surface area of 410m^2/kg and silica fume was used. Chemical components of cement and mineral admixtures are shown in Table 1. Polycarboxylate superplasticizer with solid content of 30%, Welan viscosity-enhancing agent (VEA), de-foaming agent, air-entrainment agent were employed.

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Table 1. Chemical Component of Cement and Mineral Admixtures (%)

Materials	CaO	SiO_2	Al_2O_3	SO_3	Fe_2O_3	MgO	K_2O	TiO_2	Na_2O
Cement	59.9	21.3	7.6	3.1	3.8	2.0	1.2	0.7	0.2
Fly ash	3.3	44.1	26.8	0.9	10.2	0.9	2.4	2.4	0.9
Silica fume	0.4	91.0	1.1	0.3	2.0	1.0	0.9	-	0.2

Table 2. Physical Properties of River Sand and Machine-Made Sand

Items	Packing Density(g/cm^3)	Apparent Density(g/cm^3)	Crushing Index(%)	Modulus of Fineness	Content of Rock Powder(%)
River sand	1.49	2.67	10.2	2.5	0.3
Machine-made sand	1.61	2.70	14.1	3.5	9.2

Distribution curves of particle sizes of cement, fly ash and silica fume are indicated in Fig. (**1**). It can be seen that distribution areas of particle diameters of them are different from each other. Specifically, particle diameter of silica fume is very small and narrowly distributed while that of fly ash is high and broadly distributed.

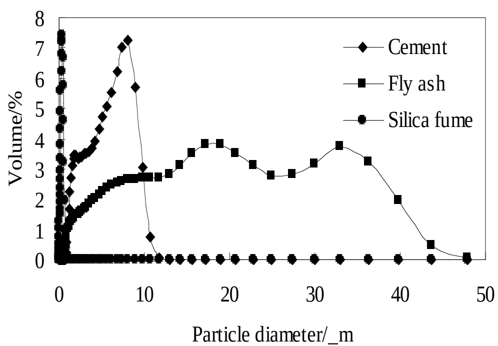

Fig. (1). Distribution of particle size of cement and mineral admixtures.

Machine-made sand as fine aggregate is made from rock of dolomite. It is an inactive aggregate. Basic physical properties of river sand and machine-made sand are shown in Table **2**. Separate sieve residue and cumulative sieve residue

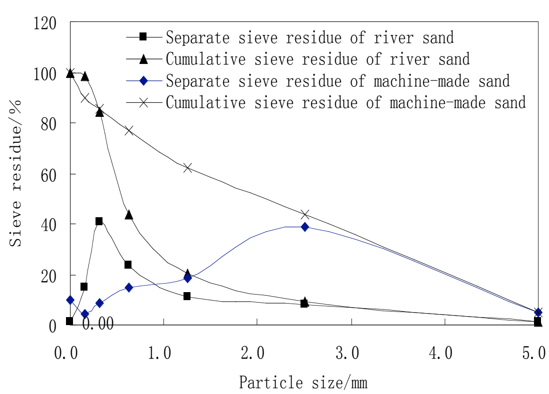

Fig. (2). Sieving curves of river sand and machine-made sand.

of machine-made sand and river sand are shown in Fig. (**2**). As illustrated in this Fig. (**2**), content of rock powder in machine-made sand is very high and the gradation is not uniform.

Coarse aggregate made from dolomite rock with maximum size of 25 mm, apparent density of 2.64g/cm^3, bulk density of 1.52g/cm^3, crushing index of 11.4% and soil content of 0.8% was used. To realize best aggregate gradation for preparing MSCC, gradation of coarse aggregate is divided into four sections: 5-10mm, 10-16mm, 16-20mm and 20-25mm.

EXPERIMENTAL METHODS

Testing Methods for Determining Workability Of Self-Compacting Concrete

Three testing methods, slump, slump flow and DTIS, are adopted for assessing properties of self-compacting concrete mixtures. In this program, Basic requirements on workability of self-compacting concrete shall meet initial slump larger than 22cm, slump flow more than 55cm and DTIS between 5s and 15s.

Testing Methods of Slump and Slump Flow

Testing method for slump of concrete mixture is carried out according to Chinese specification GBJ80. Based on tested slump, slump flows at two vertical directions in horizontal plane are read and averaged as the final slump flow.

Delivery Time of Inverted Slump Cone (DTIS)

DTIS that was designed according to the characters of MSCC is an effective parameter to reflect viscosity and cohesiveness of fresh MSCC. The procedure of delivery time measurement is defined as follows: invert the slump cone on the supporter surface up to ground a certain height. Add fresh concrete into it fully. Then float it. Fix the slump cone and remove the supporter. And allow fresh concrete to flow out from the bottom mouth of the slump cone. The delivery time when all fresh concrete flows out is recorded using the stop watch (s). The delivery time could indicate plastic viscosity and yield value of self-compacting concrete mixture. DTIS testing method is practical, convenient and repeatable.

Table 3. Properties of Concrete with River Sand or Machine-Made Sand

Serial	Sand Type	Content of Fly Ash/%	Slump/cm			Slump Flow/cm			DTIS/s		
			0h	1h	2h	0h	1h	2h	0h	1h	2h
SG1	River sand	20	26.0	25.5	23.5	70.0	68.0	65.5	7.1	9.8	13.5
SG2	Machine-made sand	0	21.0	16.0	13.5	55.0	31.0	28.0	38.0	58.5	195.0
SG3		20	21.0	18.0	15.0	49.0	35.0	29.5	36.5	72.5	188.0
SG4		40	23.5	22.0	20.5	61.0	47.0	39.0	13.9	14.0	15.9

Table 4. Effect of w/b on Properties of Concrete with Machine-Made Sand

Serial	Ratio of Water to Binder	Slump/cm		Slump flow/cm		DTIS/s		Mixture Behavior
		0h	2h	0h	2h	0h	2h	
SG5	0.4	23.0	23.5	65.0	67.0	24.5	32.1	Bleeding and segregation
SG6	0.35	23.5	23.0	64.0	58.0	12.1	15.1	Good coherence
SG7	0.32	24.5	22.5	65.0	55.0	18.0	26.0	High viscosity

Specimen Preparation, Curing and Testing

A certain amount of sand, aggregate, cement and powder admixtures according to mix proportion in each batch is firstly mixed for half minute. Then water and superplasticizer are added in the continuous mixing process for two minutes for achieving designed slump. The workability of concrete mixture is tested and then it is put into specimen molds in the dimension of 10×10×10cm without vibration.

After one day standard curing, specimens are removed from the molds. Then they are cured in standard way at curing room with the curing temperature 20±3°C and humidity no less than 90%. Testing method for compressive strength of concrete is carried out according to Chinese specification GBJ82.

PROPERTIES OF CONCRETE WITH RIVER SAND AND MACHINE-MADE SAND IN DIFFERENT MIX PROPORTIONS

On the basis of a series of experiment, basic parameters of mix proportion of self-compacting concrete with river sand is determined as follows: ratio of water to cement is 0.35; sand ratio is 50%; dosage of CS-SP1 superplasticizer is 1.2% by weight of total cementitious materials (the maximum size of coarse aggregate is 25mm; coarse aggregate gradation is 5-10mm：10-20mm：20-25mm =30％:40％:30％. Basic mix proportion of self-compacting concrete is cementitious material: sand: coarse aggregate: water: superplasticizer as 500: 860: 860: 175: 6 (kg/m^3). Workability properties of concrete with river sand and machine-made sand were investigated.

According to the results shown in Table **3** and observations during test, properties of concrete made with river sand perform well, which meets the requirement of self-compacting concrete. Problems are existed in concrete made with machine-made sand, such as slump and slump flow lower than requirements, long DTIS and high slump loss occurred in spite of the addition of large-volume fly ash. It illustrates that poorer cohesion and easier blockage exist in machine-made sand concrete compared with river sand self-compacting concrete. Thus, it is necessary to adjust and optimize parameters and key techniques of mix proportion of MSCC for meeting the required properties of self-compacting concrete.

OPTIMIZATION TECHNIQUES OF BASIC PARAMETERS OF MIX PROPORTION

Ratio of Water to Binder

Basic parameters of MSCC are determined for tests as follows: maximum size of coarse aggregate is 20mm; sand ratio is 50%; dosage of CS-SP1 superplasticizer is 1.2%; content of fly ash is 40% and content of silica fume is 5%. The workability results of concrete with machine-made sand with different ratios of w/b are shown in Table **4**.

As it shows in Table **4**, initial slump and slump flow are not changed largely with increasing ratio of w/b from 0.32 to 0.4 while initial and 2-hour DTIS decrease first and increase then. This illustrates that concrete with machine-made sand is sensitive to the ratio of w/b. When the ratio of w/b is small, concrete mixture becomes viscous. In contrast, segregation and bleeding occurred in concrete mixture with increasing the ratio of w/b. Meanwhile, DTIS becomes longer. All these indicate that workability properties of concrete with machine-made sand could not be improved if it only increases water content. Flowability and cohesion of concrete could not reach the SCC requirements if it only increases content of agents or ratio of w/c. it needs to adopt other techniques of admixture composition and large-volume

Table 5. Effect of Sand Ratio on Properties of Concrete With Machine-Made Sand

Serial	Sand Ratio/%	VEA /‰	Slump/cm			Slump Flow/cm			DTIS/s			Compressive Strength/MPa		
			0h	1h	2h	0h	1h	2h	0h	1h	2h	3d	7d	28d
SG8	45	0.4	21.5	20.5	21.5	63.0	61.0	58.0	6.5	7.0	10.0	18.0	38.1	58.1
SG9	50	0.5	26.0	25.5	22.5	72.0	71.0	72.5	8.8	10.8	15.8	28.3	49.4	73.1
SG10	55	0	23.5	22.5	21.5	64.0	53.0	54.0	26.0	39.0	38.0	25.2	43.2	65.3

Table 6. Mix Proportion of MSCC Different Graduations of Coarse Aggregate

Serial	Superplasticizer		Coarse Aggregate		VEA/‰
	Type	Dosage/%	5-10mm	10-20mm	
SG11	CS-SP1	1.3	60	40	0
SG12		1.5	50	50	0.2
SG13		1.5	40	60	0.5

Table 7. Properties of MSCC with Different Graduations of Coarse Aggregate

Serial	Slump/cm			Slump Flow/cm			DTIS/s			Compressive Strength/MPa		
	0h	1h	2h	0h	1h	2h	0h	1h	2h	3d	7d	28d
SG11	24.0	23.0	20.5	66.0	64.0	44.0	10.1	12.0	12.3	17.2	28.0	52.3
SG12	23.5	22.0	21.5	63.0	58.0	55.0	10.1	13.1	13.5	21.9	38.5	60.3
SG13	26.0	25.5	22.5	72.0	71.0	72.5	8.8	10.8	15.8	28.3	49.4	73.1

mineral admixtures addition to improve properties of self-compacting concrete.

Sand Ratio

Parameters of mix proportion of self-compacting concrete are determined as follows: Ratio of w/b is 0.35. Content of fly ash is 40%. Content of silica fume is 5%. The dosage of superplasticizer is 1.5%, and maximum size of aggregate is 20mm and aggregate gradation: 5-10mm：10-20mm is 40%: 60%.

Based on the above mix proportion, content of viscosity enhancing agent is adjusted. Effect of different sand ratio on properties of concrete with machine-made sand is shown in Table **5**.

As it shows in Table **5**, when sand ratio of self-compacting concrete is 45%, it seems that bleeding and segregation of concrete mixture occurred while slump and slump flow are not good. Meanwhile, DTIS is relatively small. When sand ratio of self-compacting concrete reaches 50%, slump and slump flow becomes very large and DTIS is reasonable. When sand ratio of self-compacting concrete reaches 55%, viscosity of concrete becomes higher and other properties of concrete mixture also are good without adding viscosity enhancing agent. Meanwhile, flow value of concrete becomes higher. DTIS, however, is too high. Regarding the development of compressive strength, compressive strength of concrete at different ages increases first and decreases then with the increase of sand ratio. Judging from the above analysis, sand ratio of MSCC should not be too low. It is suggested that sand ratio of MSCC is preferably approximate 50%.

Aggregate Gradation

Based on the above mix proportion of concrete shown above, content of superplasticizer is adjusted. Effects of different graduations of coarse aggregate on properties of concrete with machine-made sand are shown in Table **6**, **7**.

As it shows in Table **6**, **7**, different graduations of coarse aggregate affect properties of self-compacting concrete mixture to some extent. With the decrease content of median-size and small-size aggregates, flowability of self-compacting concrete becomes larger while the tendency of segregation also becomes distinctive. Thus it needs to add VEA for adjustment. From the development of compressive strength, compressive strength of self-compacting concrete becomes larger with the decrease of median-size and small-size aggregates. In general, properties of MSCC are good when the maximum size of aggregate is within 20mm. It is found that comprehensive properties of MSCC is preferably good when the maximum size of aggregate is 200mm and the aggregate gradation 5-10mm：10-20mm is 50%: 50%.

Techniques of Admixture Composition

Admixtures are key components of materials used for preparing high-performance self-compacting concrete. With

Table 8. Effect of Types of Superplasticizer on Properties of MSCC

Serial	WRA		VEA /‰	Slump/cm		Slump flow/cm				DTIS/s			Compressive strength/MPa		
	Type	Dosage/%		0h	1h	0h	1h	2h	2h	0h	1h	2h	3d	7d	28d
SG14	LX-6	1.6	10	24	23.5	20.5	61	56	42	12	14.1	18	18.9	36.5	55.3
SG15	CS-SP1	1.4	2	23.5	22.0	21.5	63	58	55	10.1	13.1	13.5	21.9	38.5	60.3
SG16	V500	2.0	5	25.5	23.5	23.5	65	66	64	7.3	7.7	10	20.5	28.5	51.6
SG17	V3320	1.5	20	23.5	22.0	20.0	60	56	50	21	27.6	31.4	20.5	36.7	54.7

Table 9. Effect of Composite Addition of Superplasticizer and Viscosity-Enhancing Agent on Properties of MSCC

Serial	WRA		VEA /‰	Slump/cm		Slump flow/cm				DTIS/s			Compressive strength/MPa		
	Type	Dosage/%		0h	1h	0h	1h	2h	2h	0h	1h	2h	3d	7d	28d
SG18	V3320	1.5	0	24	22	30	48	45	42	30	33	36.3	-	-	-
SG18-1			0.1	24.5	24	25.5	65	60	58	25.5	28	31.1	20.5	36.7	54.7
SG19	CS-SP1	1.2	0	23	22	24.8	55	50	44	24.8	27.6	31.2	-	-	-
SG19-1			0.2	23	23.5	11.1	57	55	54	11.1	12.5	14.1	18.9	36.5	55.3

the addition of admixtures, such as superplasticizer, VEA and defoamer, MSCC could achieve proper viscosity, good flowability and cohesion, plastic and mechanical properties under lower ratio of w/b.

Types of Superplasticizer

Parameters of mix proportion of MSCC are determined as follows: sand ratio is 50%; ratio of w/b is 0.35; dosage of CS-SP1 superplasticizer is 1.2%; content of fly ash is 40% ; content of silica fume is 5%; maximum size of aggregate is 20mm and aggregate gradation of 5-10mm:10-20mm is 50%:50%. Based on the above mix proportion, content of superplasticizer is adjusted to keep initial slump about 23±1cm. Effects of four types of polycarboxylate superplasticizer, namely, LX-6, CS-SP1, V500, V3320 on properties of concrete are shown in Table **8**.

As it shows in Table **8**, concrete added with SP1 and V500 superplasticizer is relatively good with less loss of slump flow. Judging from DTIS, concrete added with V500 superplasticizer has the shortest DTIS. Then it is concrete added with CS-SP1 superplasticizer. In contrast, concrete added with LX-6 and V3320 superplasticizers shares larger average values on DTIS, which indicates that concrete mixture is too viscous. Judging from compressive strength, compressive strengths of concrete added with CS-SP1 superplasticizer at the age of 3 days, 7 days and 28 days are highest. Considering properties of concrete mixture and mechanical properties, properties of CS-SP1 polycarboxylate superplasticizer are best.

Viscosity Enhancing Agent (VEA)

VEA is a necessary admixture for preparing self-compacting concrete, particularly for MSCC. Under the same conditions, Effect of composite addition of superplasticizer and VEA in different dosages on properties of MSCC are shown in Table **9**.

As it shows in Table **9**, concrete added with V3320 superplasticizer and without VEA, slump flow reaches 48cm and segregation is occurred although slump reaches 24cm. In addition, DTIS is up to 30 seconds. After added a certain amount of VEA, workability of concrete is much improved and slump flow also increases to 65cm. It almost reaches the requirements except of a little longer of DTIS. As to concrete added with CS-SP1 superplasticizer and VEA, its properties are improved in general, much shorter of DTIS in particular. Judging from the tendency of strength, early strength of concrete will be reduced with VEA while the later strength will be not affected. It indicates that it is necessary to add certain amount of VEA into MSCC to improve properties.

TECHNIQUES OF LARGE-VOLUME MINERAL ADMIXTURES ADDITION

Types and Content of Mineral Admixtures

Based on the above mix proportion shown above, effects of single addition and composite addition of different mineral admixtures on properties of MSCC are shown in Table 10.

As it shows in Table **10** and Table **11**, when content of fly ash reaches 20%, silica fume 3% and admixtures 1.5%, water bleeding and segregation are occurred while DTIS becomes too long and viscosity is too small. After a certain amount of VEA is added, viscosity of concrete is improved. Segregation, however, still exists to some extent. When it increases the amount of fly ash and silica fume and adjusts content of admixture, good properties of concrete could be

Table 10. Mix Proportion of MSCC With Different Mineral Admixtures

Serial	Content of Fly Ash/%	Content of Silica Fume/%	Grade of Coarse Aggregate		CS-SP1 WRA/%	VEA/‰
			5-10	10-20		
SG20	20	0	40%	60%	1.5	-
SG21	20	3	40%	60%	1.5	0.5
SG22	40	5	40%	60%	1.2	0.6
SG23	40	5	50%	50%	1.6	0.2
SG24	40	8	50%	50%	1.5	0.05
SG25	40	10	50%	50%	1.2	-

Table 11. Properties of MSCC with Different Mineral Admixture

Serial	Slump/cm		Slump flow/cm		DTIS/s		Compressive Strength/MPa		
	0h	2h	0h	2h	0h	2h	3d	7d	28d
SG20	24.0	24.0	67.0	66.0	37.5	68.5	23.1	44.1	59.3
SG21	25.5	22.5	71.0	72.5	27.8	53.8	28.2	49.4	58.3
SG22	24.5	23.0	62.0	53.5	10.6	13.7	14.9	27.5	51.1
SG23	24.5	23.0	66.0	52.0	6.4	6.1	18.2	32.2	55.6
SG24	23.0	23.0	62.0	58.0	15.0	32.7	17.1	35.1	53.7
SG25	21.5	19.5	45.0	34.0	12.9	20.5	16.4	28.8	59.3

Table 12. Effect of the Amount of Cementitious Material on Workability Properties of MSCC

Serial	ACE/kg • m^{-3}	VEA/ ‰	Slump/cm			Slump flow/cm			DTIS/s		
			0h	1h	2h	0h	1h	2h	0h	1h	2h
SG26-1	450	0.2	23.5	23.0	21.0	65.0	63.0	51.0	14.3	16.0	19.1
SG26-2	450	0.3	22.0	21.5	20.5	62.0	58.0	46.5	15.3	18.0	35.5
SG27	500	0	22.0	20.5	19.0	68.0	58.0	53.0	14.8	16.4	19.5
SG27-1	500	0.1	25.0	24.5	23.0	68.0	62.0	53.5	8.8	10.6	23.7
SG28-1	550	0.05	25.5	25.5	23.0	69.0	67.5	60.0	5.0	5.6	8.5
SG28-2	550	0.1	24.5	24.0	22.0	68.0	67.0	62.0	6.6	8.0	15.0

achieved. When the amount of silica fume continuously increases, cohesion will be increased. But if silica fume is added too much, that is to say, when it is up to 8%, viscosity will be remarkably increased while flow value will become smaller. When 40% fly ash and 5% silica fume are added into MSCC, workability of MSCC will be improved effectively. Compressive strength of MSCC at later ages increases quickly although it is a little low at early ages. Therefore, techniques of large-volume mineral admixtures addition are critical to prepare MSCC.

Amount of Cementitious Material (ACE)

The amount of cementitious material will significantly affect physical and mechanical properties of MSCC. Based on the above mix proportion given above, effects of the amount of cementitious material on properties of MSCC are shown in Table **12**, **13**.

As it shows in Table **12**, **13**, when the amount of cementitious material is small, slump and slump flow could not reach the requirements of SCC. With increasing the amount of cementitious material, properties of mixture of self-compacting concrete become better while slump and slump flow could reach ideal values with short DTIS. It indicates that the higher the amount of cementitious material, the better the workability of MSCC is. Judging from compressive strength, although compressive strength of every set of sample concrete at 28 days is over 50 MPa, compressive strength

Table 13. Effect of the Amount of Cementitious Material on Compressive Strength of MSCC

Serial	ACE/kg・m^{-3}	Compressive strength/MPa		
		3d	7d	28d
SG26-2	450	15.7	33.9	54.3
SG27-1	500	21.9	37.7	61.3
SG28-2	550	17.1	33.2	55.8

of concrete at different ages does not increase with the increase of the amount of cementitious material. When the amount of cementitious material reaches 500kg/m^3, compressive strength at each age is the highest.

CONCLUSIONS

Machine-made sand features in much content of rock powder, rough surface and poor graduation. Basic parameters of mix proportion of MSCC are different from that of self-compacting concrete with river sand.

Ratio of water to binder significantly affects flowability and cohesion of MSCC. As to MSCC, sand ratio shall not be too low while the maximum size of aggregate and aggregate gradations critical parameters to affect workability and mechanical properties of MSCC.

The techniques, such as composite addition of superplasticizer and viscosity enhancing agent and composite addition of large-volume fly ash and silica fume will effectively improve flowability, cohesion and mechanical properties of MSCC.

Applying the techniques such as optimization on basic parameters of mix proportion, admixture composition, high-volume mineral admixtures addition, MSCC with initial slump over 24cm, slump flow over 60cm, DTIS between 5s and 15s, compressive strength above 60MPa could be prepared.

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