Cement & Concrete Composites 33 (2011) 353–358

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Fresh and hardened properties of self-compacting concrete produced with manufactured sand

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ARTICLE INFO

Article history:
Received 4 January 2010
Received in revised form 16 November 2010
Accepted 26 November 2010
Available online 1 December 2010

Keywords:
Manufactured sand
Self-compacting concrete
Packing density
Paste volume

ABSTRACT

Self-compacting concrete (SCC) is extensively applied in many construction projects due to its excellent fresh and hardened concrete properties. In recent years, manufactured sand (Msand) produced by crushing rock deposits is being identified as a suitable alternative source for river sand in concrete. The main objective of this study is to explore the possibility of using Msand in SCC. In this process, an attempt was made to understand the influence of paste volume and w/p ratio (water to powder ratio) on the properties of self-compacting concrete (SCC) using Msand. The powder and aggregate combinations were optimised by using the particle packing approach, which involves the selection of combinations having maximum packing density. The chemical admixtures (superplasticisers, viscosity modifying agent) were optimised based on simple empirical tests. Fresh concrete tests such as slump flow, T_{500} and J-ring were performed on SCC; hardened concrete tests were limited to compressive strength. From the results, it was observed that relatively higher paste volume is essential to achieve the required flow for SCC using Msand, as compared to river sand. Low and medium strength (25–60 MPa) SCCs were achieved by using Msand based on the approach adopted in the study. Results showed that it is possible to successfully utilise manufactured sand in producing SCC.

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1. Introduction

Self-compacting concrete (SCC) is a highly flowable concrete which does not segregate and can spread into place, fill the formwork with heavily congested reinforcement without any mechanical vibration [1]. In SCC, the aggregates contribute 60–70% of the total volume. Proper choice of aggregates has significant influence on the fresh and hardened properties of concrete [2]. Aggregate characteristics such as shape, texture and grading influence workability, finishability, bleeding, pumpability, segregation of fresh concrete and strength, stiffness, shrinkage, creep, density, permeability, and durability of hardened concrete [3]. The effects of shape and texture of fine aggregate are much more important than the effects of coarse aggregate [4].

River sand (Rsand) is being used as fine aggregate in concrete for centuries. However, increase in demand and depletion of river sand, along with restrictions imposed on the exploitation of the river sand, have resulted in search for a suitable alternative. From the literature [5–7], it was identified that the alternative materials for river sand include manufactured sand (Msand), industrial by products (some forms of slag, bottom ash), recycled aggregates, etc. Among these materials, Msand is receiving great attention these days as a replacement for river sand. The Msand is produced by crushing rock deposits to obtain a well graded fine aggregate which is generally more angular and has a rougher surface texture than naturally weathered sand particles. However, by using appropriate crushing technology (Impact crushing – Comminution in this type of crusher is the result of propelling particles with a rotor moving at high speeds, against an anvil or a curtain of falling particles), it is possible to produce cubical particle shapes with uniform grading, consistently under controlled conditions [8].

Manufactured sands contain high fines content [9]. Generally, the fines are composed of rock dust rather than the silts and clays in the case of natural sands. The maximum permissible limit of Msand fines (75 μm passing) as per ASTM C 33 is 7% [10] and the limit proposed for Msand fines (150 μm passing) as per the Indian standards is 20% [11]. Due to the presence of high fines content, the Msand has a significant influence on the water demand and the workability of the mortar [5]. The high fines content in crushed fine aggregate mainly increases the yield stress of the mortar due to increased interparticle friction, and contributes to the increase in plastic viscosity. The influence of fine aggregate on the properties of mortar to a large extent depends on the paste volume of the mortar. The negative effects of poorly graded and shaped aggregates can be eliminated or significantly reduced by increasing the

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doi:10.1016/j.cemconcomp.2010.11.005

volume of paste [12]. On the other hand, the mechanical and durability properties of the concrete are reported to be considerably improved by using Msand (especially produced from granite sources in comparison with the dolomite and sandstone origin) [5,13]. For SCC, high powder (cement, cementitious materials and inert fillers) content is essential for achieving the required fresh concrete properties [14,15]. Therefore, Msand, which contains large amount of fines, can be used as an alternative to river sand. The excess fines in Msand contribute to the filler content of the SCC. However, due to the higher water demand of Msand, the suitability for usage in SCC is questionable. While a number of studies have been conducted on the use Msand in conventional concrete, there are few instances of its application in SCC. The experimental investigations consisted of two phases. The first phase of the investigation involved the optimisation of the powder and aggregate combinations by using the particle packing concept. The degree of particle packing was measured in terms of packing density. Packing density is defined as the volume fraction of the system occupied by solids. Further, with the optimised combinations, experiments were conducted to evaluate the influence of paste volume and water to powder (w/p) ratio on the fresh and hardened properties of SCC by using Msand in the second phase.

2. Materials used

In the present investigation, Ordinary Portland Cement – 53 grade [16] and fly ash (Class F – from North Chennai Power Station, India), were used. The chemical composition and the physical properties of the cement and fly ash are given in Tables 1 and 2. Msand as fine aggregate (Source – Granite, Method of production – Impact crushing) and two different sizes of coarse aggregate (crushed granite – maximum sizes 12.5 mm and 20 mm) were also employed. The physical properties of aggregates are given in Table 3. The particle size distribution of the materials (cement, fly ash, Msand, coarse aggregates) used is presented in Fig. 1. The particle size distribution of the powders (cement and fly ash) was measured by using laser diffraction method by dispersing the powder in glycerol. The gradation of Msand conforms to Zone II of Indian standards [11] (see Fig. 1). The fines content of the Msand is within the maximum limit of ASTM C 33 and IS 383. Potable water at a temperature of 28 ± 1 °C was used in order to achieve SCC. A third generation polycarboxylic ether based superplasticiser (SP) with an active solids content of 33% was used. A microbial polysaccharide was also employed as viscosity modifying agent (VMA).

Table 1
Chemical composition of cement and fly ash.

Chemical composition	Cement (% by mass)	Fly ash – Class F (% by mass)
CaO	61.18	1.41
SiO_2	20.01	60.56
Al_2O_3	4.98	32.67
Fe_2O_3	4.88	4.44
MgO	1.78	0.23
SO_3	2.36	0.02
Loss on ignition	2.18	0.21
Total chloride content	0.03	0.01
Na_2O	0.20	0.02
K_2O	0.60	0.03
Insoluble residue	1.23	0.46

Bogue compound composition of cement

Compound	% by mass
C_3S	49.82
C_2S	19.78
C_3A	4.94
C_4AF	14.84

Table 2
Physical properties of cement and fly ash.

Property	Cement	Fly ash
Specific gravity	3.15	2.00
Mean diameter (μm)	16.74	38.16
Specific surface area (Blaine's method) (m^2/kg)	355	151

Table 3
Physical properties of aggregates.

Properties	Msand	12.5 mm	20 mm
Specific gravity	2.65	2.80	2.78
Bulk density (kg/m^3)	1857	1528	1644
Void content (%)	29.95	45.45	40.86
Water absorption (%)	1.00	0.35	0.20

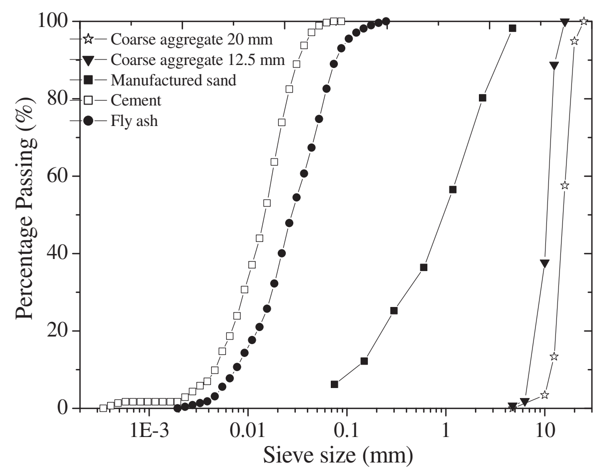

Fig. 1. Particle size distribution of the materials used.

3. Optimisation of paste and aggregate combinations

3.1. Optimisation of paste composition

The powder (cement and fly ash) combination was selected based on the particle packing concept by using Puntke test [17]. The basic principle of the Puntke test is that the water which is added to the dry materials fills the voids in between the particles and acts as a lubricant to make the materials compact efficiently. The water, which is in excess after completely filling the voids, appears at the surface of the mixture, indicating the saturation limit. The combination of 60:40 (cement:fly ash) by volume, resulting in maximum packing density, was selected for further investigations. With optimum combination of powder, the cementitious paste was prepared for different w/p ratio and superplasticiser dosage by using a planetary motion high shear (Hobart) mixer. The superplasticiser dosage was optimised in cementitious paste by using mini-slump cone test [18] for different w/p ratio. The dosage corresponding to 170 ± 10 mm without bleeding in cementitious paste was identified as the criterion for optimum SP dosage [19]. Based on these criteria, the SP dosage was optimised and the results are shown in Table 4. The VMA dosage was optimised by using the Marble test [20] in the cementitious pastes. The VMA dosage was optimised in cementitious paste with optimum SP dosage for corresponding w/p ratio. The tests were conducted only for mixtures that segregated in SCC. In the marble test, marbles were chosen instead of aggregates due to their simple shape, and similar specific gravity. Aggregates pose complications owing to their

Table 4
Optimised dosage of superplasticiser and viscosity modifying agent.

w/p ratio (vol.)	Optimum SP dosage (% of solids by weight of powder)	Optimum VMA dosage (% of solids by weight of powder)
0.7	0.23	–
0.8	0.21	–
0.9	0.18	0.007
1.0	0.16	0.011
1.1	0.14	0.014
1.2	0.12	0.021
1.5	0.07	–

irregular shape and orientation. Glass marbles of size closest to the maximum size of the aggregates were used in the experiments. When a spherical body is dropped into liquid medium, three forces act on it: the buoyancy force (Fb) (upward force), viscous force (Fd) (upward force) and the acceleration due to gravity (mg) (downward force). When the glass marble is dropped into the cementitious paste, the marble moves down till the sum of viscous and buoyancy forces equal the weight of the ball. The depth of penetration of the marble indicates the resistance offered by the paste to the downward movement of the marble. The viscosity of the paste increases with increase in the VMA dosage, which is reflected in reduction in the depth of penetration. The optimum dosages selected from paste studies were evaluated in SCC by using the sieve segregation test [21]. The optimised dosages thus determined are given in Table 4. The optimum dosage of VMA was added only to those SCC mixtures that segregated. VMA dosages lower than the optimum dosages were not sufficient enough to control the segregation in concrete. On the other hand, VMA dosages higher than optimum resulted in reduced slump flow of concrete.

3.2. Optimisation of aggregate combination

Research has shown that the packing density of concrete mixtures and the flow properties of corresponding fresh concrete are related [22]. It was observed from [23] that the aggregate combination with maximum packing density significantly influences the properties of concrete, apart from economic benefit. Therefore, the aggregate combination was optimised based on the particle packing concept.

Experiments were conducted in a systematic way to determine the packing density of different combination of aggregates.

Step 1: A mass equivalent of 12 L of coarse aggregates (12.5 mm max. size and 20 mm max. size) and Msand is taken according to the corresponding volume proportions in separate plastic trays

Step 2: The three types of aggregates are mixed manually for obtaining a proper blend.

Step 3: The mixed aggregates are poured into the steel bucket without any compaction. The bottom door of the steel bucket is then opened to make the aggregates fall instantaneously into a bottom container. This cylindrical bottom container of diameter 250 mm (more than 10 times the diameter of the maximum size of aggregates used (20 mm)) was selected to make the wall effect negligibly small.

Step 4: The excess aggregates remaining above the top level of the bottom cylinder are struck off. The mass of the cylinder along with the aggregates filled is measured and the empty mass of the cylinder is deducted to determine the exact quantity of individual aggregates filled in the bottom container.

Knowing the mass of the individual aggregate type added and the volume of the container, the void content can be calculated. The packing density of the aggregates is calculated from the void content. The equations for calculating the void content and packing density are as follows:

$$\text{Void content} = (V_c - ((M_1/S_1) + (M_2/S_2) + (M_3/S_3)))/V_c \qquad (1)$$

where V_c is the volume of the container, M_1, M_2, M_3 are the mass of each aggregate type and S_1, S_2, S_3 are the specific gravity of corresponding aggregate type.

$$\text{Packing density} = 1 - \text{void content} \qquad (2)$$

It was decided to develop a ternary packing diagram for the Msand and the two sizes of coarse aggregates based on the experimental results. By using the ternary packing diagram, it is possible to determine packing density of any given combination of aggregates. However, conducting experiments to obtain the packing density for all the combinations of aggregates is cumbersome. Therefore, 24 experiments were carried out for different combinations of Msand: 12.5 mm max. size aggregate: 20 mm max. size aggregate (by volume) for the determination of packing density of aggregates. The 24 experimental data points were selected evenly to cover the total triangular area (see Fig. 2). For developing a ternary packing diagram, 24 data points were insufficient. Therefore, a mathematical interpolation was made to get the required number of data for developing a ternary packing diagram. The different aggregate combinations of Msand: 12.5 mm max. size aggregate: 20 mm max. size aggregate resulted in a minimum packing density of 0.55 and maximum packing density of 0.70 (see Fig. 3). For validation of the interpolated data, five different combinations (05:15:80, 05:90:05, 20:70:10, 30:55:15, 50:10:30) were chosen randomly and experiments were conducted. A plot was made between the measured packing densities and calculated packing densities of the aggregates (see Fig. 4). From Fig. 4, it is evident that the calculated values of packing density are close to the measured values.

The maximum packing density of 0.70 was achieved by a set of aggregate combinations (see Fig. 3). After conducting trials, the combination of 55:15:30 (Msand: 12.5 mm max. size aggregate: 20 mm max. size aggregate) resulting in the maximum packing density of 0.70 was selected for further investigations on SCC. The packing density of 0.70 indicates a void volume of 0.3 or 300 L/m^3.

From Fig. 3, it can be observed that the packing density is significantly influenced by the maximum size aggregate (20 mm) and

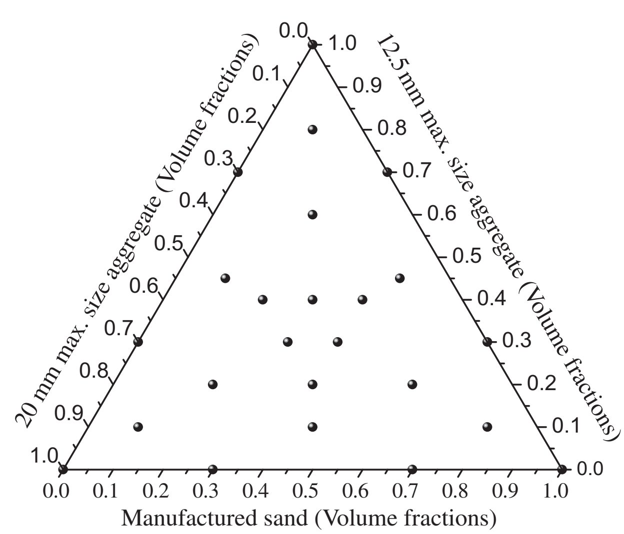

Fig. 2. Experimental data points.

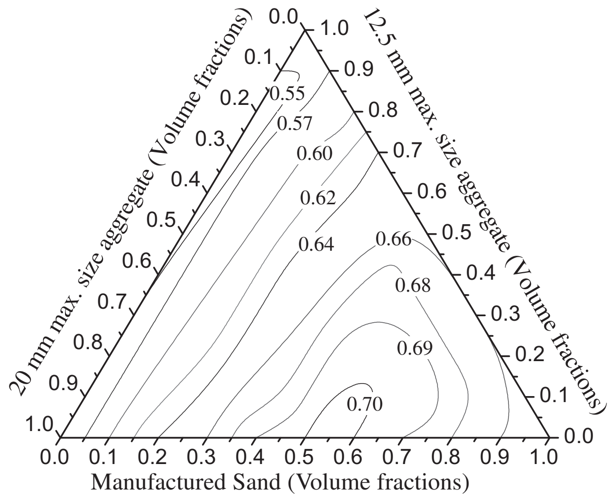

Fig. 3. Ternary packing diagram of manufactured sand with coarse aggregates.

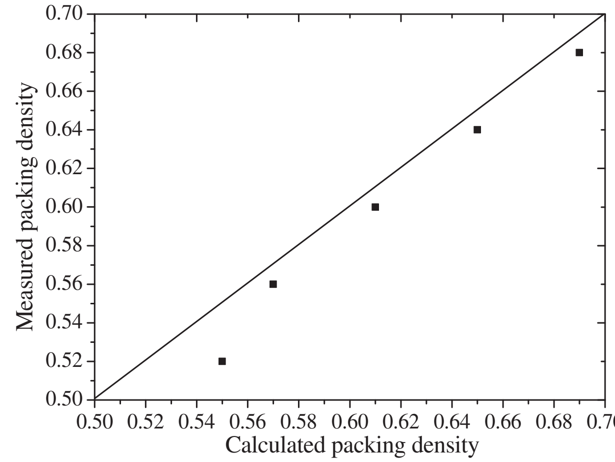

Fig. 4. Relation between calculated and measured packing density.

the minimum size aggregate (Msand) when compared to the medium size aggregates (12.5 mm) (this is in agreement with available literature [24]). In Msand, specifically, the fines content (10% of Msand is finer than 125 μm) help in better packing.

4. Experimental investigations on SCC using Msand

4.1. Fresh concrete properties

Experiments were conducted for possible combinations of the powder content (350–650 kg/m^3) and the w/p ratio (0.7–1.5) with the optimised combination of aggregates (55:15:30) to investigate the influence on fresh and hardened concrete properties. The experiments were conducted with and without optimum VMA dosage. The optimum VMA dosage was used only for mixtures that segregated. As stated earlier, the particle size fraction finer than 125 μm of Msand is about 10 %, and these fines contribute to the paste volume of the mixtures along with cement, fly ash and water.

In the present study, the paste volume was varied from 360 L to 490 L. The results of fresh concrete properties are shown in Table 5. From Fig. 5, it can be deduced that the slump flow increases with increase in paste volume. Approximately 370–390 L (which includes 20 L of air content) of paste is essential for achieving 550 mm slump flow with the given combination of aggregates having a packing density of 0.70.

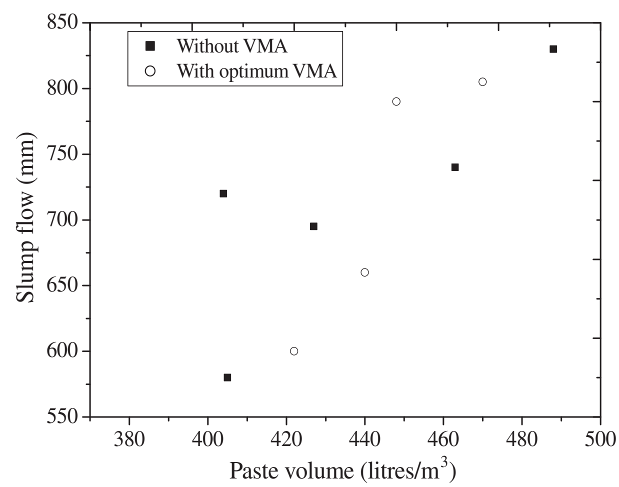

Fig. 5. Relationship between slump flow and paste volume.

The results were further analysed to estimate the required amount of paste volume in excess of void content to achieve SCC. Fig. 6 shows a plot between the excess paste volume and the slump flow. From Fig. 6, it is evident that a minimum of 70–90 L of excess paste volume, over and above the paste volume corresponding to the void content, is required for achieving the minimum slump flow

Table 5
Fresh and hardened concrete properties.

Sl. No.	Powder content (kg/m^3)	w/p ratio (vol.)	Effective Water content (L)	Paste volume of Msand fines (L)	Total paste volume (L)	Excess paste volume (L)	Slump flow (mm)	J-ring flow (mm)	T_{500} (s)	Compressive strength (at 28 days) (MPa)
1	450	0.8	134	66	367	67	20	–	–	48.6
2	450	0.9	151	68	386	86	480	360	–	42.5
3	350	1.5	195	80	405	105	580	440	1.2	16.4
4	550	0.8	164	59	427	127	695	675	9.4	50.4
5	450	1.0	168	69	404	104	720	670	2.5	36.4
6	650	0.7	169	52	463	163	740	680	8.9	60.7
7	650	0.8	195	53	488	188	830	780	1.9	52.4
Mixtures with optimum dosage of VMA										
8	450	1.1	184	71	422	122	600	560	3.4	29.4
9	450	1.2	201	72	440	140	660	630	1.6	24.9
10	550	0.9	184	60	448	148	790	765	1.5	46.5
11	550	1.0	201	61	470	170	805	760	0.8	39.0

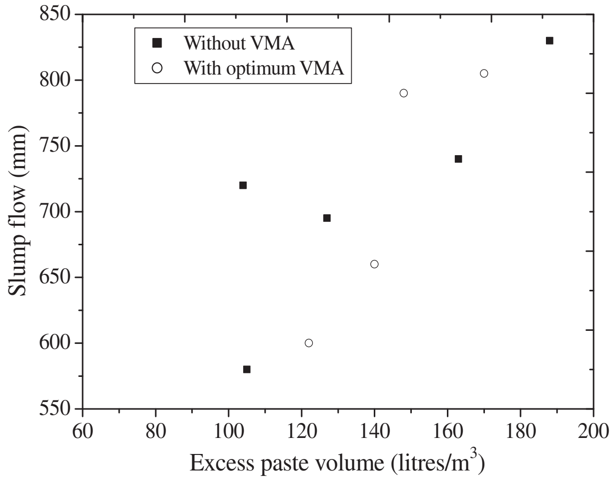

Fig. 6. Relationship between slump flow and excess paste volume.

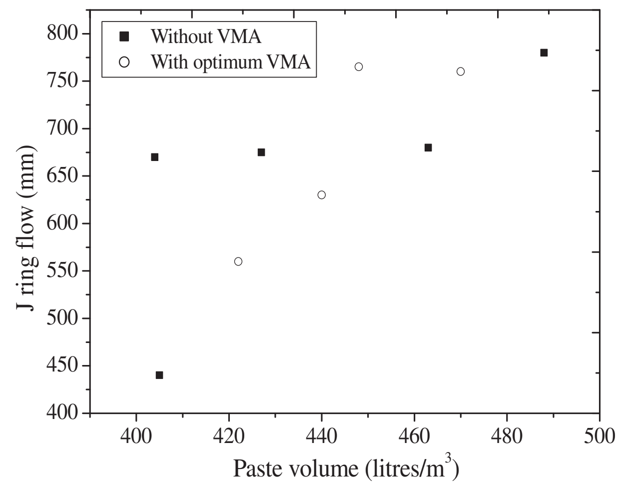

Fig. 7. Relationship between J-ring flow and paste volume.

of 550 mm. However, it has to be noted that, even with sufficient paste volume (say 70–90 L), there are chances for lesser slump flow if the water content is less than approximately 160 L which is evident from Table 5. The amount of excess paste volume (70–90 L) required to produce a slump flow of 550 mm by using Msand is relatively higher than SCC with river sand which requires approximately 50–70 L [25] over and above the paste volume corresponding to the void content of the aggregates. This higher paste volume requirement can be attributed to the effect of shape of the fine aggregate particles. Though the paste volume required is relatively higher, the point to be noted here is that the paste volume contributed by the Msand fines for different w/p ratio ranges from 50 to 80 L in excess of the paste volume contributed by the cement and fly ash with water (see Table 5). Therefore the paste volume contributed by fines of Msand (50–80 L) was effectively used for the flowability of the mixtures and hence, the powder (cement and fly ash) content can be reduced to a larger extent for achieving SCC.

Apart from slump flow test, experiments were conducted to determine the T_{500} and J-ring flow. The experimental results are given in Table 5 (arranged in the increasing order of slump flow). The T_{500} time is the time required to reach 500 mm slump flow. It indirectly indicates the viscosity of the concrete – higher the time to reach 500 mm, higher the viscosity. As per the results in Table 5, T_{500} varied between 1 and 9 s. In two cases, T_{500} time was greater than 5 s, which could be attributed to the fact that the paste had very low water content (~165 L) with high powder content (~650 kg/m^3) that caused the SCC to be highly viscous.

For assessing the passing ability of SCC, J-ring test was conducted according to ASTM C 1621 [26]. From Fig. 7, it is observed that the J-ring flow (slump flow with J-ring) increased with increase in paste volume. This could be attributed to the fact that with increase in paste volume, the aggregates are dispersed efficiently and hence the concrete passes through the reinforcement without congestion of the aggregates. The results of J-ring test are shown in Table 5. The blocking assessment was calculated as the difference between the slump flow and J-ring flow. From the results, it was observed that, the difference between slump flow and J-ring flow was in the range of 20–60 mm except one case (350 kg/m^3 powder content). The reason for higher difference in the J-ring flow in that particular case was the presence of higher aggregate content leading to increased friction between aggregates coupled with lesser paste volume leading to blocking. Further, in three cases (Sl. Nos. 5–7 in Table 5), though the paste volume is high, the difference between the slump flow and the J-ring flow is in the range of 50 mm which is considered to be noticeable blocking as per ASTM C 1621. From this, it is observed that even with high paste volume, there are chances for blocking. This indicates that apart from paste volume and paste composition, the aggregate characteristics and proportion also influence the passing ability of SCC.

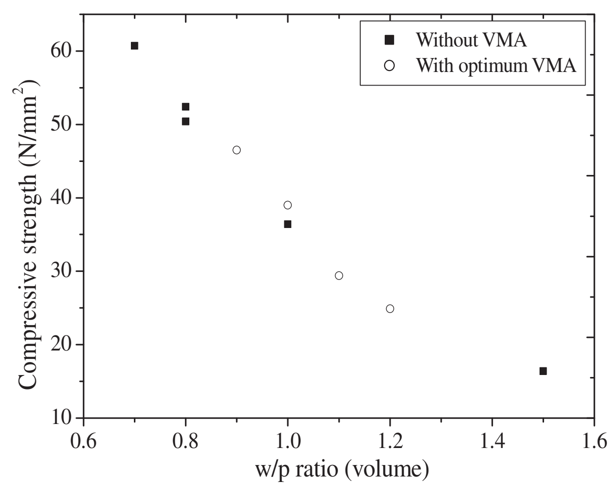

Fig. 8. Relationship between compressive strength and w/p ratio.

4.2. Compressive strength

For SCC, achieving high strengths is not difficult, due to the presence of high powder content. However, achieving low and medium strength SCC is a difficult task. Therefore, in this investigation, the emphasis was given to achieve low and medium strength SCC. Studies were conducted to investigate the influence of w/p ratio on the compressive strength of SCC. Concrete cubes of dimension 150 mm × 150 mm × 150 mm was cast and moist cured for 28 days. The compression test of concrete cube was performed as per IS 516 [27]. The average of the compressive strength of three cubes at 28 days, plotted against the w/p ratio in Fig. 8 indicates a good correlation between the compressive strength and w/p ratio. The compressive strengths for the different mixtures varied from 25 MPa to 60 MPa.

5. Conclusions

The crushing processes of Msand affect the shape, grading of the Msand and the proportion of microfines (particles passing through

75 μm), particularly when compared to natural fine aggregates. These factors may affect the performance of the SCC. Therefore, appropriate crushing technology has to be selected to ensure that the Msand produced is having cubical shapes with uniform grading under controlled conditions.

The present investigation was conducted to explore the possibility of 100% replacement of river sand by using Msand. In this context, the influence of the paste composition and paste volume on the fresh and hardened concrete properties of SCC using Msand was evaluated. The presence of high fines in Msand increases the water demand. However, the Msand fines contribute to an increase in paste volume, which is useful for the development of SCC.

The powder and aggregate combinations were optimised by using packing density criterion. The superplasticiser and VMA dosage was optimised by using empirical methods – mini-slump and marble test respectively. Further, experiments were conducted by varying the paste volume and w/p ratio. Experimental results revealed that paste volume had a predominant effect on the fresh concrete properties for a given combination of aggregates. A minimum of 160 L of water and 70–90 L of excess paste (per cubic metre of concrete) over and above the void content of the aggregates was found essential for achieving SCC with a slump flow of 550 mm. Though the paste volume required for SCC with Msand is relatively higher than SCC with river sand, the paste volume contributed by the high fines content of Msand compensates this requirement.

The results of J-ring test revealed that apart from paste volume, paste composition and aggregate characteristics also influence the passing ability of SCC. As expected, the w/p ratio had a good correlation with the compressive strength of SCC for a given cement/fly ash ratio. The compressive strength of mixes developed in this study ranged from 25 MPa to 60 MPa.

Whereas the cost of Msand is higher than that of river sand, Msand presents numerous advantages, including its contributions as filler content of the concrete (as it has excess fines that are not clay or silt), and in reducing environmental impact. This helps in achieving a lower cost to benefit ratio as compared to river sand. Moreover, the difference between the cost of Msand and river sand will likely become smaller as the use of such alternative materials increases in the future, with increased awareness of its benefits. From this study, it is evident that Msand is a suitable alternative for river sand in developing SCC.

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