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Article

Particle Packing Approach for Designing the Mortar Phase of Self Compacting Concrete

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Abstract. Self Compacting Concrete (SCC) is a tailored concrete mix, strongly dependent on the constituent proportions and the physical characteristics of the constituents. In order to achieve the self compacting concrete, mortar phase plays a vital role as it contributes to the active suspension phase of aggregates. High powder content and optimum fine aggregate is required for the desired flowability and stability of mortar. Hence, for accomplishing a self compacting concrete, the design of paste and mortar phase needs to be carefully proportioned. A positive correlation exists between the flow properties of the concrete and the packing density of the mix. The packing density of the cementitious materials plays a key role in deciding the final strength of concrete. Improved packing offers the benefit of reduction in water demand, reduced permeability, reduction in bleeding and reduced porosity of the transition zone. The objective of this study is to design the mortar phase for a self compacting concrete reinforced with glass fibres by applying the concept of particle packing. Design of paste and mortar phase was done based on particle packing approach using Puntke test. Initially the powder content (cement and slag) was arrived based on Puntke test and the optimum addition of slag was determined with the slag activity index. The super plasticizer dosage was fixed by performing flow studies using Marsh cone test and the fine aggregate content was established by Puntke Test. The selected powder to fine aggregate content established by particle packing method was taken for mini slump studies and further the optimization of glass fibres content is determined. The outcome of the current study exposed the possibility of obtaining a self compacting mortar incorporating glass fibres which in turn useful for designing the self-compacting concrete.

Keywords: Particle packing, GGBS, super plasticizer, puntke test, marsh cone, mini slump.

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1. Introduction

Self compacting concrete is (SCC) a promising technology which has got wide variety of successful applications and more particular in case of ready mix concreting. SCC maintains homogeneity and flow under its own weight which is capable of filling and passing around congested reinforcement, in the plastic state. The hardened SCC showed higher strength and durability as compared to conventionally vibrated concrete [1]. Rheology of mortar and the selection of coarse aggregate play a key role in deciding the flow properties and segregation resistance of SCC [2]. The use of high volume of cement and chemical admixture makes SCC costlier, which is a major disadvantage. The use of mineral admixtures like limestone powder, flyash and slag will be an alternative material to reduce cost [3]. Increase in cement flyash paste increases the flow properties of mortar but gets decreased with increase in sand content. Powder properties and packing of materials highly influences the flow characteristics of concrete [4]. Research in the past has provided clear understanding about the significant role of particle packing on the properties of concrete. Incorporation of finer materials as replacement of cement have shown tremendous improvement in packing density, enhancement of particle distribution, reduction of thermal cracks and in improving mechanical properties [5]. Okamura proposed the first mix design methodology for SCC in which a conservative method of mix design was adopted which had a high volume of paste content. Guidelines were suggested for obtaining a SCC which comply the standard requirements in terms of flow properties [6, 7]. Addition of fibres improves the strength and toughness, arresting the crack propagation and stress distribution across a crack. Even though, the commonly used fibres are steel, other fibres such as glass, plastic and polypropylene were also used in concrete reinforcement. The workability of concrete will be affected depending on the type of fibres used. A better fibre matrix bond is achieved in the case of SCC as compared to conventionally vibrated concrete [8]. In the present study, a simple and systematic approach using particle packing was adopted for arriving the two phase system by optimizing the paste and mortar phase. Simple experiments like Puntke test, mini slump, Marsh cone studies were considered for studying the paste and mortar flow properties. The optimized powder to sand combinations was considered for further investigation on the flow properties with different volume fractions of glass fibres.

2. Research Significance

Even though there is a growing attractiveness for SCC, a systematic and simple mix design procedure is still lacking. Extensive study on the mechanical and durability aspects of SCC is very much essential for instilling confidence in the construction industry. The paste and the mortar play a vital role in deciding the self compacting properties of fresh SCC. The production of SCC requires the careful proportioning of the paste and mortar materials. Properties of concrete are highly influenced by the optimization of ingredients. Particle packing concept was selected for optimizing the ingredients. The basic concept adopted for the current study is that, performance of the concrete mix can be improved by maximizing the packing densities of the aggregate particles and the cementitious materials. In this study, an attempt has been made to design the paste and mortar phase which will enable to produce a high quality SCC, both in fresh and hardened state. Few studies were conducted for plain SCC and fibre reinforced SCC but limited studies were conducted with glass fibres and slag. The significance of current study lies in understanding the fresh and hardened properties of paste and mortar phase with slag and glass fibres.

3. Experimental

3.1. Materials Used

The materials used in this study consist of ordinary Portland cement (OPC), ground granulated blast furnace slag (GGBS), fine aggregate and a polycarboxylic ether based super plasticizer. The mortar mixtures were prepared with 53grade OPC with fineness of 320 m^2/kg and a specific gravity of 3.18. The granulated slag used had a fineness of 450 m^2/kg and a specific gravity of 2.8. River sand passing through 2.36 mm sieve; with a specific gravity of 2.69 and fineness modulus of 2.55 was used as fine aggregate. Glass fibres with an aspect ratio of 600 and a specific gravity of 1.8 were used. A polycarboxylic ether based super plasticizer was used which had a specific gravity of 1.11 and a solid content of 40%.

3.2. Paste Studies

The paste composition greatly influence the self compacting properties of concrete since the paste phase serves as suspension medium for aggregates. A better understanding of the flow properties and the optimized quantity of glass fibre volume fraction is vital in assessing the paste composition. Puntke test was used for arriving the best combination of powder (cement : GGBS). Optimization of Super plasticizer was based on marsh cone studies. Slag activity index were determined to confirm the maximum strength of slag. Fresh properties of mortar with and without the addition of glass fibres were evaluated using mini slump test**.**

3.2.1. Packing density of paste

The concept of packing density was used to optimize the powder (Cement:GGBS) combination and was basically determined from Puntke Test [22]. The basic principle of the test is that the water which is added to the dry materials fills the voids in between the particles and act as a lubricant to make the materials to compact efficiently. The water which is excess after completely filling the voids will be on the surface indicating the saturation limit. The required mass of the cementitious materials was placed in a beaker. If a mixture of cement and other additives is used, the amount of cement has to be reduced appropriately. The materials are mixed thoroughly for homogenization before water is added. Distilled water is added gradually working the mixture with a stirrer until it acquires a closed structure after repeated tapping of the beaker. In the next step, water is added drop by drop with a pipette, mixing carefully, until the saturation point is reached. At this point, the surface smoothes itself after repeated tapping of the beaker and appears glossy. The total time taken for each experiment was approximately10 minutes. The experiment was repeated for 3 times to get the least water required to achieve saturation. From the volume of water used, the packing density was determined by using the following equation.

$$\text{Packing density} = 1-(Vw)/(Vp+Vw) \tag{1}$$

Vw = *Volume of water (cm3),* Vp = *Volume of Particle (cm3)*

3.2.2. Paste-superplasticizer compatibility

It is imperative to understand the compatibility of super plasticizers with cement. The addition of Super plasticizer in certain cements poses incompatibility problems with respect to a type of cement and Superplasticizer leading to irregularity of slump and rapid workability [9]. In the present investigation, Marsh cone studies were carried out to find the optimized dosage of superplasticizer. The Marsh cone flow is a standard test [10] and is considered appropriate for use in both the field as well as in laboratory. It consists of a funnel with a long neck and an opening of 5mm. A rigid stand was used to hold the Marsh cone in place above a glass graduated cylinder. Initially the paste is poured in the cone while the orifice is closed till the level for an appropriate volume is reached, then the orifice is opened and the time for the paste to flow out for a particular volume is noted down.

3.2.3. Slag activity index (SAI)

SAI indicates the range of strength of slag with the different replacement levels of cement. The tests are used to compare the compressive strength of mortar containing the mineral component to that of not containing the mineral component so as to test the acceptance of mineral admixture and the test was conducted as per standard guidelines [11, 12].

3.2.4. Glass fibre optimization in paste phase

In the current study, mini slump cone was used to optimize the volumetric fraction of glass fibres in the paste phase. The slump cone has a top diameter of 19 mm, bottom diameter 38mm and a height of 57mm [13]. The spreading out diameters on a horizontal metal plate is measured in two mutually perpendicular directions, after 1min of spread time. The maximum retention time and bleeding was observed visually. In the case of glass fibre addition, the concept of wetting of fibres was also considered for compensating the loss of water due to fibre addition. The additional water required for fibre wetting was calculated experimentally by deducting the weight of total wet weight of glass fibre after dipping in water to that of dry weight of glass fibre.

3.3. Mortar Studies

3.3.1. Packing density of mortar

In order to find out the maximum possible packing density of Powder: Sand combination, Puntke test was considered. The sand content used was 40%, 50% and 60% by volume. The test was conducted for two different Cement: GGBS combination (C50:G50, C60:G40) obtained from Puntke Test conducted on Powder. The procedure for the experiment was kept same as conducted on powder, except the inclusion of additional material ie Sand and finally, the packing density was determined from Eq. (1).

3.3.2. Mortar-superplasticizer compatibility

Marsh cone studies were conducted to identify the ideal dosage of Super plasticizer in the mortar phase. The test was conducted as per [10].The size of the opening used was 12.7mm. Initially the mortar is poured in the cone while the orifice is closed till the level for an appropriate volume is reached, then the orifice is opened and the time for the paste to flow out for a particular volume is noted down. The test is not recommended if the material gets clogged in the cone and does not show any continuous flow and the test results for such mixtures should be discarded.

3.3.3. Glass fiber optimization in mortar phase

The apparatus for the mini slump test of self compacting mortar consists of a brass mould in the form of frustum of cone, 60 mm high with a diameter of 70 mm at the top and 100 mm at the base. The cone was placed at the centre of a steel base plate, and was filled with mortar. Immediately after filling, the cone was lifted, the mortar spreads over the table and the average diameter (in mm) of the spread measured. The result from packing studies reveals that, the best combination of Powder: Sand is 40:60 with powder combination of (C60:G40).But for the better understanding of the behavior of Powder: sand combinations at various replacement levels, 16 mixes with 4 different powder to sand ratios were conducted. The mortar spread was visually checked for any segregation or bleeding for 20min.

4. Results and Discussions

4.1. Paste Studies

4.1.1. Puntke test

The packing density of cementitious materials was determined for different combination of Cement and GGBS. The percentage of Cement and GGBS was varied from 0 to 100 % (with an increment of10%) by volume.

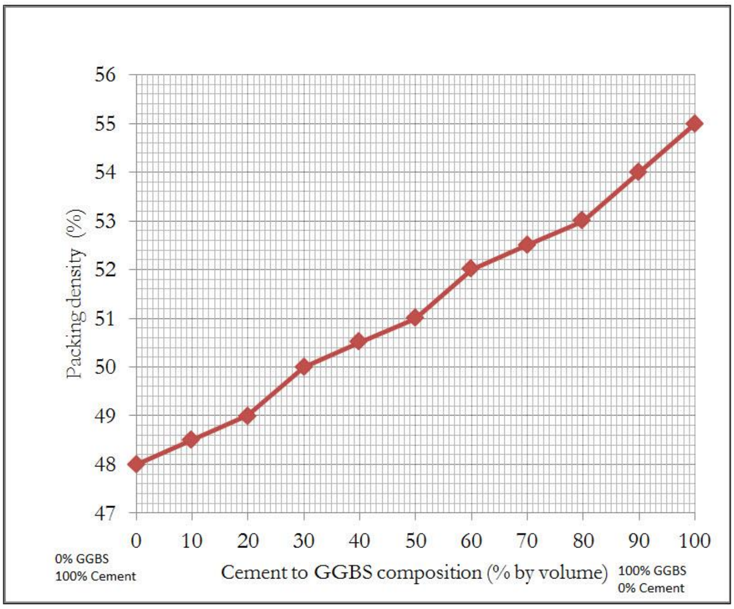


Fig. 1. Cement to GGBS vs. Packing density.

As it is observed from Fig. 1, a uniform tendency with regard to packing density was observed with increase in the GGBS volume It can be noted that, as the GGBS content increases, the packing density is also increasing marginally. This may be due to the finer particle size of the GGBS and the maximum packing density (55%) was reported for the paste containing 0% cement and 100% slag. Even though the maximum packing density is for 100% GGBS, the slag activity index exhibited a decrease in reactivity index, after 40% replacement of GGBS. High volumes up to 80% have been replaced in low strength SCCs and 40% in high strength SCCs [3]. Based on the test results, the two combinations of cement and GGBS (60:40 and 50:50) were selected for further studies.

4.1.2. Slag activity index (SAI)

For the purpose of investigating the reactivity of cement and Slag, 7day and 28day compressive strength were determined and the results for 40% and 50% are presented in Table 1. The result indicates that, the slag activity index for 40% replacement of GGBS was slightly higher at 7days and 28days, as compared to 50% replacement levels in cement mortar. In general, when the replacement level was more than 40%, the reactivity index were found to be decreased.

Table 1. Compressive strength and slag activity Index of paste at 7 and 28 days.

Mix (Cement: GGBS)	**Compressive strength at 7 days (N/mm²)**	**SAI at 7 days (%)**	**Compressive strength at 28 days (N/mm²)**	**SAI at 28 days (%)**
M_{100}	24.61	-	34.26	-
$M_{50:50}$	21.23	86.17	28.19	82.42
$M_{60:40}$	23.42	95.22	31.14	91.05

4.1.3. Cement super plasticizer compatibility–Marsh cone studies

In the paste phase, tests were conducted for two different cement to slag combinations of 60:40 and 50:50 (obtained from Puntke test based on maximum packing density). The w/p ratio of 0.3 is kept constant throughout the study and the SP dosage was varied with 0.5%, 1% & 1.5% (by the combined weight of cement and GGBS). A graph was plotted with % of SP and time of flow as represented in Fig. 2; which denoted that, the fluidity of the paste increased with increase in super plasticizer dosage upto an optimum point. However, it can be noted from Fig. 2 that, the optimum dosage of superplasticizer (the dosage beyond which the flow time does not decrease appreciably) was found to be 1 % (weight of binder).

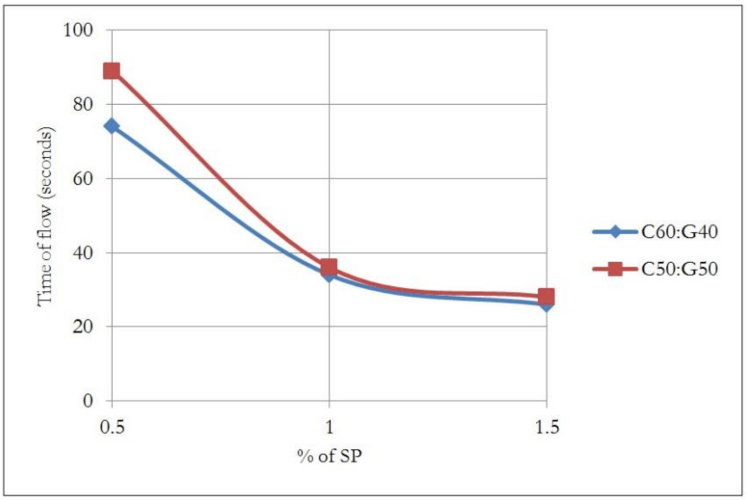


Fig. 2. % of SP vs. Time of flow.

4.1.4. Mini slump studies on paste

As stated earlier that, glass fibres have the tendency to adsorb water on the surface and requires additional water to compensate the loss in consistency of paste. Hence, extra water was required for initial wetting of fibres which was calculated to be around 16.5% by weight of fibres. This extra amount of water was made available during mixing. Based on the results from particle packing studies, two combinations of Cement to GGBS were used for the study (C60:G40 & C50:G50). Also, the w/p ratio was kept at 0.3, super plasticizer dosage of 1% and volume fraction of glass fibre (v_f) were varied from 0.1%, 0.2%, 0.3% and 0.4%. The test results on the mini slump studies for various paste combinations are given in Table 2 and the actual snapshot of the spreading and bleeding properties for each mix are given in the last two columns of the Table 2. Also, the variation of spread diameter of mortar for various dosage of glass fibres are represented in Fig. 3. The spread diameters on a horizontal base were measured in two mutually perpendicular directions, after 1min of spread time. The base plate was kept undisturbed for 10 minutes to observe bleeding and retention time. The minimum time taken to initiate the bleeding and the intensity of bleeding at different time intervals was also noted for all mixes. It is observed from Fig. 3 that, as the volume fraction of glass fibres increases, spread diameters were getting reduced. Similarly, the intensity of bleeding was increased, with the increase in glass fibre content due to the formation of minute capillary channels at the interface of matrix and glass fibres.

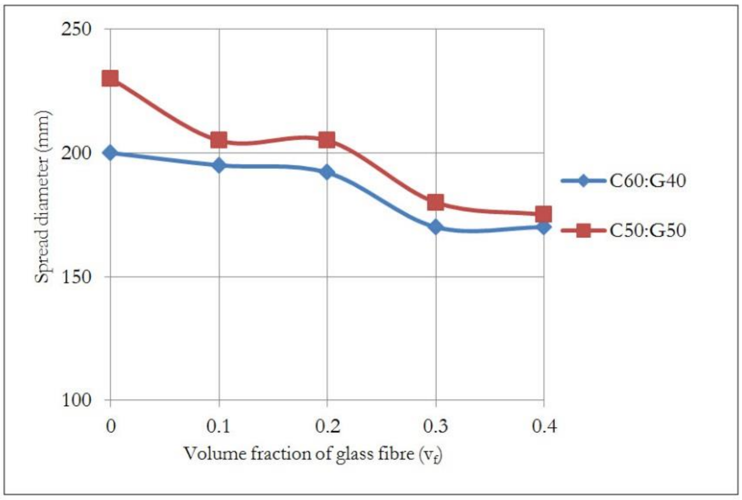


Fig. 3. Volume fraction of glass fibre vs spread diameter.

Glass fibres acts like minute capillary channels, which encourages the water to come out around the periphery. In general, C50:G50 showed better performance in terms of spread diameter, but were found to be discouraging in terms of bleeding as compared to C60:G40 mix. Finally, C60:G40 with 0.1% (V_f) performed satisfactorily in terms of spread diameter, bleeding and retention time, as compared to the rest of the mixes as provided in Table 2.

Table 2. Mix proportion and images of mini slump (paste).

Mix ID	Cement (% by vol)	GGBS (% by vol)	Cement (gms)	GGBS (gms)	V_f (%)	Spread dia (mm)	1st min	10th min
M1(a)	60	40	71.70	43.62	0	200		
M1(b)	60	40	71.70	43.62	0.1	195		
M1(c)	60	40	71.70	43.62	0.2	192		
M1(d)	60	40	71.70	43.62	0.3	170		
M1(e)	60	40	71.70	43.62	0.4	170		
M2(a)	50	50	59.78	54.52	0	230		
M2(b)	50	50	59.78	54.52	0.1	205		
M2(c)	50	50	59.78	54.52	0.2	205		
M2(d)	50	50	59.78	54.52	0.3	180		
M2(e)	50	50	59.78	54.52	0.4	175		

4.2. Mortar Studies

4.2.1. Packing studies on mortar

The objective of the packing studies conducted on mortar was to establish the best combination of powder to sand ratio in terms of packing density and the results are presented in Table 3.

Table 3. Test results on packing studies of mortar.

Trial No	Powder Sand (% by vol)	Cement: GGBS (% by vol)	Packing density factor (%)	Max packing density factor (%)
1	60:40	50:50	60	61
2	60:40	50:50	60	
3	60:40	50:50	61	
1	50:50	50:50	64	65
2	50:50	50:50	65	

3	50:50	50:50	65	
1	40:60	50:50	67	68
2	40:60	50:50	67	
3	40:60	50:50	68	
1	60:40	60:40	61	61
2	60:40	60:40	61	
3	60:40	60:40	61	
1	50:50	60:40	64	64
2	50:50	60:40	64	
3	50:50	60:40	64	
1	40:60	60:40	68	69
2	40:60	60:40	68	
3	40:60	60:40	69	

A graph was plotted with % of sand by volume in the x - axis and packing density in y - axis. From Fig. 4, it can be observed that, as the sand content increases, the packing density was also found to be increasing in which case the powder: sand combination of 40:60 (C60:G40) exhibited the maximum packing density.

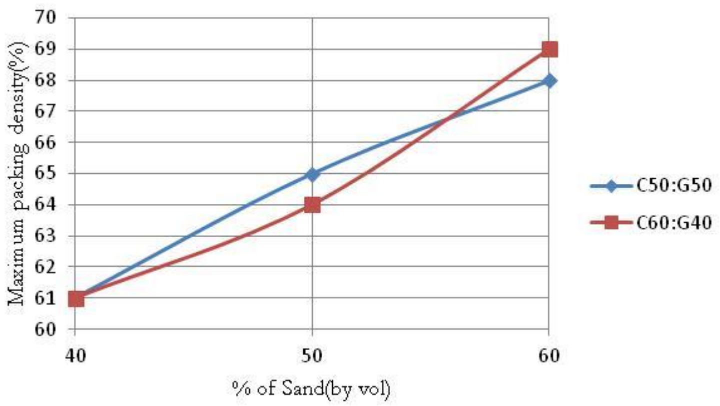


Fig. 4. Powder: Sand vs. packing density.

4.2.2. Marsh cone test for mortar

In the mortar phase, the test was carried out for powder : sand (P50:S50& P40:S60) for two different cement to slag combinations (C50:G50 & C60:G40). Initially the experiment was conducted with 1%SP and w/p ratio of 0.3 but all the four mixes showed poor flow characteristics in the Marsh cone apparatus. This suggested for an increase in the superplasticizer dosage from 1.5%, 1.75% & 2.0% (by total weight of cement and slag. From Fig. 5, it is observed that as the SP dosage increased the fluidity of the paste was also increased. The test results from Fig. 5 gives an indication about the dosage of super plasticizer (2%) needed to achieve the best rheological conditions for mortar.

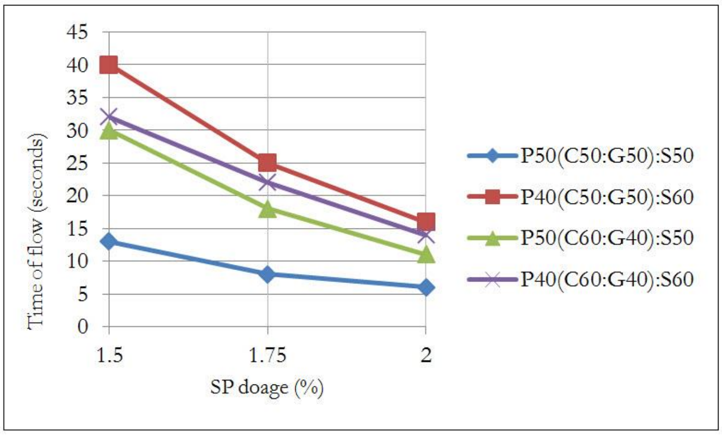
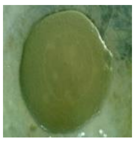


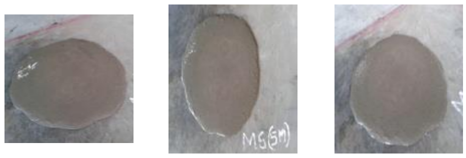
Fig. 5. SP dosage (%) vs. time of flow.

4.2.3. Flow studies

Mini slump test was conducted on 16 different mixes with 4 different powder to sand ratios, (P50:S50, P40:S60, P30:S70 and P20:S80). For each powder to sand ratio, the powder consisted of 4 different proportions of cement to GGBS (C50:G50, C60:G40, C70:G30, C80:G20). The mini slump test results are provided Table 4 and the actual snapshot of the spreading and bleeding properties for each mix are given in the last three columns of the Table 4, which indicates a clear picture of the behaviour of slump at different time intervals.

Table 4. Spread diameter for mini slump and images of flow studies.

Mix ID	Powder: Sand	Cement : GGBS	Cement (gms)	GGBS (gms)	Sand (gms)	Spread diameter (mm)	Time required to start bleeding (s)	1st min	5th min	10th min
M1	50:50	50:50	140.60	128.20	247.63	200	No bleeding till 900sec			
M2	50:50	60:40	168.75	102.60	247.63	210	180			
M3	50:50	70:30	196.87	77.00	247.63	200	No bleeding till 1200sec			
M4	50:50	80:20	225.00	51.30	247.63	210	600			
M5	40:60	50:50	112.50	102.60	297.2	225	570			

M6	40:60	60:40	134.90	82.10	297.2	242	52	
M7	40:60	70:30	157.50	61.60	297.2	220	600	
M8	40:60	80:20	179.90	41.04	297.2	230	180	
M9	30:70	50:50	84.40	76.90	346.70	230	170	
M10	30:70	60:40	101.20	61.60	346.70	202	210	
M11	30:70	70:30	118.10	46.20	346.70	207	240	
M12	30:70	80:20	134.90	30.80	346.70	170	540	
M13	20:80	50:50	56.20	51.30	396.20	No spread	10	
M14	20:80	60:40	67.50	41.04	396.20	No spread	10	
M15	20:80	70:30	78.70	30.80	396.20	No spread	10	
M16	20:80	80:20	90.00	20.50	396.20	No spread	10	

The poor mix in terms of bleeding and spread was P20:S80 which can be seen in Fig. 6. Also, it is well drawn from Fig. 7 that, the initiation time of bleeding for 50% paste to sand combinations (P50:S50) resulted in longer time for the bleeding to start. For carrying out further studies, 6 mixes were selected based on longer retention, maximum spread and minimum bleeding. The selected mix was M1, M3, M4, M5, M6, and M7, M1 and M3 which had shown minimal bleeding, spread diameter of more than 200 mm and retention period of 1200sec. Fine bleeding was observed in M4, with a spread of 210mm and retention period of 600 seconds and the mix M7 showed a spread of 220mm with a retention period of 600 seconds. It was observed that for mix M7, there was a tendency for an increase in the rate of bleeding after 900sec. However, after a very close observation it was decided to consider the two mixes M5 and M6 for further investigations. Even though the retention period of M6 [P40 (C60:G40) : S60] was only 270 seconds, it showed the maximum spread diameter of 243 mm and the bleeding observed for the same was not appreciable. On the other hand M5 [P40 (C50:G50) : S60] showed a retention period of 900sec with a spread diameter of 225mm and a very slight bleeding was observed at 1200seconds.

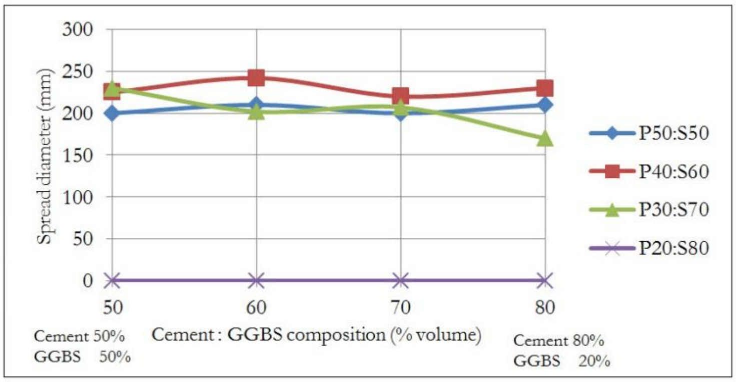


Fig. 6. Cement GGBS vs Spread diameter.

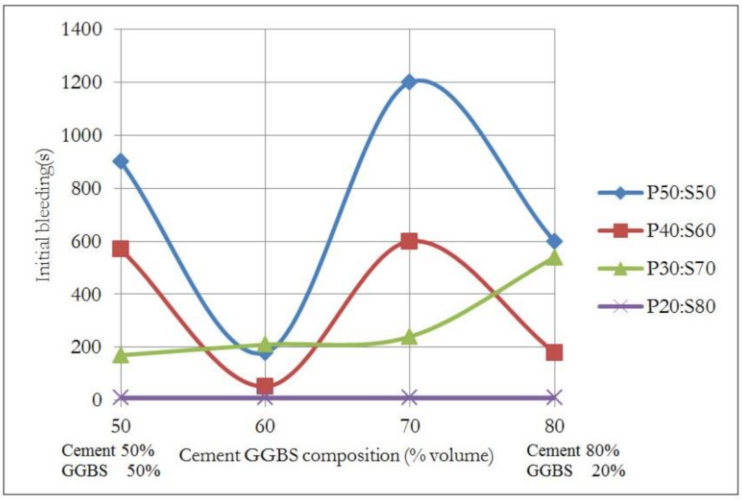


Fig. 7. Cement GGBS vs. Initial bleeding.

4.2.4. Glass fibre optimization in mortar phase.

The study was also intended to analyse the flow characteristics of optimized self flowing mortar mixes with the inclusion of glass fibres. Hence, mini slump studies were also conducted for analyzing the flow behaviour of mortar with the inclusion of glass fibres to arrive at an optimum dosage of glass fibres. The best mixes consisting of powder to sand ratio of 40:60 with cement to GGBS of 60:40 were considered to study the effect of glass fibre inclusions at various volume fractions upto 0.4%. Table 5 gives the spread diameter and the corresponding images of slump flow at 0 minute (immediately after lifting the cone), 5 minutes and 10 minutes.

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Table 5. Spread diameter of various glass fibre substituted mortar mixes.

Mix ID	V_f (%)	Diameter of Spread (mm)	0th min	5th min	10th min
M2(a)	0	240			
M2(b)	0.1	210			
M2(c)	0.2	140			
M2(d)	0.3	No spread			
M2(e)	0.4	No spread			

It can be noted from Fig. 8 that, the reduction in spread diameter occurs with the increase in glass fibre content. The bleeding and spread diameter of the mix was monitored continuously for 10minutes and the snapshot of it is given in the last three columns of Table 5. For M2 (b) & M2 (c) initial bleeding occurred within 3 minutes and thereafter a slight increase in bleeding was observed upto 7 minutes and after which there was no further bleeding. This observation clearly demonstrated that the optimum volume fraction of glass fibres is restricted to 0.1% and beyond further addidtion can definitely cause the negative effects on the flow properties of mortar.

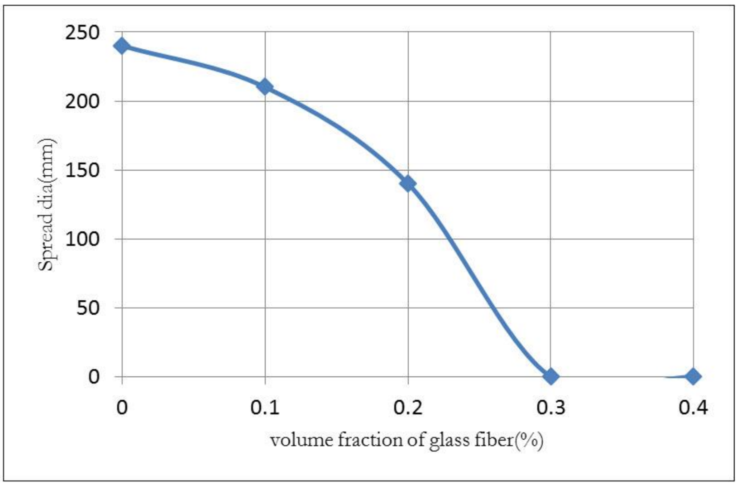

Fig. 8. Volume fraction of glass fibre vs spread diameter.

5. Conclusions

Following conclusions are drawn within the limitations of the study conducted in a two phase cementitious system:

- The proposed mix design methodology was found to be simple and conservative to arrive at an optimal material resource. A methodical study was conducted for designing the individual paste and mortar phases to arrive the right combinations of constituent materials.

- The concept of packing density using Puntke test (optimization of powder and sand), Marsh cone studies (Optimization of SP dosage), Mini Slump studies (Optimization of glass fibers) were primarily used for the present investigation.
- Punkte test was found to an ideal method for determining the exact proportions of paste and mortar phase for yielding maximum performance. Packing density was found to be dependent on the binary blends of GGBS and cement; however, the maximum GGBS has to be restricted based on the reactivity index which revealed that the ideal combination of cement to GGBS was 60:40
- The results from the Marsh cone studies indicated the optimized super plasticizer dosage in the paste phase as 1 % (combined weight of cement and GGBS).
- The paste composition greatly influences the spreading ability without segregation and bleeding, since the paste phase serves as suspension medium for aggregates.
- From the particle packing studies conducted on mortar, the ideal recipe of powder to sand ratio was found to be 40 : 60 and the super plasticizer dosage at 2% (by weight of cement and GGBS).
- The mini slump test results in mortar studies showed that the mix M5 [P40 (C50:G50) : S60] showed a highest retention period of 900sec with a spread diameter of 225mm and almost zero bleeding for longer duration.
- The inclusion of glass fibres decreased the spread; however the initial fibre wetting has compensated the mix water.
- Based on the studies conducted, addition of 0.1% volume fraction of glass fibres were found to be an optimal value for obtaining a self flowing mortar flow properties.
- Based on the present investigation, the ideal combination is P40 (C60:G40) : S60, 0.1% volume fraction of fibers and 2% Superplasticizer. In general, the arrived ideal combinations of two phase cementitious and mortar systems were found to exhibit all the required characteristics for the possible production of a self compacting concrete with glass fibers.

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