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RESPONSE OF OPTIMIZED SELF-COMPACTING CONCRETE USING PARTICLE PACKING CONCEPTS AND SUPPLEMENTARY CEMENTITIOUS MATERIALS (SCMS)

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By

Syed Ali Rizwan[1], Sufian Ahmad[2], Qamar uz Zaman[3] and Hamza, Ali[4]

Abstract

This research reports the effect of varying packing density on the flow and mechanical characteristics of Self Consolidating Concrete Systems (SCC) made with and without Secondary Raw Materials (SRMs) or supplementary cementitious materials (SCMs). The ratio of fine to coarse aggregate ratios was varied in the 20-80% range as a trial process to see the effect on the degree of packing of aggregates in the SCC mixes. Then it was compared with that based on the modified Anderson and Andreason (MAA) approach. The packing density and compressive strengths were found to be optimum when the fine-to-coarse aggregate ratio was 50:50 in terms of weights in trial mixes, while based on the MAA approach, this ratio was around 51:49 with distribution modulus "q" equal to 0.25. Fly Ash (FA) and Limestone Powder (LSP) were used in the same proportions by weight to partially replace 30% cement based on an earlier published study [1]. Theoretical results using the MAA approach and EMMA software were compared with the experimental response of SCC formulations. Results showed that SCC prepared on the basis of the MAA approach was more economical and showed better response in terms of flow, volume stability, heat of hydration and compressive strength. Using the MAA approach for SCC mix design saves the time and materials needed in the trial process of SCC design. EMMA software was utilized to adjust the mix proportion to achieve an optimized particle size distribution for a mix with the fewest voids. A modified A&A (MAA) formulation at q = 0.25 and a binder-to-aggregate ratio of 1:3.89 was attained using EMMA as optimised mixes.

Keywords: Packing Density, Self-Compacting Concrete, Fly Ash, Limestone Powder, Secondary Raw Materials, Modified Andreassen and Andersen.

1. Introduction

Self-compacting concrete (SCC) is characterized by two contradictory requirements of high deformation without bleeding and segregation. It usually requires either higher paste content or using a viscosity enhancing agent (VEA) or both to improve segregation resistance and aid in its placement, especially through the pumping process [2]. The use of Secondary Raw Materials (SRMs/SCMs) like FA and LSP can enhance the properties of SCC in terms of flow, volume stability, heat of hydration, durability, and strength due to their synergic effect [3]. Encouraging the use of SRMs in SCC translates into an indirect reduction of the CO_2 footprint and results in environment-friendly concrete [4]. Another approach for SCC mix design was proposed by Su and Miao, popularly known as the Chinese method [5], which starts with packing aggregates and then filling the voids of aggregates with paste. This

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method results in more economical concrete by reducing the amount of paste required to fill the voids. The largest possible volume of aggregates is also beneficial in terms of strength, volumetric stability, creep, permeability, and stiffness. Several packing models have been proposed that can be utilised to alter the particle size distribution (PSD) of aggregates to make the mix densely packed with minimum space between the aggregate particles. Computer software like EMMA [6] can be utilised to design the mixed composition of SCC using particle packing concepts.

1.1. Packing Models

Particle packing models have been in use for quite some time now; several researchers have contributed to them, starting from Furnas to Fuller & Thompson (F&T) and then to a more recent model proposed by Funk and Dinger, also known as the Modified Andreasen and Andersen Model (MA&A). Details and the differences between these models can be found elsewhere [7-13]. Since naturally occurring materials cannot be mono-sized and contain particles up to infinitely small size. Funk and Dinger considered it, and they incorporated both minimum and maximum sizes of particles in their model to make the mixture have the least content of voids. Mathematically MAA model can be written as:

$$CPFT = \frac{d^q - d_{min}^q}{d_{max}^q - d_{min}^q} \times 100 \qquad (1)$$

Here, CPFT means cumulative percentage finer than the diameter of particle "d" having distribution modulus "q", d_{min} and d_{max} are the minimum and maximum sizes of particles used, respectively.

Generally, a mix with more fines results in a lower distribution modulus (q) value to have a mix of optimum packing density. However, the value of q also depends on several factors like particle density, particle porosity, particle shape, and maximum & minimum size of particles used [7]. Sajjad et al. [14] used the Modified A&A model to reduce voids in fine aggregates for Self-Compacting Mortar systems (SCMs) and found 0.35 as the optimum q value to have a mix of the highest packing density. Similarly, Qamar et al. [15] suggested a lower value of q (i.e., 0.205) when SRMs are incorporated into SCM systems to increase the degree of packing in SCMs. This is because of the inclusion of finer content in the mixture. Later, it will be known that by the inclusion of coarse aggregates, the value of q raised to 0.25 for optimised packing density of SCC systems incorporating SRMs (see Fig 5).

2. Experimental

2.1. Materials

Ordinary Portland Cement of grade 53, type-1 conforming to EN-197-1 manufactured by "Bestway", Class F Fly Ash (FA) imported from Germany, Limestone Powder (LSP) manufactured locally from Margalla crush, 3rd generation, PCE-based liquid superplasticizer Viscocrete - 20 HE produced by Sika and Master Matrix 110, a Viscosity Modifying Agent (VMA), was used to prepare Self-Compacting Concrete (SCC) having a target flow of 70 ± 1cm using Abraham's cone confirming to EN 12350. All the materials used in the research were kept in air-tight containers before use to protect them from any type of moisture contact.

The chemical composition of powders was determined using X-ray fluorescence (XRF) analysis. Physical characteristics were analyzed using SEM images and Particle size distribution (PSD) by Laser granulometry. The results are shown in Table 1.

Table-1: Chemical and Physical Analysis of Powders

Samples	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Particle Size (D_{50})
OPC	19.19	0.29	4.97	3.27	0.04	2.23	65.00	0.58	0.51	0.08	3.84	16.4
FA	59.06	1.58	27.58	5.14	0.05	1.27	1.66	0.54	1.59	0.15	1.38	11.0
LSP	3.00	0.04	0.69	0.27	0.01	0.67	52.67	0.30	0.10	-	42.24	8.63

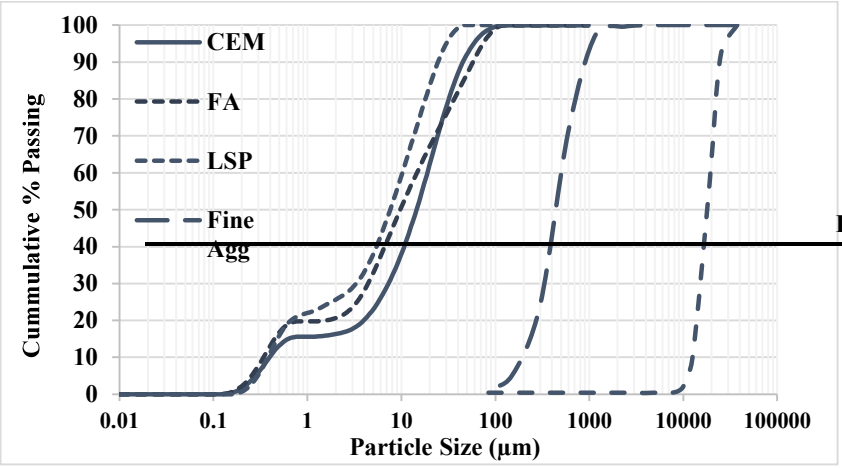

Figure-1: Particle size distribution of Materials (Powders and Aggregates)

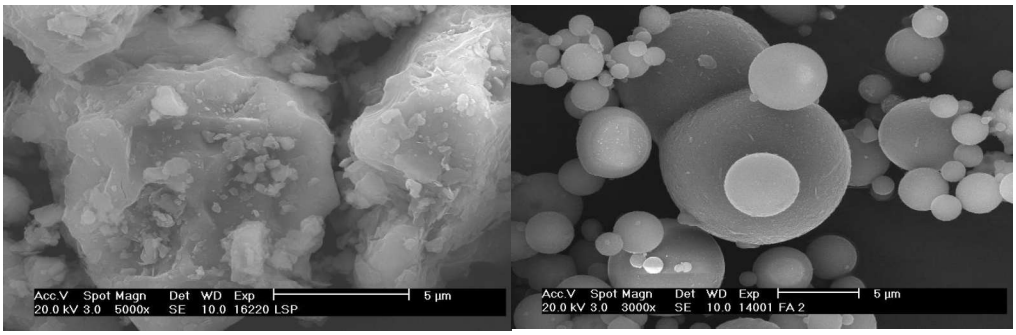

Figure-2: SEM images of LSP and FA Powders, respectively Rizwan, 2006[4]

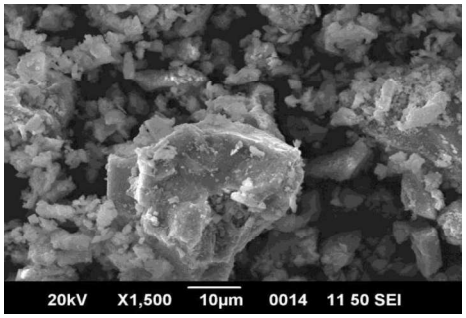

Figure-3: SEM image of OPC Powder [7]

2.2. Packing Density of Aggregate

Naturally occurring fine and coarse aggregate were mixed in ratios of 20/80, 30/70, 40/60, 50/50, 60/40, 70/30, and 80/20 to determine the optimum packing density

mixture by following the standard guidelines of BS-812. Results showed that maximum packing density can be achieved by using a fine/coarse aggregate ratio of 50/50 when naturally occurring aggregates are used, as shown in Figure 4. This also reconfirms the work done by Brouwers [16]. It is suggested that for the density of aggregates, the maximum particle size should be 10 times smaller than the internal diameter of the container to avoid the wall effect [17, 18]. Mathematically packing density can be written as

$$\alpha = 1 - e$$

$$e = \frac{100*[Gs*62.4]-BulkDensity}{Gs*62.4}$$

Here α is packing density, e is the percentage of voids in aggregates (coarse and fine), and Gs is the specific gravity of aggregates.

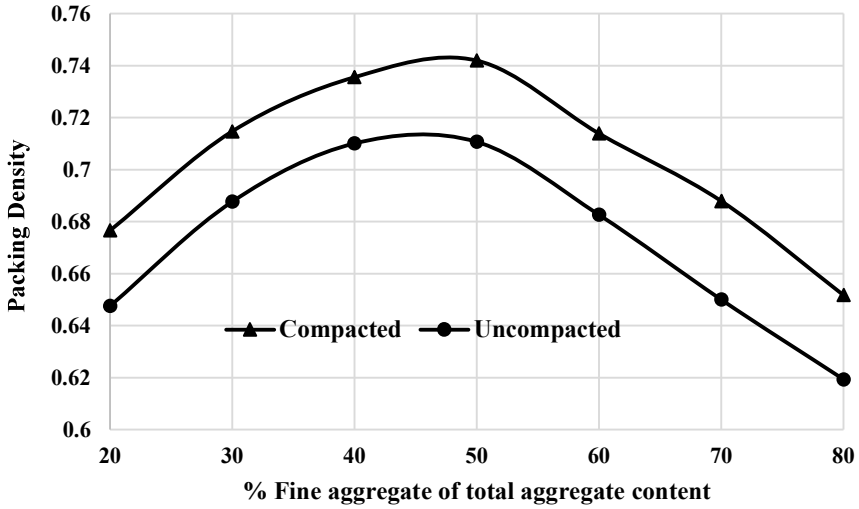

Figure-4: Packing Density of Mixes with varying Fine Aggregate content

Fig.5 shows the void ratio versus sand to coarse aggregate ratio, as reported [16].

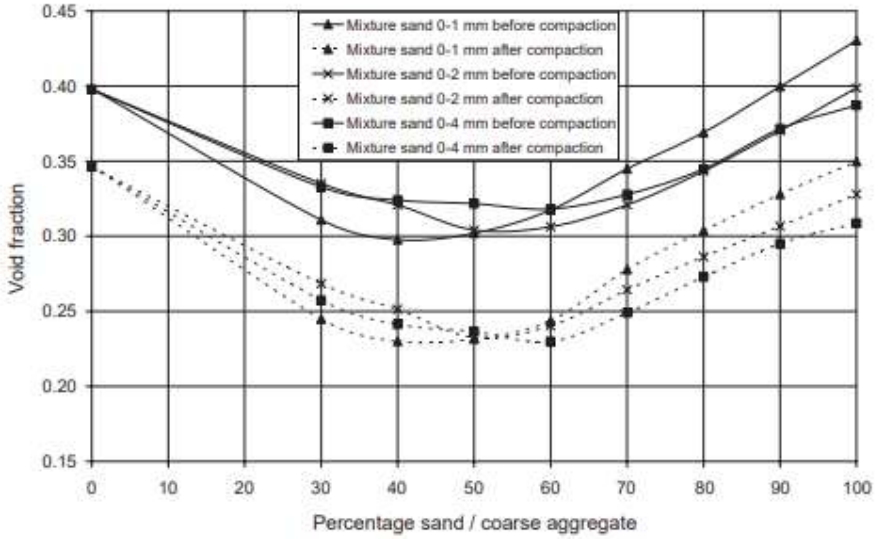

Figure-5 Void Ratio and sand to coarse aggregate ratio relation [16]

A modified A&A model was also utilized to increase the degree of packing of aggregate mixes. Different distribution modulus (q) values ranging from 0.22 to 0.28 were used to determine its relationship with packing density, which was found to be optimum at q = 0.25, as shown in Figure-6. The particle size distribution (PSD) curve of the Modified A&A Model with different values of q is shown in Figure-7, which shows an increase in % passing of material with a decrease in the value of q for a particular size of the particle.

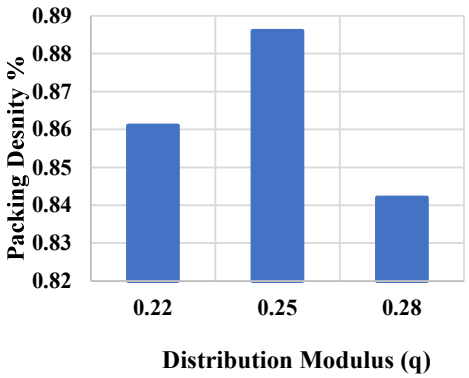

Figure-6: Packing Density of Mixes with varying Distribution Modulus (q)

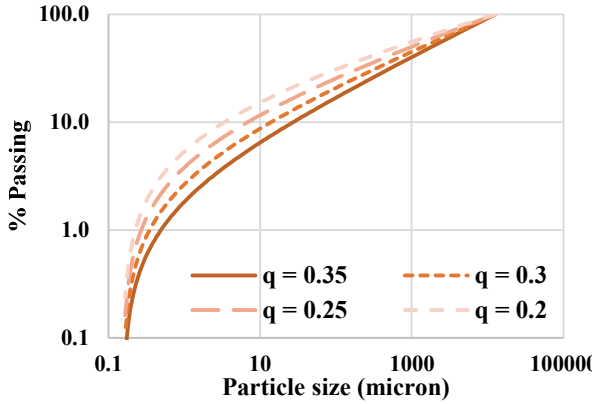

Figure-7: Particle Size Distribution for varying Distribution Modulus (q)

Three out of seven (with untailored aggregates) and one out of three (MAA model-based) optimised formulations showing greater theoretical packing density were selected for further experimental investigation on flow and other mechanical properties by varying the constituents, as given in Table-2. Figure-8 shows the packing density of the above four optimised theoretical formulations. The formulation based on the Modified A&A approach shows an 18% greater degree of packing than the one with a fine/coarse aggregate ratio of 50/50.

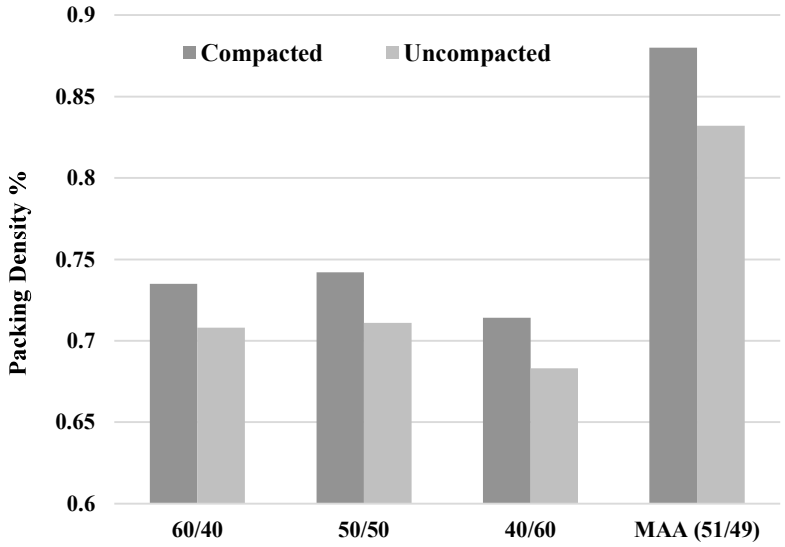

Figure-8: Theoretical Packing Density of optimized formulations

2.3. SCC Formulations Designed for Optimum Packing

To study the effect of packing density on properties of experimental SCC along with partial replacement of OPC with blends of FA and LSP (15% each by weight of cement), a total of seven mixtures were investigated, as shown in Table 2. Considering the mix design proposed by Brouwers and the practical experience of the Principal author [4,14,16], binder to aggregate ratio of 1:3 and w/c ratio = 0.42 was maintained for all the formulations. The amount of SP was adjusted for each formulation to attain a target flow of 70 ± 1cm, while VEA was used to avoid any segregation/bleeding in the control mixes without SRMs. SCC Formulations without mineral admixtures are designated as “CM” (Control Mixes), while those having SRMs/SCMs are defined as “MM” (Modified Mixes), and digits show the percentages of fine and coarse aggregate, respectively; for example, a mix CM 64 means that there are 60% fine aggregates (of the total aggregates) and 40% are coarse aggregates. Other mixes can be understood on similar lines.

The SCC mix was optimized based on the Modified A&A particle packing model. EMMA software was utilized to adjust the mix proportion to achieve an optimized particle size distribution for a mix with the fewest voids. A modified A&A (MA&A) formulation at q = 0.25 and a binder-to-aggregate ratio of 1:3.89 was attained using EMMA; details are shown in Table 2.

2.4. Mixing Regime

A 50-liter capacity pan mixer was used, and a total of 5 minutes of SCC mixing was done. Starting with dry mixing of materials for a minute at 65 rpm, followed by adding 70% water and mixing it for 1 more minute before the addition of chemical admixtures along with the remaining 30% water, mixing was continued for 3 further minutes to ensure SP activation, resulting in a uniform mix of self-compacting concrete.

Table-2: Details of SCC Formulations

Materials/ Mixes	Fine/coarse aggregate ratio	Binder to Aggregate ratio	OPC (Kg)	FA (15%) (Kg)	LSP (15%) (Kg)	Fine Agg (Kg)	Coarse Agg (Kg)	w/c=0.42 (Kg)	SP (%)	VEA %
CM64	60/40	1:3	10	-	-	18	12	4.2	1.15	-
CM55	50/50	1:3	10	-	-	15	15	4.2	1	0.4
CM46	40/60	1:3	10	-	-	12	18	4.2	1.4	0.6
MM64	60/40	1:3	7	1.5	1.5	18	12	2.94	1.7	-
MM55	50/50	1:3	7	1.5	1.5	15	15	2.94	1.59	-
MM46	40/60	1:3	7	1.5	1.5	12	18	2.94	1.65	-
MA&A (51/49)	51/49	1:3.89	5.4	1.156	1.156	15.3	14.7	2.268	1.61	-

3. Results

3.1. Flow Response of SCC Formulations

To investigate the flow response against packing density, seven SCC formulations with different packing densities were subjected to routine SCC flow tests, including slump flow spread, L-box, V-funnel, and J-Ring test, as per the EN 12350 standard.

3.1.1. SP Demand and Slump Flow Spread of SCC Formulations

Abraham's slump cone with a narrow end-up was utilized to determine the SP demand of SCC for a target flow of 70 ± 1 cm, as shown in Figure 9. Plastic Viscosity and deformability, in terms of T50 cm time and T70 cm time, respectively, were also evaluated for the mixes, and the results are shown in Figure 10.

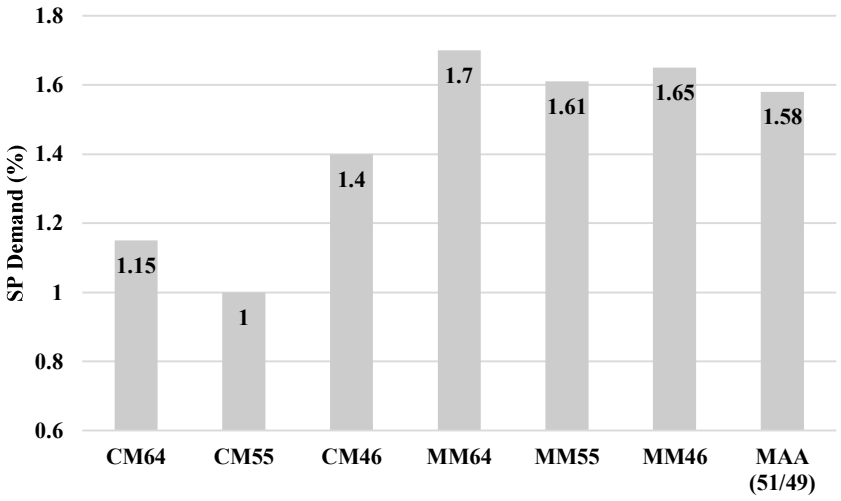

Figure-9: SP Demand of SCC Formulations

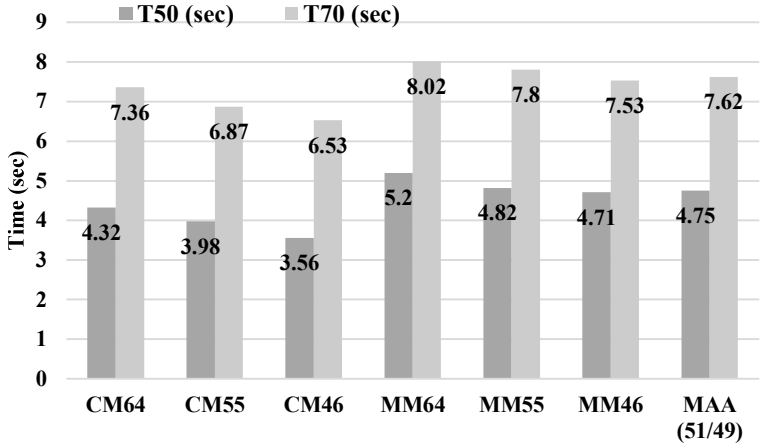

Figure-10: T50 and T70 cm flow times of SCC

3.1.2. V-Funnel Test on SCC Formulations

The formulations' viscosity was evaluated using a V-funnel apparatus. The concrete was allowed to pass through an opening of the funnel until the light appeared at the bottom, and the time required was noted, representing the viscosity of SCC as shown in Fig.11

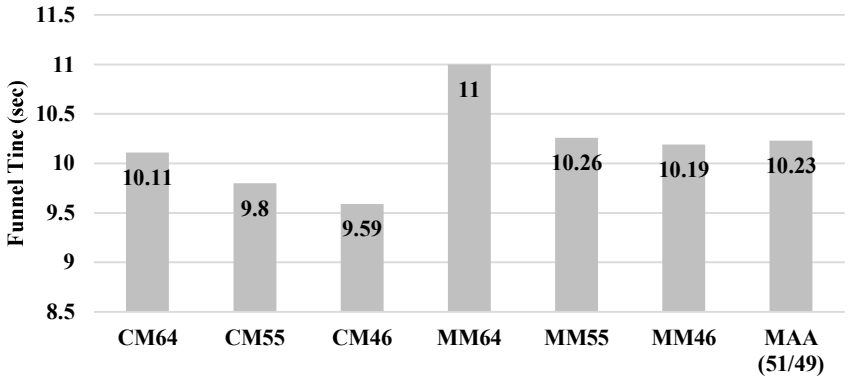

Figure-11: V-Funnel Time of SCCs

3.1.3. L-Box Test on SCC Formulations

The L-box apparatus replicates the field conditions for SCC to pass through the steel reinforcements, which shows its passing ability. The time required (T20, T40, and T60) for SCC to cover the distance of 20cm, 40cm, and 60cm at the horizontal section of L-Box after passing through reinforcements were reported. Also, the ratio of height (H2/H1) of SCC before and after passing through reinforcements is shown in Figure 12.

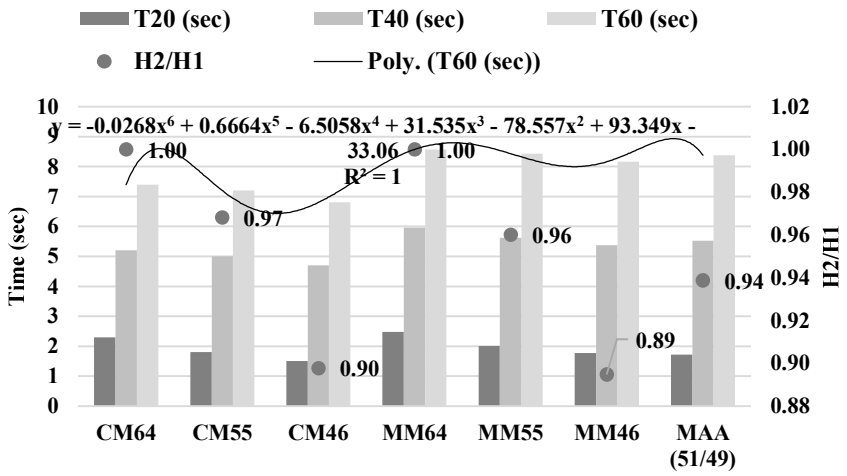

Figure-12: Flow Time for L-Box (T20, T40, T60 and H2/H1)

3.1.4. J-Ring Test on SCC Formulations

The total spread time of SCC, T50cm time, and height difference (Bj) of concrete before and after passing through the J-Ring were noted. The J-Ring response of SCC formulations is shown in Figures 13 and 14.

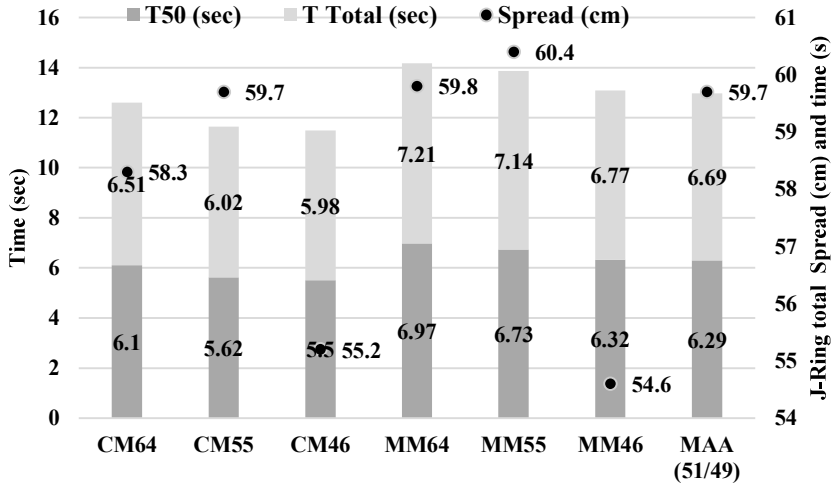

Figure-13: Flow Time for J-Ring (T50, T total and Total Spread)

Bingham number Bj can be used to characterize the rheological behavior of SCC under varying rates, and shear stresses between 1-5 indicate the non-Newtonian flow behaviour of SCC, while its value between 5-10 indicates the non-Newtonian flow behaviour of SCC with slow flows through J Ring and moderate yield stress indicating passing ability and filling ability of SCC as reflected in J-Ring test.

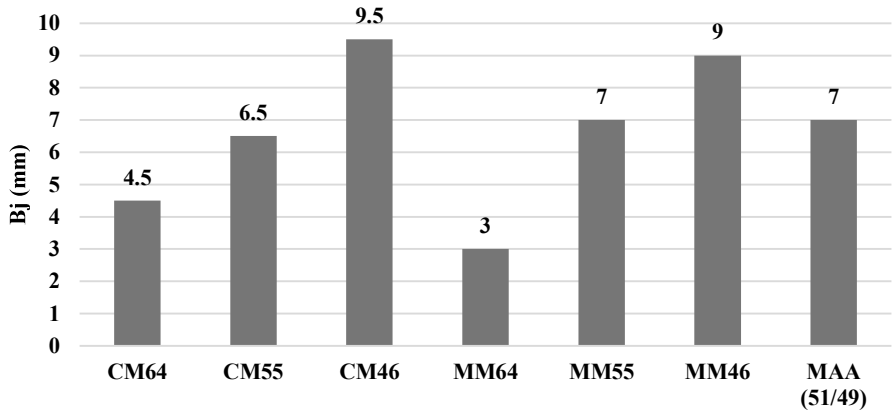

Figure-14: J-Ring Passing Ability Results (Bj)

3.1.5. Approximate Shrinkage Response of SCC Formulations

Early age shrinkage response was measured using Modified German Schwindrinne apparatus 4x6x25 cm^3 capable of measuring linear shrinkage up to 31 microns sensitivity. Schwindrinne channel was filled with the fresh SCM obtained after passing SCC through a 2mm sieve, and the channel was then covered with a plastic sheet to avoid any exchange of moisture with the environment. The shrinkage response of studied formulations is shown in Figure-15.

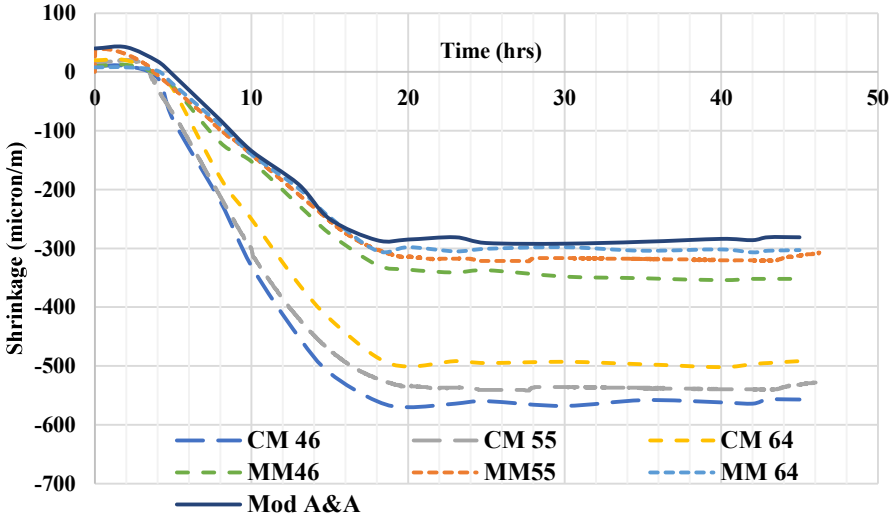

Figure-15: Simulation of Shrinkage Response of SCC formulations

Packing was highest at 50-50 % fine: coarse aggregates both in experimental investigation and as reported in [16] as shown in Figures 4 and 5, and it decreased on both sides of this ratio. The lowest shrinkage was shown by the Modified Andersen and Andreason formulation. The same was the trend in Calorimetry.

3.1.6. Approximate Calorimetry of SCC Formulations

The hydration kinetics of SCC formulations were studied using an F-CAL 8000 field Calorimeter. A sample of fresh concrete was obtained from SCC by sieving it through a 2 mm sieve. The sample was then filled in polythene bags and placed in the apparatus for 48 hours. Figure 16 shows the calorimetric response of SCC formulations, which was, in fact, that of SCM systems. Increasing sand content

reduced the exothermic temperature. Modified Anderson and Andreason formulation gave the least temperature.

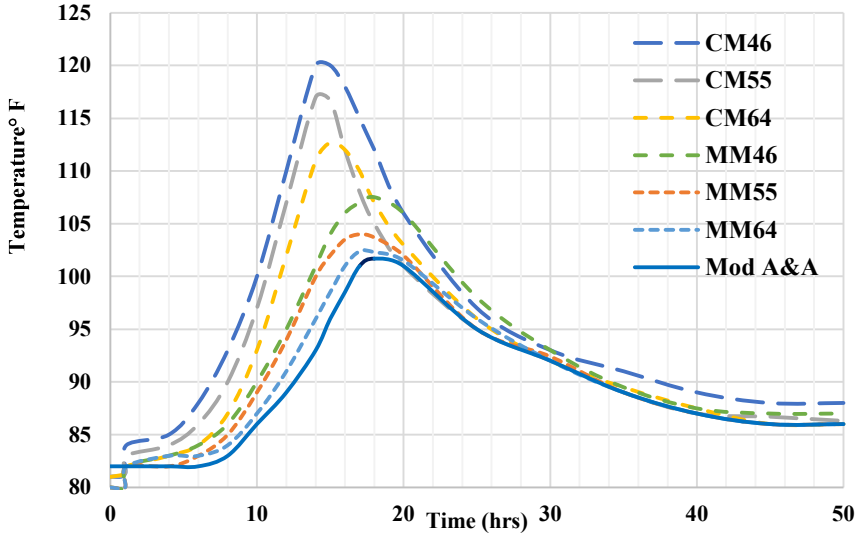

Figure-16: Calorimetry of SCC Formulations

3.1.7. Compressive Strength of SCC Formulations

The compressive strength of concrete samples dimensioning 4x4x4 inch^3 was determined according to EN 12390 standard guidelines. Samples were water-cured and were tested in SSD conditions at 1, 7, 14, and 28 days, and the results are shown in Figure-17.

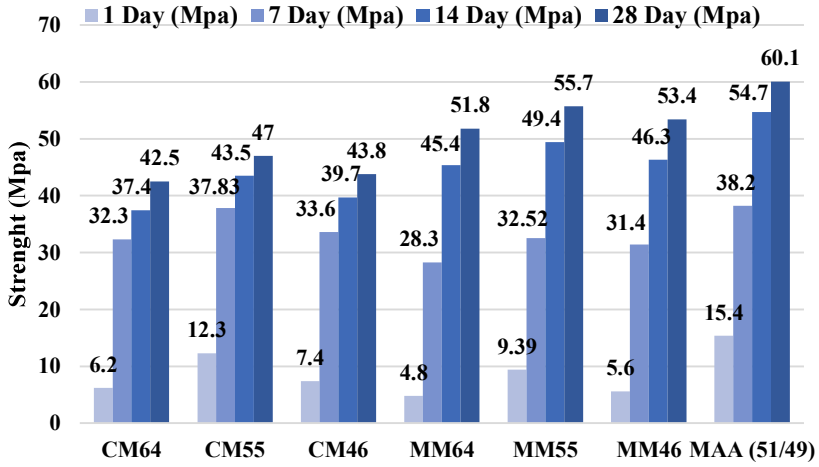

Figure-17: Compressive Strength of SCCs

4. Discussion

4.1. Flow response of SCC

Replacement of OPC by FA and LSP reduced the clinker content in SCC. By introducing SRMs/SCMs in modified SCC mixes increased the SP demand. It is thought that with higher fine aggregates, the SP demand should increase due to increased friction and reduced effective water available for hydration, as seen in Figure 9. The same is said about T50 cm and T 70 cm flow times. Funnel times decrease by decreasing sand content due to reduced internal friction. The same is true for L-box

times and J-Ring results. T50 and T70 show the viscosity and yield stress of the mixture, respectively [19, 20].

4.2. Shrinkage response of SCC

Approximate Linear early shrinkage of SCC slightly increased with reduction of sand content. This looks surprising, but remember that it was, in fact, the shrinkage of (self-compacting mortars) SCM systems as SCC was sieved through a 2 mm sieve, and the absence of coarse aggregates resulted in this response. Another factor may be increased effective water. Mod A&A formulation shows the least amount of shrinkage caused due to the hydration reaction

4.3. Calorimetric Response of SCC

The exothermic nature of the hydration reaction is investigated through calorimetry, as shown in Figure 16, which indicates the delay in the hydration reaction due to the presence of FA as a retarder and LSP as an inert material that does not take part in the hydration reaction but just encourages the growth of hydration products. Formulations having a greater amount of fine aggregate show a lower intensity of hydration reaction due to the presence of the lesser amount of OPC in the mix obtained after passing through a 2mm sieve. Figure 16 shows the calorimetric response of SCC formulations, which was, in fact, that of SCM systems. Increasing sand content reduced the exothermic temperature. Modified Anderson and Andreason formulation gave the least temperature.

4.4. Compressive strength of SCC

Figure-17 shows the compressive strength results of SCC formulations, and it appears that by introducing SRMs/SCMs, the compressive strength increased as expected for obvious reasons. However, pozzolanic activity and nucleation sites offered by FA and LSP, respectively, caused the increment in strength at 28 days of age. CM55 and MM55 formulations, possibly due to higher packing density, showed greater compressive strength at all ages. Similarly, the formulation modeled using Modified A&A (MAA) showed maximum strength, clearly showing sand's role in theoretical formulations, which is again close to a 50:50 ratio of fine and coarse aggregates by weight. However, the packing effect seems to be more dominant in the early stages.

4.5. SEM Analysis

Hydration of SCC samples was stopped by keeping them in Acetone for 24 hours followed by submerged in isopropanol for another 24 hours. Samples were then prepared for SEM analysis. Figure 19a shows the hexagonal CH crystals, slightly different sizes and morphology. Figure 19b shows the Interfacial Transition Zone (ITZ) between aggregate and paste, considered the weakest link in the reinforced concrete. The material engineers should try to make ITZ strong by using their knowledge and experience. The concrete is examined at micro-scale and the results are interpreted at macro-scale.

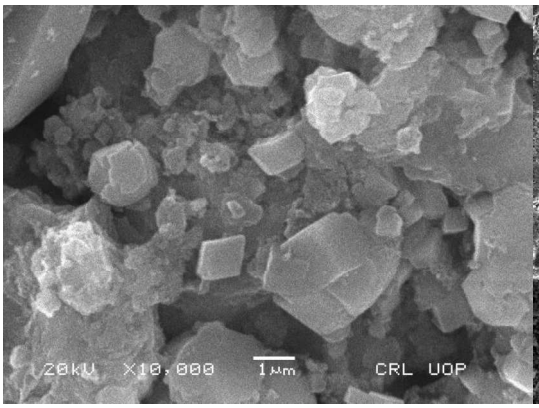

Figure-19(a): SEM Image of SCC

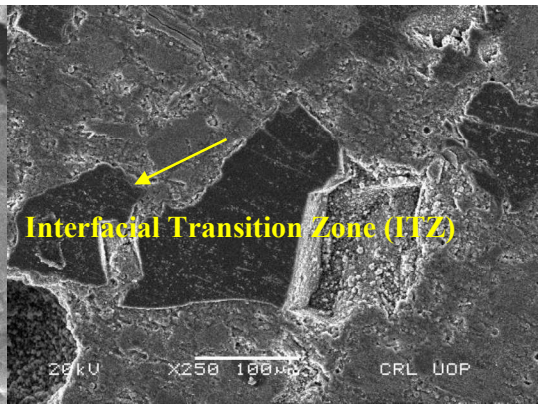

Figure-19(b): SEM Image of SCC

5. General Concluding Remarks

In the following lines, general conclusions are given which should be useful for the end users having some basic knowledge. It is hoped that researchers all over the world will benefit from this work when this paper is uploaded to the digital library of the Pakistan Engineering Congress.

Packing density is usually maximum at 50:50 of fine and coarse aggregates in both loose and compacted aggregate states, which is in agreement with [16]. Increased sand content also increases the SP demand for a given target workability in self-compacting cementitious systems. The addition of SCM also increases the SP demand. Shrinkage, Calorimetry, Strength, and micro-structural investigations also favor a 50:50 ratio of fine to coarse aggregates. Based on the results obtained, it can be concluded that the packing density of SCC directly influences the properties of concrete, like flow, SP demand, volume stability, heat of hydration, and strength. Also, blends of FA and LSP can be used as a partial replacement of cement up to 30% by weight to enhance the properties of concrete. The use of SRMs/SCMs to have environmentally friendly concrete is also recommended.

6. Acknowledgements

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