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Self-Compacting White Concrete Mix Design Using the Particle Matrix Model

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***Abstract*—**White concrete facade elements are widely used in construction industry. It is challenging to achieve the desired workability in casting of white concrete elements. Particle Matrix model was used for proportioning the self-compacting white concrete (SCWC) to control segregation and bleeding and to improve workability. The paper presents how to reach the target slump flow while controlling bleeding and segregation in SCWC. The amount of aggregates, binders and mixing water, as well as type and dosage of superplasticizer (SP) to be used are the major factors influencing the properties of SCWC. Slump flow and compressive strength tests were carried out to examine the performance of SCWC, and the results indicate that the particle matrix model could produce successfully SCWC controlling segregation and bleeding.

***Keywords*—**Mix design, particle, matrix model, white concrete.

I. Introduction

THE white concrete is used to produce concrete elements in traditional buildings and special items such as customized edifice created by creative architects. Currently, Norwegian construction industry shows growing demand for the polished facade elements made of self-compacting white concrete. Basically, Self-Compacting Concrete (SCC) is widely used in industry due to high flow ability and rheological stability, applicability for elements with complicated shapes and congested reinforcement, and without a need for vibration and compaction during the placing process [1], [2]. In general, workability of SCC is evaluated using slump flow test, segregation resistance test and J-ring test. Filling ability is normally evaluated by using slump flow test, passing ability is measured using J-ring test and the ability of the concrete to remain uniform in composition during placement and until setting is measured using segregation resistance test. To produce SCC, the major work involves designing an appropriate mix proportion and evaluating the properties of the concrete. In this process, it is a challenge to reach the required concrete workability by minimizing segregation and bleeding.

There are various methods used for proportioning of SCC concrete such as minimum paste volume method, Excess Paste Theory, Compressible Packing Model, Particle Matrix Model (PMM), etc. Most of these methods establish three things: the paste volume, paste composition, and aggregate blend. The paste volume is set to be greater than the volume of the voids between the compacted aggregates for SCC. Among these, PMM has been applied with mixed success, for self-compacting concrete (SCC) [5], [6] and high performance concrete (HPC), primarily due to the increasing tendency of the concretes to be matrix dominated as the water-powder ratio (w/p) is decreased. The model is based on paste volume, paste rheology, and aggregate properties. The paste rheology is characterized with the flow resistance ratio, which is measured with the FlowCyl device. The aggregates are characterized with the air voids modulus, which depends on the aggregate volumes, fineness moduli, and empirically determined aggregate parameters. Workability is measured at various paste volumes for each flow resistance ratio and air void modulus. The model is widely and successfully used in Norway for proportioning self- compacting concrete, high performance concrete, fiber reinforced concrete. Therefore, in this study PMM has been used for proportioning self-compacting white concrete.

This paper discusses the application of PMM to design self-compacting white concrete mixture. Moreover, it also discusses how to achieve desired workability of fresh concrete by minimizing segregation and bleeding. In this study, slump flow was used as an indicator for workability and bleeding was visually observed.

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II. Particle Matrix Model for SCWC

In general, concrete mixtures may contain 7-8 different ingredients. Proportioning of concrete involves in selecting the proper combination of materials and mixing them together to get target properties with good margin and low production cost. In addition to that, it is also important to satisfy the requirement given in standards while proportioning of concrete.

The Particle Matrix Model (PMM) can be considered as a widely used simplified model to discuss the properties of fresh concrete [3] and to proportioning fresh concrete. The model was pioneered by Ernst Mortsell for conventionally placed concrete in 1996 [4]. This model is anticipated to be particularly suitable for self-compacting concrete (SCC) [5], [6] and high performance concrete (HPC), primarily due to the increasing tendency of the concretes to be matrix dominated as the water-powder ratio (w/p) is decreased. The model divides the concrete mixture into two phases depending such as matrix phase and particle phase based on the particle sizes and their properties. Matrix phase consists of solid particles less than 0.125mm (i.e. cement, silica fume, and filler material), free water and additives. Particle phase is consisting of particles with size larger than 0.125 mm i.e. remaining aggregates [3]. In this model, flow resistance ratio is used to describe the properties of matrix phase whereas air void content of the particles is used to describe particle phase.

The amount of matrix is often expressed as the ratio of matrix volume to particle volume, or as matrix volume in liters per cubic meter per concrete (l/m^3). The matrix properties are described by rheological properties of matrix. The workability of the mixture is determined by both the properties of matrix and the properties of particle as shown in Fig. 1. The amount of matrix volume in the mixture will determine which parameter is dominant.

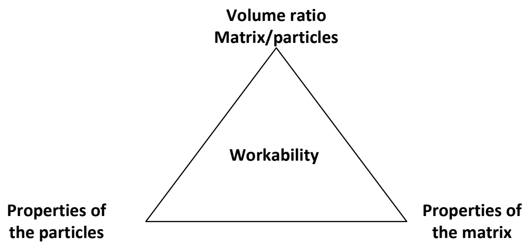

Fig. 1 Particle matrix model [3]

When required strength and durability class of concrete is known, the proportioning procedure of the PMM consists of [3], [7];

- Find and evaluate data for constituents: aggregate, cement and admixtures. The relevant data is grading of particle size, density, void volume, water absorption, water/solid content for admixtures
- The composition of aggregates regarding minimizing of void volume.
- Decide the composition of the matrix from the requirements for strength and durability, and necessary composition and volume of the matrix for the desired consistency.
- Calculation of the theoretical recipe based on volume and mass

$$TV = PV + MV + AC \tag{1}$$

where, TV = Total volume/ (l); PV = Particle volume/ (l); MV = Matrix volume/ (l); AC = Air content/ (l).

- Trial mixture and correction.

III. Materials and Experimental Approach

The experiment was carried out to design self-compacting white concrete of consistency class SF 2 (see Table I), characteristic cylindrical strength C35 and durability class M45 using PMM. SF2 (660-750 mm) is suitable for many normal applications (e.g. walls, columns) [8].

TABLE I
Slump Flow Class for Self-Compacting Concrete [8]

Class	Slump flow in mm
SF1	550 to 650
SF2	660 to 750
SF3	760 to 850

A. Materials

1) Cement

The cement has a composition and a property that is classified according to NS EN 197-1: CEM I 52, 5 R-SR5. The cement is a white Portland cement (i.e. Aalborg White) with 28 days strength is greater than 52.5 MPa. Density of the Aalborg White is 3150 kg/m³. w/c ratio was 0.4. The cement is rapid-hardening cement and is made of particularly pure white chalk and finely-ground sand.

2) Aggregates

The aggregate consists of white sand (0/2mm and 3mm/8mm) and gravel (8mm/16mm) supplied from Langnesgrunnen Marble, Norway. The sand consists of 5-10% particles <0.125mm and aggregate has absorbing moisture equal to 0.2-0.3%.

3) Admixtures

SP 40 was used as water-reducing admixture for concrete. The product is mainly based on sulfonated melamine condensate in solution. It gives the concrete a very good casting consistency. For optimal effect concrete should be mixed for at least 2 minutes after dosing. Generally, dosage of SP 40 is 0.1-2.5% of cement weight.

4) Additives

White silica is used as an additive to control bleeding and segregation. Silica consists of 90% silicon dioxide. It also has a specific surface area of > 15 m² / g.

5) Stabilizer

In this experiment, liquid-based viscosity modifying admixture: Sika stabilizer 4R was used to improve stability and segregation resistance of concrete mixes without significant reduction of slump or flow board measurement.

6) Air content

A typical value of 2% air content was chosen to provide good frost resistance because EN 206-1 has not recommended air content for concrete of durability class M45.

Table II illustrates the properties of different materials.

TABLE II
Properties of Material

Material	Density (kg/m³)	Water absorbent (%)	Water content (%)
0-2 mm sand	2710	0.2	0
3-8 mm sand	2710	0.3	0
8-16 mm gravel	2710	0.3	0
Aalborg white cement	3150	0	0
White silica	3170	< 1	0
Water	1000	100	-
SP 40	1000	0	60

B. Selection of Matrix Volume

The variation of matrix volume with slump flow can be plotted as in Fig. 2 [9]. For SCC, the matrix volume is usually in the range 330-360 l/m^3 depending on the void volume in the particle phase [7]. In addition, it is required to maintain water/binder-ratio < 0.6 in SCC according to EN 206-1 [10]. Lower the water/binder ratio results larger the matrix volume and reduced w/b-ratio contributes to increased stability. Therefore, 340 l/m^3 matrix volume was chosen to start the trial batches.

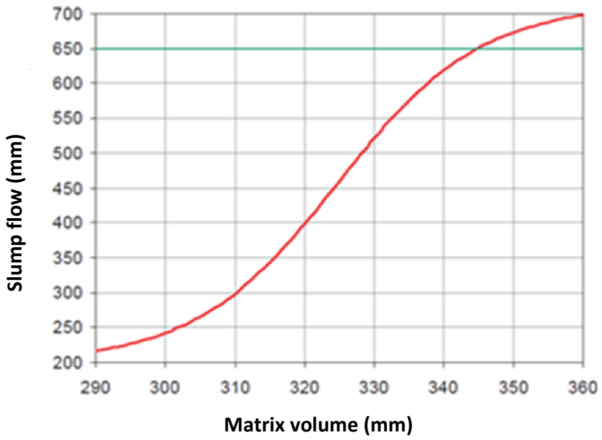

Fig. 2 Variation of Matrix volume vs slump flow [9]

C. Trial Batches and Tests on SCWC Properties

Initially, an experiment was carried out to understand the behavior of SP 40. Samples were prepared with different percentages of SP 40 i.e. 0.5%, 1.3%, 1.5%, 1.8%, 1.9% and 2.0%(within normal dosage: 0.5% to 2% according to EN 934-2:2001(admixtures quantity should not more than 5% by mass of the cement content of the concrete) and results shown in Fig. 3. It could be found that the mixture was not meeting at least SF1 consistency class when the SP 40 content was less than 1.9% of cement weight. Therefore, SP 40 was chosen as 1.9% of cement weight for further experiment. However, with 1.9% of SP 40, the slump flow was 540mm. To prepare SCWC, it was required to have at least 650mm of concrete slump flow.

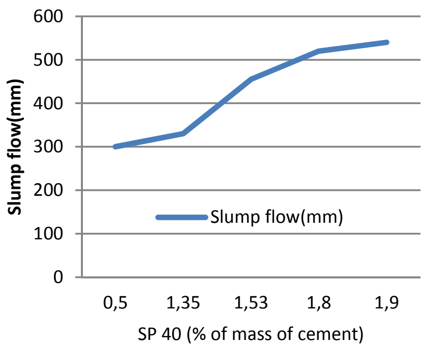

Fig. 3 SP 40 percentage vs. Slump flow

White silica was chosen to control segregation and bleeding in white concrete without exceeding the maximum dosage of 5% to 10% of the cement weight according to the standard. For 340 l/m^3 matrix volume, water/binder ratio 0.45 and varying white silica content 0-5% of mass of cement, slump flow was measured and given in Fig. 4. It was found that slump flow dropped exceeding 2% silica content which reduces the workability of concrete. Therefore, optimum value of silica dosage lay in between 2%-3%.

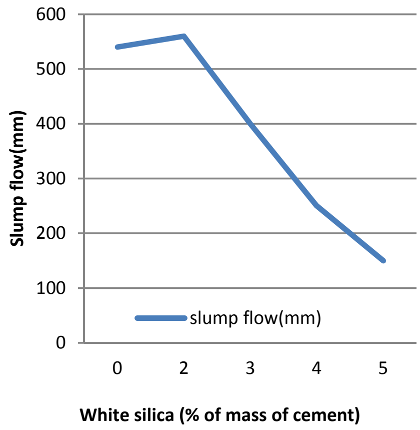

Fig. 4 White silica percentage vs. Slump flow

The aim of this experiment was to prepare white concrete with consistency class SF2, which gives slump flow 660-750 mm by controlling segregation and bleeding. To get the higher consistency, it was required to increase the matrix volume. The experiments were carried out increasing matrix volume of 340 l/m^3 to 360 l/m^3 and 370 l/m^3 with white silica percentage 2%-3% and with SP 40 percentage of 1.9%. Table III shows the materials for matrix volume 340 l/m^3, 360 l/m^3 and 370 l/m^3 with white silica percentage 2%-3% and SP 40 percentage of 1.9%.

TABLE III
MIX DESIGN FOR DIFFERENT MATRIX VOLUMES

Material	Type	Matrix volume		
		340 (l/m^3)	360 (l/m^3)	370 (l/m^3)
		Amount of material (kg/m^3)		
Cement	Aalborg White	408	420	441.14
Sand	0-2 mm	1038	1005.6	989.4
Sand	3-8 mm	301	291.6	286.86
Gravel	8-16 mm	451.5	437.4	430.23
Required water		174.67	188.41	189.35
Admixture	SP 40 (1.9%)	7.75	7.98	8.38
Silica		0-12.24 (0-4%)	8.4 (2%)	9.7 (2.2%)
W/C		0.4	0.47	0.44
W/B		0.45	0.46	.45
Total amount of water		183.67	197.4	198.5

Initially, it was found that optimum silica percentage was varied in between 2%-3% for matrix volume of 340 l/m^3. Using this result and increasing matrix volume to 360 l/m^3, the next experiment was carried out to see the behavior of slump flow with silica percentage varying 2%-3%. As given in Table IV, 2.2% silica percentage gave 690 mm slump flow. It was notice that the mixture was not stable and bleeding of water. Therefore, 0.1% of stabilizer R4 was used in the next trial to overcome the problem and got slump flow 670 mm. To increase consistency of the mixture by reaching higher slump flow, the experiment was carried out for matrix volume 370 l/m^3 as well by starting with silica dosage 2.2% and the slump flow was 690 mm. By increasing silica content up to 2.8%, it could be reached 710mm slum flow. However, stability of the mixture was not good enough at this stage. Therefore, 0.12% of stabilizer R4 was used to get more stable mixture with minimum bleeding of water. As a result of this, slump flow was reduced to 690 mm.

TABLE IV
TRIAL SAMPLES OF DIFFERENT SILICA PERCENTAGE AND MATRIX VOLUMES AND OBTAINED CONSISTENCY CLASSES

Matrix volume (l/m^3)	Silica percentage (% of mass of cement)	SP 40% (% of mass of cement)	Slump flow (mm)	Stabilizer R4 % (% of mass of cement)	Consistency class
340	0	1.9	540	-	SF1
	2	1.9	560	-	SF1
	3	1.9	400	-	-
360	2	1.9	670	-	SF2
	2.2	1.9	690	-	SF 2 (unstable, bleeding of water)
	2.2	1.9	670	0.1	SF 2 (Stable and no bleeding)
370	2.2	1.9	690	-	SF 2
	2.8	1.9	710	-	SF 2(unstable, bleeding of water)
	2.8	1.9	690	0.12	SF2(Stable and no bleeding

IV. RESULTS

Considering the results of trials of experiments and making adjustments focusing on minimizing separation/bleeding of water(visual observation), while achieving a consistency class SF 2, the mix design given in Table V was proposed to produce SCWC controlling bleeding and segregation. In this case, the consistency class was SF 2 with 690 mm slump flow achieved. The mixture was tested by casting a flat floor tile to investigate the surface finish as shown in Fig 5. After curing of 28 days, it was observed that surface was very few defects. In addition to that, 28 days average strength was found 64.1 MPa.

TABLE V
PROPOSED MIX DESIGN WITH REQUIRED CONSISTENCY SF 2

Material	Type	Weight (Kg/m^3)
Cement	Aalborg White	441.14
Sand	0-2 mm	1016
Sand	3-8 mm	299.2
Gravel	8-16 mm	448.8
Water		189.23
Admixture	SP 40 (1.9%)	8.38
Silica	Hvit (2.8%)	12.35
Stabilizer	4R (0.12%)	0.53
Water/binder = 0.44	Water/cement = 0.45	
Total amount of water	198.5 kg	

(a)

(b)

Fig. 5 (a) Casting of facade element; (b) Slump flow

V. CONCLUSION

The self-compacting white concrete mixture was designed to achieve slump flow of 690 mm using PMM. The proposed mix design is given in Table V. One of the main challenges to achieve higher degree of workability is to control segregation and bleeding. In this context, addition of 2.8% of silica and

0.12% of stabilizer R4 to the mixture enhanced resistance to bleeding and segregation. To verify the finding of the experiment, the facade element was casted using the mix design proposed in Table V. In addition, it was observed that increasing silica content more than 3% resulting decrease in slump flow less than 300mm. Therefore, further experiments are needed to adjust the amount of silica content to get more economical design.

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