CHARACTERIZATION OF SELF COMPACTING CONCRETE IN TERMS OF BINGHAM CONSTANTS

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Abstract

The purpose of this experimental work is to determine the domain of the Bingham constants within which a concrete mix possesses self-compactability. Flow characteristics or the rheological characteristics of concrete were expressed by using the Bingham model. Yield shear stress and the plastic viscosity are the two flow properties included in the Bingham model. A range of the combinations of yield shear stress and plastic viscosity was identified within which the concrete is likely to be self-compactable.

To determine the self-compactability of a concrete three index properties were determined by experiments. Those three properties are the filling ability, passing ability and the segregation resistance. To measure the filling ability, slump flow by Abram's cone, T50cm slump flow time and V funnel test were used. To measure the passing ability, J ring test was used. V funnel at T5min test was used to test the resistance to segregation. Self-compactability was judged by comparing the results with the acceptable regions given in the EFNARC publications. Yield shear stress and the plastic viscosity were calculated by using the rotational speed and the applied torque on the concrete which were measured by a coaxial type cohesiometer.

The analysis of data by statistical procedures led to the charts showing variations of the workability indices with the water powder ratio and the superplasticizer dosage for different water cement ratios. Those charts are useful when proportioning self-compacting concrete mixes.

Keywords: Bingham Constants, Filling Ability, Passing Ability, Rheological Characteristics, Segregation Resistance, Self Compacting Concrete.

1. Introduction

Self-compacting concrete (SCC) is a special kind of concrete that does not require any vibration when placing. SCC is able to flow under its own weight and completely fill the restricted sections as well as the congested reinforcement structures without the need of mechanical vibration. SCC has the ability to remain homogeneous while transporting and placing without any significant separation of material constituents. There are several advantages of SCC over conventional concrete. It is environmental friendly because it doesn't need vibration when placing, it is simple to place in complicated formwork and passes through the highly congested reinforcement, accelerate the construction process. Also it has the higher and homogeneous concrete quality across the entire concrete cross section and the higher early strength are the advantages (Huang et al. 2003, Okamura and Masahiro 2003, EFNARC 2002).

SCC was first developed in Japan in 1988 and later in 1990's in European countries as a one solution for the lack of skilled labors to place the concrete in construction. SCC is basically a concrete which no need of vibration to achieve the compaction in placing (Okamura and Masahiro, 2003). Workability requirement of SCC include high deformability, passing ability and proper resistance to segregation (Huang et al., 2003). By reducing the coarse aggregate content, increasing the paste content, lowering the water powder ratio and by adding Superplasticizer (High Range Water Reducing Admixture) the workability can be increased (EFNARC 2005, Okamura 1997). The most commonly used test to determine workability in practice is the slump cone test. Either the vertical slump distance or the horizontal spread of the concrete can be measured. But for SCC slump test alone cannot be taken as the suitable test (Brower and Ferraris 2003).

SCC acts as a fluid. Therefore the flow properties have to be measured. Fluid which obeys the Newton's law is called a Newtonian fluid. But SCC does not obey the Newton's law. In the case of a concentrated suspension like concrete yield stress exists. Therefore the flow properties or the rheological properties of self compacting concrete can be quantified with model which has two parameters. Most widely used model in the world is the Bingham model. Bingham model has two constants. This model contains two intrinsic flow properties of fresh concrete. Namely yield shear stress and the plastic viscosity (Tettersall pp108, 109).

In this paper, the domain of Bingham constants within which a concrete mix possesses self-compatibility is discussed. The rheological properties (plastic viscosity and yield shear stress) are measured using coaxial type rheometer to determine the ranges.

1.1 Three key fresh properties

Self-Compacting concrete is a special kind of concrete and the three key fresh properties are, (EFNARC 2002)

1. **Filling ability** – The ability of SCC to flow into and fill completely all spaces within the formwork, under its own weight.

2. **Passing ability** – the ability of SCC to flow through tight openings such as spaces between steel reinforcing bars without segregation or blocking.
3. **Segregation resistance** – The ability of SCC to remain homogeneous in composition during transport and placing.

1.2 Acceptable regions for SCC

There are acceptable ranges for test results for a concrete mixture to behave as self compactable concrete. Typical acceptance ranges for self compacting concrete with a maximum aggregate size of 20mm as follows (EFNARC 2005).

Table 1: Acceptance Regions for SCC (EFNARC 2005)

Method	***Unit***	***Typical range of values***	
		Minimum	***Maximum***
Slump flow by Abrams cone	*mm*	*650*	*800*
T50cm slump flow	*sec*	*2*	*5*
J-ring	*mm*	*0*	*10*
V-funnel	*sec*	*6*	*12*
Time increase, V-funnel at T5minutes	*sec*	*0*	*+3*

1.3 Rheology of self compacting concrete.

Rheology is the science dealing with the flow and the deformation of matter. Fresh concrete workability is most often associated with the slump value. But slump value does not completely describe the workability of some concrete mixtures (Brower and Ferraris 2003). Two self compacting concrete mixtures with the same slump value can have different flow capabilities when filling reinforced formwork.

Since the SCC behaves as a fluid the flow properties of SCC should be measured in a rheological point of view. But it doesn't obey to the Newtonian's law. So the BINGHAM model should be used to measure the flow properties.

1.4 Bingham model

Some fluids does not flow under small stress, they begins to move when some critical stress is reached. This critical stress is called the yield value. The material which possesses a yield value but has a flow curve which is linear for stresses above the yield value has a flow relationship. An equation for such material is known as Bingham model (Tettersall pp108, 109). It has two constants, which are yield stress τ_0 and plastic viscosity μ. The Bingham model is usually expressed mathematically as:

$$\tau = \tau_0 + \mu D \tag{1}$$

τ = shear stress
τ_0 = yield stress
μ = plastic viscosity
D = rate of change shear strain

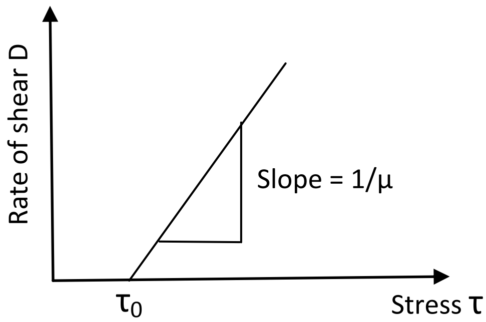

Figure 1: The Bingham model

1.5 Mix design

There is several mix design procedures used in the world. The most common method is the "ACI absolute volume method of proportioning". But for the special requirement for the SCC several modifications are needed. (EFNARC 2005)

1.6 Typical ranges of proportions. (EFNARC 2005)

- Water/powder ratio by volume of 0.80 to 1.10
- Total powder content - 160 to 240 liters (400-600 kg) per cubic meter.
- Coarse aggregate content normally 28 to 35 per cent by volume of the mix.
- Water/cement ratio is selected based on requirements in EN 206. Typically water content does not exceed 200 litres/m^3.
- The sand content balances the volume of the other constituents.

2. Objectives and scope of the study

2.1 Objectives

The main objective of the project is to determine the domain of Bingham constants within which a concrete mix possesses self-compatibility. To measure that several concrete mixtures will be prepared by varying the proportions of material for the concrete. The concrete mixtures will be prepared according to specifications given in literatures, which were introduced as self-compactable. The ranges of amount of materials selecting so that the concrete mixtures are willing to be possess self-compactability. After preparation the mixes they should be tested for self-compactability by several test methods as given in the specifications. Then the rheological properties (plastic viscosity and yield shear stress) are measured and determine the ranges within which the concrete mix possesses self compactability

2.2 Scope of study

The mix compositions used in the experiment are given in table 02.

Table 2: Mix Compositions

Mix No	***water (L / m3)***	***w/c (by mass)***	***w/p (by volume)***	***HRWR (L/100kg of cement)***
1	*180*	*0.40*	*0.90*	*1.30*
2	*180*	*0.40*	*0.80*	*1.80*
3	*180*	*0.40*	*0.76*	*2.00*
4	*180*	*0.40*	*0.71*	*2.25*
5	*180*	*0.40*	*0.73*	*2.50*
6	*190*	*0.40*	*0.80*	*2.00*
7	*200*	*0.40*	*0.80*	*2.50*
8	*195*	*0.40*	*0.80*	*2.50*
9	*190*	*0.60*	*0.80*	*2.50*
10	*190*	*0.50*	*0.80*	*2.50*
11	*190*	*0.50*	*0.70*	*2.50*
12	*190*	*0.50*	*0.90*	*2.50*
13	*190*	*0.45*	*0.85*	*2.20*
14	*190*	*0.45*	*0.80*	*2.30*
15	*190*	*0.45*	*0.90*	*2.10*
16	*190*	*0.55*	*0.90*	*2.90*
17	*190*	*0.55*	*0.85*	*2.70*
18	*190*	*0.55*	*0.8*	*2.50*
19	*190*	*0.50*	*0.85*	*2.70*
20	*190*	*0.50*	*0.75*	*2.20*
21	*190*	*0.45*	*0.75*	*2.40*
22	*190*	*0.45*	*0.70*	*2.40*
23	*190*	*0.55*	*0.85*	*3.00*
24	*190*	*0.5*	*0.80*	*2.40*
25	*190*	*0.45*	*0.90*	*2.40*
26	*190*	*0.50*	*0.75*	*2.50*
27	*190*	*0.55*	*0.75*	*2.30*

3. Methodology

3.1 Selection of ingredients

General suitability is established for cement conforming to EN 197-1. Holcim Superi which is CEM II/A, was selected to use in the experiment. Filler material is used to increase the cohesiveness between the ingredients of the concrete. Dolomite powder (<0.075mm) was used as the filler material because of its availability and the low price. Glenium was used as the superplasticizer to obtain desired flow ability. Aggregates shall conform to EN 12620. The maximum size of the aggregates depends on the particular application and is usually limited to 20 mm.

3.2 Mix design procedure

For the experiment the water content is fixed. Typically the water content is between 150 l/m^3 -200 l/m^3 (EFNARC 2005). Initially 180 l/m^3 was selected as the water content. Then for the purpose of obtaining the self compacting mixes water content was increased to190 l/m^3. Water cement ratio is decided to varying between 0.4 and 0.6 by mass. Coarse aggregate should be within 28% and 35% by volume as specified in the EFNARC (EFNARC 2002). Coarse aggregate content used in the experiment was 28% by volume. Fine aggregate content is to balance the volume of the other constituents (EFNARC 2002).

For determination of the water powder ratio of concrete, initially water powder ratio for zero slump (βp) was determined in the paste with the selected proportions of cement and dolomite. This test was done by the flow table apparatus. Slump was measured for different w/p ratios. Mini slump test was used to determine the optimum superplasticizer dosage for the different powder (filler) cement ratios. Initially the test was done only for the cement slurry. Then test was done for powder cement ratios 0.33 and 0.9. V funnel test was performed at varying water powder ratios in the range of (0.8- 0.9) x βp to determine the optimum water powder ratio and superplasticizer dosage in the cement mortar. Target value of the time to pass the V funnel is 7-11 s. Finally concrete was mixed for the mortar values which were within the required region.

Finally concrete was mixed for the mortar values which were within the required region. Based on the results obtained, necessary modifications were carried out according to Trouble shooting Guide of EFNARC guidelines (EFNARC 2002). There are 27 mix design proportions by varying the water cement ratio, water powder ratio and the superplasticizer dosage.

3.3 Testing of concrete

To determine the filling ability of the concrete slump flow test, T50cm and the V funnel tests were used. To measure the passing ability J ring apparatus was used. V funnel test at T 5 minutes is used to measure the resistance to the segregation of the concrete. This test was carried out after carrying out the V funnel test. Necessary modifications were carried out and trial mixes were produced to obtain proper mix designs to satisfy the test requirements.

3.4 Measuring rheological properties

Rheometers are used to measure the rheological properties of concrete. Coaxial type rheometer was used in the experiment. There are two cylinders in the coaxial type rheometers. Concrete mixture was poured to the gap between the inner cylinder and the outer cylinder up to a specified height. Then the outer cylinder was rotated in varying speed and the torque on the inner cylinder was measured. Then the graph of the variation of the torque on the inner cylinder with the rotational speed was plotted. Plastic viscosity and the shear stress were calculated by using the gradient and the intercept of the graph.

Figure 2: Rheometer

3.4.1 Coaxial cylinder viscometer equations

After measuring the Torque induced on the inner cylinder for speeds of the outer cylinder a graph is plotted Torque (T) against rotational speed (Ω). The slope of the graph is 1/s. Then the following equations give the yield stress (τ_0) and plastic viscosity (μ) (Tettersall pp108, 109).

$$\mu = \frac{1}{4\pi h}\left(\frac{1}{R_b^2} - \frac{1}{R_c^2}\right)\frac{1}{S} \tag{2}$$

$$\tau_0 = \frac{T_2\left(\frac{1}{R_b^2} - \frac{1}{R_c^2}\right)\frac{1}{S}}{4\pi \mathrm{h} \ln\left(\frac{\mathrm{R_c}}{\mathrm{R_b}}\right)} \tag{3}$$

Where; S = Ω/T
Rb = Radius of inner cylinder
Rc = Radius of outer cylinder
h = height of the cylinder

3.5 Hardened properties

For each trial mix 3 cubes and 3 cylinders were cast to obtain the compressive strength. Altogether 81 cubes (150mm x 150mm) and 81 cylinders (150mm φ x 300mm) were cast. Cubes were used to measure the 7 day strength and 28 day strength. Cylinders were used to measure 7 day strength.

4. Results and discussion

4.1Test results of workability properties of SCC

Table 3: Summary of workability indices of the test mixes

Mix No	Slump flow by Abram's cone (mm)	T50cm slump flow (s)	V- funnel time (s)	J ring height difference (mm)	V-funnel at T5min (s)	Qualification as SCC
1	445	-	16.59	24.29	6.22	Disqualified
2	678	6.40	16.90	23.81	6.78	Disqualified
3	720	3.13	14.59	24.68	4.24	Disqualified
4	600	5.47	13.97	20.60	6.48	Disqualified
5	635	5.20	30.50	23.50	12.50	Disqualified
6	690	4.05	14.52	16.50	3.04	Disqualified
7	715	4.24	5.53	55.00	0.56	Disqualified
8	775	3.35	17.91	24.25	0.34	Disqualified
9	675	2.99	7.37	23.50	4.70	Disqualified
10	740	2.10	8.24	9.50	1.65	Qualified
11	740	2.38	17.34	6.00	11.59	Disqualified
12	795	1.90	4.33	3.25	0.72	Disqualified
13	655	3.53	6.97	9.75	2.93	Qualified
14	715	3.00	8.67	6.75	2.55	Qualified
15	620	2.64	5.12	5.75	1.73	Disqualified
16	740	1.69	4.95	13.50	1.16	Disqualified
17	715	3.28	6.77	6.50	2.44	Qualified
18	715	2.24	6.22	5.75	1.70	Qualified
19	750	2.01	7.15	4.00	15.30	Disqualified
20	725	2.41	7.80	9.25	2.84	Qualified
21	730	3.35	10.56	12.75	4.49	Disqualified
22	725	3.65	10.53	10.50	4.21	Disqualified
23	690	2.02	6.36	9.75	0.63	Qualified
24	673	3.51	10.27	6.75	0.72	Qualified
25	720	2.06	7.81	5.00	2.59	Qualified
26	645	4.04	11.91	10.00	2.80	Qualified
27	490	-	21.38	21.50	7.09	Disqualified

- Slump flow was used to measure the filling ability of SCC. Qualified region as SCC is between 650mm-800mm. When ever the diameter is high it has the greater ability to fill the form work.
- V funnel flow time was used to measure the filling ability of SCC. Qualified region of V funnel flow time for SCC is between 6-12 s. Lower the flow time is greater the filling ability.
- T_{50cm} slump flow time was used to measure the filling ability of concrete. For a self compacting mix the value should be within 2-5 seconds. Lower value of flow time represents a greater filling ability.
- Height difference just before and after the J-ring was measured. For SCC the value should be below 10mm. Lesser the value indicates higher the passing ability.
- Here the time increase should be less than 3 s for a SCC mix. Greater value of time increase indicates a higher segregation.

4.2Variation of yield shear stress with plastic viscosity

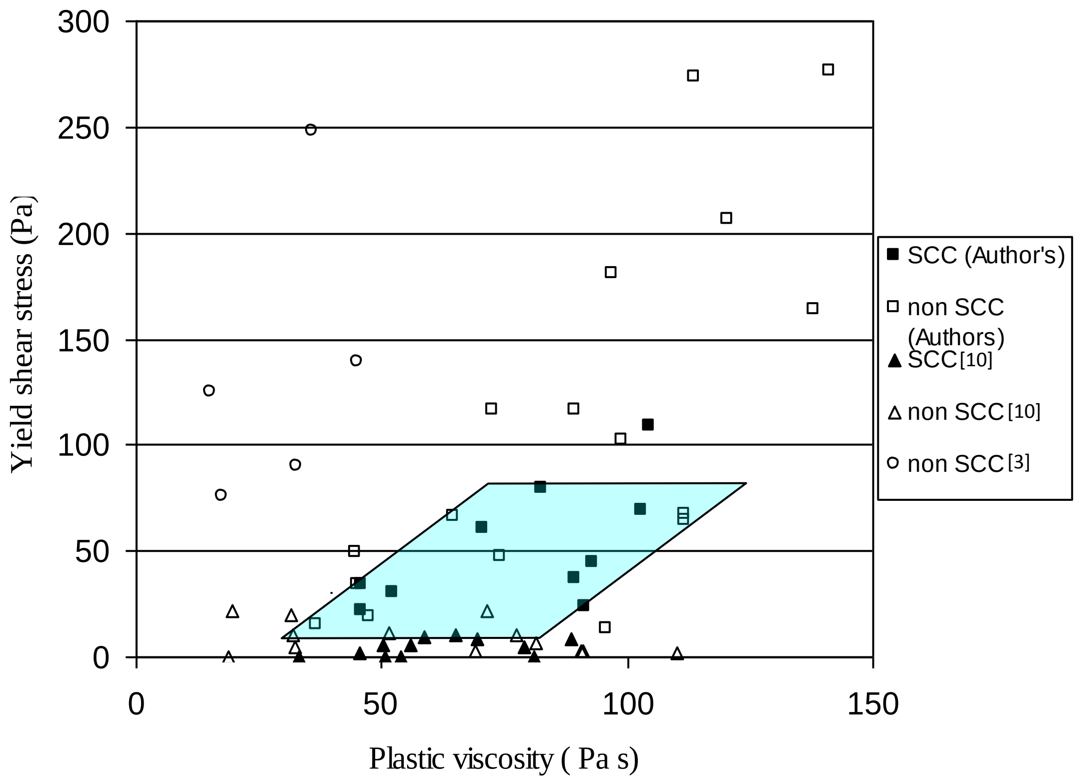

Figure 3: Domain of shear stress and plastic viscosity of self-compacting concrete

Coloured area of the Fig 3 is the area of the combinations of the yield shear stress and the plastic viscosity of concrete mixes which are having the self compacting properties. Range of plastic viscosity and yield shear stress within which concrete mixes possesses self compactibility are given in the table 4.

Table 4: Range of yield shear stress and plastic viscosity

Parameter	***Range***
Yield shear stress (Pa)	*8-80*
Plastic viscosity (Pa s)	*40-108*

5. Conclusions

The following conclusions were drawn based on the observation made in the reported investigation. The conclusions are true within the scope of the investigation.

1. **Qualified mix proportions as SCC**

Valid mixes as SCC were selected according to the guidelines given in the EFNARC (EFNARC 2002) guidelines. The ranges of the mix composition within which the concrete mixes posses self compactability are given in the Table 5.

Table 5: Qualified mix proportions as SCC

w/c (by mass)	*w/p (by volume)*	*HRWR / (L/100kg of cement)*
0.45	*0.8-0.9*	*2.2-2.4*
0.50	*0.75-0.8*	*2.2-2.5*
0.55	*0.8-0.85*	*2.5-3.0*

- For w/c = 0.45

When w/p ratio decreasing from 0.8, V funnel flow time increases and the T 50cm slump flow time increases. That means the filling ability of the mix decreases with decreasing of the w/p ratio. J ring height difference also increases with the w/p ratio. That means the passing ability decreases with the decreasing of the w/p ratio. Decreasing the superplasticizer dosage below the value of 2.2 L/100kg decreases the slump diameter. That means the filling ability of the mix decreases with increasing of the superplasticizer dosage.

- For w/c = 0.50

When w/p ratio decreasing from 0.75, V funnel flow time increases. That means the filling ability of the mix decreases with decreasing of the w/p ratio. Decreasing the superplasticizer dosage below the value of 2.2 L/100kg decreases the slump diameter. That means the filling ability of the mix decreases with increasing of the superplasticizer dosage. Increasing the superplasticizer dosage above a value of 2.5 L/100kg causes increase of time increase of V funnel at T 5min value. That means increasing of Segregation.

- For w/c = 0.55

When w/p ratio is decreasing from 0.80, V funnel flow time increases. That means the filling ability of the mix decreases with decreasing of the w/p ratio. Decreasing the superplasticizer dosage below the value of 2.5 L/100kg decreases the J ring height difference. That is decreasing the passing ability. Increasing the superplasticizer dosage above a value of 3.0 L/100kg causes increase of time increase of V funnel at T 5min value. That means increasing of Segregation.

2. Range of yield shear stress and plastic viscosity for SCC

Coaxial type cohesiometer used to measure the variation of torque with rotational speed. From that the values of plastic viscosity and yield shear stress were calculated. Then the range of the Bingham constants (plastic viscosity and yield shear stress) within which concrete mixes behaves as self compacting mixes were obtained. The range is given in the Table 6.

Table 6: Range of yield shear stress and plastic viscosity

Parameter	***Range***
Yield shear stress (Pa)	*8-80*
Plastic viscosity (Pa s)	*40-108*

Concrete mixes which have the plastic viscosity and yield shear stress combination within the range given in the Table 6 are more likely to be self compacting concrete. But some self compactable mixes had the plastic viscosity and yield shear stress combination not within that region. And some non self compactable mixes had the plastic viscosity and yield shear stress combination within that region.

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