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Investigating the Reliability of Selected Mix Design Methods for the Production of Super-Workable Concrete

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Abstract:- In order to proffer solution to the difficulties experienced in achieving a super-workable concrete commonly known as Self Compacting Concrete, four mixture design methods were carefully selected and investigated. Three mixes were designed for each method considered in accordance with their specifications. The methods considered are: the American Concrete Institute, EFNARC, European Project Group and the Optimal Mixture Design (Yu *et al*) methods. The results disclosed that the EFNARC method is the most reliable method in the production of super-workable concrete as it significantly satisfies the fresh properties of the concrete.

Keywords:- *Mix Design Methods, Super-Workable Concrete and Fresh Properties.*

I. INTRODUCTION

Super-workable concrete commonly called Self-Compacting Concrete (SCC) was first discovered in Japan since 1988. Its discovery was a landmark achievement in concrete construction which helped to solve the problem of inadequate compaction leading to durability issues of concrete structures. Also, SCC was a solution to the diminishing number of skilled workers which was quite expensive too (Okamura and Ouchi 2003; Goodier, 2003).

SCC also referred to as Self-Consolidating, Self-Placing or Self-Leveling Concrete (ACI 2007) is a special type of concrete which can flow into form-work corners and reinforcement gaps only by its self-weight without the need for external compaction or mechanical vibration, whilst recording minimal bleeding and segregation (Umar and Al-Tamimi 2011; Su, Hsu and Chai, 2001).

The most appealing attributes of Super-workable concrete are those of its fresh properties, which has to do with the passing and filling abilities, and the resistance to segregation, which leads to health, economic, technological and aesthetic advantages in terms of noise reduction, cost of labour and smooth finishes (ACI 2007).

Irrespective of the attractive qualities of SCC, one major drawback of super-workable concrete is its cost of production which relates to the use of high quantity of Portland cement. An option to bring down the production cost of super-workable concrete is to bring in mineral admixtures like fly ash as partial replacement for cement (Uysal and Sumer 2011). Secondly, it is considered challenging to design because of the need to balance the characteristics of its fresh properties (Sedran and de Larrard 1999). Numerous efforts have been made to develop an optimized mixture design method for super-workable concrete, however, no specific mixture design method has been successfully developed to meet all fresh concrete criteria (Grdic, Despotovic and Toplicic-Curcic, 2008; BIBM *et al.* 2005). This study will seek to investigate the reliability of different mix design methods to produce SCC.

II. EXPERIMENTAL PROGRAM

➢ *Materials*

Cement: Hanson Heidelberg Portland cement product (CEM I 52,5N) with density of 3029 kg/m^3 and in conforming to BS EN 197-1 was used.

Aggregate: Fine aggregate obtained within Coventry, United Kingdom with grain size not greater than 4.75 mm and having density of 2670 kg/m^3 was used. The coarse aggregate has grain size not greater than 19 mm and a density of 2525 kg/m^3. The particle size distribution graphs can be seen in figure 1.

Fly ash: Pulverized fuel ash produced in Scotland and conforming to BS EN ISO 9002:1994, with a density of 2090 kg/m^3 was used.

Super-plasticizer: A poly-carboxylate polymer based super-plasticizer (ADVA flow 411) from Grace Construction and in conformity with EN 934-2 and having a recommended dosage of 600 ml- 1200 ml/ 100 kg of cement was used.

➢ *Methods*

The experiment consists of preparing mixture designs in line with the standards considered in this study as shown in Table 1. About 30 litres of concrete was mixed in accordance with the selected methods to accommodate all relevant tests.

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MIX DESIGN METHODS	CEMENT	ADMIXTURE	WATER	FINE AGGRE.	COARSE AGGR.	HRWRA	w/p	REMARK
EFNARC (2002)	160-240 ltrs (400 - 600 kg/m^3)		Max. $200kg/m^3$	Rest of mix volume		28 – 35% by vol.	0.8 – 1.1 by vol.	Self-compatibility is achieved by trial mixes
YU et al (2005)	30 – 40% of powder		-	Sand mortar ≤ 0.44 by vol. s/a = 45-50%	≤ 33% of mix vol.	>0.5% of cement	≤ 0.4	-
BIBM et al (2005)	380 – 600 kg/m^3		150 – 210 kg/m^3	48 – 55% of total aggr. wgt.	750 – $1000kg/m^3$	-	0.85 – 1.1	Self-compatibility is achievd by trial mixes
ACI (2007)	Powder =386 – $457kg/m^3$; Mortar = 68 – 72% of mix; Paste =34 – 40% of mix				28 – 32% of mix vol.	-	0.32 – 0.45 by mass	Self-compatibility is achieved by trial mix

Table 1:- Mix design methods considered

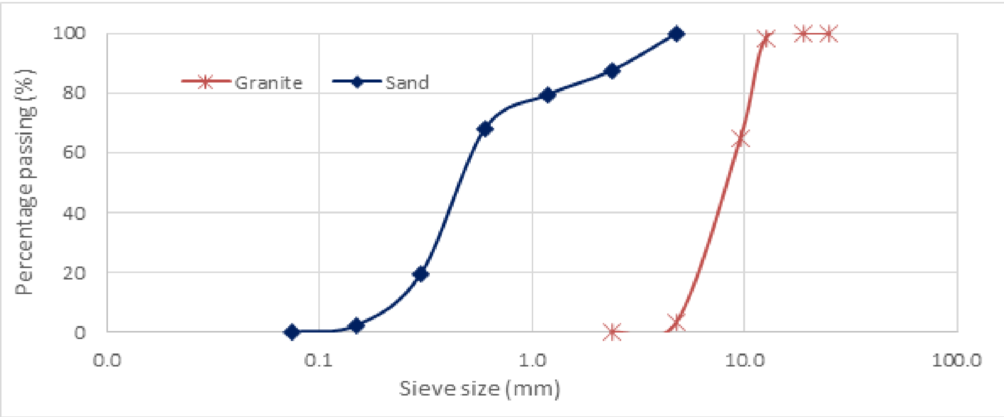

Fig 1:- Sieve analysis of aggregates

➢ *Concrete mix proportions*

The mix ratios for the concrete are shown in Table 2. All concrete mix were prepared in accordance with the specifications of the mix design methods considered.

MIX DESIGN ID	CEMENT (kg)	PFA (kg)	POWDER (kg)	FINE (kg)	COARSE (kg)	WATER (kg)	SP(kg)	W/P (mass)	w/p (vol.)
EFNARC (2002)									
EFN-M1-40P	330	220	550	850	750	175	7.8	0.32	0.82
EFN-M2-40P	340	240	600	760	750	200	4.6	0.33	0.85
EFN-M3-40P	300	200	500	840	820	158	6.8	0.32	0.81
YU et al (2005)									
YU-M1-40P	330	220	580	785	785	165	6.4	0.3	
YU-M2-40P	300	200	500	780	790	180	4.4	0.36	
YU-M3-40P	300	200	500	790	820	175	5.2	0.35	
EUROPEAN PROJECT GROUP (BIBM et al 2005)									
BIB-M1-40P	330	220	550	764	788	190	5		0.89
BIB-M2-40P	348	232	520	790	775	175	7.2		0.87
BIB-M3-40P	270	180	450	870	800	172	7.2		0.98
AMERICAN CONCRETE INSTITUTE (ACI 2007)									
ACI-M1-40P	280	187	467	890	740	155	9.2	0.33	
ACI-M2-40P	285	190	475	840	745	185	7.2	0.31	
ACI-M3-40P	276	184	460	895	780	161	8.4	0.35	
EFN-M1-40P represents 1st mix for EFNARC method with 40% PFA, YU-M2-40P represents 2nd mix for Yu et al method with 40% PFA, BIB-M3-40P represents 3rd mix for BIBM et al method with 40% PFA and similar to all other mix identities									

Table 2:- Concrete mixture proportions for various methods

➢ *Tests*

The tests carried out are only those relating to the fresh properties which include: Visual Stability Index (VSI), Slump-flow and T500, V-funnel and L-box tests. These tests were conducted in quick pace as soon as the concrete mixture was ready. The slump-flow and T_{500} tests were conducted together, then the V-funnel test preceded the L-box test (Testing SCC 2005). The VSI test was carried out immediately after the slump flow test using the eye to observe the presence of mortar halos and patty. This is intended to physically confirm the extent of stability of the concrete mixture. The rating for this test is as shown in Table 3.

VSI rating	Indication
0	Highly stable, no evidence of segregation in slump flow patty
1	Stable, no mortar halo or aggregate pile in slump flow patty, but slight segregation
2	Unstable, a slight mortar halo (<10mm) and/or aggregate pile in slump flow patty
3	Highly unstable, clearly segregating by evidence of a large mortar halo (>10mm)

Table 3:- Visual Stability Index (VSI) rating for SCC (PCI 2003:30)

T500 and slump flow tests measures the flow rate and flow ability of super-workable concrete in the absence of obstacles. The tests were conducted in compliance with the EFNARC specification, which is in agreement with BS EN 12350-8:2010. The recommended ranges for a good filling ability are: 2-5secs for T500 and 650mm-800mm for slump flow. The pictorial view of the test is shown in Plate 1.

V-funnel test measures viscosity and filling ability of super-workable concrete. It was conducted in compliance with BS EN 12350-8:2010. Plate 2 shows the pictorial view of the test.

L-box text measures the passing ability of super-workable concrete. It was conducted in conformity with BS EN 12350-8:2010. The ratio of the difference in height of the vertical section (H_1) and that of the horizontal section (H_2) was taken as the L-box reading (see Plate 3).

Plate 1: Slump-flow test.

Plate 2: V-funnel test

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Plate 3: L-box test

III. RESULTS

Table 4 shows the results of tests carried out to investigate the fresh properties of super-workable concrete for the mixture design methods considered. The results are graphically displayed in Figures 2, 3, 4, and 5.

Mix design ID	Slump flow (mm)	t_{500} (s)	V-funnel (s)	L-box (H_1/H_2)	VSI
EFNARC (2002)					
EFN-M1-40P	690	2.3	6.6	0.82	0
EFN-M2-40P	720	1.82	5.4	0.92	2
EFN-M3-40P	660	4.65	10.3	0.83	0
Yu *et al* (2005)					
YU-M1-40P	668	2.4	6	0.81	0
YU-M2-40P	635	1.9	5.89	0.71	1
YU-M3-40P	656	3.9	6.11	0.68	0
European Project Group (BIBM *et al* 2005)					
BIB-M1-40P	727.5	2	6.83	0.9	1
BIB-M2-40P	668	2.3	6.89	0.82	0
BIB-M3-40P	574	2.9	5.92	0.66	0
American Concrete Institute (2007)					
ACI-M1-40P	612	3.7	9.9	0.68	1
ACI-M2-40P	540	3.3	7.6	0.57	0
ACI-M3-40P	615	2.6	6.8	0.76	1

Table 4:- Test results on fresh properties of super-workable concrete.

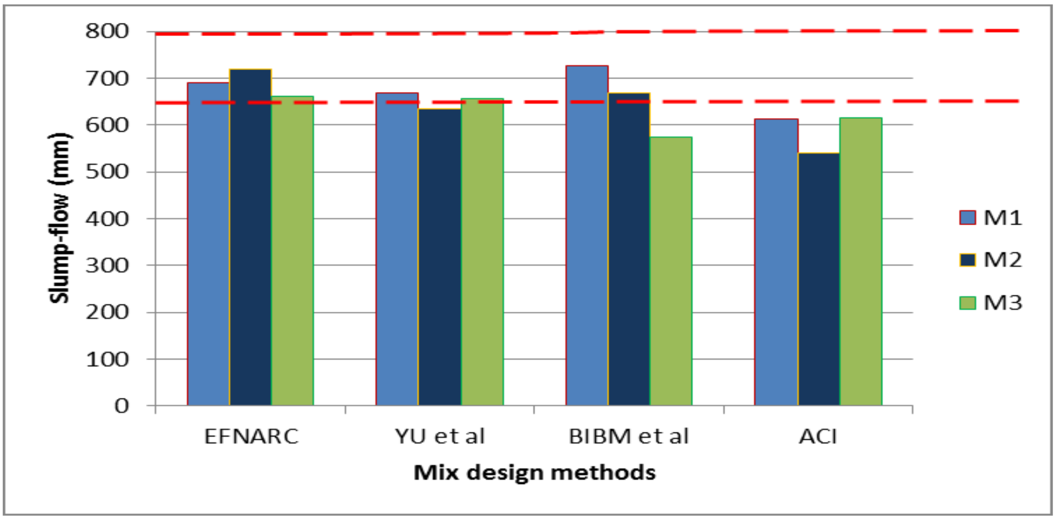

Fig 2:- Slump-flow results for the different methods

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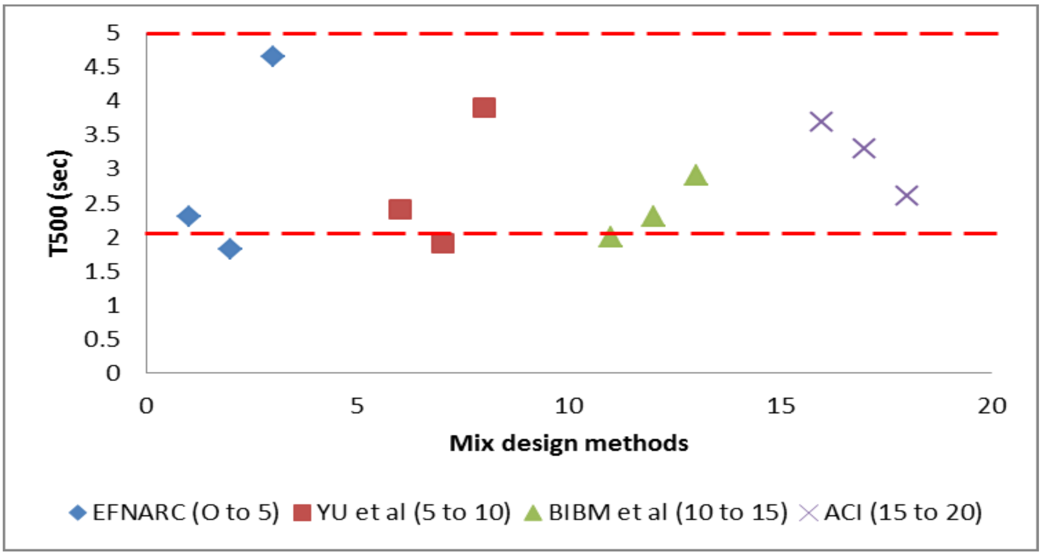

Fig 3:- T500 results for the different methods

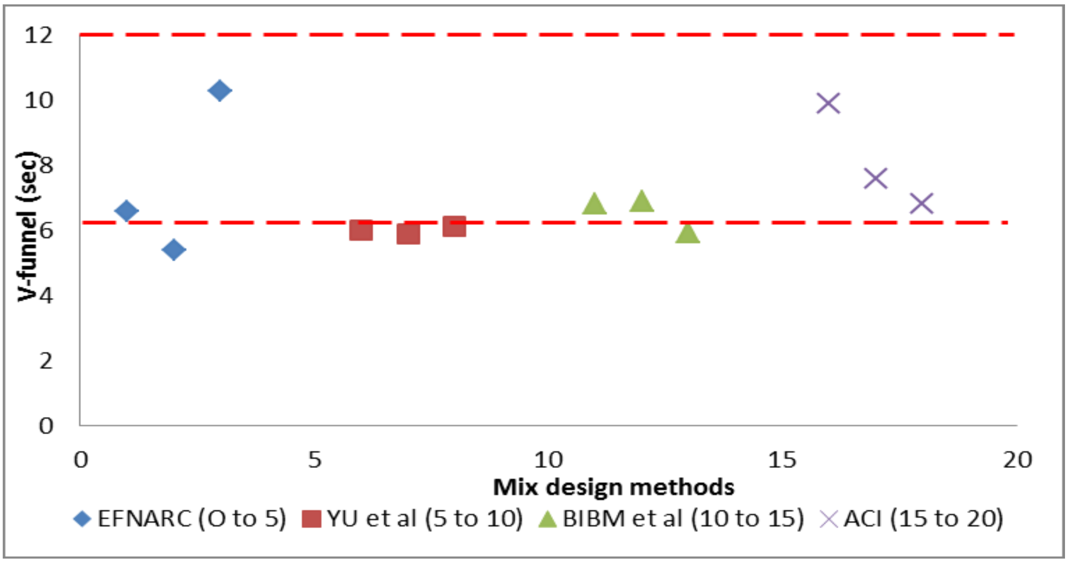

Fig 4:- V-funnel results for the different methods

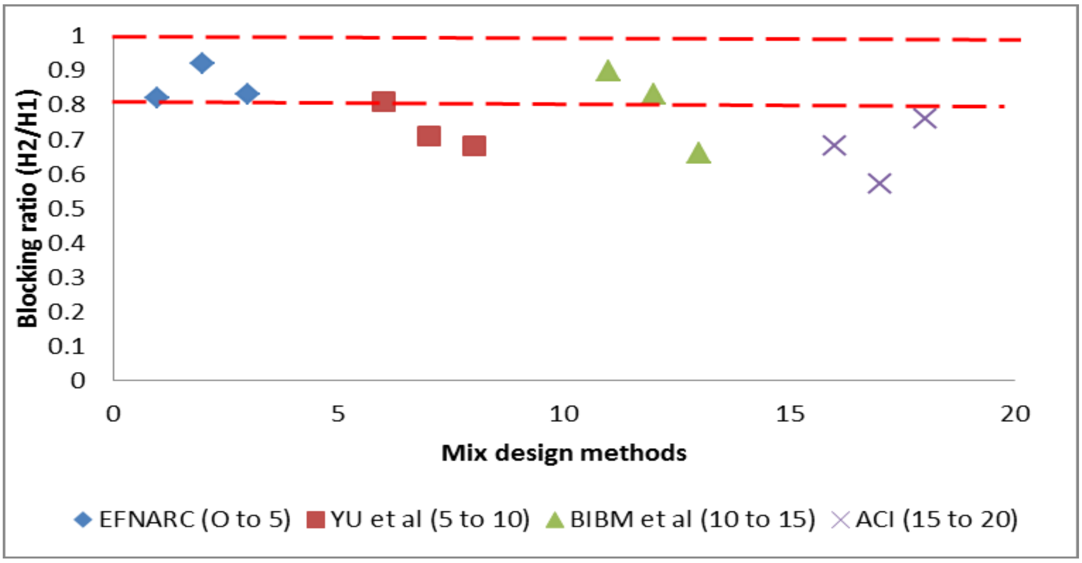

Fig 5:- L-box results for the different methods

IV. DISCUSSIONS

- *EFNARC (2002)*

Figure 2 shows that all concrete mixtures produced using the EFNARC method achieved a slump-flow within the standard range; this simply tells that the concrete has a good filling ability. Also, the V-funnel and T_{500} results showed in Figures 3 and 4, falls within the specified range except for mix EFN-M2-40P which reveals slight segregation, which may be as a result of no VMA in the mixture. Figure 5 shows that the L-box results are within the target range, thus indicating a satisfactory passing ability. From Table 4, the VSI rating shows 0 and 1, which is an indication of good stability, except for mix EFN-M2-40P which had slight segregation. Generally, it can be inferred that the EFNARC method is adequate for the design of super-workable concrete.

- *Optimal mixture design (Yu et al. 2005)*

Figures 2, 3 and 4 showed that all concrete mixtures produced with this method are within the target range for slump-flow, T_{500} and V-funnel, apart from the mixture tagged YU-M2-40P which had a low slump-flow, T_{500} and V-funnel values. This can be linked to the low dosage of super-plasticizer recommended by this method. The mixtures within the target ranges signify good filling ability. From Figure 5, the second and third mixtures fall outside the specified range, indicating poor passing ability; this can be ascribed to the high coarse to total aggregate ratio proposed by this method. From Table 4, VSI test was satisfied for all mixes.

- *European Project Group (BIBM et al. 2005).*

From Figure 2, 3, 4 and 5, the first two mixtures fall within the target ranges as they show good filling and passing abilities. The third mix (BIB-M3-40P) only satisfied the T_{500} test, implying a good viscosity however the filling and passing ability is poor. This could be a consequence of low powder content or insufficient proportioning of super-plasticizer and VMA dosages in the mix. From Table 4, VSI test was satisfied for all mixes. The results also reveal that this method can be suitable for both the powder and combined types of super-workable concrete, but not too suitable for the VMA type. Although, the reduced range for water-powder ratio proposed by this method, compared to that of EFNARC method, makes it a little stressful to develop a mix design for the powder type super-workable concrete which requires very low water-powder ratio.

- *American Concrete Institute (2007)*

Figures 2, 3 and 4 reveals an unsatisfactory slump-flow but high T_{500} and V-funnel values. This indicates poor filling ability, but a highly viscous SCC mixture. This could be due to insufficient super-plasticizer dosage. From Figure 5, it is seen that all mixes are below the target range, which is indicative of poor passing ability. This may also be attributed to an insufficient super-plasticizer dosage. Table 4 reveals a satisfactory VSI results for this method. The range of powder content proposed by this method, when compared to EFNARC‟s classifications shows that super-workable concrete produced with this method is more of the VMA type.

A careful observation of Tables 1 and 4 shows that the entire mixes designed with powder content less than 480 kg/m^3 resulted in low slump value.

V. CONCLUSIONS

The following are the conclusions drawn from this study:

- The EFNARC mixture design method satisfies all fresh properties of Super-workable concrete, and it is flexible and adequate for SCC production.
- The mixture design method proposed by BIBM *et al* satisfies all fresh properties of super-workable concrete, but is more convenient for the production of the combined type concrete, depending on the material properties.
- To achieve a good passing ability of a super-workable concrete using the Yu *et al* mixture design method, it is advisable to adopt equal percentage of fine and coarse aggregates in the mix.
- The ACI mixture design is difficult to achieve because of the low paste content recommend by the method. Hence, it is deemed not suitable for massive concrete work.

In summary, it can therefore be concluded that the EFNARC mixture design method is the most suitable in the production of super-workable concrete.

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