SELF-COMPACTING HIGH-PERFORMANCE CONCRETE IN TERMS OF MIXING PROPORTIONS AND PROCEDURE

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Self-compacting high-performance concrete (SCHPC) is a special type of concrete, which could perform optimally with respect to flow characteristics, strength, transport properties and durability while maintaining the required service life under a given set of material load exposure conditions. Therefore, the production of SCHPC involves more stringent control on the selection of constituent materials than do other types of concrete. Optimal mix design of SCHPC is assessed to optimise fresh and hardened properties. The optimisation has been based on the basic material aspects of SCHPC, namely, aggregate fraction distribution, water to cement (w/c) ratio, and cement content, in addition to the mixing procedure. Thus, all the proposed factors have to be considered to achieve the maximum possible compressive strength by taking into considerations the minimum required highrange water reducer admixture (HRWRA) dosage. SCHPC proved its sensitivity to the ingredient proportions and mixing procedure, which is much more than other types of concrete, where they had a significant effect on the compressive strength and workability performance of SCHPC.

Keywords: self-compacting concrete, high-performance concrete, compressive strength, mixing proportions, mixing procedure

1. SELF-COMPACTING CONCRETE

Self-compacting concrete (SCC) is a special type of concrete which spreads through congested reinforcement, reaches every corner of frameworks and consolidates under its own weight, thus providing excellent filling capability and good segregation resistance *(Khayat, 1999)*. Such difficulties, such as lack of skilled workers and durability damages caused by inadequate compaction, complex and difficult shapes of structural elements and congestion of steel reinforcement, were the main motivations for Japanese researchers to introduce SCC, which offers health and safety benefits *(Okamura and Ouchi, 2003)*. However, normal SCC remains prone to poor durability and strength, which could be overcome by the use of cement replacing materials (CRMs) and reduction of the water to binder (w/b) ratio.

2. HIGH-PERFORMANCE CONCRETE

High-performance concrete (HPC) was introduced by researchers as a result of their trials for overcoming the drawbacks of conventional normal concrete. They changed the concrete constituents, mixing procedure and carrying process to improve the particular zone of hydrated paste in the proximity of aggregates, which is called the interfacial transition zone (ITZ). The American Concrete Institute (ACI) defines HPC as 'a concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing' *(ACI CT-13, 2013)*. The major disadvantage of HPC is its low flow and filling capability caused by the low w/b ratio, which could overcome by the use of High-range water reducer admixture (HRWRA) and CRMs.

An alternative in the advancement of concrete technology is the combination of the performance characteristics *high strength and durability* of HPC with the workability characteristics *high flow and filling capability* of SCC to produce Self-compacting high-performance concrete (SCHPC).

3. SELF-COMPACTING HIGH-PERFORMANCE CONCRETE

SCHPC is a special type of concrete, which could perform optimally with respect to flow characteristics, strength, transport properties and durability while maintaining the required service life under a given set of material load exposure conditions. SCHPC's performance at fresh and hardened states differentiate it from ordinary concrete types. This feature is driven by the incorporation of special ingredients in certain proportions, such as HRWRA and CRMs, in addition to standard materials used for all concretes, such as aggregates, sand, cement and water *(Safiuddin, 2008)*.

The proportions of SCHPC mixtures also differ from those used in ordinary concrete; binder volume, fine aggregate and powders and HRWRA are higher in the former than in the

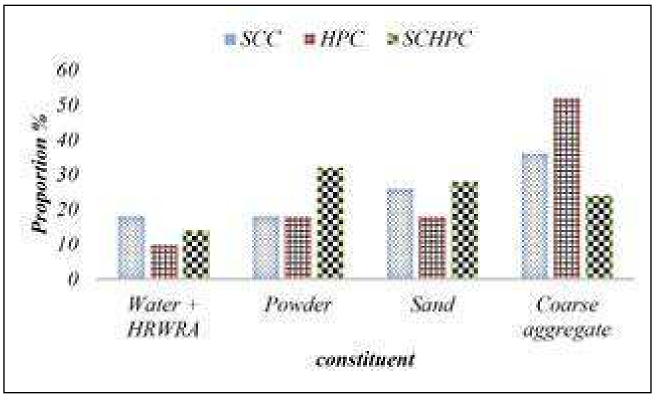

Fig. 1: Typical constituents' ratios of SCC, HPC and SCHPC

latter, whereas the w/b ratio and coarse aggregate are lower. The w/b ratio is recommended to be from 0.2 to 0.4 in case of SCHPC *(Persson, 2001). Ghanbari (2011)* proposed typical ratios of constituents for normal SCC and HPC and for SCHPC, as shown in ***Fig.1***.

3.1 Advantages of SCHPC

SCHPC offers more advantages than does ordinary concrete and includes the advantages of SCC and HPC; these advantages could be grouped into three *(Cameron, 2003; Okamura and Ouchi, 2003; EFNARC, 2005; EFNARC, 2002; Safiuddin, 2008)*, which are discussed in the following sub-sections.

3.1.1 Constructional value

SCHPC flows through and around reinforcing steel under self-weight without using any means of compaction, thereby enhancing compactness and reducing porosity and consequently providing improved strength. Its own compaction facilitates and simplifies the execution process of complex design elements and cast of complicated architectural forms, especially in case with large amounts of reinforcement in small sections. SCHPC is also a watertight concrete; it reduces transport properties, enhances durability and eliminates surface pores, thus providing good finishing without the need for improvement.

3.1.2 Environmental value

The construction environment could be improved with reduction of construction noise and decrease of construction time, where a concrete vibrating equipment is not required. SCHPC consumes large amounts of CRMs (waste materials), which saves the environment from excessive waste materials, cement production and disposal places.

3.1.3 Economic value

SCHPC helps in decreasing the number of required labourers for the transport and placement of concrete, thereby reducing the costs of construction and saving large quantities of concrete due to the reduced sections of structural components. This material allows for a quickened reuse of formwork, which can last longer due to the elimination of vibration equipment and thus enhances the production rate.

3.2 Performance criteria of SCHPC

The use of HRWRA for producing high levels of workability and segregation-resistant concretes was introduced more than

Table 1: Performance criteria of SCHPC (Safiuddin, 2008)

Methods	*Properties*	*Performance criteria*
	SCC properties	
Slump	*Filling ability*	*250–280 mm*
Slump flow	*Filling ability, segregation resistance*	*550–850 mm*
V-funnel flow	*Filling ability, segregation resistance*	*5–14 s*
Orimet flow with 80 mm orifice	*Filling ability, segregation resistance*	*2.5–9 s*
Filling percentage in fill-box	*Filling ability, passing ability*	*90%–100%*
Blocking ratio in L-box	*Filling ability, passing ability, segregation resistance*	*>0.8*
Filling height in U-box	*Filling ability, passing ability*	*30 mm*
Slump cone – J-ring flow	*Reduction in slump flow as measure of passing ability*	*50 mm*
Penetration depth	*Segregation resistance*	*8 mm*
Sieve segregation	*Segregation resistance*	*18%*
	HPC properties	
Air content by pressure method	*Fresh air content*	*4%–8%*
Axial compression on cylinders	*28- and 91-day compressive strength*	*>40 MPa*
Ultrasonic pulse velocity by PUNDIT	*Physical quality or condition (packing, uniformity, etc.)*	*≥4575 m/s*
Porosity by fluid displacement method	*Porosity by fluid displacement method*	*7%–15%*
Absorption by water saturation technique	*Water absorption as indicator of durability*	*3%–6%*
True electrical resistivity by Wenner probe	*Electrical resistance to corrosion*	*>5–10 kΩ-cm*
Rapid chloride ion penetration	*Electrical charge passed as indicator of corrosion resistance*	*<2000 C*
Normal chloride ion penetration at 6 months	*Penetrated chloride value as indicator of corrosion resistance*	*<0.07%*
Durability factor after 300 cycles of freeze-thaw	*Resistance to freezing and thawing*	*>0.8*

one decade before the development of SCHPC (The first prototype of SCHPC was developed in 1988.) *(Okamura, 1995; Safiuddin, 2008; Collepardi, 1976)*. The Japanese concrete industry commercialised SCHPC in the forms of 'non-vibrated concrete', 'super-quality concrete', and 'biocrete'.

SCHPC has to fulfil the performance criteria of SCC in the fresh state and of hardened HPC to ensure adequate mechanical and durability properties. *Safiuddin (2008)* summarised these performance criteria, which could be specified for SCHPC by an examination of several SCC and HPC works *(Bui et al., 2002; Khayat, 2000; Kosmatka and Cement Association of, 2002; EFNARC, 2005; EFNARC, 2002)*. These performance criteria are presented in ***Table 1***.

3.3 Material aspects of SCHPC

Similar to ordinary concrete, SCHPC consists of cement, coarse aggregates, fine aggregates and water; however, HRWRA and CRMs are highly important in SCHPC. The characteristics of its ingredients highly affect its performance in fresh and hardened states. Therefore, the production of SCHPC involves more stringent control on the selection of constituent materials than do other types of concrete. The constituent materials are the defining factors in achieving the expected benefits from SCHPC.

3.3.1 Coarse aggregate

Coarse aggregate is that retained in a 4.75 mm (No. 4) sieve. It is a main ingredient and constituent of concrete and distinguishes concrete from mortar. The physical characteristics, porosity and grading of coarse aggregate significantly influence the performance of SCHPC by affecting its fresh and hardened properties *(Okamura, 1995; Xie et al., 2002)*. The use of small coarse aggregates measuring 20–25 mm at most is preferred in SCHPC for enhanced strength and reduced segregation *(Kwan, 2000)*. Round and angular aggregates are advantageous for SCHPC either in fresh or hardened state; however, round aggregates are better than angular aggregates for improved flowing ability, whereas rough and angular aggregates lead to high strength and strong interfacial bond *(Geiker et al., 2002; Taylor et al., 1996)*. The porosity and reactivity of coarse aggregates play an important role in the durability of SCHPC; porous aggregates negatively affect strength and frost resistance.

The gradation of coarse aggregates is likewise important for the fresh and hardened properties of SCHPC; well-graded coarse aggregates enhance the flowing ability and segregation resistance in fresh concrete *(Neville, 2009)*. It also produces dense particle packing, which improves hardened properties *(Tasi et al., 2006)*.

3.3.2 Cement replacement materials

CRMs or supplementary cementing materials are powder materials that contribute to the properties of hardened concrete through hydraulic and/or pozzolanic activity. In case of SCHPC; high strength and good durability are the prime goals. Thus, CRMs are highly important to achieving these objectives and an essential material that must be used for promoting SCHPC. CRMs are considerably helpful in enhancing concrete's properties through their physical and chemical effects on material packing and microstructure *(Hassan et al., 2000; Hooton, 2000; Khatri et al., 1995)*. Such standards specify the physical and chemical requirements for natural and artificial CRMs, which provide the limits for fineness, expansion or contraction, pozzolanic activity, uniformity, reactivity, limits for several chemical components and igneous loss.

3.3.3 High-range water reducer admixture

The SCHPC cannot be achieved without the use of HRWRA, which is also known as superplasticiser. It improves the flowing ability and reduces the yield stress and plastic viscosity of concrete by its liquefying action *(Yen et al., 1999)*. HRWRA helps in enhancing the strength and durability of concrete by improving hydration through increased dispersion of cement particles and decreased quantity of mixing water for a given flowing ability *(Hover, 1998)*. HRWRA comes in four types, among which polycarboxylate HRWRA, a second-generation HRWRA, is generally preferred for producing SCHPC. The required amount of HRWRA changes significantly with the concrete's constituents, especially with the substantial difference between the CRMs in their structures and physical properties and with the roughness and absorption of the used aggregate.

3.4 Sustainable SCHPC

The construction industry is among the fields most affected by the ongoing sustainability debate primarily due to the substantial environmental impact resulting from the production of building materials, construction of buildings and structures and the subsequent use thereof *(Mueller et al., 2017)*. Concrete can become green or environmental friendly when one or more of the following properties is achieved *(Suhendro, 2014)*.

1. It uses waste materials as at least one of its components.
2. Its production process does not lead to environmental destruction.
3. It enhances the durability of concrete, thereby extending the latter's service life and reducing long-term resource consumption.
4. It exhibits superior performance and life cycle sustainability without destroying natural resources.

For developing clean concrete production technologies that reduce CO_2 emission and consumed energy or fuel derived from fossil in the cement manufacturing process, the use of recycled cement/concrete and alternative aggregates is being explored.

Approximately 10% of the total man-made CO_2 emitted into the atmosphere is produced during cement manufacturing *(Long et al., 2015)*. Researchers have attempted to produce sustainable concrete mainly through utilising waste materials (construction or industrial waste) and evaluating the sustainability of these new types of concrete not only by their ecological impact but also by their technical performance, i.e. their mechanical, physical and chemical properties *(Mueller et al., 2017)*. As *Ajdukiewicz and Kliszczewicz (2002)* stated in their research, green high-performance concrete is the future of concrete development. Thus based on the materials aspects of SCHPC, three possibilities could propose a sustainable SCHPC:

1. Recycled concrete aggregate could be used partially for producing SCHPC, which is a porous crushed aggregate.
2. Unpossessed waste powder materials could be used as CRMs for producing SCHPC without any processing preceding the use or consumption of any energy for this purpose.
3. An optimised minimum dosage of HRWRA could be used for producing SCHPC using waste powder materials and recycled concrete aggregate.

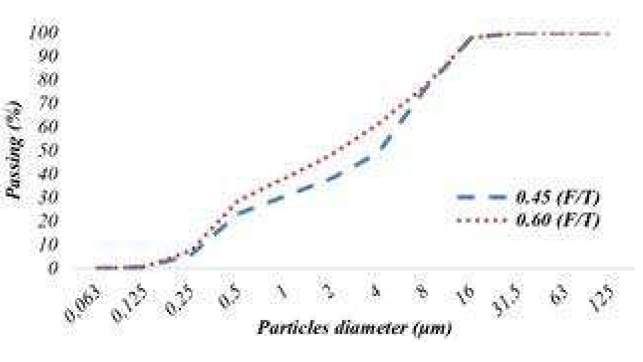

Fig. 2: Grading curves of the aggregate

4. CASE STUDY: REFERENCE SCHPC MIXTURE OPTIMIZATION

An initial optimisation exercise was performed for specifying the most appropriate constituent proportions and mixing procedure of the reference mixture of SCHPC. *Ahmad and Alghamdi (2014)* defined the optimization of the concrete mixture design as 'a process of search for a mixture for which the sum of the costs of the ingredients is lowest, yet satisfying the required performance of concrete, such as workability strength and durability'.

The optimization was based on the targeted compressive strength and workability performance, which were 75 MPa and (SF2 class of slump flow and VF1 viscosity class) respectively. Four variables were optimised, namely, aggregate fraction distribution, water to cement (w/c) ratio, cement content, and mixing procedure. Two aggregate fraction distributions were optimised. The first one was 45% for 0/4 mm fraction and 55% for 4/16 mm fraction, whereas the second was 60% for 0/4 fraction and 40% for 4/16 fraction, which of which fit the requirements of BS *EN 1260:2002+A1 (2008)* and shown in ***Fig. 2***. In addition, two w/c ratios, namely, 0.35 and 0.38, were selected to be tested for their effect on the HRWRA demand and compressive strength. Finally, two amounts of cement content, namely, 450 and 500 kg/m^3, were investigated.

4.1 Experimental program

An experimental program was considered in the purpose of studying the effect of the proposed factors and optimizing the reference SCHPC mixture design. Eight concrete mixtures have been produced with taking into consideration two typical levels of each of the three key factors affecting the performance of concrete mixtures, in addition to observe the efficiency of the mixing procedure and the demanded dosage of HRWRA to achieve the intended workability. The combinations of the levels of the three factors for all eight-trial mixtures are shown in ***Table 2***.

Ordinary Portland cement CEM I 42.5 N in accordance with *BS EN 197-1 (2011)* has been used, as well as the maximum aggregate size used was 16 mm, which has been chosen based on the literature investigations. The aggregate was a natural river quartz and mainly in two proportions; the fine fraction of aggregate (0/4 mm) and the coarse fraction of aggregate (4/16 mm). The mixing water was tap water that complies with the requirements of *BS EN 1008:2002 (2011)* while to achieve the rheological properties of the fresh SCHPC; HRWRA has been used. The used HRWRA was Sika ViscoCrete-5 Neu, which is a modified polycarboxylates aqueous solution.

Table 2: Trail mixtures (key factors)

Mixture name	*Fine to total aggregate ratio (F/T) %*	*Water to cement ratio (w/c) %*	*Cement content (Cc) kg/m^3*
M1	*0.45*	*0.35*	*500*
M2	*0.45*	*0.35*	*450*
M3	*0.45*	*0.38*	*450*
M4	*0.45*	*0.38*	*500*
M5	*0.60*	*0.35*	*500*
M6	*0.60*	*0.35*	*450*
M7	*0.60*	*0.38*	*450*
M8	*0.60*	*0.38*	*500*

Eight concrete mixtures were produced in consideration of the aforementioned variables. For each; four (150x150x150 mm) concrete cubes have been tested for the compressive strength at age of 28 days. The most appropriate mixing procedure was performed for a total mixing time of 4.5 min partitioned into three stages by using an electric concrete mixer. After each stage, the ingredients were manually mixed for achieving the highest homogeneity. ***Fig. 3*** explains the mixing procedure, which has been proposed based on a number of trials for achieving the minimum HRWRA demand and higher strength. The slump flow and v-funnel tests have been conducted directly after mixing to check if the mix achieved the SF2 slump flow class and VF1 viscosity class based on *EFNARC (2005)*. The SF2 slump flow class is ranged by 660 – 750 mm while the VF1 viscosity class is ranged by 6 – 10 seconds.

4.2 STATISTICAL PROGRAM

Analysis of variance (ANOVA) has been used for examining the significance of the factors considered for developing the strength model and subsequently fitting an empirical model for compressive strength in terms of the significant mixture factors using multiple linear regression. ***Table 3*** shows the statistical terminologies, which they are important conduct and understand the ANOVA as proposed by *Ahmad and Alghamdi, (2014).*

5. RESULTS

The optimal reference mixture with target compressive strength reaching 75 MPa and (SF2 and VF1) as a targeted classification for the fresh properties had the following spec-

Fig. 3: Mixing procedure

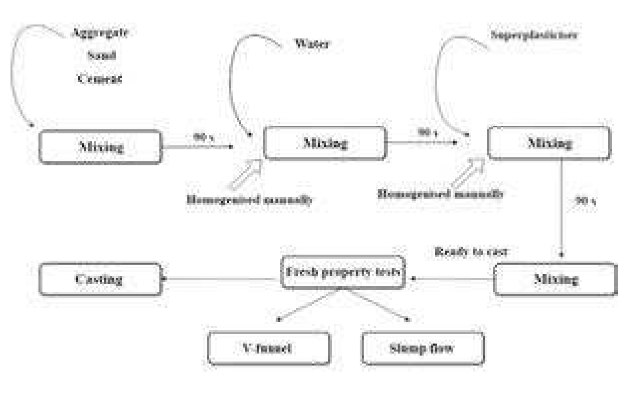

Table 3: Description of the statistical terminologies used in ANOVA.

Statistical terminology	*Description*
Degree of Freedom (df)	*It is the number of values in the final calculation of a statistic that are free to vary.* *df = n-1, where n represents the number of groups.*
Sum of Squares (SS)	*It is the squared distance between each data point (Xi) and the sample mean (m), summed for all n data points.*
Mean Square (MS)	*It is the sum of squares divided by the degrees of freedom.*
F-Ratio	*It is ratio of MS of the concerned factor to the MS of the error. A higher F-Ratio indicates a significant effect of the factor.*
P-Value	*It is a measure of acceptance or rejection of a statistical significance of a factor based on a standard that no more than 5% (0.05 level) of the difference is due to chance or sampling error. In other words, if the P-value for a factor is 0.05 or more, it would not have effect on the dependent variable.*

ifications: 500 kg/m^3 cement content, 45% for 0/4 mm aggregate fraction, 55% for 4/16 mm aggregate fraction and 0.35 w/c ratio. It is M1 mixture in ***Table 4***, which shows the average 28-day compressive experimentally (Sc) for all the eight concrete mixtures along with the minimum dosage of the needed HRWRA to achieve the targeted classification for the fresh properties. The data given in ***Table 2*** and Sc values given in ***Table 4*** has been utilized for statistical analysis to examine the significance of the mixture factors and subsequently to obtain a multiple linear regression model for compressive strength in terms of the factors considered.

Table 4: Compressive strength test results based on experiments and Eq. (1)

Mixture name	*compressive strength based on experiments (Sc) MPa*	*HRWRA dosage kg/m^3*	*compressive strength based on Eq. (1) (Sc') MPa*
M1	*81.98*	*1.5*	*81.23*
M2	*79.29*	*2*	*78.13*
M3	*73.27*	*2*	*73.49*
M4	*75.04*	*1.5*	*76.59*
M5	*77.36*	*1.75*	*77.98*
M6	*73.73*	*2.25*	*74.88*
M7	*70.59*	*2.25*	*70.24*
M8	*74.92*	*1.75*	*73.34*

Based on the ANOVA test results which done with the Microsoft Excel solver 2013 by utilizing the experimental program results; the multiple linear regression model for the compressive strength has been obtained ($R^2 = 0.903$):

$$Sc' = 114.019 - 21.656(F/T) - 154.425(w/c) + 0.062(Cc) \qquad \text{Eq. (1)}$$

Where is the 28-day compressive strength in MPa based on Eq. (1), Cc is the cement content in kg/m^3, w/c is the water to cement ratio by mass, and F/T is the fine to total aggregate ratio by mass. However, the proposed model in Eq. (1) is limited to the range values of the proposed variables.

The results of ANOVA for the compressive strength model are presented in ***Table 5***, which shows that the three factors have a significant effect on the compressive strength and workability performance of SCHPC due to the low P-Value (less than 0.05). Thus all the proposed factors have to be considered to achieve the maximum possible compressive strength of SCHPC by taking into considerations the minimum required HRWRA dosage. SCHPC proved its sensitivity to the ingredient proportions and mixing procedure, which is much more than other types of concrete.

Table 4 also shows the results of compressive strength based on the proposed model in Eq. (1). In addition, it refers to the optimal reference SCHPC mixture, which complies with the experimental results but with more confidence with its optimal combination. The value of statistical optimization could be clearer in case of more complicated model or in case of a higher number of variables and levels.

6. CONCLUSION

Optimal mix design of self-compacting high-performance concrete (SCHPC) is assessed based on the basic material aspects of SCHPC, namely, aggregate fraction distribution, w/c ratio, and cement content, in addition to the mixing procedure. Thus, all the proposed factors have to be considered to achieve the maximum possible compressive strength by taking into considerations the minimum required high range water reducer admixture dosage. SCHPC proved its sensitivity to the ingredient proportions and mixing procedure, which is much more than other types of concrete. Where the proposed factors had a significant effect on the compressive strength and workability performance of SCHPC. As well as the main issues of SCHPC have been introduced with suggestions for a sustainable SCHPC through using rrecycled concrete aggregate as a partial replacement of natural aggregate and unpossessed waste powder materials as cement replacing materials, in addition to optimising the minimum required dosage of HRWRA.

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Table 5: ANOVA for compressive strength test results

	df	*SS*	*MS*	*F*	*Significance F*	
Regression	*3*	*83.297*	*27.766*	*12.785*	*0.016*	
Residual	*4*	*8.687*	*2.172*	-	-	
Total	*7*	*91.984*	-	-	-	
Source	***Coefficients***	***Standard Error***	***P-value***	***Lower 95%***	***Upper 95%***	***Significance***
Intercept	*114.019*	*16.502*	*0.002*	*68.202*	*159.837*	-
(F/T) %	*-21.656*	*6.947*	*0.036*	*-40.944*	*-2.368*	*yes*
(w/c) %	*-154.425*	*34.736*	*0.011*	*-250.867*	*-57.984*	*yes*
(Cc) kg/m³	*0.062*	*0.021*	*0.041*	*0.004*	*0.120*	*yes*

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