STUDY ON PARAMETERS INFLUENCING THE PROPERTIES OF SELF COMPACTING CONCRETE USING TAGUCHI OPTIMIZATION METHOD

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This study aims at simplifying the process of mix design of Self Compacting Concrete (SCC) which is generally done through trial and error. Concrete being a heterogeneous material, the desired qualities are attributed to several factors, in addition SCC has the requirement of better workability, which leads to the complexity in the design process. In this paper, the various factors affecting the strength and workability of SCC such as Total Cementitious Material (TCM) content, water-cementitious material ratio, percentage of fly ash replacement, coarse aggregate content and fine aggregate content were analyzed with four different values for each factor. Based on the Taguchi optimization method, an orthogonal array with sixteen experiments was designed to obtain the best factors for the SCC mix. The performance parameters selected were slump flow value for flowing ability, T_{5min} of V funnel test for segregation resistance, L Box ratio for passing ability and compressive strength test for strength aspect. The results indicated that the TCM content and water-cementitious material ratio plays an important role in the workability of SCC, whereas TCM content and coarse aggregate content are predominant in the compressive strength of SCC.

Keywords: *self-compacting concrete, Taguchi, orthogonal array, fly ash, workability*

1. Introduction

The uniqueness of SCC lies in the fresh state which distinguishes it from normal vibrated concrete and these properties such as filling ability, passing ability and segregation resistance should remain consistent throughout the process of transporting, placing and finishing. The performance of SCC largely depends on the proportions of the materials used and hence a proper mix design is required to achieve a workable SCC with desired strength [1, 2]. Though there are several procedures of mix design for SCC proposed by different researchers, no mix design can be adopted without trial and error due to variations in the conditions and applications for which they were developed. But it would be more beneficial to know about the various factors causing the properties of SCC to vary in various environments. The rational method proposed by Okamura is simple and can be adopted in the field by adjusting the water content and superplasticizer dosage where the proportions of solid contents are fixed. To achieve the desired strength the water content has to be fixed based on trials. Some modifications were made to this method of mix design and were given in the guidelines laid by the European Federation of National Associations Representing for Concrete (EFNARC) which are widely accepted and applied practically [3, 4]. The limitations for the water powder ratio, paste content and aggregate content are given which helps in making experimental trials easier. When supplementary cementitious materials are used to improve the workability of SCC the water demand varies and hence to achieve the desired strength of concrete, trials are to be made. Hence the SCC with supplementary cementitious materials should be designed in such a way that, the hardened properties are comparable to that of normal concrete without any supplementary cementitious materials [3].

Bleeding and segregation are major issues while producing SCC. Supplementary cementitious materials lend a helping hand by increasing the paste content thereby reducing shrinkage and heat of hydration [5, 6]. But these materials sometimes act as mere fillers in the concrete hence the strength of concrete is to be taken care of. Both chemical and mineral admixtures are used to enhance the workability of concrete. But due to availability and economy, mineral admixtures are mostly used in SCC, which also makes the concrete more sustainable. The performance of SCC highly depends on the effects of addition or replacement of these industrial by-products.

Since there are numerous factors governing the performance of SCC, it is difficult to formulate a mix design procedure that requires laborious works to conduct experiments on a trial and error basis. The method recommended by Taguchi is used in the study to find the effect of the controllable factors with the least number of experiments by adopting a special set of orthogonal array. In the Taguchi experiment design, a loss function is used to calculate the deviation between the experimental value and the desired value which is further

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transformed into a utility function also called the Signal-to-Noise (S/N) ratio. The S/N ratio based on Mean squared deviation is calculated which considers mean and standard deviation to find out the rank of each factor [7-9].

2. Materials

The materials used for the study include cement, fly ash, fine aggregate, coarse aggregate, superplasticizer and water.

The properties of these materials are given below:

Ordinary Portland cement of 53 grade with a specific gravity of 3.15 was used which confirms to the requirements of IS 269:2015 [10].

Class F Fly ash with a specific gravity of 2.2 procured from Ennore Thermal power plant, Tamil Nadu, India, that satisfies the requirements of IS 3812 (Part 1):2013 [11].

Crushed granite coarse aggregate of maximum nominal size 12.5 mm and a specific gravity of 2.8 was used confirming to IS 2386-3:1963(R2016) [12].

Natural river sand belonging to Zone II with a specific gravity of 2.5 was used confirming to IS 383:2016 [13].

Polycarboxylic ether-based superplasticizer of relative density 1.09 was used. Ordinary potable water was used for mixing and curing.

3. Selection of Control Factors And Their Level

3.1 Total cementitious material content

The TCM content was selected as 400, 450, 500 and 550 kg/m^3 which are in the prescribed range given in EFNARC guidelines. Higher cementitious material content results in an increase in the paste matrix which leads to better workability of the SCC. Whereas in the case of compressive strength, an optimum dosage of TCM makes the transition zone between the paste matrix and the aggregate as stronger. Hence it is necessary to determine the optimal cementitious material content for the better performance of SCC.

3.2 Water-cementitious material ratio

The Water-Cementitious material ratio plays a major role in determining the strength and workability of SCC. A higher water-cementitious material ratio leads to segregation and bleeding whereas a lower water-cement ratio affects the flowing ability of the SCC. In this study, the water-cementitious material ratio is chosen as 0.36, 0.38, 0.40 and 0.42 to arrive at the optimum ratio.

3.3 Fly ash content

The use of supplementary cementitious material increases the matrix content of SCC thereby the flowability is increased. Fly ash being finely divided and spherical in shape, acts as a viscosity modifying agent and filler in the concrete. The role of fly ash in the enhancement of compressive strength is evident only at later ages due to the delayed onset of hydration [14]. Hence the determination of fly ash replacement percentage is very crucial as higher percentages of fly ash replacement may decrease the mechanical properties of concrete. In this study, the fly ash at 30, 40, 45 and 50% replacement to cement by weight was considered to ascertain an optimum level of replacement [15, 16].

3.4 Coarse aggregate content

Coarse aggregate content is mainly responsible for the strength of concrete, but when SCC is concerned a higher percentage of coarse aggregate content may affect the workability [17]. In this study, the coarse aggregate content at 52, 50, 48 and 45% corresponding to the total volume of aggregate was considered to find an optimum level.

3.5 Fine aggregate content

The influence of fine aggregates on the fresh properties of the SCC is significantly greater than that of coarse aggregate [3]. The fine aggregate content is taken as 48, 50, 52 and 55% of the total volume of aggregate which is in the range of 48 to 55% as per EFNARC guidelines [3]. The selection of fine aggregate proportion is to be made on trials to ensure workability and target strength.

4. Experimental Program

The Taguchi method can be effectively used for reducing the number of trials in the mix design. Here TCM content, water-cementitious material ratio, percentage of fly ash, coarse aggregate proportion and fine aggregate proportion were selected as parameters for the study. The various levels adopted for these control factors are given in Table 1.

The requirement criteria of SCC such as passing ability, filling ability, segregation resistance and compressive strength were used as the testing parameters. An orthogonal array consisting of sixteen experiments with five factors at four levels was constructed as given in Table 2 based on the equation recommended by Taguchi [eqn. (1)].

$$\text{Number of experiments} = f \times (l-1) + 1 \qquad (1)$$

Where f is the number of control factors and *l* is the number of levels

The mix proportions for the array of experiments have been mentioned in Table 3.

4.1 Test Methods and Analysis

As described earlier the characteristics of the resulting concrete were evaluated based on parameters such as slump flow value (flowing ability), V funnel at $T_{5minutes}$ (segregation

Table 1

Control factors and their Level

Control factors		Levels of Factors			
		1	2	3	4
Total Cementitious Content (kg/m^3)	A	400	450	500	550
Water-Cement ratio	B	0.36	0.38	0.4	0.42
Fly ash Content (%)	C	30	40	45	50
Coarse Aggregate percentage (%)	D	52	50	48	45
Fine aggregate percentage (%)	E	48	50	52	55

Table 2

Orthogonal array of experiments

Experiment No.	Factor and Level combination				
	A	B	C	D	E
1	1 (400)	1 (0.36)	1 (30)	1 (52)	1 (48)
2	1 (400)	2 (0.38)	2 (40)	2 (50)	2 (50)
3	1 (400)	3 (0.40)	3 (45)	3 (48)	3 (52)
4	1 (400)	4 (0.42)	4 (50)	4 (45)	4 (55)
5	2 (450)	1 (0.36)	2 (40)	3 (48)	4 (55)
6	2 (450)	2 (0.38)	1 (30)	4 (45)	3 (52)
7	2 (450)	3 (0.40)	4 (50)	1 (52)	2 (50)
8	2 (450)	4 (0.42)	3 (45)	2 (50)	1 (48)
9	3 (500)	1 (0.36)	3 (45)	4 (45)	2 (50)
10	3 (500)	2 (0.38)	4 (50)	3 (48)	1 (48)
11	3 (500)	3 (0.40)	1 (30)	2 (50)	4 (55)
12	3 (500)	4 (0.42)	2 (40)	1 (52)	3 (52)
13	4 (550)	1 (0.36)	4 (50)	2 (50)	3 (52)
14	4 (550)	2 (0.38)	3 (45)	1 (52)	4 (55)
15	4 (550)	3 (0.40)	2 (40)	4 (45)	1 (48)
16	4 (550)	4 (0.42)	1 (30)	3 (48)	2 (50)

Table 3

Mix Proportions

Experiment No	Cement Content (kg/m^3)	Fly ash content (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Water (l/m^3)	Superplasticizer (l/m^3)
1	280.00	120.00	1008.38	731.35	144	4.360
2	240.00	160.00	950.72	746.99	152	4.360
3	220.00	180.00	898.25	764.58	160	4.360
4	200.00	200.00	828.57	795.69	168	4.360
5	270.00	180.00	874.23	787.07	162	4.905
6	315.00	135.00	816.02	740.90	171	4.905
7	225.00	225.00	911.89	688.93	180	4.905
8	247.50	202.50	868.54	655.12	189	4.905
9	275.00	225.00	769.14	671.47	180	5.450
10	250.00	250.00	802.37	630.43	190	5.450
11	350.00	150.00	840.99	726.86	200	5.450
12	300.00	200.00	850.02	667.93	210	5.450
13	275.00	275.00	797.58	651.73	198	5.995
14	302.50	247.50	818.95	680.59	209	5.995
15	330.00	220.00	699.60	586.33	220	5.995
16	385.00	165.00	741.59	606.96	231	5.995

resistance), L Box ratio (passing ability) and compressive strength [18].

The slump flow is the mean of the largest diameter of the flow spread of the concrete and the diameter of the spread at right angles to it in the slump cone test. A visual assessment for any indication of mortar/paste separation at the circumference of the flow and any aggregate separation in the central area also gives some indication of segregation resistance. The higher the slump flow value, the greater its ability to fill formwork under its own weight [3].

The V funnel at $T_{5minutes}$ test is used to determine the segregation resistance. First the time taken by the fresh concrete to flow out of a V funnel of capacity of about 12 litres is measured in seconds. After the test has been performed, the funnel is refilled with the concrete with trap door closed and left undisturbed for 5 minutes, then the trap door of the V funnel is opened and the time taken for complete discharge of concrete is measured in seconds which is taken as $T_{5minutes}$ value, greater than V funnel time.

The L Box test is used to determine the passing ability of the concrete in the presence of reinforcements without segregation or blocking. The apparatus consists of a rectangular-section box in the shape of an 'L', with a vertical and horizontal section, separated by a moveable gate, in front of which vertical lengths of reinforcement bar are fitted. The fresh concrete is filled in the vertical section and the gate is raised to allow concrete to flow in the horizontal section. The height of the concrete in the horizontal section is measured at the near end (H_1) and far end (H_2) to the vertical section of the L-box and the L-box ratio (H_2/H_1) is estimated.

Higher the ratio, better is the passing ability of the concrete.

The compressive strength of concrete after curing for 28 days is determined using a Compression Testing Machine and is expressed in N/mm^2. Higher is the compressive strength, better is the performance of the concrete [19].

To understand the effect of the various control factors mentioned previously, a Signal-Noise (S/N) ratio for each factor was calculated by mean squared deviation based on two criteria namely the larger the better $(S/N)_L$ and smaller the better $(S/N)_S$ characteristics using the equation (2) and (3) respectively.

$$(S/N)_L = -10 \times \log_{10}(1/y^2/n) \quad (2)$$

$$(S/N)_S = -10 \times \log_{10}(y^2/n) \quad (3)$$

The S/N ratio of performance parameters such as slump flow value, L Box ratio and compressive strength was calculated using the larger the better criteria since higher the value better is the result and the V funnel at $T_{5minutes}$ were calculated based on smaller the better criteria since lesser the value better is the result.

5. Results and Discussions

Table 4 shows the experimental value obtained from the various tests and the corresponding calculated S/N ratio in decibel (dB).

5.1 Slump flow value

The slump flow value of the concrete ranged between 643 mm and 735 mm satisfying the acceptable range of 650 – 800 mm as per EFNARC guidelines. Table 5 shows the response table for the S/N ratio of each control factor with respect to the slump flow criteria and Figure 1 shows the factor effect plot for slump flow value.

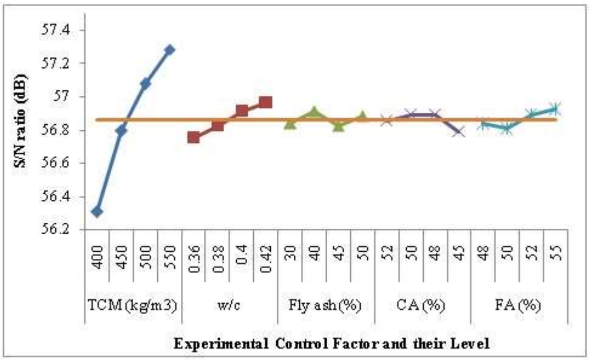

Fig.1 - Factor effect plot for Slump flow value

From Table 5 and Figure 1, it was found that the water-cementitious material ratio was a significant factor in the flowing ability of SCC. The highest response was found at a water-cementitious material ratio of 0.42 which is found to be the highest level.

5.2 V Funnel at $T_{5minutes}$ value

The V-funnel at $T_{5minutes}$ test value ranged between 12.4 and 14.7 seconds satisfies the

Table 4

Experimental value and Signal-Noise ratio

Experiment No	Experimental Value				S/N ratio (dB)			
	Slump flow (mm)	T_{5min} (seconds)	L-Box ratio	Compressive strength (N/mm^2)	Slump	T_{5min}	L-Box ratio	Compressive strength
1	643	14.7	0.8	29.40	56.16	-23.35	-1.94	29.37
2	652	14.1	0.81	27.30	56.28	-22.98	-1.83	28.72
3	658	13.9	0.81	24.60	56.36	-22.86	-1.83	27.82
4	661	13.2	0.8	22.10	56.40	-22.41	-1.94	26.89
5	693	12.8	0.88	30.08	56.81	-22.14	-1.11	29.57
6	682	13.6	0.92	30.64	56.68	-22.67	-0.72	29.73
7	694	13.9	0.94	30.60	56.83	-22.86	-0.54	29.71
8	696	14.2	0.84	31.50	56.85	-23.05	-1.51	29.97
9	691	12.6	0.85	30.80	56.79	-22.01	-1.41	29.77
10	712	13.1	0.89	28.90	57.05	-22.35	-1.01	29.22
11	723	13.2	0.97	34.43	57.18	-22.41	-0.26	30.74
12	731	12.9	0.91	32.64	57.28	-22.21	-0.82	30.28
13	728	13.1	0.93	29.48	57.24	-22.35	-0.63	29.39
14	732	12.4	0.92	25.40	57.29	-21.87	-0.72	28.10
15	731	12.6	0.95	26.30	57.28	-22.01	-0.45	28.40
16	735	12.4	0.97	23.10	57.33	-21.87	-0.26	27.27

Table 5

Signal-Noise (S/N) Response Table for Slump value

Control Factor		Mean Signal-Noise Ratio $(S/N)_m$ corresponding to each level (dB)				$Max(S/N)_m - Min(S/N)_m$	Rank
		Level 1	Level 2	Level 3	Level 4		
TCM (kg/m^3)	A	56.30	56.79	57.08	57.28	0.209	2
Water/cement ratio	B	56.75	56.83	56.91	56.97	0.212	1
Fly ash(%)	C	56.84	56.91	56.82	56.88	0.090	5
Coarse Aggregate (kg/m^3)	D	56.85	56.89	56.89	56.79	0.106	4
Fine Aggregate (%)	E	56.84	56.81	56.89	56.92	0.116	3

Table 6

Signal-Noise (S/N) Response Table T_{5min} of V Funnel Test.

Control Factor		Mean Signal-Noise Ratio $(S/N)_m$ corresponding to each level (dB)				$Max(S/N)_m$ - $Min(S/N)_m$	Rank
		Level 1	Level 2	Level 3	Level 4		
TCM (kg/m^3)	A	-22.90	-22.68	-22.24	-22.02	0.88	1
Water/cement ratio	B	-22.46	-22.47	-22.53	-22.38	0.15	5
Fly ash (%)	C	-22.57	-22.34	-22.45	-22.49	0.24	4
Coarse Aggregate (kg/m^3)	D	-22.57	-22.58	-22.30	-22.27	0.30	3
Fine Aggregate (%)	E	-22.69	-22.43	-22.52	-22.24	0.44	2

Table 7

Signal-Noise (S/N) Response Table of L Box ratio

Control Factor		Mean Signal-Noise Ratio $(S/N)_m$ corresponding to each level (dB)				$Max(S/N)_m$ - $Min(S/N)_m$	Rank
		Level 1	Level 2	Level 3	Level 4		
TCM (kg/m^3)	A	-1.88	-0.97	-0.88	-0.52	1.37	1
Water/cement ratio	B	-1.27	-1.07	-0.77	-1.13	0.50	3
Fly ash (%)	C	-0.80	-1.05	-1.37	-1.03	0.57	2
Coarse Aggregate (kg/m^3)	D	-0.87	-1.03	-1.05	-1.13	0.26	4
Fine Aggregate (%)	E	-1.23	-1.01	-1.00	-1.01	0.22	5

Table 8

Signal-Noise (S/N) Response Table for compressive strength

Control Factor		Mean Signal-Noise Ratio $(S/N)_m$ corresponding to each level (dB)				$Max(S/N)_m$ - $Min(S/N)_m$	Rank
		Level 1	Level 2	Level 3	Level 4		
TCM (kg/m^3)	A	28.20	29.74	30.00	28.29	1.45	1
Water/cement ratio	B	29.52	28.94	29.17	28.60	0.34	5
Fly ash (%)	C	29.28	29.24	28.91	28.80	0.44	3
Coarse Aggregate (kg/m^3)	D	29.36	29.70	28.47	28.70	1.24	2
Fine Aggregate (%)	E	29.24	28.87	29.30	28.82	0.42	4

acceptance range of 0 - +3 seconds of the V-funnel test as per EFNARC guidelines. This parameter is set to smaller the better parameter and the S/N response table and the factor effect plot are given in Table 6 and Figure 2 respectively.

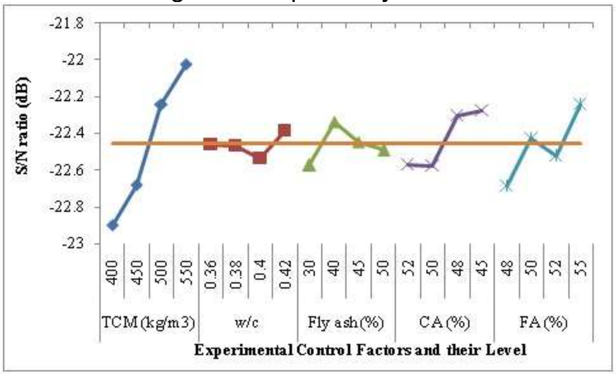

Fig. 2 - Factor effect plot for T_{5min} of V Funnel Test

From Table 6, the most significant factor affecting the segregation resistance is TCM content and the maximum response is obtained at the highest level of the control factor (TCM at 550 kg/m^3).

5.3 L Box Ratio

The value of the L Box ratio varied from 0.8 to 0.97 satisfies the acceptance range of 0.8 – 1.0 as per EFNARC guidelines. The Signal-Noise response ratio table and the factor effect graph are given in Table 7 and Figure 3 respectively.

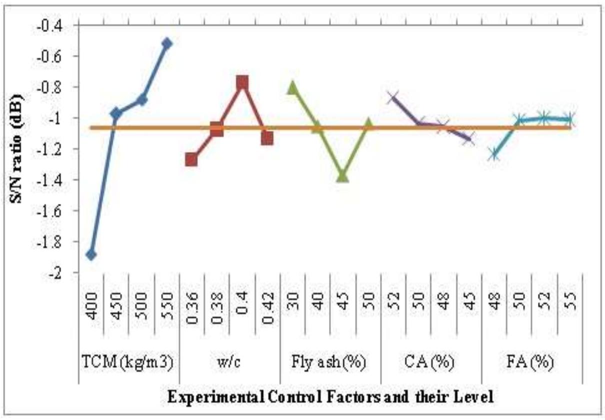

Fig. 3 - Factor effect plot for L Box ratio

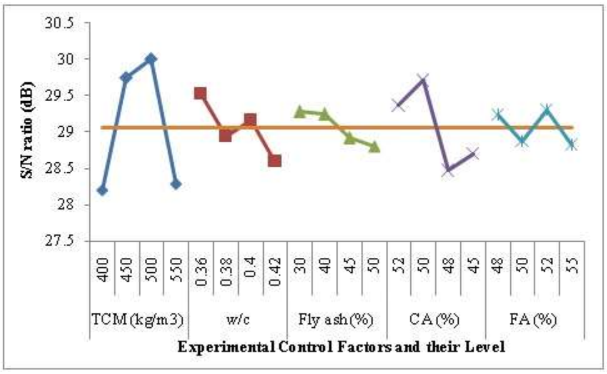

Fig. 4 - Factor effect plot for Compressive strength

5.4 Compressive strength

The S/N response table and the Factor effect plot for compressive strength are given in Table 8 and Figure 4 respectively.

From Figure 4, it is evident that compressive strength is influenced by the factor TCM content and secondly the coarse aggregate content. However, the maximum response is obtained at Level 3 of the control factor (TCM at 500 kg/m^3).

6. Conclusions

This study investigated the applications of the Taguchi optimization method in determining the significant parameters such as TCM content, water-cementitious material ratio, percentage of fly ash replacement, coarse aggregate content and fine aggregate content influencing the properties of SCC such as flowing ability, segregation resistance, passing ability and compressive strength. Based on the investigations, the following conclusions are drawn:

1. The flowability of SCC is primarily influenced by the water-cementitious material ratio and the TCM content. The percentage of fine aggregate by volume of total aggregate content also has an influence on the flowability.
2. The segregation resistance is influenced by TCM content and percentage of fine aggregate by volume of total aggregate content.
3. The passing ability of the SCC is primarily affected by the TCM content. All other factors play a minor role in the passing ability of SCC since there is not much variation in the maximum and minimum values of the S/N ratio.
4. The compressive strength is influenced by the TCM content and the coarse aggregate content which make the transition zone to be stronger. It is observed that the TCM content of 400 kg/m^3 with 52% of coarse aggregate proportion in total aggregate gives better strength whereas in the case of TCM content of 450 kg/m^3, 500 kg/m^3 and 550 kg/m^3 the better strength is achieved at 50% of coarse aggregate content in total aggregate.

Taguchi method is a statistical method that determines the factor level combination of parameters that reduces the performance variability and finding the factor level that brings the performance closest to the target. This method when used in analyzing the various factors which affect a particular parameter of SCC is determined accurately in terms of rank and hence it is a suitable method to determine the factors that affect the quality of SCC most and least quantitatively before making trials and errors. This helps in the production of SCC with consistent quality and robustness.

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