

Prediction of Self-Compacting Rubberized Concrete Mechanical and Fresh Properties using Taguchi Method

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Abstract

The effect and optimization of using self-compacting rubberized concrete was investigated by using Taguchi method. Design of experiment was performed via orthogonal array to accommodate four factors with four levels. These factors were the percentage of fine rubber, coarse rubber, fly ash and viscoconcrete in the concrete mix. The signal-to-noise (S/N) ratio and the analysis of variance (ANOVA) were employed to study the performance characteristics of self-compacting rubberized concrete (SCRC). Rubberized concrete can be improved using the concrete proportioned as self-compacting concrete. The results indicate that there was a reduction in the strength with increasing rubber content but there was an increase in impact resistance. However, the replacement of 10% of coarse aggregate with coarse rubber gave more strength than that of zero rubber mix by 124% at 90 days. Replacement of 20% of both fine and coarse aggregates with fine and coarse rubber respectively, increased impact resistance by 453% compared to the corresponding SCRC control mix.

Keywords: Rubber; Recycling; Self-compacting; Taguchi method; ANOVA

Introduction

Self-Compacting Concrete (SCC) is a sophisticated high-performance concrete [1] described as the “most revolutionary step” in concrete technology over the last two decades due to its impact on economic and environmental sustainability in the construction industry [2]. It offers the advantages of increased productivity rates, decreased manpower, and elimination of the noise and fuel consumption associated with vibrator plant [3]. In comparison with plain concrete, it has the ability to fully self-compact under its own weight and has high flow ability and filling rates, reduced blocking in congested reinforced areas, and high segregation resistance, as well as high durability, low permeability and high compressive strength [4].

Solid waste disposal is a major environmental issue on cities around the world [5]. The volume of polymeric waste like tire rubber is increasing. The waste tires rubber becomes an environmental problem due to its non-biodegradable nature. Up to now a small part is recycled and millions of tires are just stockpiled; land filled or buried and used as fuel in many industries. Recycling end-of-life vehicle tires as alternative aggregates to produce a new class concrete is an innovative option with environmental, economic and performance benefits [5].

Many researchers have therefore used rubber particles as aggregates in concrete production to eliminate poor deformation capacity, low tensile strength, and improve energy absorption capacity. Aggregate rubber particles enhanced deformation and energy absorption capacities while they decreased workability and mechanical properties [6]. Self-compacting rubberized concrete (SCRC) was produced to diminish the negative effect of rubber aggregate on the mechanical properties and workability of concrete [7]. Due to the high powder content of SCC its microstructure is very compacted and dense, which results in high mechanical strength and brittle failure modes. Therefore, (SCRC) composites could be used for applications requiring deformable (high ductility concrete with high flowability and low/medium strength (<35 MPa), which is difficult to achieve using SCC using alternative aggregates that are environmentally friendly (sustainable concrete). In infrastructure applications the range of strength is usually between 28 and 35 MPa. In applications such as bridge barriers and road foundations, concrete with high deformation and high toughness is desirable while >35 MPa compressive strength is not required [5,8].

Aim of Work

In the current research fresh and hardened properties of (SCRC) were investigated using Taguchi method. Sixteen different concrete mixes were designed with the same water/powder ratio W/P (P=cement+fly ash). Their self-compacting characteristics and final mechanical behavior are reported and discussed.

Parameter Design Methodology

Taguchi's parameter design method is a powerful tool for optimizing the characteristic performance of a product/process. Optimization quality characteristic minimizes Sensitivity to Noise (S/N) (uncontrollable) factors. In the present study, four control factors were chosen with four levels as shown in Table 1.

Design of experiment

The experiment was designed based on the orthogonal array technique. An orthogonal array is a fractional factorial design. It is obtained by assigning the selected factors and their levels to appropriate columns of L16 orthogonal array. This array has 16 rows and 4 columns, each row represents a trial condition and each column accommodates a specific process parameter. The main effects can be estimated. The numbers in each column indicate the levels of specific factors (A, B, C and D). Taguchi Orthogonal Array Design is L16 (4**4). Factors are 4. Runs are 16 [9-11].

Taguchi's orthogonal array approach of experimental design

Taguchi's target is developing products that achieve the target value on a consistent basis. The variation around the target value should be minimized. In other words, quality is achieved by minimizing the

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Level	Factors			
	A	B	C	D
	Replacement of fine aggregates by fine rubber	Replacement of coarse aggregates by coarse rubber	Fly-ash (cement %)	Viscocrete (cement %)
1	0%	0%	20%	2.00%
2	10%	10%	25%	2.25%
3	15%	15%	30%	2.50%
4	20%	20%	35%	2.75%

Table 1: Control factors of the experimental work.

Exp. No.	Factors			
	% Replacement by volume of aggregate		Addition (% wt of cement)	
	Fine rubber	Coarse rubber	Fly ash	viscocrete
1	0	0	20	2
2	0	10	25	2.25
3	0	15	30	2.5
4	0	20	35	2.75
5	10	0	25	2.5
6	10	10	20	2.75
7	10	15	35	2
8	10	20	30	2.25
9	15	0	30	2.75
10	15	10	35	2.5
11	15	15	20	2.25
12	15	20	25	2
13	20	0	35	2.25
14	20	10	30	2
15	20	15	25	2.75
16	20	20	20	2.5

Table 2: Experimental test design of control factors with factor levels.

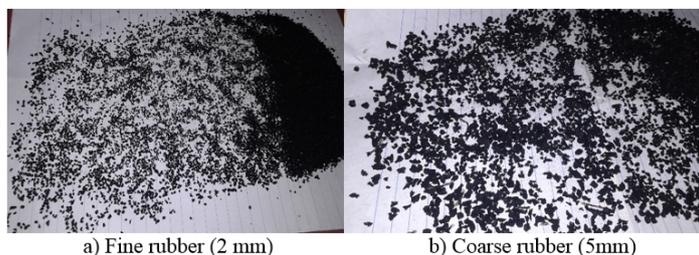


Figure 1: Fine and coarse rubber.

deviation from the target. Factors and levels are illustrated in Table 1; the mixes are given in Table 2. Factor A is replacement of fine aggregate by fine rubber (1 mm) (replaced by 0%, 10%, 15% and 20%). Factor B is replacement of coarse aggregate by coarse rubber (5 mm) (replaced by 0%, 10%, 15% and 20%). Factor C is addition of fly ash as a ratio of cement (added by 20, 25, 30, and 35%). Factor D is using superplasticizer (viscocrete) as a ratio of cement (2.00%, 2.25%, 2.50% and 2.75%) [11,12].

Materials and Methods

Materials

All test specimens were fabricated using locally available materials.

Cement: A locally produced ordinary Portland cement (42.5 N) produced by Lafarge Company meeting the requirement of E.S. 373/2003 was used with constant content (400 kg/m³) for all mixes.

Fly ash: Sika fly ash type P from Sika Egypt Company (El Obour factory) was used as addition to cement.

Fine aggregate: The sand used was local natural siliceous sand with fineness modulus 2.77 and specific gravity 2.64.

Coarse aggregate: Coarse aggregate used was natural crushed limestone with maximum aggregate size of 12 mm to achieve the requirement of self-compacting concrete.

Super plasticizer: A high range water reducer without retarding was used. (Sika viscocrete 3425) was used as a demand for producing SCC. It meets the requirements for superplasticizers according to ASTM-C- 494 Types G and F and BS EN 934 part 2: 2001.

Fine rubber aggregate: The fine crumb rubber used in this research is produced by MARSO factory at 10th Ramadan city-Egypt with size of (1 mm) and was used as a partial replacement (by volume) of fine aggregate (Figure 1).

Coarse rubber aggregate: The coarse rubber used in this research is produced by MARSO factory at 10th of Ramadan city-Egypt with one size of (5 mms) and was used as a partial replacement (by volume) of coarse aggregate (Figure 1).

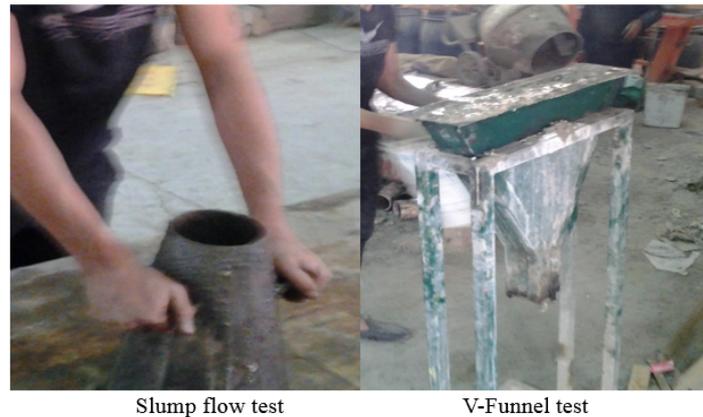


Figure 2: Fresh tests.



Figure 3: Hardened tests.

Water: Fresh tap water was used with water /binder ratio $w/b=0.37$.

Mix contents and procedure

Mix contents: The cement content was constant at 400 kg/m^3 for all mixes with water/binder* ratio of 0.37 and the mix proportion ratio (of weight) for cement: sand: dolomite was 1:2.125:2.125 respectively.

*binder=cement + fly ash

Mixing procedure: It was carried out in three stages; dry mix for 2 min, adding 75% of (water+S.P) and mixing for 2 min and a final mix for not less than 3 min after adding the remaining amount of (water+S.P). Subsequently, the fresh properties of SCRC mixes; Flowability and Passing-ability tests (slump flow, T50, V-Funnel and J-Ring) were determined. Concrete specimens were cast in standard steel molds. After 24 h from mixing, all the specimens were de-molded and cured in wet canvas for 7 days.

Tests

Fresh tests: Fresh tests were performed according to the procedure recommended by EFNARC committee (European Federation for Specialist Construction Chemicals and Concrete Systems) [13]. (Figure 2).

Slump flow test: Slump flow value describes the flowability of a fresh mix in unconfined conditions. It is a sensitive test that can normally be specified for all self-compacting concretes, as the primary check that the fresh concrete consistence meets the specification [8] (Figure 2).

V-funnel: When performing the V-funnel test, a V shaped funnel

is filled with fresh concrete and the time taken for the concrete to flow out of the funnel is measured and recorded as the V-funnel flow time (Figure 2).

Hardened SCRC

Compressive strength test: Test was carried out on $15 \times 15 \times 15 \text{ cm}$ cubes and according to ASTM C39-86. The capacity of the compression machine used is 2000 KN.

Impact test: Beams $10 \text{ cm} \times 10 \text{ cm} \times 50 \text{ cm}$ were prepared for this test. The impact resistance was assessed by measuring the ability of concrete specimens to withstand repeated blows of a free falling load (3 kg) at a constant travelling height of 40 cm above the midpoint of the tested concrete beam which was supported on two ends. The load was then left to fall freely on the top side of the concrete beam and the number of impact blows to cause failure was recorded [14-16]. Figure 3 shows the hardened tests set up.

Results

Fresh properties

Experimental test results of fresh properties for slump flow and V-Funnel tests for SCRC are shown in Table 3.

Hardened properties

Experimental test results of compressive strength for SCRC are shown in Table 4. Table 5 shows test results for impact resistance which represented by numbers of blows.

Mix. No.	Slump (mm)	V-funnel(sec.)	Mix. No.	Slump (mm)	V-funnel (sec.)
1	723	3.65	9	675	13.94
2	735	3.79	10	690	7.2
3	755	3.56	11	550	18.25
4	720	6.47	12	585	14.97
5	710	7.81	13	665	6.16
6	740	5.89	14	630	11.03
7	715	6.71	15	605	17.53
8	645	5.72	16	560	9.22

Table 3: Experimental test results (fresh properties).

Mix. No.	Compressive strength (Mpa)			Mix. No.	Compressive strength (Mpa)		
	7 days	28 days	90 days		7 days	28 days	90 days
1	33.2	47.7	52	9	22.1	31.6	44.5
2	40.3	53.3	64.4	10	21.3	32.9	37.3
3	27.6	37.7	44.4	11	20.4	24.8	32.2
4	21.6	34.7	45.6	12	19	24.3	29
5	28.4	42.1	48.3	13	23	38.4	32.2
6	23.9	35.8	43.9	14	23.9	25.7	33.6
7	21.9	33.2	41.2	15	20.8	24.8	30.2
8	20.2	26	38.3	16	18.3	20.2	29.8

Table 4: Compressive strength test results (hardened properties).

Mix. No.	Impact (blows)	Mix. No.	Impact (blows)
	28 days		28 days
1	17	9	23
2	13	10	21
3	15	11	31
4	15	12	31
5	29	13	35
6	23	14	54
7	22	15	55
8	22	16	77

Table 5: Impact test results.

Analysis and Discussion

Design of experiment data is used to analyze the mean response function. In Taguchi technique, the variation of the response is examined using an appropriately chosen S/N ratio. This ratio is the mean (signal) to the standard deviation (noise). The ratios, derived from the quadratic loss function, are expressed on a decibel (dB) scale. The formula used to compute the S/N ratio depends on the objective function. Generally, three standard S/N equations are widely used to classify the objective function as: 'larger the better', 'smaller the better', or 'nominal the best'. Focusing on the strength characteristic, a larger S/N ratio is always desirable.

In the present study, compressive and impact resistance are 'larger is better' types of quality characteristic since the goal is to maximize the strength. The standard S/N ratio computing formula for this type of response is:

$$\left(\frac{S}{N}\right)_i = -10 \log \left[\frac{1}{n} \sum_{j=1}^n \frac{1}{Y_{ij}^2} \right] \quad (1)$$

V-funnel is a 'smaller is better' type of quality characteristic since the goal is to minimize them. The standard S/N ratio computing formula for this type of response is:

$$\left(\frac{S}{N}\right)_i = -10 \log \left[\frac{1}{n} \sum_{j=1}^n Y_{ij}^2 \right] \quad (2)$$

Where 'i' is the number of a trial; 'Yij' is the measured value of quality characteristic for the ith trial and jth experiment; 'n' is the number of repetitions for the experimental combination. Signal-to-noise ratios are computed using Equation (1) for each experimental condition for compressive and impact resistance. The factor effects can be separated out in terms of S/N ratio.

The analysis of variance (ANOVA) is also performed to study the relative significance of the process parameters. The contributions of the various parameters are quantified.

Fresh properties

The filling ability and stability of SCRC in the fresh state can be defined by four key characteristics namely flow ability, viscosity, passing ability, and segregation resistance. Each characteristic can be addressed by one or more test methods [13]. For instance, flow ability can be measured via slump flow test, viscosity can be measured through the V-funnel flow time tests.

Self-compacting concrete requirements in the fresh state that are appropriate for a given application should be selected from one or more of above mentioned four key characteristics and then specified by class or target value. To define the flow ability, viscosity, passing ability, and segregation resistance of the produced SCRC, slump flow diameter and V-funnel flow time of the all produced concretes were measured and presented.

Slump flow test: The average values of S/N ratios of the control

factors for slump flow test are shown in Table 6 and Figure 4. Table 7 shows the analysis of variance for this test. Increasing rubber content decreased slump flow diameter but increasing fly ash and/or viscocrete increased slump flow diameter. Addition fly ash to the mix increased cement paste volume which made the mix more flowability. Viscocrete increased the viscosity of concrete which increased the slump flow diameter.

V-Funnel test: As mentioned above, V-Funnel test is measuring the viscosity like T50 test. But here, viscocrete has 2nd rank in S/N analysis which mean that it has a big effect on V-Funnel test. However, using the highest content of viscocrete (2.75%) increased the time of this test as shown in Figure 5. like T50, increasing rubber content increased V-Funnel time. The average values of S/N ratios of the control factors for this test are shown in Table 8 and Figure 5. Table 9 shows the analysis of variance for this test.

Hardened properties

The mean of three tested values at 28 days was recorded to determine the compressive and impact resistance for all mixtures.

Compressive strength: It was found that increasing rubber content decreased the compressive strength. The deterioration in

compressive strength can logically be attributed to (i) the low modulus of elasticity (E) for rubber particles and high Poisson ratio (ν) which may encourage premature cracking under load, (ii) increased porosity due to air entrainment from rubber particles, and (iii) weak bonding in the interfacial transition zone between the cement paste and rubber particles which could be due to crack initiation from the voids that form between crumb rubber particles and cement paste. Therefore, under compression loading the aggregates can be susceptible to pullout resulting in particle perimeter voids and crack initiation sites. For fly ash, increasing fly ash content increased compressive strength as it works as a filler which fills the voids on concrete. Using 35% of fly ash as addition to the mix gave highest compressive strength. Viscocrete has small effect on compressive strength. It had the 4th rank in S/N analysis. But the addition of super plasticizer in (SCC) gives more strength in early age. The average values of S/N ratios of the control factors for compressive strength test are shown in Table 10 and Figure 6. Table 11 shows the analysis of variance for this test.

Impact resistance: Increasing rubber content led to increase impact resistance. The impact resistance, as a number of blows, increased from 17 blows for mix No.1 (no rubber replacement) to 77 blows for mix No.16 (20% fine rubber and 20% coarse rubber). This gain of impact resistance of SCRC is due to the ability of rubber

Level	Fine rubber (A)	Coarse rubber (B)	Fly ash (C)	Viscocrete (D)
1	57.3	56.81	56.08	56.4
2	56.92	56.87	56.33	56.2
3	55.88	56.27	56.58	56.58
4	55.76	55.91	56.87	56.69
Delta	1.54	0.96	0.78	0.49
Rank	1	2	3	4

Table 6: Response of signal to noise ratios for slump flow (larger is better).

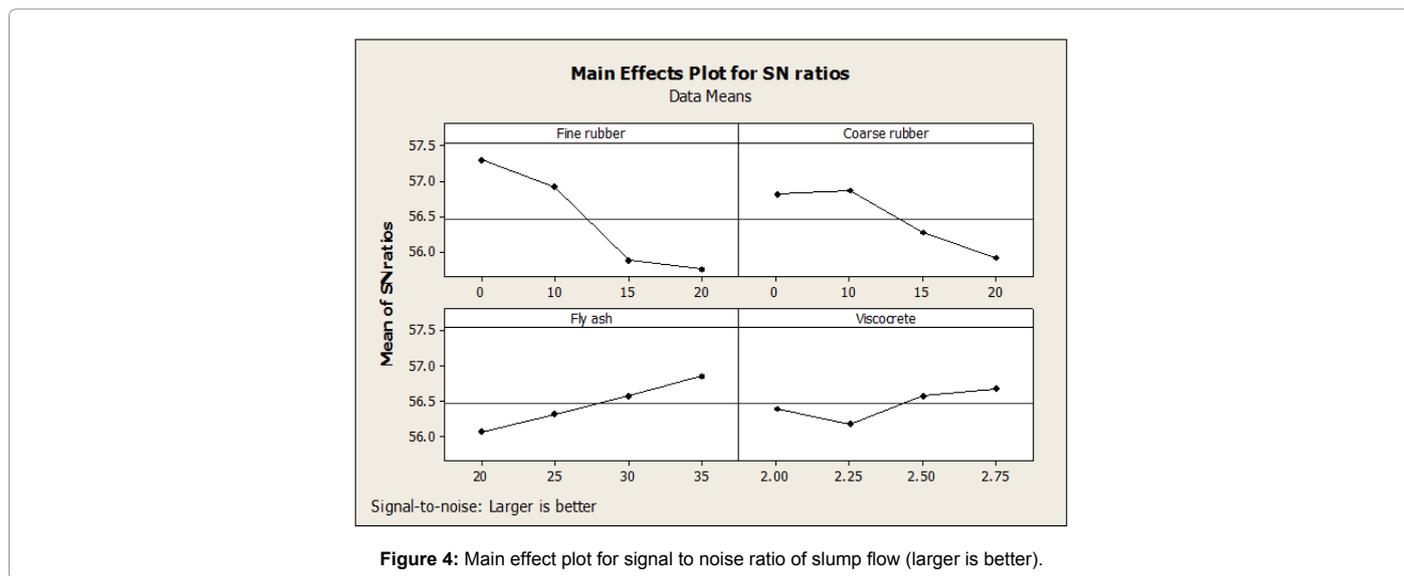


Figure 4: Main effect plot for signal to noise ratio of slump flow (larger is better).

Source	DF	Seq SS	Adj SS	Adj MS	Contribution %
Fine rubber	3	40345	40345	13448.3	61.27
Coarse rubber	3	13407	13407	4469.1	20.36
Fly ash	3	6557.4	6557.4	2185.8	9.96
Viscocrete	3	3182.4	3182.4	1060.8	4.83
Error	3	2344.9	2344.9	781.6	3.56
Total	15	65837	-	-	100

Table 7: Analysis of Variance for slump flow test, using adjusted SS for tests.

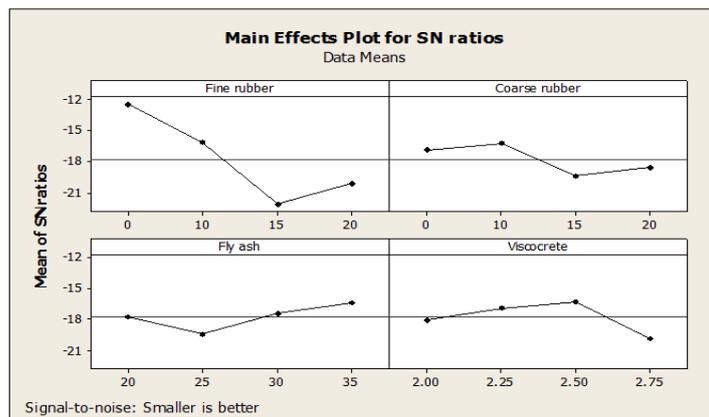


Figure 5: Main effect plot for signal to noise ratio of V-funnel results (smaller is better).

Level	Fine rubber (A)	Coarse rubber (B)	Fly ash (C)	Viscocrete (D)
1	-12.52	-16.94	-17.79	-18.03
2	-16.23	-16.24	-19.45	-16.93
3	-22.19	-19.42	-17.48	-16.33
4	-20.2	-18.54	-16.42	-19.85
Delta	9.67	3.17	3.03	3.51
Rank	1	3	4	2

Table 8: Response of signal to noise ratios for V-funnel (smaller is better).

Source	DF	Seq SS	Adj SS	Adj MS	Contribution %
Fine rubber	3	209.95	209.95	69.984	59.57
Coarse rubber	3	46.302	46.302	15.434	13.13
Fly ash	3	39.52	39.52	13.173	11.21
Viscocrete	3	33.017	33.017	11.006	9.36
Error	3	23.628	23.628	7.876	6.7
Total	15	352.42	-	-	100

Table 9: Analysis of variance for V-funnel test, using adjusted SS for tests.

Level	Fine rubber (A)	Coarse rubber (B)	Fly ash (C)	Viscocrete (D)
1	52.62	51.93	49.66	49.98
2	50.57	51.04	50.65	50.6
3	48.98	49.43	49.5	50.12
4	48.46	48.23	50.82	49.94
Delta	4.15	3.7	1.32	0.66
Rank	1	2	3	4

Table 10: Response of signal to noise ratios for compressive strength of 28 days (larger is better).

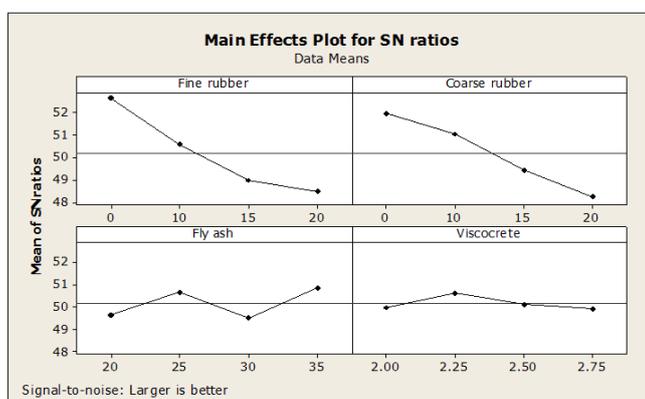


Figure 6: Main effect plot for signal to noise ratio of compressive strength after 28 days (larger is better).

Source	DF	Seq SS	Adj SS	Adj MS	Contribution %
Fine rubber	3	65266	65266	21755	52.098
Coarse rubber	3	46506	46506	15502	37.12
Fly ash	3	8413	8413	2804	6.71
Viscocrete	3	3273	3273	1091	2.61
Error	3	1818	1818	606	1.45
Total	15	125275	-	-	100

Table 11: Analysis of variance for 28 days compressive strength, using adjusted SS for tests.

Level	Fine rubber (A)	Coarse rubber (B)	Fly ash (C)	Viscocrete (D)
1	23.06	27.01	29.99	29.09
2	28.24	28.11	28.82	27.7
3	28.57	28.96	28.45	28.69
4	34.35	30.15	26.97	28.75
Delta	11.29	3.14	3.03	1.39
Rank	1	2	3	4

Table 12: Response of signal to noise ratios for impact resistance after 28 days (Larger is better).

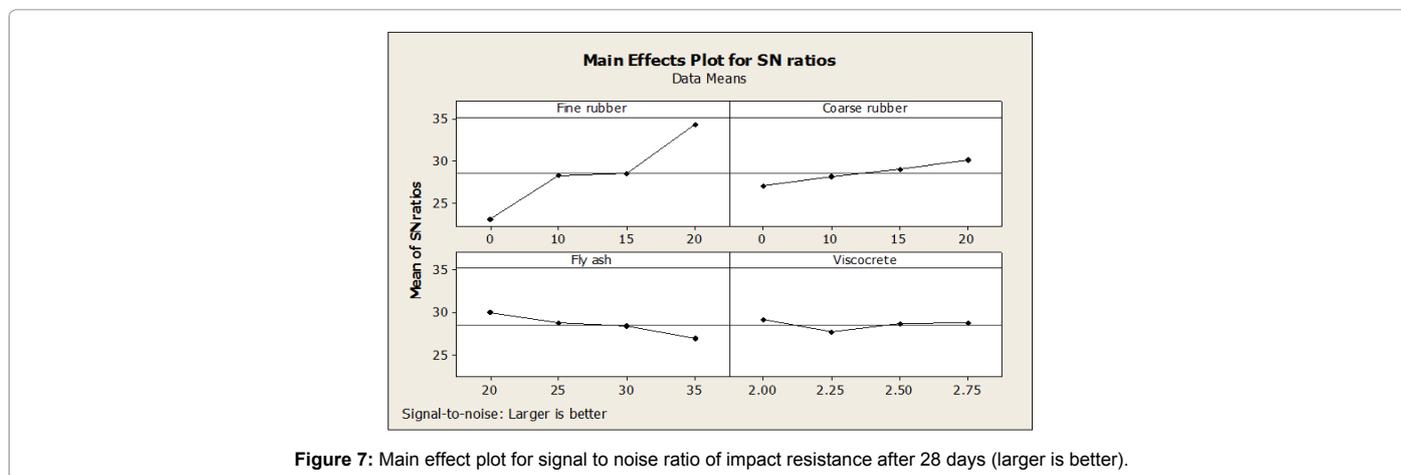


Figure 7: Main effect plot for signal to noise ratio of impact resistance after 28 days (larger is better).

Source	DF	Seq SS	Adj SS	Adj MS	Contribution %
Fine rubber	3	3514.4	3514.4	1171.45	75.14
Coarse rubber	3	467.47	467.47	155.82	10
Fly ash	3	443.13	443.13	147.71	9.47
Viscocrete	3	146.41	146.41	48.8	3.13
Error	3	105.24	105.24	35.08	2.25
Total	15	4676.6	-	-	100

Table 13: Analysis of variance for 28 days impact resistance, using adjusted SS for tests.

particles to absorb the plastic energy, which generated from the falling of a mass from a certain height. In addition, the high deflection of the rubberized concrete increases the ability to withstand more energy. Table 12 and Figure 7 shows the average values of S/N ratios of the control factors for T50 test. The analysis of variance for this test is shown in Table 13. The percentage of variance for this test is shown in Table 13. The percentage of fine rubber replacement was the most significant parameter influencing the impact resistance. The percentage contribution was 75.14%.

Prediction of Optimum Quality Characteristic

The predicted mean of the quality characteristic for slump flow, V-Funnel, compressive strength and impact resistance is computed using the following equation:

$$S_{mp} = \bar{Y} + (\bar{A}_0 - \bar{Y}) + (\bar{B}_0 - \bar{Y}) + (\bar{C}_0 - \bar{Y}) + (\bar{D}_0 - \bar{Y}) + (\bar{E}_0 - \bar{Y})$$

It is the grand average of performance characteristic.

$$(\bar{A}_0 - \bar{Y}), (\bar{B}_0 - \bar{Y}), (\bar{C}_0 - \bar{Y}), (\bar{D}_0 - \bar{Y}) \text{ and } (\bar{E}_0 - \bar{Y})$$

The following values of factors were chosen: A=20%, B=20%, C=35%, D=2.75%

From the analysis of S/N ratio and the mean response characteristic, the mean values for SCRC have been predicted as shown in Table 14.

A confirmation mix was performed with the selected factors (A=20%, B=20%, C=35%, D=2.75%) and the results were recorded in Table 14. These results were compared with the predicted values, illustrated in Table 14, which obtained from Minitab program. The ratio between the actual values and the predicted values are also illustrated in Table 14 which is in range of 10% difference so experimental results could be confirmed.

Conclusion

Taguchi Method was used to predict the mechanical properties of self-compacting rubberized concrete in terms of compressive strength and impact resistance and fresh properties in terms of slump flow

Test	Experimental results of the confirmation mix	Taguchi predicted value	Ratio of predicted value and actual value
Slump flow	645 mm	618.28 mm	95.85%
V-funnel	10.224 seconds	11.0663 seconds	108.31%
Compression	19.34 MPa	20.1 MPa	96.23%
Impact	51 blows	55 blows	107.85%

Table 14: Taguchi predicted values and actual values for SCRC.

diameter and V-Funnel time. The analysis shows that the proposed Taguchi technique was adequate to predict the above properties.

The study also considered examining the influence of different concrete mix proportioning parameters that included fine rubber, coarse rubber, fly ash and viscocrete contents on the studied mechanical and fresh properties.

The analysis of variance using ANOVA shows that the percentage of fine rubber replacement was the most significant parameter influencing the studied mechanical and fresh properties. The percentage contribution was 61.3%, 59.6%, 52.1% and 75.14% for slump flow diameter, V-Funnel, compressive strength and impact resistance respectively.

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