CHAPTER 4

TEST RESULTS OF RUBBERIZED CONCRETE AT LOW VOLUME FRACTIONS

4.1. INTRODUCTION

The main focus in this chapter is to determine the benefits of implementing rubber particles into concrete mixtures at low volume fractions. The test results for rubberized concrete mixes are presented in this chapter. As previously mentioned in chapter three, a total of 30 mixtures were cast, three mixtures were cast as control with no additives and the other 27 mixtures were designed using fractional factorial method of experimentation to study the effect of five parameters, each at three levels, three concrete grades (C20, C25 and C30), three rubber volume fractions as an additive to concrete (0.5%, 1.5% and 2.5%), three types of additives (without , polypropylene fiber 0.2% and 10% silica fume as cement replacement by weight), Three types of rubber particles (4mm granules and two types of rubber fibers with different aspect ratios) and Three types of surface treatments for rubber particles (rubber treated with NaOH solution, Plain rubber and rubber treated with PVA).

Test results included in this chapter are;

1- Compressive strength test.
2- Slump test.
3- Static modulus of elasticity.
4- Impact resistance (drop weight test).
5- Flexural toughness test.
6- Abrasion resistance test.

Fractional factorial method of experimentation was considered to organize the tested variables and to analysis the test results.

4.2. COMPRESSIVE STRENGTH TEST RESULTS

4.2.1. Test Results and Discussion

The cube compressive strength test was implemented for concrete after of 7 and 28 days. Table 4.1 presents the results of the cube compressive strength test for 27 mixes of rubberized concrete and the 3 control mixes. From this table, it can be seen that, concrete compressive strength is strongly affected by the change of the studied parameters and their levels. In general, as expected, the cube compressive strength decreases with the increase in rubber content. According to Khatib, Z.K. and Bayomy [17], Fattuhi and Clark [21], and Topcu [3] this may be attributed to two reasons. First, the lack of adhesion between rubber particles and cement paste, so soft rubber particles may behave as voids in the concrete matrix. Secondly, as the rubber particles are much softer than the surrounding matrix, on loading, cracks are initiated quickly around the rubber particles, which accelerate the failure in the rubber-cement matrix. Vice versa, Liang Hsing Chou et al. [41] indicated that the loss in strength is due to local imperfection in the hydration of cement, induced by the addition of heterogeneous and hydrophobic rubber particles.

Rubberized concrete, especially for fibrous rubber, demonstrated a ductile mode of failure and had the ability to absorb plastic energy under compressive load, which is also stated by the previous investigators [21 and 41].

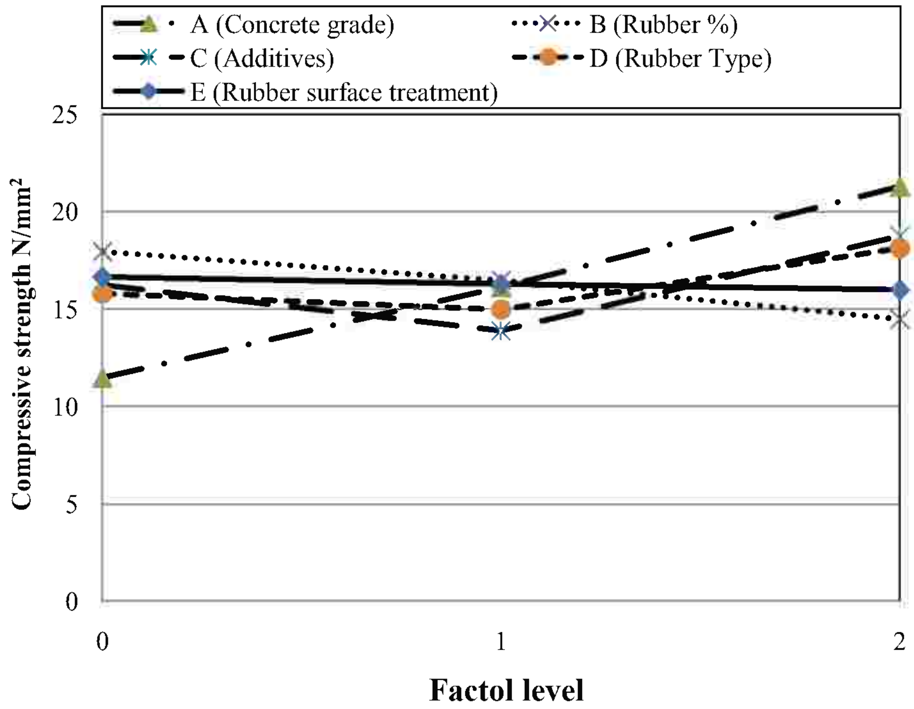
4.2.2. Effect of Different Factors on Compressive Strength

Fractional factorial method of experimentation was considered to organize the tested variables and to analysis the test results. The effect of each factor level on cube compressive strength after 28 days is shown in Figures 4.1 and 4.2. Table 4.2 presents the average response of each factor level on cube compressive strength after 7 and 28 days. The average responses are calculated as the average cube compressive strength of the 9 mixes with the same factor level, as shown below Table 4.2. Also, the contribution of each factor on cube compressive strength after 7 and 28 days is illustrated in Figure 4.3 and Figure 4.4. It can be seen from Table 4.2 and Figure 4.4 that Factor A (concrete grade) has the most significant effect on compressive strength, while Factor D (rubber surface treatment) has the lowest effect on compressive strength.

From Figure 4.4, the contribution of factor A (concrete grade) on concrete compressive strength is 44% after 28 days, so it is considered the most important factor of all the studied parameters. To study the effect of factor A (Concrete grade), it can be seen from Table 4.2 and Figure 4.2 that concrete compressive strength increases gradually with the increase in concrete grade. This behavior is normal, due to the increase in cement content.

Table 4.1 Average cube compressive strength of all concrete mixes

Mix No	Factor description					Cube compressive strength (MPA)	
	A (Concrete grade)	B (Rubber %)	C (Additives)	D (Rubber Type)	E (Rubber surface treatment)	7 Days	28 Days
1	C20	0.50%	None	Crumb 4mm	NaOH	14.42	19.44
2		1.50%	Polyp 0.2%	Crumb 4mm	PVA	8.68	13.49
3		2.50%	S.F 10%	Crumb 4mm	Without	11.35	14.92
4		0.50%	S.F 10%	Fiber 8	Without	13.35	19.38
5		1.50%	None	Fiber 8	NaOH	11.34	16.14
6		2.50%	Polyp 0.2%	Fiber 8	PVA	7.764	11.52
7		0.50%	Polyp 0.2%	Fiber 4	PVA	12.76	18.53
8		1.50%	S.F 10%	Fiber 4	Without	12.51	17.96
9		2.50%	None	Fiber 4	NaOH	11.18	14.44
10	C25	0.50%	S.F 10%	Crumb 4mm	PVA	19.47	29.48
11		1.50%	None	Crumb 4mm	Without	12.57	21.90
12		2.50%	Polyp 0.2%	Crumb 4mm	NaOH	11.54	16.33
13		0.50%	Polyp 0.2%	Fiber 8	NaOH	12.37	18.72
14		1.50%	S.F 10%	Fiber 8	PVA	18.17	25.12
15		2.50%	None	Fiber 8	Without	13.89	20.25
16		0.50%	None	Fiber 4	Without	24.58	30.34
17		1.50%	Polyp 0.2%	Fiber 4	NaOH	13.77	18.69
18		2.50%	S.F 10%	Fiber 4	PVA	18.78	27.60
19	C30	0.50%	Polyp 0.2%	Crumb 4mm	Without	18.13	27.46
20		1.50%	S.F 10%	Crumb 4mm	NaOH	27.56	35.15
21		2.50%	None	Crumb 4mm	PVA	18.45	21.84
22		0.50%	None	Fiber 8	PVA	17.64	30.53
23		1.50%	Polyp 0.2%	Fiber 8	Without	21.51	27.07
24		2.50%	S.F 10%	Fiber 8	NaOH	18.75	27.99
25		0.50%	S.F 10%	Fiber 4	NaOH	28.84	39.08
26		1.50%	None	Fiber 4	PVA	22.17	32.30
27		2.50%	Polyp 0.2%	Fiber 4	Without	18.57	23.26
					Mean	16.30	22.92
C20	C20	-	-	-	-	14.89	21.40
C25	C25	-	-	-	-	18.43	26.97
C30	C30	-	-	-	-	23.23	32.37



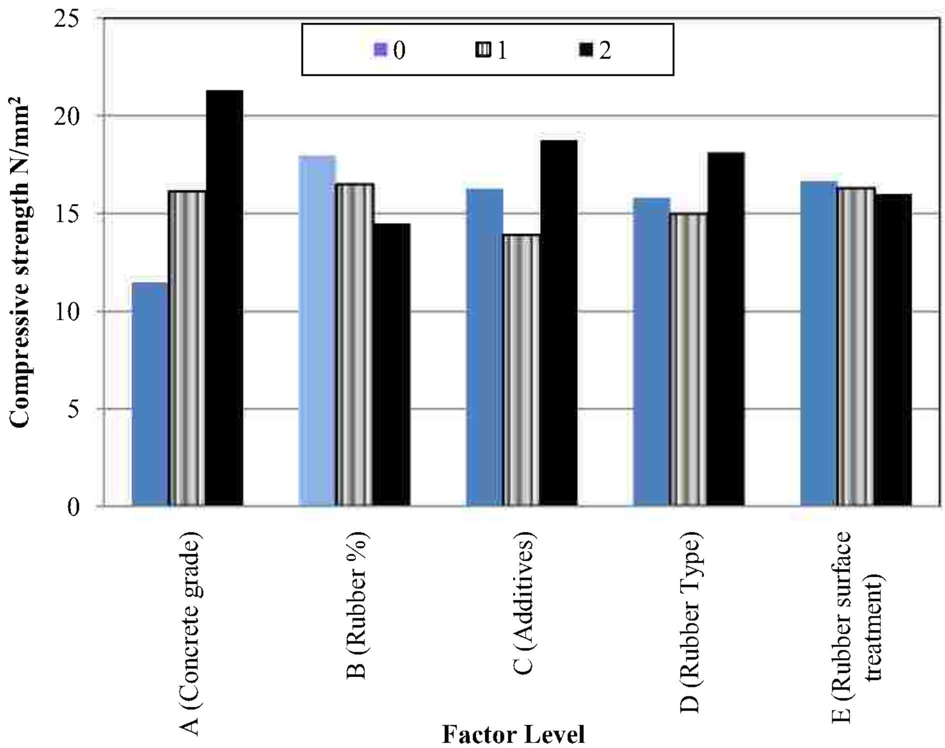
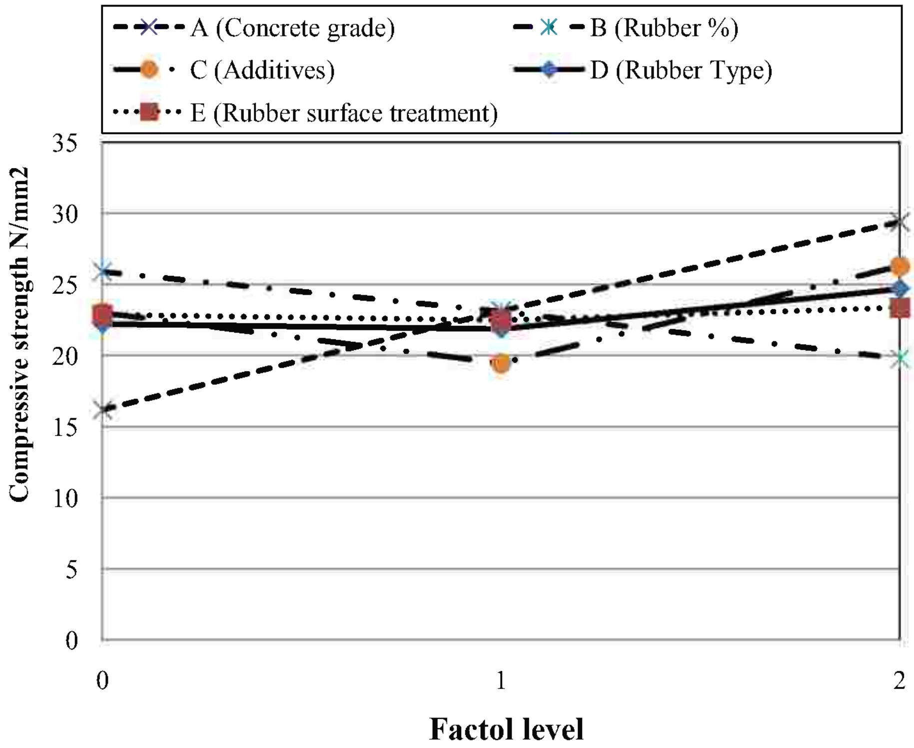


Fig 4.1 Factors affecting compressive strength after 7 days



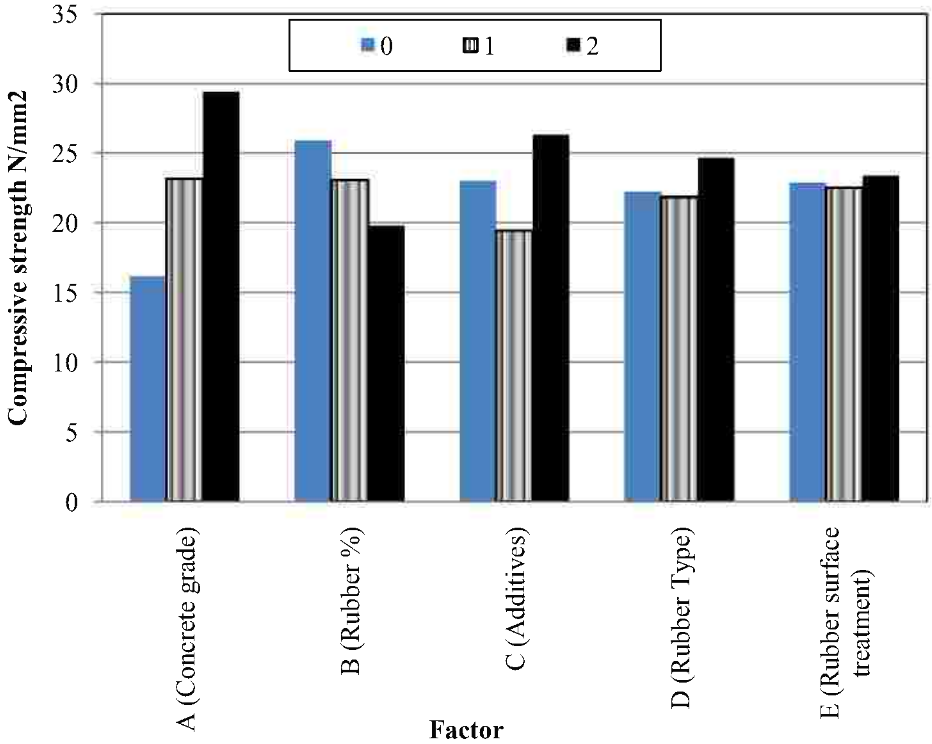


Fig 4.2 Factors affecting compressive strength after 28 days

Table 4.2 Average response of each factor level on cube compressive strength after 7 and 28 days

Factor	Factor level	Factor description	Average Compressive strength (MPa)	
			7 days	28 days
A (Concrete grade)	0	C20	11.48	16.20
	1	C25	16.13	23.16
	2	C30	21.29	29.41
B (Rubber %)	0	0.5%	17.95	25.88
	1	1.5%	16.48	23.09
	2	2.5%	14.48	19.79
C (Additives)	0	None	16.25	23.02
	1	Polyp 0.2%	13.90	19.45
	2	S.F 10%	18.75	26.30
D (Rubber Type)	0	Crumb 4mm	15.80	22.22
	1	Fiber 8	14.98	21.86
	2	Fiber 4	18.13	24.69
E (Rubber surface treatment)	0	NaOH	16.64*	22.89
	1	Without	16.27	22.50
	2	PVA	15.99	23.38

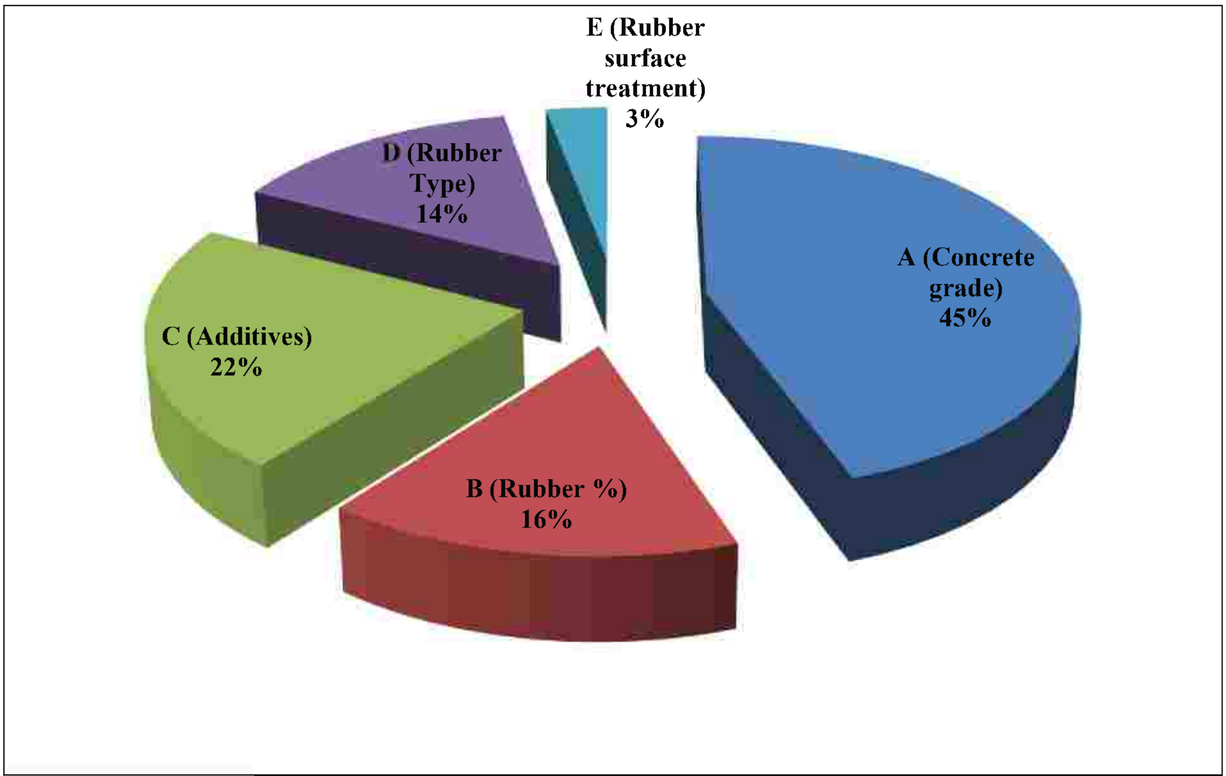
* Each cube compressive strength value is the average of all results of the same factor level.
Example: for average response at age of 7 days of NaOH treatment "level 0 of factor E" = (14.42 + 11.34+ 11.18 + 11.54 + 12.37 + 13.77 + 27.56 + 18.75 + 28.84) / 9 = 16.64N / mm^2

Also, factor B (rubber volume fraction %) has significant effect on concrete compressive strength. From Figure 4.4, the contribution of factor B is 20%. As shown in Table 4.2 and Figure 4.2, the compressive strength decreased gradually with the increase in rubber content.

As for factor C (additives), the contribution on concrete compressive strength is 23% after 28 days. The addition of the polypropylene fiber decreases the compressive strength comparing to rubber concrete with no additives, while the addition of silica fume increases the compressive strength significantly. Erhan Gu¨neyisi [43] attributed the increase in strength, when silica fume is used, is due to the increase in homogeneity and decrease the number of large pores in cement paste; this filling effect of silica fume is due to its finer particle size, thus providing a good adherence between rubber and the cement matrix.

For factor D (rubber type), compressive strength varied slightly with change in rubber type. Fiber 4 gives the highest cube compressive strength values, while Fiber 8 gives the lowest values with littler difference from crumb rubber. The same results for fibrous rubber are given by investigation by Hai Huynh [23] and Raimundo K. Vieira et al. [25] for low volume fractions of rubber particles in concrete.

Finally, From Figure 4.4 it may be conducted that factor E (rubber surface fraction) is the least important factor of the studied parameters and factor levels that affect concrete compressive strength.

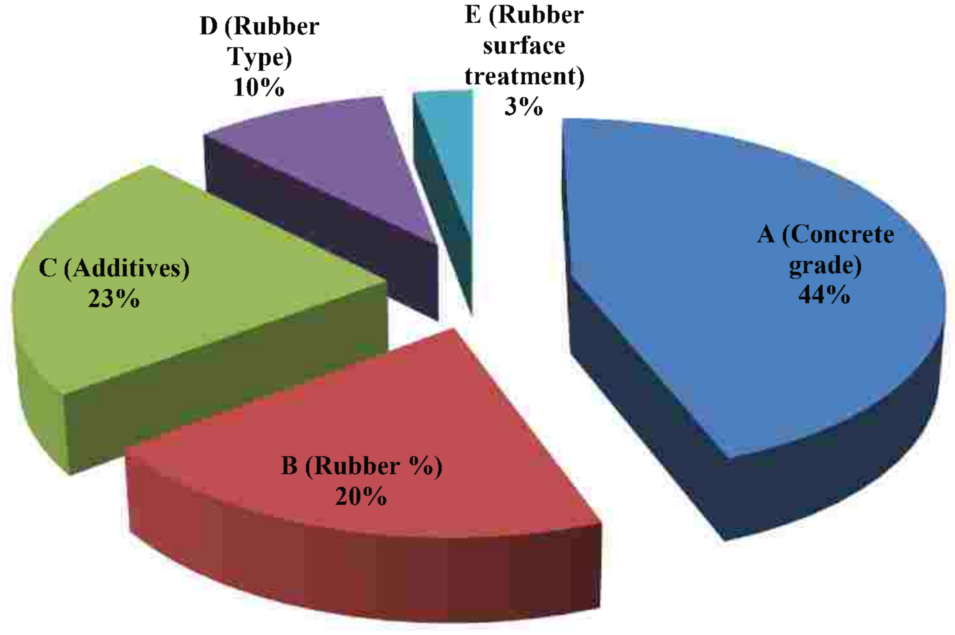


Factor	A	B	C	D	E	Total
Factor description	(Concrete grade)	(Rubber %)	(Additives)	(Rubber Type)	(Rubber surface treatment)	
Difference	9.81	3.47	4.85	3.15	0.65	21.93
Contribution %	44.7%	15.8%	22.1%	14.4%	3.0%	100%

Figure 4.3 The contribution of each factor on cube concrete compressive strength after 7 days

4.2.3. Two-Factor Interactions

The two-way tables of AxB, AxC and BxC are presented in Tables 4.3 and 4.4. Figure 4.5 and Figure 4.6 illustrate the effect of two factor interaction at different factor levels after 7 and 28 days on cube compressive strength. From these figures, it can be stated that, the highest concrete compressive strength is obtained by the combination of these factor levels; C30 concrete grade, 0.5% rubber volume fraction and the addition of 10% silica fume as cement replacement by weight. Also, these figures can be used to define the optimum performance by interaction between factors levels. For example, the lowest strength is given by using C20 concrete grade, 2.5% rubber volume fraction, and 0.2% polypropylene fiber.



Factor	A	B	C	D	E	Total
Factor description	(Concrete grade)	(Rubber %)	(Additives)	(Rubber Type)	(Rubber surface treatment)	
Difference	13.21	6.09*	6.85	2.83	0.88	29.86
Contribution (%)	44.2%	20.4%**	22.9%	9.5%	2.9%	100%

* Each cube compressive strength value is the difference between the higher and lower responses for each factor.
Example: For difference in Rubber% "Factor B" = 25.88-19.79 =6.09 N / mm^2, where 25.88 is the highest response of factor B and 19.79 is the lowest response.
** The % of affection of Rubber % "Factor B" = 6.09 / 29.86 *100% = 20.4%

Figure 4.4 The contribution of each factor on cube concrete compressive strength after 28 days

Table 4.3 Two-way tables for compressive strength after 7 days

a) AxB Interaction

A (Concrete grade)	B (Rubber %)			
	0.5%	1.5%	2.5%	Mean
C20	13.51	10.84	10.10	11.48
C25	18.81	14.84	14.74	16.13
C30	21.54	23.75	18.59	21.29
Mean	17.95	16.48	14.48	16.30

b) AxC Interaction

A (Concrete grade)	C (Additives)			
	None	Polyp 0.2%	S.F 10%	Mean
C20	12.32	9.73	12.40	11.48
C25	17.01	12.56	18.81	16.13
C30	19.42	19.40	25.05	21.29
Mean	16.25	13.90	18.75	16.30

c) BxC Interaction

B (Rubber %)	C (Additives)			
	None	Polyp 0.2%	S.F 10%	Mean
0.5%	18.88	14.42	20.55	17.95
1.5%	15.36	14.65	19.41	16.48
2.5%	14.51	12.62	16.29	14.48
Mean	16.25	13.90	18.75	16.30

Table 4.4 Two-way tables for compressive strength after 28 days

a) AxB Interaction

A (Concrete grade)	B (Rubber %)			
	0.5%	1.5%	2.5%	Mean
C20	19.12	15.86	13.63	16.20
C25	26.18	21.90	21.39	23.16
C30	32.36	31.51	24.36	29.41
Mean	25.88	23.09	19.79	22.92

b) AxC Interaction

A (Concrete grade)	C (Additives)			
	None	Polyp 0.2%	S.F 10%	Mean
C20	16.67	14.51	17.42	16.20
C25	24.16	17.91	27.40	23.16
C30	28.22	25.93	34.07	29.41
Mean	23.02	19.45	26.30	22.92

c) BxC Interaction

B (Rubber %)	C (Additives)			
	None	Polyp 0.2%	S.F 10%	Mean
0.5%	26.77	21.57	29.31	25.88
1.5%	23.45	19.75	26.08	23.09
2.5%	18.84	17.04	23.50	19.79
Mean	23.02	19.45	26.30	22.92

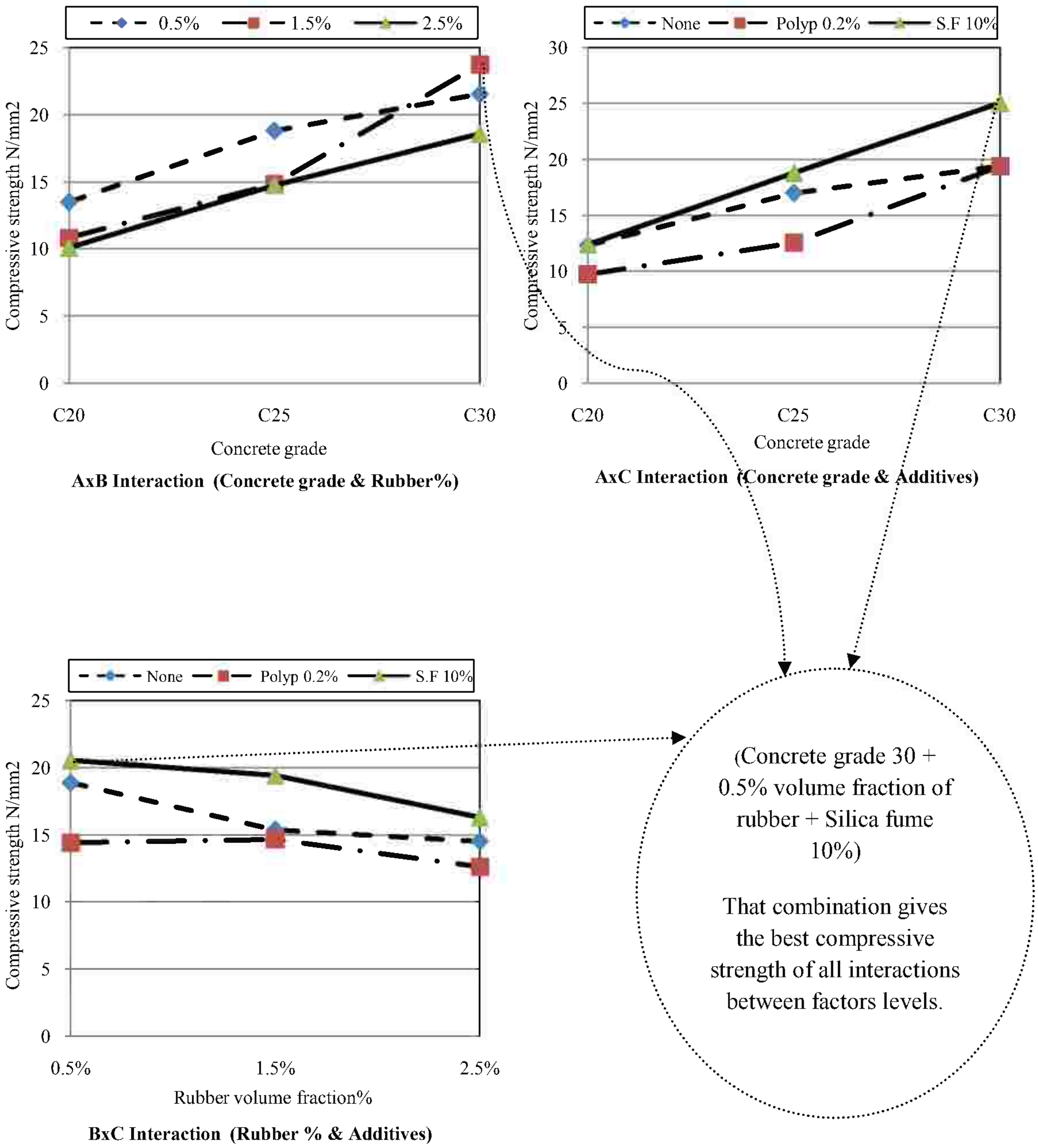


Figure 4.5 Effect of two factor interaction at different factor levels after 7 days on cube compressive strength

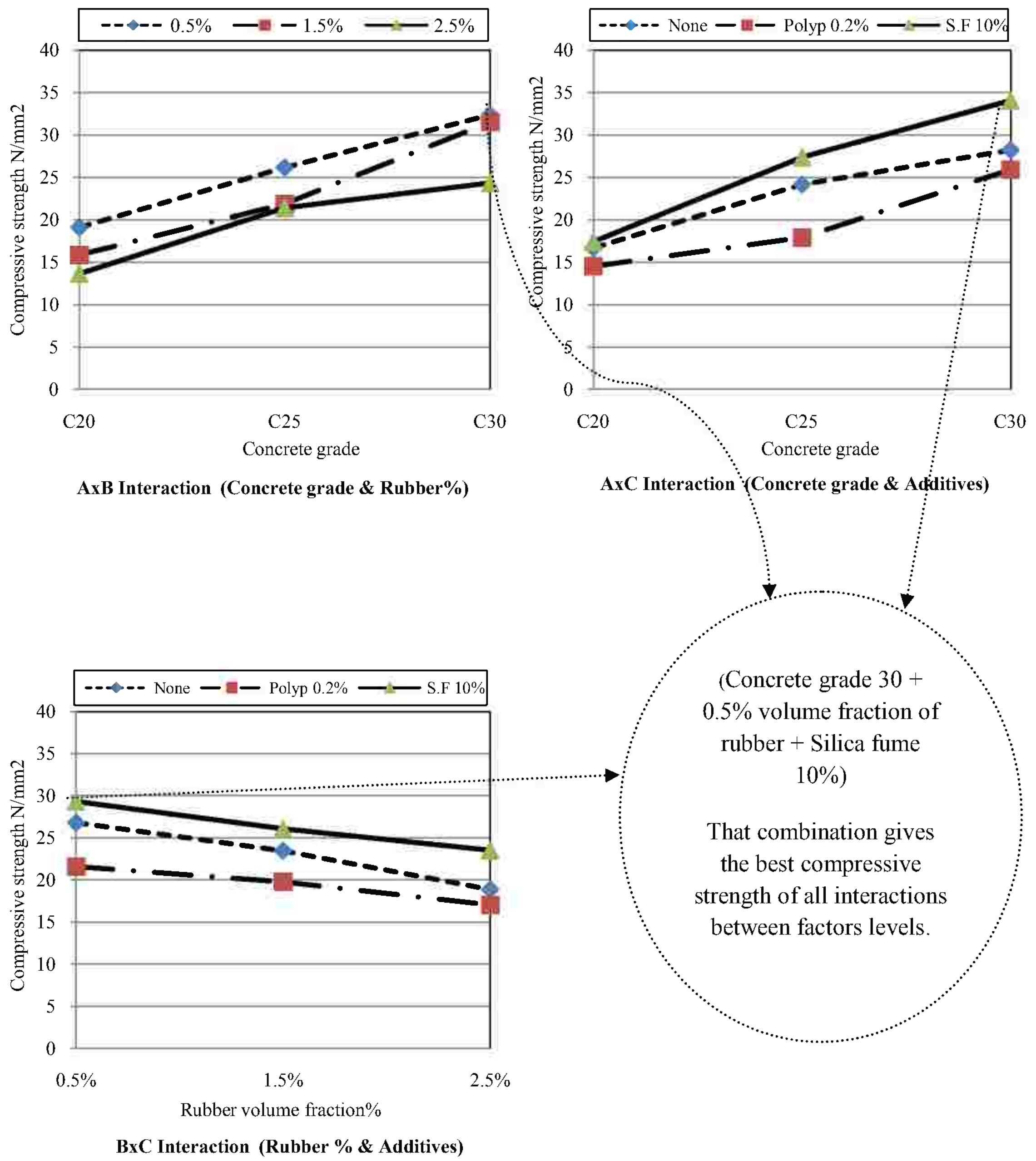


Figure 4.6 Effect of two factor interaction at different factor levels after 28 days on cube compressive strength

4.2.4. Prediction of Concrete Strength Using Classical Method of Analysis

Table 4.5 shows the average responses after 28 days of the main factors and the two factor interaction of factors A (rubber type), B (rubber volume fraction) and C (Surface treatment of rubber particles). An example for the calculations of the average response of the main factors and the average response of the two factors interaction is shown below Table 4.5. Each two factors interaction consists of 9 values, where each value is the average of the 3 mixes of the same two factors levels.

Table 4.5 The average responses of main factors and interactions of factors A, B and C on 28 days compressive strength

Factor level	A (Concrete grade)	B (Rubber %)	C (Additives)	D (Rubber Type)	E (Rubber surface treatment)	AxB	AxC	BxC
0	16.20	25.88	23.02	22.22	22.89*			
1	23.16	23.09	19.45	21.86	22.50			
2	29.41	19.79	26.30	24.69	23.38			
00						19.12	16.67	26.77
01						15.86	14.51	21.57
02						13.63	17.42	29.31
10						26.18	24.16	23.45
11						21.90	17.91**	19.75
12						21.39	27.40	26.08
20						32.36	28.22	18.84
21						31.51	25.93	17.04
22						24.36	34.07	23.50

* Each value is the average of all results with the same factor level,
Example: for average response after 28 days of NaOH treatment "level 0 of factor E" = (19.44 + 16.14+ 14.44 + 16.33 + 18.72 + 18.69 + 35.15 + 27.99 + 39.08) / 9 = 22.89 N / mm^2
** Average response of AxC interaction at levels of A = 1 (C20) and C =1 (Concrete without additives) = (16.33 +18.72 +18.69) / 3 = 17.91 N / mm^2

Classical method of analysis [53-56] was used to expect all the 243 responses at any treatment combination based on the equation:

$$\mathbf{X_{ijklm} = - \mu - X_{i....} - X_{.j...} - X_{..k..} + X_{...l.} + X_{....m} + X_{ij...} + X_{i.k..} + X_{.jk..}} \quad \text{.................} \quad \textbf{Eq. 4.1}$$

Where:

- **μ** is the mean of all 27 results.
- $\mathbf{X_{ijklm}}$ the value or result corresponding to the treatment combination
- **i, j, k, l, m** are the arbitrary level of factors A,B,C,D,E correspondently.

To check the model presented in the equation, the expected response of Mix Number16 at 28 days (with factor levels = 10021) is calculated as follows:

$$\mathbf{X_{10021} = - \mu - X_{1....} - X_{.0...} - X_{..0..} + X_{...2.} + X_{....1} + X_{10...} + X_{1.0..} + X_{.00..}}$$

$$\mathbf{X_{10021} = - 22.92 - 23.16 - 25.88 - 23.02 + 24.69 + 22.50 + 26.18 + 24.16 + 26.77}$$

$$\mathbf{= 29.32\ N/\ mm^2}$$

The expected value by the classical method of analysis is very close to the actual response of Mix Number16 which was 30.34 N/ mm^2. The expected 243 compressive strength after 28 days for all treatment combinations are presented in Tables 4.6.

From the expected responses, some mixes at specific treatment combinations give the best compressive strength. For crumb rubber, the highest value for concrete grade C30 is given by mix "20202" with compressive strength 36.83 MPA, this mix contains low rubber content 0.5%, silica fume 10% and PVA surface treatment of rubber particles. It is also noticed that crumb rubber gives the highest values for all concrete grades when it is combined with PVA surface treatment of rubber particles and silica fume. For Fiber 8, the highest compressive strength of concrete grade C30 is given by mix "20212" with compressive strength of 36.47 MPA. The mix consists of 0.5% rubber volume fraction, silica fume 10% and PVA surface treatment of rubber particles. For Fiber 4, the highest compressive strength expected value of all the 243 treatment combinations is given by mix "20222" with compressive strength of 39.30 MPA. The mix consists of 0.5% rubber, silica fume 10% and PVA rubber surface treatment at concrete grade C30. For mixes at concrete grade C25 and C20, all mixes show acceptable values comparing to control mixes except for crumb rubber at concrete grade C20.

The classical method of analysis is used to expect the response of any treatment combination based on **Eq. 4.1**. To verify the accuracy of this method, 5 mixes were cast at different treatment combinations (different combination of factor levels). The mixes were chosen randomly from all the 243 treatment combinations. The cube compressive strength of the mixes and the variance from the expected values are presented in Table 4.7. The cube compressive strengths of the five mixes can be expected using **Eq. 4.1** (the classical method of analysis), as illustrated before for mix Number16. It can be seen that from Table 4.7, that the actual cube compressive strengths of the mixes are very close to the values that are expected by the classical method of analysis.

Table 4.6 The expected 243 compressive strength after 28 days for all treatment combinations

a) Concrete grade 20								
A	B	C	D	E	Mix No	28 days Comp st		Variance (%)
						Actual data	Calculated	
0	0	0	0	0	1	19.44	19.64	1.02
0	0	0	0	1			19.26	
0	0	0	0	2			20.13	
0	0	0	1	0			19.27	
0	0	0	1	1			18.89	
0	0	0	1	2			19.77	
0	0	0	2	0			22.10	
0	0	0	2	1			21.72	
0	0	0	2	2			22.60	
0	0	1	0	0			15.85	
0	0	1	0	1			15.46	
0	0	1	0	2			16.34	
0	0	1	1	0			15.48	
0	0	1	1	1			15.10	
0	0	1	1	2			15.97	
0	0	1	2	0			18.31	
0	0	1	2	1			17.93	
0	0	1	2	2	7	18.53	18.80	1.49
0	0	2	0	0			19.65	
0	0	2	0	1			19.27	
0	0	2	0	2			20.14	
0	0	2	1	0			19.29	
0	0	2	1	1	4	19.38	18.91	-2.45
0	0	2	1	2			19.78	
0	0	2	2	0			22.12	
0	0	2	2	1			21.74	
0	0	2	2	2			22.61	
0	1	0	0	0			15.86	
0	1	0	0	1			15.47	
0	1	0	0	2			16.35	
0	1	0	1	0	5	16.14	15.49	-4.02
0	1	0	1	1			15.11	
0	1	0	1	2			15.98	
0	1	0	2	0			18.32	
0	1	0	2	1			17.94	
0	1	0	2	2			18.81	
0	1	1	0	0			13.57	
0	1	1	0	1			13.18	
0	1	1	0	2	2	13.49	14.06	4.23

0	1	1	1	0			13.20	
0	1	1	1	1			12.82	
0	1	1	1	2			13.69	
0	1	1	2	0			16.03	
0	1	1	2	1			15.65	
0	1	1	2	2			16.52	
0	1	2	0	0			15.96	
0	1	2	0	1			15.57	
0	1	2	0	2			16.45	
0	1	2	1	0			15.59	
0	1	2	1	1			15.21	
0	1	2	1	2			16.08	
0	1	2	2	0			18.42	
0	1	2	2	1	8	17.96	18.04	0.44
0	1	2	2	2			18.91	
0	2	0	0	0			12.31	
0	2	0	0	1			11.93	
0	2	0	0	2			12.80	
0	2	0	1	0			11.95	
0	2	0	1	1			11.56	
0	2	0	1	2			12.44	
0	2	0	2	0	9	14.44	14.78	2.35
0	2	0	2	1			14.39	
0	2	0	2	2			15.27	
0	2	1	0	0			11.91	
0	2	1	0	1			11.53	
0	2	1	0	2			12.41	
0	2	1	1	0			11.55	
0	2	1	1	1			11.17	
0	2	1	1	2	6	11.52	12.04	4.51
0	2	1	2	0			14.38	
0	2	1	2	1			14.00	
0	2	1	2	2			14.87	
0	2	2	0	0			14.44	
0	2	2	0	1	3	14.92	14.06	-5.76
0	2	2	0	2			14.93	
0	2	2	1	0			14.08	
0	2	2	1	1			13.69	
0	2	2	1	2			14.57	
0	2	2	2	0			16.91	
0	2	2	2	1			16.53	
0	2	2	2	2			17.40	

b) Concrete grade 25								
A	B	C	D	E	Mix No	28 days Comp st		Variance
						Actual data	Calculated	
1	0	0	0	0			27.24	
1	0	0	0	1			26.86	
1	0	0	0	2			27.73	
1	0	0	1	0			26.87	
1	0	0	1	1			26.49	
1	0	0	1	2			27.36	
1	0	0	2	0			29.70	
1	0	0	2	1	16	30.34	29.32	-3.36
1	0	0	2	2			30.19	
1	0	1	0	0			19.35	
1	0	1	0	1			18.97	
1	0	1	0	2			19.85	
1	0	1	1	0	13	18.72	18.99	1.44
1	0	1	1	1			18.61	
1	0	1	1	2			19.48	
1	0	1	2	0			21.82	
1	0	1	2	1			21.44	
1	0	1	2	2			22.31	
1	0	2	0	0			29.74	
1	0	2	0	1			29.36	
1	0	2	0	2	10	29.48	30.23	2.55
1	0	2	1	0			29.37	
1	0	2	1	1			28.99	
1	0	2	1	2			29.87	
1	0	2	2	0			32.20	
1	0	2	2	1			31.82	
1	0	2	2	2			32.70	
1	1	0	0	0			22.43	
1	1	0	0	1	11	21.90	22.05	0.68
1	1	0	0	2			22.92	
1	1	0	1	0			22.06	
1	1	0	1	1			21.68	
1	1	0	1	2			22.56	
1	1	0	2	0			24.90	
1	1	0	2	1			24.51	
1	1	0	2	2			25.39	
1	1	1	0	0			16.05	
1	1	1	0	1			15.67	
1	1	1	0	2			16.54	
1	1	1	1	0			15.69	

1	1	1	1	1			15.30	
1	1	1	1	2			16.18	
1	1	1	2	0	17	18.69	18.52	-0.93
1	1	1	2	1			18.13	
1	1	1	2	2			19.01	
1	1	2	0	0			25.02	
1	1	2	0	1			24.64	
1	1	2	0	2			25.51	
1	1	2	1	0			24.65	
1	1	2	1	1			24.27	
1	1	2	1	2	14	25.12	25.15	0.10
1	1	2	2	0			27.48	
1	1	2	2	1			27.10	
1	1	2	2	2			27.98	
1	2	0	0	0			20.61	
1	2	0	0	1			20.23	
1	2	0	0	2			21.10	
1	2	0	1	0			20.25	
1	2	0	1	1	15	20.25	19.87	-1.90
1	2	0	1	2			20.74	
1	2	0	2	0			23.08	
1	2	0	2	1			22.70	
1	2	0	2	2			23.57	
1	2	1	0	0	12	16.33	16.12	-1.26
1	2	1	0	1			15.74	
1	2	1	0	2			16.62	
1	2	1	1	0			15.76	
1	2	1	1	1			15.38	
1	2	1	1	2			16.25	
1	2	1	2	0			18.59	
1	2	1	2	1			18.21	
1	2	1	2	2			19.08	
1	2	2	0	0			25.23	
1	2	2	0	1			24.85	
1	2	2	0	2			25.72	
1	2	2	1	0			24.87	
1	2	2	1	1			24.49	
1	2	2	1	2			25.36	
1	2	2	2	0			27.70	
1	2	2	2	1			27.32	
1	2	2	2	2	18	27.60	28.19	2.14

c) Concrete grade 30								
A	B	C	D	E	Mix No	28 days Comp st		Variance (%)
						Actual data	Calculated	
2	0	0	0	0			31.22	
2	0	0	0	1			30.84	
2	0	0	0	2			31.72	
2	0	0	1	0			30.86	
2	0	0	1	1			30.48	
2	0	0	1	2	22	30.53	31.35	2.69
2	0	0	2	0			33.69	
2	0	0	2	1			33.31	
2	0	0	2	2			34.18	
2	0	1	0	0			27.30	
2	0	1	0	1	19	27.46	26.92	-1.98
2	0	1	0	2			27.79	
2	0	1	1	0			26.93	
2	0	1	1	1			26.55	
2	0	1	1	2			27.42	
2	0	1	2	0			29.76	
2	0	1	2	1			29.38	
2	0	1	2	2			30.25	
2	0	2	0	0			36.34	
2	0	2	0	1			35.96	
2	0	2	0	2			36.83	
2	0	2	1	0			35.97	
2	0	2	1	1			35.59	
2	0	2	1	2			36.47	
2	0	2	2	0	25	39.08	38.80	-0.71
2	0	2	2	1			38.42	
2	0	2	2	2			39.30	
2	1	0	0	0			29.84	
2	1	0	0	1			29.46	
2	1	0	0	2			30.34	
2	1	0	1	0			29.48	
2	1	0	1	1			29.10	
2	1	0	1	2			29.97	
2	1	0	2	0			32.31	
2	1	0	2	1			31.93	
2	1	0	2	2	26	32.30	32.80	1.55
2	1	1	0	0			27.42	
2	1	1	0	1			27.04	
2	1	1	0	2			27.91	
2	1	1	1	0			27.06	

2	1	1	1	1	23	27.07	26.67	-1.46
2	1	1	1	2			27.55	
2	1	1	2	0			29.89	
2	1	1	2	1			29.50	
2	1	1	2	2			30.38	
2	1	2	0	0	20	35.15	35.05	-0.30
2	1	2	0	1			34.66	
2	1	2	0	2			35.54	
2	1	2	1	0			34.68	
2	1	2	1	1			34.30	
2	1	2	1	2			35.17	
2	1	2	2	0			37.51	
2	1	2	2	1			37.13	
2	1	2	2	2			38.00	
2	2	0	0	0			21.39	
2	2	0	0	1			21.01	
2	2	0	0	2	21	21.84	21.88	0.20
2	2	0	1	0			21.03	
2	2	0	1	1			20.65	
2	2	0	1	2			21.52	
2	2	0	2	0			23.86	
2	2	0	2	1			23.48	
2	2	0	2	2			24.35	
2	2	1	0	0			20.86	
2	2	1	0	1			20.48	
2	2	1	0	2			21.35	
2	2	1	1	0			20.50	
2	2	1	1	1			20.11	
2	2	1	1	2			20.99	
2	2	1	2	0			23.33	
2	2	1	2	1	27	23.26	22.94	-1.35
2	2	1	2	2			23.82	
2	2	2	0	0			28.63	
2	2	2	0	1			28.24	
2	2	2	0	2			29.12	
2	2	2	1	0	24	27.99	28.26	0.97
2	2	2	1	1			27.88	
2	2	2	1	2			28.75	
2	2	2	2	0			31.09	
2	2	2	2	1			30.71	
2	2	2	2	2			31.58	

The maximum variance is -10.31% for mix Number1, as the actual cube compressive strength is 11.31 Mpa, while the expected cube compressive strength from the classical method of analysis is 12.41 MPa. The mix with the maximum value of cube compressive strength of all the 243 treatment combination was cast in this group. The expected cube compressive strength from the classical method of analysis is 39.30 MPa. The actual compressive strength of this mix is 37.40 MPa, which is lower than the expected value by 4.83%. Thus, it may be conducted that rubberized concrete with low volume fraction of rubber particles can obtain compressive strength comparable to normal concrete.

Table 4.7 The actual and expected test results of cube compressive strength

Mix Number		**1**	**2**	**3**	**4**	**5**
Treatment combination		02102	11111	11201	11221	20222
Factor description	**A (Concrete grade)**	C20	C25	C25	C25	C30
	B (Rubber %)	2.5%	1.5%	1.5%	1.5%	0.5%
	C (Additives)	Polyp.	Polyp.	Silica fume	Silica fume	Silica fume
	D (Rubber type)	Crumb rubber	Fiber 8	Crumb rubber	Fiber 4	Fiber 4
	E (Rubber surface treatment)	PVA	Plain	Plain	Plain	PVA
Actual cube compressive strength (MPa)		11.13	16.16	22.90	28.20	37.40
Expected compressive strength (MPa)		12.41	15.30	24.64	27.10	39.30
Variance %		-10.31%	5.62%	-7.06%	4.06%	-4.83%

From previous analysis, the compressive strength decreases gradually with increasing in rubber content, especially for low grade concrete. The addition of silica fume is required to obtain high compressive strength, as silica fume significantly improves the interface interaction between rubber particles and the cement matrix. Also, for rubber type, the best performance is given by Fiber 4. As for rubber surface treatment; PVA gives slightly better compressive strength comparing to NaOH solution.

4.2.5. Analysis of Variance (ANOVA)

The analysis of variance (ANOVA) of 1/9 replicate fractional factorial of 3^5 design, based on the Principle Block with 3 replications for compressive strength after 28 days, is shown in Table 4.8. The error variance was determined from the within-cell variance with 58 degrees of freedom. The table shows that all factors have extremely significant effect on compressive strength, except for E (rubber surface treatment). Also, the quadratic component of factor A (concrete grade) and factor B (rubber volume fraction %) have insignificant effect on concrete compressive strength. The interaction between AxB (concrete grade and rubber volume fraction %) and AxC (Concrte grade and additives) are also extremely significant, while the interaction between and Bxc (rubber volume fraction % and additives) has highly significant effect on concrete compressive strength.

Table 4.8 Analysis of variance of 1/9 replicate fractional factorial of 3^5 design with 3 replications for 28 days cube compressive strength

Source of variation	Sum of squares (SS)	Degree of freedom (D.f)	Mean squares (MS)	Variance ratio (F)	Degree of significance	
A = Concrete grade						
Linear A	2354.93	1	2354.93	1327.10	P<0.1%	Extremely Significant
Quadratic A	2.25	1	2.25	1.27		Insignificant
B = Rubber volume fraction%						
Linear B	500.73	1	500.73	282.18	P<0.1%	Extremely Significant
Quadratic B	1.14	1	1.14	0.64		Insignificant
C = Additives	633.09	2	316.55	178.39	P<0.1%	Extremely Significant
D = Rubber type	127.99	2	64.00	36.07	P<0.1%	Extremely Significant
E = Rubber surface treatment	10.37	2	5.18	2.92	5%<P<10%	Hardly significant
AB	106.53	4	26.63	15.01	P<0.1%	Extremely Significant
AC	143.95	4	35.99	20.28	P<0.1%	Extremely Significant
BC	29.65	4	7.41	4.18	P<1%	Highly significant
Error variance	102.92	58	1.77			

P<0.1%		Extremely Significant	
P<1%		Highly significant	
1%<P<5%		Significant	
5%<P<10%		Hardly significant	
P<10%		Insignificant	
Degree of freedom of each component		1	
Degree of freedom of each effect A,B,C,D,E		2	
Degree of freedom of two-factor interaction AB,AC,BC		4	
Degree of freedom of error		58	
F (critical points) for	(1,58)	(2,58)	(4,58)
F(0.001)	11.97	7.77	5.31
F (0.01)	7.09	4.99	3.66
F (0.05)	4.01	3.16	2.53
F (0.1)	2.80	2.40	2.05

4.3. SLUMP TEST

4.3.1. Test Results and Discussion

Table 4.9 presents the slump values for all concrete mixes. From this table, it can be seen that rubberized concrete achieves slump varies from 10 mm to 55 mm as compared to 30mm to 32mm for control mixes without rubber. The same slump for rubberized concrete is also reported by Gideon Momanyi Siringi [11] for crumb rubber and Liang Hsing Chou [41] for fibrous rubber. Fractional factorial method of experimentation was used to organize the tested variables and to analyze the results.

Table 4.9 Slump test results of all concrete mixes

Mix No	Factor description					Slump (mm)
	A (Concrete grade)	B (Rubber %)	C (Additives)	D (Rubber Type)	E (Rubber surface treatment)	
1	C20	0.50%	None	Crumb 4mm	NaOH	20
2		1.50%	Polyp 0.2%	Crumb 4mm	PVA	10
3		2.50%	S.F 10%	Crumb 4mm	Without	25
4		0.50%	S.F 10%	Fiber 8	Without	30
5		1.50%	None	Fiber 8	NaOH	55
6		2.50%	Polyp 0.2%	Fiber 8	PVA	30
7		0.50%	Polyp 0.2%	Fiber 4	PVA	10
8		1.50%	S.F 10%	Fiber 4	Without	23
9		2.50%	None	Fiber 4	NaOH	10
10	C25	0.50%	S.F 10%	Crumb 4mm	PVA	25
11		1.50%	None	Crumb 4mm	Without	40
12		2.50%	Polyp 0.2%	Crumb 4mm	NaOH	30
13		0.50%	Polyp 0.2%	Fiber 8	NaOH	30
14		1.50%	S.F 10%	Fiber 8	PVA	60
15		2.50%	None	Fiber 8	Without	55
16		0.50%	None	Fiber 4	Without	13
17		1.50%	Polyp 0.2%	Fiber 4	NaOH	15
18		2.50%	S.F 10%	Fiber 4	PVA	18
19	C30	0.50%	Polyp 0.2%	Crumb 4mm	Without	15
20		1.50%	S.F 10%	Crumb 4mm	NaOH	25
21		2.50%	None	Crumb 4mm	PVA	50
22		0.50%	None	Fiber 8	PVA	45
23		1.50%	Polyp 0.2%	Fiber 8	Without	40
24		2.50%	S.F 10%	Fiber 8	NaOH	45
25		0.50%	S.F 10%	Fiber 4	NaOH	30
26		1.50%	None	Fiber 4	PVA	25
27		2.50%	Polyp 0.2%	Fiber 4	Without	13
					Mean	16.30
C20	C20	-	-	-	-	30
C25	C25	-	-	-	-	32
C30	C30	-	-	-	-	31

4.3.2. Effect of Different Factors on Slump

The effect of each factor level on slump test results is shown in Figure 4.7. Table 4.10 presents the average response of each factor level on slump test results. Also, the contribution of each factor on slump values is illustrated in Figure 4.8. It can be seen from Table 4.10, Figure 4.7 and Figure 4.8 that Factor D (rubber type) has the most significant effect on slump, while Factor D (rubber surface treatment) has the lowest effect.

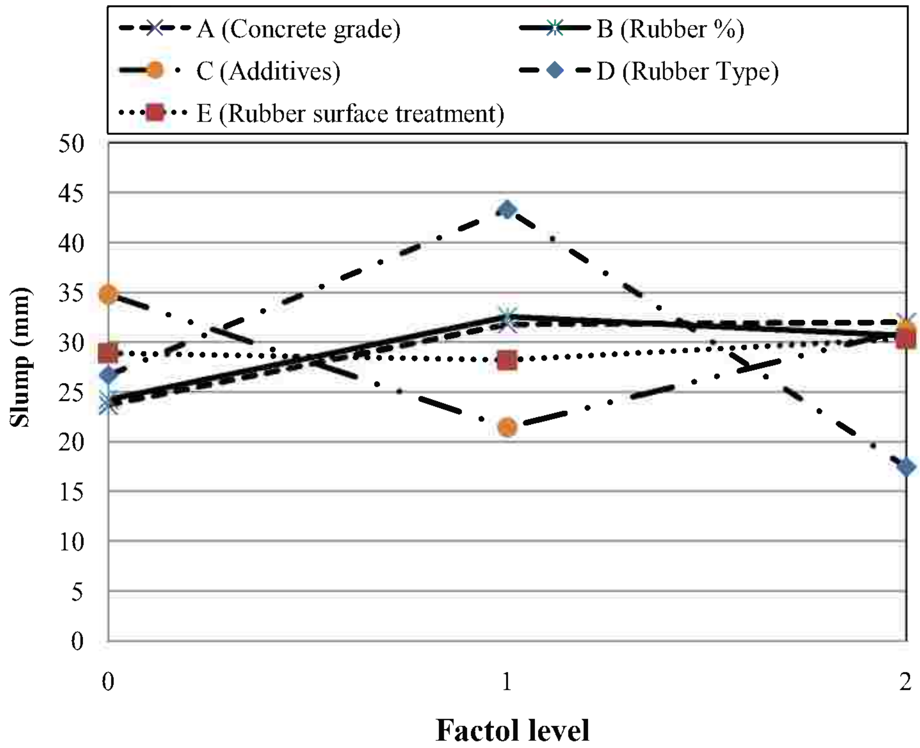
From Figure 4.8, the contribution of factor A (concrete grade) on slump test results is 14%. To study the effect of factor A (Concrete grade), it can be seen from Table 4.10 and Figure 4.7, that the slump of rubberized concrete is lower at C20 concrete grade.

Also, factor B (rubber volume fraction %) has the same contribution on slump test results as Factor A (concrete grade). As shown in Table 4.10 and Figure 4.7, the slump test results increases with the increase in rubber content. Moreover, the 1.5% volume fraction gives slightly higher slump values than 2.5% volume fraction.

As for factor C (additives), the contribution on concrete slump is 23%. The addition of the polypropylene fiber decreases the slump test results to 21mm comparing to 35mm for rubberized concrete without additives. Also, the addition of silica fume decreases the slump values slightly to 31mm.

Table 4.10 Average response of each factor level on slump test results

Factor	Factor level	Factor description	Slump (mm)
A (Concrete grade)	0	C20	24
	1	C25	32
	2	C30	32
B (Rubber %)	0	0.5%	24
	1	1.5%	33
	2	2.5%	31
C (Additives)	0	None	35
	1	Polyp 0.2%	21
	2	S.F 10%	31
D (Rubber Type)	0	Crumb 4mm	27
	1	Fiber 8	43
	2	Fiber 4	17
E (Rubber surface treatment)	0	NaOH	29
	1	Without	28
	2	PVA	30



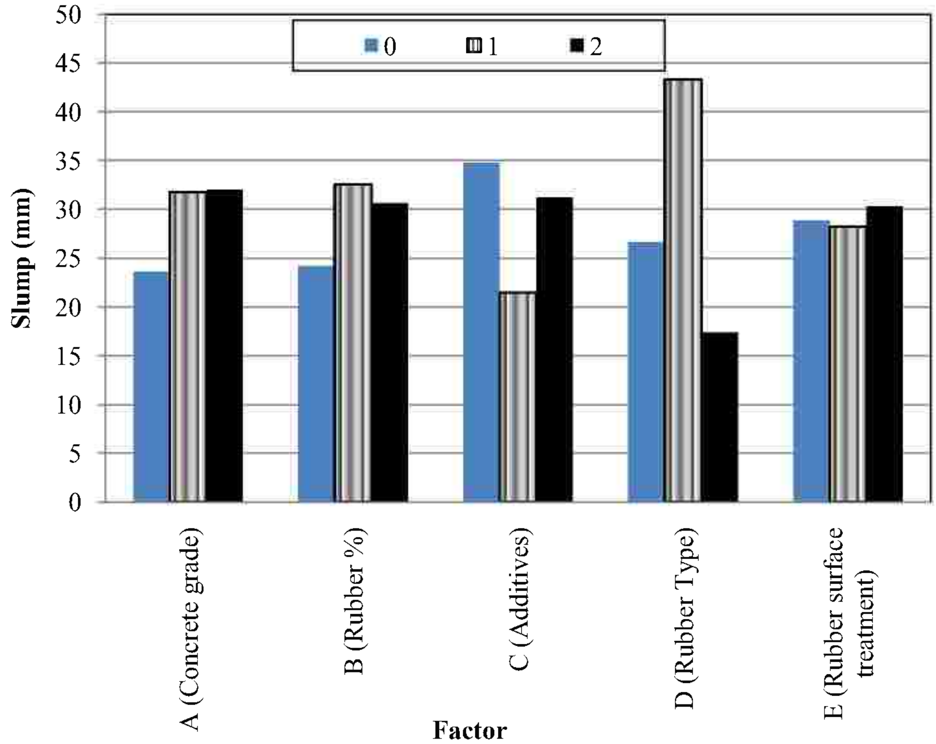
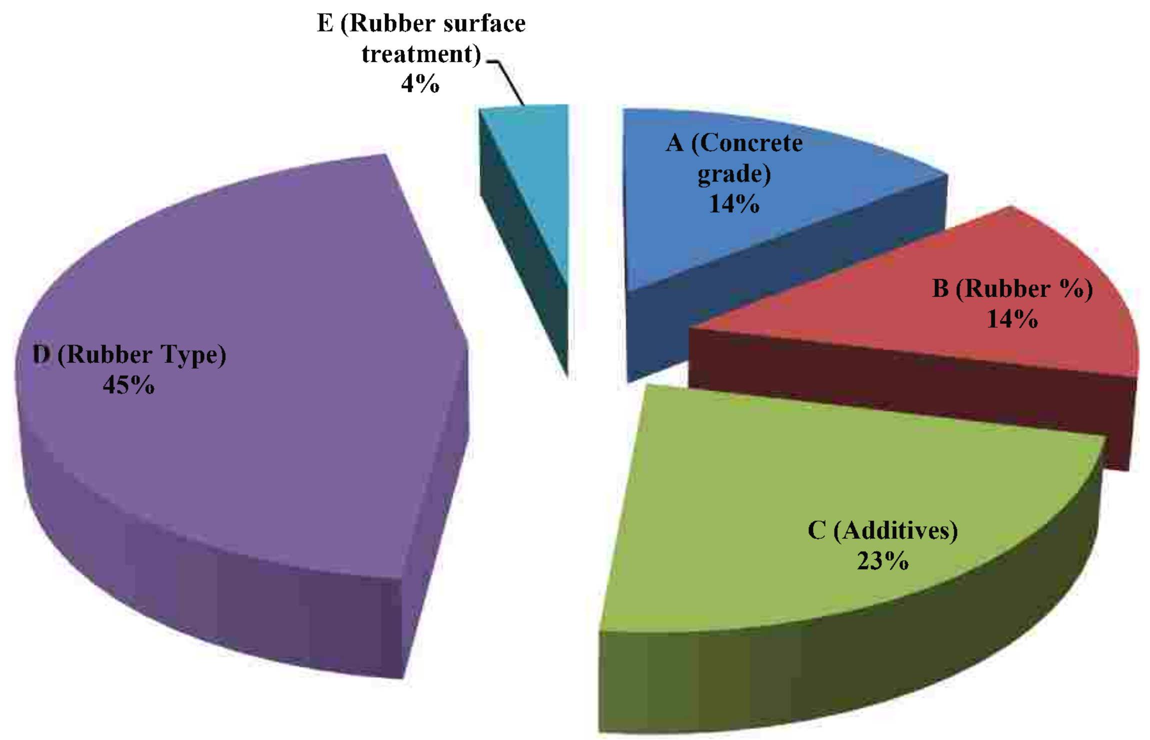


Figure 4.7 Factors affecting slump test results

It is clear that from Figure 4.8, that factor D (rubber type) has the most significant effect on rubberized concrete slump. Also, from Table 4.10 and Figure 4.7, Fiber 8 yields high slump test results of 43mm as compared to 27mm and 17mm for crumb rubber and Fiber 4, respectively. The same results for is also reported by Hai Huynh et al. [23]. Hai Huynh noticed a decrease in slump for fibrous rubber with the same size as Fiber 4 comparing to rubberized concrete with crumb rubber. The reduction in slump for Fiber 4 may be attributable to its large aspect ratio which prevents free flow of the mixture.

Finally, From Figure 4.8 it may be conducted that factor E (rubber surface fraction) is the least important factor of the studied parameters and factor levels that affect concrete slump.



Factor	A	B	C	D	E	Total
Factor description	(Concrete grade)	(Rubber %)	(Additives)	(Rubber Type)	(Rubber surface treatment)	
Difference	8.33	8.33	13.33	25.89	2.11	58.00
Contribution (%)	14.4%	14.4%	23.0%	44.6%	3.6%	100%

Figure 4.8 The contribution of each factor on slump test results

4.3.3. Two-Factor Interactions

Table 4.11 shows the two-factor interactions of AxB, AxC and BxC. Figure 4.9 illustrates the effect of two factor interaction at different factor levels on slump test results. From this figure, it is clear that the best slump is obtained by the combination of these factor levels; C30 concrete grade, 1.5% rubber volume fraction and without additives to rubberized concrete. Also, this figure can be used to define the optimum performance by interaction between factors levels. For example, the lowest slump is given by using C20 concrete grade, 0.5% rubber volume fraction, and 0.2% polypropylene fiber.

Table 4.12 shows the average responses of the main factors and the two factor interaction of factors A (rubber type), B (rubber volume fraction) and C (Surface treatment of rubber particles).

Table 4.11 Two-way tables for slump test results

a) AxB Interaction

A (Concrete grade)	B (Rubber %)			
	0.5%	1.5%	2.5%	Mean
C20	20.00	29.33	21.67	23.67
C25	22.67	38.33	34.33	31.78
C30	30.00	30.00	36.00	32.00
Mean	24.22	32.56	30.67	29.15

b) AxC Interaction

A (Concrete grade)	C (Additives)			
	None	Polyp 0.2%	S.F 10%	Mean
C20	28.33	16.67	26.00	23.67
C25	36.00	25.00	34.33	31.78
C30	40.00	22.67	33.33	32.00
Mean	34.78	21.44	31.22	29.15

c) BxC Interaction

B (Rubber %)	C (Additives)			
	None	Polyp 0.2%	S.F 10%	Mean
0.5%	26.00	18.33	28.33	24.22
1.5%	40.00	21.67	36.00	32.56
2.5%	38.33	24.33	29.33	30.67
Mean	34.78	21.44	31.22	29.15

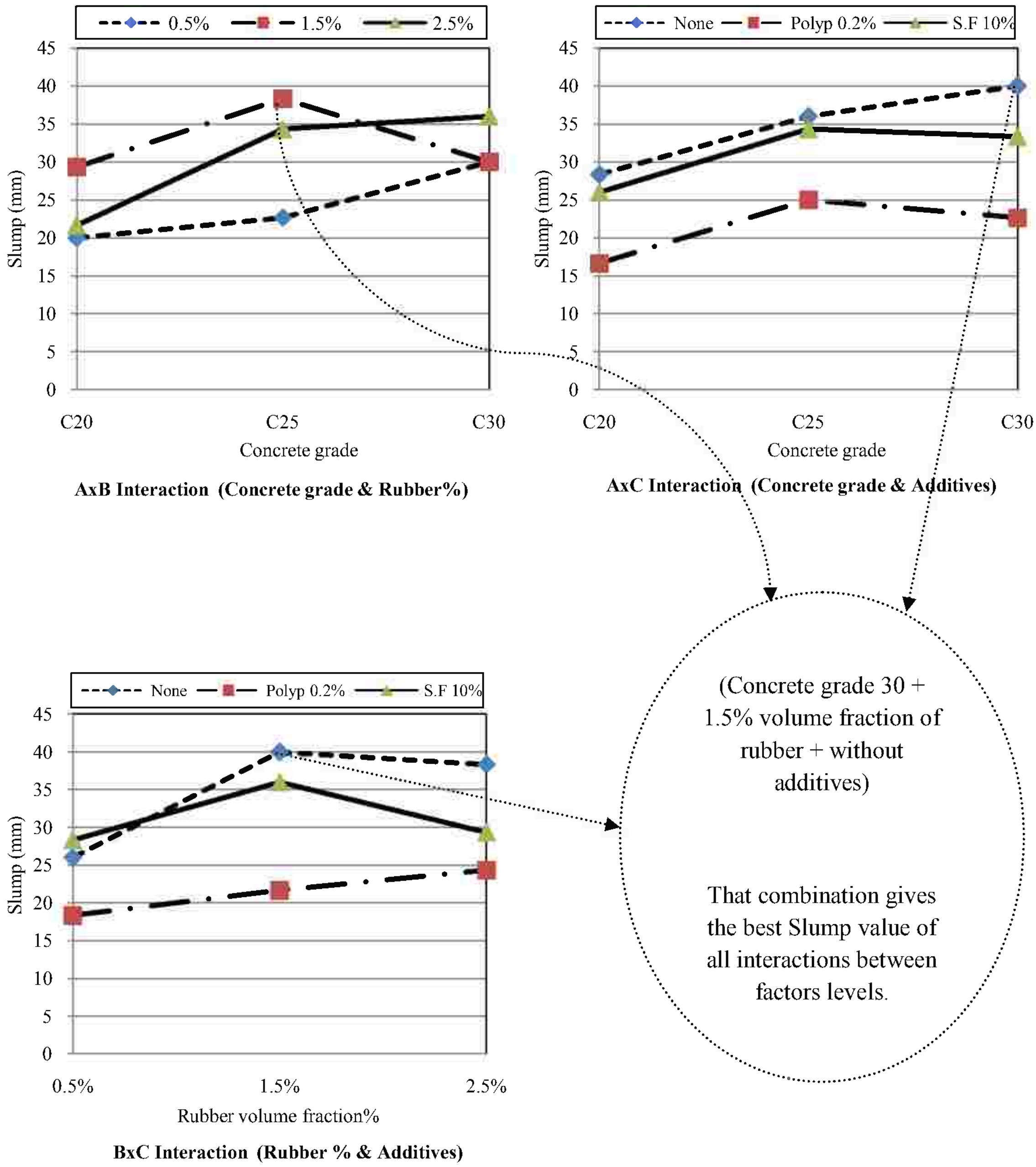


Figure (4-9) Effect of two factor interaction at different factor levels on slump test results

Table 4.12 The average responses of main factors and interactions of factors A, B and C on slump test results

Factor level	A (Concrete grade)	B (Rubber %)	C (Additives)	D (Rubber Type)	E (Rubber surface treatment)	AxB	AxC	BxC
0	23.67	24.22	34.78	26.67	28.89			
1	31.78	32.56	21.44	43.33	28.22			
2	32.00	30.67	31.22	17.44	30.33			
00						20.00	28.33	26.00
01						29.33	16.67	18.33
02						21.67	26.00	28.33
10						22.67	36.00	40.00
11						38.33	25.00	21.67
12						34.33	34.33	36.00
20						30.00	40.00	38.33
21						30.00	22.67	24.33
22						36.00	33.33	29.33

4.4. STATIC MODULUS OF ELASTICITY TEST

4.4.1. Test Results and Discussion

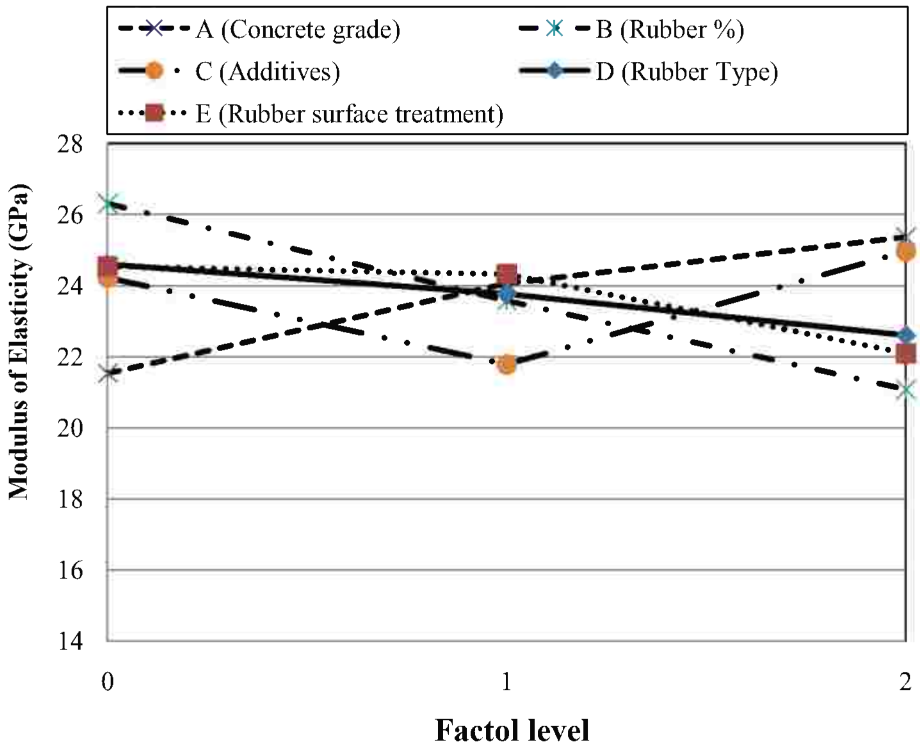
The static modulus of elasticity test was implemented for concrete after 28 days. Table 4.13 shows static modulus of elasticity test results after 28 days. From this table, almost all the rubberized concrete mixes give lower static modulus of elasticity than control mixtures, which is also found by Gideon Sirigni [11] and Topcu [3]. The rubberized concrete doesn’t experience the typical brittle failure, but rather a ductile plastic failure mode. The reason is that rubber particles behave like springs, which delay the widening of the existing cracks. The failure occurs when the bond between rubber particles and cement matrix is overcome by the applied load [3].

4.4.2. Effect of Different Factors on The Static Modulus

Fractional factorial method of experimentation was used to organize the tested variables and to analyze the results. The effect of each factor level on the static modulus of elasticity is shown in Fig8. Table 4.14 presents the average response of each factor level on the static modulus of elasticity. Also, the contribution of each factor on the static modulus of elasticity is illustrated in Figure 4.11. It can be seen from Table 4.14, Figure 4.10 and Figure 4.11that Factor B (rubber volume fraction) has the most significant effect on the static modulus of elasticity, while Factor D (rubber type) has the lowest effect on the static modulus of elasticity.

Table 4.13 Static modulus of elasticity of all concrete mixes

Mix No	Factor description					Modulus of elasticity (Gpa)
	A (Concrete grade)	B (Rubber %)	C (Additives)	D (Rubber Type)	E (Rubber surface treatment)	
1	C20	0.50%	None	Crumb 4mm	NaOH	28.30
2		1.50%	Polyp 0.2%	Crumb 4mm	PVA	16.58
3		2.50%	S.F 10%	Crumb 4mm	Without	20.14
4		0.50%	S.F 10%	Fiber 8	Without	25.91
5		1.50%	None	Fiber 8	NaOH	21.68
6		2.50%	Polyp 0.2%	Fiber 8	PVA	19.58
7		0.50%	Polyp 0.2%	Fiber 4	PVA	19.85
8		1.50%	S.F 10%	Fiber 4	Without	22.59
9		2.50%	None	Fiber 4	NaOH	19.17
10	C25	0.50%	S.F 10%	Crumb 4mm	PVA	29.29
11		1.50%	None	Crumb 4mm	Without	27.27
12		2.50%	Polyp 0.2%	Crumb 4mm	NaOH	21.25
13		0.50%	Polyp 0.2%	Fiber 8	NaOH	24.01
14		1.50%	S.F 10%	Fiber 8	PVA	22.45
15		2.50%	None	Fiber 8	Without	24.29
16		0.50%	None	Fiber 4	Without	26.02
17		1.50%	Polyp 0.2%	Fiber 4	NaOH	22.08
18		2.50%	S.F 10%	Fiber 4	PVA	19.89
19	C30	0.50%	Polyp 0.2%	Crumb 4mm	Without	27.59
20		1.50%	S.F 10%	Crumb 4mm	NaOH	30.09
21		2.50%	None	Crumb 4mm	PVA	20.89
22		0.50%	None	Fiber 8	PVA	26.14
23		1.50%	Polyp 0.2%	Fiber 8	Without	25.18
24		2.50%	S.F 10%	Fiber 8	NaOH	24.60
25		0.50%	S.F 10%	Fiber 4	NaOH	29.67
26		1.50%	None	Fiber 4	PVA	24.25
27		2.50%	Polyp 0.2%	Fiber 4	Without	19.90
					Mean	16.30
C20	C20	-	-	-	-	31.66
C25	C25	-	-	-	-	33.55
C30	C30	-	-	-	-	35.80



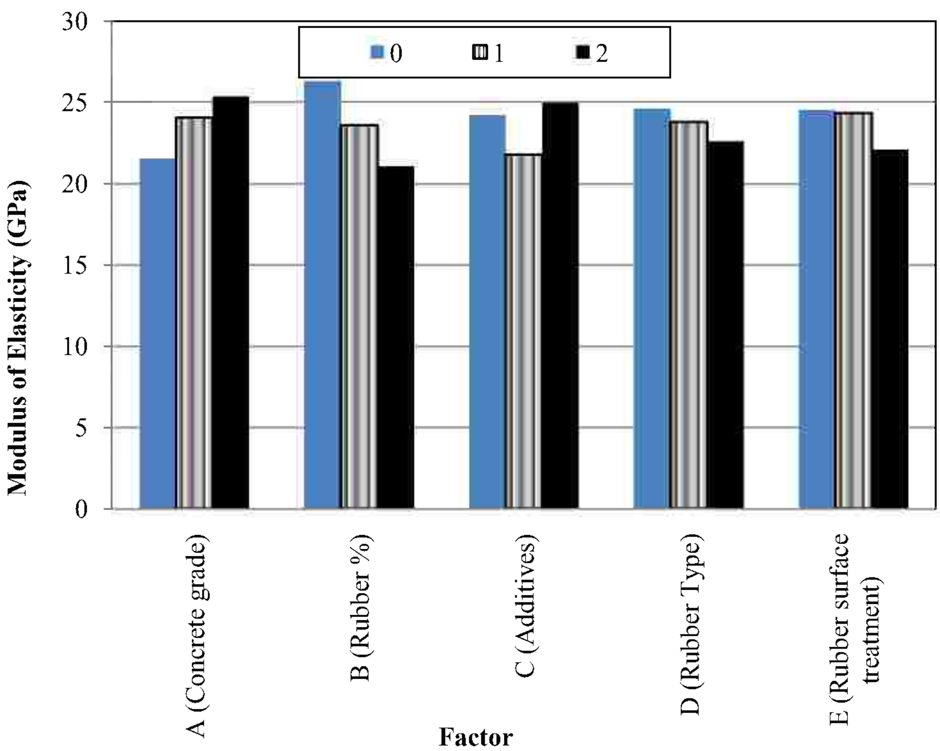


Figure 4.10 Factors affecting static modulus of elasticity test results

Table 4.14 Average response of each factor level on static modulus of elasticity

Factor	Factor level	Factor description	Modulus of elasticity (MPa)
A (Concrete grade)	0	C20	21.53
	1	C25	24.06
	2	C30	25.37
B (Rubber %)	0	0.5%	26.31
	1	1.5%	23.57
	2	2.5%	21.08
C (Additives)	0	None	24.22
	1	Polyp 0.2%	21.78
	2	S.F 10%	24.96
D (Rubber Type)	0	Crumb 4mm	24.60
	1	Fiber 8	23.76
	2	Fiber 4	22.60
E (Rubber surface treatment)	0	NaOH	24.54
	1	Without	24.32
	2	PVA	22.10

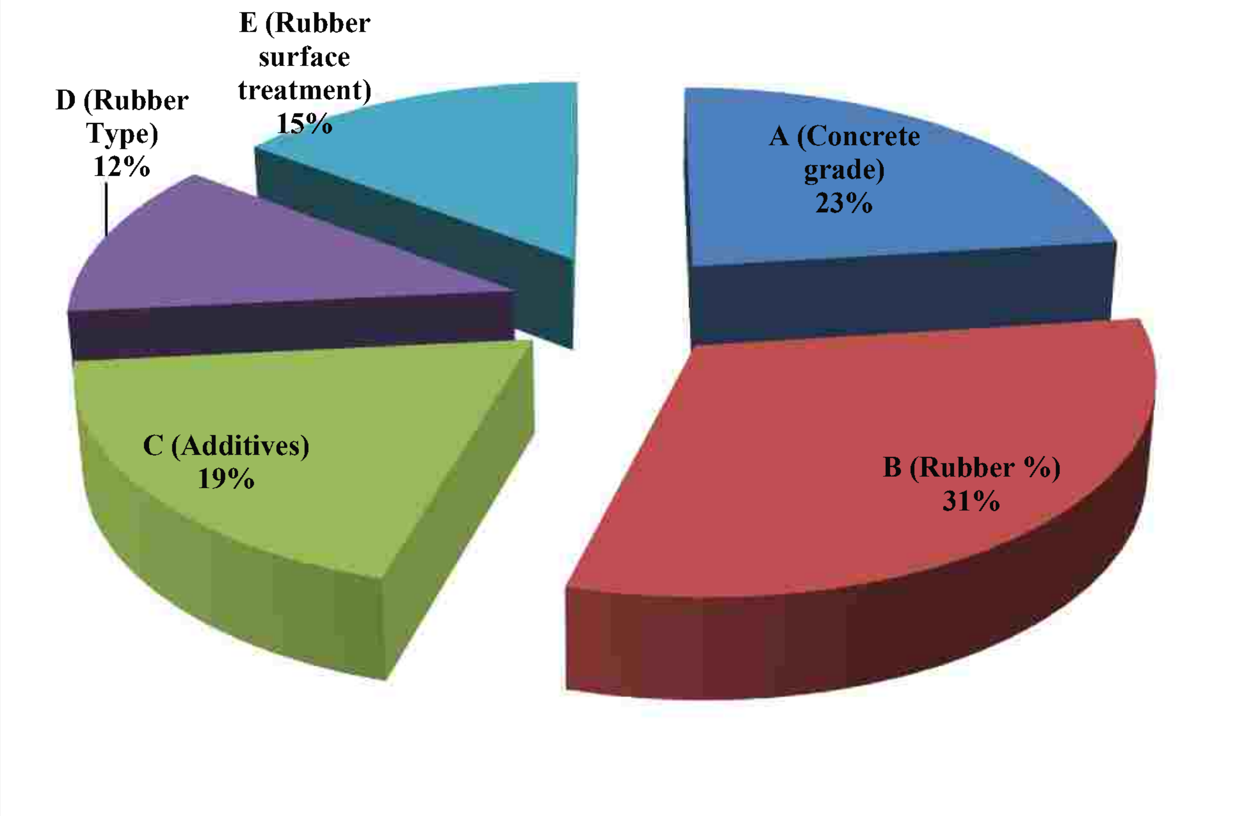
From Figure 4.11, the contribution of factor A (concrete grade) on the static elastic modulus is 23%. To study the effect of factor A (Concrete grade), it can be seen from Table 4.14 and Figure 4.10, that the elastic modulus of rubberized concrete increases gradually with the increase in concrete grade.

Also, from Figure 4.11, factor B (rubber volume fraction %) has the most significant effect on the static elastic modulus, as the contribution of factor B is 31%. As shown in Table 4.14 and Figure 4.10, the static modulus of elasticity decreases gradually from 26.31GPa to 21.08GPa with the increase in rubber content from 0.5% to 2.5%.

As for factor C (additives), the contribution on static modulus of elasticity is 19%. The addition of silica fume slightly increases the static modulus of elasticity comparing to rubberized concrete without additives. The static modulus of rubberized concrete with silica fume and rubberized concrete without additives are 24.22GPa and 24.96GPa respectively, while the addition of polypropylene fiber decreases the static modulus to 21.78GPa.

From Figure 4.11, it may be conducted that factor D (rubber type) has the least important effect of the studied parameters and factor levels on the static modulus of elasticity. The same results for the static modulus of elasticity for crumb rubber are reported by Gideon Sirigni [11] and Topcu [3].

Finally, From Figure 4.11, the contribution of factor E (rubber surface fraction) on the static elastic modulus is 15%. PVA surface treatment of rubber particles tends to lower the elastic modulus of rubberized concrete slightly. The elastic modulus of rubberized concrete with rubber treated with NaOH solution, plain rubber and PVA are 24.54Gpa, 24.32Gpa and 22.10GPa, respectively.



Factor	A	B	C	D	E	Total
Factor description	(Concrete grade)	(Rubber %)	(Additives)	(Rubber Type)	(Rubber surface treatment)	
Difference	3.83	5.23	3.18	1.99	2.44	58.00
Contribution (%)	23.0%	31.4%	19.1%	12.0%	14.6%	100%

Figure 4.11The contribution of each factor on static modulus of elasticity

4.4.3. Two-Factor Interactions

Table 4.15 shows the two-factor interactions of AxB, AxC and BxC. Figure 4.12 illustrates the effect of two factor interaction at different factor levels on the static modulus of elasticity. From this figure, it is clear that the highest value of the static modulus of elasticity is obtained by the combination of these factor levels; C30 concrete grade, 0.5% rubber volume fraction and silica fume as 10% cement replacement by weight. Also, this figure can be used to define the optimum performance by interaction between factors levels. For example, the lowest value of the static modulus of elasticity is given by using C20 concrete grade, 2.5% rubber volume fraction, and 0.2% polypropylene fiber.

Table 4.16 shows the average responses of the main factors and the two factor interaction of factors A (rubber type), B (rubber volume fraction) and C (Surface treatment of rubber particles).

Table 4.15 Two-way tables for static modulus of elasticity

a) AxB Interaction

A (Concrete grade)	B (Rubber %)			
	0.5%	**1.5%**	**2.5%**	**Mean**
C20	24.69	20.28	19.63	21.53
C25	26.44	23.93	21.81	24.06
C30	27.80	26.51	21.80	25.37
Mean	26.31	23.57	21.08	23.65

b) AxC Interaction

A (Concrete grade)	C (Additives)			
	None	**Polyp 0.2%**	**S.F 10%**	**Mean**
C20	23.05	18.67	22.88	21.53
C25	25.86	22.44	23.88	24.06
C30	23.76	24.22	28.12	25.37
Mean	24.22	21.78	24.96	23.65

c) BxC Interaction

B (Rubber %)	C (Additives)			
	None	**Polyp 0.2%**	**S.F 10%**	**Mean**
0.5%	26.82	23.81	28.29	26.31
1.5%	24.40	21.28	25.04	23.57
2.5%	21.45	20.24	21.54	21.08
Mean	24.22	21.78	24.96	23.65

4.4.4. Prediction of The Elastic Modulus Using Classical Method of Analysis

Classical method of analysis was used to expect all the 243 responses for any treatment combination, as illustrated previously. It is observed that rubberized concrete with the least elastic modulus is the treatment combination 02122, which is the combination of these factor levels; C20 concrete grade, 2.5% volume fraction, polypropylene fiber and Fiber 4 treated with PVA. The expected static modulus of elasticity of this mix is 15.20 GPa with 52% reduction comparing to control mix with same concrete grade.

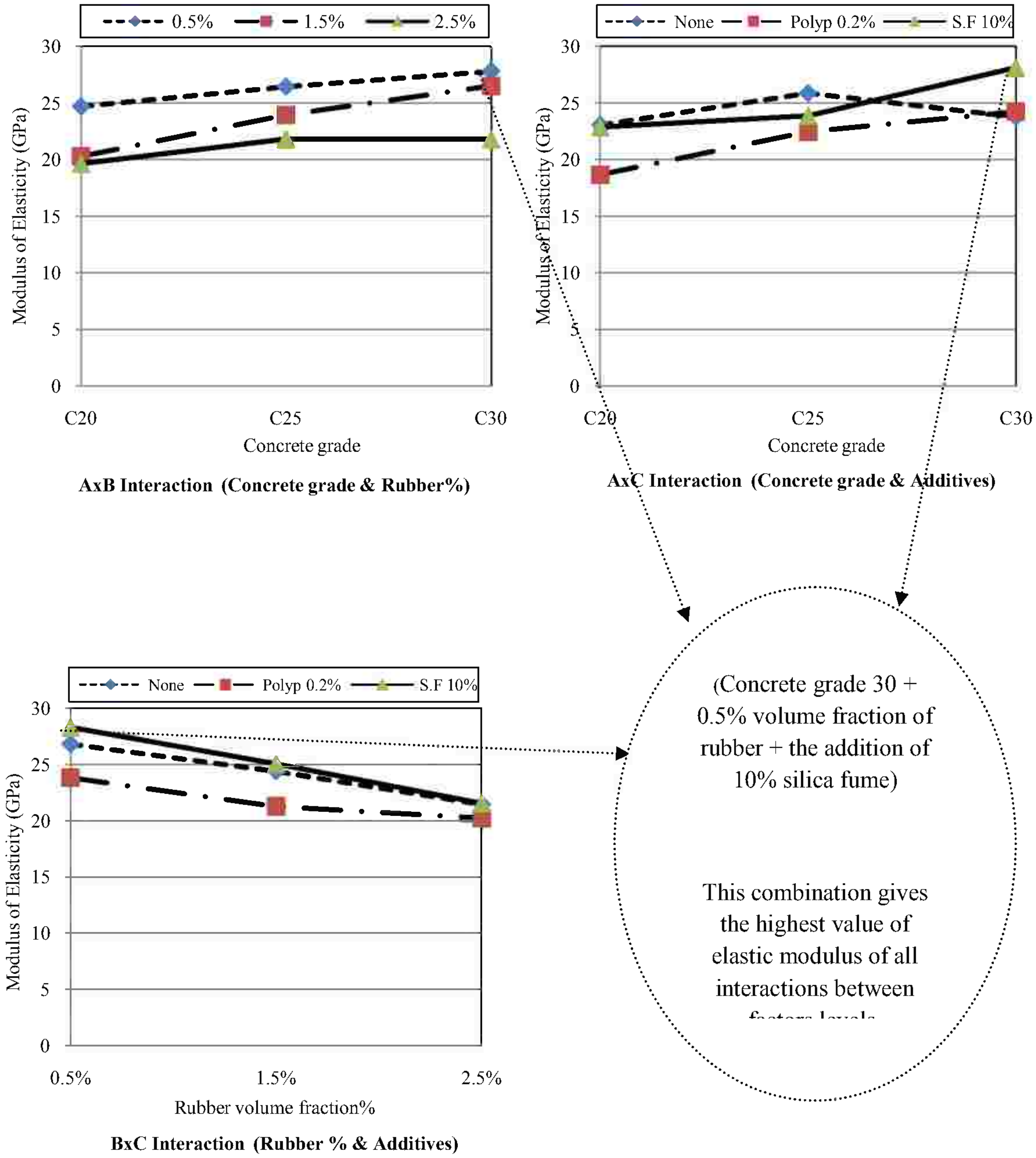


Figure 4.12 Effect of two factor interaction at different factor levels on static modulus of elasticity

Table 4.16 The average responses of main factors and interactions of factors A, B and C on static modulus of elasticity

Factor level	A (Concrete grade)	B (Rubber %)	C (Additives)	D (Rubber Type)	E (Rubber surface treatment)	AxB	AxC	BxC
0	21.53	26.31	24.22	24.60	24.54			
1	24.06	23.57	21.78	23.76	24.32			
2	25.37	21.08	24.96	22.60	22.10			
00						24.69	23.05	26.82
01						20.28	18.67	23.81
02						19.63	22.88	28.29
10						26.44	25.86	24.40
11						23.93	22.44	21.28
12						21.81	23.88	25.04
20						27.80	23.76	21.45
21						26.51	24.22	20.24
22						21.80	28.12	21.54

4.5. IMPACT RESISTANCE

4.5.1. Test Results and Discussion

The drop weight test was implemented for conventional and rubberized concrete mixes after 28 days. Table 4.17 presents the number of blows to first crack and failure based on the drop weight test. From this table, it is noticed that some mixes exhibits high impact resistance comparing to control mixtures. The impact resistance of rubberized concrete with fibrous rubber seems to be suitable for applications where high impact resistance is required. The no of blows till failure for control mixtures are 66, 75 and 90 for concrete grades C20, C25 and C30 respectively, while the number of blows till failure for rubberized concrete (mix number27) is 204.

4.5.2. Effect of Different Factors on Impact Resistance

Fractional factorial method of experimentation was used to organize the tested variables and to analyze the results. The effect of each factor level on first crack and failure impact resistance is shown in Figures 4.13 and 4.14. Table 4.18 presents the average response of each factor level on first crack and failure impact resistance. Also, the contribution of each factor on first crack and failure impact resistance 28 days is illustrated in Figures 4.15 and 4.16. It can be seen from Table 4.18 and Figures 4.15 and 4.16 that Factor D (rubber type) has the most significant effect on first crack and failure impact resistance, while Factor E (rubber surface treatment) has the lowest effect on impact resistance.

Table 4.17 Drop weight test results of all concrete mixes

Mix Number	Factor description					Impact resistance (No. of blows)	
	A (Concrete grade)	B (Rubber %)	C (Additives)	D (Rubber Type)	E (Rubber surface treatment)	First crack	Failure
1	C20	0.50%	None	Crumb 4mm	NaOH	54	78
2		1.50%	Polyp 0.2%	Crumb 4mm	PVA	66	120
3		2.50%	S.F 10%	Crumb 4mm	Without	54	81
4		0.50%	S.F 10%	Fiber 8	Without	48	66
5		1.50%	None	Fiber 8	NaOH	42	57
6		2.50%	Polyp 0.2%	Fiber 8	PVA	60	90
7		0.50%	Polyp 0.2%	Fiber 4	PVA	96	120
8		1.50%	S.F 10%	Fiber 4	Without	68	120
9		2.50%	None	Fiber 4	NaOH	75	126
10	C25	0.50%	S.F 10%	Crumb 4mm	PVA	54	108
11		1.50%	None	Crumb 4mm	Without	54	96
12		2.50%	Polyp 0.2%	Crumb 4mm	NaOH	66	98
13		0.50%	Polyp 0.2%	Fiber 8	NaOH	69	105
14		1.50%	S.F 10%	Fiber 8	PVA	60	96
15		2.50%	None	Fiber 8	Without	57	117
16		0.50%	None	Fiber 4	Without	60	114
17		1.50%	Polyp 0.2%	Fiber 4	NaOH	90	165
18		2.50%	S.F 10%	Fiber 4	PVA	120	150
19	C30	0.50%	Polyp 0.2%	Crumb 4mm	Without	76	105
20		1.50%	S.F 10%	Crumb 4mm	NaOH	54	84
21		2.50%	None	Crumb 4mm	PVA	66	114
22		0.50%	None	Fiber 8	PVA	60	108
23		1.50%	Polyp 0.2%	Fiber 8	Without	66	126
24		2.50%	S.F 10%	Fiber 8	NaOH	84	120
25		0.50%	S.F 10%	Fiber 4	NaOH	144	168
26		1.50%	None	Fiber 4	PVA	120	150
27		2.50%	Polyp 0.2%	Fiber 4	Without	150	204
					Mean	75	114
C20	C20	-	-	-	-	54	66
C25	C25	-	-	-	-	60	75
C30	C30	-	-	-	-	66	90

Table 4.18 average response of each factor level on impact resistance

Factor	Factor level	Factor description	Impact resistance (Number of blows)	
			First crack	first crack
A (Concrete grade)	0 1 2	C20 C25 C30	63 70 91	95 117 131
B (Rubber %)	0 1 2	0.5% 1.5% 2.5%	73 69 81	108 113 122
C (Additives)	0 1 2	None Polyp 0.2% S.F 10%	65 82 76	107 126 110
D (Rubber Type)	0 1 2	Crumb 4mm Fiber 8 Fiber 4	60 61 103	98 98 146
E (Rubber surface treatment)	0 1 2	NaOH Without PVA	75 70 78	111 114 117

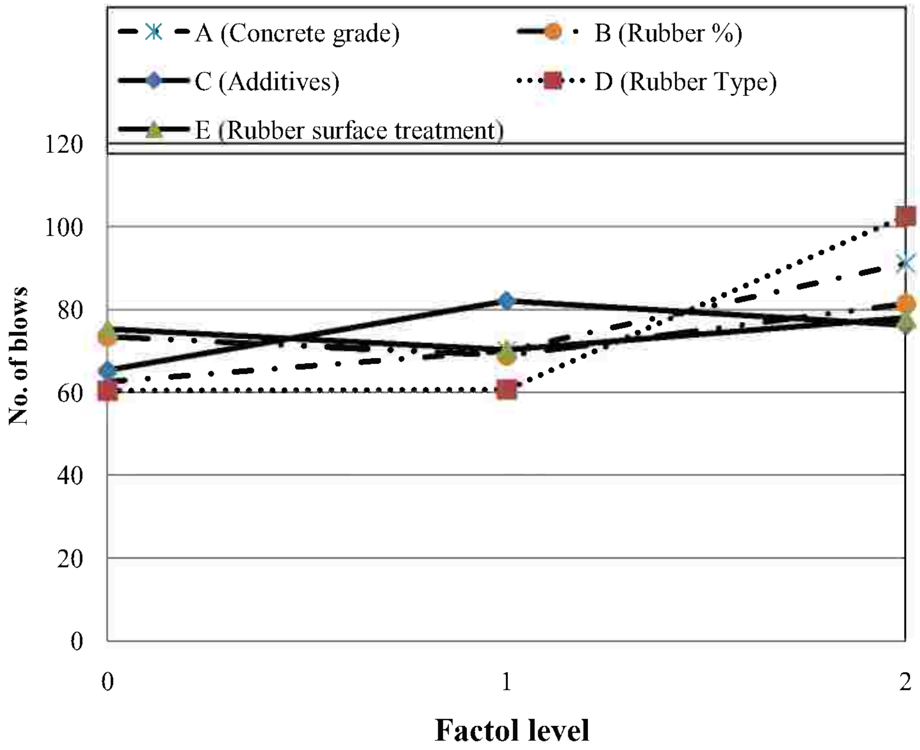
From Figure 4.15 and Figure 4.16, the contribution of factor A (concrete grade) on first crack and failure impact resistance is 26% and 29% respectively. To study the effect of factor A (Concrete grade), it can be seen from Table 4.18 and Figure 4.14, that the number of blows till failure of rubberized concrete grades C20, C25 and C30 are 95, 117 and 131, respectively. The number of blows for conventional concrete grades C20, C25 and C30 are 66, 75 and 90, respectively. Thus, it can be conducted that rubberized concrete maintain higher impact resistance than conventional concrete.

Also, factor B (rubber volume fraction %) has a contribution of 12% on impact resistance. As shown in Table 4.18 and Figure 4.13 and Figure 4.14, the number of blows till first crack and failure increases gradually with the increase in rubber content.

As for factor C (additives), the contribution on concrete impact resistance is 16%. The addition of silica fume improved the impact resistance till first crack but has slight effect on impact resistance till failure comparing to rubberized concrete without additives. On the other hand, the polypropylene fiber improves the impact resistance till failure, as the fibers maintain the cracks from widening under impact load.

It is clear that from Figures 4.15 and 4.16, that factor D (rubber type) has the most significant effect on rubberized concrete impact resistance. Also, from Table 4.18 and Figures 4.13 and 4.14, the number of blows till failure for rubberized concrete with crumb rubber, Fiber 8 and Fiber4 are 98, 98 and 146, respectively. Thus, Fiber 4 has the most significant effect in increasing the impact resistance of rubberized concrete. This behavior may be attributed to the higher aspect ratio of Fiber 4.

Finally, From Figures 4.15 and 4.16, it may be conducted that factor E (rubber surface fraction) is the least important factor of the studied parameters and factor levels that affect rubberized concrete impact resistance.



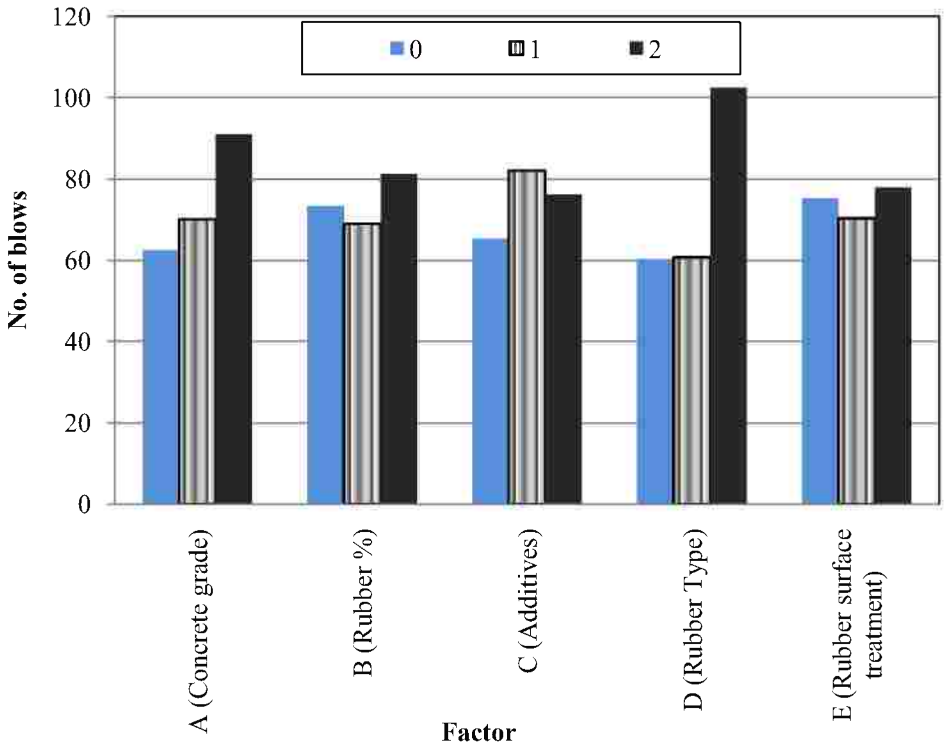


Figure 4.13 Factors affecting first crack impact resistance

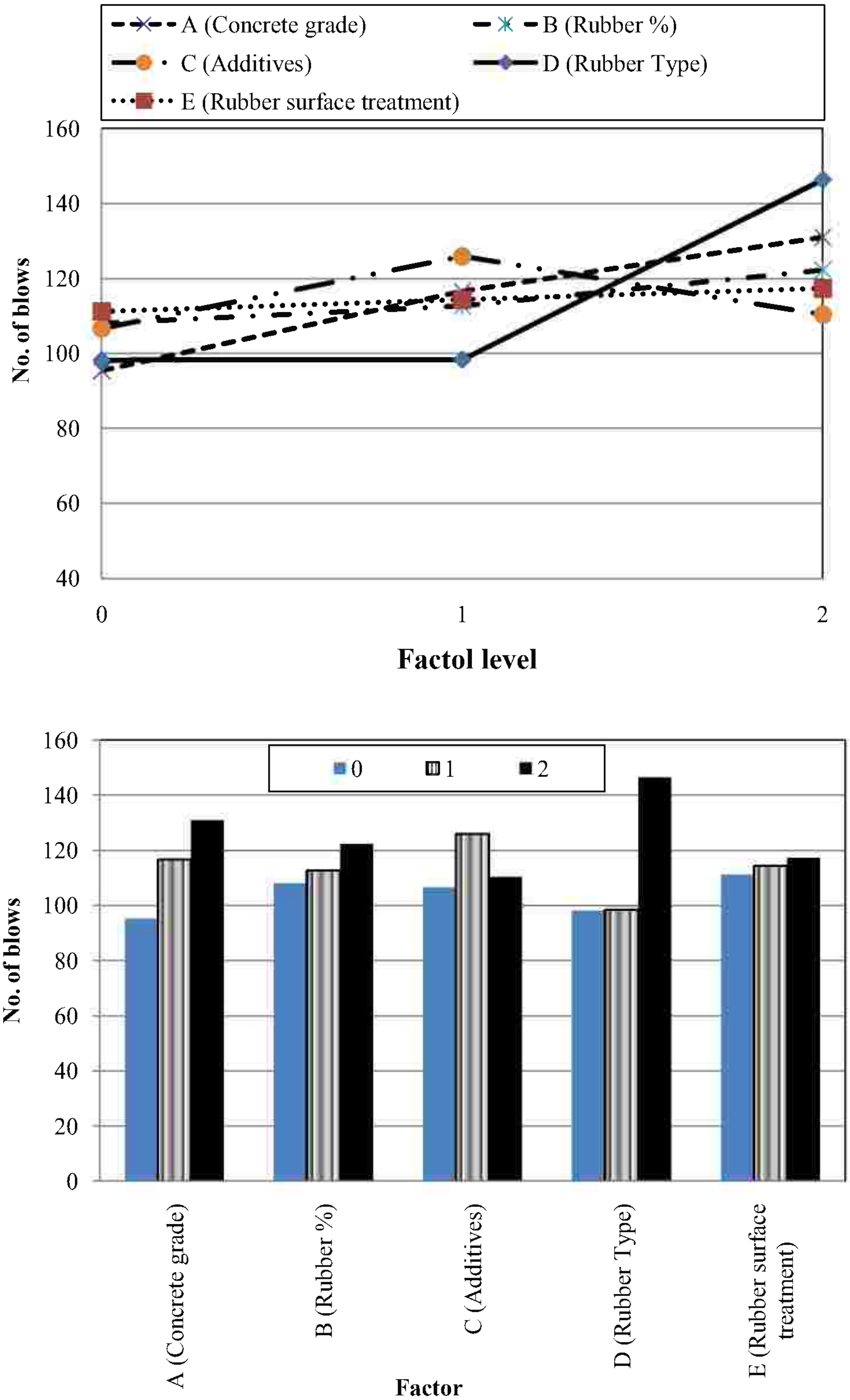
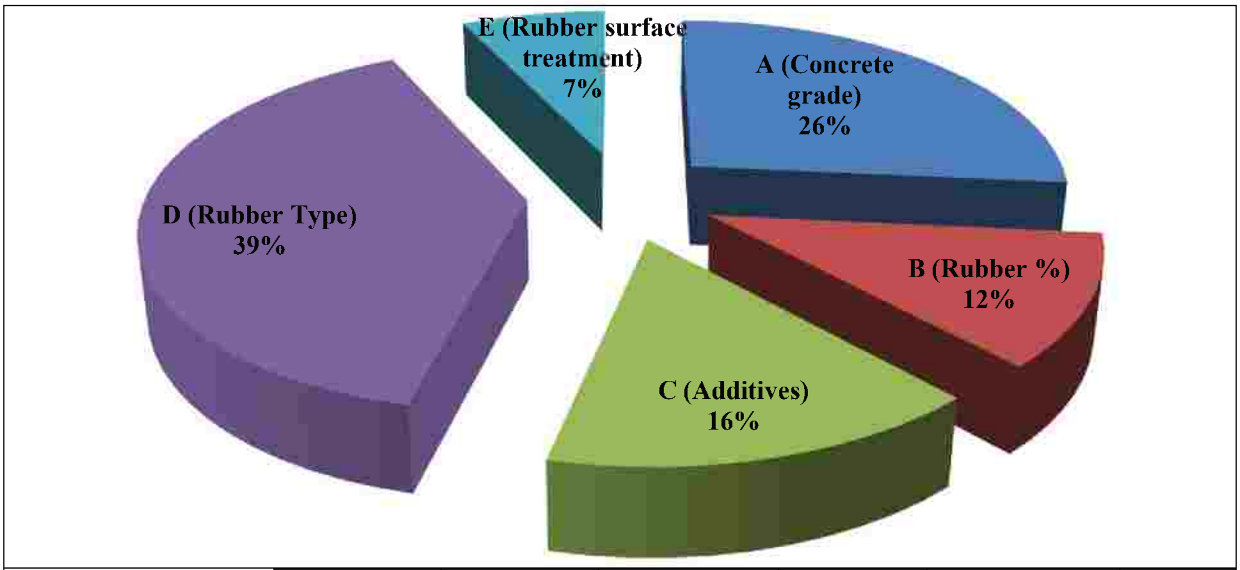
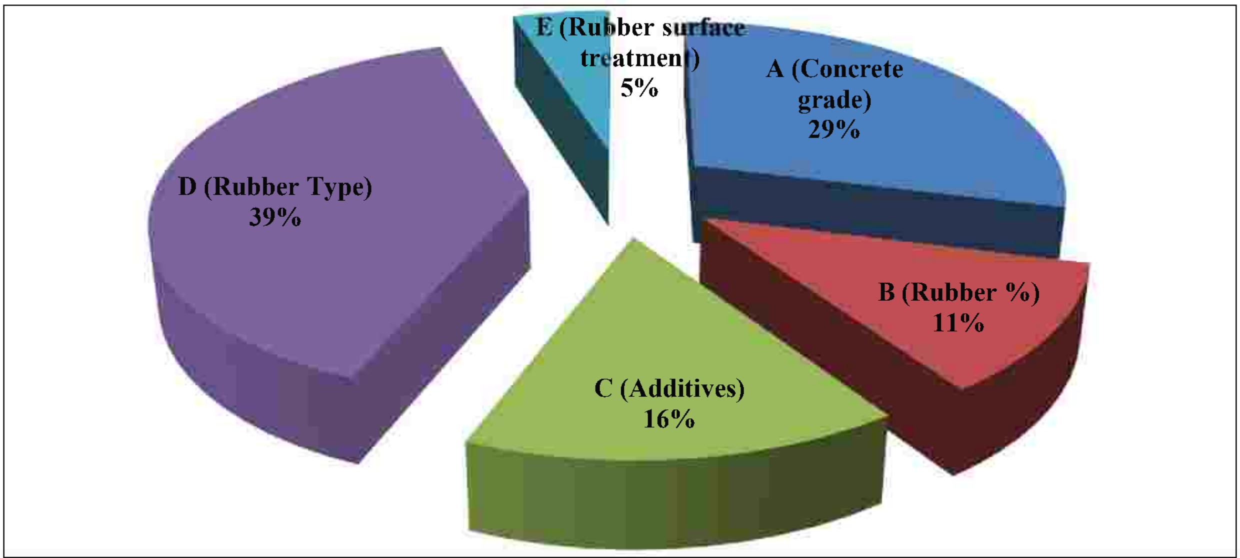


Figure 4.14 Factors affecting failure impact resistance



Factor	A	B	C	D	E	Total
Factor description	(Concrete grade)	(Rubber %)	(Additives)	(Rubber Type)	(Rubber surface treatment)	
Difference	28.51	12.44	16.73	42.16	7.71	107.56
Contribution (%)	26.5%	11.6%	15.6%	39.2%	7.2%	100%

Figure 4.15 The contribution of each factor on first crack impact resistance



Factor	A	B	C	D	E	Total
Factor description	(Concrete grade)	(Rubber %)	(Additives)	(Rubber Type)	(Rubber surface treatment)	
Difference	35.67	14.22	19.22	48.11	6.11	123.33
Contribution (%)	28.9%	11.4%	15.6%	39.1%	5.0%	100%

Figure 4.16 The contribution of each factor on failure impact resistance

4.5.3. Two-factor interactions

Tables 4.19 and 4.20 show the two-factor interactions of AxB, AxC and BxC for first crack and failure impact resistance. Figure 4.17 and Figure 4.18 illustrate the effect of two factor interaction at different factor levels on impact resistance till first crack and failure respectively. From these figures, it is clear that the best impact resistance is obtained by the combination of these factor levels; C30 concrete grade, 2.5% rubber volume fraction and 0.2% polypropylene fiber as an additive to rubberized concrete.

Tables 4.21 and 4.22 show the average responses of the main factors and the two factor interaction of factors A (rubber type), B (rubber volume fraction) and C (Surface treatment of rubber particles) for first crack and failure impact resistance.

Table 4.19 Two-way tables for first crack impact resistance

a) AxB Interaction

A (Concrete grade)	**B (Rubber %)**			
	0.5%	**1.5%**	**2.5%**	**Mean**
C20	66.00	58.67	63.00	62.56
C25	61.00	68.00	81.00	70.00
C30	93.20	80.00	100.00	91.07
Mean	73.40	68.89	81.33	74.54

b) AxC Interaction

A (Concrete grade)	**C (Additives)**			
	None	Polyp 0.2%	S.F 10%	Mean
C20	57.00	74.00	56.67	62.56
C25	57.00	75.00	78.00	70.00
C30	82.00	97.20	94.00	91.07
Mean	65.33	82.07	76.22	74.54

c) BxC Interaction

B (Rubber %)	**C (Additives)**			
	None	Polyp 0.2%	S.F 10%	Mean
0.5%	58.00	80.20	82.00	73.40
1.5%	72.00	74.00	60.67	68.89
2.5%	66.00	92.00	86.00	81.33
Mean	65.33	82.07	76.22	74.54

Table 4.20 Two-way tables for failure impact resistance

a) AxB Interaction

A (Concrete grade)	B (Rubber %)			
	0.5%	1.5%	2.5%	Mean
C20	88.00	99.00	99.00	95.33
C25	109.00	119.00	121.67	116.56
C30	127.00	120.00	146.00	131.00
Mean	108.00	112.67	122.22	114.30

b) AxC Interaction

A (Concrete grade)	C (Additives)			
	None	Polyp 0.2%	S.F 10%	Mean
C20	87.00	110.00	89.00	95.33
C25	109.00	122.67	118.00	116.56
C30	124.00	145.00	124.00	131.00
Mean	106.67	125.89	110.33	114.30

c) BxC Interaction

B (Rubber %)	C (Additives)			
	None	Polyp 0.2%	S.F 10%	Mean
0.5%	100.00	110.00	114.00	108.00
1.5%	101.00	137.00	100.00	112.67
2.5%	119.00	130.67	117.00	122.22
Mean	106.67	125.89	110.33	114.30

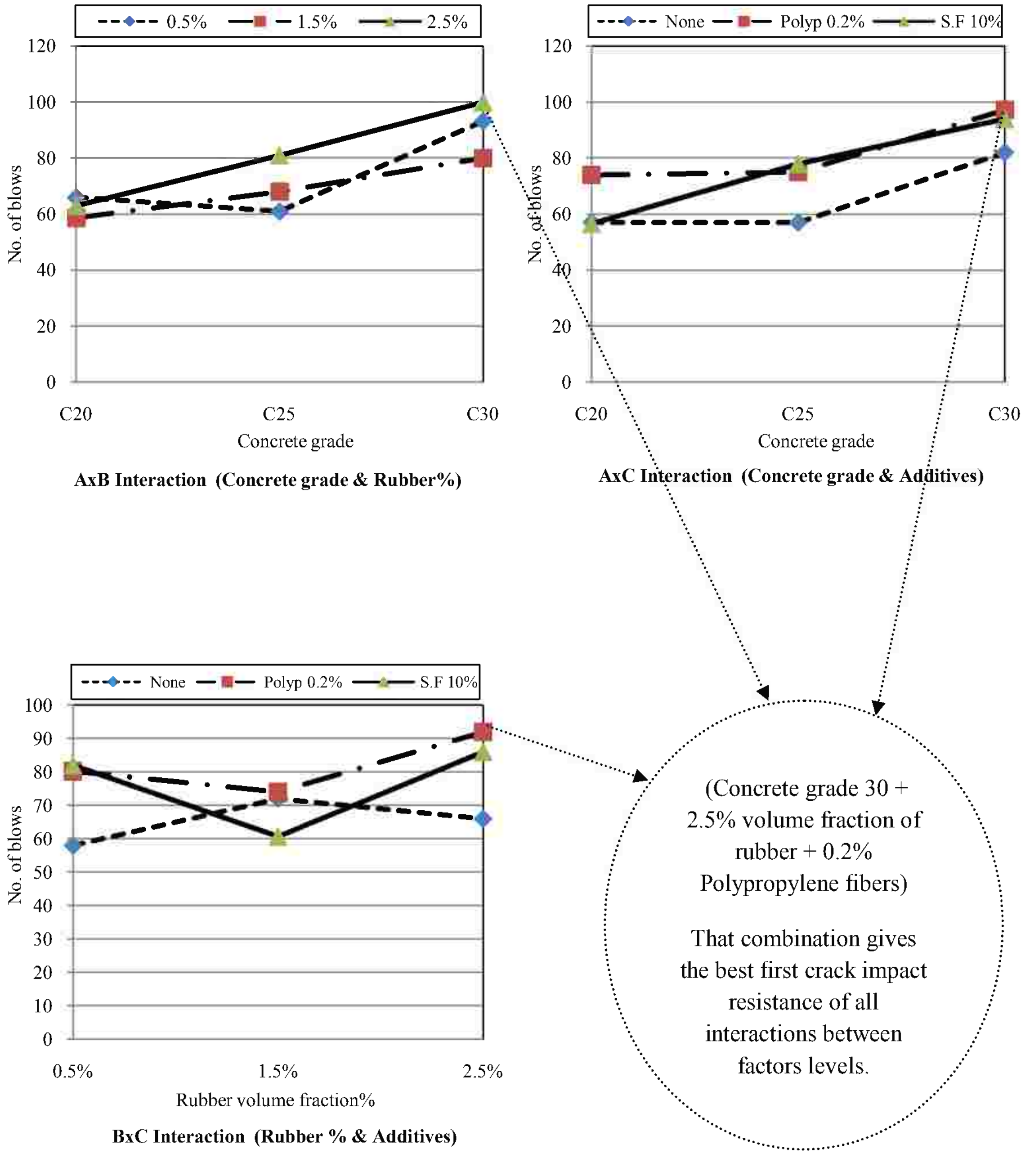


Figure 4.17 Effect of two factor interaction at different factor levels on first crack impact resistance

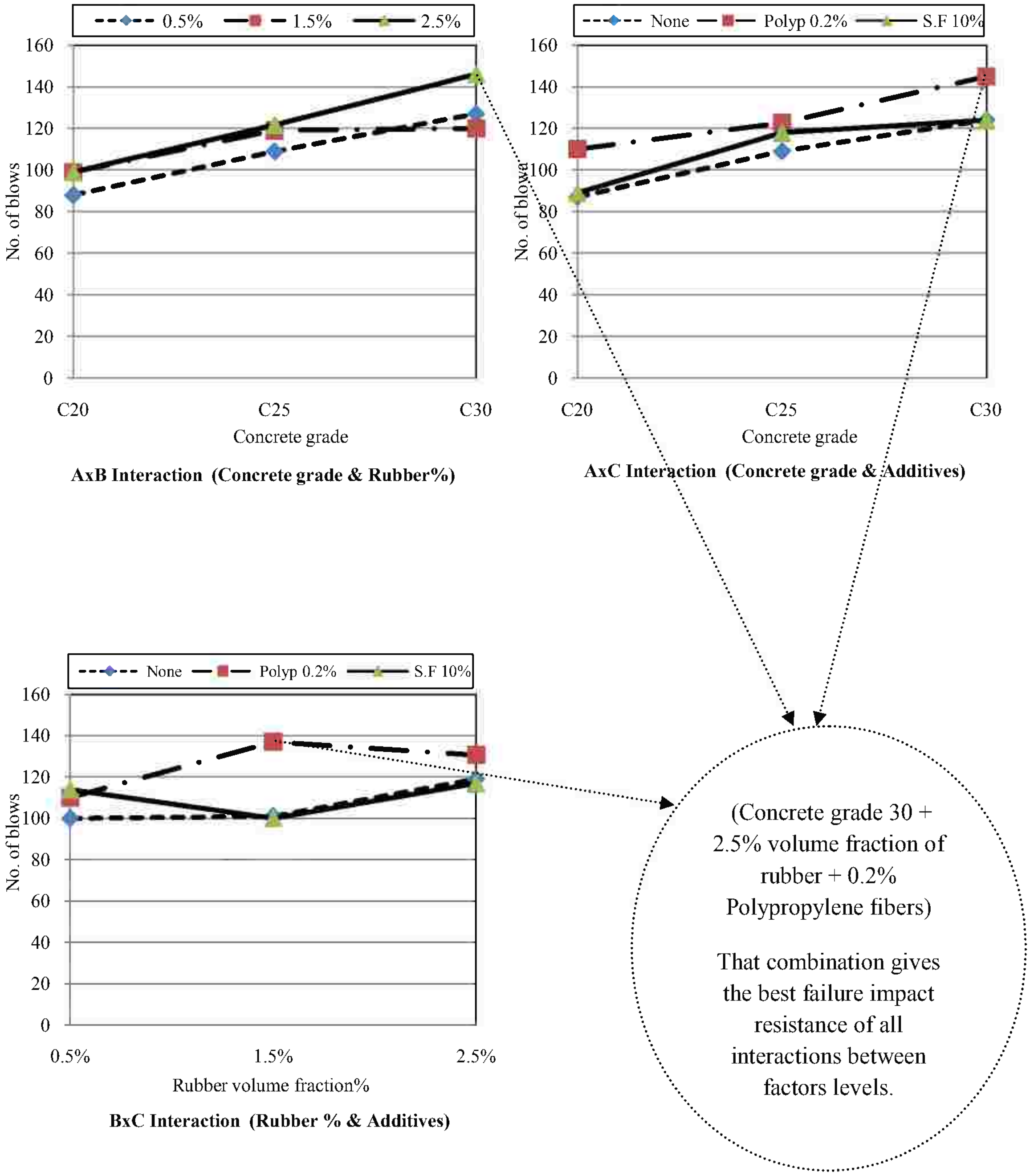


Figure 4.18 Effect of two factor interaction at different factor levels on failure impact resistance

Table 4.21 The average responses of main factors and interactions of factors A, B and C on first crack impact resistance

Factor level	A (Concrete grade)	B (Rubber %)	C (Additives)	D (Rubber Type)	E (Rubber surface treatment)	AxB	AxC	BxC
0	63	73	65	60	75			
1	70	69	82	61	70			
2	91	81	76	103	78			
00						66	57	58
01						59	74	80
02						63	57	82
10						61	57	72
11						68	75	74
12						81	78	61
20						93	82	66
21						80	97	92
22						100	94	86

Table 4.22 The average responses of main factors and interactions of factors A, B and C on failure impact resistance

Factor level	A (Concrete grade)	B (Rubber %)	C (Additives)	D (Rubber Type)	E (Rubber surface treatment)	AxB	AxC	BxC
0	95	108	107	98	111			
1	117	113	126	98	114			
2	131	122	110	146	117			
00						88	87	100
01						99	110	110
02						99	89	114
10						109	109	101
11						119	123	137
12						122	118	100
20						127	124	119
21						120	145	131
22						146	124	117

4.6. FLEXURAL TOUGHNESS

4.6.1. Test Results and Discussion

Flexural toughness is a measure of the energy absorption capacity. Table 4.23 presents the results of flexural strength and toughness test for the 27 mixes of rubberized concrete and the 3 control mixes. From this table, it can be seen that the flexural strength of rubberized concrete is quite similar to that of control mixes. On the other hand, rubberized concrete gives better results than conventional concrete in term of flexural toughness. Topcu [3] reported that, rubberized concrete shows high capacity of absorbing plastic energy, as the failed specimens withstand measurable post-failure loads and undergo significant displacement. Thus, the concrete mass has able to withstand loads even when it is highly cracked. Also, Gideon Momanyi Siringi [11] reported an increase in toughness of rubberized concrete comparing to conventional concrete.

4.6.2. Effect of Different Factors on Flexural Strength and Toughness

Fractional factorial method of experimentation was considered to organize the tested variables and to analysis the test results. The effect of each factor level on flexural strength and toughness is shown in Figure 4.19 and Figure 4.20. Table 4.24 shows the average response of each factor level on flexural strength and toughness. The average responses are calculated as the average flexural strength or toughness of the 9 mixes with the same factor level

The contribution of each factor on flexural strength and toughness is illustrated in Figure 4.21 and Figure 4.22. It can be seen from Figure 4.21, that Factor A (concrete grade) is the main effect of the studied parameters, while the other factors has a little effect on flexural strength. For flexural toughness, all the studied parameters have significant effect, except for Factor E (rubber surface treatment). Thus, analysis of the results focuses on flexural toughness rather than flexural strength.

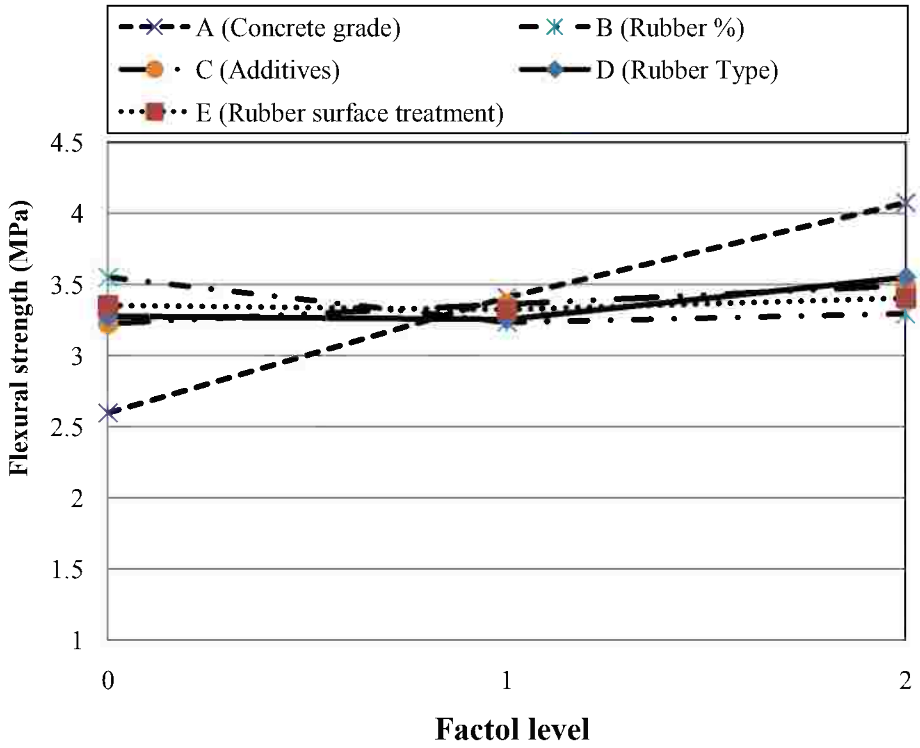
From Figure 4.22, the contribution of factor A (concrete grade) on flexural toughness is 33%, so it is considered the most important factor of all the studied parameters. To study the effect of factor A (Concrete grade), it can be seen from Table 4.24 and Figure 4.20 that flexural increases gradually with the increase in concrete grade.

Also, factor B (rubber volume fraction %) has significant effect on flexural toughness. From Figure 4.22, the contribution of factor B is 15%. As shown in Table 4.24 and Figure 4.20, the flexural toughness increases with the increase in rubber content. The flexural toughness of rubberized concrete with rubber content 0.5%, 1.5% and 2.5% are 6.62, 6.71 and 7.95 KN.mm, respectively.

As for factor C (additives), the contribution on flexural strength is 15%. The flexural toughness of rubberized concrete without additives, with addition of polypropylene fiber and silica fume are 7.07, 7.76 and 6.45 KN.mm, respectively. The addition of the polypropylene fiber improves the flexural toughness comparing to rubber concrete with no additives and silica fume.

Table 4.23 Flexural strength and Toughness of all concrete mixes

Mix No	Factor description					Flexural strength (MPa)	Toughness T_{150} (KN.mm)
	A (Concrete grade)	B (Rubber %)	C (Additives)	D (Rubber Type)	E (Rubber surface treatment)		
1	C20	0.50%	None	Crumb 4mm	NaOH	3.03	5.67
2		1.50%	Polyp 0.2%	Crumb 4mm	PVA	3.06	5.71
3		2.50%	S.F 10%	Crumb 4mm	Without	2.78	5.00
4		0.50%	S.F 10%	Fiber 8	Without	2.68	4.43
5		1.50%	None	Fiber 8	NaOH	1.78	4.25
6		2.50%	Polyp 0.2%	Fiber 8	PVA	2.58	6.00
7		0.50%	Polyp 0.2%	Fiber 4	PVA	2.48	5.75
8		1.50%	S.F 10%	Fiber 4	Without	1.88	3.54
9		2.50%	None	Fiber 4	NaOH	3.11	9.23
10	C25	0.50%	S.F 10%	Crumb 4mm	PVA	3.66	4.27
11		1.50%	None	Crumb 4mm	Without	2.74	5.35
12		2.50%	Polyp 0.2%	Crumb 4mm	NaOH	2.68	6.31
13		0.50%	Polyp 0.2%	Fiber 8	NaOH	3.11	6.29
14		1.50%	S.F 10%	Fiber 8	PVA	3.92	9.75
15		2.50%	None	Fiber 8	Without	3.00	9.68
16		0.50%	None	Fiber 4	Without	4.16	7.44
17		1.50%	Polyp 0.2%	Fiber 4	NaOH	3.68	9.23
18		2.50%	S.F 10%	Fiber 4	PVA	3.74	8.00
19	C30	0.50%	Polyp 0.2%	Crumb 4mm	Without	4.20	8.09
20		1.50%	S.F 10%	Crumb 4mm	NaOH	3.86	4.36
21		2.50%	None	Crumb 4mm	PVA	3.48	6.00
22		0.50%	None	Fiber 8	PVA	3.83	7.50
23		1.50%	Polyp 0.2%	Fiber 8	Without	4.29	9.68
24		2.50%	S.F 10%	Fiber 8	NaOH	4.10	8.55
25		0.50%	S.F 10%	Fiber 4	NaOH	4.83	10.11
26		1.50%	None	Fiber 4	PVA	3.91	8.50
27		2.50%	Polyp 0.2%	Fiber 4	Without	4.19	12.75
					Mean	3.36	7.09
C20	C20	-	-	-	-	2.81	2.34
C25	C25	-	-	-	-	3.75	3.13
C30	C30	-	-	-	-	4.50	3.75



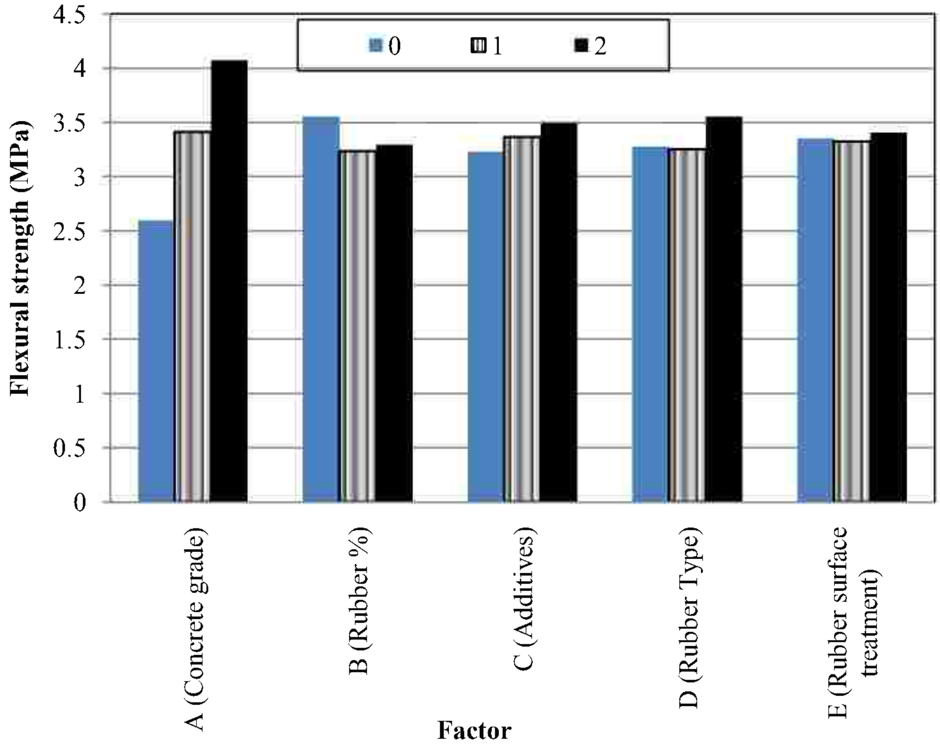
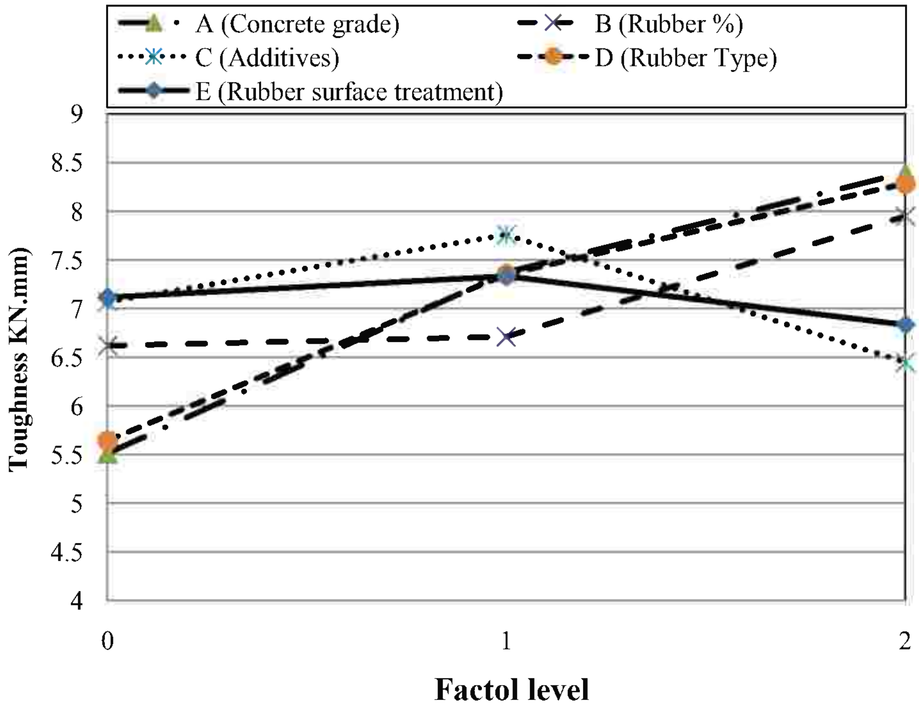


Figure 4.19 Factors affecting Flexural strength



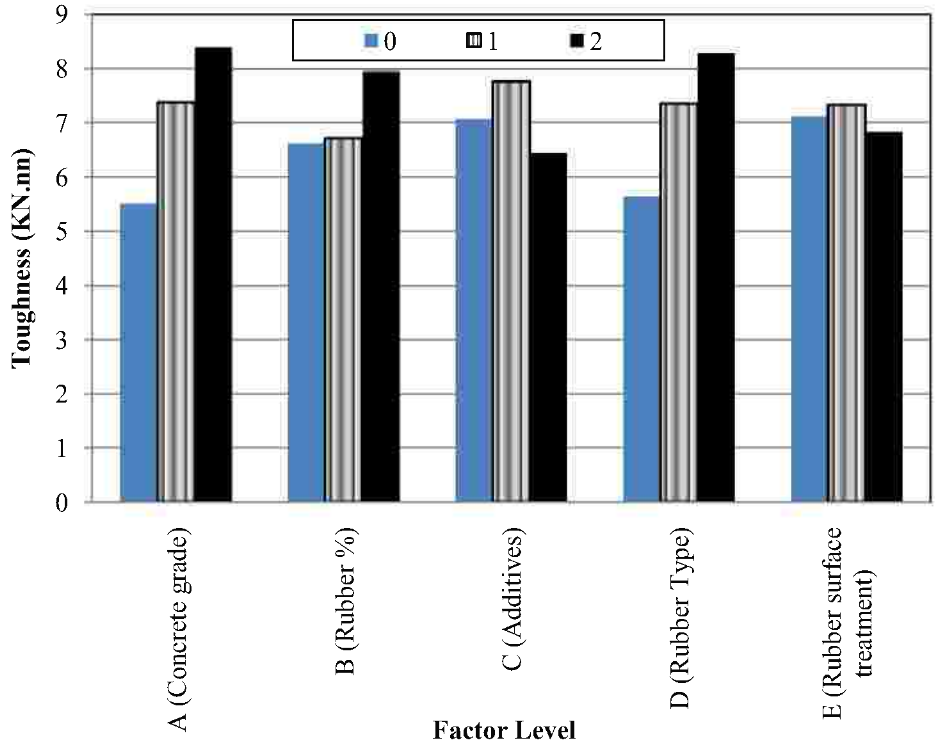


Figure 4.20 Factors affecting Flexural toughness

Table 4.24 Average response of each factor level on Flexural strength and toughness

Factor	Factor level	Factor description	Flexural strength (MPa)	Toughness T_{150} (KN.mm)
A (Concrete grade)	0 1 2	C20 C25 C30	2.60 3.41 4.08	5.51 7.37 8.39
B (Rubber %)	0 1 2	0.5% 1.5% 2.5%	3.55 3.23 3.30	6.62 6.71 7.95
C (Additives)	0 1 2	None Polyp 0.2% S.F 10%	3.23 3.36 3.49	7.07 7.76 6.45
D (Rubber Type)	0 1 2	Crumb 4mm Fiber 8 Fiber 4	3.28 3.25 3.55	5.64 7.35 8.28
E (Rubber surface treatment)	0 1 2	NaOH Without PVA	3.35 3.32 3.41	7.11 7.33 6.83

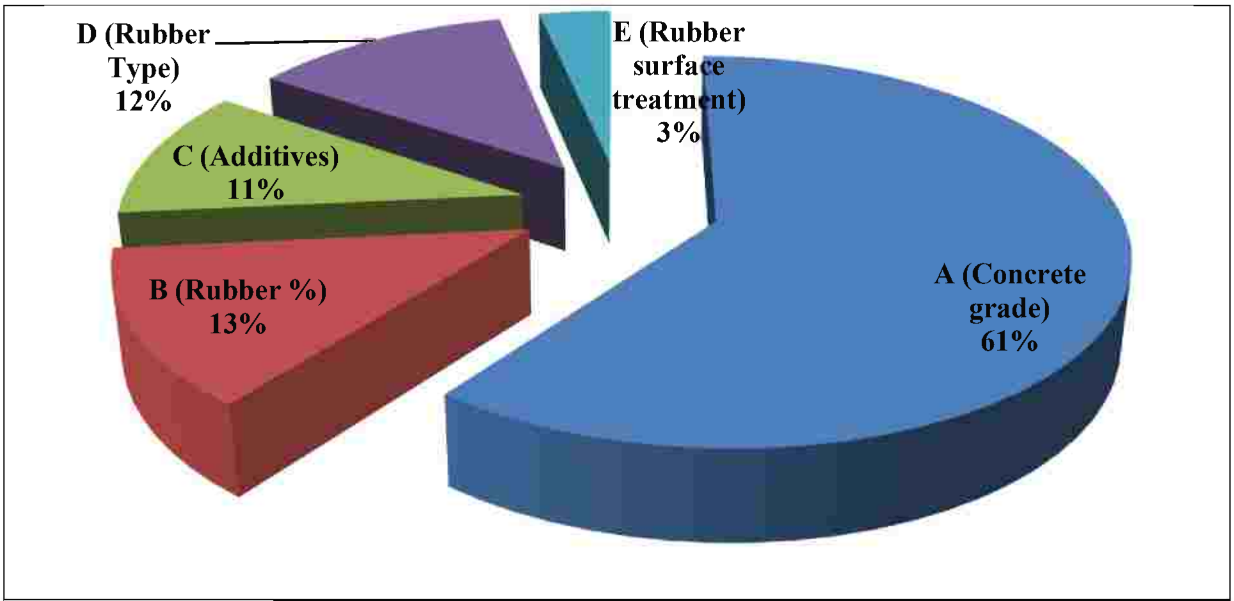
For factor D (rubber type), has significant effect on concrete flexural toughness. From Figure 4.22, the contribution of factor D is 31%. The flexural toughness of rubberized concrete with crumb rubber, Fiber 8 and Fiber 4 are 5.64, 7.35 and 8.28 KN.mm, respectively. Fiber 4 gives the best values for flexural toughness, while crumb rubber gives the lowest values. The increase in toughness of rubberized concrete with fibrous rubber may be attributed to the fact that fibers rubber holds cracks from widening.

Finally, From Figure 4.22 it may be conducted that factor D (rubber surface fraction) is the least important factor of the studied parameters and factor levels that affect flexural toughness

4.6.3. Two-Factor Interactions

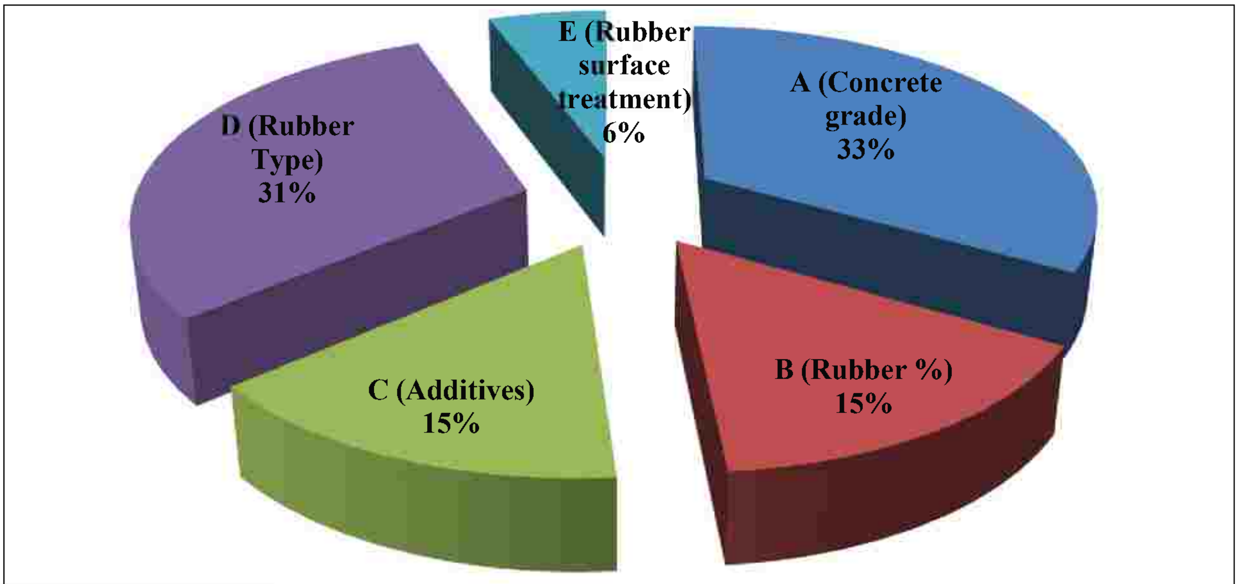
Table 4.25 and Table 4.26 show the two-factor interactions of AxB, AxC and BxC for flexural strength and toughness. Figures 4.23 and 4.24 illustrate the effect of two factor interaction at different factor levels on flexural strength and toughness. From this figures, it can be stated that, the best flexural toughness is obtained by the combination of these factor levels; C30 concrete grade, 2.5% rubber volume fraction and the addition of 0.2% polypropylene fiber. Also, this figure can be used to define the optimum performance by interaction between factors levels. For example, the lowest toughness is given by using C20 concrete grade, 1.5% rubber volume fraction, and 10% silica fume as replacement to cement by weight.

Tables 4.27 and 4.28 show the average responses on flexural strength and toughness of the main factors and the two factor interaction of factors A (rubber type), B (rubber volume fraction) and C (Surface treatment of rubber particles).



Factor	A	B	C	D	E	Total
Factor description	(Concrete grade)	(Rubber %)	(Additives)	(Rubber Type)	(Rubber surface treatment)	
Difference	1.48	0.32	0.27	0.30	0.08	2.44
Contribution (%)	60.5%	13.0%	10.9%	12.2%	3.4%	100%

Fig 4.21 The contribution of each factor on Flexural strength



Factor	A	B	C	D	E	Total
Factor description	(Concrete grade)	(Rubber %)	(Additives)	(Rubber Type)	(Rubber surface treatment)	
Difference	2.88	1.33	1.31	2.64	0.50	8.67
Contribution (%)	33.3%	15.3%	15.1%	30.5%	5.7%	100%

Figure 4.22 The contribution of each factor on Flexural toughness

Table 4.25 Two-way tables for flexural strength

a) AxB Interaction

A (Concrete grade)	B (Rubber %)			
	0.5%	1.5%	2.5%	Mean
C20	2.73	2.24	2.82	2.60
C25	3.65	3.44	3.14	3.41
C30	4.28	4.02	3.92	4.08
Mean	3.55	3.23	3.30	3.36

b) AxC Interaction

A (Concrete grade)	C (Additives)			
	None	Polyp 0.2%	S.F 10%	Mean
C20	2.64	2.71	2.44	2.60
C25	3.30	3.16	3.77	3.41
C30	3.74	4.23	4.26	4.08
Mean	3.23	3.36	3.49	3.36

c) BxC Interaction

B (Rubber %)	C (Additives)			
	None	Polyp 0.2%	S.F 10%	Mean
0.5%	3.67	3.26	3.72	3.55
1.5%	2.81	3.68	3.22	3.23
2.5%	3.20	3.15	3.54	3.30
Mean	3.23	3.36	3.49	3.36

Table 4.26 Two-way tables for flexural toughness

a) AxB Interaction

A (Concrete grade)	B (Rubber %)			
	0.5%	1.5%	2.5%	Mean
C20	5.28	4.50	6.74	5.51
C25	6.00	8.11	8.00	7.37
C30	8.57	7.52	9.10	8.39
Mean	6.62	6.71	7.95	7.09

b) AxC Interaction

A (Concrete grade)	C (Additives)			
	None	Polyp 0.2%	S.F 10%	Mean
C20	6.38	5.82	4.32	5.51
C25	7.49	7.28	7.34	7.37
C30	7.33	10.18	7.67	8.39
Mean	7.07	7.76	6.45	7.09

c) BxC Interaction

B (Rubber %)	C (Additives)			
	None	Polyp 0.2%	S.F 10%	Mean
0.5%	6.87	6.71	6.27	6.62
1.5%	6.03	8.21	5.88	6.71
2.5%	8.30	8.35	7.18	7.95
Mean	7.07	7.76	6.45	7.09

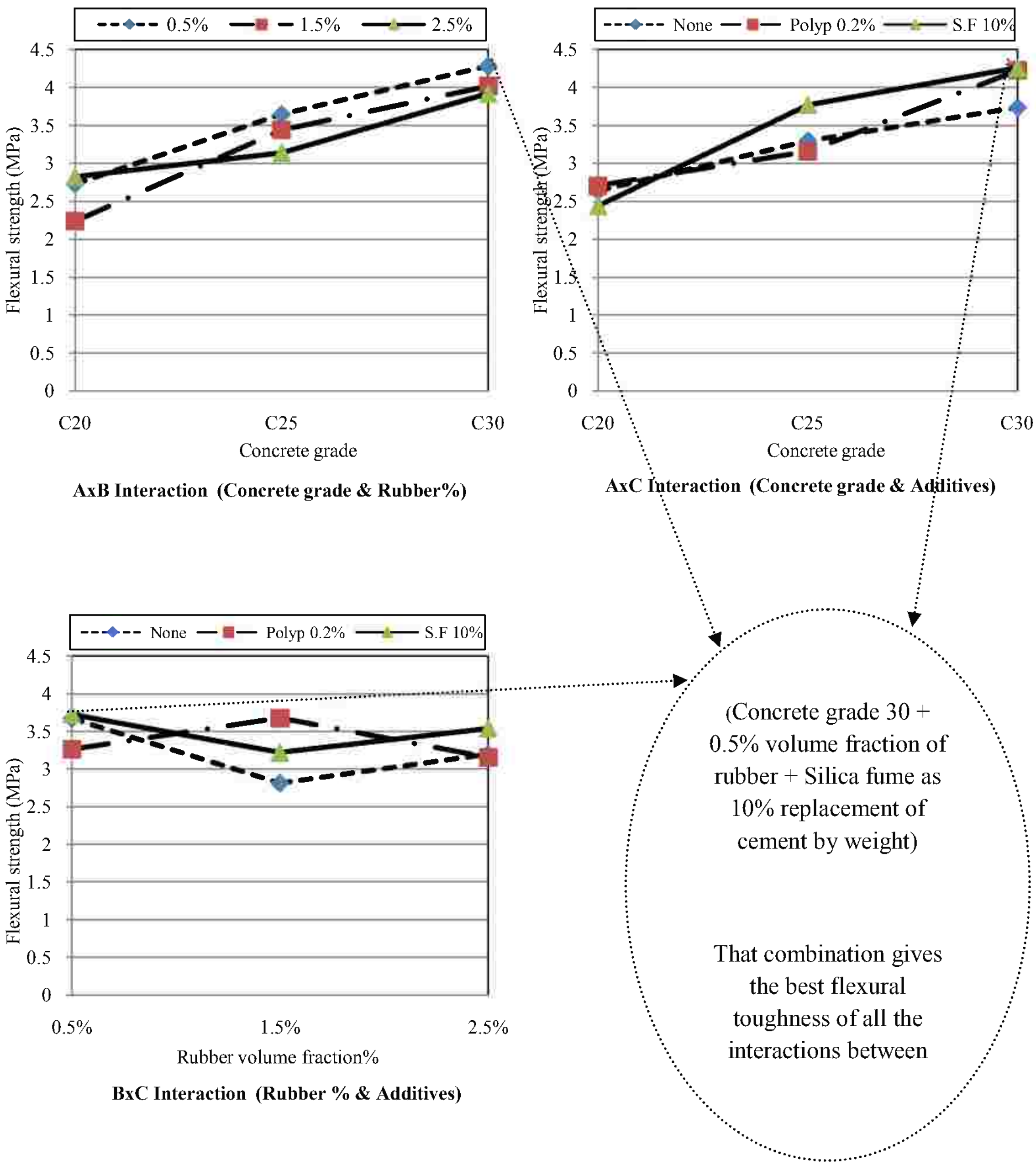


Figure 4.23 Effect of two factor interaction at different factor levels on flexural strength

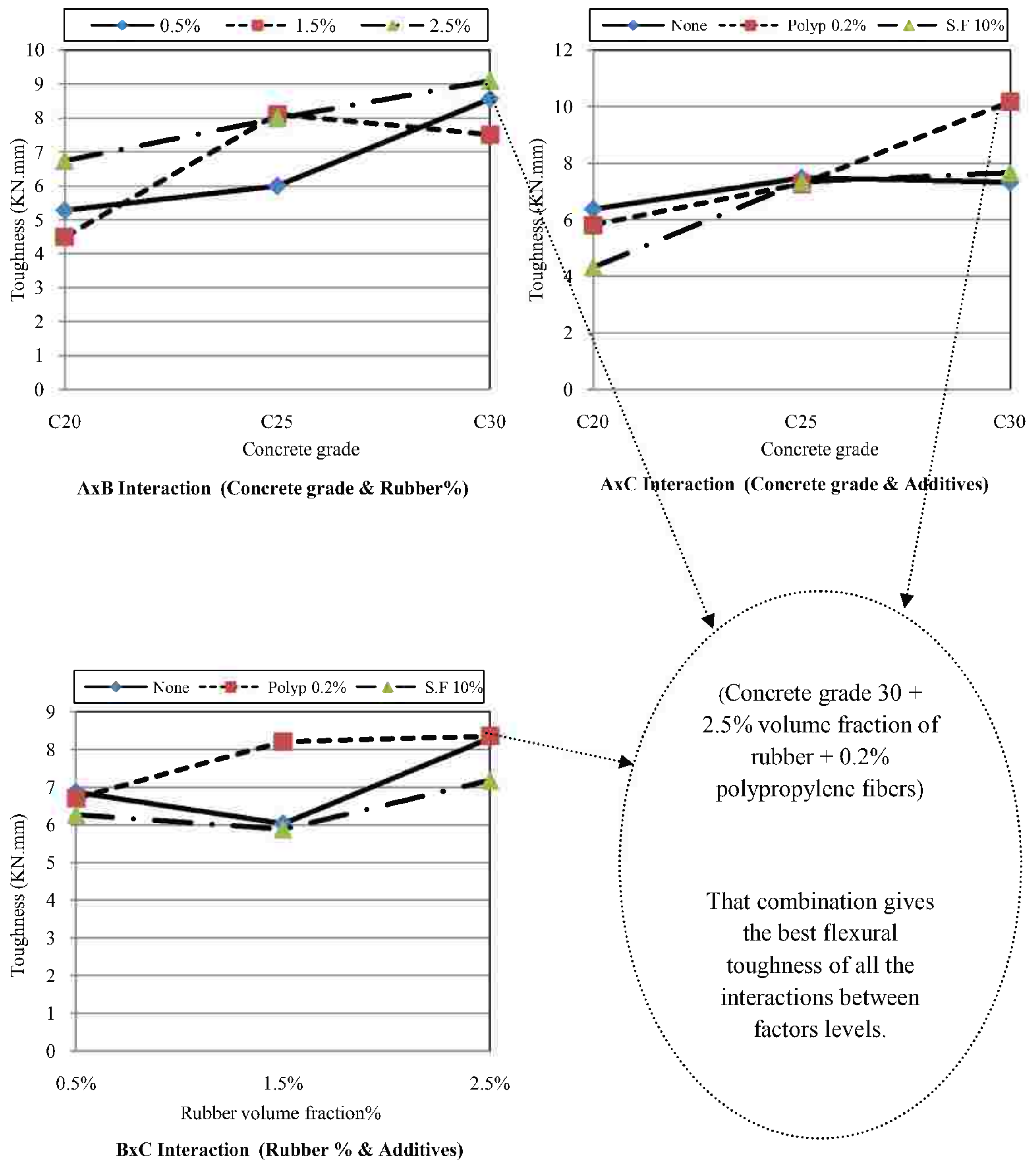


Figure 4.24 Effect of two factor interaction at different factor levels on flexural toughness

Table 4.27 The average responses of main factors and interactions of factors A, B and C on flexural strength

Factor level	A (Concrete grade)	B (Rubber %)	C (Additives)	D (Rubber Type)	E (Rubber surface treatment)	AxB	AxC	BxC
0	2.60	3.55	3.23	3.28	3.35			
1	3.41	3.23	3.36	3.25	3.32			
2	4.08	3.30	3.49	3.55	3.41			
00						2.73	2.64	3.67
01						2.24	2.71	3.26
02						2.82	2.44	3.72
10						3.65	3.30	2.81
11						3.44	3.16	3.68
12						3.14	3.77	3.22
20						4.28	3.74	3.20
21						4.02	4.23	3.15
22						3.92	4.26	3.54

Table 4.28 The average responses of main factors and interactions of factors A, B and C on flexural toughness

Factor level	A (Concrete grade)	B (Rubber %)	C (Additives)	D (Rubber Type)	E (Rubber surface treatment)	AxB	AxC	BxC
0	5.51	6.62	7.07	5.64	7.11			
1	7.37	6.71	7.76	7.35	7.33			
2	8.39	7.95	6.45	8.28	6.83			
00						5.28	6.38	6.87
01						4.50	5.82	6.71
02						6.74	4.32	6.27
10						6.00	7.49	6.03
11						8.11	7.28	8.21
12						8.00	7.34	5.88
20						8.57	7.33	8.30
21						7.52	10.18	8.35
22						9.10	7.67	7.18

4.7. ABRASION RESISTANCE

4.7.1. Test Results and Discussion

Table 4.29 shows the thickness loss due to abrasion test the 27 mixes of rubberized concrete and the 3 control mixes. From this table, it is noticed that all rubberized concrete mixes have abrasion resistance comparable to control mixtures.

Table 4.29 Thickness loss due to abrasion test for all concrete mixes

Mix No	Factor description					Thickness loss (mm)
	A (Concrete grade)	B (Rubber %)	C (Additives)	D (Rubber Type)	E (Rubber surface treatment)	
1	C20	0.50%	None	Crumb 4mm	NaOH	2.87
2		1.50%	Polyp 0.2%	Crumb 4mm	PVA	2.73
3		2.50%	S.F 10%	Crumb 4mm	Without	3.11
4		0.50%	S.F 10%	Fiber 8	Without	3.09
5		1.50%	None	Fiber 8	NaOH	3.70
6		2.50%	Polyp 0.2%	Fiber 8	PVA	3.29
7		0.50%	Polyp 0.2%	Fiber 4	PVA	3.11
8		1.50%	S.F 10%	Fiber 4	Without	3.46
9		2.50%	None	Fiber 4	NaOH	3.26
10	C25	0.50%	S.F 10%	Crumb 4mm	PVA	2.60
11		1.50%	None	Crumb 4mm	Without	2.98
12		2.50%	Polyp 0.2%	Crumb 4mm	NaOH	3.13
13		0.50%	Polyp 0.2%	Fiber 8	NaOH	3.05
14		1.50%	S.F 10%	Fiber 8	PVA	3.30
15		2.50%	None	Fiber 8	Without	3.22
16		0.50%	None	Fiber 4	Without	3.10
17		1.50%	Polyp 0.2%	Fiber 4	NaOH	3.21
18		2.50%	S.F 10%	Fiber 4	PVA	2.70
19	C30	0.50%	Polyp 0.2%	Crumb 4mm	Without	2.92
20		1.50%	S.F 10%	Crumb 4mm	NaOH	2.50
21		2.50%	None	Crumb 4mm	PVA	2.80
22		0.50%	None	Fiber 8	PVA	2.84
23		1.50%	Polyp 0.2%	Fiber 8	Without	3.41
24		2.50%	S.F 10%	Fiber 8	NaOH	3.03
25		0.50%	S.F 10%	Fiber 4	NaOH	2.56
26		1.50%	None	Fiber 4	PVA	2.77
27		2.50%	Polyp 0.2%	Fiber 4	Without	2.95
					Mean	3.03
C20	C20	-	-	-	-	3.53
C25	C25	-	-	-	-	3.11
C30	C30	-	-	-	-	2.96

4.7.2. Effect of Different Factors on Abrasion Resistance

Fractional factorial method of experimentation was considered to organize the tested variables and to analysis the test results. The effect of each factor level on abrasion resistance is shown in Figure 4.25. Table 4.30 shows the average response of each factor level on abrasion resistance. The contribution of each factor on abrasion resistance is illustrated in Figure 4.26. It can be seen from this figure, that Factor D (rubber type) is the most significant effect of the studied parameters.

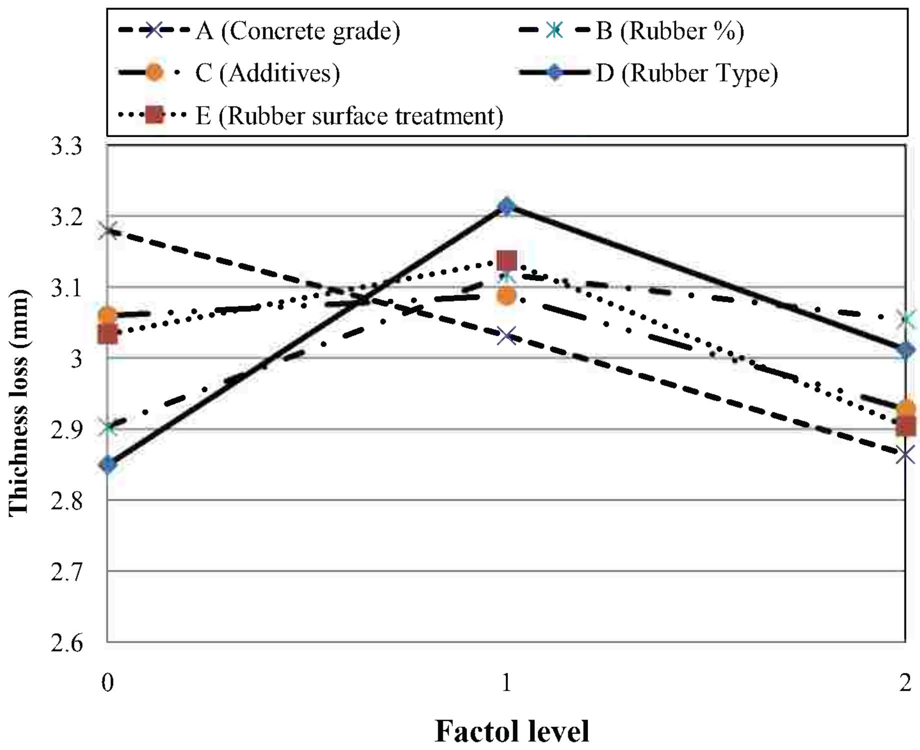
Table 4.30 Average response of each factor level on abrasion resistance

Factor	Factor level	Factor description	Thickness loss (mm)
A (Concrete grade)	0	C20	3.18
	1	C25	3.03
	2	C30	2.86
B (Rubber %)	0	0.5%	2.90
	1	1.5%	3.12
	2	2.5%	3.05
C (Additives)	0	None	3.06
	1	Polyp 0.2%	3.09
	2	S.F 10%	2.93
D (Rubber Type)	0	Crumb 4mm	2.85
	1	Fiber 8	3.21
	2	Fiber 4	3.01
E (Rubber surface treatment)	0	NaOH	3.03
	1	Without	3.14
	2	PVA	2.90

From Figure 4.26, the contribution of factor A (concrete grade) on abrasion resistance is 25%. To study the effect of factor A (Concrete grade), it can be seen from Table 4.30 and Figure 4.25 that thickness loss decreases gradually with the increase in concrete grade.

Also, the contribution of factor B is 17%. As shown in Table 4.30 and Figure 4.25, the abrasion resistance decreases with the increase in rubber content. The thickness loss of rubberized concrete with rubber content 0.5%, 1.5% and 2.5% are 2.90, 3.12 and 3.05mm, respectively.

As for factor C (additives), the contribution on abrasion resistance is 12%. The thickness loss due to abrasion test for rubberized concrete with no additives, polypropylene fiber and silica fume are 3.06, 3.09 and 2.93 mm, respectively. The addition of the silica fume improves the abrasion resistance comparing to rubber concrete with no additives and polypropylene fiber.



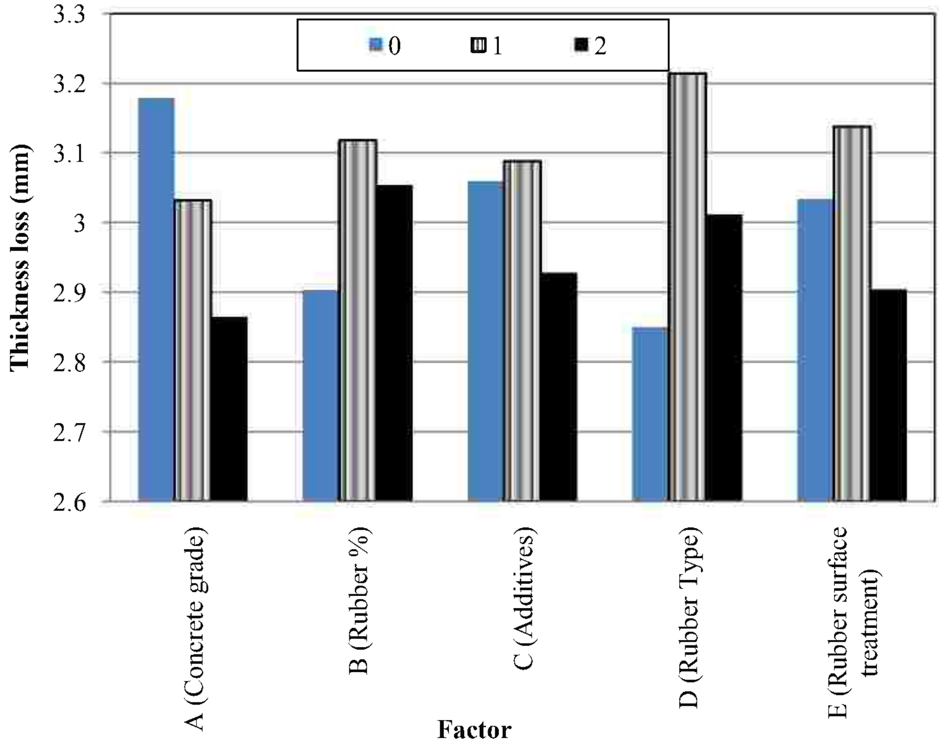
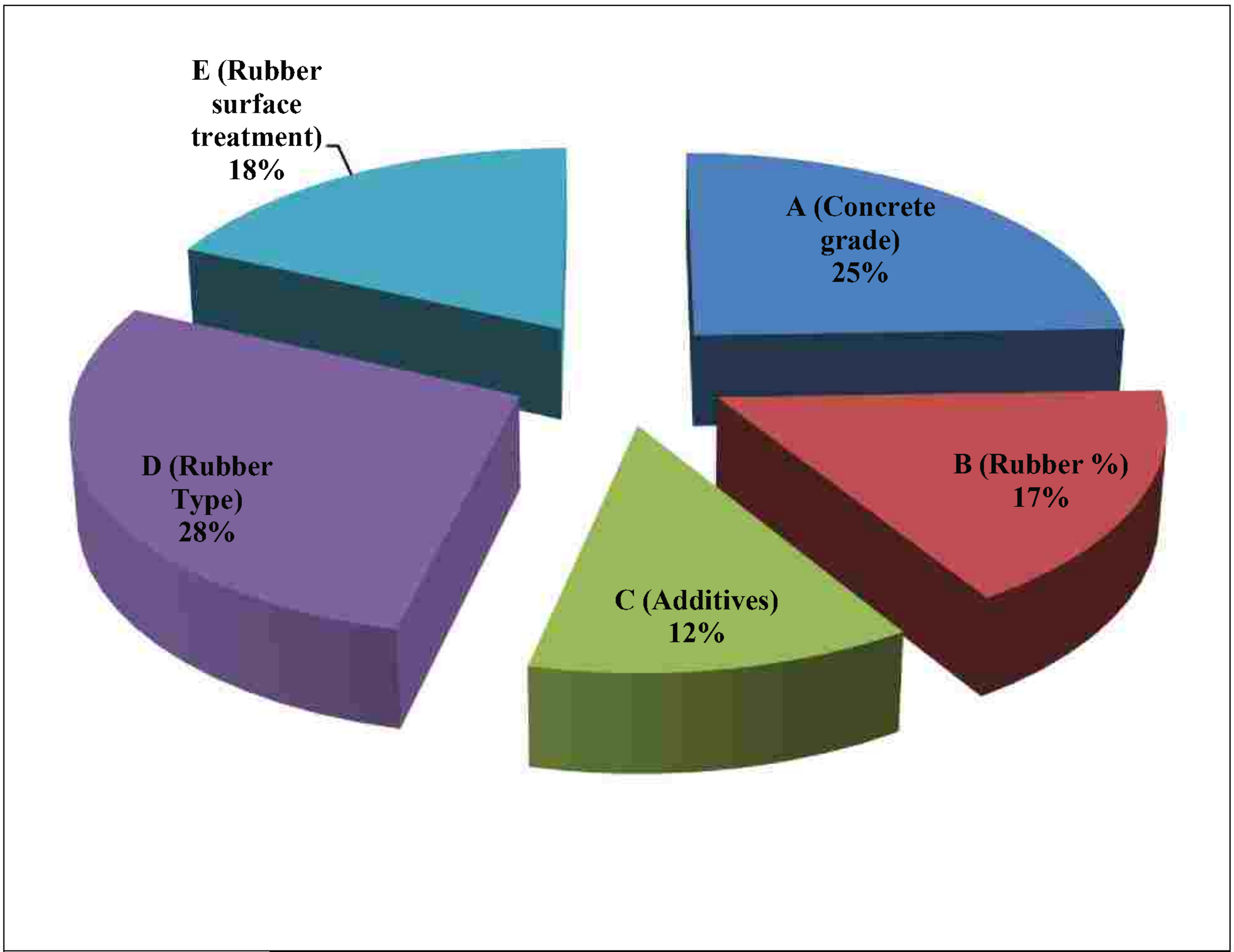


Figure 4.25 Factors affecting abrasion resistance

For factor D (rubber type), has the most significant effect on concrete abrasion resistance. From Figure 4.26, the contribution of factor D is 28%. The thickness loss due to abrasion test for rubberized concrete with crumb rubber, Fiber 8 and Fiber 4 are 2.85, 3.21 and 3.01mm, respectively. Crumb rubber gives the best values for abrasion resistance, while Fiber 8 gives the lowest values.

Also, From Figure 4.26, factor E (rubber surface fraction) has significant effect on abrasion resistance. PVA surface treatment of rubber particles gives the best abrasion resistance comparing to treatment with NaOH solution and plain rubber particles.



Factor	A	B	C	D	E	Total
Factor description	(Concrete grade)	(Rubber %)	(Additives)	(Rubber Type)	(Rubber surface treatment)	
Difference	0.31	0.21	0.16	0.36	0.23	1.29
Contribution (%)	24.5%	16.7%	12.4%	28.3%	18.1%	100%

Figure 4.26 The contribution of each factor on abrasion resistance

4.7.3. Two-Factor Interactions

Table 4.31 shows the two-factor interactions of AxB, AxC and BxC for thickness loss due to abrasion test. Figure 4.27 illustrates the effect of two factor interaction at different factor levels on abrasion resistance. It can be stated that the best abrasion resistance is given by the combination of 0.5% rubber volume fraction of Crumb rubber using surface treatment by PVA and silica fume as 10% replacement of cement by weight.

Tables 4.32 presents the average responses on thickness loss, due to abrasion test, of the main factors and the two factor interaction of factors A (rubber type), B (rubber volume fraction) and C (Surface treatment of rubber particles).

Table 4.31 Two-way tables for thickness loss due to abrasion test

a) AxB Interaction

A (Concrete grade)	B (Rubber %)			
	0.5%	1.5%	2.5%	Mean
C20	3.02	3.30	3.22	3.18
C25	2.91	3.16	3.02	3.03
C30	2.77	2.89	2.93	2.86
Mean	2.90	3.12	3.05	3.03

b) AxC Interaction

A (Concrete grade)	C (Additives)			
	None	Polyp 0.2%	S.F 10%	Mean
C20	3.28	3.04	3.22	3.18
C25	3.10	3.13	2.87	3.03
C30	2.80	3.09	2.70	2.86
Mean	3.06	3.09	2.93	3.03

c) BxC Interaction

B (Rubber %)	C (Additives)			
	None	Polyp 0.2%	S.F 10%	Mean
0.5%	2.94	3.03	2.75	2.90
1.5%	3.15	3.12	3.09	3.12
2.5%	3.09	3.12	2.95	3.05
Mean	3.06	3.09	2.93	3.03

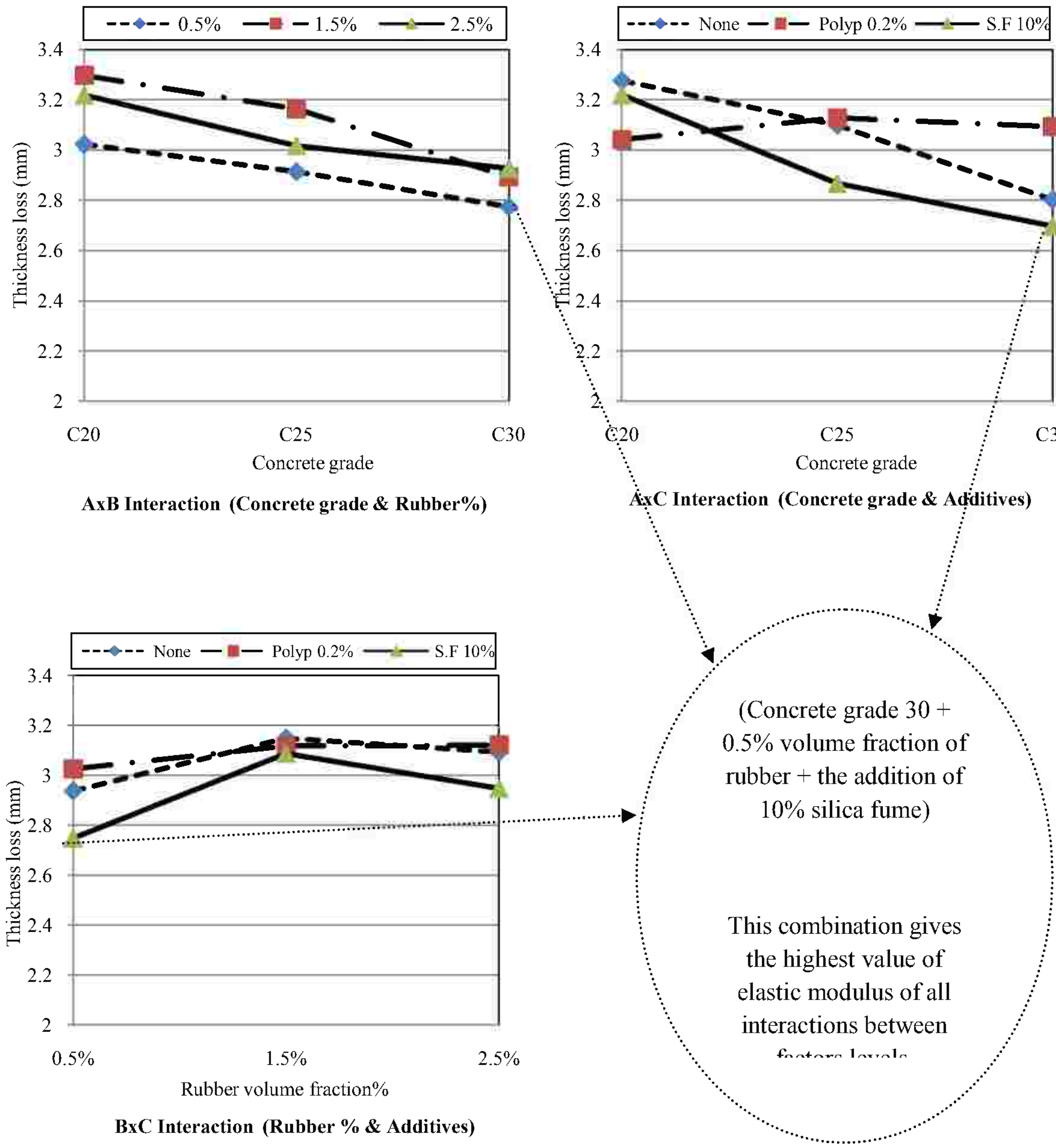


Figure 4.27 Effect of two factor interaction at different factor levels on abrasion resistance

Table 4.32 The average responses of main factors and interactions of factors A, B and C on abrasion resistance

Factor level	A (Concrete grade)	B (Rubber %)	C (Additives)	D (Rubber Type)	E (Rubber surface treatment)	AxB	AxC	BxC
0	3.18	2.90	3.06	2.85	3.03			
1	3.03	3.12	3.09	3.21	3.14			
2	2.86	3.05	2.93	3.01	2.90			
00						3.02	3.28	2.94
01						3.30	3.04	3.03
02						3.22	3.22	2.75
10						2.91	3.10	3.15
11						3.16	3.13	3.12
12						3.02	2.87	3.09
20						2.77	2.80	3.09
21						2.89	3.09	3.12
22						2.93	2.70	2.95