Contemporary Engineering Sciences, Vol. 6, 2013, no. 5, 225 - 237
HIKARI Ltd, www.m-hikari.com
http://dx.doi.org/10.12988/ces.2013.3531

Tensile Strength of Steel Fiber Reinforced Concrete

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Abstract

Studies have shown that the addition of steel fibers in a concrete matrix improves all the mechanical properties of concrete, especially tensile strength, impact strength, and toughness. The resulting material possesses higher tensile strength, consolidated response and better ductility.

Accordingly, this study moves toward deriving an expression that relates split cylinder tensile strength of fiber reinforced concrete to cylindrical compressive concrete strength and fiber reinforcement index, based on data gathered for a wide spectrum of concrete grades, ranging from 20 MPa to 102 MPa.

Regression analysis was carried out on gathered data. Eventually a mathematical expression that predicted split cylinder tensile strength of steel fiber reinforced concrete was eventually derived. The predicted values fit well with experimental data.

Keywords: Steel Fiber Reinforced concrete, composite concrete

1. Introduction

Early technological development of steel fiber reinforced concrete (SFRC) was hampered by lack of information and authenticated measures until the early

1960's. Since that, researchers have done extensive researches on SFRC, driven by the promising performance enhancements in terms of strength, durability and toughness. Studies have shown increasing evidence that the brittle behavior of concrete can be overcome by the addition of short steel fibers of small diameters in the concrete mix [1, 2]. ACI Committee 544[3] reported that the addition of steel fibers in a concrete matrix improves all mechanical properties of concrete, especially tensile strength, impact strength, and toughness. Identifying the correlation between the tensile strength as the dependent variable and each of the aspect ratio and the volumetric ratio as independent variables is an important aspect of successful design.

Concrete fiber composites have been found more economical for use in Airport and Highway Pavements, Bridge Decks, Erosion resistance structures, slope stabilization, Refractory concrete, Earthquake resistance structures and Explosive resistance structures [4]

In the design of concrete structures, the two essentially considered material properties are compressive and tensile strengths. Compressive strength is a major parameter in the case of structural applications, whereas flexural strength is an essential parameter in pavement applications. In certain applications, toughness is a vital parameter [5].

The observations given by published literature indicate that the selection of SFRC volumetric fraction can be chosen within the range of 1 to 2.5% by concrete absolute volume [6].

Few studies have been carried out towards investigating the relationship between the split tensile strength and the compressive strength of SFRC. The available relationships are either based on limited number of specimens or narrow range of fiber content or fiber aspect ratio. Ashour et al [7] suggested the following equation for high strength concrete specimens of a single aspect ratio, *l/d* of 75

$$f_{sp} = 4.95 - 2.13\ v_f \qquad (1)$$

Where v_f is the volumetric fiber content.

More parameters were presented within the expression addressed by Ashour et al [8], as follows:

$$f_{sp} = \frac{f_{cuf}}{(20 - \sqrt{F})} + 0.7 + \sqrt{F} \qquad (2)$$

Where f_{cuf} is the cube strength of fiber reinforced concrete [MPa].

f_{sp} is the splitting strength of fiber reinforced concrete [MPa].

F is fiber reinforcement index = *(l/d).* v_f *.*D_f

l and *d* are steel fiber length and diameter respectively.

D_f is a bond factor.

Studies carried out by Yazici et al. [9], Holschemacher et al.[10] and others concluded that in case of SFRC, volumetric fraction as well as the aspect ratio (l/d) are two major factors in terms of performance enhancement.

The aim of the present work is to develop an expression that correlates SFRC split strength with concrete cylindrical compressive strength and fiber reinforcement index, using nonlinear regression analysis. The importance of the study is that it employs a large number of experimental data of SFRC obtained from previous researches. Such data cover a variety of factors of significant effect on the SFRC split strength. This may serve as useful tool to quantify the effect of fiber reinforcement on strength in terms of fiber reinforcing index.

2. Data analysis and statistical modelling

Table 1 includes experimental data concerning 358 SFRC cylindrical specimens. The values of compressive strength f'_c, splitting tensile strengths f_{sp}, volumetric fiber content v_f, and fiber aspect ratio l/d are listed. These data were gathered from several research papers, (Batson [11], Craig et. al [12], Sharma [13], Robert and Victor [14], El-Niema [15], Ashour et al [7], Ashour et al [8], Ghosheh [16], Padmarajaiah [17], Marar and Celik [18], Kwak [19], Ayish [20], Bani-Yasin [21], Rjoub and Rasheed [22]). Gathered data encompass compressive strength values from 20.65 MPa to 102 MPa. and include concrete without fiber reinforcement and with fiber reinforcement. All the compressive strength values presented in Table 1 are either for cylinders of standard dimensions (150x300mm) or converted to standard cylindrical strengths using conversion factors presented in Table 2. Regression analysis was carried out to predict the split strength, f_{sp} value. The scatter plot of experimental values of f'_c versus f_{sp} indicated that the expected relation could take the general expression

$$f_{sp} = \alpha + \beta \times ((v_f \times \frac{l}{d})^{\chi}) \times \sqrt{f'_c} \qquad (3)$$

Parameters that were statistically insignificant were discarded; eventually the model coefficients were determined. The values of calculated regression coefficients (α, β and χ) were found to be (0.614, 0.4 and 1.029) respectively.

Ultimately, the mathematical expression that predicts split cylinder tensile strength of fiber reinforced concrete f_{sp} is concluded as follows:

$$f_{sp} = (0.614 \; + 0.4 \; (v_f \times \frac{l}{d})^{1.029}) \times \sqrt{f'_c} \qquad (4)$$

The P-values for the coefficients of regression analysis (α, β and χ) are illustrated in Table (3). Their values are less than 0.001. Such low p-values indicate that the predictors have a significant effect on the response variable. Also,

the adjusted coefficient of determination, R^2 is 0.840, implying that the regression predicted values are acceptably close to the observed data.
Eqn (4) can be normalized by dividing its two sides by the term $\sqrt{f_c^{'}}$ as follows

$$\frac{f_{sp}}{\sqrt{f'_c}} = (0.614 + 0.4 \ (v_f \times \frac{l}{d})^{1.029}) \qquad (5)$$

Equation (5) could be further simplified as follows

$$\frac{f_{sp}}{\sqrt{f'_c}} = (0.6 + 0.4 \times \ (\%FRI)) \qquad (6)$$

Where $FRI = v_f .l/d$

Figure (1) illustrates the scatter plot of %FRI versus the experimental split strength divided by $\sqrt{f_c^{'}}$ for the data listed in Table 1. The plot illustrates an upper and lower bounds derived by regression analysis. (Figure 2) illustrates the experimental split strength values versus the predicted values according to Eqn. (7). It indicates that the predicted values are close to test result values. The plot of the data in both figures (Figure 1 and Figure 2) confirms the reliability of the derived expression.
Eqn. (6) may be written in the following form

$$f_{sp} = (0.6 + 0.4 \ (v_f \times \frac{l}{d}) \ ) \times \sqrt{f'_c} \qquad (7)$$

3. Conclusions

The following conclusions can be drawn from this study:

1- A mathematical expression that predicts the split tensile strength of steel fiber reinforced concrete is derived.

2- The suggested equation correlates the split tensile strength of steel fiber reinforced concrete with concrete compressive strength and fiber reinforcement index.

3- The predicted values of the splitting tensile strength are in good agreement with the experimental results. Thus the validity of the suggested expression is verified against the experimental results gathered from previous researches.

4- The outcomes of descriptive statistical analysis confirm the credibility of the derived expression.

5- Concrete compressive strength, fiber content and the fiber aspect ratio are the major effectual parameters in specifying the tensile strength of fiber concrete.

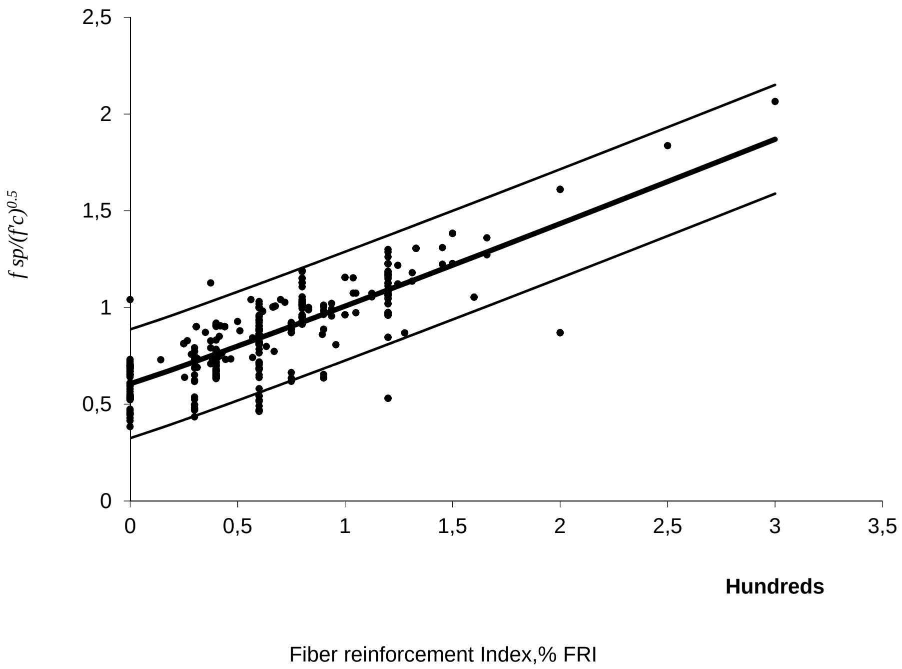

Fig. 1 Relationship between steel fiber reinforcement index % FRI and $f_{sp}/(f'_c)^{0.5}$

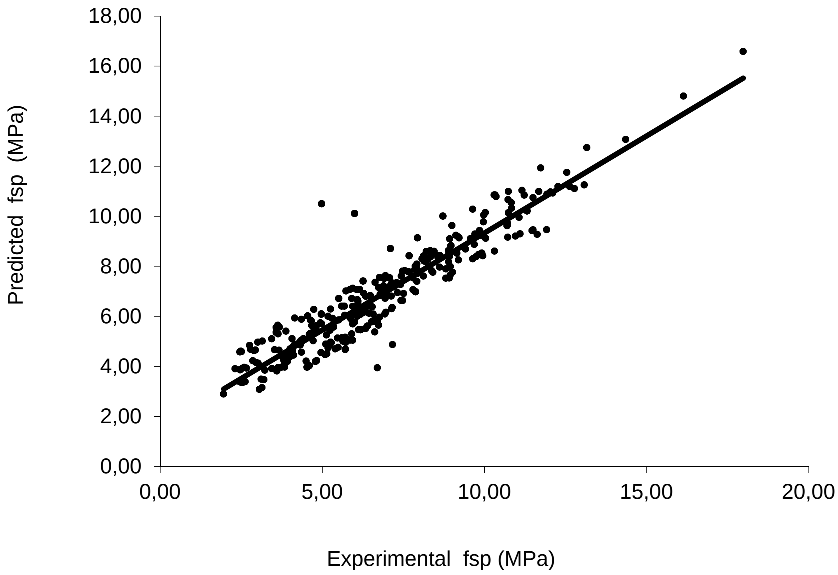

Fig. 2 Experimental versus predicted split strength.

Appendix

Table 1. Compressive strength, fiber reinforcement index and split cylinder strength

Marar and Celic [18] (Compression, splitting, Cylinders 150x300)							
no	FRI	f'c (Mpa)	f_{sp} (MPa)	no	FRI	f'c (Mpa)	*f_{sp} (MPa)*
1	0	32.06	3.2	20	0	73.5	5.13
2	30	32.66	3.93	21	30	76.02	5.68
3	60	34.11	4.72	22	60	78.48	6.95
4	75	36.28	5.35	23	75	80.09	8.26
5	90	37.46	5.9	24	90	84.63	8.93
6	105	39.27	6.1	25	105	86.22	9.97
7	120	39.85	6.84	26	120	88.97	10.83
8	37.5	33.73	4.12	27	37.5	76.96	6.94
9	75	34.63	5.24	28	75	78.85	8.14
10	93.75	36.61	6.18	29	93.75	84.48	9.12
11	112.5	38.31	6.53	30	112.5	87.4	10.03
12	131.25	39.63	7.15	31	131.25	89.52	11.16
13	150	41.17	7.87	32	150	91.49	11.74
14	41.5	33.99	4.36	33	41.5	78.02	7.51
15	83	35.26	5.94	34	83	80.95	8.89
16	103.75	37.09	6.54	35	103.75	86.21	10.71
17	124.5	39.73	7.07	36	124.5	89.19	11.5
18	145.25	41.27	7.86	37	145.25	91.73	12.54
19	166	42.87	8.33	38	166	93.56	13.16
Craig et al [12]							
no	FRI	f'c (Mpa)	f_{sp} (MPa)	no	FRI	f'c (Mpa)	f_{sp} (MPa)
39	0.00	40.69	3.45	43	120.00	28.97	4.55
40	42.00	40.00	5.72	44	200.00	47.59	6.00
41	100.00	43.45	6.34	45	120.00	40.00	6.07
42	90.00	35.86	5.31	46	160.00	45.52	7.10
Sharma [13]							
no	FRI	f'c (Mpa)	f_{sp} (MPa)	no	FRI	f'c (Mpa)	f_{sp} (MPa)
47	0	42.3	4.55	51	72	48.6	7.16
48	0	43.2	4.6	52	67.5	47.7	6.96
49	0	47.7	4.83	53	67.5	43.2	6.62
50	0	46.8	4.79				

Batson [11]							
no	FRI	f'c (Mpa)	f_{sp} (MPa)	no	FRI	f'c (Mpa)	f_{sp} (MPa)
54	44	40.19	5.71	63	61.6	39.71	6.18
55	44	40.19	5.71	64	61.6	39.71	6.18
56	44	40.19	5.71	65	61.6	39.71	6.18
57	44	40.19	5.71	66	61.6	39.71	6.18
58	30.8	40.19	5.71	67	61.6	39.71	6.18
59	30.8	40.19	5.71	68	61.6	39.71	6.18
60	30.8	40.19	5.71	69	61.6	39.71	6.18
61	30.8	40.19	5.71	70	61.6	39.71	6.18
62	61.6	39.71	6.18				
Ghosheh [16]							
no	FRI	f'c (Mpa)	f_{sp} (MPa)	no	FRI	f'c (Mpa)	f_{sp} (Mpa)
71	0	42.49	4.56	78	75	42.67	5.69
72	0	41.9	4.53	79	56.25	40.47	6.62
73	0	41.9	4.53	80	93.75	40.85	6.11
74	26.6	42.49	5.4	81	37.5	40.47	7.17
75	35	39.7	5.49	82	75	40.11	5.51
76	70	41.42	6.7	83	0	41.42	6.7
77	37.5	40.11	5.24				
Bani-Yasin [21]							
no	FRI	f'c (Mpa)	f_{sp} (MPa)	no	FRI	f'c (Mpa)	f_{sp} (Mpa)
84	0.00	23.83	2.62	99	0.00	51.90	5.66
85	0.00	23.57	2.49	100	0.00	49.64	5.23
86	0.00	23.27	2.54	101	0.00	52.13	5.64
87	0.00	24.20	2.49	102	0.00	53.80	5.73
88	0.00	23.75	2.46	103	0.00	52.94	5.86
89	0.00	23.82	2.51	104	0.00	52.89	5.94
90	30.00	25.83	2.86	105	30.00	54.25	6.44
91	30.00	24.66	3.02	106	30.00	55.54	6.12
92	30.00	24.90	2.97	107	30.00	54.72	6.13
93	60.00	27.39	3.44	108	60.00	55.72	7.42
94	60.00	26.41	3.15	109	60.00	55.85	7.28
95	60.00	25.99	3.01	110	60.00	56.80	7.29
96	75.00	26.68	3.88	111	75.00	55.26	7.65
97	75.00	25.63	3.64	112	75.00	55.88	7.55
98	75.00	26.19	3.58	113	75.00	55.58	7.48

Ayish[20]							
no	FRI	f'c (Mpa)	f_{sp} (Mpa)	no	FRI	f'c (Mpa)	f_{sp} (Mpa)
114	0	20.1	3.1	119	60	22.78	2.94
115	30	21.37	3.23	120	60	24.65	2.76
116	60	22.753	3.67	121	60	23.02	2.79
117	60	22.91	3.53	122	90	24.65	3.58
118	0	20.65	3.14	123	90	25.45	3.63
124	60	22.15	4.08	140	90	24.73	3.68
125	0	32.76	3.84	141	30	53.52	5.96
126	30	34.48	4.15	142	30	52.03	6.08
127	60	35.72	4.66	143	30	53.66	5.91
128	60	36.43	4.36	144	60	51.74	5.73
129	0	32.60	3.74	145	60	52.74	5.86
130	60	35.96	4.64	146	60	53.35	5.94
131	30	21.73	2.48	147	30	54.52	6.26
132	30	22.07	2.31	148	30	53.66	6.57
133	30	21.55	2.47	149	30	54.29	6.45
134	60	22.33	2.49	150	60	54.85	6.89
135	60	22.08	2.46	151	60	56.68	7.3
136	60	22.16	2.51	152	60	54.14	7.13
137	30	22.72	2.6	153	90	56.64	8.56
138	30	22.32	2.66	154	90	56.03	8.34
139	30	22.25	2.54	155	90	56.72	8.63

Kwak [19]							
no	FRI	f'c (Mpa)	f_{sp} (Mpa)	no	FRI	f'c (Mpa)	f_{sp} (Mpa)
156	0.00	60.72	4.32	158	46.88	66.54	6.08
157	31.25	61.89	5.88	159	31.25	29.88	3.83

Craig [12]							
no	FRI	f'c (Mpa)	f_{sp} (Mpa)	no	FRI	f'c (Mpa)	f_{sp} (Mpa)
160	0	40.69	3.45	164	120	28.97	4.55
161	42	40.00	5.72	165	200	47.59	6.00
162	100	43.45	6.34	166	120	40.00	6.07
163	90	35.86	5.31	167	160	45.52	7.10

El-Neima [15] (Comp, splitting, cylinders 150x300mm)							
no	FRI	f'c (Mpa)	f_{sp} (Mpa)	no	FRI	f'c (Mpa)	f_{sp} (Mpa)
168	0.00	22.34	1.96	186	25.00	61.70	6.39
169	51.08	26.19	4.50	187	25.00	39.90	5.14
170	89.39	28.57	4.60	188	66.50	61.70	7.88
171	127.70	29.73	4.74	189	133.00	67.20	10.70
172	38.30	24.62	3.60	190	25.00	61.70	6.39
173	67.03	25.24	3.88	191	25.00	39.20	5.09
174	95.75	25.38	4.07	192	66.50	61.70	7.88

(cont) El-Neima [15] (Comp, splitting, cylinders 150x300mm)							
175	25.35	23.79	3.12	193	150.00	76.70	12.11
176	44.37	24.76	3.64	194	200.00	79.50	14.36
177	63.38	25.17	4.01	195	250.00	77.20	16.14
178	25.00	61.70	6.39	196	300.00	75.80	17.98
179	25.00	39.90	5.14	197	66.50	42.30	6.52
180	66.50	61.70	7.88	198	100.00	41.40	7.43
181	133.00	67.20	10.70	199	66.50	55.70	7.48
182	50.00	59.30	7.14	200	66.50	42.30	6.52
183	100.00	60.00	8.95	201	133.00	71.90	11.07
184	150.00	67.00	11.32	202	150.00	67.00	11.32
185	200.00	55.90	12.04				
Robert [14]							
no	FRI	f'c (Mpa)	f_{sp} (MPa)	no	FRI	f'c (Mpa)	f_{sp} (MPa)
203	0.00	54.15	2.90	206	42.75	56.72	5.90
204	14.25	55.96	5.60	207	57.00	54.15	5.60
205	28.50	59.47	6.00	208	57.00	51.40	6.20
Rjoub and Rasheed [22]							
no	FRI	f'c (Mpa)	f_{sp} (MPa)	no	FRI	f'c (Mpa)	f_{sp} (MPa)
209	0	55.22	4.96	284	0	59.76	5.18
210	0	63.71	5.11	285	0	65.65	5.26
211	0	71.06	5.71	286	0	74.69	5.91
212	0	80.87	6.34	287	0	84.84	6.74
213	0	91.85	6.62	288	0	94.78	6.77
214	40	59.76	5.18	289	40	63.07	6.1
215	40	65.65	5.26	290	40	78.66	6.79
216	40	74.69	5.91	291	40	88.3	7.36
217	40	84.84	6.74	292	40	93.94	8.81
218	40	94.78	6.77	293	40	97.06	8.95
219	60	62.51	7.13	294	60	65.21	7.32
220	60	76.71	7.8	295	60	80.42	7.95
221	60	85.62	8.62	296	60	90.17	8.9
222	60	92.98	9.64	297	60	94.97	9.75
223	60	97.03	9.83	298	60	98.11	9.92
224	80	64.73	8.12	299	80	67.31	8.41
225	80	78.91	8.93	300	80	81.14	9.15
226	80	88.01	9.69	301	80	92.93	10.04
227	80	94.67	10.96	302	80	96.62	11.1
228	80	99.21	11.47	303	80	99.98	11.5
229	120	66.81	9.22	304	120	69.08	9.71
230	120	80.82	9.98	305	120	82.29	10.74
231	120	91	10.73	306	120	94.17	11.23
232	120	96.73	11.68	307	120	96.35	12.04

(cont) Rjoub and Rasheed [22]							
233	120	100.18	12.27	308	120	100.2	12.63
234	0	65.25	5.28	309	0	51.22	3.95
235	0	70.21	5.47	310	0	60.85	4.1
236	0	79.51	6.12	311	0	69.39	4.42
237	0	89.27	6.58	312	0	80.11	4.75
238	0	98.92	6.93	313	0	86.48	4.98
239	40	66.23	6.32	314	40	54.71	4.94
240	40	79.42	6.97	315	40	67.91	5.94
241	40	90.79	7.92	316	40	79.31	6.28
242	40	94.13	8.92	317	40	89.76	6.63
243	40	99.94	9.02	318	40	93.62	6.91
244	60	67.37	7.8	319	60	55.84	6.41
245	60	82.66	8.37	320	60	69.42	7.04
246	60	91.89	9.2	321	60	81.61	7.68
247	60	95.62	9.95	322	60	90.31	8.2
248	60	99.98	10.31	323	60	94.28	8.57
249	80	69.71	8.81	324	80	57.88	7.23
250	80	84.31	9.42	325	80	73.07	7.92
251	80	93.76	10.72	326	80	82.60	8.45
252	80	96.2	11.63	327	80	92.61	9.57
253	80	100.12	11.92	328	80	95.31	9.92
254	120	71.23	9.85	329	120	59.12	8.21
255	120	85.21	10.84	330	120	74.24	9.00
256	120	94.78	11.93	331	120	84.63	9.64
257	120	98.71	12.78	332	120	93.11	10.36
258	120	101.3	13.08	333	120	96.72	10.74
259	0	48.74	3.8	334	0	57.87	4.08
260	0	58.81	4.01	335	0	64.08	4.25
261	0	67.31	4.34	336	0	75.31	4.63
262	0	74.92	4.63	337	120	84.42	4.82
263	0	80.77	4.81	338	120	93.64	4.15
264	40	52.63	4.68	339	120	52.63	4.68
265	40	61.27	4.97	340	0	61.72	4.97
266	40	74.67	5.51	341	0	74.67	5.51
267	40	82.89	6.15	342	0	82.89	6.15
268	40	91.07	6.26	343	40	91.07	6.26
269	60	54.01	6.05	344	60	54.01	6.05
270	60	62.89	6.48	345	60	62.89	6.48
271	60	76.63	7.08	346	60	76.63	7.08
272	60	84.62	7.91	347	60	84.62	7.91
273	60	92.86	8.08	348	60	92.82	8.08
274	80	55.22	6.83	349	80	52.2	6.83
275	80	64.73	7.44	350	80	64.73	7.44

(cont) Rjoub and Rasheed [22]							
No	FRI	f'c (Mpa)	f_{sp} (MPa)	No	FRI	f'c (Mpa)	f_{sp} (MPa)
276	80	78.98	8.12	351	80	78.98	8.12
277	80	87.03	8.97	352	80	87.03	8.97
278	80	93.91	9.2	353	80	93.91	9.2
279	120	56.77	7.68	354	120	56.77	7.68
280	120	66.82	7.94	355	120	66.82	7.94
281	120	80.11	8.72	356	120	80.11	8.72
282	120	88.18	4.98	357	120	88.18	4.98
283	120	94.22	10.3	358	120	94.22	10.33

Table 2: Conversion factors to standard cylindrical strength [15]

Cylinders 7.5x150 mm	0.95	Cylinders 100x200 mm	0.97	cylinders 150x300 mm	1
Cubes 100x100x100mm	0.78	Cubes 150x150x150mm	0.8	Cubes 200x200x200mm	0.83

Table 3: Estimated parameters using regression analysis

	$\alpha = 0.614$	$\beta = 0.4$	$\chi = 1.029$	$R^2 = 0.841$	adjusted $R^2 = 0.840$
P value	< 0.001	< 0.001	< 0.001		

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Received: May 27, 2013