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Designing, Proposing and Comparing the Methods Predicting the Compressive Strength of the Ferrocement Mortar

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Abstract

Ferrocement is a mixture of Portland cement and sand applied over layers of woven or expanded steel mesh and closely spaced small-diameter steel rods rebar. So that the Ferrocement mortar is one of its components, and different parameters affect its compressive strength, prediction of the compressive strength of Ferrocement before construction can seriously affect its properties and costs.

In this study, DIN, ACI and BS methods were used to examine the mix design of Ferrocement mortar. To this end, an equation was proposed for prediction of a 28-day strength based on the weight of cement, water, fine aggregate, nano silica, micro silica, and slump value. Results of previous researcher in this regard were evaluated to verify the equation and the designed mix designs.

Results showed that the prediction based on the proposed equation had more favorable standard deviation and less error than did other equations and statistical methods besides its applicability for the mix design of all types of cement mortars.

Keywords: Ferrocement; compressive strength; mix design; prediction

1. Introduction

Ferrocement is a mixture of Portland cement and sand applied over layers of woven or expanded steel mesh and closely spaced small-diameter steel rods rebar, which used as compound-curved sheets of a concrete ideal for such applications as hulls for boats, shell roofs, and water tanks [1-3].

Today, the advancement of concrete industry has made the ferrocement mortar and concrete the focus of scholars [4]. Its relatively high efficiency [5] and also high speed rate of construction has drawn more attention. Ferrocement with its many features, such as the different degrees of coarseness, plasticity, durability, mechanical strength, and crack resistance, has various applications more than do other types of concrete [6 - 7]. Usually, ferrocement is used in boat-building industry,

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water resources, barns, pipes, roofs of houses and workshops, and also construction of low-cost houses besides repairs [8 - 9]. The physical properties of the fresh and self-compacting concrete can be predicted through replacing the fly ash with cement at different water/cement proportions and also using the fuzzy logic model [10]. In this regard, mathematical equations show more favorable predictions, especially for porosity [11].

If the compressive strength of concrete and cement mortars is supposed to be predicted, the impact factor of each parameter affecting the compressive strength of concrete and logical limits for parameters of the mix design should be determined for the compressive strength of self-compacting concrete using Scheffe method [12]. Other prediction methods, such as the genetic algorithm [13] and neural network (ANN), can predict the 28-day compressive strength of self-compacting concrete [14]. Moreover, many studies have been performed on ferrocement mortar and the effect of varieties of additives on its mechanical properties, and several models have been developed for ferrocement components [15-18].

In this study, the 28-days compressive strength of cement and ferrocement mortar was predicted besides examining some methods predicting the compressive strength of concrete and ferrocement mortar and proposing an appropriate equation adjusted on the basis of the mix design of cement and Ferrocement mortar. The accuracy of the prediction was determined using the data of previous researchers [19 - 20]. Then, the mix design of Ferrocement mortar was designed for different strengths using DIN [21] and ACI [22] codes, and strengths of the design were compared with the proposed equation and finally compared with those of equations proposed for prediction of the compressive strength of the cement and Ferrocement mortar by previous studies.

2. The compressive strength prediction methods introduced by previous researchers

One of the methods used for prediction of compressive strength of concretes and cement mortars is the use of non-destructive testing, such as ultrasonic testing. Previous researchers showed that the compressive strength of 84 mix designs changed favorably after changing the type of aggregates, but they did not change significantly after changing the type of cement [23]. Moreover the compressive strength of concrete with a desirable approximate regarding the mix design using Scheffe equation and simplex analysis has been predicted [24].

It also proposed an equation for prediction of the 28-days compressive strength of the concrete containing fly ash instead of cement [25]. In this equation, S28 is the 28-days compressive strength in MPa; C is the cement weight; w is the water weight; and f is fly ash weight.

$$S_{28} = 16.8\left(\frac{C}{w} - 2.014 \times \frac{f}{w}\right) + 9.2 \tag{1}$$

Moreover, the following equation was presented regarding the chemical properties of the cement, the water/cement proportion, and the amount of calcium oxide of the cement [26].

$$f_c = \left[\left(16.45 \times \left(\frac{w}{b}\right)^{-1.26}\right) \times (\log c - 1.8) - 10.91 \times \ln\left(\frac{w}{b}\right) + 3.96\right] \tag{2}$$

$$C = W_c \times CaO_2$$

In the above equation, fc is the 28-days compressive strength, w/b is the proportion of water to powder materials, Wc is the cement weight in kg/m^2; and CaO_2 is the percentage of calcium oxide in the cement.

3. Numerical details

To determine the percentage of mixed materials for making the Ferrocement mortar, DIN, ACI, and BS [27] codes could be used considering a series of assumptions appropriate to the properties of the Ferrocement mortar.

3.1. Deutsches Institut für Normung (DIN) design

In DIN codes, the mix design of concrete had been regulated on the basis of properties of sand and percentage of aggregate breakage. In this mix design of Ferrocement mortar, the percentage of aggregate breakage was determined as 100%, and fineness modulus of all designs was assumed to be 3, the minimum value mentioned in the codes. Furthermore, the largest dimension of aggregates was 4.75 mm, specific weight of the cement, gravel, and water was respectively 3.1, 2.5, and 1 per cubic meter, and percentage of the super plasticizer was determined regarding the cement.

Subsections must be outline numbered. All equations should be typed using any Microsoft equations editor (MS Equation 3.0, Math Type…etc.). A nomenclature at the end of the manuscript should list out all Latin and Greek symbol definitions consecutively.

3.2. American Standard Institute (ACI) design

In ACI method, the slump range was determined as 75-100 and 150-175 after correcting the strength. The largest dimension of aggregates was 4.75 mm, and at least 9.5 mm of the aggregates' dimension was designed. The amount of free water was determined through extrapolation from the ACI's table. Moreover, the amount of sand was zero, and the amount of gravel was calculated using the absolute volume method.

3.3. British Standard (BS) design

The BS codes use two methods for correcting the strength of concretes. The first method uses a mathematic formula to increase the strength. The second method assumes an incremental coefficient with regard to the type of concrete or mortar in order to promote the strength of concretes. The quality of the mortar in this study was assumed normal, and its coefficient was 1.6 according to the codes. The largest dimension of the aggregates in this method was also determined as 4.75 mm, and the amount of water was measured through extrapolation.

The water/cement proportion was obtained using the table of the strengths up to 90 MPa. The amount fine aggregates was obtained after determining the weight of cement and water, the weight of fresh mortar from a specific table, and also assuming the weight of coarse aggregates as zero. In mix designs where super plasticizer was used, the amount of water was reduced in proportion to the amount of super plasticizer. The characteristics of mix designs are shown in Table 1.

Table 1 Compressive strength mix design based on DIN, ACI, and BS standard.

	Mixture no.	F_C PLAN (MPa)	F_C Suggested formula 3 (MPa)	F_C Suggested formula 1 (MPa)	F_C Suggested formula 2 (MPa)	SP (%)	slump (mm)	W/C	water (kg)	cement (kg)	FA (kg)
DIN	1	20	34.87	39.8	35.68	0	-	0.54	280	520	1146
	2	30	44.29	49.03	56.25	0	-	0.43	349	818	869
	3	20	35.30	39.76	32.6	0.5	-	0.56	260	467	1373
	4	30	43.93	47.78	49.27	0.5	-	0.44	282	642	1177
	5	40	51.35	56.79	70.49	0.5	-	0.36	307	864	935
	6	20	35.51	39.76	31.27	1	-	0.56	238	427	1461
	7	30	44.21	47.78	47.47	1	-	0.44	258	587	1281
	8	40	51.76	56.79	68.15	1	-	0.36	281	790	1060
ACI	1	20	32	38	42	0	75-100	0.582	247	424	1440
	2	30	43	48	60	0	75-100	0.435	247	568	1325
	3	40	54	62	86	0	75-100	0.32	247	772	1160
	4	20	32	38	42	0.5	75-100	0.582	222	382	1536
	5	30	40	57	77	1	75-100	0.35	198	565	1451
	6	40	55	62	86	1	75-100	0.32	198	618	1408
	7	20	30	38	42	0	150-175	0.582	267	459	1363
	8	30	41	48	60	0	150-175	0.435	267	614	1238
	9	40	53	62	86	0	150-175	0.32	267	834	1060
	10	20	31	38	42	0.5	150-175	0.582	240	413	1466
	11	30	42	48	60	1	150-175	0.435	214	491	1470
	12	40	54	62	86	1	150-175	0.32	214	668	1328
BS	1	20	17	30	28	0	-	0.8	263	329	1633
	2	30	28	37	41	0	-	0.6	263	438	1524
	3	40	38	47	58	0	-	0.45	263	584	1378
	4	50	51	62	86	0	-	0.32	263	822	1140
	5	60	57	71	104	0	-	0.27	263	974	988
	6	20	17	30	28	0.5	-	0.8	237	296	1712
	7	30	28	37	41	0.5	-	0.6	237	395	1614
	8	40	40	47	58	1	-	0.45	210	468	1582
	9	50	53	62	86	1	-	0.32	210	658	1392
	10	60	60	71	104	1.5	-	0.27	197	731	1357

Super Plasticizer= PS, Water = W, Cement= C, Fine Aggregates = FA, Compressive strength 28 -days = F_C

4. The equation proposed in this study

Considering that the equation of the constituents of ferrocement mortar did not have a linear correlation with its strength, logarithmic functions were used to present an appropriate equation. In this study, the proposed equation and its limits used for predicting the 28-days compressive strength of the ferrocement mortar is defined as follows:

$$f_{c(MPa)} = 10(\log_{10}\left(\left(\frac{c}{w}\right)^{10}\times\frac{Fa}{c}\right)) + \frac{w-s}{50} + N + M \quad (3)$$

$$N = \left(\frac{n}{Binder}\right) \times 200 \times \log_{10}\left(\frac{c}{w}\right)$$

$$\mathrm{M} = \left(\frac{\mathrm{m}}{\mathrm{Binder}}\right) \times 80 \times \log_{10}\left(\frac{\mathrm{c}}{\mathrm{w}}\right)$$

The limits are as follows:

$$0.8 < \frac{c}{w} < 2.9\,, \qquad 2 < \frac{Fa}{c} < 3\,, \qquad 0 < s < 250,$$

$$0 < \frac{n}{Binder} < 0.1, \quad 0 < \frac{m}{Binder} < 0.15$$

Where, *fc* is the 28-days compressive strength of the mortar; *c/w* is the weight ratio of cement to water; Fa/c is the weight ratio of fine aggregate to cement; w is the weight of water; s the amount slump in mm; n/Binder is the nanosilica/cement weight ratio, and m/Binder is the micro silica/cement weight ratio.

5. Analysis of the proposed equation

The equation proposed in this study and its limits were examined for three different mix designs that were designed for making Ferrocement mortar and cement mortar, and their 28-days compressive strength was predicted. The comparison of them is shown in Table 2.

Table 2 Comparison of experimental results [19-20] by predicted formula.

Mixture no.	FA/B	W/B	cement (kg/m^3)	FA (kg/m^3)	SP (%)	slump (mm)	NS (gr)	F_C PLAN (MPa)	F_C Suggested formula 3 (MPa)	F_C Suggested (MPa) formula 1	F_C Suggested (MPa) formula 2
1	2	0.400	702	1404	0	8	0	47.87	48.23	51.17	58.40
2	2	0.425	690	1380	0	27	0	47.53	45.53	46.76	54.2
3	2	0.450	678	1357	0	96	0	43.70	41.89	46.54	50.36
4	2	0.475	667	1334	0	131	0	39.80	39.04	44.54	46.49
5	2	0.500	656	1312	0	213	0	38.17	35.41	42.8	43.94
6	2	0.35	450	900	0	-	0	58.7	51.7	57.2	63
7	2	0.35	445.5	900	0	-	4.5	62.7	52.26	56.72	62.7
8	2	0.35	441	900	0	-	9	68.2	52.75	56.24	62.46
9	2	0.35	436.5	900	0	-	13.5	73.3	53.21	55.76	62.1
10	2	0.4	450	900	0	-	0	50.8	46.40	51.2	46.87
11	2	0.4	445.5	900	0	-	4.5	54.5	46.79	50.78	46.64
12	2	0.4	441	900	0	-	9	57.1	47.17	50.36	46.41
13	2	0.4	436.5	900	0	-	13.5	62.7	47.52	49.94	46.18
14	2	0.5	450	900	0	-	0	36.6	37.61	42.8	24.81
15	2	0.5	445.5	900	0	-	4.5	38.9	37.81	42.46	24.63
16	2	0.5	441	900	0	-	9	40.3	37.99	42.12	24.46
17	2	0.5	436.5	900	0	-	13.5	41.8	38.14	41.79	24.29
18	2.25	0.400	661	1488	0	6	0	54.04	48.54	51.26	57.18
19	2.25	0.425	650	1463	0	15	0	51.89	45.94	48.76	52.95
20	2.25	0.450	640	1440	0	28	0	47.92	43.40	46.5	49.21
21	2.25	0.475	630	1417	0	60	0	44.61	40.67	44.49	45.98
22	2.25	0.500	620	1395	0	139	0	39.78	37.04	42.8	42.98
23	2.25	0.350	684	1538	1.85	65	0	56.53	52.66	57.28	67.48
24	2.25	0.375	672	1513	1.15	61	0	48.94	49.94	54	61.84
25	2.25	0.400	661	1488	1.25	90	0	48.04	46.86	51.26	57.18
26	2.25	0.425	650	1463	0.5	90	0	44.75	44.44	48.76	52.95
27	2.5	0.400	625	1562	0	5	0	52.93	48.67	51.2	55.81
28	2.5	0.425	615	1538	0	15	0	51.27	46.12	48.78	51.82
29	2.5	0.450	606	1514	0	30	0	46.61	43.47	46.49	48.09
30	2.5	0.475	597	1492	0	89	0	43.73	40.28	44.64	45.06
31	2.5	0.500	588	1470	0	179	0	39.71	36.38	42.8	42.07
32	2.5	0.35	450	1125	0	-	0	55.7	52.72	57.2	63
33	2.5	0.35	445.5	1125	0	-	4.5	60.5	53.23	56.72	62.7
34	2.5	0.35	441	1125	0	-	9	65.8	53.72	56.24	62.46
35	2.5	0.35	436.5	1125	0	-	13.5	70.5	54.18	55.76	62.18
36	2.5	0.4	450	1125	0	-	0	46.87	47.37	51.2	46.87
37	2.5	0.4	445.5	1125	0	-	4.5	46.64	47.76	50.78	46.64
38	2.5	0.4	441	1125	0	-	9	46.41	48.14	50.36	46.41
39	2.5	0.4	436.5	1125	0	-	13.5	46.18	48.49	49.94	46.18
40	2.5	0.5	450	1125	0	-	0	24.81	38.58	42.8	24.81
41	2.5	0.5	445.5	1125	0	-	4.5	24.63	38.78	42.46	24.63
42	2.5	0.5	441	1125	0	-	9	24.46	38.96	42.12	24.46
43	2.5	0.5	436.5	1125	0	-	13.5	24.29	39.11	41.79	24.29
44	2.5	0.350	645	1612	2.2	62	0	54.88	52.80	57.14	65.7
45	2.5	0.375	635	1586	1.85	75	0	52.35	49.85	54.02	60.49
46	2.5	0.4	625	1562	1.35	72	0	49.70	47.33	51.2	55.81
47	2.5	0.425	615	1538	1.25	67	0	46.77	45.08	48.76	51.82
48	2.75	0.400	592	1628	0	10	0	51.75	48.69	51.16	54.53
49	2.75	0.425	583	1604	0	18	0	51.03	46.12	48.69	50.56
50	2.75	0.450	575	1581	0	45	0	44.57	43.31	46.49	47.07
51	2.75	0.475	567	1559	0	95	0	41.84	40.26	44.61	44.07
52	2.75	0.500	559	1537	0	189	0	39.75	36.37	42.96	41.29

Fine Aggregates = FA, Binder = B, Water = W, Super Plasticizer= PS, Nano silica = NS, Compressive strength 28 - days = Fc

A three-dimensional figure was drawn for each mix design based on the compressive strength in order to examine the accuracy of the proposed equations. Figure 1 shows the prediction fit line of the three equations for the mix design of Ferrocement mortar. In this mix design, nano silica was used in the Ferrocement mortar. Considering that no parameter as nano silica or micro silica was determined in equations 1 and 2 proposed by previous researchers, the standard deviation of these two equations is less than that of the equation proposed in this study, and their error is greater than that of the equation proposed in this study. Given that the nano silica and micro silica were not used in the mix design of the cement mortar, but the value of its slump was reported, and equations 1 and 2 did not take into account the effect of slump on the compressive strength of the cement mortar.

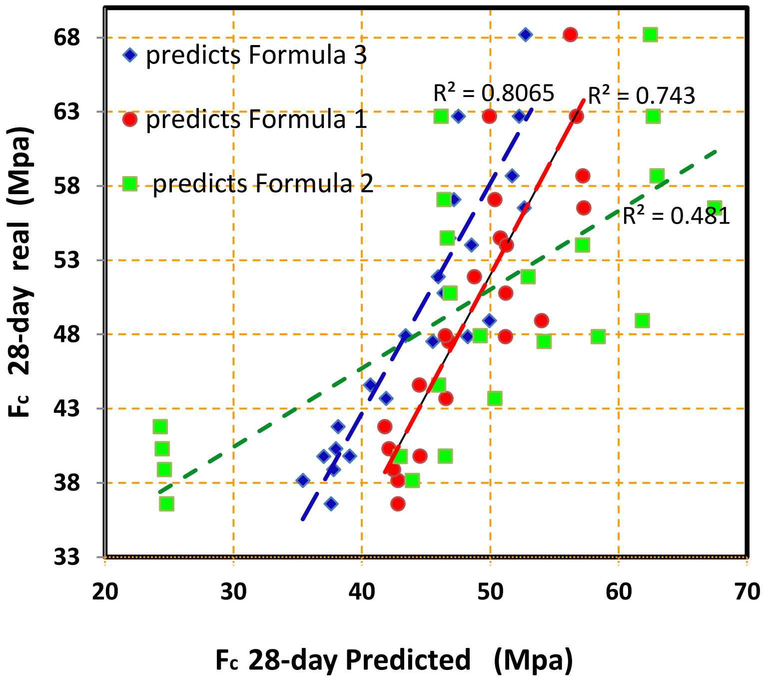


Fig1. Prediction of Ferro-cement mortar by suggestion fournula1

Figure 2 shows the effect of W/B and nano silica on the compressive strength and their comparison.

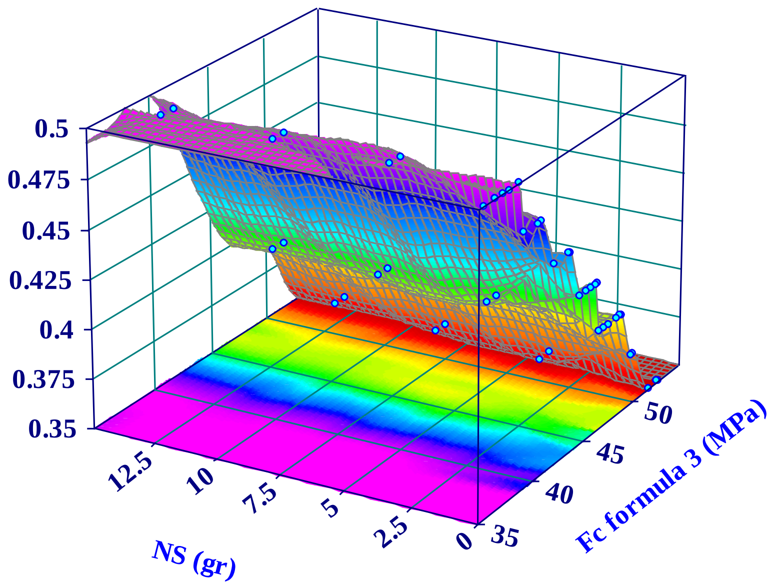
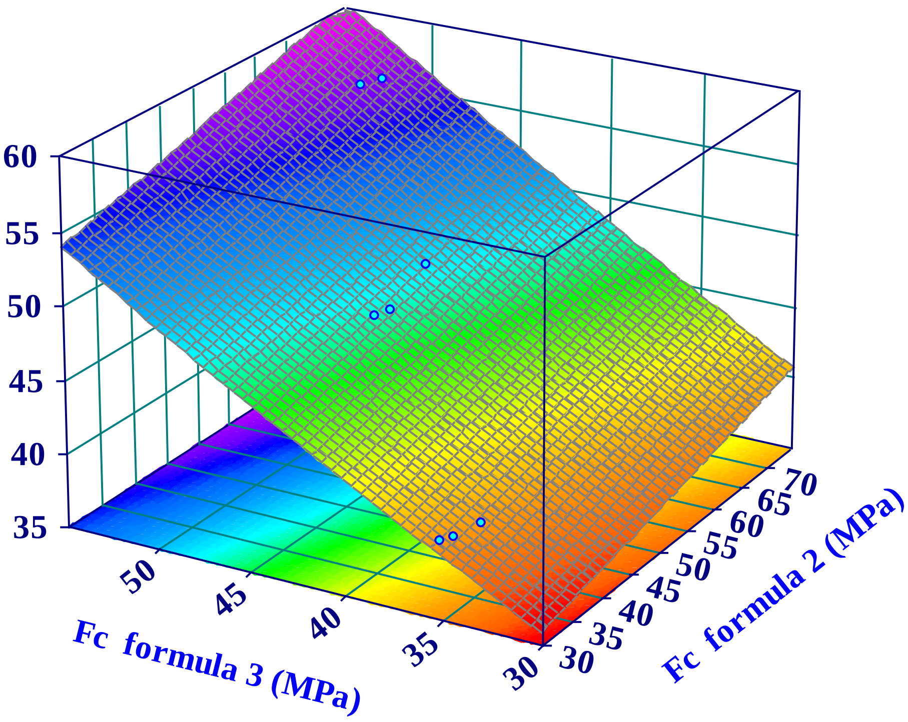


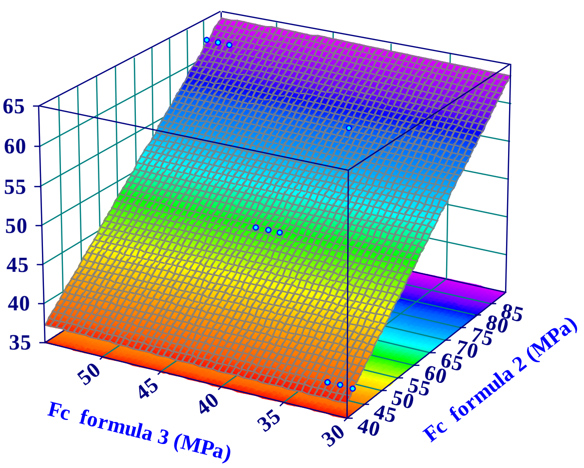
Fig.2 Comparison of W/B and NS and Fc.

The figure shows that the increase in the amount of nano silica when the strength ranges 35-42 MPa will increase the compressive strength, and higher strengths could not be really compared due to the lack of lab data. Moreover, the comparison of W/B with the compressive strength in the figure revealed that the increase in the above ratio resulted in the reduction of the compressive strength.

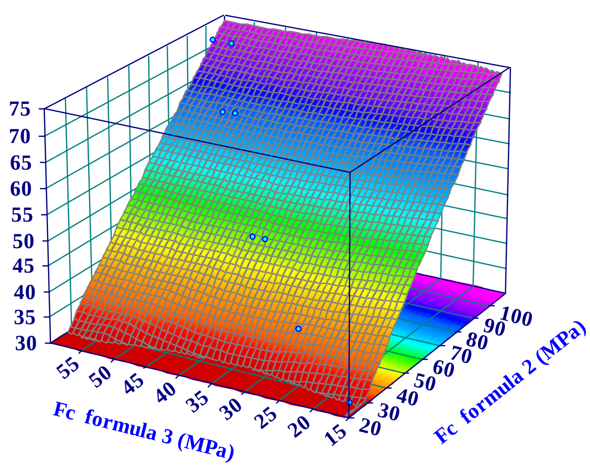
Figure 3-A is the three-dimensional depiction of the compressive strength of the equations and standards of designing through DIN method. The figure shows that the compressive strengths are more dispersed when the strength increases from 30 MPa to 60 MPa, and if the strength is closer to 30 MPa, the three methods strengths will be closer. Therefore, it can be concluded that the equations of previous researchers more conformed to the DIN codes for concretes with normal strength, and in respect of high-strength concretes, different parameters largely affected the strength and could not be predicted through simple equations.



A



B



C

Fig.3 Comparison of Fc by formula 1, 2, 3 for DIN (A), ACI (B), BS (C) Standard.

Figure 3-B is the three-dimensional depiction of the compressive strength of the equations and standards of designing through ACI method. The strength of the mix design using ACI method more conformed to the three equations; especially in the compressive strength range 15-40 MPa. Furthermore, the data dispersion at high compressive strength in this method was more accurate than that in DIN method. Compared to other equations, Equation 3 was closer to the ACI method in prediction of the compressive strength. It should be noted that Equation 1 made a greater error than Equation 3 did because parameters of Equation 1 were linear, and it did not take account of the parameters affecting the compressive strength of the cement mortar. Figure 3-C depicts the comparison of the mix design using BS with the equations and has a more gentle slope than Figure 3 does, and this might be due to the unclear slump of the mortar because the advantage of the proposed equation is to take into account the slump of the mortar that leads to the prediction of the strength of the mortar more accurately than other equations do.

The effect of c/w on the 28-days compressive strength of the ferrocement mortar is more than that of Fa/c, and it should be considered in equations. It must be noted that the compressive strength of the cement alone has received less attention. If the effect of this compressive strength can be determined, the fresh and mechanical properties of the ferrocement mortar are significantly changed, and this cannot be ignored.

Finally, based on the studies, the compressive strength of the ferrocement mortar containing nano silica and micro silica can be predicted with a favorable approximate through choosing the parameters, their appropriate proportions, and proper limits. Moreover, the prediction of the compressive strength using the equations formulated on the basis of weight ratios of the mix design is more accurate than that using other methods, including statistical methods. In this regard, a comprehensive equation can be used for prediction of the compressive strength in a broad spectrum of mix designs

6. Conclusions

Based on the results of this research, the below conclusions can be drowned:

1- The 28-days compressive strength of the ferrocement mortar can be predicted using the proposed equation with its appropriate constrained.

2- Because the relationship between the strength of concrete and its components are nonlinear, furthermore, the physical property of fresh concrete and concrete additives in the final strength is effective and equation 3 involving both subjects:

$$f_{c(MPa)} = 10(\log_{10}\left(\left(\frac{c}{w}\right)^{10} \times \frac{Fa}{c}\right)) + \frac{w-s}{50} + N + M \qquad (3)$$

Prediction of compressive strength of concrete will be better that in comparison with equation 1and 2 due to that equation 1 is linear and equation 2 just involved amount of w/b.

4- Results show that the proposed equation (Eq. 3) for ACI standard, the predictions will closer to reality in comparison with other standards such as BS and DIN.

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