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The Application of Taguchi Method for Obtaining Optimized HPFRCC Mixture Design and Presenting a Linear Model for Determining Compressive Strength

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Abstract: This study has investigated the effect of different sand granularity and also microsilice percents on the compressive strength of self-compacting cement composites' matrix with high performance in laboratory. In this regard, 8 mixture designs were studied in order to obtain optimized granular martix and a more optimal mix design was selected in terms of compressive strenght. In order to achive optimal mix design, 8 test samples were developed by Taguchi algorithm and undergone compressive strength. The 8 samples from two basic design in 6 graularity factors were samples. In other 6 mix designs for optimal granularity, ratios 5, 10, 15, 20, 25 and 30% microsilice to cement were studied until the optimal matrix regrding compressive strength for using self compacting High Performane Fiber-Reinforced Cementitious Composites (HPFRCC) was determined. Then, 1 and 2% ribbed plastic fibre was added and compressive and tensile strength tests were conducted on these samples. In order to study the characteristics of fresh concrete including self-compact concrete flow, slump test and for transmission capapcity and self-compact concrete stability against separation, L-shape test was conducted. Results of this study showed that type of sand granularity has essential role in the tests of fresh concrete and compressive strength. Because of brittleness of matrix, addig fibres has high effect on the increase of compressive strength and prevention of brittle break out along with cracks due to not usig coarse grains and microsilice as a pozzolan and filling material has positive role for improving characteristics of this matrix.

Key words: Sand granulaity, optimal matrix, self-compact concrete, microsilice, ribbed palstic fibre, HPFRCC

INTRODUCTION

During recent year, we have observed frequent earthquakes in the country. There are also structures in the country that their inadequacy against earthquake has become clear. Therefore, researcher tries to introduce a new generation of concrete as self-compact High Performance Reinforced Cementitious Composites (HPFRCC) in order to improve these structures.

Adding pozzolan materials to concrete not only improves the strength characteristics of concrete but also causes widespread increase in its durability. Microsilice is known as the widely used and economic pozzolan in concrete community in Iran and throughout the world. In this study, we tried that by adding different percent of microsilice in order to obtain optimal matrix for using in HPFRCC, document changes in the compressive strength as an indicator of concrete strength characteristics. Based on this, mix designs was set and all tests were conducted and compared in age 7, 28 and 42 days.

Self-compact concrete is a new phenomenon in aggregate science which only two decades age. This concrete compacts under its weight without need to any shaker and has high efficiency. Implementation problem and high cost of labor in Japan enhanced the idea of developing self-compact concrete by Okamoura in 1986 and the first instance of self-compact concrete was completed and developed in 1988. This concrete with its special characteristics, provides new facilities that by using them, we can cope the problem of unsuitable compactness in concrete structures including reduction in age and durability of the structures (Okamura, 1997). Although, significant time has passed from late 1980s that self-compact concrete was introduces but there is no yet standard mix design. Presented recommendations only determine the ratio of aggregates which is only a guide and there is no acceptable universal method. Therefore, mix design is based on the trial and error. Self-compact concrete mixes contain strong lubricants and viscosity correcting additives or powder materials are used to maintain the viscosity. Super lubricant is necessary in order to produce concrete with flowing capability. Amount of coarse grain in self-compact concrete is less than conventional concrete in order to reduce the risk of blocking concrete inside reinforcements (Swamy and Bandyopadhyay, 1975).

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Mix designs of this concrete all include cement without coarse grain. Therefore, they are called grout or fiber reinforced cement composites. This cement composites have many applications, separately or along with steel reinforcements and pre-stress anchor. These aggregates are used as repair and improvement aggregates. Single applications include thick productions like roof coverage, cement tables, pipes, meshed slabs and superstructure. Fiber which is one of the indicators of this concrete, is used in compound applications in order to enhance other structure aggregates like reinforced and pre-stressed concrete and steel. An example of these applications is structures resistive against earthquake, impact, reinforced beams and columns and burying beams and trusses in composited in the steel in order to improve ductility. Particular applications include decks of bridges and offshore platforms, air stations, very tall structures and structures resistive against the explosion and structures related to banks and other important structures. HPFRCC (Shi and Yilung, 2008) was first distinguished by Namman and Reinhardt in 1996 from FRC. In 1990s with careful look are the structure of matrix, fiber and break out mechanism, new generation of fiber concrete, i.e., FRC was innovated with special performance or HPFRCC. In one hand, fiber-reinforced cement concrete is used because of suitable viscosity, high lubrication, improvement of durability and mechanical characteristics like shrinkage strain and compressive, tensile and bending strength in different renewal and improvement purposes (Li and Wang, 2003). Obvious increase in tensile strength and ductility and decrease in shrinkage are common effects in the fiber-reinforced cement composites (Sangtarashha *et al.*, 2009). High cement volume in the self-compact cement composites causes excess shrinkage and reduces their ductility. This makes using self-compact mixes in the repairing structures difficult, especially in seismic areas. In addition, cracks caused by tensile stresses of shrinkage are canals for entering harmful external factors which reduces the durability of composite and the structure in long-term (Bissonnette *et al.*, 1999). Fine-grain and its ratio in this concrete has important effect. An optimal graining has continuous distribution in graining, minimum void spaces and amount of cement for filling void spaces.

Therefore, researcher first considers effect of size and granularity of sand grains in mix designs. Then, different microsilice to cement percent in optimal mix design is evaluated regarding compressive strength in the best granularity. Finally, 1 and 2% ribbed plastic fibers are added to the design and by conducting tests on the fresh concrete their compressive strength is evaluated.

METHODOLOGY

Aggregates: Consumed sand was natural and river type sand that its specific weight is 2.6 g/cm^3, softness module is 2.8 and moisture absorption in 5%. Consumed cement is type II cement from Delijan cement factory with specific weight 3.15 g/cm^3. Super lubricant is Poly Carboxylic Ether (PCE) based on carboxylit. Microsilice used in this study obtained from Semnan ferrosilicon factory which has specific surface 35500 cm g^{-1}.

Mix ratios: At first, 8 mix designs based on 2 levels and 6 factors were developed from Taguchi analysis according to Table 1. But, considering that by conducting self-compact tests, compressive tests were taken from mix designs, all designs were compared regarding the compressive strength. In next step, different percent of microsilice was added to the optimal mix design obtained by Taguchi analysis and then, compressive strength test was done on 6 samples with same graining and optimal mix design was determined. Then, 1 and 2% ribbed polymer fiber was added to optimal mix design and compressive and tensile tests. Tests related to self-compact concrete was conducted on the designs.

Constructing samples: For each mix design, 9 cubic samples by dimensions 10×10×10 (cm) and 72 samples were developed. For designs containing fibers in addition to cubic samples, 4 cylindrical 15×30 samples were developed for testing compressive strength. In order to maintain the moisture of concrete surface in 24 h concrete molds were maintained under plastic, then removed from molds and placed in the water in 18°C. Mixing was such that first, sand is mixed with one-third water and then cement is added to the mixture. Water and lubricant is added to the mixture and in mixed designs containing microsilice, cement and microsilice was separately mixed and then added to the mixture. In mixtures containing fibers, fiber is added in the last step to the mixture, although 4-5 min was recommended in these references but due to test conditions and completing the mixture, fiber is mixed 8 min with the concrete.

Taguchi algorithm: In order to find suitable orthogonal array and signal to noise values related to each factor

Table 1: Basic designs and factors for Taguchi algorithm

Basic design	Desing factors (mm) 0/25-0/15	0/3-0/25	1/2-0/3	1/7-1/2	2-1/7	4/75-2
1	4/11	2/74	1/668	6/322	7/65	440
2	3/2	8/14	6/133	5/64	1/13	6/913

Table 2: Suggested mix designs based on Taguchi algorithm in Minitab

Designs	Sand (kg/m^3) 0/25-0/15 (mm)	0/3-0/25 (mm)	1/2-0/3 (mm)	1/7-1/2 (mm)	2-1/7 (mm)	75/4-2 (mm)	Cement (kg/m^3)	Water (kg/m^3)	Super lubricant (kg/m^3)
A	4/11	2/74	1/668	6/322	7/65	440	700	286	10
B	4/11	2/74	1/668	5/64	1/13	6/913	700	286	10
C	4/11	8/14	6/133	6/322	7/65	6/913	700	286	10
D	4/11	8/14	6/133	5/64	1/13	440	700	286	10
E	3/2	2/74	6/133	6/322	1/12	440	700	286	10
F	3/2	2/74	6/133	5/64	7/65	6/913	700	286	10
G	3/2	8/74	1/668	6/322	1/13	6/913	700	286	10
H	3/2	8/14	1/668	5/64	7/65	440	700	286	10

Table 3: Results of fresh concrete test in self-compact design

	Slump flow		V-shape funnel		L-shape box	
Designs	Slump (cm)	T_{50cm} (sec)	T (sec)	T_{5min} (sec)	H_1/H_2	$T_{40-20cm}$ (sec)
A	54	4/3	4/5	9/9	67/0	3/3
B	56	2/3	1/6	4/10	65/0	5/2
C	52	5/3	5/5	8/10	55/0	7/2
D	50	4/4	7/5	2/11	63/0	8/2
E	49	5/4	3/5	11	61/0	9/3
F	51	8/5	1/5	1/12	59/0	2/3
G	48	1/7	7/4	4/12	51/0	1/4
H	55	7/3	6	1/10	66/0	5/3

Table 4: Compressive strength of suggested designs based on the algorithm

Designs	Compressive strength (kg/cm^2) 7 days	28 days	42 days	Weight of sample (g)
A	535	605	616	2505
B	510	580	598	2680
C	507	565	580	2490
D	564	589	608	1950
E	547	593	610	2130
F	516	587	604	2220
G	529	585	609	2860
H	505	542	564	2240

from MATLAB Software was used. Regarding that our purpose is reaching to maximum compressive strength, we used the expression “larger is better” in the software. According to Table 1-3, we will consider the number of levels and factors in Taguchi algorithm in Minitab program such that algorithm is considered in 2 levels and 6 factors. These 6 factors are based on Table 1 of grains. These two designs were tested and have self-compact concrete conditions.

Table 4 shows the results of compressive strength of three samples in which compressive strength of 8 mixture design was documented and compared in ages 7, 28 and 42 days in which design A had the highest compressive strength.

Then, design A which has the most optimal sand graining regarding maximum compressive strength and self-compact characteristics was selected and 5, 10, 15, 20, 25 and 30% microsilice was added to cement that their details were shown in Table 5.

A significant point in self-compact tests is that not using coarse grains has positive effect on homogenity and prevention of deparating cement grout. In plastic phase, it improves transmission capacity from reinforcement mesh. Fine grain sands have significant effect in slump test for the speed of concrete flow (Table 6 and 7).

Figure 1-4 show the linear changes of concrete efficency with the increase of microsilicce in relation to optimal design A.

Rgarding Fig. 1 and 2, we can find that using 20% microsilice to cement increases the diameter of slump flow and reduces the time to reaching diameter 50 cm. As seen, using excess amounts reduces the diameter of slump flow because of blocking and increases the time to reach diameter 50 cm.

Regarding Fig. 3 and 4, it was seen that by increasing microsilice, the speed of concrete movement in horizontal line of L box increases and this trend continues until the ratio 20% microsilice to cement was added. Increase in microsilice reduces the speed of passing from horizontal surface box L. As expected in addition to compressive strength, Fig. 1-4 show that mix design M is minimum or maximum.

After sample M was selected as optimal mix design, to this 1 and 2% volume, ribbed polymer fibers 9 and 18 kg in m^3 was added and called P and Q design. Compressive and tensile strength tests were conducted on these designs. Results of fresh and hardened composite tests are presente in Table 8-9.

As predicted, regarding Table 8, increase in fiber in HPFRCC has significant effect on the efficeny. For example by increasing 18 kg/m^3 ribbed polymer fiber, 24 cm of slump flow diameter to optimal matrix reduces. The time to reach diameter 50 cm is also increased.

As results of V-shape funnel increases, increase in fiber increases visocity such that by increase in cosumed fiber, time of exiting concrete from funnel has increased.

As seen, adding fibers has not significant effect on the compressive strength. But adding 1 and 2% fibers to compressive strength optimal matrix, increases it 4 and 5.3 times.

Table 5: Final mix designs to achieve optimal matrix for mix design A

	Sand (kg/m^3)									
Designs	0/25-0/15 (mm)	0/3-0/25 (mm)	1/2-0/3 (mm)	1/7-1/2 (mm)	2-1/7 (mm)	75/4-2 (mm)	Cement (kg/m^3)	Water (kg/m^3)	Microsilice (kg/m^3)	Super lubricant (kg/m^3)
J	4/11	2/74	1/668	6/322	7/65	440	700	286	35	5/10
K	4/11	2/74	1/668	6/322	7/65	440	700	286	70	11
L	4/11	2/74	1/668	6/322	7/65	440	700	286	105	5/11
M	4/11	2/74	1/668	6/322	7/65	440	700	286	140	12
N	4/11	2/74	1/668	6/322	7/65	440	700	286	175	5/12
O	4/11	2/74	1/668	6/322	7/65	440	700	286	210	13

Table 6: Results of fresh concrete tests for final designs

	Slump flow		V-shape funnel		L-shape box	
Designs	Slump (cm)	T_{50cm} (sec)	T (sec)	T_{5min} (sec)	H_1/H_2	$T_{40-20cm}$ (sec)
J	68	8/2	9/4	7/8	65/0	5/2
K	70	3/2	5/5	3/9	67/0	2/3
L	74	1/2	9/5	4/9	73/0	3
M	76	9/1	1/6	9/9	81/0	3/2
N	76	2/2	7/5	5/9	75/0	5/5
O	77	2	3/6	10	78/0	4/2

Table 7: Compressive strength for secondary designs

	Compressive strength (kg/cm^2)			
Designs	7 days	28 days	42 days	Sample weight (g)
J	547	700	740	2650
K	575	696	748	2650
L	538	771	765	2670
M	589	786	780	2685
N	518	710	680	2690
O	490	660	678	2700

Table 8: Fresh HPFRCC test results

	Slump flow		V-shape funnel		L-shape box	
Designs	Slump (cm)	T_{50cm} (sec)	T (sec)	T_{5min} (sec)	H_1/H_2	$T_{40-20cm}$ (sec)
P	59	4/2	5/7	12	78/0	1/2
Q	52	9/3	1/8	3/15	89/0	8/1

Table 9: Compressive and tensile strength of final designs

Designs	Compressive strength (28 days) (kg/cm^2)	Tensile strength (kg/cm^2)	Weight
M	786	30	2685
P	791	120	2688
Q	798	160	2691

MATHEMATICAL MODEL FOR OPTIMAL MIX DESIGN WITH STATISTICAL METHODS

Optimization of mix ratios for concretes with high efficency which includes different components and constraints is a difficult and time-consuming work. Statistical empirical design and analytic methods were established in order to optimize mix design of products like concrete that their final characteristics depends on the their relative vlaue but this is not much considered in concrete industry (Simon *et al*., 1997).

In simple words, concrete is a mix of water, portland cement, fine and coarse gran aggregates. Additional components like chemical composition and mineral compounds may add in order to increase certain charcteristic of fresh or hardened concrete to main mix. Concretes with high efficency typically has 6 elements.

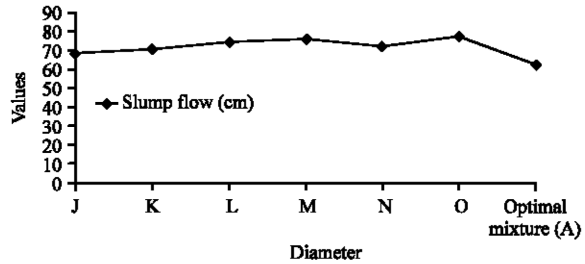

Fig. 1: Linear diagram of slump flow

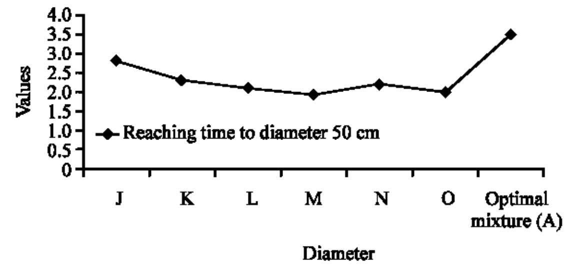

Fig. 2: Linear diagram for reaching to diameter 50 cm

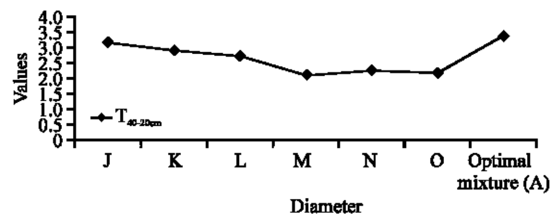

Fig. 3: Linear diagram $T_{40-20cm}$ (sec)

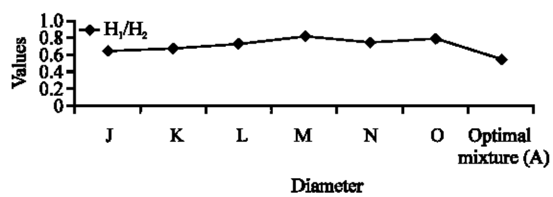

Fig. 4: Linear diagram H_1/H_2

Table 10: Mix components and their limit

Upper bound	Lower bound	Variable	Sand granuarity (mm)
25/0-15/0	X_1	2/3	11/4
30/0-25/0	X_2	14/8	74/2
2/1-30/0	X_3	133/6	668/1
7/1-2/1	X_4	64/5	322/6
2-7/1	X_5	13/1	65/7
2-4/75	X_6	440	913/6

In this research, 6 factors which are granularity are considered as design variables. Table 10 shows the variable with graining and upper and lower bound fot that variable.

Selection of test design depends on several criteria likne estimation of major model, estimation of repeatability and conformity with the model. The best test design depends on selecting main model which explains data. For this test, first-order Scheffe polynominal was selected as an acceptable model for each charateristic which is function of 6 components. Linear model presented for 42 days strength based on design variables is:

$$Y = a_1X_1 + a_2X_2 + a_3X_3 + a_4X_4 + a_5X_5 + a_6X_6$$

In this relation, Y is 42 days compressive strength and a_i is constant coefficent. X_i shows volume of components that:

$$X_1 + X_2 + X_3 + X_4 + X_5 + X_6 = 1$$

Regarding above formual, there is a need to conduct 6 tests for a_i constant coefficents. Results of these tests are presented in Table 2 and 4. By solving one system with 6 equations and 6 unknowns these constant coefficent is determied:

$$Y = -2409X_1 + 454X_2 + 376X_3 + 540X_4 - 2035X_5 + 851X_6$$

From non-linear model, we can conclude that the highest effect belongs to increase in grain volume (2-4.75) and reduction in graining (0.15-0.25) in 42 days compressive strength.

CONCLUSION

- The best sand grain size for HPFRCC concrete matrix with 40% sand is 0.3-1.2 mm
- Using microsilice has positive effects on the rheologic features of self-compact cement concrete. Although, we know that microsilice or pozzolan enhances the cement-based concretes
- Amount of optimal microsilice in this concrete is 20% that as seen in above diagrams, excess consumption has negative effect on rheologic characteristics of self-compact characteristics and reduces the compressive strength in low ages and has not considerable in the compressive strength in high ages
- Microsilice as a pozzolan and filling meterial has positive role on the improement of features of this matrix. Due to fine grains by filling voids, it improves cement microstructure
- Using ribbed fibers increases friction strength with concrte and transfers tensile stresses in wide cracks and increase in ductility and absorbing more energy. Using fibers reduces efficency and characteristics of fresh concrete that has acceptable results compared to fiber concretes
- Linear Scheffe polynominal for HPFRCC concrete showed that the effect of fine to coarse grain ratio in compressive strength is 3 times. Increase in fine grain and decrease in coarse grain decreases 42 days compressive strength

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