Front. Struct. Civ. Eng. 2019, 13(4): 821–830
https://doi.org/10.1007/s11709-019-0518-6

RESEARCH ARTICLE

Optimizing the compressive strength of concrete containing micro-silica, nano-silica, and polypropylene fibers using extreme vertices mixture design

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ABSTRACT Many studies have evaluated the effects of additives such as nano-silica (NS), micro-silica (MS) and polymer fibers on optimizing the mechanical properties of concrete, such as compressive strength. Nowadays, with progress in cement industry provides, it has become possible to produce cement type I with strength classes of 32.5, 42.5, and 52.5 MPa. On the one hand, the microstructure of cement has changed, and modified by NS, MS, and polymers; therefore it is very important to determine the optimal percentage of each additives for those CSCs. In this study, 12 mix designs containing different percentages of MS, NS, and polymer fibers in three cement strength classes(CSCs) (32.5, 42.5, and 52.5 MPa) were designed and constructed based on the mixture method. Results indicated the sensitivity of each CSCs can be different on the NS or MS in compressive strength of concrete. Consequently, strength classes have a significant effect on the amount of MS and NS in mix design of concrete. While, polymer fibers don't have significant effect in compressive strength considering CSCs.

KEYWORDS mixture method, compressive strength, nano-silica, micro-silica, polypropylene fibers

1 Introduction

To produce a strong concrete with a specific compressive strength, studies on the amount of compounds and related additives are required, and even, account should be taken of, the rotation time of the mixer system at every stage, to make an optimal mixing plan for improvement of the characteristics of concrete or reduce production costs [1–7]. According to the British Standard [8], Sika manual [9], and the Indian Conventional and Reinforced Standard [10], cement compressive strength is one of the factors that affect the compressive strength of concrete and mortar which should be taken into account during cement processing. Recently, cement strength classes(CSCs), that is, 32.5, 42.5, and 52.5 MPa, were applied on various structural types under the same conditions of production, operation, and testing, which in turn resulted in different amounts of compressive strength [11]. In the present paper, fiber mixtures were used in the concrete to improve the ductility and strength of concrete structures against continuous loading, impact, fatigue, and earthquake [12,13]. Among the various types of fibers, polypropylene has attracted the attention of researchers due to its characteristics like reduced weight and cost, neutrality, resistance to corrosion and acids, excellent toughness, and increased resistance to contractive cracking [14–16]. Reinforcement fibers are used to reduce crack development growth in the structure and to improve the tensile and flexural strength of concrete [17–20]. Now, considering that fiber has no significant effect on the compressive strength of concrete, the nano-silica (NS) factor with a pozzolanic feature is very promising for the concrete technology and for improving the characteristics of concrete [21–28]. NS is an additive called polymer, which has an additional effect on concrete by improving durability, mechanical properties, concrete performance, strength, and flexibility, to enhance concrete. Since NS is effective in concrete mechanical properties, it increases

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Article history: Received Mar 5, 2018; Accepted Jun 24, 2018

resistance to water penetration and 28-day compressive strength of concrete by increasing the cement adhesion resistance [27,29–31]. NS increases the compressive strength of concrete by filling concrete pores, increases the density by filling empty spaces between cement grains, accelerates the cement hydration, and increases the strength of hardened cement paste in the early age of concrete [32–36]. Characteristics of NS used in concrete are improvement of microstructures, reduced permeability, reduced porosity, and increased compressive strength [7,37,38]. Characteristics of the concrete mixed with certain percentages of NS in the cement paste are shown in this study to enhance the mechanical properties of hardened cement paste, compressive strength, and concrete permeability [39–41]. In addition, due to the fact that NS increases compressive strength, this study also used micro silicon and silica fume, also called micro-silica (MS), a byproduct used as pozzolan [42]. The particle softness of MS makes its grains 100 times smaller and softer than cement, and this gives MS the filling and pozzolanic properties, filling the pores between the cement grains in concrete, increasing the reaction surface to mediate the microscopic response of concrete and also, to increase the concrete strength and stability of aggregates, and reduce the permeability [43–48]. Qing et al. [32] showed that NS has better pozzolanic characteristics than MS and increases the strength [7]. Nili et al. [49] considered in their study that a mixture of 6% MS and 7% NS, aged 7 and 28 days, respectively, has a higher compressive strength. Investigating various percentages of NS and MS, Li et al. [28] revealed that addition of 10% NS and MS separately to cement, increased the compressive strength of concrete by 26% and 15%, respectively. There are several ways to optimize the mixing plan, specifically, optimal design of experiment (DOE), factorial design, Taguchi design, response level design, and mixture design. Since they are rapid and cost effective, they can optimize more than one variable at a time [50,51]. Optimization methods are used to reduce the time of the experiment, and such a design shows the effects of interactions between the variables by using mathematical models [52–54]. The experimental modeling of a statistical method can reduce the number of experiments significantly and increase the conclusion reliability [55]. Optimal DOE is a better alternative for studying the effect of input parameters with fewer experiments and the result of mixture modeling for process improvement, product development and optimization is one of the management principles in the cement and concrete industry [56–58]. The standard mixture design includes the following models: simplex-lattice, simplex-centroid, and extreme vertices; the latter was used in this study [59,60]. The extreme vertices methodology is used in modeling with advanced boundary constraints [61]. Here, a type of modeling with statistical analysis was used to identify the best factor for optimization of concrete properties [62]. So far, there has been no research on the optimization of compressive strength of concrete by extreme vertices. Here, the article about to investigate the effect of factors such as polypropylene fibers, MS, NS, and water to cement ratio on mechanical properties of concrete, like the compressive strength of concrete made with CSCs 32.5, 42.5, and 52.5 in 28 days with 36 laboratory samples in 12 mixing designs using the mixture optimization methodology.

2 Experimental

2.1 Materials and instruments

In this research, three strength classes of Portland cement types 32.5, 42.5, and 52.5 (MPa) were used. Cement type I was obtained from Sabzevar Cement Factory and Cement type II from Torbat Heydarieh Cement Factory. Fine- and coarse-grained siliceous aggregates were used according to the grading in the ASTM Standard in relation to grading of aggregates used in concrete. It should be noted that the percentage of fine- grains used is 50% w.r.t of the total fine- and coarse-grains. Silica fume added during mixing was powdery and gray in color. This multipurpose mixture is used to increase durability, strength, and density as well as make the concrete resistant to sulfate and to reduce permeability. NS used was a super-pozzolan colorless liquid based on nanotechnology which is very effective and used in small amounts. Polymer fibers (polypropylene) are used as secondary reinforcement of concrete or mortar to reduce shrinkage and cracking and increase the durability of concrete in the long run. The fibers are added to the dry or fresh mixture together with other aggregates according to the manufacturer's instructions at the time of construction. Based on expectations, the amount used varied between 0.5 and 2 kg/m^3. Another method is to mix the fibers in water before adding to the dry mixture. In the present study, the fibers were mixed using the first method. In addition, a polycarboxylate (PCE) based super-lubricant was applied in the aggregates by 0.2% to 1.2% of the cement weight percentage (depending on the slump considered).

In this study, (10 cm × 10 cm × 10 cm) experimental cubic samples were constructed for determination of compressive strength, in 12 mix designs and with three cement strength class types, with the number of samples totaling 36 sample designs shown in Fig. 1. The mixture plan for constructed concrete samples is given by weight in Table 1. As shown in the mixture plan table, mixture plan 1 is taken as the control and has no fiber. The mixture plans 2 to 6 do contain fibers and have a water to cement ratio of 0.5; also, mixture plans 7 to 12 contain MS and NS and have a water to cement ratio of 0.4. In the second group of six mixture plans, the combined effect of MS and NS on

Fig. 1 Construction and testing process of the specimens

the compressive strength of the concrete was considered. The total amount of MS and NS is 10% of the cement weight, which is the same in all relevant mixture designs (7 to 12), the difference being in the amounts of MS and NS.

2.2 Experimental design

In this study, Minitab 16 software package was used to accurately design the precise combination of the vertices mixture design, analysis of experimental data and optimization of the required proportion of three component mixture of MS (*X*1), NS (*X*2) and polypropylene fibers (*X*3) for optimize the compressive strength [59].

By using extreme vertices design the Minitab software generated 17 runs for each compressive strength and experimentally for each run prior to model and so far optimizing the first mixture proportion with the software the production rate optimize of component were determined. To applying results for modeling, each experiment repeated at least three times.

Extreme vertices design is a method used in mixture experiments when constraints are applied on factors. These factor constraints reduce the spatial volume of the factors and the factor level from 0 to 100%. Also, design of the acute angles (vertices) can only be a choice for correction of the amplitude of the angles. Its determination of the linear constraints may justify limiting the factors and choosing the vertex and its mean as the design points. The extreme vertices design is an optimal mixing plan that only covers smaller spaces inside the simplex. This method is used when the design space of the lattice is not simplex. The current study design is subject to limitations by upper and lower bounds, and the extreme vertices design aims to choose the design points that cover the space sufficiently [61].

3 Results and discussion

3.1 Cox response trace plots

The effect of NS, MS, and polymer fibers variables as well as the sensitivity level of each of the variables, based on the response (compressive strength) is shown in Fig. 2 as well as its effects. For all three types of CSCs (32.5, 42.5, and 52.5 MPa) separately, MS and NS as well as polypropylene fibers with CSC of 32.5 MPa is presented in Fig. 2(a). It shows that increasing amounts of nano and micro-concrete improves compressive strength at 28 days. It has also been confirmed by other researchers. On the other hand, the question of which variable has a greater impact on the improvement and the process expressed through the variable sensitivity [59,63]. Here, the MS and NS variables are more susceptible to polypropylene fibers and increasing the amount of fiber does not have much effect on improving the compressive strength. Also, between two sensitive variables MS and NS show sensitivity. Researchers have stated that the addition of MS is due to filling as well as pozzolanic properties which make filling the pores between particles of cement in concrete and by increasing the reaction level cause improvement in the compressive strength of concrete in CSC of 32.5 MPa [64,65].

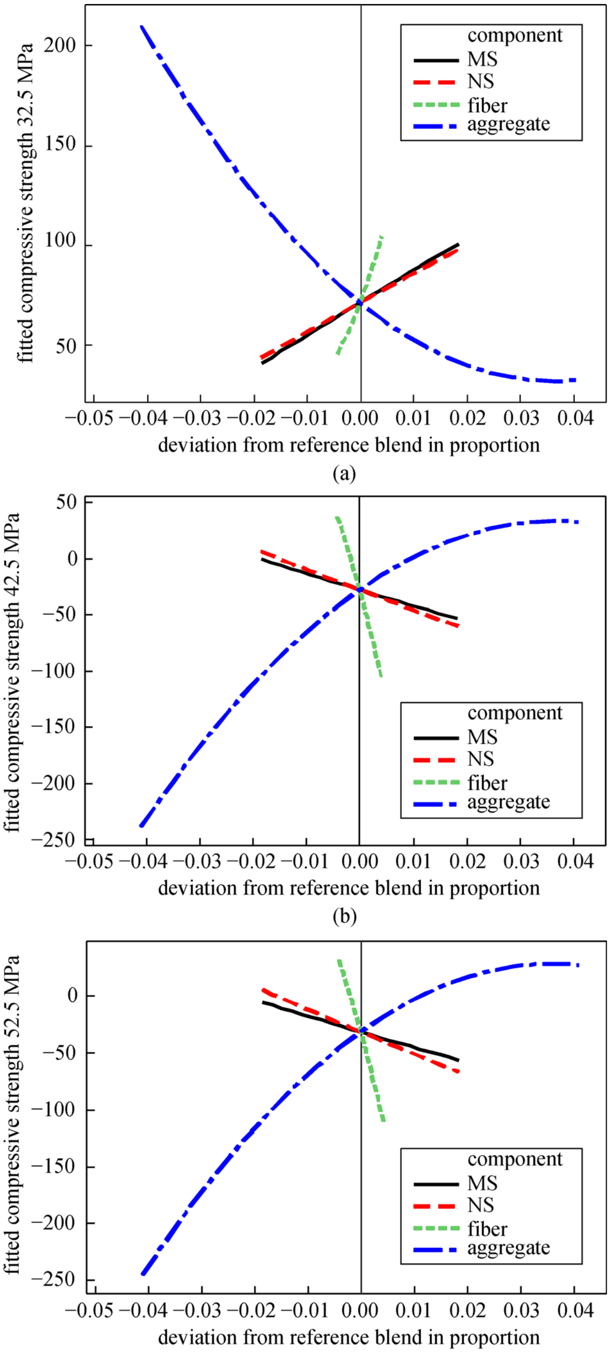
The sensitivity of variables on compressive strength, for example where CSCs of 42.5 and 52.5 MPa have been used, respectively, is as shown in Figs. 2(b) and 2(c). Increasing the amount of MS, NS, and fiber in these two graphs decreases compressive strength; this result is also seen through the gradient of the graph. On the other hand, there are more sensitive MS and NS variables on the response.

From Fig. 2, it can be concluded that cement with a strength class of 32.5 MPa, has a greater sensitivity

Table 1 Mix design of concrete containing, MS and NS and polypropylene fibers

plan number	cement(g)	water(g)	NS	MS	aggregate (g)	fiber
$C_{32.5}P_0$	1330	665	0.0%	0.0%	3600	0.0%
$C_{42.5}P_0$	1330	665	0.0%	0.0%	3600	0.0%
$C_{52.5}P_0$	1330	665	0.0%	0.0%	3600	0.0%
$C_{32.5}P_1$	1330	665	0.0%	0.0%	3600	0.5%
$C_{42.5}P_1$	1330	665	0.0%	0.0%	3600	0.5%
$C_{52.5}P_1$	1330	665	0.0%	0.0%	3600	0.5%
$C_{32.5}P_2$	1330	665	0.0%	0.0%	3600	0.1%
$C_{42.5}P_2$	1330	665	0.0%	0.0%	3600	0.1%
$C_{52.5}P_2$	1330	665	0.0%	0.0%	3600	0.1%
$C_{32.5}P_3$	1330	665	0.0%	0.0%	3600	1.3%
$C_{42.5}P_3$	1330	665	0.0%	0.0%	3600	1.3%
$C_{52.5}P_3$	1330	665	0.0%	0.0%	3600	1.3%
$C_{32.5}P_4$	1330	665	0.0%	0.0%	3600	1.8%
$C_{42.5}P_4$	1330	665	0.0%	0.0%	3600	1.8%
$C_{52.5}P_4$	1330	665	0.0%	0.0%	3600	1.8%
$C_{32.5}P_5$	1330	665	0.0%	0.0%	3600	2.2%
$C_{42.5}P_5$	1330	665	0.0%	0.0%	3600	2.2%
$C_{52.5}P_5$	1330	665	0.0%	0.0%	3600	2.2%
$C_{32.5}M_1N_0$	1197	532	0.0%	12.0%	3600	0.0%
$C_{42.5}M_1N_0$	1197	532	0.0%	12.0%	3600	0.0%
$C_{52.5}M_1N_0$	1197	532	0.0%	12.0%	3600	0.0%
$C_{32.5}M_2N_1$	1197	532	3.0%	8.0%	3600	0.0%
$C_{42.5}M_2N_1$	1197	532	3.0%	8.0%	3600	0.0%
$C_{52.5}M_2N_1$	1197	532	3.0%	8.0%	3600	0.0%
$C_{32.5}M_3N_2$	1197	532	7.9%	3.0%	3600	0.0%
$C_{42.5}M_3N_2$	1197	532	7.9%	3.0%	3600	0.0%
$C_{52.5}M_3N_2$	1197	532	7.9%	3.0%	3600	0.0%
$C_{32.5}M_4N_3$	1197	532	5.5%	5.5%	3600	0.0%
$C_{42.5}M_4N_3$	1197	532	5.5%	5.5%	3600	0.0%
$C_{52.5}M_4N_3$	1197	532	5.5%	5.5%	3600	0.0%
$C_{32.5}M_5N_4$	1197	532	1.5%	9.5%	3600	0.0%
$C_{42.5}M_5N_4$	1197	532	1.5%	9.5%	3600	0.0%
$C_{52.5}M_5N_4$	1197	532	1.5%	9.5%	3600	0.0%
$C_{32.5}M_6N_5$	1197	532	11.1%	0.0%	3600	0.0%
$C_{42.5}M_6N_5$	1197	532	11.1%	0.0%	3600	0.0%
$C_{52.5}M_6N_5$	1197	532	11.1%	0.0%	3600	0.0%

Note: Cement strength class = C.



(a)

(b)

(c)

Fig. 2 Cox response trace plots for concrete specimens (a) CSC 32.5 MPa; (b) CSC 42.5 MPa; (c) CSC 52.5 MPa

compared to CSCs of 42.5 and 52.5 MPa. Also, the sensitivity of CSCs of 42.5 and 52.5 MPa can be attributed to the effect of these two variables on compressive strength is almost the same in two graphs.

3.2 Matrix of mixture contour plots

Using contour plots, the relationship between the response variable (compressive strength) with three factors MS, NS, and polypropylene fibers can be seen simultaneously. The effect of the factors on cements with CSCs of 32.5, 42.5, and 52.5 MPa was determined separately. It was found that for cement with CSC of 32.5 MPa, shown in Fig. 3(a), reducing the amount of fiber and increasing the same percentage of MS and NS simultaneously, the compressive strength is highest. Also, the effect of low and high fibers in MS and NS on compressive strength is not effective. However, it can be effective in low compressive strength.

Also, in order to investigate the effect of factors on the compressive strength of CSC of 42.5 MPa in Fig. 3(b), it can be seen that the MS and NS have the greatest impact on compressive strength. However, the fiber has little impact on two other factors. On the other hand, in concrete samples with CSC of 52.5 MPa in Fig. 3(c), the MS had the greatest effect on compressive strength while NS and fiber have no effect on compressive strength.

Therefore, it results from all three figures that in CSC of 32.5 MPa, the MS and NS factors are more effective compared to CSC of 42.5 MPa. Also, in cement with strength class of 52.5 MPa, no MS, NS, and fiber are unaffected.

3.3 Optimization of the responses

The optimized response (compressive strength) for all three types of CSC in Fig. 4 is studied in this form, y is the highest compressive strength and d shows the utility of the combination and the range is from 0 to 1, where 1 indicates the ideal mode. Therefore, for a more detailed examination of these properties, the maximum compressive strength in CSC 32.5 MPa is presented in Fig. 4(a). The optimal amount for cement strength class of 32.5 MPa is 5.3% MS and 5.7% NS and cement strength class of 42.5 MPa. In Fig. 4(b), under optimal optimization, there is 6.7% MS and 4.3% NS with cement strength class of 52.5 MPa. In Fig. 4(c), under optimal optimization, 8.3% MS and 2.4% NS is created. Also, in a study on the effect of each of the MS and NS factors on the CSC, the result showed that they are equally effective on the compressive strength and the polymer fiber factor has less effect on the compressive strength. The results obtained from Fig. 4 show that whenever there is an increase in CSC, the effect of MS and NS on compressive strength decreases. Also, the compressive strength decreases, thus the optimum percentage of MS is 5.7% while NS is 5.3% in CSC of 32.5 MPa which improves compressive strength.

4 Conclusions

In the present study, the compressive strength and application of the mixing method was investigated to optimize the mixing plan of the concrete made from MS,

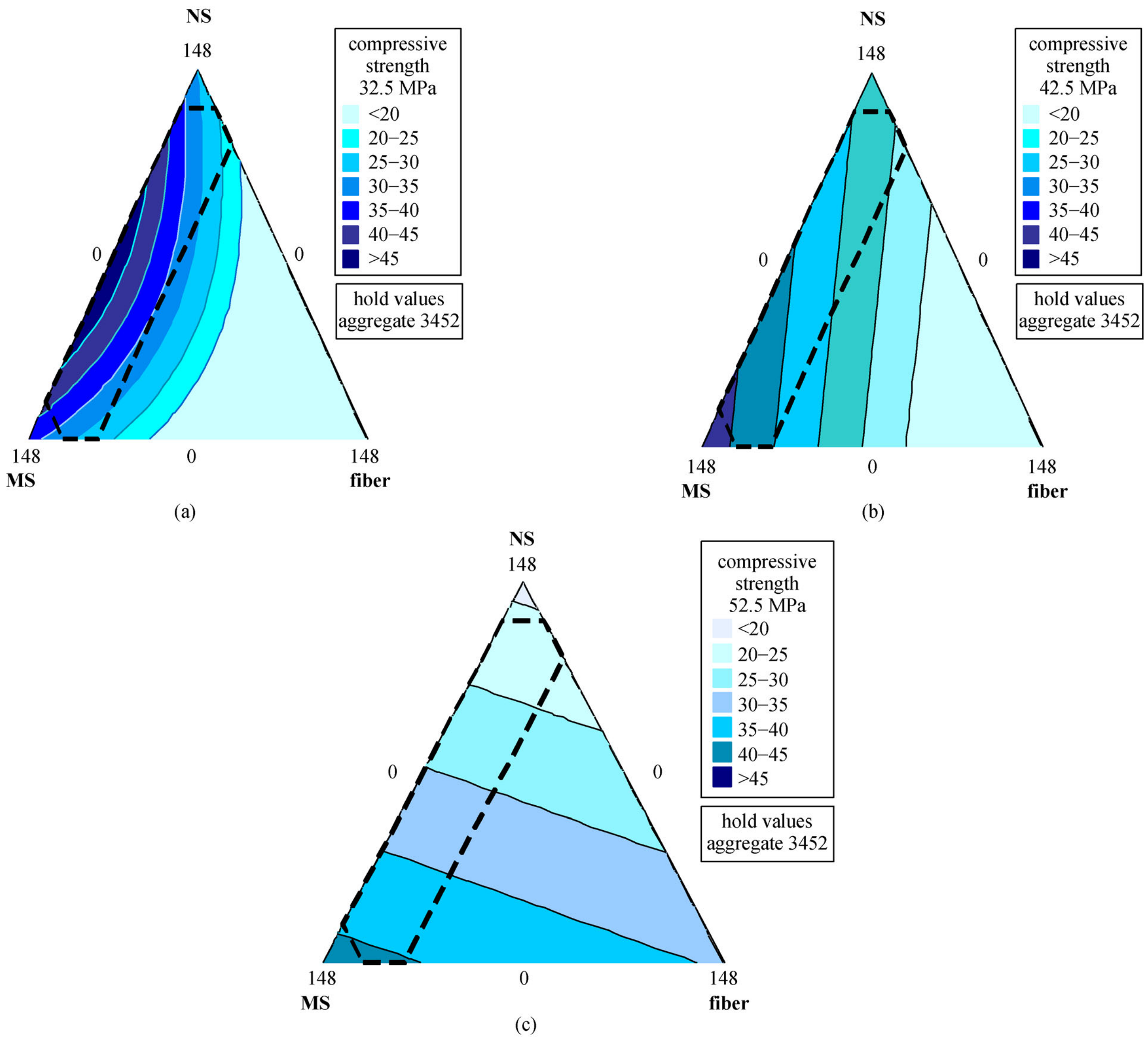


Fig. 3 Mixture contour plot of compressive strength (a) 32.5 MPa; (b) 42.5 MPa; (c) 52.5 MPa

NS, and fibers. According to the results of DOE, a subset of which is the extreme vertices method to find the optimal level of factors and determine the effect of each factor on the compressive strength, it is concluded that:

1) The uses of polypropylene fibers have no significant effect on the compressive strength.

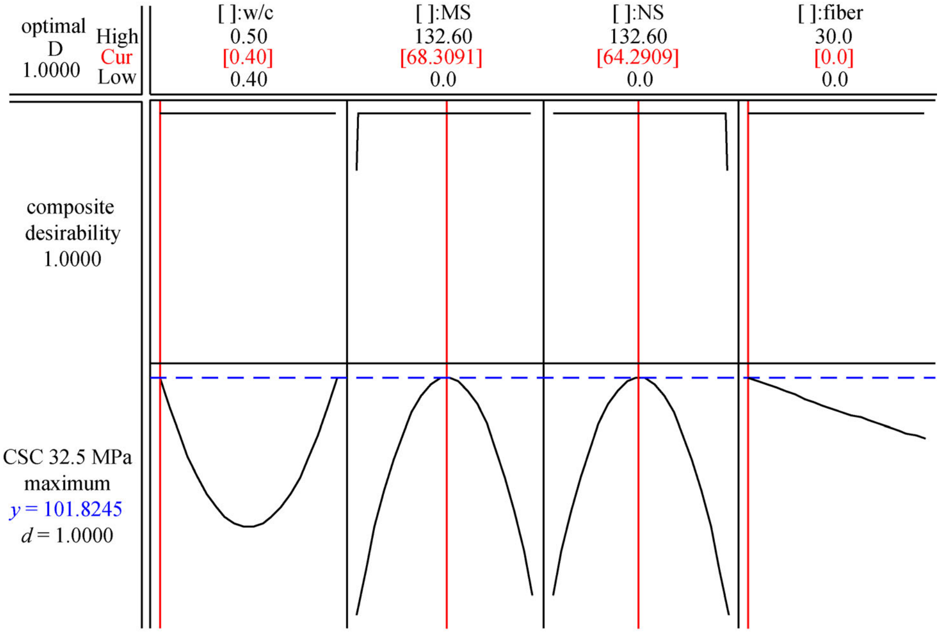
2) CSCs have a significant effect on the amount of MS and NS used.

3) In the mixture plan in which cement with a compressive strength of 32.5 MPa was used, simultaneous use of the two additives: NS and MS, increased the compressive strength of concrete equally.

4) In the mixture plan in which cement with a compressive strength of 42.5 MPa was used, the effect of MS is greater than that of the other two factors, because MS increases compressive strength by filling the capillary pores.

5) In a concrete with 52.5 MPa cement strength class, the most effective factor in the compressive strength is MS and the effect of NS is less than that of the concrete which has strength of 42.5 MPa.

6) the results of optimization obtained from extreme vertices mixture method shows mix designs with cement in a strength class of 32.5 MPa (5.3% MS and 5.7% NS) and in cement with a strength class of 42.5 MPa (6.7% MS and 4.3% NS) as well as in cement with a strength class of 52.5 MPa (8.3% MS and 2.4% NS) as optimal designated values.


optimal
D
1.0000
High
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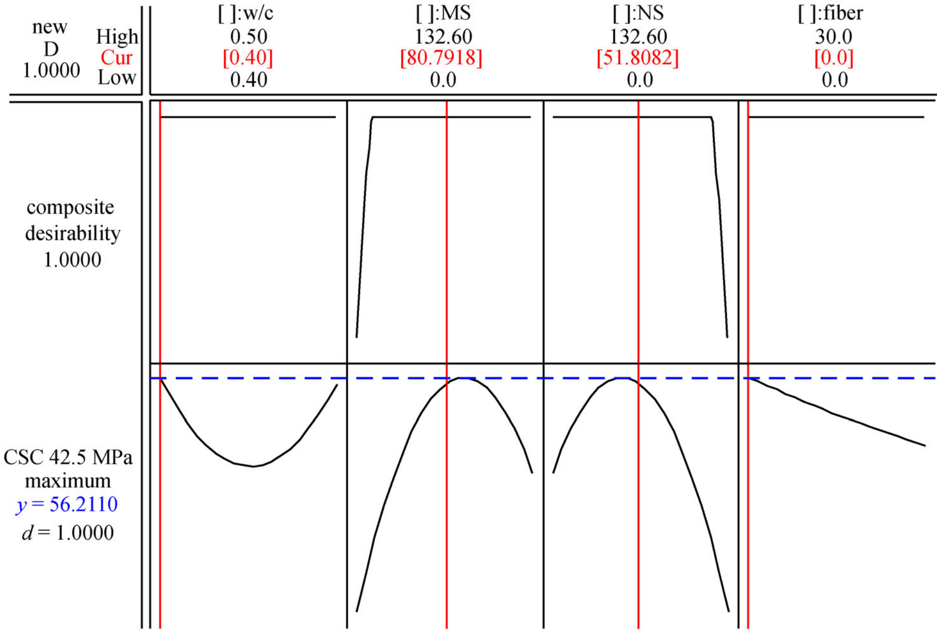
Low
[ ]:w/c
0.50
[0.40]
0.40
[ ]:MS
132.60
[68.3091]
0.0
[ ]:NS
132.60
[64.2909]
0.0
[ ]:fiber
30.0
[0.0]
0.0
composite
desirability
1.0000
CSC 32.5 MPa
maximum
y = 101.8245
d = 1.0000

(a)


new
D
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composite
desirability
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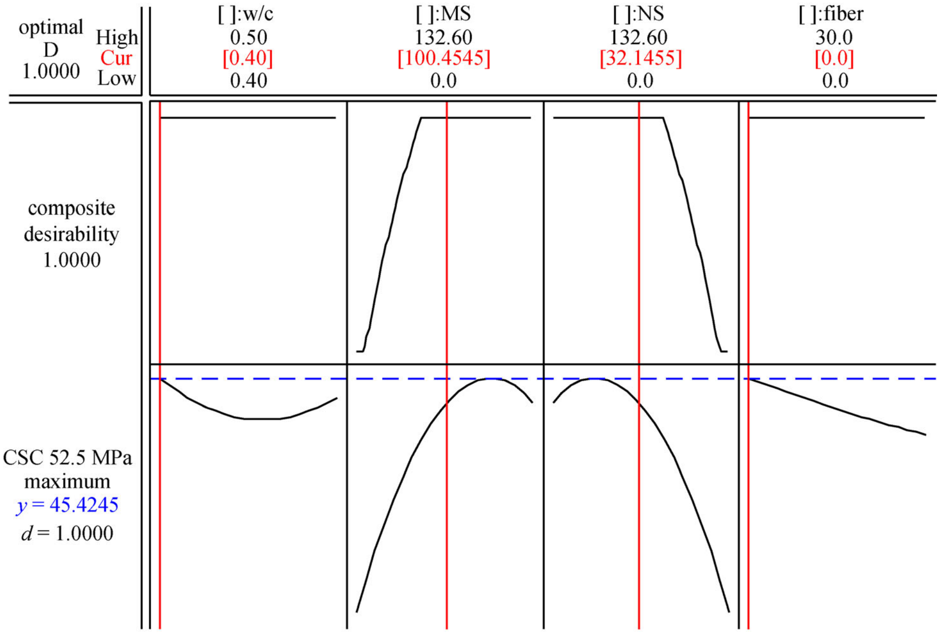
CSC 42.5 MPa
maximum
y = 56.2110
d = 1.0000

(b)



(c)

Fig. 4 Response optimization plots showing the optimized mixture for the maximum production compressive strength for CSCs (a) 32.5 MPa; (b) 42.5 MPa; and (c) 52.5 MPa

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