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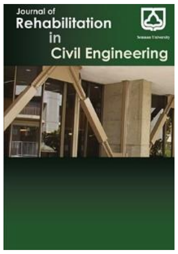

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Simultaneous Effect of Aggregate and Cement Matrix on the Performance of High Strength Concrete

Nabiollah Ahmadi[1], Majid Yazdandoust[2*], Mahmoud Yazdani[3]

1. Department of Civil Engineering, Shahid Rajaee Teacher Training University, Tehran, Iran
2. Department of Civil Engineering, Tafresh University, Tafresh, Iran
3. Department of Civil Engineering, Tarbiat Modares University, Tehran, Iran

[*] Corresponding author: *mj.yazdandoust@tafreshu.ac.ir*

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ABSTRACT

In the current experimental work, the simultaneous effect of fineness modulus, water-to-cementitious materials [W/(C+M)], and also micro silica content were investigated on workability, mechanical and physical properties of high strength concrete. For this purpose, 45 mix-designs were made by selecting five different ratios of micro-silica, three W/(C+M) ratios, and three distributions of particle size and then the slump, compressive strength, elastic modulus, and split tensile strength of each designed concrete mixture were determined. Findings showed that increasing the micro-silica content up to 10 wt% improves the mechanical properties of concrete and then leads to a reduction in strength parameters, so that the effect of changes in the micro-silica content on mechanical parameters of concrete becomes more prominent with increasing and decreasing the fineness modulus of aggregate and W/(C+M) ratio, respectively. It was also observed that increasing the micro-silica content leads to reducing the slump and unit weight of concrete so that this reduction is more noticeable in the low fineness modulus of aggregate and water-cement ratio.

1. Introduction

Today, concrete is recognized as one of the key materials in the industry, and the development of industries is highly dependent on it. Despite the simplicity of its components, the complex interaction of concrete components has complicated its

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behavior. This complexity becomes more problematic when additives are also added to the concrete mix design. In this situation, determining the simultaneous effect of all components on the performance of concrete before presenting the mix-design, is inevitable.

Pozzolan materials are an integral part of the concrete that with improving the cement matrix, play an important role in achieving desirable characteristics of concrete. Improvement of strength, workability, and durability are the advantages of using these materials [1-6]. The type of pozzolan and the amount of its contribution are two major parameters that play an influential role in developing a homogenous media and improving the mechanical and physical properties of concrete [7-10]. The amount of pozzolan that affects concrete specifications depending on the properties of the other concrete components, such as the aggregate type, the aggregate-size distribution, the fineness moduli (FM), and the water-to-cementitious materials W/(C+M) ratio. Therefore, investigation of the simultaneous effects of pozzolan proportions and the specifications of the other concrete components is inevitable to attain a concrete with ideal performance [11-14]. Among all pozzolan materials, micro-silica is the most popular additive that is cost-effective and available, the reasons for widely used in concrete mix design. Several published research works indicate that using the precise amount of micro-silica in mix design has a significant effect on improving the concrete performance [15-17].

The FM is another factor affecting concrete specifications [18]. It is defined as Eq. 1and is often used as an index of average fineness for the combination of aggregates.

$$FM = \frac{\sum_{i}^{n}(percent\ retained\ on\ ith\ sieve)}{100} \quad (1)$$

where n is the number of sieve in a standard set. Bittencourt et al. [19] indicated that the effect of FM on concrete parameters is completely dependent on the water-cement (W/C) ratio and its optimal value should be determined according to the water content. Poon and Lam [20] and Karamloo et al. [21] showed that the aggregate type and the maximum aggregate size are also two other factors that affect the effectiveness of FM. Despite the mutual influence of aggregate properties, W/C ratio and the amount of pozzolan, the effect of each of them on concrete parameters have been studied separately [22-25], however, their simultaneous effect has received less attention [25-27]. Therefore, in this study, an attempt was made to evaluate the simultaneous effect of FM, W/(C+M) ratio and also micro-silica content on workability, physical and mechanical properties of high strength concrete. For this purpose, first, 45 mix-designs were made by selecting five different ratios of micro-silica to cement), three W/(C+M) ratios, and three distributions of particle size. Then, the slump, compressive strength, split tensile strength, and elastic modulus of each designed concrete mixture were determined.

2. Experimental program

2.1. Materials

General-purpose ordinary Portland cement (OPC) type I, was used as the binder in the current study. Mechanical, physical, and chemical properties of this cement are given in Tables 1, 2, and 3, respectively. The micro-silica used in this study was prepared from

AZNA Silica Fume Company, Tehran. The chemical composition of micro-silica is presented in Table 4.

Table 1. Mechanical properties of OPC.

Curing time (day)	Compressive Strength (kg/cm^2)
3	224
7	287
28	403

Table 2. Physical properties of OPC.

Property	Value	Unit
Blain Specific Surface	3100	cm^2/gr
Setting Time Vicat	64.9	min
Auto Clave Expansion	140	%
Water for Normal Consistency	25	%

Table 3. Chemical properties of OPC.

Chemical Blends	Constitutive Percent (%)	Chemical Blends	Constitutive Percent (%)
SiO_2	20.96	Na_2O	0.45
Al_2O_3	5.78	K_2O	0.55
Fe_2O_3	3.12	Loss	1.60
CaO	62.72	Total	99.90
MgO	2.42	Insol Rez	0.44
SO_3	2.30	Free CaO	1.2
Clinker composition according to Bogue’s calculations			
C_3S	46.11	2.79	$CaSo_4$
C_2S	25.38	-----	MgO
C_3A	9.91	93.67	Total
C_4AF	9.48		

Table 4. Chemical properties of micro-silica.

Chemical Blends	Constitutive Percent (%)	Chemical Blends	Constitutive Percent (%)
MgO	0.97	H_2O	0.80
Na_2O	0.31	Sic	0.50
K_2O	1.01	C	0.30
P_2O_5	0.16	SiO_2	94.6-96.4
SO_3	0.10	Fe_2O_3	0.87
Cl	0.04	Al_2O_3	1.32
Color	66	CaO	0.49

Due to low W/(C+M) ratios, a superplasticizer based *Melamine Formaldehyde Sulfonate* was used. To develop the strength in concrete specimens, the crushed dolomite was used as coarse and fine aggregates. The mechanical and physical properties of dolomite aggregates are given in Table 5. The dolomite aggregates were broken into different sizes using a laboratory stone crusher, then were combined according to the intended particle size gradation. To produce three particle size gradations with different FMs, a constant distribution of coarse aggregate and three distributions of fine aggregate with FMs equal to 2.86, 3.06, and 3.26 were used. The particle size distributions of coarse material and fine aggregates are presented in Table 6 and Figure 1, respectively.

Table 5. Mechanical and physical properties of aggregates.

Property	Value	Unit
Compressive Strength	228.3	MPa
Elasticity Modulus	64.9	GPa
Unit Weight	1650	Kg/m^3
Density	2.678	-
Water Absorption	0.4	%

Table 6. Coarse material size distribution.

Sieve No.	Sieve size (mm)	Sieve ExtantPercent	Sieve Passing Percent
3/8"	9.525	100.0	0.0
1/4"	6.35	40.0	60.0
4	4.75	10.0	30.0
8	2.36	0.00	10.0

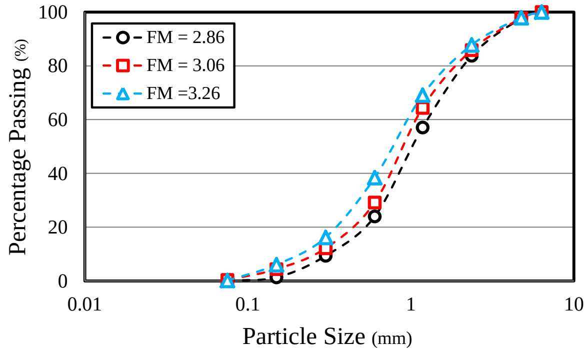


Fig. 1. Particle size distributions diagrams of fines with different FMs.

2.2. Mix designs

The absolute volume method recommended by ACI 211 was used in the current study to scheme the mixed designs [28]. Following the ACI recommendations, the volume ratio of each component to the total volume of concrete was selected, then using the related density of components, the weight of each component was obtained. On the suggestion of ACI 211.2, the apparent volume of coarse aggregates should be determined based on the nominal maximum size of aggregate and the FM of fine aggregates. Hence, the volume of coarse grains was selected equal to 0.59, 0.61, and 0.63 for particle size distributions with the FMs equal to 3.26, 3.06, and 2.86, respectively. On the other hand, considering the grade of cement content equal to 550 kg/m^3, four weight ratios of micro-silica to cement (M/C) include 0, 5, 10, and 15 replacement ratios. The amount of superplasticizer was also considered equal to 2 wt% of cementitious materials, according to the manufacturer's recommendation. Finally, based on the volume of all components, the volume of fine aggregates was calculated for each mix design. The details of mixed designs are presented in Table 7.

2.3. Mixing, sampling, curing, and testing

After determining the volume of each component for each mix design and calculating the weight of concrete (using specific gravity), the components were weighed and combined by two steps using a laboratory mixer with a revolving speed of 26 cycles/rpm. In the first step, coarse and fine aggregates were mixed with half of the total water for about 5 minutes, as recommended by Juenger and Jennings [29]. Then, the cement, micro-silica, and superplasticizer dissolved in the rest of the water, were added to the contents of the mixer and the mixing continued for the next 5 minutes.

Table 7. Mix designs, C = cement; W = water; and M = micro-silica.

Mix design	Coarse apparent volume (m^3)	C (kg/m^3)	W (kg/m^3)	M (kg/m^3)	Fine apparent volume (m^3)
Mix 1	0.59	550.0	132.0	0.0	0.33
Mix 2	0.59	550.0	176.0	0.0	0.29
Mix 3	0.59	550.0	220.0	0.0	0.24
Mix 4	0.59	522.5	132.0	27.5	0.30
Mix 5	0.59	522.5	176.0	27.5	0.26
Mix 6	0.59	522.5	220.0	27.5	0.22
Mix 7	0.59	495.0	132.0	55.0	0.28
Mix 8	0.59	495.0	176.0	55.0	0.23
Mix 9	0.59	495.0	220.0	55.0	0.19
Mix 10	0.59	467.5	132.0	82.5	0.25
Mix 11	0.59	467.5	176.0	82.5	0.20
Mix 12	0.59	467.5	220.0	82.5	0.16
Mix 13	0.59	440.0	132.0	110.0	0.22
Mix 14	0.59	440.0	176.0	110.0	0.18
Mix 15	0.59	440.0	220.0	110.0	0.13
Mix 16	0.61	550.0	132.0	0.0	0.32
Mix 17	0.61	550.0	176.0	0.0	0.28
Mix 18	0.61	550.0	220.0	0.0	0.23
Mix 19	0.61	522.5	132.0	27.5	0.29
Mix 20	0.61	522.5	176.0	27.5	0.25
Mix 21	0.61	522.5	220.0	27.5	0.20
Mix 22	0.61	495.0	132.0	55.0	0.26
Mix 23	0.61	495.0	176.0	55.0	0.22
Mix 24	0.61	495.0	220.0	55.0	0.18
Mix 25	0.61	467.5	132.0	82.5	0.24
Mix 26	0.61	467.5	176.0	82.5	0.19
Mix 27	0.61	467.5	220.0	82.5	0.15
Mix 28	0.61	440.0	132.0	110.0	0.21
Mix 29	0.61	440.0	176.0	110.0	0.16
Mix 30	0.61	440.0	220.0	110.0	0.12
Mix 31	0.63	550.0	132.0	0.0	0.31
Mix 32	0.63	550.0	176.0	0.0	0.26
Mix 33	0.63	550.0	220.0	0.0	0.22

Mix 34	0.63	522.5	132.0	27.5	0.28
Mix 35	0.63	522.5	176.0	27.5	0.24
Mix 36	0.63	522.5	220.0	27.5	0.19
Mix 37	0.63	495.0	132.0	55.0	0.25
Mix 38	0.63	495.0	176.0	55.0	0.21
Mix 39	0.63	495.0	220.0	55.0	0.16
Mix 40	0.63	467.5	132.0	82.5	0.22
Mix 41	0.63	467.5	176.0	82.5	0.18
Mix 42	0.63	467.5	220.0	82.5	0.13
Mix 43	0.63	440.0	132.0	110.0	0.19
Mix 44	0.63	440.0	176.0	110.0	0.15
Mix 45	0.63	440.0	220.0	110.0	0.11

After preparation the concrete mix, slump tests were performed on each mix with 3-time repeats according to ASTM C143 [30]. Based on this test, the workability of fresh concrete was evaluated by measuring the dropped height of fresh concrete during the raising of the slump cone. After evaluating the workability of fresh concretes, 100×100×100 mm cubic and 75×100 mm cylindrical specimens were prepared to determine the compressive strength and split tensile strength tests, respectively. To prepare cubic specimens, the fresh concrete was poured and compacted in two layers in each mold. This process was made for cylindrical specimens by pouring fresh concrete into molds through 3 layers. The prepared specimens were kept in conventional laboratory conditions at a temperature of 23±2 °C for one day and then were taken out of molds and finally were cured in water at 20±5 °C. Also, the density of fresh concretes was measured after sampling by calculating the mass of concrete required to fill specimens.

Compressive strength tests were carried out according to the EN 12390-3 scheme [31] at the age of 7 and 28 days with 3-time repeats using a 2000 kN actuator with a loading rate of 0.2-0.4 MPa/s (Figure 2). Based on the ASTM C496-90 [32], the rate of loading for splitting tensile strength test was considered as 0.02-0.04 MPa/s (Figure 3).

3. Results and discussion

By conducting 135 slump and density tests and also by carrying out 270 compressive and split tensile strength tests on 45 different mix designs, the simultaneous effect of micro-silica/cement ratio (M/C), the water/binder W/(C+M) ratio, and the FM of aggregates evaluated the physical and mechanical properties of fresh and hardened concretes.

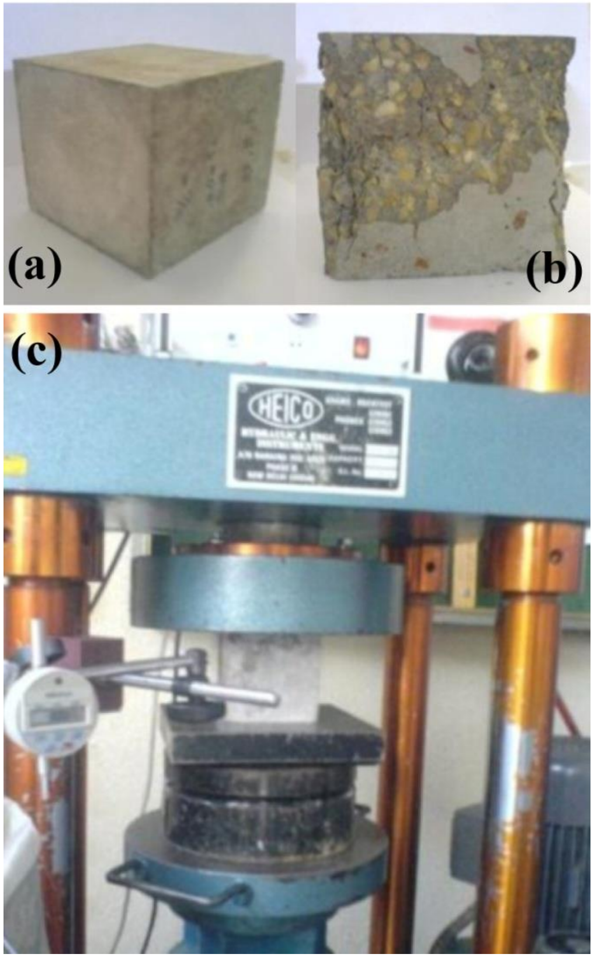


Fig. 2. Cubic specimens (a) before and (b) after compressive test; (c) Concrete compressive strength testing machine.

Fig. 3. (a) Cylindrical specimen and (b) Concrete Tensile strength testing machine.

By considering the three main principles (stated below as a, b, and c), the obtained results are discussed in terms of mechanical and physical parameters in this section.

a) Because micro-silica particles are finer than cement grains, the specific surface area of micro-silica is higher and consequently, the tendency of micro-silica particles to absorb water is greater.

b) Due to the lower density of micro-silica than cement grains, partial replacement of cement by micro-silica reduces the unit density of concrete.

c) The decrease in the resistance of cement paste is due to the increase in voids that are the result of excess water unconsumed in the hydration processes.

3.1. Mechanical properties

3.1.1. Compressive strength and modulus of elasticity:

The results of compressive tests on cubic specimens (varied in W/(C+M) ratios), micro-silica contents, and FM are given in Figure 4.

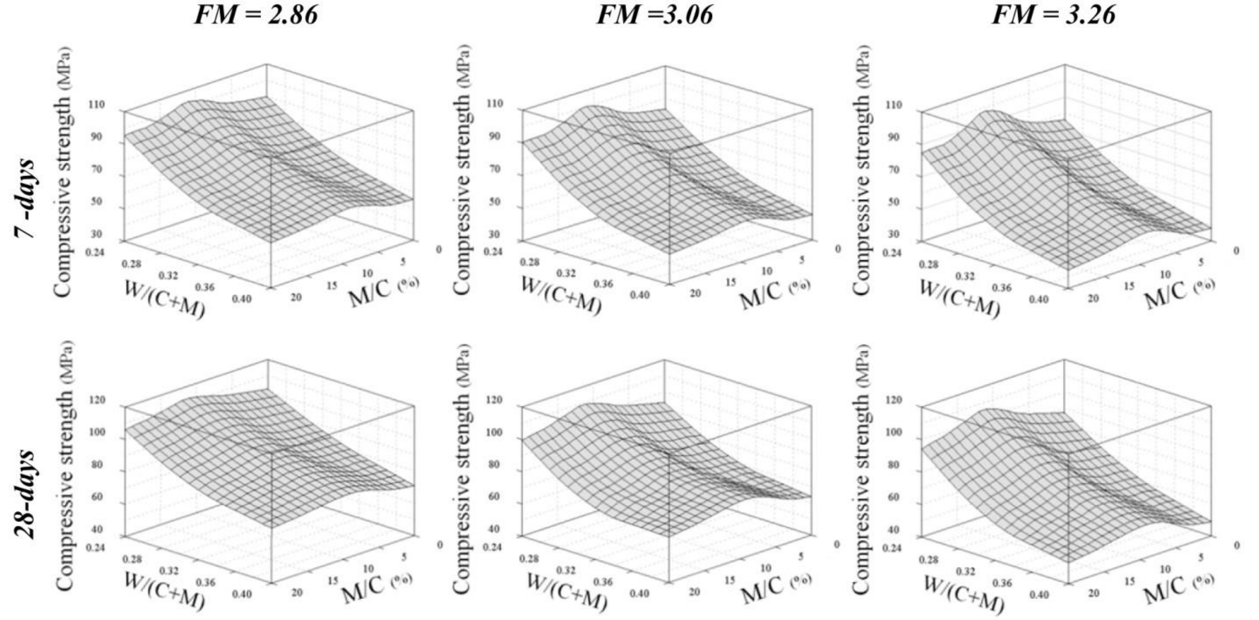


Fig. 4. Compressive strength at 7 and 28-days age specimens with different micro-silica content, FM, and W/(C+M) ratios.

The results indicate that increasing the micro-silica content from 0 to 10% leads to an increase in the compressive strength of concrete for all FM values and W/(C+M) ratios. At the age of 28 days when the W/(C+M) ratio equals 0.24, this increase reaches 114 and 105 MPa in concrete mixes having FM values of 2.86 and 3.26, respectively. Increasing the compressive strength when using 0 to 10% micro-silica can be attributed to the reduction of voids in the cement matrix and filler effects of micro-silica particles. This leads to the formation of a strong matrix and, consequently, leads to an increase in concrete compressive strength as schematically shown in Figure 5.

With increasing the micro-silica content from 10 to 20%, a gradual reduction in compressive strength is observed. The reduction of compressive strength by passing a micro-silica ratio of 10% can be attributed to increasing the distances between cement particles due to the replacement of micro-silica particles between them. In many studies, this phenomenon has been used to scale down the strength of concrete in small-scale models [33-36]. This reduces the interaction between the cement particles and consequently the weakness of the cement matrix (Figure 6). According to the above description, 10% micro-silica content can be introduced as the optimal percentage in concrete mixes to achieve the maximum strength. Since micro-silica is an expensive additive, the use of this optimal percentage can play a significant role in lowering the costs.

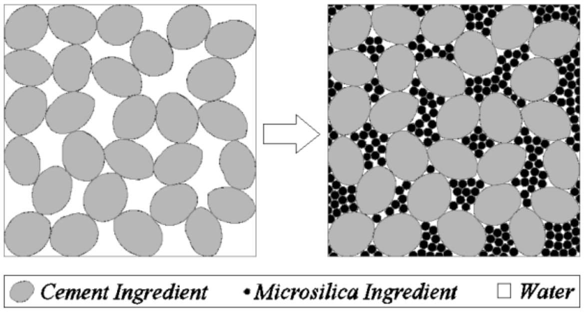


Fig. 5. Filling of cement void ratios with micro-silica particles.

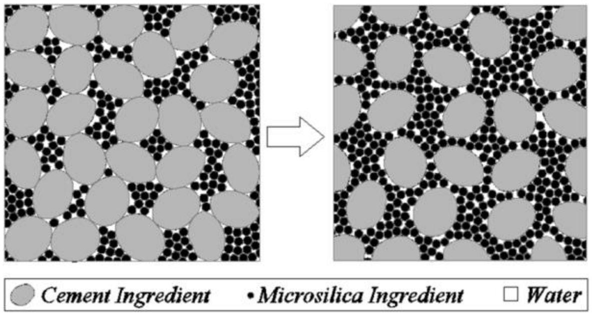


Fig. 6. Dispersing cement particles by increasing the micro-silica ingredient.

Moreover, changes in the percentage of micro-silica negatively affect the concrete compressive strength, particularly when the ratio of W/(C+M) increases. However, the rate of increase and reduction of compressive strength due to increasing the micro-silica content becomes negligible with increasing W/(C+M) ratios. This reduction could be due to the presence of excess water in the cement matrix. This means that after the hydration process, the occupied spaces became air-filled by excess water, and consequently, the cement matrix became a highly porous medium. This phenomenon diminishes the positive effect of micro-silica on the integrity and the strength of the cement matrix. Hence, it can be concluded that low W/(C+M) ratios should be used to achieve the greater effectiveness of micro-silica.

On the other hand, the effect of changes in the percentage of micro-silica on the concrete compressive strength becomes more prominent with increasing the FM of aggregate. This phenomenon can be attributed to a decrease in interlocking of aggregate particles and the consequent weakening of the aggregate structure due to increasing the FM. In this situation, the cement matrix plays a major role in providing concrete strength. This makes the role of micro-silica content also be highlighted in improving the mechanical parameters of concrete (Figure 7).

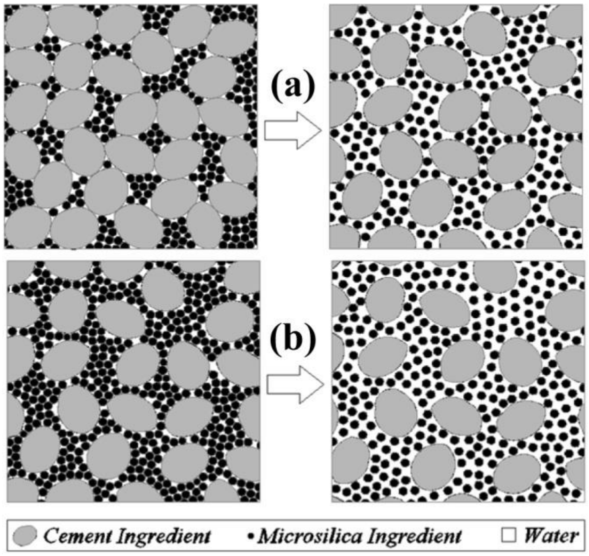


Fig. 7. Dispersing of cement particles in respect to increase of extra water in different weighted percent of micro-silica (a) 0 to 10% micro-silica content; (b) 10 to 20% micro-silica content.

Another point that can be drawn from the results is that the effect of the above-mentioned items becomes negligible with increasing the concrete age. This is due to the strong dependence of the concrete strength on the strength of cement in the early ages. This dependence makes the effect of change in micro-silica content and W/C ratio on concrete strength more obvious at this range of time. This phenomenon has also been reported by Massana et al. [16] and Lee et al. [17].

The elastic modulus of concrete is an influential parameter in the mixing design and analysis of concrete structures that its importance and prominent role has been reported in many studies [34-41]. To determine the value of secant elastic modulus related to each mix design, the load-creep behavior of specimens was recorded during compressive strength tests. The variation of elastic modulus versus W/(C+M) ratio and micro-silica content is given in Figure 8 separately for each FM value.

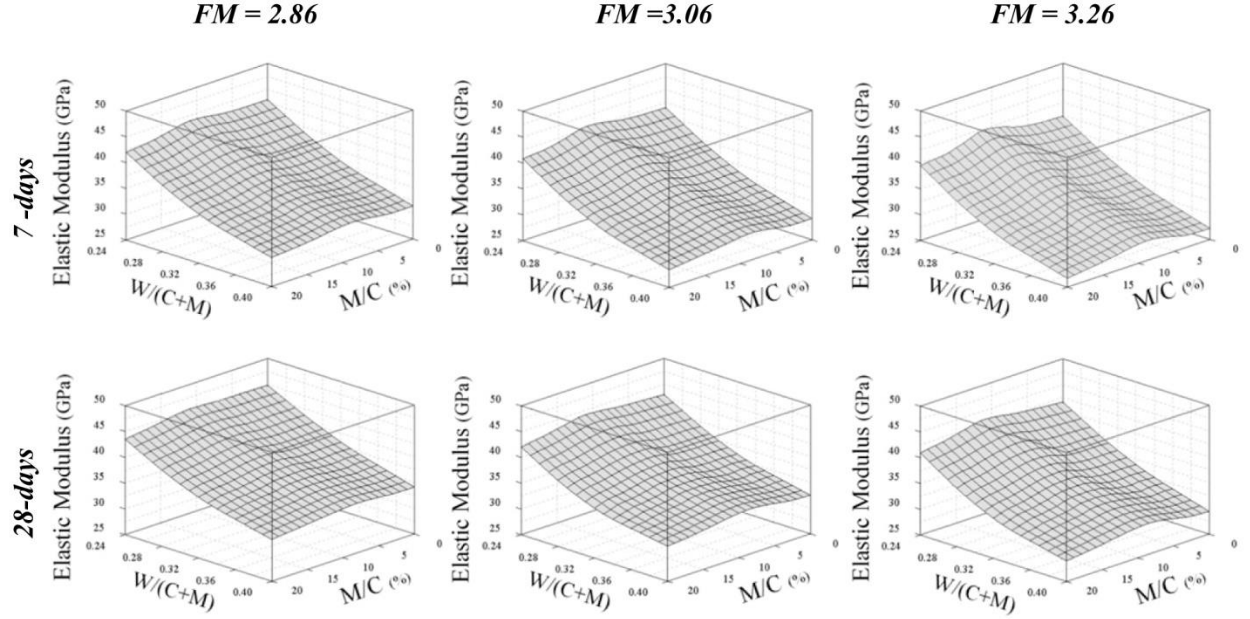


Fig. 8. Modulus of elasticity of 7 and 28-days age specimens with different micro-silica content, fineness modulus, and W/(C+M) mass ratios.

Findings show that the value of secant elastic modulus strongly increases with decreasing W/C ratio, while an increasing and then a reverse trend is observed during increasing the micro-silica content and the maximum value of elastic modulus occurs in micro-silica content equal to 10%. At the age of 7 days with a W/(C+M) ratio of 0.40, the maximum value of elastic modulus was measured to about 33 and 30 GPa for concretes with FM values of 2.86 and 3.26, respectively. This occurrence is comparable with that observed in compressive strength. The only difference between these occurrences is related to the change in micro-silica content, influencing the elastic modulus, especially for specimens cured at longer age.

3.1.2. Split tensile strength:

The results of split tensile strength tests on specimens made with different W/(C+M) ratios, micro-silica contents, and FM values at the age of 7 and 28 days are given in Figure 9. Comparing Figures 9 and 4 indicates that the split tensile strength behavior of specimens is entirely affected by changes in compressive strength and closely follows so that the tensile strength can be defined as a function of the compressive strength, as Equation 2:

$$f_{st} = \beta f_C{}^{\alpha} \tag{2}$$

where f_{st} and f_c are the 28-day split tensile and compressive strengths (MPa), respectively, β and α are two constant coefficients that with increasing the W/C ratio, they vary between 0.19 to 0.21 and 0.68 to 0.73, respectively. These two coefficients have been proposed for high strength concrete equal to 0.248 and 0.717 by Bhanja and Sengupta [42]. Reducing the compressive strength and increasing β and α due to the increase in W/(C+M) ratio indicate that the tensile strength is less affected by changes in W/(C+M) ratio than compressive strength.

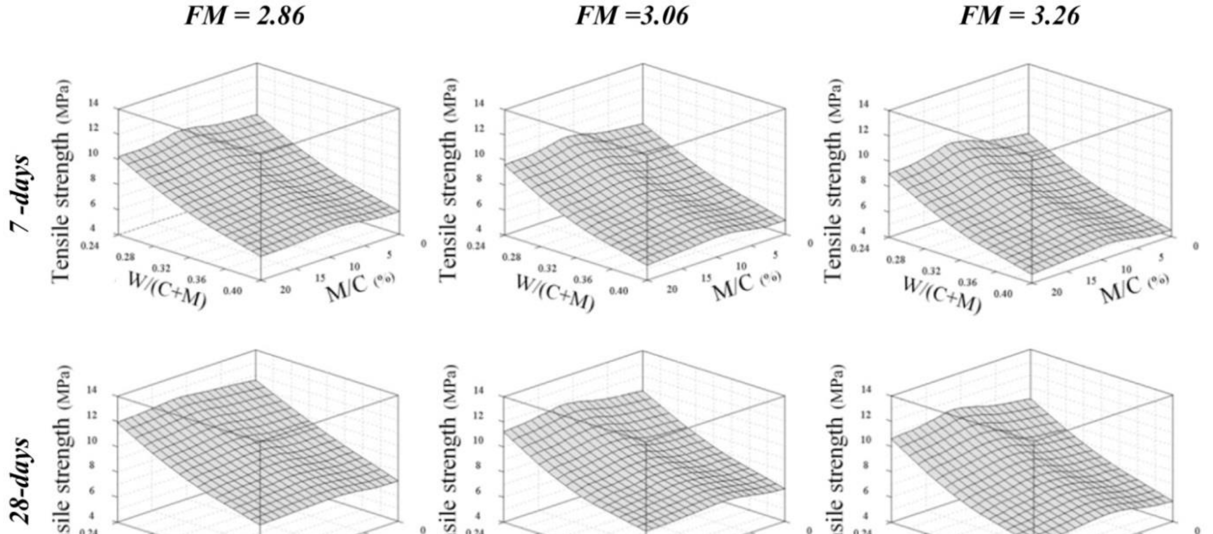


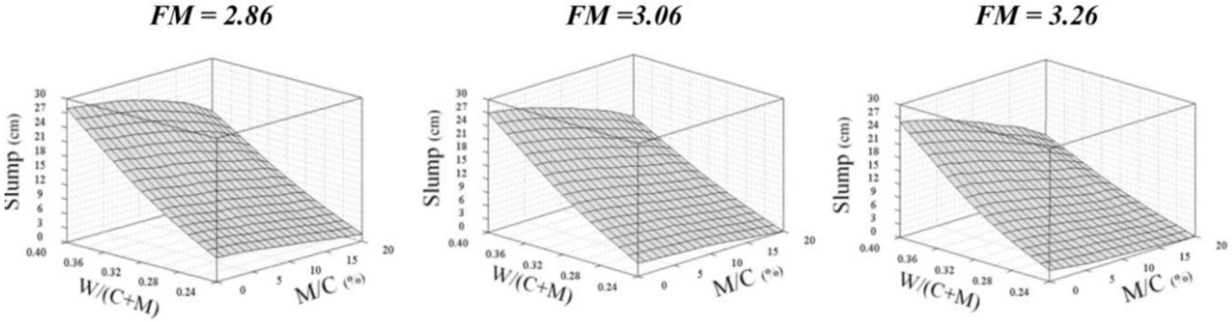
Fig. 9. Tensile strength of 7 and 28-days age specimens with different micro-silica content, FM, and W/(C+M) mass ratios.

3.2. Physical properties

Slump and unit weight are the two main factors in a concrete mixing design. The studies on concrete mixing design, achieving a design with the lowest unit weight and the maximum workability has been one of the main goals of researchers [43-47]. In addition to these factors, water absorption capacity is another important factor that plays a prominent role in concrete performance [48-53]. The studies showed that increasing the water absorption capacity of concrete can jeopardize the long-term performance of concrete [54-55]. However, among these three factors, slump and unit weight were select as two important physical properties of concrete to investigate the simultaneous effect of fineness modulus, W/(C+M) ratio, and micro-silica content on them.

3.2.1. Slump tests:

The variation in slump values versus W/(C+M) ratio and micro-silica content is given in Figure 10, separately for each FM. The results indicate that increasing the micro-silica content leads to reducing the concrete slump in all FM values and W/(C+M) ratios. This reduction, which was measured to about 70% in concrete with an FM value of 2.86, becomes more noticeable in mixes designed with more W/(C+M) ratios and FM values. This can be attributed to the higher specific surface area of the micro-silica than cement. By increasing the micro-silica content in the cement admixture, the tendency of the cement mixture to absorb water increases, and consequently less water remains to lubricate aggregates. This leads to a sharp decrease in the concrete workability. Since more lubrication is needed to improve the workability of concretes consisting of larger aggregates, the effect of water shortage on the workability is more pronounced in concretes made of larger aggregates. Therefore, considering the increase in FM values due to increasing the size of aggregates, it is expected that the effect of water reduction on the workability of concrete consisting of materials with more FM values will be more prominent, as seen in Figure10.



FM = 2.86 ***FM =3.06*** ***FM = 3.26***

Fig. 10. Slump of specimens with different micro-silica content, FM values, and W/(C+M) ratios.

3.2.2 Unit weight:

The variation of fresh density of concrete versus FM values, micro-silica content, and W/C ratio are given in Figure 11. Findings show that regardless of the type of particle size gradation and W/(C+M) ratio, the increase in the amount of micro-silica leads to decreasing the unit weight of concrete. This unit weight reduction, which occurs with a similar trend in all values of FM and W/(C+M) ratio, happens due to two main reasons including (1) the replacement of heavy cement particles with light micro-silica particles; (2) the increase in concrete porosity due to the tendency to absorb water. The unit weight reduction during the increase in the micro-silica content has been reported by Zareei et al. [56] and Hussain et al. [57]. Hence, it can be concluded that particle size gradation and W/(C+M) ratio do not affect the variation rate of concrete unit weight versus micro-silica content and these two parameters can be ignored when determining the optimal amount of micro-silica in the concrete mix design.

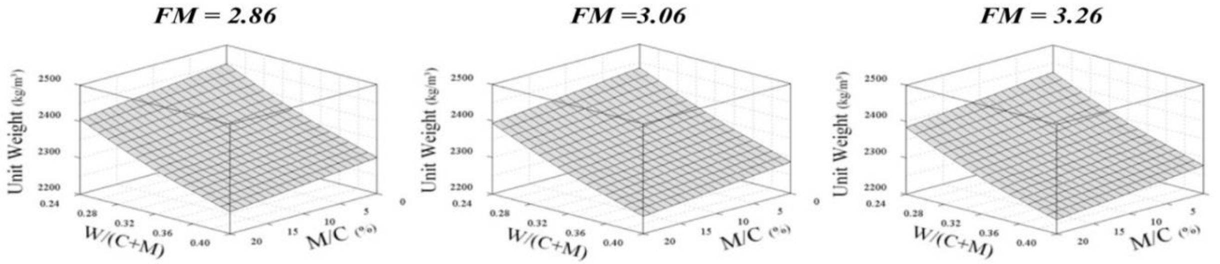


Fig. 11. Unit weight of specimens with different micro-silica content, fineness modulus, and water-to-cement mass ratios.

4. Conclusion

In the current study, the simultaneous effect of W/(C+M) ratio, micro-silica content, and FM values were investigated on mechanical and physical properties of high strength concrete. For this purpose, 45 mix-designs were prepared by selecting five different ratios of micro-silica (0, 5, 10, 15, 20 %), three W/(C+M) ratios (24, 32, 40%), and three distributions of particle size (FM values of 2.86, 3.06, 3.26) and the slump, compressive strength, split tensile strength and elastic modulus of each concrete mix-designs were determined. The following main conclusions are drawn from the results:

1- Increasing the micro-silica content from 0 to 10% for all FMs and W/(C+M) ratios, led to increasing the compressive strength, while this trend was reversed with increasing the micro-silica content from 10 to 20%.

2- The effect of changes in the micro-silica content on mechanical parameters of concrete became more prominent with increasing and decreasing the FM of aggregate and W/C, respectively.

3- The effect of micro-silica content on tensile strength and elastic modulus was less than compressive strength in all ratios of W/(C+M) and FMs.

4- It was observed that the effect of changes in the micro-silica content on mechanical parameters of concrete becomes negligible with increasing concrete age.

5- Increasing micro-silica content led to reducing the slump in all FMs and W/(C+M) ratios.

6- The effect of changes in the micro-silica content on the slump became noticeable with increasing the W/C ratio and FM.

7- It was found that increasing micro-silica content can play an important role in decreasing the concrete unit weight.

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Notations

C	cement weight
FM	fineness modulus
f_c	compressive strength
f_{st}	split tensile strength
M	microsilica weight
W	water weight
α, β	constant coefficient in equation of split tensile strength.

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