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An Investigation on the Effect of Aggregates Packing Density on the Properties of High-Performance Concrete Mixtures

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ABSTRACT: This study aims to investigate the influence of dry packing density of aggregates on the mechanical and durability properties of high-performance concrete (HPC) mixtures. For this purpose, four different aggregate gradations were investigated, including ideal Fuller-Thompson curve (F), ideal Andreasen-Andersen curve (A) and their modified Funk and Dinger forms (MA and MF). The sequence of dry packing density of the aggregate gradations was as *A >F>MA>MF*. However, in contrast to the dry packing density results, the mixtures with the MF curve outperformed those with the other aggregate gradations in the durability and mechanical properties. Likewise, the mixture with the ideal Andreasen-Andersen curve (A) had lower compressive strengths and a higher diffusivity. Thus, the results indicated that the packing density of dry aggregates could not be indicative of the packing density of concrete and consequently the durability and mechanical characteristics of HPC. Moreover, the differences between the properties of the mixtures were more evident at lower w/cm ratios especially at w/cm of 0.31. For instance, the difference between the compressive strength of HPC mixtures with the MF and An aggregate gradations was about 14 MPa over 28 days. This study has been carried out on the concrete mixtures with compressive strengths up to 110 MPa.

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1- Introduction

Packing density could be defined as the ratio of solid volume to the total volume. Optimization of the packing density means to choose the size and amount of particles properly [1]. Since aggregates form 60-80 % of concrete volume, optimization of aggregate proportioning would be a significant factor to improve the packing density of concrete. In other words, the particles should be chosen in the way that the smaller ones could fill the voids between larger particles [2]. Furthermore, aggregate packing density and gradation have important effects on the concrete characteristics [3-5].

Aggregates with higher packing density have less void content and, as a result, need lower cement paste to fill up empty spaces that makes the mixtures more economical. Thus, increasing the packing density is crucial for producing composite materials such as ceramics and concrete [6]. Glavind and Pedersen [7] have shown that packing density has significant effects on both fresh and hardened concrete.

Packing density could be investigated experimentally and theoretically [8]. However, the theoretical approaches have several limitations on predicting the packing density [9, 10]. These methods are difficult to use, the software programs should be developed and the idealization assumptions must be considered. Thus, several aggregate gradations have been proposed to enhance the packing density of concrete. Among them, the Fuller-Thompson (F) and Andreasen-Andersen (A) grading curves have found widespread applications in concrete mix design [11]. The aforementioned aggregate gradations are described by Equation 1.

$$p(d)=\left[\frac{d}{d_{max}}\right]^q \tag{1}$$

Where P is the fraction that can pass through a sieve with opening diameter d; dmax is the maximum particle size of aggregates and the parameter q should have the values of 0.5 and 0.37 for Fuller-Thompson and Andreasen-Andersen grading curves, respectively.

For any real size distribution, a lower limit (d_{min}) should be considered. Thus, compared to the ideal Fuller-Thompson or Andreasen–Andersen curves, it is needed to consider the smallest dimension of particles in addition to the maximum size of particles. The modified Funk and Dinger [12] form of the aforementioned grading curve is presented by Equation 2.

$$p(d)=\frac{d^q-d_{min}{}^q}{d_{max}{}^q-d_{min}{}^q} \tag{2}$$

In which, d_{min} = minimum particle diameter for grading curve. In recent years, in order to obtain the optimum packing density, different aggregate gradations have been utilized. Yu et al. used Funk and Dinger grading curve (Equation 2) with q=0.23 in Ultra-High Performance Fiber Reinforced Concrete [13]. It has been reported that using Funk and Dinger grading curve may provide a dense skeleton of Ultra-High Performance concrete with a lower binder content [13]. Abd-Elrahman and Hillemeier produced high-performance concrete with compressive strength up to 80 MPa by using the ideal Fuller-Thompson grading curve $[d/d_{max}]^{0.5}$[14]. Jalal et al. used Equation 1 grading curve with q=0.45 to improve packing density in the high performance concrete [15, 16].

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Polymer concrete with compressive strength up to 110 MPa has been produced by using ideal Fuller-Thompson grading curve [17]. Parhizkar et al. [18] have used Fuller-Thompson grading curve to increase durability of high performance concrete subjected to acid degradation.

In some studies, grading curves of Equation 1 and 2 were used to produce lightweight composites with the enhanced segregation resistance and engineering properties [19- 22]. Also, it has been suggested that the use of appropriate Funk and Dinger grading curves could improve the fluidity of self-consolidating concrete [23]. To achieve a densely compacted concrete matrix with appropriate mechanical properties in ultra-lightweight fiber reinforced concrete, Funk and Dinger grading curve with q=0.35 has been used [24]. Utilizing Funk and Dinger grading curve has improved packing density of aggregates and consequently, the compressive strength of zero slump concretes [25, 26]. Madani et al. [27] utilized Funk and Dinger aggregate gradation with q=0.5 to investigate the influence of ultrafine particles on the properties of concrete. In RCCP mixtures, Equation 1 with q value of 0.45 has been proposed [28].

Yu et al. [29] utilized modified Andreasen and Andersen grading curve (Funk and Dinger gradation with the exponent of 0.37) to design the concrete matrix. They obtained a dense matrix based on the appropriate application of modified Andreasen and Andersen gradation, which had relatively higher binder efficiency and high compressive and flexural strengths. Wang et al. [30] investigated the effect of Andreasen and Andersen gradation on chloride permeability in ultra-high-performance concrete. They showed that using this curve, a concrete with high resistance against chloride penetration could be achieved. Fuller-Thompson gradation is a widely utilized particle size distribution by researchers. Gonzalez et al. [31] investigated the properties of high-performance concrete made with recycled fine ceramic and coarse mixed aggregates. They reported that utilized Fuller-Thompson curve could lead to the low contents of permeable pore volume, chloride ion penetration and water absorption. They also showed that the mechanical properties were higher than those of conventional concrete and the increase of compressive strength from 28 to 180 days is higher than that of conventional concrete.

As it was shown, in recent years, in order to reach the high packing density of concrete mixtures, different aggregate gradations have been utilized and suggested. However, it is not clear which grading curve could provide the highest packing density among the others to improve the concrete properties. On the other hand, it is a common method to evaluate the packing density of aggregates in the dry state. The present study aims to investigate the influence of the dry packing density of aggregates as a criterion to produce high-performance concrete mixtures. Furthermore, the differences between the effects of different ideal gradations have not been considered in the other studies. In most of the other studies, an ideal curve has been utilized to reach a high packing density, however, it is not clear which ideal gradation could have a better performance in enhancing the durability and mechanical properties in high-performance concrete.

In this research, different types of aggregate gradations with different packing densities were studied, including Fuller-Thompson (F) grading curve, Andreasen–Andersen (A) grading curve and their modified forms (MA and MF). The results could be useful in designing high-performance concrete mixtures. In this research, Equation 1 with exponent 0.5 is called the Fuller curve and that with exponent 0.37 is called the Andreasen curve. The aggregate gradation represented by Equation 2 with exponent 0.5 is called the modified Fuller curve and that with exponent 0.37 is called the modified Andreasen curve.

2- Experimental program

2- 1- Materials properties

In this study, a type I/42.5 Portland cement in accordance with ASTM C150 [32], was used in concrete mixtures. The utilized silica fume was in conformance with the ASTM C1240 [33] and was supplied by AZNA Ferroalloy Company. Similar to the investigations performed by Madani et al. 2012 [34] and Madani et al. 2014 [35], to use silica fume in the concrete mixtures, it was mixed with water in a mass concentration of 30% and then was dispersed for 4 min by a high shear mixer. The chemical and physical characteristics of the silica fume and cement are shown in Table 1.

Table 1. Physical properties and chemical composition of the cement and silica fume

Properties	cement	silica fume
Silica (SiO_2)	21.2	92.3
Iron oxide (Fe_2O_3)	3.8	1
Alumina (Al_2O_3)	4.6	1.3
Calcium oxide (CaO)	62	1.6
Magnesium oxide (MgO)	1.4	0.9
Sulfur trioxide (SO_3)	2.45	0.11
Sodium oxide (Na_2O)	0.28	0.25
Potassium oxide (K_2O)	0.59	0.79
Loss on ignition	1.02	1.53
Moisture content	0.3	0.2
Surface area (m^2/g)	0.314	21

The fine aggregate was a silica sand with a maximum dimension of 4.75 mm, saturated surface dry density of 2640 kg/m^3 and water absorption of 2.03%. The coarse aggregate was a crushed silica stone with a maximum size of 19 mm, saturated surface dry density of 2630 kg/m^3 and water absorption of 0.9%. A Polycarboxylic ether based superplasticizer was used in the mixes to reach the desired workability. Silica powder was also used to adjust the fine dimensions in the aggregate gradations. Silica powder, cement and silica fume size distributions were determined by laser diffraction spectrometry as shown in Figure 1.

2- 2- Mix design and specimens preparation

The concrete mixtures were prepared at three different w/cm ratios of 0.31, 0.38 and 0.45. The cementitious materials content was kept constant at a level of 400 kg/m^3. 12 mixtures were designed without silica fume and 12 mixes were designed with silica fume at 6% cement replacement level. The sequence of preparing mixtures in this study was as follows:

1. Mixing dry ingredients in a mixer for 1.5 min.
2. Adding water and silica fume slurry to the dry ingredients.
3. Mixing the mixtures for 2 minutes while adding

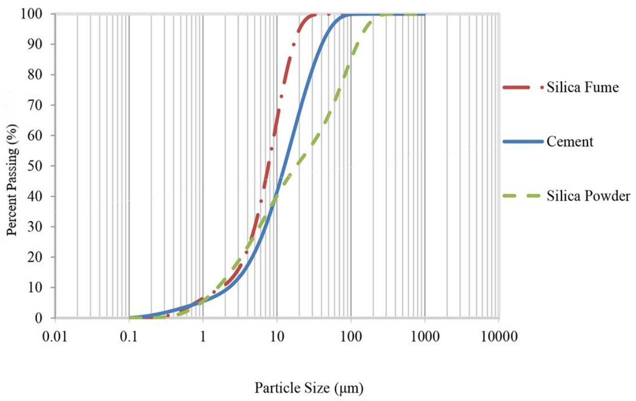

Fig. 1. Particle size distributions of silica powder, silica fume and cement

superplasticizer to reach the desired workability.

4. Continue mixing for another 4 minutes.

It should be noted that the amount of water in silica fume slurry was considered as a part of mix water. Mix proportions are given in Table 2. For all mixtures, the slump was kept constant in the range of 120±20 mm. To minimize water evaporation, all specimens were covered for 24 hours after casting. After demolding, the specimens were cured with Calcium Hydroxide (CH)-saturated water at 22±2°C until the time of testing.

2- 3- Test methods

2- 3- 1- Packing density

In the current study, the aggregates were first dried by putting them in a 100 °C oven for 24 hours. Then, the aggregates were mixed according to the ideal aggregate gradations; afterward, the aggregates were poured into a 4-liter steel container and weighted. At another time, the steel container was filled with the mixed aggregates in two layers and each layer was placed and vibrated on a vibrating table for 30 seconds. By knowing the mass of each aggregate type and the volume of the container, void content and packing density of the aggregates were calculated (Equations 3 and 4) [36].

$$void\ content\ (e) = (V_C - ((M_1/G_1)+(M_2/G_2)+(M_3/G_3)))/V_C \qquad (3)$$

$$PF = 1 - void\text{ - }content \qquad (4)$$

Where V_c is the volume of the container; M_1, M_2, M_3 are the mass of each aggregate type; G_1, G_2, and G_3 are the specific gravities of the corresponding aggregate types.

As mentioned previously, different types of aggregate gradations have been widely used in studies. However, it is not still clear that which gradation has a higher packing density together with higher mechanical and durability characteristics, thus this study investigated the influence of packing density of aggregate gradations on the properties of

Table 2. Mixture proportions of concrete mixtures

Mix	cement (Kg/m³)	silica fume (Kg/m³)	silica powder (Kg/m³)	fine aggregate (Kg/m³)	coarse aggregate (Kg/m³)	water (Kg/m³)	sp (Kg/m³)
MA-.37-.45	400	-	72	884	854	180	1.7
MF-.5-.45	400	-	36	774	994	180	1
A-.37-.45	400	-	272	847	697	180	3.1
F-.5-.45	400	-	145	732	946	180	2
MA-.37-.38	400	-	76	938	888	152	4.4
MF-.5-.38	400	-	37	882	1036	152	2.8
A-.37-.38	400	-	284	888	722	152	6.4
F-.5-.38	400	-	151	754	981	152	4
MA-.37-.31	400	-	78	966	923	124	8
MF-.5-.31	400	-	40	846	1079	124	4.8
A-.37-.31	400	-	295	924	750	124	12
F-.5-.31	400	-	157	786	1020	124	6.8
MA-.37-.45-SF	376	24	72	886	848	180	2.2
MF-.5-.45-SF	376	24	36	775	989	180	1.35
A-.37-.45-SF	376	24	272	846	688	180	3.7
F-.5-.45-SF	376	24	145	723	936	180	2.4
MA-.37-.38-SF	376	24	76	928	883	152	4.9
MF-.5-.38-SF	376	24	37	813	1030	152	3.5
A-.37-.38-SF	376	24	281	880	717	152	7.2
F-.5-.38-SF	376	24	149	747	974	152	5.3
MA-.37-.31-SF	376	24	78	957	918	124	9
MF-.5-.31-SF	376	24	40	846	1071	124	5.8
A-.37-.31-SF	376	24	295	922	746	124	13.1
F-.5-.31-SF	376	24	157	784	1014	124	7.6

high performance concretes. For this purpose, different types of ideal grading curves were investigated, including Fuller-Thompson (F), modified Fuller-Thompson (MF), Andreasen-Andersen (A) and modified Andreasen-Andersen (MA). The most significant difference between the gradations is attributed to the dimensions lower than 150 µm. For instance, the concrete mixtures with w/cm of 0.38 and with aggregate gradations of A, F, MA and MF have powder contents of about 284, 150, 76 and 37 kg/m^3, respectively. The modified Andreasen-Andersen and Fuller-Thompson curves (Funk and Dinger curves with the exponents of 0.37 and 0.5, respectively) do not require particles finer that 75 µm in their gradations according to Equation 2; therefore, it is possible to have coarser aggregates in the mixtures without significant amount of stone powder or ultrafine sand. Table 3 shows the ideal gradations investigated in this research.

2- 3- 2- Compressive strength

Compressive strength test results were determined at the ages of 3, 7, 28, 90 and 365 days according to BS EN 12390-3 [37]. At each age, four cubic specimens with the dimension of 100 mm were tested.

2- 3- 3- Rapid Chloride Migration Test (RCMT)

The RCMT was carried out in accordance with the NT BUILD 492 [38] at the ages of 28 and 90 days. For each mixture, three specimens were tested to measure their chloride resistivity. In this method, the diffusion of chloride ions into 50 mm thick concrete disks is accelerated by applying an external electrical potential for a specified duration. In this method, the magnitude of applied voltage is set based on initial current passed through the specimen. At the end of the test, the average depth of chloride diffusion is measured by splitting the specimen and spraying 0.1 M AgNO3 on the broken surfaces. The chloride migration coefficient is estimated by Equation 5 [38].

$$D_{nssm} = \frac{0.0239(273+T)\times L}{(U-2)\times t}\times\left(X_{d}-0.0238\right)\times\sqrt{\frac{(273+T)\times L\times X_d}{U-2}} \quad (5)$$

D_{nssm} : *Non-steady-state migration coefficient*, $\times10^{-12} m^2/s$

U: Absolute value of the applied voltage, V;
T: Average value of the initial and final temperatures in the anolyte solution, °C;
L: Thickness of the specimen, mm;
X_d: Average value of the penetration depths, mm;
t: Test duration, hour

2- 3- 4- Permeable voids

The permeable voids content was determined as per ASTM C642 [39] at the ages of 28 and 90 days. In this method, cylindrical specimens with 50 mm height and 100 mm diameter were oven dried at 105 °C until a constant weight was obtained. Afterward, the dried specimens were immersed in water until they reached a constant weight. The permeable voids content was calculated as follows:

$$Permeable\ voids\ (\%) = \frac{g_2 - g_1}{g_2}\times 100 \quad (6)$$

$$g_1: Bulk\ density,\ dry = \left[\frac{A}{(C-D)}\right]\times\rho \quad (7)$$

$$g_2: Apparent\ density,\ dry = \left[\frac{A}{(A-D)}\right]\times\rho \quad (8)$$

A = mass of oven-dried sample in the air, g
C = mass of surface-dry sample in the air after immersion and boiling, g
D = apparent mass of sample in water after immersion and boiling, g
ρ = density of water = 1 mg/m^3 = 1 g/cm^3.
g_1: Bulk density, dry
g_2: Apparent density

2- 3- 5- Dry density

The dry density was measured in accordance with BS EN 12390-7[40].

3- Results and discussion

3- 1- Water demand of concrete mixtures

The superplasticizer contents of the mixtures are presented in Figure 2. The results indicate that the concretes with the modified grading curves had a lower water demand compared to their corresponding unmodified forms. Thus, it seems that the modified grading curves may be more economical. At similar w/cm ratios, the mixtures with the modified Fuller-Thompson grading curve had the minimum superplasticizer demand and the mixtures with the Andreasen grading curve had a maximum superplasticizer content. For instance, for the mixes with silica fume at w/cm of 0.31, the mixture with the Andreasen curve had about 125% higher superplasticizer level compared to the mixture with the modified Fuller curve. However, by increasing the w/cm ratio, the differences were reduced. This may be attributed to the finer dimensions of the Andreasen grading curve compared to the other aggregate gradations. The following sequence for the water demand of concrete mixtures was achieved:

$$A > F \sim MA > MF \quad (9)$$

3- 2- The packing density of grading curves of dry aggregates

The packing densities of the aggregate gradations are presented in Figure 3. As shown, the mixture of aggregates with Andreasen grading curve had the highest packing density and the modified Fuller-Thompson grading curve had the lowest packing density among the grading curves. The

Table 3. Percent passing of aggregates in grading curves

grading curve	Sieve size								
	19	12.7	9.525	4.75	2.36	1.18	0.6	0.3	0.15
MA-0.37	100	84.1	74.1	54.0	38.3	26.3	17.2	9.9	4.3
MF-0.5	100	80.5	68.8	46.7	30.9	19.9	12.3	6.7	2.8
A-0.37	100	86.2	77.5	59.9	46.2	35.8	27.8	21.5	16.7
F-0.5	100	81.8	70.8	50.1	35.2	24.9	17.8	12.6	8.9

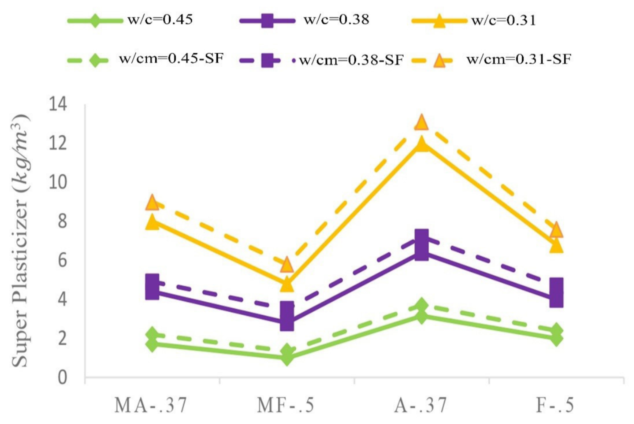

Fig. 2. Comparison of superplasticizer dosage at different w/cm ratios

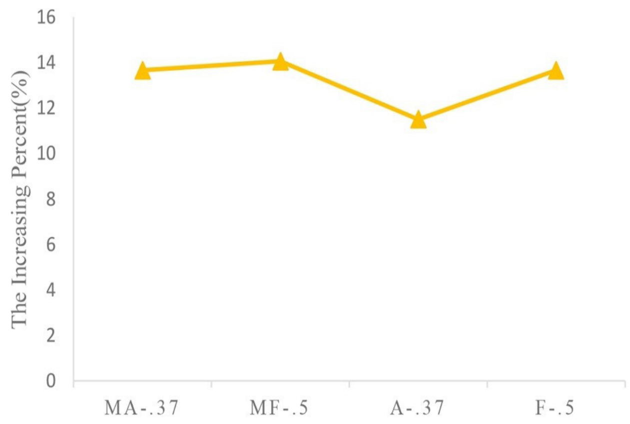

Fig. 4. Packing density enhancement level in vibrated aggregate mixture compared to the non-vibrated aggregates

modified Andreasen grading curve and the Fuller curve had almost equal packing density values. The following sequence for the maximum packing density was achieved:

$$A > F \sim MA > MF \tag{10}$$

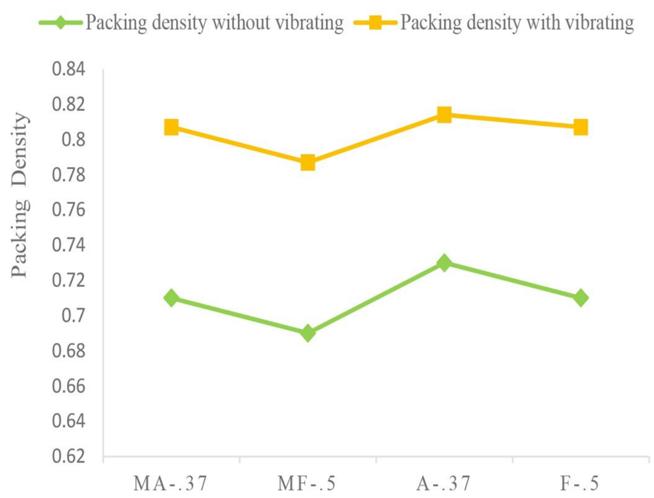

Fig. 3. A comparison of packing density of different grading curves

As shown in Figure 4, vibrating the mixtures of the aggregates has caused 12±2 % increase in packing density of all the mixtures. However, a similar trend to Equation 7 was still observed.

3- 3- Investigation on the packing density by considering the dry density of hardened concrete

As displayed in Figure 5, in contrast to the packing density test results of aggregates, at similar w/cm ratio, the concrete mixtures with the Andreasen curve had the lowest dry density and those with the modified Fuller curve had the highest dry density. As dry density is defined by the ratio of solid mass to volume, it can be concluded that in a constant volume, the mixtures with the modified Fuller curve had a higher solid content. Hence, the modified fuller curve should provide higher packing densities. The sequence of the packing density of the mixtures was obtained as follows:

$$MF > F \sim MA > A \tag{11}$$

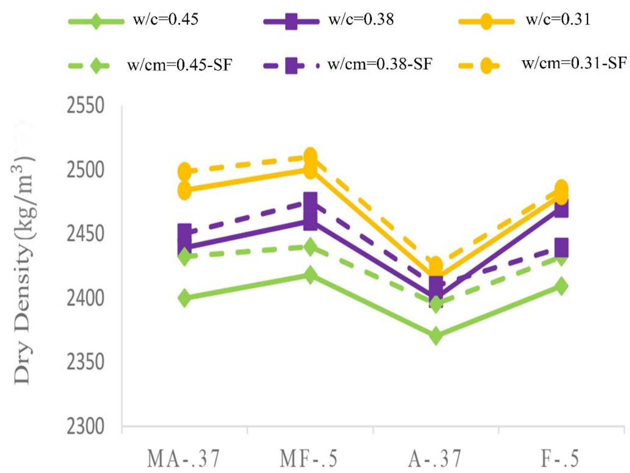

Fig. 5. A comparison between the dry densities of the HPC mixtures

The determination of packing density of aggregates in the dry state is a widely used method in studies [36, 41, 42]. However, it should be considered that in combination with cement paste, the moisture content and compaction level of the aggregates are changed, hence the packing density is different from that in the dry state. Accordingly, the differences between the sequence of packing densities obtained in this section and those obtained in the previous section could be due to the influence of cement paste on the compaction of aggregates. It should be mentioned that reducing the w/cm ratio and the use of silica fume led to the enhanced packing density values.

3- 4- Permeable voids

As shown in Figure 6, the mixtures with the modified Fuller-Thompson gradation had the minimum permeable voids. Inconsistency between the aggregate packing density and concrete permeable voids indicates that concluding on the packing density of concrete by considering the packing density of dry aggregates is not a reliable method. As shown in Figure 6, the mixtures with the Andreasen grading curve had the maximum permeable voids, and consequently, should have the minimum packing density among the other mixtures. The minimum permeable voids content was mainly attributed to the mixtures with the modified Fuller-Thompson grading curve. The following sequence for the permeable voids of the mixtures has been achieved:

$$MF > F \sim MA > A \tag{12}$$

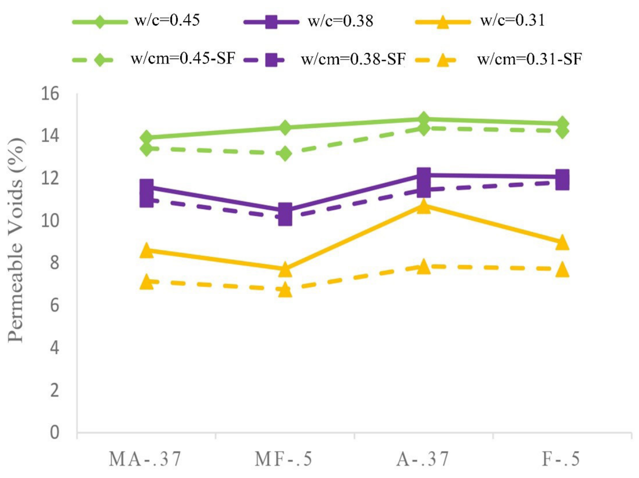

Fig. 6. Permeable voids of concrete mixtures

Using silica fume reduced the permeable voids but it was not as effective as changing the w/cm ratio. On the other hand, the influence of silica fume on reducing the permeable voids was not as significant as its effect on the reduction of chloride penetration. The reason could be due to the effect of silica fume on creating a tortuous pore structure. Several research studies have shown that silica fume cannot not reduce the pore volume [43].

3- 5- Compressive strength

The average results of compressive strengths at the ages of 3 to 365 days are presented in the Figures 7 to 11. As shown in Figure 7, in three days, the mixtures with the Andreasen gradation had the lowest compressive strength among the other mixes. Other gradations have almost equal compressive strengths, however, in some cases, a slight increase in compressive strength could be observed for the modified Fuller aggregate gradation. By increasing the w/cm ratio, especially at w/cm of 0.45, the effect of Andreasen gradation on reducing the compressive strength has been diminished and similar strengths were obtained compared to the other mixtures. The following trend could be noticed for the effect of aggregate gradations on compressive strengths in three days.

$$MF \geq F \sim MA > A \tag{13}$$

The similar trend on compressive strength to that obtained in three days was also observed at later ages and the Andreasen grading curve had the lowest compressive strength compared to the other gradations at low w/cm ratios. The results of this section are in a good agreement with the results obtained in section 3.3 on the influence of aggregate gradations on the packing density of concretes. In other words, the mixtures with Andreasen gradation which had the lowest dry density (packing density) had lower compressive strengths. It must be noted that the Andreasen curve had the highest packing density of aggregates.

At the ages of 3 days and 7 days, the compressive strengths of the mixtures were higher than 40 MPa and 45 MPa, respectively, even in w/cm ratio of 0.45. Also, the compressive strengths of concrete mixtures with w/cm ratio of 0.31 have been higher than 60 MPa. By increasing the age, the compressive strengths were enhanced. Over 365 days, the mixtures with Andreasen grading curve at w/cm ratio of 0.45 had the minimum compressive strength which was about 60 MPa. In this regard, the concrete mixtures were in the range of high-performance concrete according to ACI 363-10 [44]. At 365 days, with w/cm ratio of 0.31, the minimum compressive strength of the silica fume incorporated concretes was about 82 MPa for the mixture with the Andreasen gradation and the highest strength was about 111 MPa for the mixture with the modified Fuller gradation. In other words, the mixture with the lowest dry packing density of aggregates (MF) outperforms that with the highest dry packing density of aggregates (A) by about 30% in compressive strength at low w/cm ratios.

Replacing cement with silica fume did not have a positive effect on compressive strength in 3 days and lower strengths were obtained. This could be due to the slow pozzolanic reactivity of silica fume at an early age and the reduced cement content. At later ages, a higher rate of pozzolanic reactivity of silica fume occurred, leading to higher compressive strengths compared to the plain mixtures at the ages of 28 to 365 days.

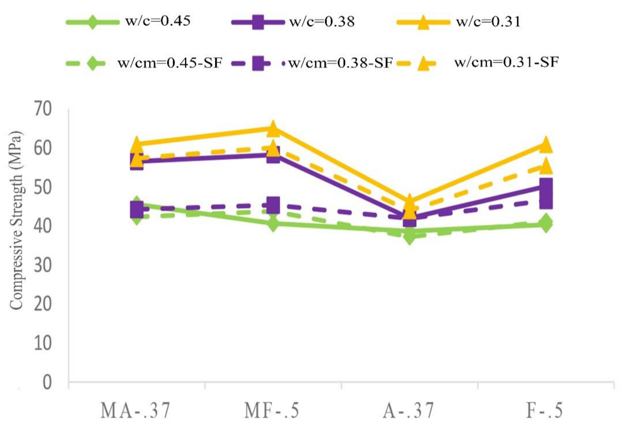

Fig. 7. Compressive strength test results in 3 days

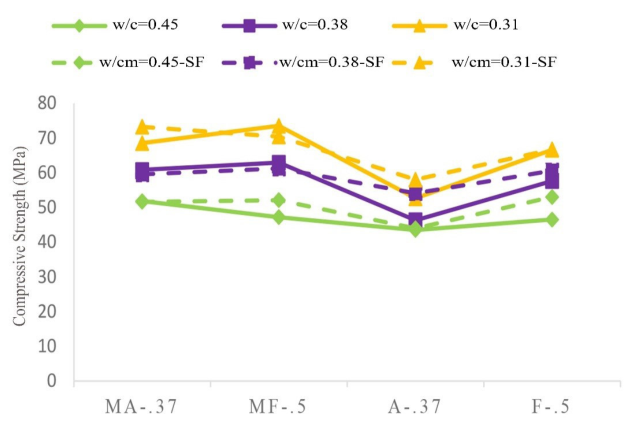

Fig. 8. Compressive strength test results in 7 days

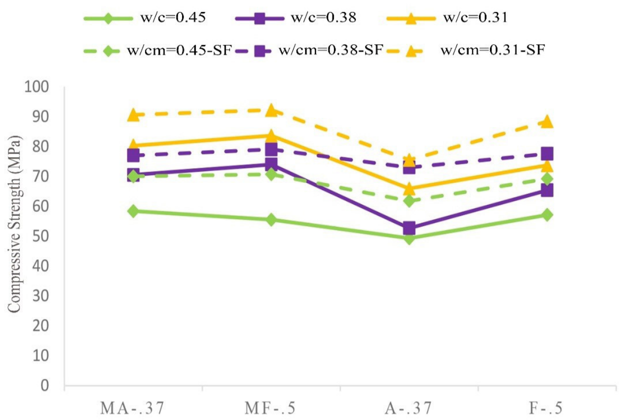

Fig. 9. Compressive strength test results in 28 days

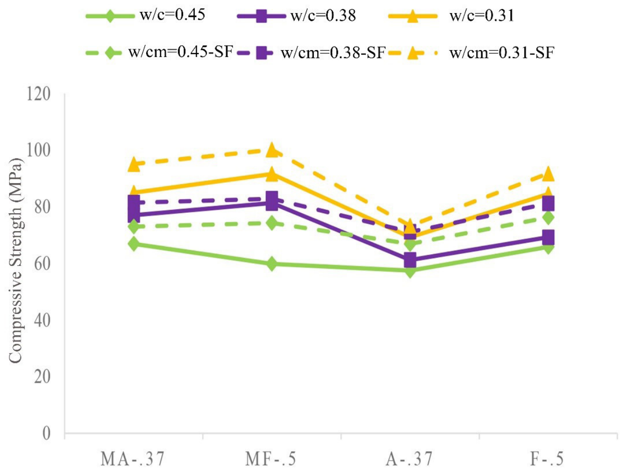

Fig. 10. Compressive strength test results in 90 days

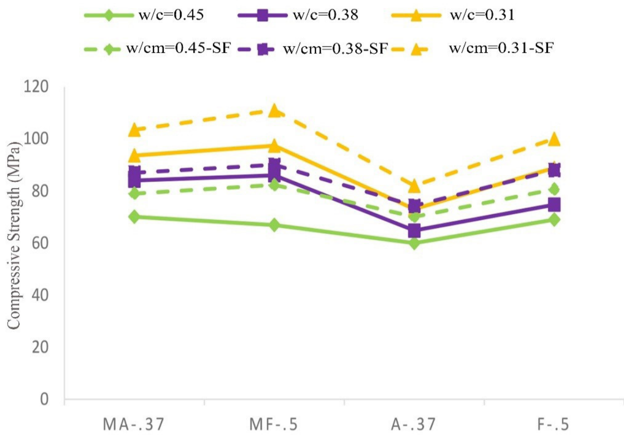

Fig. 11. Compressive strength test results in 365 days

3- 6- Rapid Chloride Migration Test (RCMT)

The average results of RCMT are shown in Figures 12 and 13. As can be seen in the figures, the dry packing density of aggregates is not an indicative of the resistance of concrete specimens against chloride ions penetration. The maximum RCMT coefficients were observed for the mixtures with Andreasen gradation which had the lowest dry packing density of aggregates and the minimum chloride diffusivity was obtained for the modified Fuller aggregate gradation. The differences between the gradations were reduced by increasing the w/cm ratio. The results of this section have a good conformance with those of the dry density. The following sequence of the chloride resistivity of the mixtures has been achieved:

$$MF \geq MA > F > A \tag{14}$$

Using silica fume has caused a significant reduction in RCMT coefficient. This effect is mainly due to the high pozzolanic reactivity of this material which blocks the capillary pores in cement matrix [43]. This reduction is more evident at higher w/cm ratio and has a great influence on improving the durability of the mixtures. Reducing w/cm ratio causes considerable reduction of RCMT coefficient of all the mixtures. In order to improve the durability, using silica fume had a significant influence compared to changing the aggregate gradations or reducing w/cm ratio.

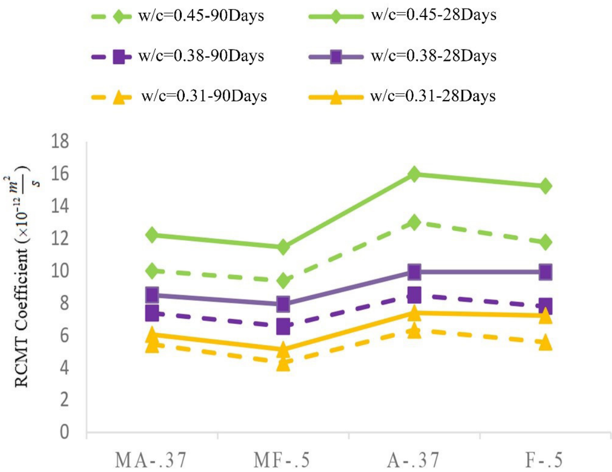

Fig. 12. RCMT coefficients of concrete mixtures without silica fume

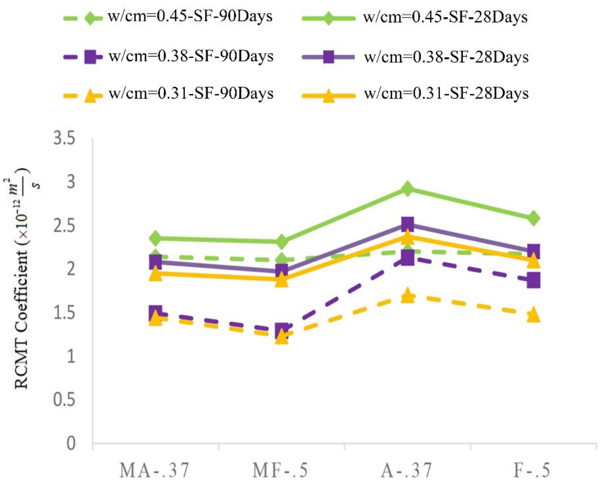

Fig. 13. RCMT coefficients of concrete mixtures containing silica fume

4- Conclusion

This paper presents the mix design and properties assessment for High Performance Concretes (HPC). The design of the concrete mixtures was based on the aim to achieve a densely compacted cementitious matrix, employing four different aggregate gradations. From this study, the following conclusions could be drawn:

- The results indicated that the mixtures with the ideal gradations of F, MF and MA outperformed the Andreasen grading curve in the mechanical and durability characteristics. However, it should be pointed out that the A gradation has a considerable amount of particles lower than 75 µm. In this research, it has not been considered that cement and silica fume have also very fine particles. As a matter of fact, high content of particles finer than 75 µm may adversely influence the packing density of the mixture. There should be compatibility between the contents of the particles ranging from ultrafine ones to large aggregates. In other words, the mixture with a grading curve may have better characteristics with lower cementitious materials. Thus, further studies must be carried out to determine the optimum level of cementitious materials for the ideal gradations.
- Mixtures with lower w/cm ratios and with silica fume had a higher dry density which indicates that these mixtures have higher packing densities. Therefore, the improved mechanical and durability characteristics of these mixtures are mainly attributed to their higher packing density, particularly for the lower w/cm levels. In addition to the highest packing density of the mixtures with silica fume, this material could enhance the microstructure properties of the cement composites as a result of creating a homogenous and tortuous microstructure.
- The packing density of aggregates in the dry state was not an indicative of the mechanical and durability properties of concrete which may lead to misleading consequences. For instance, the results of dry density of aggregates indicate that the Andreasen aggregate gradation should have a higher packing density compared to the modified fuller gradation, however, the results showed that at w/cm of 0.31, the mixture with Andreasen gradation had about 30% lower strength compared to the mixture with the modified fuller gradation.
- There was no observed correlation between the results of the packing density of dry aggregates and the mechanical and durability properties of concrete.
- In contrast to the results obtained on the packing density of dry aggregates, the concrete mixtures with the Fuller-Thompson (F) grading curve had the highest dry density (packing density) and consequently improved mechanical and durability properties compared to the similar mixes with different gradations.
- The differences between the aggregate gradations were more obvious for the mixtures with lower w/cm ratios especially at w/cm of 0.31 and at high w/cm ratios, the differences were diminished.
- By using ideal aggregate gradations high performance concretes with strengths higher than 100 MPa were obtained.
- The Mixtures with modified Andreasen (MA) aggregate gradation outperformed those with Andreasen gradation (A) at similar w/cm ratios.
- The Mixtures with the modified Fuller-Thompson (MF) aggregate gradation had a relatively higher performance compared to the other grading curves in enhancing the durability and mechanical characteristics.
- Using silica fume caused a significant decrease in rapid chloride migration coefficient. The improvement of the resistance to chloride penetration at the ages of 28 to ages 90 days for the mixtures, including silica fume was significant such that the performance of the mixture with w/cm ratio of 0.45 at the age of 90 days was similar to the performance of the similar mixtures in w/cm ratio of 0.31 at the age of 28 days.
- Silica fume led to a reduction in strength at early ages, however at the ages 28 to 90 days improved compressive strengths were observed.

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