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Research Article

EVALUATION OF THE DEPENDENCY OF THE COMPRESSIVE STRENGTH OF CONCRETE ON THE CORE DRILLING DIRECTION THROUGH ANOVA TEST

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ABSTRACT

Determination of the compressive strength of concrete in existing reinforced concrete structures is important, particularly in some cases. Destructive and non-destructive test methods are used to determine the compressive strength in such structures. Amongst these, coring is the most widely used method as a destructive method in determining the compressive strength in existing reinforced concrete structures. However, even though numerous studies have been carried out on the variation of the determined compressive strength depending on the coring direction, the discussions continue. In this study, concrete blocks containing fly ash (FA) and silica fume (SF) and aggregates of different maximum sizes were produced. In the mixtures, cement was replaced by fly ash at ratios of 20%, 40%, and 60% and silica fume at ratios of 5%, 10%, and 15%, respectively. Two aggregates with the maximum aggregate sizes of 16 mm and 31.5 mm were used in the production of the concrete blocks. The concrete blocks were kept in a laboratory by covering them with burlaps moistened intermittently for 28 days and then cores of 10 cm diameter were taken and cut to have 20 cm height then capped and tested to determine compressive strength. Core drilling was carried out parallel and perpendicular to the casting direction and then the compressive strengths were determined. Cubes of 15 cm were also prepared and tested to determine the compressive strength level of concrete and to make comparisons accordingly. The compressive strength of mineral-added core samples taken parallel to the casting direction is higher than those of taken perpendicular to the casting direction, in all mixtures. The ANOVA test applied on the results obtained, it was found that the maximum aggregate size (D_{max}) and the core drilling direction with respect to casting direction is statistically significant in terms of the compressive strength of concrete produced using fly ash and silica fume at certain substitution ratios.

Keywords: Core, coring direction, fly ash, silica fume, aggregate size, compressive strength, anova test.

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1. INTRODUCTION

Concrete is the most widely used construction material because of economy and its advantage in terms of durability and mechanical properties [1]. The compressive strength of concrete takes priority over most other properties of practical significance since it is a direct indication of concrete quality [2]. To ensure concrete quality, standard test specimens are prepared, cured, and tested in accordance with the relevant standard specifications and codes. One question arises whether the standard test specimens can represent in situ-strength of concrete. The answer to this question becomes even more important when the strengths of standard test specimens are found to be lower than the specified value. In this case, either the strength of concrete in the actual structure is low or the specimens are not actually representing the concrete in the structure. The problem is generally solved by drilling and testing core specimens from the suspected structure. Furthermore, it may be necessary to assess the current strength of concrete of an old structure to determine whether the strength and durability are adequate for its future use when the concrete is doubted, or the structure is indented to be used for higher stress conditions. For such cases, assessing of concrete strength becomes inevitable. The techniques used for assessment may be destructive and/or non-destructive. Core testing, relatively destructive, represents the most useful and reliable way to assess the properties of the concrete in the structure compared to non-destructive techniques. Therefore, the common way of determining the in-situ strength of concrete is accepted to be to drill and test concrete cores [3-6]. However, the strength results obtained on cores should be carefully interpreted because they are affected by several factors such as core diameter, core length-to-diameter ratio, moisture condition of the core specimen, the direction of drilling, the presence of reinforcement steel bars in the core and even the strength level of the concrete [7-10].

In a study [11] carried out for determining the compressive strength of 100 mm diameter cores with a length-to-diameter ratio of 2; it was found that the strengths obtained were in the order of the strength of standard cylinder being the biggest, the strength of cores taken parallel to the casting direction being the second, and the strength of cores taken perpendicular to the casting direction being the lowest. It was reported in this study that the strength of cores taken parallel to the casting direction yielded the highest strength compared to those measured for cylinder and cubes of 150 mm produced in the laboratory. It was also pointed out that the cores of 75 mm diameter taken parallel and perpendicular to the casting direction yielded 10% and 6% lower strengths compared to reference concrete, respectively.

The effects of core diameter, core length-to-diameter, type of coarse aggregate, coring direction, moisture condition of the core, and the presence of reinforcing steel bars in the cores and the strength of cores produced from concrete of different strength level have been underlined elsewhere [12]. Based on the results of the study, it was found that the strengths of the cores were decreased as the length-to-diameter ratio increases, as the core diameter decreases, in the presence of reinforcement, in the presence of coarse aggregate, increased moisture, coring parallel to the casting direction, and at lower concrete strength levels.

In the works given elsewhere [13-14], it was pointed out that the strengths of cores produced using aggregates of different maximum sizes gradually decreased as the maximum aggregate size increases. The core strength of concretes produced using aggregate with a maximum aggregate size of 20 mm is lower compared to the core strength of concrete produced using aggregate with a maximum aggregate size of 10 mm. The reason for this was attributed to the fact that the cores taken from concretes having a greater maximum aggregate size may be damaged more easily compared to the cores taken from concretes having smaller maximum aggregate size during the drilling process [15].

It was reported in some studies that the cube/core strength ratio of concretes produced using aggregates with a maximum aggregate size of 20 mm is greater than that produced using aggregate with a maximum aggregate size of 10 mm. This is because the cores taken from concretes produced using aggregate with greate r maximum aggregate size may be damaged more easily compared to those produced using aggregate with smaller maximum aggregate size [13-15].

Although numerous studies have been carried out relating to the parameters affecting the strength of core, discussions associated with the effect of coring direction and the maximum size of the aggregate on the strength of concrete continue. Concrete blocks incorporating fly ash and silica fume at different ratios were produced to investigate the effects of coring direction on the compressive strength of concrete. Productions of concretes were performed using aggregates of the same origin but with two different maximum aggregate sizes of 16 mm and 31.5 mm. Following 28 days of curing, the cores of 10 cm diameter and 20 cm length were extracted from each concrete block and tested to measure the strength of concrete. Three cores of parallel to the casting direction and three cores of perpendicular to the casting direction were extracted from each concrete block produced from the same batch. To determine the concrete strength level and to make comparisons, cubes of 15 cm were also prepared.

2. EXPERIMENTAL STUDY

2.1. Materials

2.1.1. Aggregate

In the study concretes were produced using limestone crushed aggregate with maximum aggregate sizes of 16 mm and 31.5 mm. Crushed sand and sea sand were used as fine aggregate in the productions. Saturated surface dry specific gravity, along with the water absorption capacity of the aggregates are given in Table 1. The gradations of the aggregates, along with the boundary curves for both maximum aggregate sizes are given in Figure 1 and Figure 2, respectively.

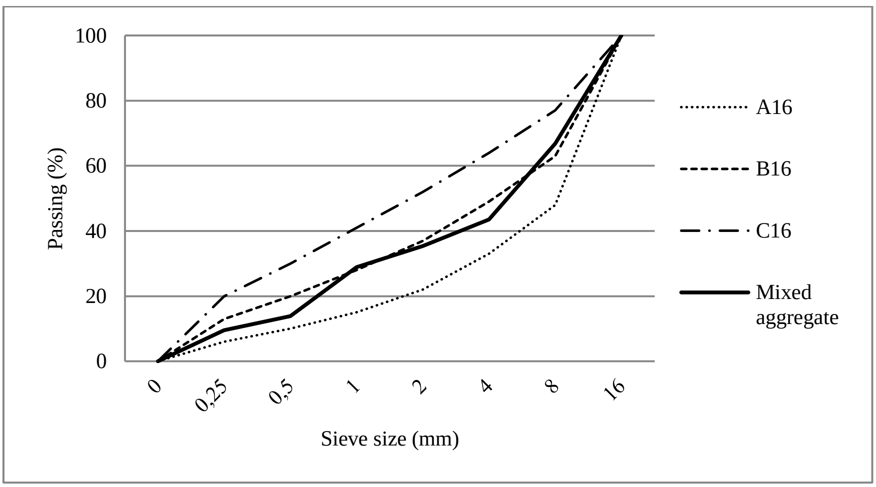

Figure 1. Gradation curve of the mixed aggregate with a maximum aggregate size of 16 mm

Table 1. Specific gravity and absorption capacity of the aggregates

Aggregate	Specific gravity	Absorption, %
Crushed limestone (D_{max}=31.5 mm)	2.68	1.0
Crushed limestone (D_{max}=16 mm)	2.67	1.5
Crushed sand	2.57	3.0
Sea sand (washed)	2.49	4.7

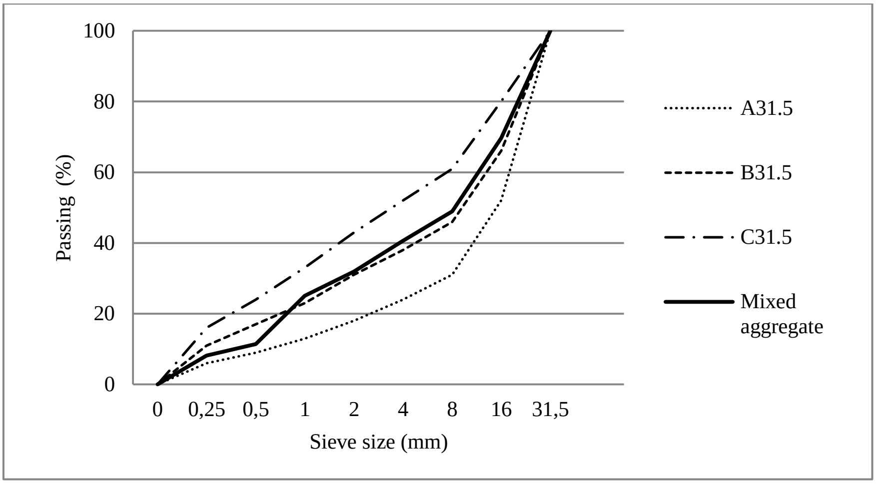

Figure 2. Gradation curve of the mixed aggregate with a maximum aggregate size of 31.5 mm

2.1.2. Cement

Table 2. Chemical composition, physical and mechanical properties of cement, fly ash and silica fume

		Cement	Fly ash	Silica fume
Chemical composition (%)				
SiO_2		19.46	61.57	93.00
Al_2O_3		5.11	20.25	0.58
Fe_2O_3		3.31	7.30	2.79
CaO		60.23	1.54	0.60
MgO		2.08	---	1.00
SO_3		3.05	---	0.50
Na_2O		0.27	---	1.00
K_2O		0.69	---	0.10
Loss on Ignition		3.00	---	0.50
Physical properties				
Specific gravity		3.12	2.34	2.20
Specific surface, cm^2/g		4260	2920	220000
Mechanical properties				
Compressive Strength, MPa	2-day	28	---	---
	7-day	40.4	---	---
	28-day	51.5	---	---

CEM I 42.5 R type Portland cement manufactured by Aşkale-Trabzon cement plant was used in the production of the concretes. Chemical composition, along with some physical and mechanical properties of cement are given in Table 2.

2.1.3. Fly Ash

The fly ash used in the study was provided by Zonguldak-Çatalağzı power generating plant. Chemical composition, along with some physical and mechanical properties of fly ash used is provided in Table 2.

2.1.4. Silica Fume

Chemical composition, along with the specific gravity of silica fume used in the study is given in Table 2. Silica fume was provided from Antalya Ferrochrome Production Facility, Turkey.

2.1.5. Chemical Admixture

In the production of concretes, the slump of concrete was tried to be kept between 10 and 15 cm using a polycarboxylate ether-based chemical admixture.

2.2. Concrete Mix Design and Methodology

In the experimental program, concrete blocks incorporating fly ash and silica fume at different ratios were produced. In preparing mixes, while fly ash (FA) was replaced at ratios of 20%, 40%, and 60%, silica fume (SF) was replaced at ratios of 5%, 10%, and 15% by weight of cement. The productions were carried out using limestone aggregates with maximum aggregate sizes of 16 mm and 31.5 mm. Three cores of 10 cm diameter from each concrete block were drilled at the end of 28 days. While some of the cores were drilled parallel to casting, some of them were drilled perpendicular to casting. The cores were cut to have 20 cm length then capped and tested to determine compressive strength. Cubes of 15 cm were also produced and tested to determine the concrete class and to make comparisons accordingly.

The mix proportions regarding the scope of the experimentation are detailed in Table 3. Water to binder ratio was kept constant as 0.60 for all mixes. A polycarboxylate ether-based chemical admixture was employed to have a slump ranging between 10 and 13 cm.

Two concrete blocks measuring 15x20x50 cm and three cube specimens of 15 cm were produced from each mix. The concrete blocks produced were kept in a laboratory by covering them with burlaps moistened intermittently for 28 days. The cubes were cured in standard condition. As schematically shown in Figure 3, three cores from one of the blocks were drilled in casting direction and three cores were drilled from the other block in perpendicular to the casting direction. The cores were cut to have 20 cm height then capped using sulphur capping material and compressive strengths were measured under axial loading. The coring and capping processes are illustrated in Figure 4.

Table 3. Mix proportions

Mix No	D_{max} (mm)	Type of mineral additive	Replacement ratio with cement (%)	Material quantities (kg/m^3)					Slump (cm)
				Cement	Water	Aggregate	Mineral additive	Admixture	
1	31.5	No additive	0	300	180	1856	0	1.59	10
2		FA	20	240		1840	60	1.26	11
3			40	180		1824	120	0.78	12
4			60	120		1807	180	0.48	13
5		SF	5	285		1851	15	3.45	11
6			10	270		1846	30	3.78	10
7			15	255		1841	45	5.19	10
8	16	No additive	0	300		1803	0	3.72	10
9		FA	20	240		1787	60	2,60	10
10			40	180		1771	120	1.77	11
11			60	120		1754	180	1.14	12
12		SF	5	285		1798	15	4.59	10
13			10	270		1793	30	5.07	13
14			15	255		1788	45	5.82	10

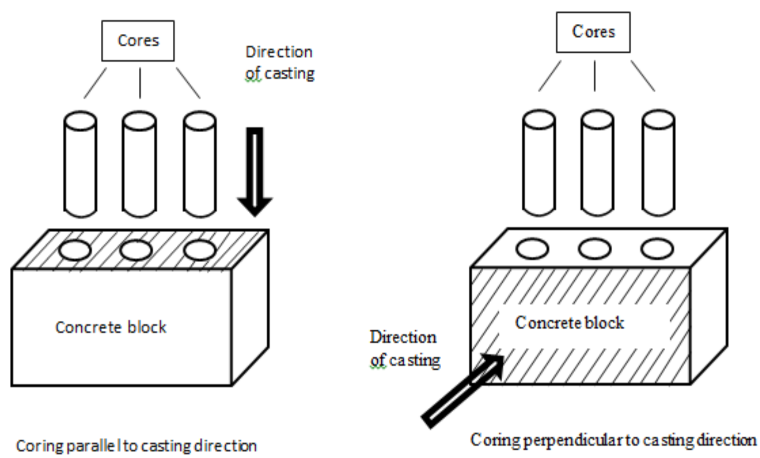

Figure 3. Schematic illustration of coring from concrete blocks depending on casting direction

Figure 4. Coring process (left) and capping process (right)

2.3. Experiments Performed

2.3.1. Slump Measurements

Slumps taken in accordance with TS EN 12350-2 [16] standard are tabulated in Table 3 for each batch.

2.3.2. Unit Weight Measurements

The unit weights of fresh concretes performed in accordance with TS EN 12350-6 [17] standard is tabulated in Table 3 for each batch.

2.3.3. Compressive Strength Measurements

The compression test was conducted in accordance with TS EN 12390-3 [18] standard and the specimens used in determining the compressive strengths are illustrated in Figure 5.

Figure 5. Cubes of 15 cm (left) and cores (right) on which compression test performed

3. RESULT AND DISCUSSION

3.1. Interpretation of Compressive Strength Measurements

Figure 6 illustrates the variation of the compressive strengths of cubes of 15 cm produced using FA and SF at different replacement ratios and exposed in standard curing condition for 28 days. The figure illustrates strength measurements for both concretes produced using maximum aggregate sizes of 16 mm and 31.5 mm. As seen from the figure, there is a considerable decrease in compressive strength as the replacement ratio of FA increases, independent of the maximum aggregate size. However, the same figure indicates that the change in the compressive strength seems to be quite negligible considering the increase in SF replacement ratio. Compared to the concretes without FA, the compressive strengths of the concretes containing 20%, 40%, and 60% FA, decrease approximately 25%, 45%, and 75%, respectively. Contrarily, concretes containing SF indicates a slight increase in compressive strength with respect to those without SF. The increase is significant in concretes produced using aggregate with a maximum aggregate size of 16 mm compared to those produced using aggregate with a maximum aggregate size of 31.5 mm with a favor of about 10%, independent of the SF replacement ratio.

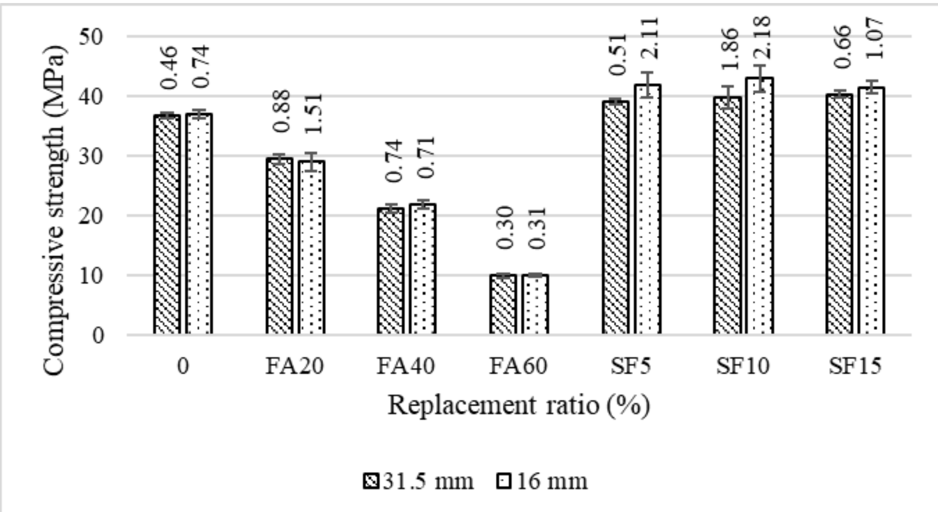

Figure 6. Compressive strengths of cubes of 15 cm cured in standard curing condition

Figure 7 illustrates compressive strengths measured on cores taken parallel to the casting direction from concrete blocks produced using FA and SF at different replacement ratios. As seen from the associated figure, the compressive strengths were decreased significantly as the replacement ratio of FA increases, independent of the maximum aggregate size. On the contrary, concretes produced using SF and containing aggregate of 16 mm indicate a significant increase in the compressive strength as opposed to those containing aggregate with a maximum aggregate size of 31.5 mm with a slight increase. It can be seen from the same figure that the compressive strength of concretes produced using 16 mm aggregate is greater at a level of approximately 20% than those produced using aggregate with a maximum aggregate size of 31.5 mm, regardless of the SF replacement ratio.

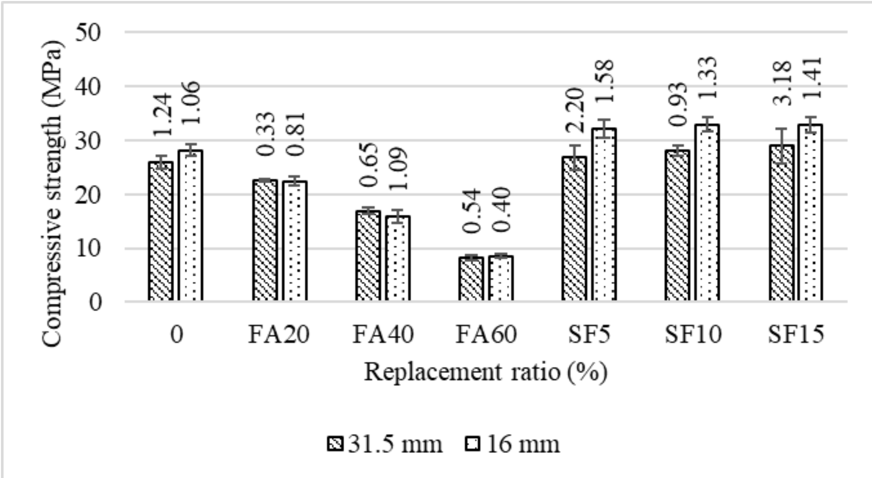

Figure 7. Compressive strengths of cores taken parallel to the casting direction

Figure 8 illustrates compressive strengths measured on cores taken perpendicular to the casting direction from concrete blocks produced using FA and SF at different replacement ratios. As seen from the figure, the compressive strengths decrease significantly as the replacement ratio of FA increases, independent from the maximum aggregate size. However, the compressive strengths of concretes produced using aggregate with a maximum aggregate size of 16 mm are relatively higher than those produced using aggregate with a maximum aggregate size of 31.5 mm. It can also be seen from the same figure that the compressive strengths of both concretes produced using aggregates with maximum aggregate sizes of 16 mm and 31.5 mm increase moderately as the replacement ratio of SF increases. It can also be seen that the compressive strengths of concretes produced using aggregate with a maximum aggregate size of 16 mm indicates a considerable increase in strength compared to those produced using aggregate with a maximum aggregate size of 31.5 mm, being maximum with a SF replacement ratio of 10%.

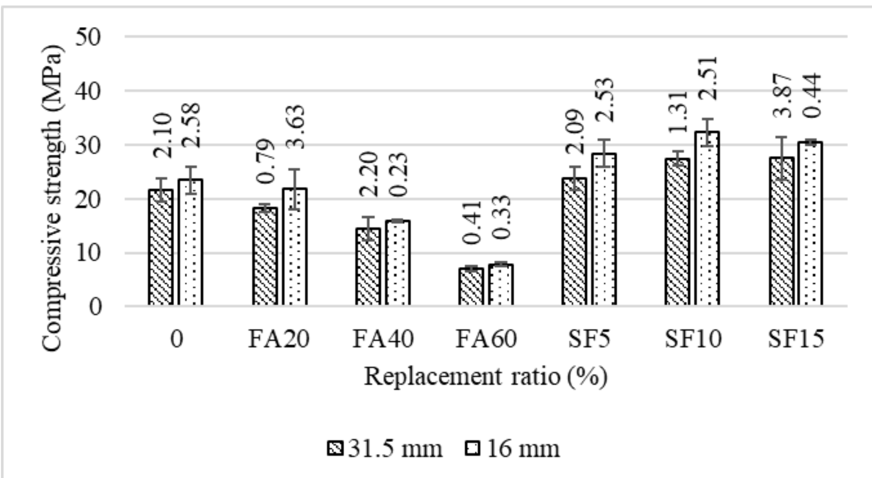

Figure 8. Compressive strengths of cores taken perpendicular to the casting direction

Figure 9 illustrates the variation in the compressive strength measurements of cores extracted from concrete blocks produced using FA and SF at different replacement ratios and using aggregate with a maximum aggregate size of 31.5 mm. The illustration conveys information about the cores taken parallel and perpendicular to the casting direction. As clearly seen from the figure, the compressive strengths of cores taken parallel to the casting direction are slightly greater than those taken perpendicular to the casting direction. This is valid for concretes with FA and SF and is independent of replacement ratio of FA and SF. The case is also valid for concretes without mineral additives. The difference between the strength of the cores taken in different coring direction may be associated with the event of water pockets occurring beneath the aggregates. This obviously results in weak interfacial zone between the aggregates and the cement paste which in turn adversely affects the compressive strength of the cores particularly to those taken perpendicular to the casting direction [12], [19]. Following the process of placing of concrete, the bleed water accumulates under the aggregates in the concrete mixture then during hardening of the concrete; the bleed water beneath the aggregates leaves their place for the pores. These pores do not significantly affect the compressive strength of the cores taken parallel to the casting direction as the pores close under pressure. However, the compressive strength of the cores taken perpendicular to the casting direction is significantly affected due to the cleavage occurring between the aggregates and cement paste [20, 21]. It is stated that the reduction in the strength of the cores taken perpendicular to the casting direction is attributed to the water accumulation beneath the aggregates. The reason for having lower strength for cores taken perpendicular to the casting direction may be related to the occurrence of longitudinal cracks resulting from excessive loads and the existence of the weak interfacial zone [22].

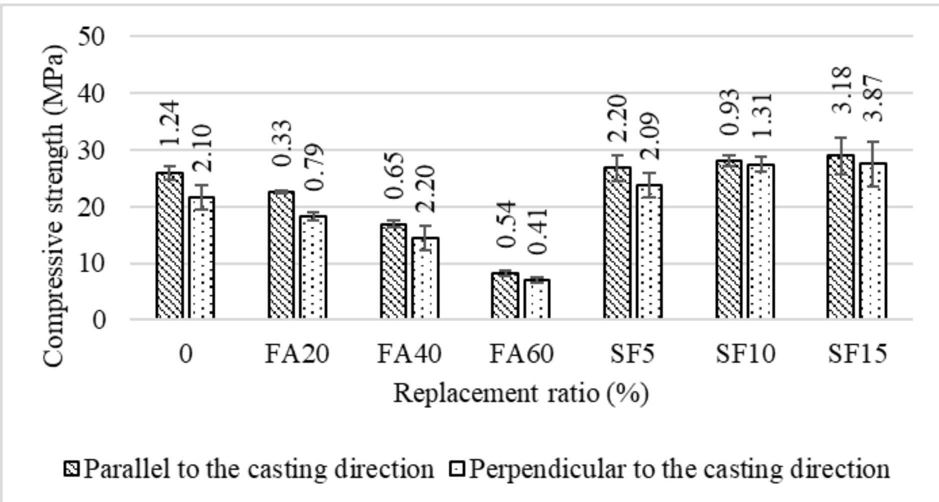

Figure 9. Strength of cores taken parallel and perpendicular to the casting direction of concrete with 31.5 mm aggregate

Figure 10 illustrates the variation of the compressive strength measurements of the cores extracted from concrete blocks produced using FA and SF at different replacement ratios and using aggregate with a maximum size of 16 mm. The figure conveys information about the cores both taken parallel and perpendicular to casting direction. As clearly seen from the figure, the compressive strengths of the cores taken parallel to casting direction are relatively higher than those taken perpendicular to casting direction. This is valid for concretes produced using FA and SF and is independent of replacement ratio. The difference between the strengths seems to be more conspicuous for concretes without mineral additive. It has been pointed out that the cores taken parallel to the casting direction yielded 14% higher strength compared to the strength of the cores taken perpendicular to the casting direction [23]. Being valid for both aggregates with maximum aggregate sizes of 16 mm and 31.5 mm, this is 19% in the present study. It has been stated elsewhere that the ratio between the compressive strength of the cores taken parallel to the casting direction to the compressive strength of the cores taken perpendicular to the casting direction is at a level of 1.08. It has been also pointed out in another study that the ratio changes between 0.96-1.14 [22,24,25]. In the present study, this is approximately 1.19 for concretes without additive.

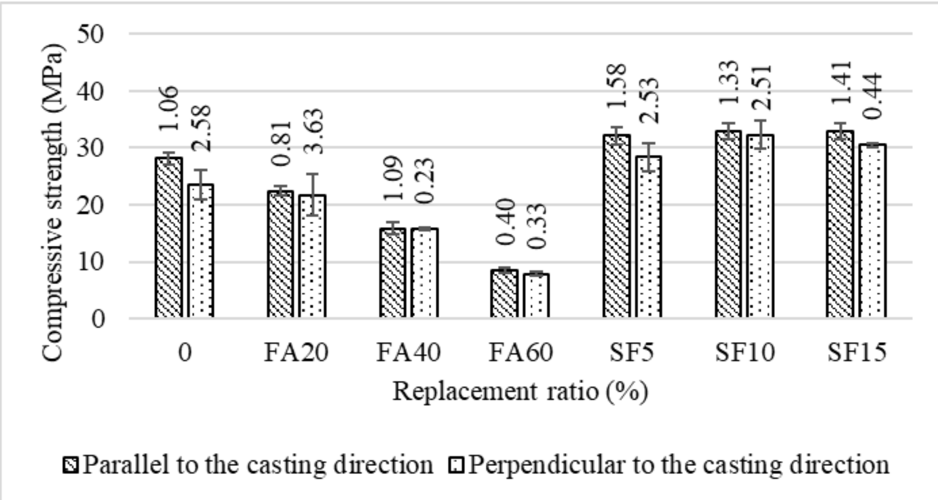

Figure 10. Strength of cores taken parallel and perpendicular to the casting direction of concrete with 16 mm aggregate

3.2. Statistical Evaluation of the Compressive Strength Measurements in view of Coring Direction

Figure 11 illustrates the relationship between the compressive strengths of 15 cm cubes produced using aggregates with maximum aggregate sizes of 16 mm and 31.5 mm. A coefficient of correlation of 0.99 is obtained which is statistically significant and indicates a perfect relation. The slope of the relationship is 1.07. This indicates that the difference between the compressive strengths of the cubes produced using aggregates of different maximum aggregate sizes is significant. In other words, this clearly shows that D_{max} has a determining effect on the compressive strength of concrete.

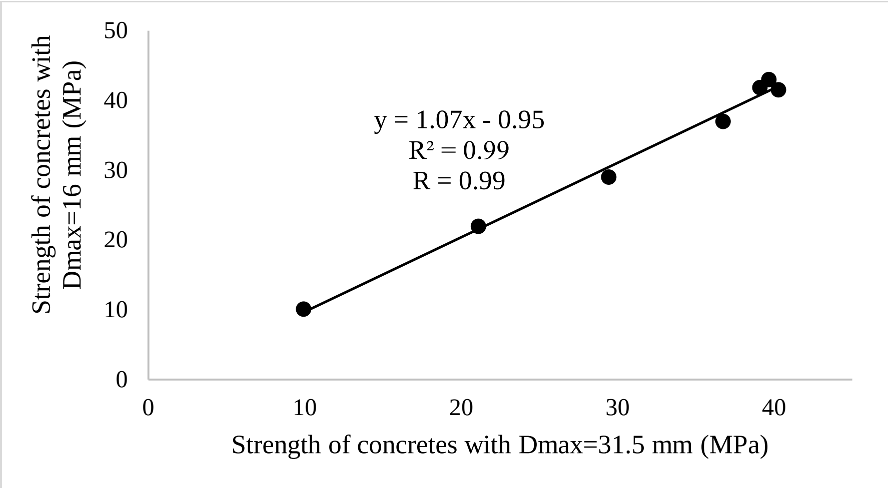

Figure 11. Relation between the strength of 15 cm cubes produced with 16 mm and 31.5 mm aggregate

Figure 12 illustrates the relationship between the compressive strengths of the cores taken parallel to the casting direction of concretes produced using aggregates with maximum aggregate sizes of 16 mm and 31.5 mm. The correlation coefficient of the relationship is 0.98, which means that there is a statistically significant correlation between the compressive strength of the cores taken parallel to the casting direction. As seen from the figure the slope of the relationship is 1.25. The slope of the relationship is an indication of how much the dependent variable depends on the independent variable. Based on this, the strength of the concrete produced using aggregate with a maximum aggregate size of 16 mm is strongly dependent on the strength of the concrete produced using concrete with a maximum aggregate size of 31.5 mm.

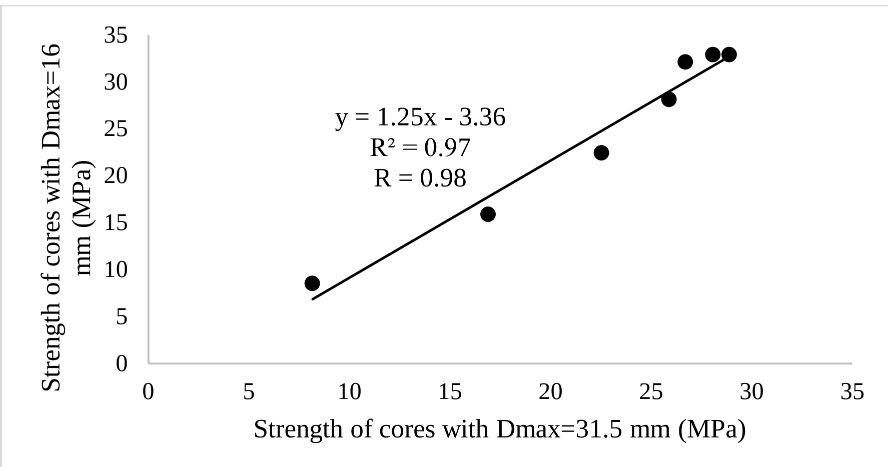

Figure 12. Relation between the strength of cores taken parallel to the casting direction

Figure 13 illustrates the relationship between the compressive strengths of the cores taken perpendicular to the casting direction of concrete blocks produced using aggregates with maximum aggregate sizes of 16 mm and 31.5 mm. The relationship is statistically strong with a correlation coefficient of 0.99. The slope of the relationship is 1.16 which indicates that the compressive strength of the concrete produced using aggregate with a maximum aggregate size of 16 mm is highly dependent on the compressive strength of concrete produced with a maximum aggregate size of 31.5 mm.

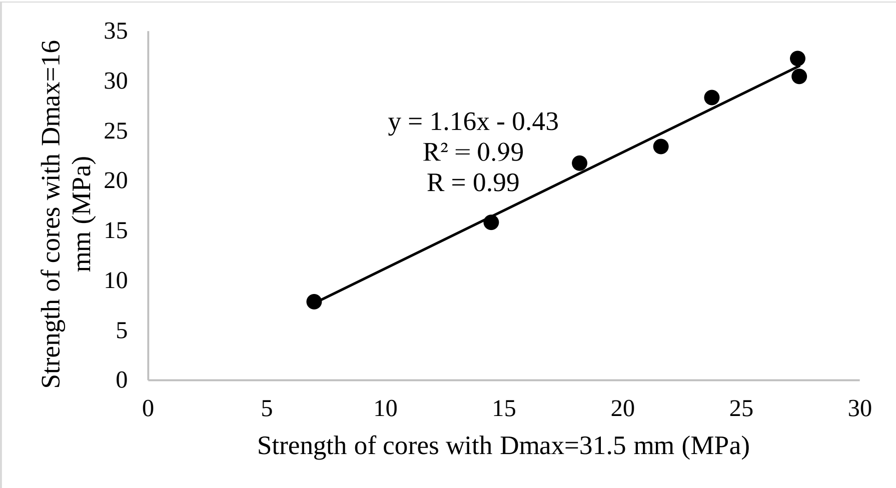

Figure 13. Relation between the strength of cores taken perpendicular to the casting direction

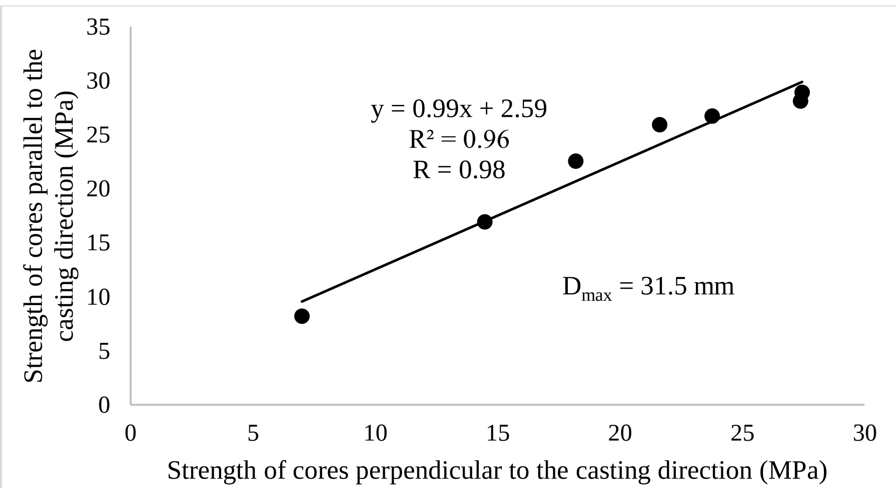

Figure 14. The relation between the strength of cores taken parallel and perpendicular to the casting direction

Figure 14 illustrates the relationship between the strength of the cores taken parallel and perpendicular to the casting direction. The maximum aggregate size used in concrete where the cores are taken is 31.5 mm. As can be seen from the graph, the relationship is statistically strong with a correlation coefficient of 0.98. Although the relationship with a slope of 0.99 indicates that the compressive strengths of the cores taken parallel to the casting direction is statistically dependent on the compressive strengths of the cores taken perpendicular to the casting direction, the compressive strength of the cores taken parallel to the casting direction is somewhat higher than those taken perpendicular to the casting direction. In other words, the increase in the compressive strength of the cores taken parallel to the casting direction is not reflected in the compressive strength of the cores taken perpendicular to the casting direction. This can be attributed to the aggregate/cement paste interface characteristics that deteriorate if the maximum aggregate size increases [19].

Figure 15 illustrates the relationship between the strength of the cores taken parallel and perpendicular to the casting direction. The maximum aggregate size used in concrete where the cores are taken is 16 mm. As can be seen from the graph, the relationship is statistically strong with a correlation coefficient of 0.98. The slope of the linear regression line is 1.08 which indicates that the compressive strengths of the cores taken parallel to the casting direction is statistically dependent on the compressive strengths of the cores taken perpendicular to the casting direction. Moreover, this relation indicates that the compressive strength of the cores taken perpendicular to the casting direction is somewhat lower than those taken parallel to the casting direction. In other words, the reflection of the increase in the compressive strength of the cores taken perpendicular to the casting direction to the compressive strength of the cores taken parallel to the casting direction becomes more evident. This can be attributed to the aggregate/cement paste interface properties that strengthen in case the maximum aggregate size decreases [21].

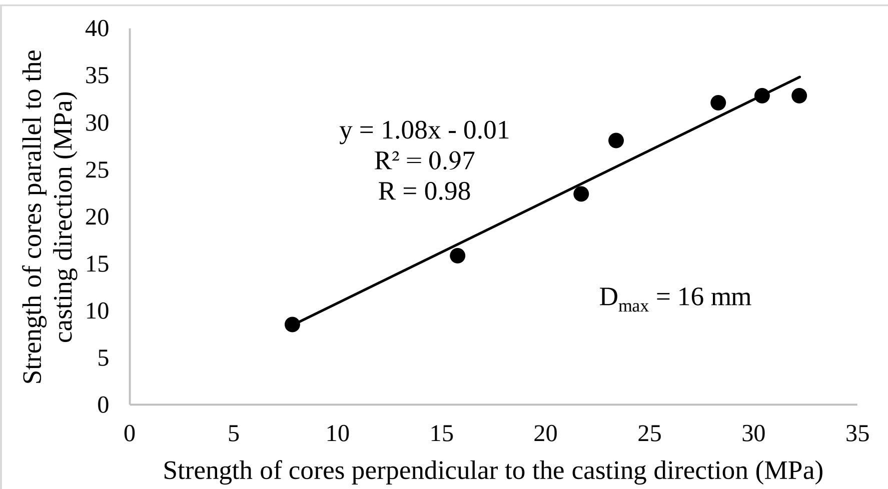

Figure 15. The relation between the strength of cores taken parallel and perpendicular to the casting direction

Analysis of Variance (abbreviated as ANOVA) is a collection of statistical models used in statistical science to analyze group averages and related processes (such as intra- and inter-group variation) [26]. Here, the ANOVA test was applied to determine separately whether the effects of the maximum aggregate size (D_{max}) and the core drilling direction on concrete compressive strength are statistically significant based on a significance level of 5% (p=0.05). The p-value is defined as the probability under the assumption of no effect of obtaining a result equal to or greater than what was actually observed. In other words, p stands for probability and measures how likely it is that any observed difference between groups is due to chance. Being probability, p can take any value between 0 and 1. Values close to 0 indicate that the observed difference is unlikely to be due to chance, whereas a p value close to 1 suggests no difference between the groups other than due to chance. For a 0.05 significance level, in case the calculated p-value is smaller than 0.05 indicates that the factor under question is statistically significant, otherwise, it is not [27-29].

The factors affecting the p-value are effect size, size of sample and spread of measurements in a data set [30]. The spread of measurements in a data set is measured commonly with standard deviation. The bigger the standard deviation, the more the spread of measurements and the lower the p-value.

The ANOVA test outcomes regarding the effect of the maximum aggregate size (D_{max}) and the core drilling direction on the compressive strength of the concrete mixtures containing fly ash at different ratios are tabulated in Table 4. As can be seen from the table, the p-values, calculated considering the F-values, determined for the effects of the D_{max} and the core drilling direction on the compressive strength of concrete are quite smaller than the significance level of p=0.05. The general conclusion that can be drawn from the ANOVA test summarized in the table below is that the D_{max} and the core drilling direction on the compressive strength of concrete are statistically significant since the calculated p-value is smaller than 0.05. In other words, the effects of the D_{max} and the core drilling direction on the compressive strength of concrete can never be neglected.

Table 4. The ANOVA test outcomes for the compressive strength of concretes containing fly ash

Source	Sum of Squares	Degree of Freedom	Mean Squares	F-value	p-value
Effect of D_{max}	14.48	1	14.476	5.24	0.0272
Effect of casting direction	62.65	1	62.655	22.68	0
Error	116.02	42	2.762		
Total	2137.05	47			

The ANOVA test outcomes regarding the effect of the maximum aggregate size (D_{max}) and the core drilling direction on the compressive strength of the concrete mixtures containing silica fume at different ratios are tabulated in Table 5. As can be seen from the table, the p-values, calculated considering the F-values, determined for the effects of the D_{max} and the core drilling direction on the compressive strength of concrete are rather smaller than the significance level of p=0.05. The general conclusion that can be drawn from this test summarized in the table is that the D_{max} and the core drilling direction on the compressive strength of concrete are statistically significant. Briefly, the effects of the D_{max} and the core drilling direction on the compressive strength of concrete can never be neglected.

Table 5. The ANOVA test outcomes for the compressive strength of concretes containing silica fume

Source	Sum of Squares	Degree of Freedom	Mean Squares	F-value	p-value
Effect of D_{max}	173.47	1	173.47	39.84	$1.4147x10^{-7}$
Effect of casting direction	81.824	1	81.824	18.79	$8.9248x10^{-5}$
Error	182.896	42	4.355		
Total	663.335	47			

4. CONCLUSIONS

In the light of the realized experimental study, along with statistical evaluation the following conclusions may be drawn:

- The compressive strength of concrete significantly decreases as the replacement ratio of FA is increased. This is more apparent for concretes kept in standard curing condition and the reduction in strength is independent of core drilling direction.
- The compressive strength of 15 cm cubes produced using FA reduces significantly as the substitution ratio increases. However, being more pronounced for concretes containing SF, the compressive strength of concretes produced using aggregate with a maximum aggregate size of 16 mm, is rather higher than that produced using aggregate with a maximum aggregate size of 31.5 mm, independent of substitution ratio.
- Being more obvious for concretes produced using aggregate with a maximum aggregate size of 16 mm, the compressive strength measured on cores taken parallel and perpendicular to the casting direction slightly increases as the substitution ratio of SF is increased.
- The compressive strength of cores taken parallel to the casting direction is higher than those taken perpendicular to the casting direction for concretes produced using FA and SF with a maximum aggregate size of 31.5 mm, being valid for all substitution ratios. This is quite consistent with concretes containing FA and SF with a maximum aggregate size of 16 mmm.
- Based on the outcomes of the ANOVA test, the effects of the D_{max} and the core drilling direction on the compressive strength of concrete containing fly ash and silica fume are found to be statistically significant for a significance level of p=0.05, irrespective of substitution ratio.
- Overall, the core drilling direction with respect to casting direction is statistically significant in determining the compressive strength of concrete. This seems to be independent of the type of mineral additive and the substitution ratio used. Likewise, the maximum aggregate size is also statistically significant that should be taken into account in dealing with the strength of concrete.

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