Effects of aggregate grading on the properties of steel fibre-reinforced concrete

M Acikgens Ulas[1], K E Alyamac[2] and Z C Ulucan[3]

[1] Fırat University, Faculty of Architecture, Department of Architecture, 23119, Elazig, TURKEY
[2] Purdue University, Faculty of Engineering, School of Civil Engineering, West Lafayette, USA
[3] Fırat University, Faculty of Engineering, Department of Civil Engineering, 23119, Elazig, TURKEY

E-mail: merveacikgenc@firat.edu.tr

Abstract. This study investigates the effects of changing the aggregate grading and maximum aggregate size (D_{max}) on the workability and mechanical properties of steel fibre-reinforced concrete (SFRC). Four different gradations and two different D_{max} were used to produce SFRC mixtures with constant cement dosages and water/cement ratios. Twelve different concrete series were tested. To observe the properties of fresh concrete, slump and Ve-Be tests were performed immediately after the mixing process to investigate the effects of time on workability. The hardened properties, such as the compressive, splitting tensile and flexural strengths, were also evaluated. In addition, the toughness of the SFRC was calculated. Based on our test results, we can conclude that the grading of the aggregate and the D_{max} have remarkable effects on the properties of fresh and hardened SFRC. In addition, the toughness of the SFRC was influenced by changing the grading of the aggregate and the D_{max}.

1. Introduction

The term steel fibre-reinforced concrete (SFRC) is used to describe concrete containing hydraulic cement, water, fine or fine and coarse aggregates with discontinuous discrete steel fibres. SFRC is designed to enhance the ductility of the concrete by delaying the onset of tension cracks or blocking the propagation of cracks [1-3]. Furthermore, the addition of steel fibres in plain concrete can increase the tensile strength and toughness [4,5]. As the steel fibres affect the mechanical properties of the concrete positively, they also affect workability negatively. Since the main components of the SFRC are similar to conventional concrete, the fresh and hardened properties are affected by the cement content, the water/cement ratio and the aggregate properties other than steel fibres [1,6]. The water/cement ratio is one of the most widely researched parameter because of its major influence on the workability and concrete strength. The influences of aggregate parameters on the properties of the SFRC, however, are generally not as well appreciated [1,3,7]. Since approximately 75% of the concrete volume is occupied by aggregates, it is known that the aggregate properties greatly affect the performance of the concrete. Numerous parameters related to the aggregates, such as chemical and mineral compositions, shape, roughness, degree of weathering, specific gravity, hardness, strength, physical and chemical stability and pore structure, affect the properties of the concrete. Moreover,

particle size distribution known as grading or gradation and the maximum aggregate size (D_{max}) have significant effects on the fresh and hardened properties of the concrete [2,4,5,7,8].

The grading describes the distribution of aggregate particles of various sizes. The D_{max} can vary, but in any aggregate composition, particles of different dimensions will be present. The grading of a given sample can be used to tell if an aggregate composition is too coarse, too fine or lacing in a particular size. Aggregate gradations also reflect the amount of voids that must be filled by cement paste and the surface area of aggregates that needs to be coated with cement paste. Moreover the surface area of the aggregates determines the amount of water necessary to wet all of the solids. Thus, grading is important for determining the workability and tendency for segregation. Grading can also influence the economy of the mixture by determining the amount of cement paste. In addition, grading become important because the hardened properties of concrete cannot be fully realized if the concrete is unworkable and difficult to compact [3,9]. Thus, the grading of the aggregates affects both the fresh and hardened properties of the concrete.

Well-graded aggregates can give workable mixes that can be properly transported, placed and compacted [9]. The American Concrete Institute (ACI) committee 544 recommends combined aggregate gradations for SFRC. Compared SFRC to conventional concrete, some SFRC mixtures are characterized as having higher cement and finer aggregate for workability decreasing with fibre content. Therefore, increasing the fibre volume fraction (V_f) and D_{max} can also increase the tendency for clustering of the fibres and improving bond strength between steel fibres and concrete [2,10]. To prevent the clustering of steel fibres, the coarse aggregate content should be less than 55% of the total combined aggregate content by absolute volume. To provide better workability, SFRC requires increasing the paste content, limiting the D_{max} between 10 mm and 38 mm, and optimization of the grading of the aggregate [2,6]. According to Yang et al. [11], considering that the sand particles were more uniform and spherical in shape, the concrete likely had a lower void content, which improved its workability and uniformity of strength [11]. Thus, the composition of the aggregates has effects on both fresh and hardened SFRC. Chenkui and Guofan [12] investigated the hardened properties of SFRC produced with two different D_{max} values, four different fine to coarse aggregate ratios and different types of steel fibres with different V_f. SFRC containing larger amounts of coarse aggregate had good performance, and all strength values showed improvements with the addition of steel fibres.

Most standards related to the grading of concrete aggregates recommend gradations expressed as percent by mass passing a specified set of test sieves. Moreover, standards give charts or logarithmic grading curves which provide recommended limits for gradations [2,13-15]. In this way, it is possible to easily determine the different sizes of aggregates needed to obtain the best concrete mixture. In this paper, rather than investigating only aggregate ratios in a narrow range, different grading curves with different D_{max} values are considered. We experimentally investigate the properties of both fresh and hardened SFRC. Dvorkin et al. recommended that the SFRC composition can only be optimized by determining the coarse and fine aggregate fractions with the best fresh properties [16]. With this purpose, this paper deals with the effects of 4 different aggregate gradations with 2 different D_{max}.

2. Experimental Program

2.1. Material Properties

CEM I 42.5 N type ordinary Portland cement (PC) was used in all mixtures. Specific gravity and specific surface of the cement were respectively 3.1 g/cm^3 and 3749 cm^3/g. This cement type complies with the requirements of the TS EN 197-1 [17] standard.

The workability of a cement matrix generally decreases with the addition of steel fibres. With the use of chemical admixtures, however, it is possible to maintain the workability without adding extra water [2,18]. For all mixtures, a polycarboxylate-based super plasticizer (SP) admixture was used. The specific gravity of the admixture was 1.1 g/cm^3.

The steel fibres added to the SFRC mixtures were hooked end-type. The tensile strength of the steel fibres was 1250 MPa and the modulus of elasticity was 200 GPa. The fibre length (l) was 60 mm and the fibre diameter (d) was 0.75 mm; therefore, the aspect ratio (l/d) was 80.

Two groups of crushed calcareous aggregates were used, the first group has D_{max}=16 mm, and the second group has D_{max}=31.5(32) mm. These two groups of aggregates were sieved and divided according to the basic sieve series which is given by the TS 706 EN 12620 [19] standard. Aggregates, divided into the sieve sizes, were added to concrete mixtures with the percentages of designed gradations. 8 types of gradations were calculated on the basis TS 802 [15] standard. The specific gravity of coarse (31.5~8mm), medium (8~2mm) and fine (1mm~filler) aggregates were respectively 2.68, 2.60 and 2.58 g/cm³. The water absorption rate of coarse (31.5~8mm), medium (8~2mm) and fine (1mm~filler) aggregates were 0.3, 2.2 and 3%, respectively.

2.2. Mixture Proportions

All of the SFRC mixtures were prepared with constant cement dosage to provide normal strength values. The *W/C* ratio and the amount of SP were also kept constant. Moreover, the volume fractions (V_f) of the steel fibre were 0% (for reference or plain concrete) and 1%. The proportions used in the SFRC mixtures are listed in table 1, with the aggregate contents given according to sieve sizes. For example, $\frac{16}{8}$ means that the aggregates passed through a 16 mm square mesh sieve and were retained on an 8 mm square mesh sieve. Furthermore, the numbers 16 and 31.5 (32) in the mixture codes refer to the D_{max} values of the mixtures. The letters before the numbers define the grading curves of the mixtures. The mixture code with R means that the mixture was produced without steel fibres (reference series) (table 1).

The volumes of the aggregates were the same for all of the mixtures. Thus, the volume of cement paste was also constant for all of the mixtures. The aggregate compositions were prepared for the grading curves, which are shown in figure 1.

Table 1. SFRC mixture proportions.

| Mixture Proportions (kg/m³)													
					Aggregates divided by sieve sizes (mm)								
Mix Code	PC	W/C	Steel Fibre	SP	$\frac{32}{16}$	$\frac{16}{8}$	$\frac{8}{4}$	$\frac{4}{2}$	$\frac{2}{1}$	$\frac{1}{0.5}$	$\frac{0.5}{0.25}$	$\frac{0.25}{0.125}$	<0.125
R-A16	350	0.5	0	7.0	0	282	420	402	310	181	109	91	36
A16	350	0.5	78.5	7.0	0	282	420	402	310	181	109	91	36
A32	350	0.5	78.5	7.0	282	696	274	201	128	91	72	54	54
R-AB16	350	0.5	0	7.0	0	216	365	374	310	208	154	118	82
AB16	350	0.5	78.5	7.0	0	216	365	374	310	208	154	118	82
AB32	350	0.5	78.5	7.0	216	621	265	210	146	118	100	100	72
R-B16	350	0.5	0	7.0	0	151	310	347	310	235	199	145	127
B16	350	0.5	78.5	7.0	0	151	310	347	310	235	199	145	127
B32	350	0.5	78.5	7.0	151	546	256	219	164	145	127	145	91
R-C16	350	0.5	0	7.0	0	19	201	292	310	308	290	217	181
C16	350	0.5	78.5	7.0	0	19	201	292	310	308	290	217	181
C32	350	0.5	78.5	7.0	19	414	237	219	201	199	181	217	145
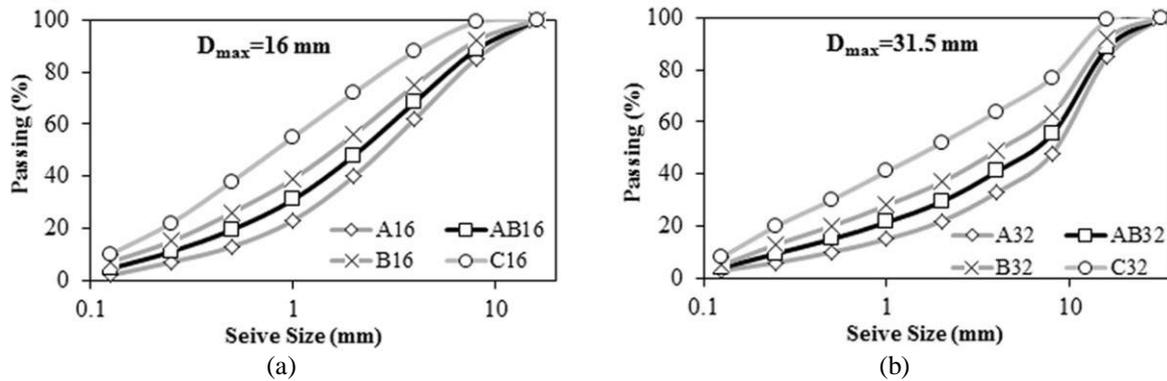
Figure 1. Gradation curves of aggregates for (a) D_{max}=16 mm and (b) D_{max}=31.5 mm.

The grading curves were designed based on the grading recommendations of TS 802 [15]. In figure 1, grading curves A, B and C, which are given by TS 802 [15], are the limits for the gradations of aggregates that produce economically feasible and workable concrete. According to the standard, the section between A and B represents the most workable and economical concrete mixture (i.e., favorable section). The section between B and C (serviceable section) can also be used. As the curve approaches the 100% line, the aggregate composition becomes finer, whereas as the graphic approaches the 0% line, the aggregate composition becomes coarser [3]. Thus, TS 802 [15] recommends that the limits A and C should not be exceeded.

In this study, two different D_{max} values and four different grading curves were used as A, B, C and AB (figure 1). For each D_{max}, the AB curve was the average of the A and B curves. The *W/C* ratio and SP content were determined to provide a 10~15 cm slump value for the R-AB16 mixture because adding steel fibres reduced the workability of the fresh concrete.

It was considered that the fineness modulus (*k*) and the fine to coarse aggregate ratios were varied for the 8 different aggregates. Before the testing procedures, it was helpful to calculate the parameters of the aggregates (table 2).

Table 2. Calculated parameters of aggregate gradings.

D_{max}=16 mm					D_{max}=31.5 mm				
Code	Fineness Modulus (*k*)	Fine Aggregate (%)	V_{void} (%)	Fine/Coarse (%)	Code	Fineness Modulus (*k*)	Fine Aggregate (%)	V_{void} (%)	Fine/Coarse (%)
A	4.7	62	38	1.61	A	5.8	32	37	0.48
AB	4.3	68	36	2.14	AB	5.4	40	35	0.68
B	3.9	75	35	2.96	B	4.9	48	33	0.94
C	3.2	88	34	7.28	C	4.1	63	31	1.73

The fineness modulus is used to characterize and evaluate a grading curve. This parameter is tied to the particle size distribution and can be obtained by adding the cumulative percentages of materials retained on each of the standard sieves and dividing the sum by 100. The larger fineness modulus is, the coarser the aggregate is, whereas the lower the fineness modulus is, the finer the aggregate is [9, 19]. In addition, considering coarse aggregates as particles larger than 4 mm and fine aggregates as particles smaller than 4 mm, according to TS 706 EN 12620 [19] standard, the fine/coarse aggregate ratios can be calculated by the mass of each aggregate group.

The void volume or content (V_{void}) of the aggregate particles are presented in table 2. The space between aggregates is another important parameter. To measure the V_{void} the aggregates are placed in a

container of known volume. The weight is then measured and the volume is calculated by dividing the aggregate weight by the specific gravity. The V_{void} of the aggregate particles is obtained using,

$$V_{void} = \left[1 - \frac{V_a}{V_c}\right] \times 100 \qquad (1)$$

where V_{void} is the void volume or content of the aggregate particles (%), V_a is the volume of the aggregates (dm^3) and V_c is the volume of the container (dm^3).

As shown in table 2, larger D_{max} values make the gradations coarser. In addition, the V_{void} decreases. As mentioned before, the volume of cement paste needed to fill between the aggregate particles is constant for all mixtures. Thus, variable V_{void} for different gradations might result in incomplete filling. It is known that unfilled V_{void} in concrete can adversely affect the properties of the concrete.

2.3. Test Procedure

Firstly, to determine the fresh properties of concrete mixtures, Slump and Ve-Be tests were performed after immediately casting according to the TS EN 12350-2 [20] and the TS EN 12350-3 [21], respectively.

Hardened concrete tests were performed on concrete specimens cured in water for 28 days. To determine mechanical properties, 150×150×150 mm cube specimens were used for compressive and splitting tensile strength as recommended by respectively the TS EN 12390-3 [22] and the TS EN 12390-6 [23]. Moreover, to determining flexural strength and toughness, 4-point flexural strength test was performed on 150×150×500 mm prismatic beam specimens, according to the TS 10515 [24] standard. During the flexural strength test, changing of load and deflection of beam specimens were recorded, and the load-deflection curves of specimens were obtained.

3. Results and Discussions

3.1. Fresh Concrete Test Results

Conventional slump measurements cannot determine the workability of SFRC mixtures adequately because compaction by mechanical vibration is recommended in most SFRC applications. The Ve-Be test is more suitable for assessing the workability of SFRC mixtures [1-3]. Thus, in this study, Ve-Be tests were performed in addition to slump tests.

Figure 2 provides the respective slump values. As expected, the addition of steel fibres significantly reduced the workability of the fresh mixtures. Most of SFRC slump values were zero, especially for SFRC mixtures with D$_{max}$=31.5 mm (figure 2).

The Ve-Be times are shown in figure 3. The Ve-Be times increased with the addition of steel fibres, with increasing D$_{max}$ values compared to the reference mixtures. Because increasing the Ve-Be time means that the workability decreases, it can be said that steel fibre addition reduces the workability. Thus, changing the grading of the aggregate has a noticeable effect on the workability.

In figure 3, the workability of the reference mixtures are not very different from each other. The mixtures graded B were the most workable mixtures compared to the other gradations (figure 3).

Mixtures graded C performed poorly in terms of workability. The C grading was the finest gradation used in this study (the lowest fineness modulus in table 2). As the grading becomes finer, the aggregate surface are becomes higher leading to decreased workability [1,3,9]. The A grading was the coarsest gradation used in this study (the fewest fine aggregates and the highest fineness modulus in table 2). The workability of A mixture was very low, especially for SFRC. It is known that very coarse aggregates produce harsh and unworkable concrete mixtures [3]. Metha and Monteiro [3] content that aggregate grading and D_{max} can be specified due to the reasons such as mixing, placing, etc. Moreover, for mixtures with D_{max}=16 mm and D_{max}=31.5 mm (figure 3), the workability of the mixtures tends to decrease with higher D_{max}. This proves that coarser aggregates reduce the workability. Furthermore, especially with the addition of steel fibres, the SFRC mixtures tend to clustering due to the D_{max} and grading of aggregates [1,2]. This is why the ACI 544-1R [2] report specifies the D_{max} and grading of

aggregates for SFRC mixtures and recommends a lower volume fraction of steel fibres to be used with larger D_{max} values. Here, we emphasize that from A to C, finer gradations of aggregates positively affect the workability to a certain degree.

The Ve-Be data were more variable than the slump data. Thus, Ve-Be tests are obviously more suitable for measuring the workability of SFRC mixtures in this study. Most of the slump values for the SFRC mixtures were 0, whereas the Ve-Be times varied (figures 2 and 3).
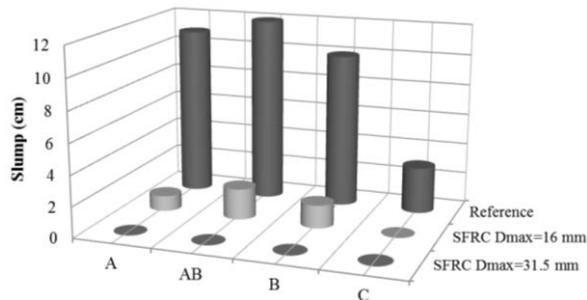
Figure 2. Slump values of the mixtures.
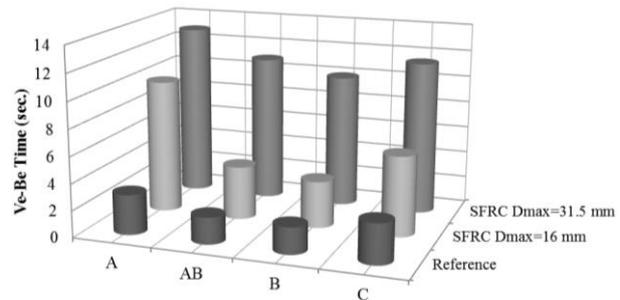
Figure 3. Ve-Be times of the mixtures.

3.2. Hardened Concrete Test Results

Figure 4 shows the changes in compressive strength (f_c) of the specimens. The aggregate grading influenced the compressive strength of both SFRC and reference concretes. The effect of steel fibres on compressive strength is negligible and the compressive strength of concrete increases with increasing D_{max} [3,7,25,26]. Although the differences between compressive strength of SFRC and reference were not very large, changing the gradation, and especially the D_{max}, affected the compressive strength with a constant cement dosage and *W/C* ratio. Increasing the D_{max} increased the compressive strength (figure 4). It can be seen in figure 4 that the grading is more influential than the presence of steel fibres on the compressive strength, especially when increasing the coarse aggregate content with D_{max}.
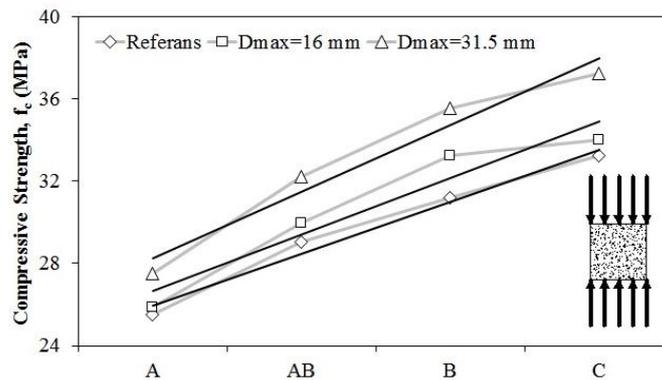

Figure 4. Compressive strengths of specimens.

It is also seen in figure 4 that the compressive strength of both SFRC and the reference concrete increases as the fineness modulus and V_{void} of aggregate particles decrease from A to C (table 2). As explained before, all of the mixtures had the same volume of cement paste. It is well known that unfilled voids by the cement paste decrease the mechanical strength of concrete. In addition, these voids can also increase by the lower workability [1,3].
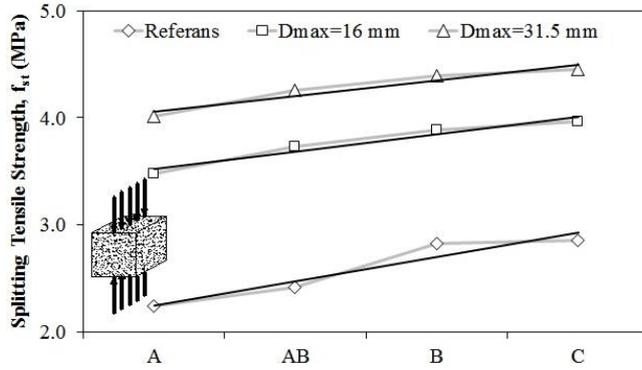
**Figure 5.** Splitting tensile strengths of specimens.
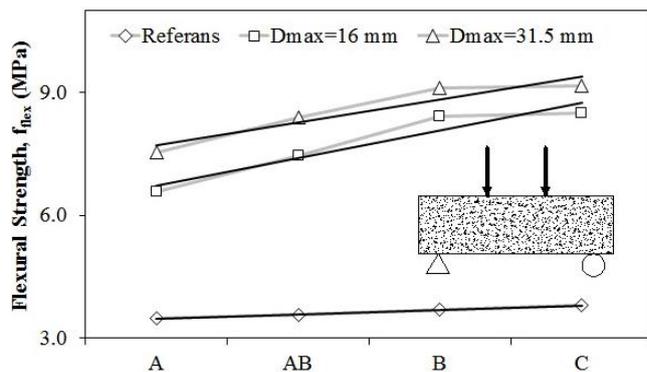
**Figure 6.** Flexural strengths of specimens.
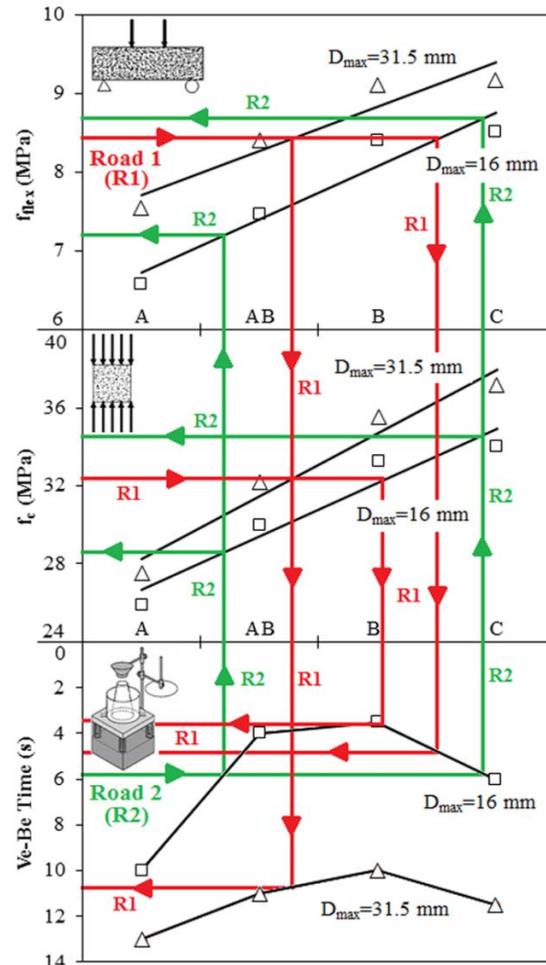
Figure 7. Relationship between Ve-Be times, compressive and flexural strengths.

The compressive strengths of specimens with the finest grading C were higher than specimens with the coarsest grading A (figure 4). Considering a constant cement dosage and *W/C* ratio, it is possible to increase the compressive strength by almost 30% for D_{max}=16 mm and 35% for D_{max}=31.5 mm by changing the aggregate grading. The compressive strength of concrete has the greatest influence on the cost of structures. The economic value tends to increase with increasing strength. Cement with the most expensive production unit cost (almost 10 to 15 times as much as the price of aggregates) has the largest influence on both the economic value and the compressive strength of the concrete [3,27,28]. Here, on account of maintaining a constant cement dosage, *W/C* ratio, amount of SP and V_f. Thus, the costs of the mixtures were almost the same. If the cost of one SFRC mixture is considered as constant, the cost per unit compressive strength (1 MPa) of the SFRC mixtures varies. Changing the gradation from A to C reduces the cost per unit compressive strength (1 MPa) while maintaining the mixture proportions. In this way, more economical SFRC mixtures can be provided by changing the aggregate gradation (figure 4).

Figure 5 and 6 gives the splitting tensile (f_{st}) and flexural strengths (f_{flex}) under ultimate loads. Aggregate grading affected the splitting tensile and flexural strength for both SFRC and plain concrete. Changing the gradation and the D_{max} affected the splitting tensile strength values for constant cement dosages and *W/C* ratios (figure 5). Steel fibres have a remarkable effect on the splitting tensile and flexural strength other than the compressive strength. Because steel fibres make concrete less brittle and more ductile, adding steel fibres in plain concrete increases the tensile strength of the

concrete [4,5,8,12]. As expected, the steel fibres enhanced the splitting tensile and flexural strengths of the concrete specimens.

For both plain concrete and SFRC, the tensile and flexural strength increased with decreasing V_{void} for both D_{max} values of the A to C gradations (table 2 and figures 5 and 6). It was explained previously that voids decrease the mechanical strength. As with the compressive strength, the influence of larger D_{max} on the tensile and flexural strength of SFRC was greater (figure 6). It is also known that coarse aggregates with higher D_{max} values enhance the ultimate flexural strength of SFRC [12].

Figure 7 provides a general comparison among gradations for Ve-Be times and f_c and f_{flex} of SFRC. As is seen in figure 7, there is a relationship between strength values and Ve-Be time. For the SFRC mixtures, changing the grading had a variable effect on the workability. This variability can be compared with the compressive and flexural strengths of the SFRC specimens. If Road 1 is followed, it is seen that a larger D_{max} produces concrete with lower workability for the same f_c and f_{flex}. If Road 2 is followed, it is seen that the finer grading produces concrete with higher fc and f_{flex} for the same workability and D_{max}. Thus, for a constant cement dosage and W/C ratio, aggregate grading alone can be determinative factor for both fresh and hardened SFRC.

3.2.1. Toughness of SFRC. Plain concrete was exceeded at once the deflection that corresponds to the ultimate flexural strength; on the other hand, the SFRC continues to carry on notable loads even at the deflections considerably in excess of the fracture deflection of the plain concrete. Because the failure occurs due to fibre debonding which is depend on bond stresses occurred between steel fibre and concrete matrix, the SFRC does not break suddenly after the first crack unlike plain concrete. Bond stress depends on concrete quality as much as it depends on fibre characteristics. The toughness (*T*) value, defined as the area under the load-deflection curve, reflects the energy absorption of deflected specimen to the specified deflection value [1,29,30]. It is known that D_{max} has a slight effect on the toughness [12] although studies in the literature are insufficient which investigated the relationship between the grading and the toughness.
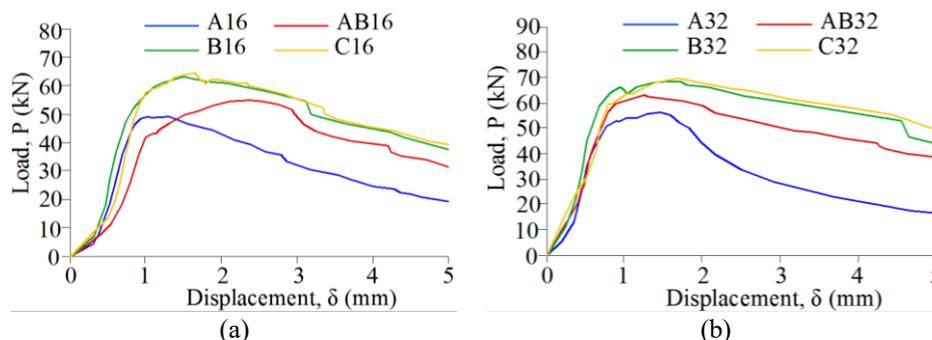

Figure 8. Load – displacement curves of SFRC specimens for (a) D_{max}=16 mm and (b) D_{max}=31.5 mm.

Figure 8 gives the load (P)-deflection (*δ*) curves of SFRC specimens. Figure 9 provides the toughness of the SFRC specimens. From A to C gradation, finer grading affected toughness of SFRC positively for both D_{max} values. It can be said that larger D_{max} increased 10% toughness of SFRC (figure 9).
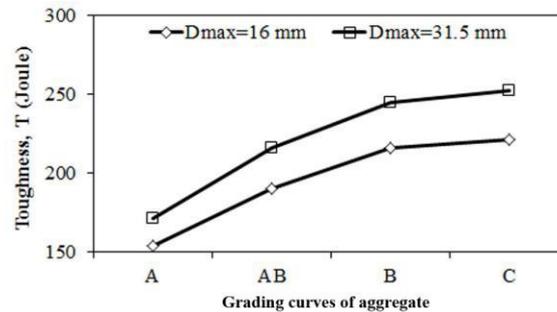
Figure 9. Toughness of SFRC specimens.

4. Conclusions

Based on our experimental results on the effects of gradation and D_{max} on SFRC properties with constant cement dosages and W/C ratios, the following conclusions can be drawn.

In addition to reduce of the workability by using 1% steel fibres, most of the slump values of the SFRC mixture were 0. The results of the Ve-Be tests were more variable than the slump tests for SFRC. Changing the aggregate grading had a noticeable effect on the workability of both SFRC and reference concrete. The finest and the coarsest grading showed low workability for both D_{max} values. SFRC mixtures with smaller D_{max} were more workable.

The compressive, splitting tensile and flexural strengths of the hardened specimens were investigated experimentally. Improved mechanical test results were observed with increasing D_{max}. All of the mechanical properties were increased with finer gradation for both D_{max} values. Unfilled voids negatively affected the mechanical properties. In terms of the toughness of the SFRC specimens, increasing the D_{max} slightly increased the toughness of SFRC. The toughness increased with finer gradations.

For the future studies, gradation curves may be defined with more parameters instead of with just one fineness modulus parameter since the volume of voids between aggregate particles was affected the properties of SFRC this much. Finally, it is possible to improve both the workability and mechanical properties of SFRC by changing the aggregate grading and D_{max} while maintaining a constant cement dosage and W/C ratio. In addition, by choosing the right grading and D_{max}, SFRC mixtures can be produced economically in terms of the cost per unit strength.

Acknowledgements

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