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Investigation of The Size Effect of Self-Compacting Concrete on Direct Tensile Strength

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Abstract: The correct determination of direct tensile strength is very important in reinforced concrete building design. Unless otherwise specified in the building codes, the tensile strength that should be used in building design is direct tensile strength. However, the direct tensile strengths stated in the codes are usually found by formulas based on compressive strength, flexural tensile strength or splitting tensile strength. The fact that direct tensile tests are difficult to apply and there are no clear principles in the building codes, as in indirect methods, have led to a limited number of studies on direct tensile strength. In previous studies on direct tensile tests, certain standards were not established regarding the sizes and shapes of the samples subjected to the test. In this study, the size effect of self-compacting concrete (SCC) on direct tensile strength was investigated. In this context, direct tensile strengths of dog-bone type SCC specimens of different thicknesses were compared. The experimental direct tensile strengths were compared with the experimental splitting and flexural tensile strength, and also their proximity to tensile strengths expressed in certain building codes such as TS500, Eurocode and ACI 318 were investigated. As a result of the study, it was revealed that there is an inverse proportion between the thickness of the specimen and the direct tensile strength, and depending on the increase in the specimen thickness, the experimental direct tensile strengths approached the tensile strengths specified in the building codes.

Keywords: Direct tensile strength; size effect; self-compacting concrete

Kendiliğinden Yerleşen Betonun Doğrudan Çekme Dayanımına Boyut Etkisinin Araştırılması

Öz: Özellikle çekme gerilmelerinin kritik seviyede olduğu yapı elemanlarının tasarımında betonun çekme gerilmesi önemli parametrelerden biridir. Yapı şartnamelerinde çoğunlukla bahsedilen çekme dayanımı doğrudan çekme dayanımıdır. Ancak şartnamelerde ifade edilen çekme dayanımları, genellikle basınç dayanımı veya dolaylı yöntemlerle bulunan çekme dayanımlara bağlı formüllerle bulunmaktadır. Doğrudan çekme testlerinin uygulamasının zor olması ve dolaylı yöntemlerde olduğu gibi belli şartname esaslarının olmaması doğrudan çekme dayanımı ile ilgili çalışmaların sınırlı sayıda kalmasına neden olmuştur. Bu nedenle doğrudan çekme testleri ile ilgili yapılan önceki çalışmalarda teste tabi tutulan numune ebatları ve şekilleri ile ilgili belli standartlar oluşmamıştır. Bu çalışmada kendiliğinden yerleşen betonun (KYB) doğrudan çekme dayanımına boyut etkisi incelenmiştir. Bu kapsamda farklı kalınlıklarda dog-bone tipi KYB numunelerin doğrudan çekme dayanımları karşılaştırılmıştır. Deneysel doğrudan çekme dayanımları, deneysel yarmada çekme ve eğilmede çekme dayanımları ile karşılaştırılmış olup aynı zamanda TS500, Eurocode ve ACI 318 gibi yapı şartnamelerinde ifade edilen teorik çekme dayanımlarına yakınlıkları araştırılmıştır. Çalışma neticesinde numune kalınlığı ile doğrudan çekme dayanımı arasında ters orantı olduğu ve numune kalınlıklarının artmasına bağlı olarak, deneysel doğrudan çekme dayanımlarının şartnamelerde belirtilen teorik çekme dayanımlarına yaklaştığı ortaya konulmuştur.

Anahtar Kelimeler: Direkt çekme dayanımı; boyut etkisi; kendiliğinden yerleşen beton

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1. Introduction

Self-compacting concrete (SCC) is a type of concrete with a low water/cement ratio, does not require any vibration or consolidation, can place under its weight in the mold, has high fluidity and deformation capability [1-3]. In recent years, the usage area of SCC in reinforced concrete structures has become widespread. It is widely used especially in heavily reinforced or low-thickness structural members where tensile stresses are critical.

The correct determination of the tensile strength of concrete is especially important in structures where tensile stresses are critical. In addition to capacity calculations, the tensile stress of the concrete must be known precisely to determine the serviceability limits of the structures due to crack formation [4]. The tensile strength of the concrete also affects the durability of concrete against environmental effects. Crack formation in concrete increases the permeability of concrete and thus accelerates deterioration in concrete and corrosion in reinforcement. Splitting and flexural tensile tests are often used to determine the tensile strength of concrete. However, since these tests are indirect methods, the results obtained are used in building design by multiplying with the coefficients specified in the building specifications. Therefore, no real tensile strength can be found for concrete from these test results. To determine the tensile strength and fracture properties of concrete exactly, it is necessary to apply a direct tensile test to the concrete [5]. However, direct tensile testing is a difficult test in terms of practice. Many factors such as the physical difficulty of applying the load to the sample, the second-order effects that may occur due to eccentricity, the problems that may occur in the placement of the concrete in the mold, the necessity of high precision of the measurements, have caused a limited number of studies on direct tensile tests in the literature. Researches in the literature indicated that out-of-control factors greatly affect the direct tensile strength results. Contamine et al. [6] reported that the design of the clamps attached to the device, the homogeneity of the tensile field and the position of the extensometer affected the tensile test results. Swaddiwudhipong et al. [7] stated that minimizing the load eccentricity significantly improved the test results, with the curing age the tensile strength increased less than the compressive strength. Research on the direct tensile strength of SCC reported that the direct tensile strength is lower than the indirect tensile strength and that the specimen does not crack due to shear and bending effects as a result of good grip at the ends of the specimen [8]. Dasthi et al. [9] concluded that the compressive strength and direct tensile strength results are consistent with each other, aggressive environmental conditions reduce the tensile strength, and fiber reinforcement at a certain rate increases the direct tensile strength. Tunc et al. [10] proposed a numerical method to determine the tensile strength of lightweight concrete.

1.1. Research Significance

It was understood that direct tensile tests were not carried out according to specific standards but based on the researchers' own experience and the results of other studies in the literature when the limited number of studies on direct tensile tests were examined. For this reason, there is no consensus about the shape and size of the sample subjected to the test. In the literature, usually dog-bone shaped specimens were subjected to direct tensile testing. However, it was found that the sizes of the samples subjected to the tensile test were quite different from each other when the studies were examined [11-16]. Therefore, the effect of sample cross-section dimensions on direct tensile strength is a subject that needs to be investigated. In this framework, direct tensile tests of SCC specimens in the dog-bone shape of different sizes were carried out. Direct tensile test results were compared with indirect tensile test results and the values in the specifications.

1.2. Concept Of Tensile Strength in Building Codes

It is necessary to know the tensile strength of concrete in reinforced concrete building design. Especially in designs where shear stresses are critical, it is very important to determine the tensile strength of concrete correctly. In the specifications, direct tensile strength is generally expressed with some empirical formulas based on flexural tensile strength, splitting tensile strength or compressive strength [17-20]. Generally, in all building codes, the tensile strength of concrete is calculated by multiplying the square root of the compressive strength with certain coefficients. These coefficients may vary depending on the building codes. In some codes, direct tensile strength is not used in the design. In ACI 318, the tensile strength of concrete is expressed in splitting tensile strength. The specified equations are valid for normal concrete. ACI 318 has defined a coefficient of λ to reflect the low tensile strength properties of lightweight concrete compared to normal concrete with the same compressive strength. By using this coefficient, the low shear strength and friction properties of lightweight concrete are taken into account. In normal concretes, the λ coefficient is taken as 1. Empirical formulas for tensile strengths according to various building codes are given below (Eqn. (1-8)).

$$f_{ct} = 0.56\lambda\sqrt{f_c'} \text{ (ACI 318)} \tag{1}$$

$$f_r = 0.62\lambda\sqrt{f_c'} \text{ (ACI 318)} \tag{2}$$

$$f_{ct} = 0.52\sqrt{f_c'} \text{ (TS500)} \tag{3}$$

$$f_r = 0.70\sqrt{f_c'} \text{ (TS500)} \tag{4}$$

$$f_{ctk} = 0.35\sqrt{f_c'} \text{ (TS500)} \tag{5}$$

$$f_{ctm} = 0.30\sqrt[3]{f_c'^2} \text{ (Eurocode)} \tag{6}$$

$$f_{ctk\,0.05} = 0.21\sqrt[3]{f_c'^2} \text{ (Eurocode)} \tag{7}$$

$$f_{ctk\,0.95} = 0.39\sqrt[3]{f_c'^2} \text{ (Eurocode)} \tag{8}$$

where, f_{ct} splitting tensile strength, f_r flexural tensile strength, f_{ctk} direct tensile strength, $f_{ctk\,0.95}$ upper characteristic tensile strength, $f_{ctk\,0.05}$ lower characteristic tensile strength, f_{ctm} mean tensile strength, f_c' compressive strength.

2. Material and Method

In this study, direct tensile strength, splitting tensile strength, flexural tensile strength and compressive strength of SCC specimens were investigated. In this framework, 9 cylinder samples of 100x200 mm, 3 beam samples of 100x100x500 mm, 3 cubic samples of 150x150x150 mm and a total of 12 dog-bone type direct tensile samples in different sizes were prepared (Fig.1).

Figure 1. SCC samples

The tensile strengths of SCC specimens of different sizes were compared with each other, and the approximation of the test results to the theoretical formulas in the building codes was investigated.

Besides, the relationship between direct tensile strengths and indirect tensile strengths is also discussed.

2.1. Self-Compacting Concrete (SCC)

SCC is sensitive to optimum mixing ratios, aggregate type, shape and humidity. For this reason, many trials have been made to determine the mixing ratio to be used in the study. SCC workability classification and mixing ratios were made following the recommendations of the EFNARC [21] committee and ACI 211.1-91 [22]. Table 1 shows the mixing ratios of SCC. The most important feature of SCC is its degree of fluidity. Slump flow test and V-funnel test, which are the most common methods for measuring the flow properties and quality, were applied. Slump-flow test was performed in accordance with ASTM C 1611 [23]. The slump-flow test measures the ability of concrete to deform under its own weight against friction without any external force. V-flow testing was performed in accordance with EN12350-9 [24]. In the V funnel test, the flow time is measured under the weight of the concrete itself. For SCC, flow time is recommended to be less than 6 seconds [25]. Workability properties are given in Table 2.

Table 1. Mix proportion of SCC

Cement (kg/m³)	Fly Ash (kg/m³)	Coarse Aggregate (kg/m³)	Fine Aggregate (kg/m³)	Water (kg/m³)	Plasticizer (kg/m³)	Density (kg/m³)
370	315	914	985	225	3.75	2380

Table 2. Workability properties of SCC

Test	Results	Workability classes
V-funnel flow time (Vf) (seconds)	5	VS1/VF1 (≤8)
Slump flow diameter (DF) (mm)	763	SF3 (760–850)
Slump flow time (T50) (seconds)	1.91	VS1/VF1 (≤2)

Fly ash obtained from Afşin-Elbistan Thermal Power Plant was used to provide fluidity SCC and to reduce the need for viscosity-increasing chemical additives. Fly ash reduces the heat of hydration, reducing the cracking potential of concrete and improving its rheological properties [26,27]. The spherical structure of fly ash particles is one of the main features that provide fluidity in concrete. The fly ash used is in the C class fly ash class according to ASTM C 618 [28] and its specific gravity has been determined as 2.21. PC 42.5 Portland cement was used in SCC mixes in accordance with BS EN 197-1 [29]. The specific gravity of cement has been determined as 3.15. The chemical compositions of cement and fly ash are shown in Table 3. In the mixture, river aggregate with a maximum particle size of 8 mm was used as coarse aggregate, and sand with a maximum particle size of 4 mm was used as fine aggregate. The grading of the aggregates used in the mixtures is shown in Figure 2. According to ASTM C127-15 [30], the specific gravity of the coarse and fine aggregate used in the mixture was determined as 2.60 and 2.43, respectively. The mixtures were mixed in concrete mixers with a capacity of 100 dm³. The aggregates used in the mixture were kept at 105 degrees for 24 hours before entering the mixture, ensuring that they become completely dry. Polycarboxylic Ether-based glenium 51 additive with a PH degree of 6-7 were used as a plasticizer in all mixtures. In pilot studies, it has been determined that the amount of plasticizer is of critical importance. The plasticizer used more than necessary caused the separation of aggregate particles from the cement paste. Conversely, the workability degree of SCC does not meet the standards of the EFNARC committee. No agglomerations were allowed during the mixing, each material in the mixture was mixed for 5 minutes. City mains water was used as mixing water. Using pH indicator paper, it was observed that the PH degree of the mains water was around 7. All samples were cured in water for 28 days.

Table 3. Chemical Compositions

Chemical Composition	Portland Cement	Fly Ash
CaO	61,80	53,54
SiO2	20,72	18,17
Al2O3	5,60	9,20
Fe2O3	4,18	3,26
MgO	2,55	1,72
SO3	2,80	11,44
Na2O	0,14	0,17
K2O	0,82	0,38

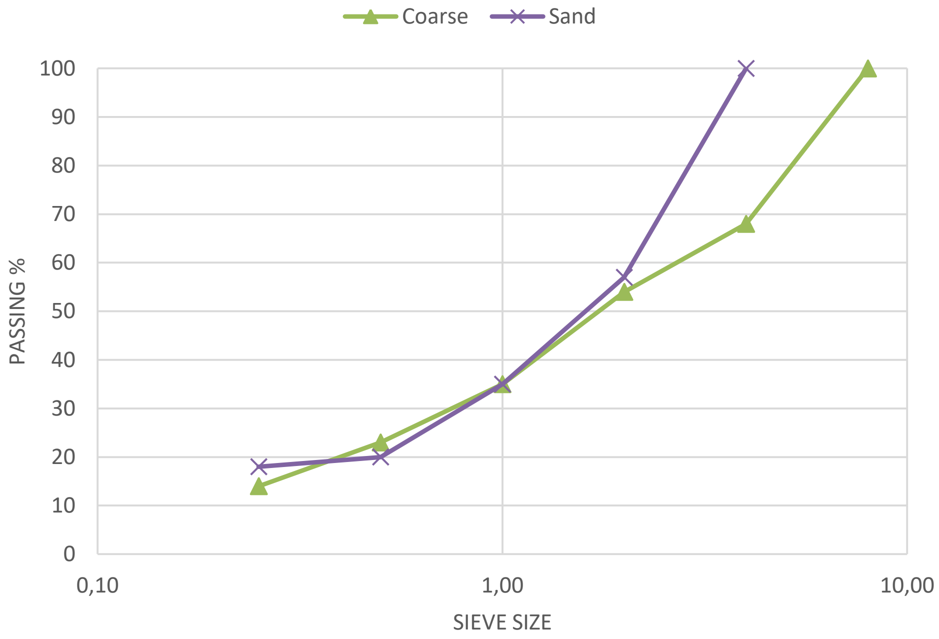

Figure 2. Gradation of aggregates used in the mixture

2.2. Compressive Strength Test

It is directly related to other mechanical properties of concrete's compressive strength. For this reason, the compressive strength test is generic test. The compressive strength tests of the samples were carried out in accordance with EN 12390-3 [31] and ASTM C39 / 39 M [32] with a 2000 kN capacity press (Fig.3). 3 cubes of 150x150x150 mm and 6 SCC samples of ø100x200 mm were prepared. Compressive strengths of 7 and 28 days of cylindrical samples and 28 days of cube samples were found. The sulfur cap was prepared for cylinder samples and their contact surfaces were made flat. The loading rate was determined as 0.24 MPa / s.

Figure 3. Compressive strength test

2.3. Splitting Tensile Strength Test

Splitting tensile strength test was carried out in a 2000 kN capacity press in accordance with ASTM C496 / C496 M [33] standards (Fig.4). In the splitting tensile test, the load is applied to the specimen vertically along its length. Its application is relatively simple and gives reliable results [34]. Another advantage of the split tensile test is that the test results show a narrow distribution [35]. For the splitting tensile test, 3 SCC samples of ø100x200 mm were prepared. Strength results were determined following the equation given (Eq.8). Where P is the ultimate load, L is the sample length, D is the sample diameter. The loading rate was determined as 48.9 kN / s. 25 mm wide and 3 mm thick wooden pieces were placed on the contact surfaces so that the load could be properly applied to the sample

$$f_{ct} = \frac{2P}{\pi \mathrm{LD}} \ (MPa) \tag{9}$$

Figure 4. Splitting tensile test

2.4. Flexural Tensile Strength Test

One of the indirect methods used to determine the tensile strength of concrete is the flexural strength tensile test. The flexural test is based on determining the strength of concrete under flexural loads in unreinforced concrete. A three-point bending test was carried out in accordance with EN 12390-5 [36] standards (Fig.5). In this context, 100x100x500 mm SCC beam samples were prepared. A load was applied to the middle of the rectangular sample. The loading rate was determined as 180 kg/min. The samples were subjected to the wet bending test immediately after curing was finished. The stress found as a result of the bending test was made following the given equation (Eq.9). Where P is the ultimate load, L is the distance between bearings, b is the width, d is the depth. Flexural strength is also known as the modulus of rupture.

$$f_r = \frac{3PL}{2\mathrm{b}d^2}\ (MPa) \tag{10}$$

Figure 5. Flexural tensile strength test

2.5. Direct Tensile Test

Unless otherwise specified, the tensile stress that should be used in the design in the building codes is the tensile stress determined directly from the tensile test result. Therefore, the tensile strength used in the design is determined approximately. The acceptance of the results obtained by indirect methods in the design specifications has led to a decrease in the interest in direct tensile testing, which is already difficult to do in practical engineering. For all these reasons, the specification basis has not been encountered as in other tensile tests related to direct tensile testing. In pilot studies, direct tensile specimens were produced in various forms, but both fracture types and stress values were not satisfactory. In this study, a dog-bone type specimen, which is used more frequently in the literature, was used. Since the middle section of the cross-section is narrow in the dog-bone type sample, the fracture can be manipulated in the middle region. Thus, the actual fracture behaviour of the sample can be determined by preventing fracture from the gripping points. Dog-bone type specimens of various thicknesses were produced and subjected to direct tensile testing. Results of direct tensile tests and indirect tensile tests were compared. Also, the relations between the theoretical tensile strength results and the experimental tensile strength results in the specifications were investigated. Figure 6 shows the dimensions of the dog-bone type sample used in the tensile test. The biggest challenge of direct tensile testing is the gripping of the sample to the testing machine. For this reason, grip plates suitable for dog-bone-type samples were produced. Grip plates consist of a combination of 4 metal plates of 15 mm thickness, which are quite rigid prepared by laser cutting method. The samples are fixed to the grip plates in a way that does not create any eccentric force in the sample. Sample molds were created by bending and welding a 5 mm thick sheet plate. Molds for concrete samples, samples with different thicknesses and tensile test setup are shown in Figure 7. A total of 12 samples were produced with different thicknesses. A total of 12 samples were produced with different thicknesses. Maximum attention was paid to the concrete casting of the samples, and by using the vibration table, the concrete was fully settled in the mold.

Sample names are made according to thicknesses. For example, DT-30-1 represents the No. 1 direct tensile sample of 30 mm thickness.

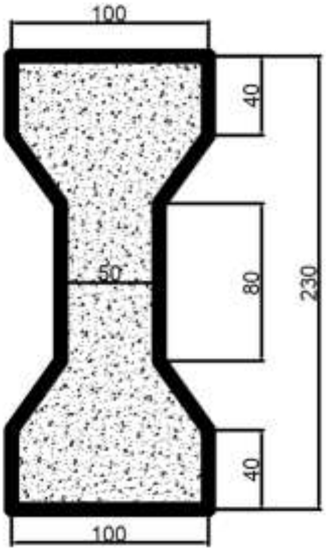

Figure 6. Dog-bone sample size

Figure 7. a-) Molds, b-) Dog-bone type SCC specimens of different thickness c-) Direct tensile test

3. Results and Discussion

3.1. Compressive Strength, Flexural Tensile and Splitting Tensile Strength Results

The results of the compressive strength, flexural tensile strength and splitting tensile strength test results and the theoretical values in the building codes are shown in Table 4. As a result of the compression tests, it was observed that the average compressive strength of the 7-day cylinder samples was 74.21% of the average pressure resistance of the 28-day cylinder samples. The average compressive strength of 28-day cube samples is 29.92% higher than the average of 28-day-old cylinder samples. 7- and 28-days compressive strength is consistent with the results of Günaydın and Güçlüer [37]. The graphic regarding the compressive strength is shown in Figure 8.

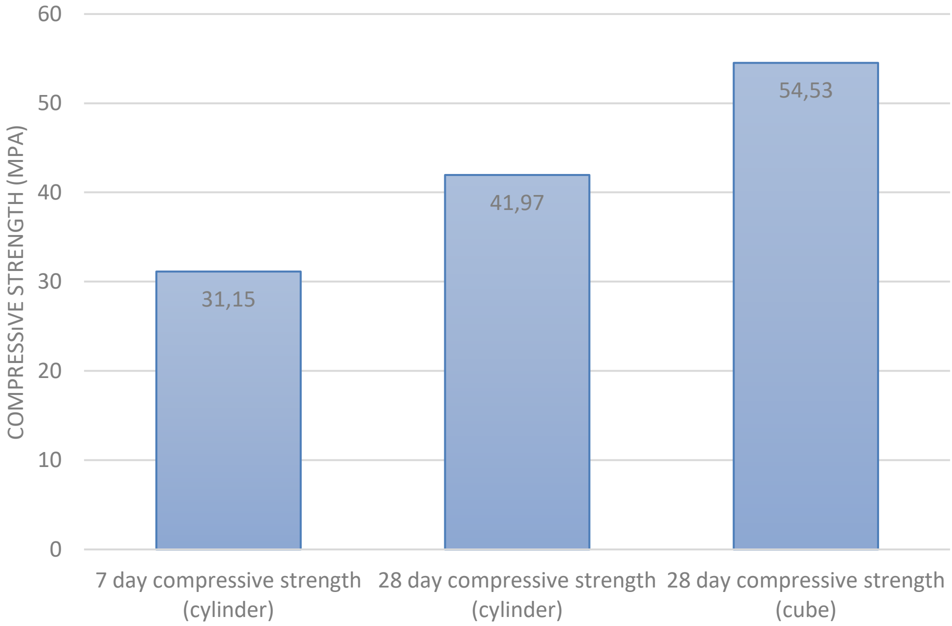

Figure 8. Compressive strength results of SCC specimens

The tensile strength found by the three-point bending test was determined to be 32.21% higher than the tensile strength found with the splitting tensile test. The ratios between the tensile strengths obtained by indirect methods coincide with the studies in the literature on the mechanical properties of SCC [38]. In various building codes and studies, it is stated that the flexural tensile strength is between 0.3 and 1.0 times the square root of the compressive strength. [39]. As a result of the experimental study, it was observed that the flexural tensile strength was closer to TS500 values. However, it was determined that the experimental results were closer to the values specified in the ACI 318 code when splitting tensile strengths were examined.

Table 4. Compressive, splitting tensile and flexural tensile strength results

Label ID	**7-day compressive strength (MPa) (cylinder)**	**28-day compressive strength (MPa) (cylinder)**	**28-day compressive strength (MPa) (cube)**	**28-day splitting tensile strength (MPa)**	**28-day flexural tensile strength (MPa)**	**Splitting tensile strength (MPa) (ACI318)**	**Flexural tensile strength (MPa) (ACI318)**	**Splitting tensile strength (MPa) (TS500)**	**Flexural tensile strength (MPa) (TS500)**
1	30,11	42,96	54,25	4,55	6,14	3,67	4,06	3,40	4,58
2	32,22	39,63	56,80	4,47	5,90	3,52	3,90	3,27	4,40
3	31,14	43,32	52,55	4,52	5,85	3,68	4,08	3,42	4,60
Average	31,15	41,97	54,53	4,51	5,96	3,62	4,01	3,36	4,52

Experimental splitting tensile strength is 24.58% higher than the theoretical splitting tensile strength in ACI 318 and 34.22% more than the theoretical splitting tensile strength in TS500. Experimental flexural tensile strength is 48.62% higher than theoretical flexural tensile strength in ACI 318 and 31.18% higher than theoretical flexural tensile strength in TS 500. Besides, there is a comment in ACI 318 that the flexural tensile strength should be between 10% and 15% of the compressive strength. It has been determined that the experimental strengths remain within these values specified in the specification. The values specified in the building codes are the values generally used for normal concrete design. Studies have shown that the tensile strength of SCC is lower than that of normal concrete [40]. In Figure 9, experimental splitting and flexural tensile strength results and theoretical strengths in building codes are shown together.

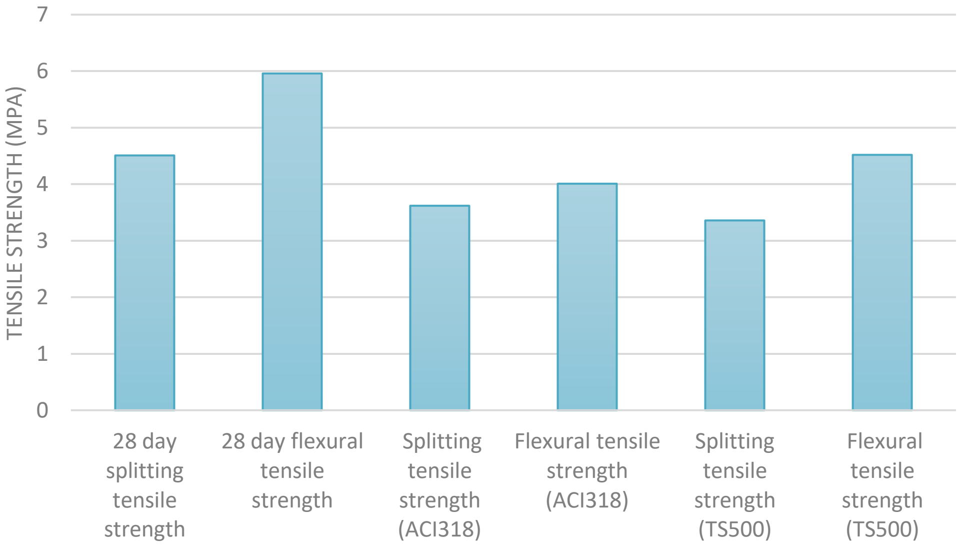

Figure 9. Splitting and flexural tensile strength results

3.2. Direct Tensile Test Results

Direct tensile strength results are shown in Table 5 and Fig.10. Direct tensile strength results are shown in Table 5 and Fig.10. The experimental direct tensile strengths were compared with the theoretical tensile strengths in Eurocode and TS500 specifications. While a single direct tensile strength formula is defined in the TS500 (f_{ctk}), in Eurocode the mean tensile strength (f_{ctm}), lower characteristic tensile strength ($f_{ctk\ 0.05}$) and upper characteristic tensile strength ($f_{ctk\ 0.95}$) values are defined. As a result of the tests, it has been determined that the ultimate loads increase with the increase in the thickness of the sample, but the tensile strength decreases due to the increase of the cross-sectional area. The average tensile strengths of samples in the DT-30, DT-40, and DT-50 series were determined as 3.10 MPa, 2.94 MPa, and 2.42 MPa, respectively. Accordingly, the tensile strength of DT 50 samples was found to be 21.48% lower than DT 40 samples and 28.09% lower than DT 30 samples. When compared with the theoretical values in the building codes, it has been determined that the direct tensile strengths of the specimens in the DT-50 series are the closest to the theoretical strengths in TS 500. The theoretical tensile strengths specified in the TS500 are 37.16% higher than the experimental tensile strength average of DT-30 samples, 30.08% more than DT-40 samples, and 7.07% more than DT-50 samples. When examined in terms of Eurocode, it has been determined that the experimental results are close to the lower characteristic tensile strength, which is one of the tensile strength expressions defined in the Eurocode. It was found that the lower characteristic tensile strength of DT-30 and DT-40 samples were 22.52% and 16.20% more than the experimental tensile strength, respectively. On the other hand, the theoretical tensile strength is 4.54% less than the experimental tensile strength of DT 50 samples when the tensile strengths obtained as a result of the direct tensile test were compared with the tensile strength results in Eurocode. In terms of the size effect, the experimental results coincide with the results of the study conducted by Choi et al. [41].

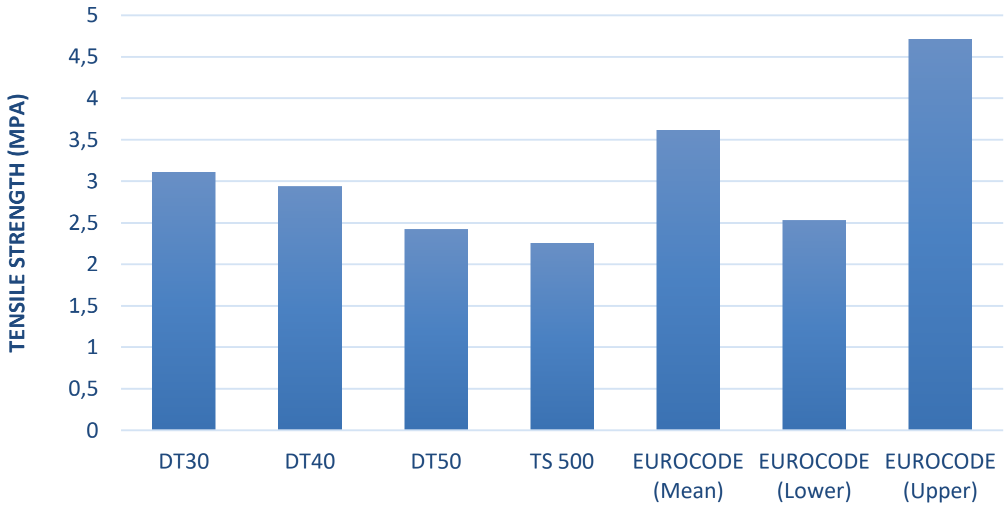

Figure 10. Tensile strength results

Table 5. Direct tensile strength results

Label ID	Ultimate load (N)	Direct tensile strength (MPa)	Average	Direct tensile strength (TS500) (MPa)	Mean direct tensile strength (Eurocode) (MPa)	Lower characteristic tensile strength (Eurocode) (MPa)	Upper characteristic tensile strength (Eurocode) (MPa)
DT-30-1	4710	3,14	3,10	2,26	3,62	2,53	4,70
DT-30-2	4450	2,96					
DT-30-3	4811	3,20					
DT-40-1	5740	2,87	2,94				
DT-40-2	5927	2,96					
DT-40-3	5991	2,99					
DT-50-1	5927	2,37	2,42				
DT-50-2	6011	2,40					
DT-50-3	6221	2,48					

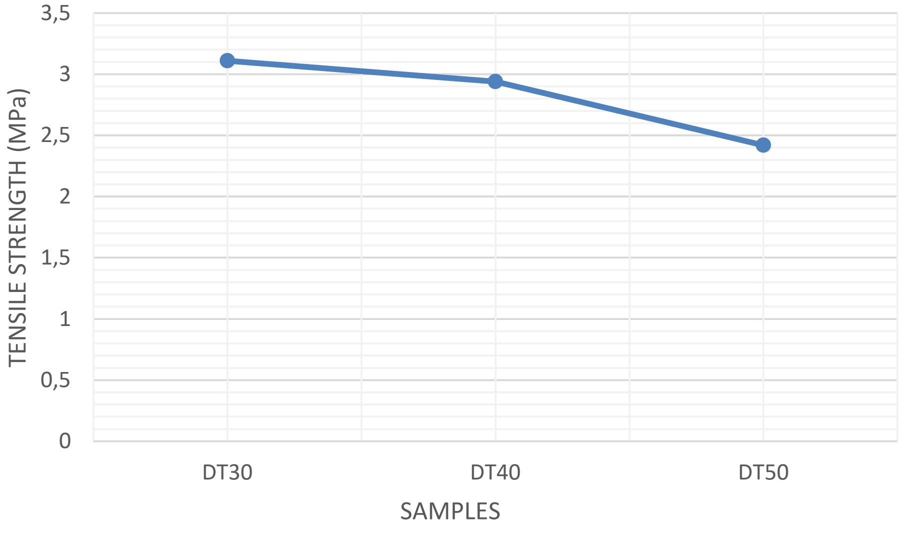

Figure 11. Sample thickness - direct tensile strength relationship

As shown in Figure 11, it has been confirmed that the experimental direct tensile strength is inversely proportional to the sample sizes following the literature. Zhong et al. [42] investigated the effects of size effect on splitting tensile strength. Accordingly, similar to the current study, it was observed that as the sample size increased, the strengths decreased. Samples reached their capacity by breaking from the region where the cross-section narrowed as expected. It was seen that the lower the sample thickness, the closer the fracture to the gripping points when the fracture types were examined. Also, it has been determined in the study that the load eccentric significantly reduces the strength. Some tests were repeated due to some samples were not correctly placed in the device.

4. Conclusion

In the present study, the size effect on the direct tensile strength of SCC concrete was investigated. In this context, dog-bone type specimens of different thicknesses were produced and subjected to direct tensile testing. The relations between the tensile strengths found by the direct tensile method and tensile strengths found by indirect methods were investigated, and the proximity of the experimental results to the tensile strengths found according to the empirical formulas specified in the building codes was examined. The results found are given below in summary

1- It has been determined that the tensile strength found as a result of the three-point bending test is 32.21% greater than the tensile strength found as a result of the splitting tensile test. Experimental splitting tensile strength is 24.58% higher than the theoretical splitting tensile strength in ACI 318 and 34.22% higher than the theoretical splitting tensile strength in TS500. Experimental flexural tensile strength is 48.62% higher than the theoretical flexural tensile strength in ACI 318 and 31.18% more than the theoretical flexural tensile strength in TS 500. It was determined that ACI 318 code in terms of flexural tensile strength, TS500 code in terms of splitting tensile strength were found to be on the safe side.
2- As a result of the direct tensile test, it has been determined that the ultimate load increases but the tensile strength decreases due to the increase in sample thickness. It was observed that the direct tensile strength of DT30 samples was 28.09% higher than the direct tensile strength of DT50 samples.
3- As the sample thickness increases, the direct tensile strength approaches the theoretical tensile strength specified in TS500. In terms of the Eurocode, the direct tensile strength is closer to the lower characteristic tensile strength defined in the code than other tensile strength expressions as the thickness increases
4- In the direct tensile tests, it was understood that the eccentricity significantly affected the direct tensile strength. Even at the slightest axis shift, samples can fail at lower loads than expected
5- Increasing the number of samples in future studies on the size effect on the direct tensile strength may provide more realistic results in statistical terms. Also, different types of studies on the direct tensile strength of lightweight concrete can contribute to the literature.

Authors' Contributions

AG: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, acquisition.
UA: Conceptualization, Methodology, Data curation, Writing - review & editing.

Competing Interests

The authors declare that they have no competing interests.

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