The Tension Stiffening Stress-Strain Relationship of Concrete in tension, newly developed test methods and implementation

Nuroji Nuroji[1], Mohamad Agung Dwi Prawiro [2], Hsuan-Teh Hu[3], Han Ay Lie [1a]

[1]*Department of Civil Engineering, Diponegoro University, Semarang, Indonesia*
[2]*Master Program in Civil Engineering, Diponegoro University, Semarang, Indonesia*
[3]*Department of Civil Engineering National Cheng Kung University, Tainan City, Taiwan*

[a)] *Corresponding author:* hanaylie@lecturer.undip.ac.id

Abstract. Research on the compression behavior of concrete has been widely carried out, on the other hand, information about the behavior of concrete in tension was limited. The existing concrete tension tests are the splitting, direct tensile, and rupture tests. These methods provide information on the tensile strength of concrete through concrete tension stiffening tests. This paper aims to elaborate on the experimental study to develop and construct the equation of concrete tensile strength based on the tension stiffening effect mechanism. The basic principle of this newly proposed method was the composite action between steel and concrete. The straight and continuous steel bar was embedded in concrete to ensure no eccentricity that could interfere with research data due to the bending moment. 45 Specimens made from cylinder concrete with 101.6 mm diameter and 450 mm length, steel bar embedded at the center of the section. Three concrete mixes with actual compressive strength of 31.66 MPa, 40.27 MPa, and 46.60 MPa and steel bar diameters of 15.9 mm, 18.7 mm, and 21.7 mm were used as variables. The test was performed by applying an incremental tensile loading at both ends of the steel specimen with a load rate of 5-10 kN/minute to obtain a force-displacement relationship. The curve must be lessened with steel bar response to get the load-displacement of tension concrete, and then by dividing load with concrete area and displacement with the length of both LVDT can be generated stress-strain of tension concrete. This study shows that the tension-stiffening effect is affected by the reinforcement ratio. Where the reinforcement ratio increases, the tension-stiffening decreases. The steel bar to concrete-area ratio higher tends to more cracks. The concrete tensile strength of this research is taken from the stress of the first crack indicates very close to the direct tensile test but slightly higher.

Keyword : first crack; tension stiffening; concrete tensile strength.

INTRODUCTION

The tensile strength of concrete was closely related to the behavior of brittle concrete materials, where the tensile capacity of this material is much lower than the compressive capacity. So in design, the concrete tensile strength is often neglected, while the cracks in concrete can affect reinforced concrete behavior, especially on a deflection. The cracked-reinforced concrete member will experience a significant increase in deflection due to a flexural stiffness reduction caused by the effect of tensile concrete below the neutral axis diminishing [1]. Therefore, neglecting concrete tension in analysis can lead to result deviation [2].

The tensile strength of most concrete generally does not exceed 10% of the compressive strength [3]. Tensile strengths of concrete depended on the compressive strengths, type of cement, type of aggregate, and on sand-gravel ratios [4]. Previous research stated that the tensile strength obtained from splitting tests for low and high compressive strength is only 10% and 5% of the compressive strength [5]. For this reason, the concrete used for the structure is generally added with steel reinforcement which is often called a reinforced concrete structure. The tensile strength of concrete can be determined by several methods. The first is the flexural test which most often used to determine the concrete tensile strength, where plain concrete beam subjected to two point loads to produce pure bending moment, and then tensile stress can be calculated by using the usual beam formula. The second one is splitting test, where cylindrical specimen subjected to uniform line load along the specimen until the specimen splits. The last method is a direct tensile test in which the concrete bars receive axial tensile forces until collapse. The direct tensile strength test is the most representative because the tensile stress is obtained from the axial tensile

The 7th International Conference on Science and Technology (ICST22)
AIP Conf. Proc. 3026, 080023-1–080023-10; https://doi.org/10.1063/5.0199956
Published by AIP Publishing. 978-0-7354-4894-0/$30.00

test of concrete [6]. However, the test is very susceptible to the occurrence of eccentricities which can interfere with the test results. So far, the tensile strength of concrete is conducted through cylinder splitting and flexural tests, which often indicate over-estimate results.

This research is aimed to develop a method of concrete tensile strength test through tension uniaxial testing of concrete composite elements embedded with a reinforcing bar in the center of the section to avoid the effect of eccentricity. From this method will be generated a graph of the stress-strain relationship of the concrete in tension, where the tensile strength of the concrete can be determined based on the concrete stress that causes the initial crack in the test object [7].

EXPERIMENTAL

Material Model

The Experimental investigations were modeled in the form of reinforced concrete (RC) cylinder with 450 mm length and 101.6 mm (4 inches) diameter. An embedded steel bar was placed at the center of the concrete section with diameter variations (16 mm, 19 mm, and 22 mm). The specimens were applied a tensile uniaxial load at each end handle of the steel bar with incremental loading. This model was cured for 28 days of concrete age and placed inside a pond to minimize the effect of shrinkage.

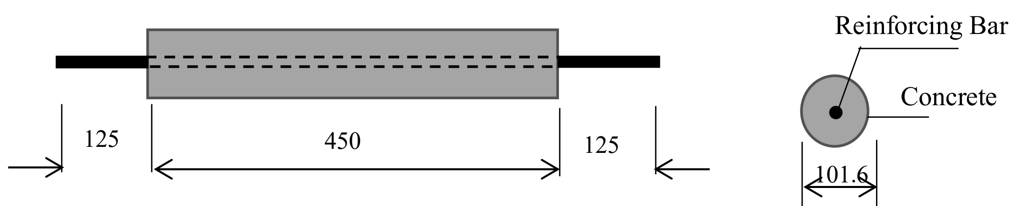

FIGURE 1. Details of specimen.

Material Propeties

The properties of the specimen were using Pozzolan Portland Cement (PPC) highest type of PC, where the water-cement ratio, applied for every concrete strength that is 0.6, 0.52, and 0.42 for mixed design 20 Mpa, 30 Mpa, and 40 Mpa compressive concrete strength, respectively. The mold was made from polyvinyl chloride (PVC) pipe with 4 inches and (101.6 mm) diameter. Molding was opened two days after casting then the specimen was placed in a pond for curing. Detail of specimens as shown in Figure1.The actual compressive strength produced from the cylindrical compression test is presented in table 1. While the diameter and yield stress of the steel bar as shown in table 2.

Table 1. Concrete compressive strength

Grade of Compressive Strength (MPa)	Strength of Mix Design	Compressive Strength (MPa)	Average Compressive Strength (MPa)
A	20	32.23 32.75 30.00	31.66
B	30	38.83 41.72 40.28	40.27
C	40	44.98 45.68 49.15	46.60

Table 2. Diameter and tensile strength of steel bars

Identification Mark	Actual Diameter (mm)	Yield Stress (MPa)
D16	15.9	471.18
D19	18.7	475.49
D22	21.7	358.03

In this research, several specimens were tested with concrete compressive strength and rebar diameter as the research variable. The specimen nomenclature was defined based on concrete compressive strength and diameter of steel rebar. For example, AD16 indicates the concrete strength is grade A, and the rebar diameter is 16 mm. Variables of specimens are presented in table 3 below.

Table 3. Speciments variable

Code of Specimen	Amount of Specimen	D (mm)	L (mm)	Section Area (mm^2)	Age (Days)	fc' (Mpa)	Yield Stress
AD16	5	16	450	8107.31	28	32.23	471.18
AD19	5	19					
AD22	5	22					
BD16	5	16	450	8107.31	28	40.27	475.49
BD19	5	19					
BD22	5	22					
CD16	5	16	450	8107.31	28	46.60	358.04
CD19	5	19					
CD22	5	22					

Experimental Setup

This experimental model was designed as reinforced concrete to determine the load-displacement response of composite elements. The specimen was subjected to uniaxial tension load incrementally by using Universal Testing Machine (UTM). Load increment applied based on load control system with loading rate 5-10 kN/minute. Load data was directly recorded by UTM, while displacement was measured with Linear Variable Displacement Transducer (LVDT) and recorded by the data logger. Two clamps were placed at the bottom and top ends as support of two LVDTs to avoid slip between the steel bar and UTM grip. The setup of this experiment is shown in figure 2.

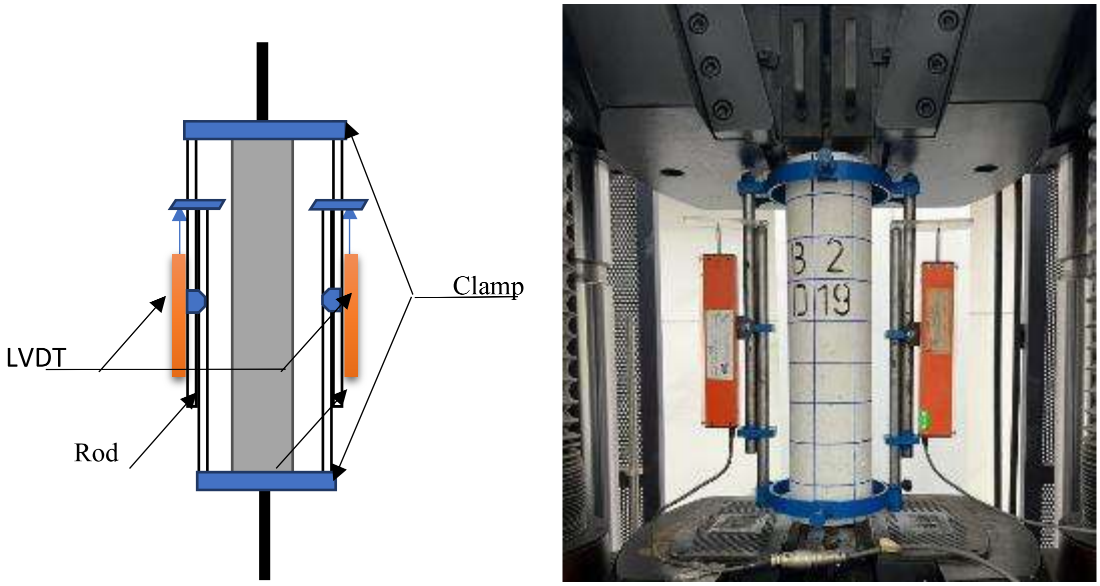

FIGURE 2. Specimen and setup

EXPERIMENTAL RESULTS

Load Displacement

The data on load and displacement could be used to generate a load-displacement relationship curve which represents structure behavior. The average load-displacement data from several valid experiment data were averaged. Then must be lessened with steel bar response to obtain the load-displacement curve of concrete in tension, and then by dividing load with concrete area and displacement with the length of both LVDT can be generated stress-strain of tension concrete. The tensile strength of concrete can be determined from stress causing the first concrete crack taken from the stress-strain curve. The load-displacement curve of each valid specimen and its average for concrete strength A, B, and C presented in figures 3 until 11.

The load-displacement curve for AD16, AD19, and AD22 were presented in figures 3, 4, and 5, respectively. While the load-displacement curve for BD16, BD19, and BD22 were presented in figures 6, 7, and 8, respectively. Then the load-displacement curve for CD16, CD19, and CD22 were presented in figures 9, 10, and 11, respectively. From figures 3 to 11 can be derived to stress-strain curves of cencrete in tension for each compressive strength as shown in figures 12, 13, and 14. The tension stiffening is affected by the percentage of reinforcement ratio. As the percentage of the reinforcement increased, the tension stiffening decreased. The same result is also stated by Allam et.al and Wu and Gilbert [8,9].

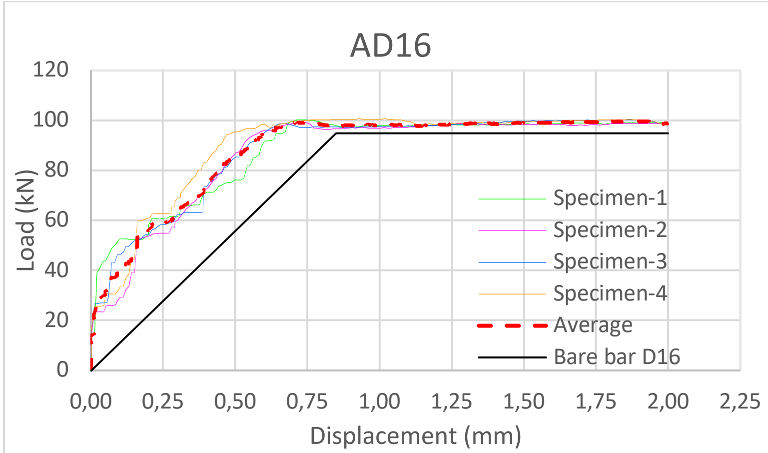

FIGURE 3. Load-displacement curve of specimen with concrete strength grade A and rebar diameter 16 mm

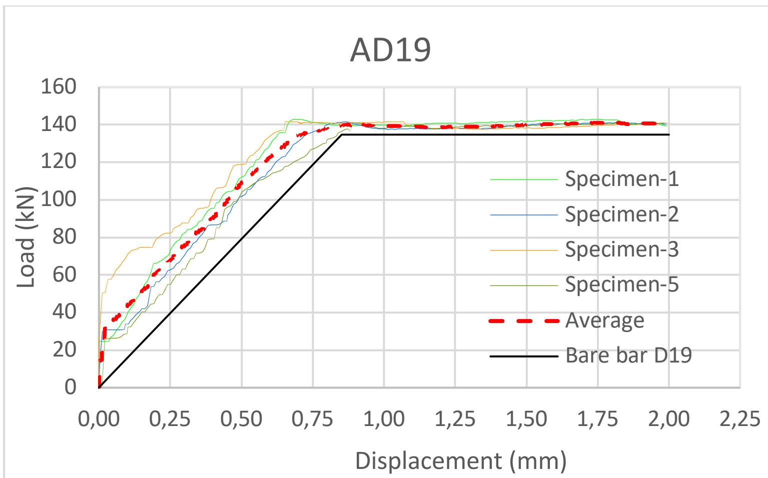

FIGURE 4. Load-displacement curve of specimen with concrete strength grade A and rebar diameter 19 mm

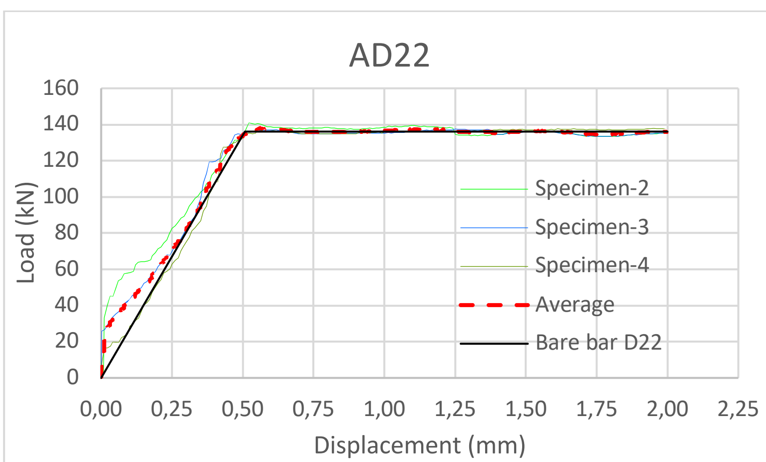

FIGURE 5. Load-displacement curve of specimen with concrete strength grade A and rebar diameter 22 mm

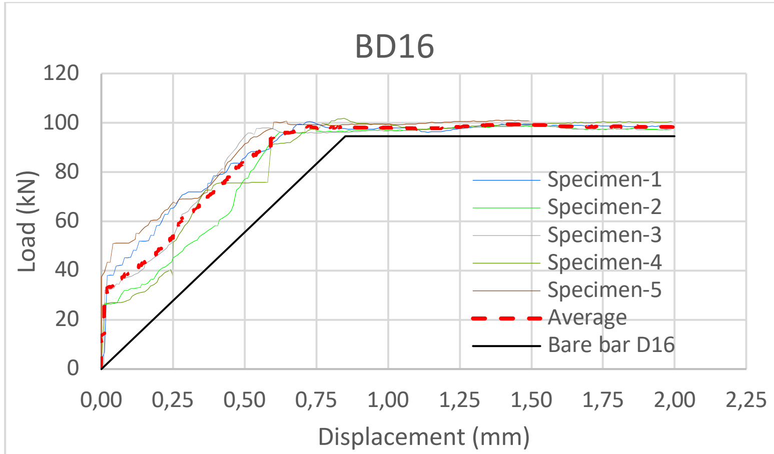

FIGURE 6. Load-displacement curve of specimen with concrete strength grade B and rebar diameter 16 mm

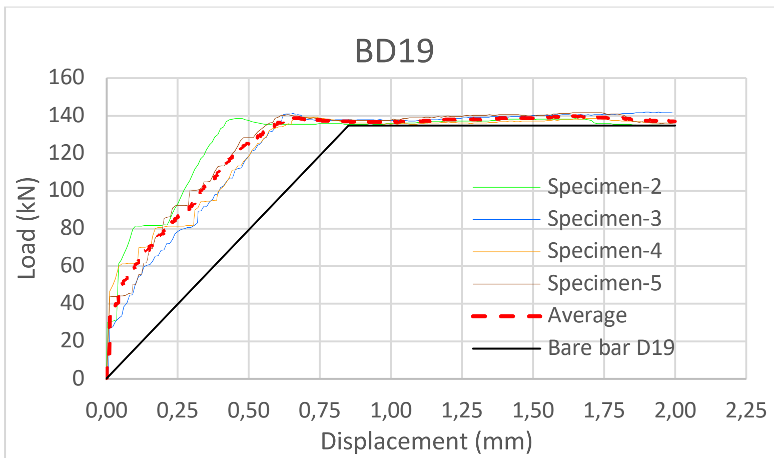

FIGURE 7. Load-displacement curve of specimen with concrete strength grade B and rebar diameter 19 mm

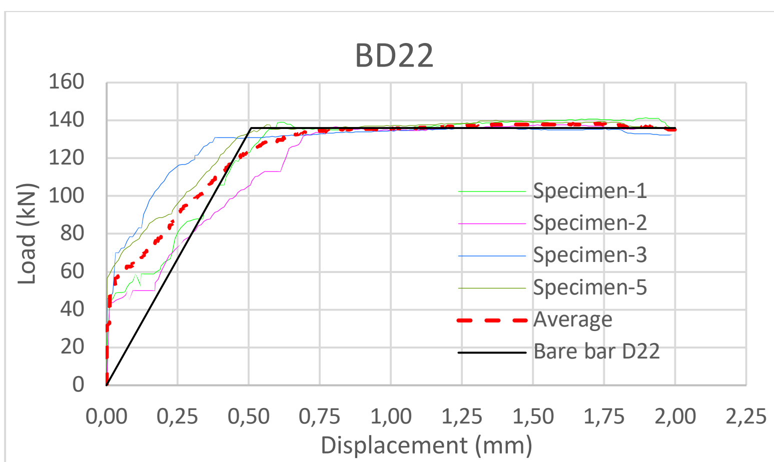

FIGURE 8. Load-displacement curve of specimen with concrete strength grade B and rebar diameter 22 mm

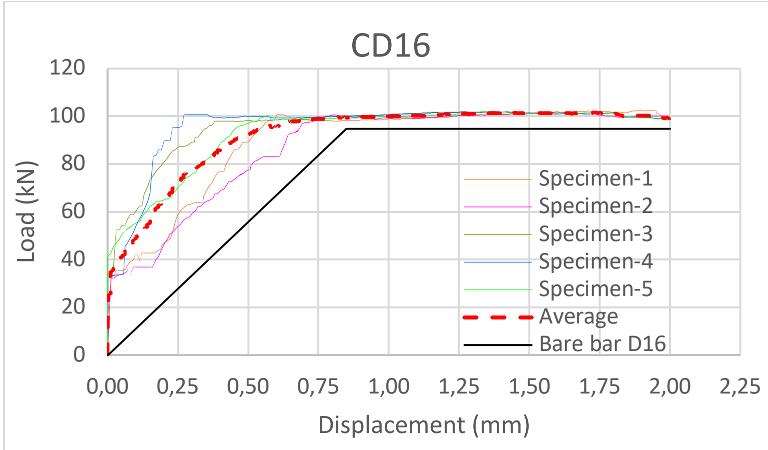

FIGURE 9. Load-displacement curve of specimen with concrete strength grade C and rebar diameter 16 mm

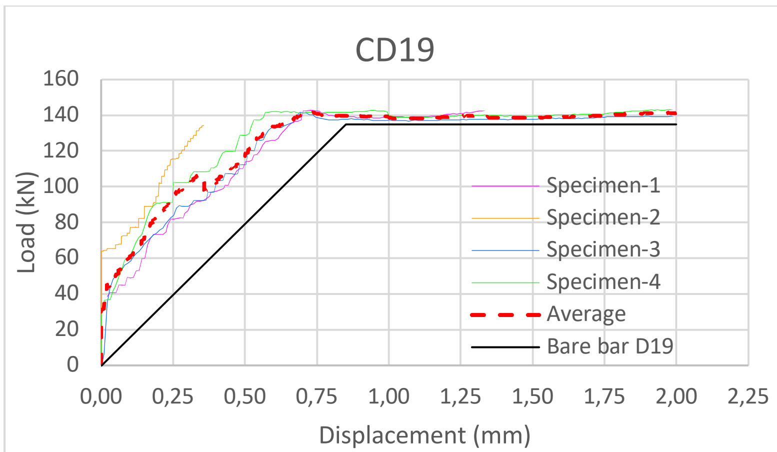

FIGURE 10. Load-displacement curve of specimen with concrete strength grade C and rebar diameter 19 mm

30 March 2024 13:38:54

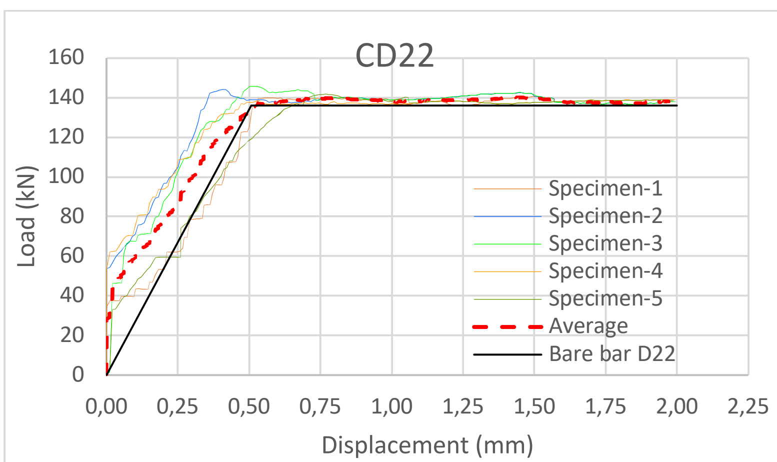

FIGURE 11. Load-displacement curve of specimen with concrete strength grade C and rebar diameter 22 mm

Concrete cracks occur if the concrete tensile strength is exceeded and followed by a high displacement increase of the specimen due to the release of energy from the concrete, causing the reinforcement strain to increase higher in the crack gap. Assuming that the first high-strain increase of the stress-strain curve is the first crack, even though the strain still raises around two times. So, the concrete tensile strength can be determined based on the stress of the first crack.

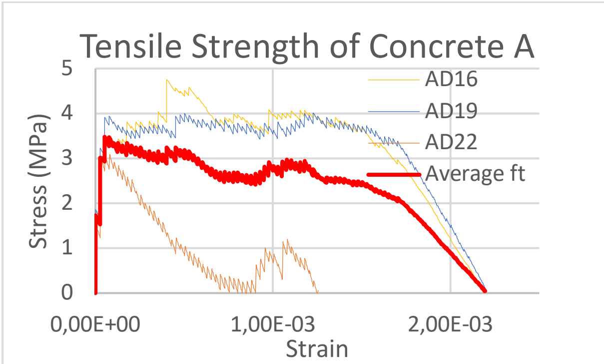

FIGURE 12. Stress-strain curve of concrete strength grade A

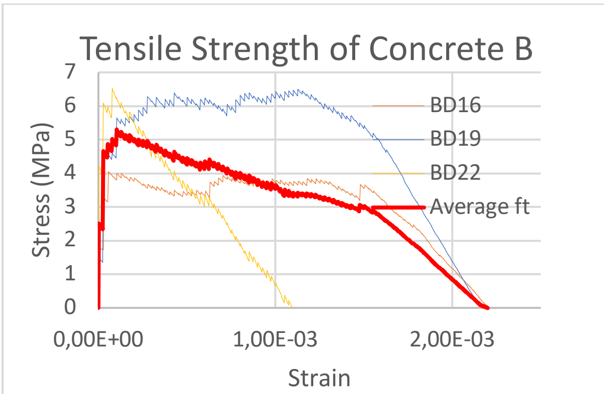

FIGURE 13. Stress-strain curve of concrete strength grade B

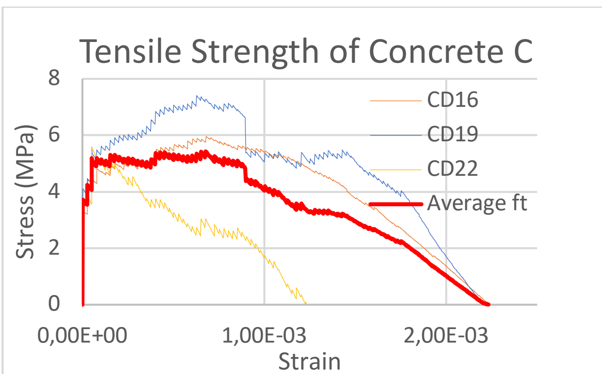

FIGURE 14. Stress-strain curve of concrete strength grade C

From figures 12, 13, and 14, the concrete tensile strength for each compressive concrete strength can be specified as presented in table 4.

TABLE 4. Concrete tensile strength

Concrete Grade	Compressive concrete strength f'_c (MPa)	Concrete tensile strength f_t (MPa)	$\sqrt{f'_c}$ (MPa)	$f_t/\sqrt{f'_c}$
A	32.23	32.23	5.68	0.30
B	40.27	40.27	6.35	0.38
C	46.60	46.60	6.83	0.37
	Average of $f_t/\sqrt{f'_c}$			0.35

The concrete tensile strength equation resulting from the tension stiffening test is below.

$$f_t = 0.35\sqrt{f_c'} \quad (1)$$

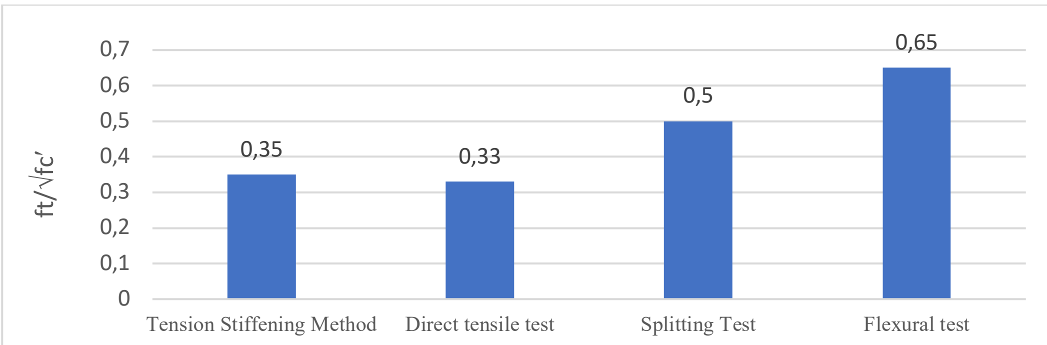

FIGURE 15. Comparison tensile strength test method

The comparison result of this research to other tensile strength test methods is presented in figure 15. Base on figure 15 indicates that the concrete tensile strength obtained from this research is very close to the direct tensile test. Event hough the experimental result is slightly higher than a direct tensile test. It may be caused by eccentricity, where both handles of steel bars are not in line which makes results deviation.

The output from this research was not only to evaluate the concrete tensile strength through tension stiffening behavior of concrete but also cracks development and propagation on concrete were observed during testing. Observation of all specimens indicates that the steel bar ratio increases tend to more cracks as shown in figure 16.

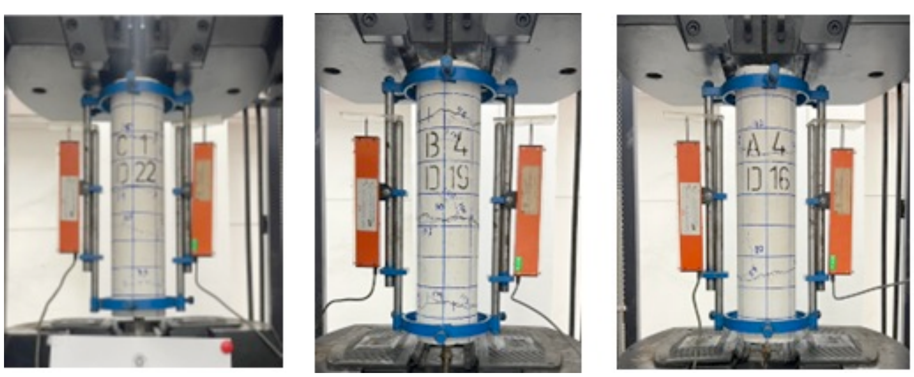

FIGURE 16. Cracks pattern on specimens of D22, D19, and D16

CONCLUSION

The results of this research may be concluded that the tension stiffening is affected by the steel bar ratio. The steel bar to concrete-area ratio higher tends to produce more cracks. The concrete tensile strength of this research is taken from the stress of the first crack, where the ratio of concrete tensile strength to the square root of concrete compressive strength is 0.35, which is close to the direct tensile test method, and the value is slightly higher.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to The Indonesian Ministry of Research, Technology, and Higher Education (Ristekdikti) for research funding through BIMA research scheme.

REFERENCES

1. A. Sokolov. Tension Stiffening Model For Reinforced Concrete Beams. Doctoral Dissertation. Technological Sciences, Civil Engineering (02T). Vilnius Gediminas Technical University, 2010.
2. J. J. Kim, M. R. Taha . Experimental and numerical evaluation of direct tension test for cylindrical concrete specimens. *Adv Civ Eng*. 2014;2014. doi:10.1155/2014/156926.
3. E. F. O'Neil, B. D. Neeley, and J. D. Cargile. Tensile properties of very-high-strength concrete for penetration-resistant structures. Shock and Vibration 6 (1999) 237–245.
4. L. Schuman and J. J. Tucker. Tensile and Other Properties of Concretes Made with Various Types of Cements. Research Paper RP1552 Part of Journal of Research of the National Bureau of Standards, Volume 31. August 1943.
5. N. Arıoglu, Z. C. Girgin, and E. Arıoglu. Evaluation of ratio between splitting tensile strength and compressive strength for concretes up to 120 MPa and its application in strength criterion. ACI Material Journal/ January-February 2006.
6. A. K. H. Kwan and S. H. Chu. Direct tension behaviour of steel fibre reiforced concrete measured by a new test method. *Eng Struct*. 2018;176(May):324-336. doi:10.1016/j.engstruct.2018.09.010.
7. A. Aryanto, B. J. Winata. Tension stiffening behavior of polypropylene fiber-reinforced concrete tension members. *J Eng Technol Sci*. 2021;53(2). doi:10.5614/j.eng.technol.sci.2021.53.2.9.
8. S. M. Allam, M. S. Shoukry, G. E. Rashad, and A. S. Hassan. Evaluation of tension stiffening effect on the crack width calculation of flexural RC members. *Alexandria Eng J*. 2013;52(2):163-173. doi:10.1016/j.aej.2012.12.005.
9. H. Q. Wu and R. I. Gilbert. An experimental study of tension stifening in reinforced concrete members under short-term and long-term loads. 2008;(October):32.