Correlation of tensile strength of blended cement concrete with specimen dimensions and aggregate size: A practical test review

Nilupul Amarasinghe
Sri Lanka Institute of Information Technology, Malabe, Sri Lanka
nilupul.amarasinghe256@gmail.com
Nihal Somaratna
Sri Lanka Institute of Information Technology, Malabe, Sri Lanka
nihal.s@sliit.lk

ABSTRACT

Test specimen dimensions affect most strength properties of concrete. The existing empirical relationships in this regard are predominantly based on concrete samples made by using Ordinary Portland cement (OPC). An important recent trend in Sri Lanka has been the increasing use of blended cements. This makes it necessary to examine whether the relationships hold for blended cements as well. In this study, split cylinder tensile strength tests were conducted to determine whether the specimen size and the tensile strength of concrete prepared using a blended cement (Portland Composite Cement (PCC)) display relationships similar to OPC. Tests were conducted on specimens using two cement types – OPC and PCC - and three concrete mix ratios and a range of specimen dimensions to study the effect of the specimen length (L), diameter (D), and aggregate size (a) on the split cylinder tensile strength (T). The data was examined using dimensional analysis based on Buckingham's π theorem. A slight increasing trend was observed in the ratio of split cylinder tensile strength to mean a compressive strength (T/fc,mean) with an increasing L/D ratio. As for the ratio of the aggregate size to the specimen diameter (a/D), the analysis showed an increasing trend in T/fc,mean values with an increasing a/D ratio, indicating a significant correlation between T/fc,mean and a/D. A nonlinear regression analysis was used in an attempt to determine a functional relationship among the non-dimensional parameters T/fc,mean, L/D, and a/D. But the differences in the derived relationships for different concrete mixes were too large for reaching a common relationship. Perhaps this was due to the small number of data points available. It was seen that relationships established for OPC may hold true for PCC too. However, the data used was limited in range and more comprehensive further tests should be conducted to confirm these findings.

KEYWORDS: *Concrete, Tensile strength, OPC, PCC, Buckingham's π theorem, Dimensional analysis*

1 INTRODUCTION

Already there are correlations that demonstrate how specimen dimensions affect the tensile strength of concrete. Most of them are based on research done with Ordinary Portland Cement (OPC). At present, the use of blended cements also is becoming popular. OPC and supplementary cementitious materials (SCMs) including fly ash, slag, or silica fume are combined to create blended cements. These materials are added to the cement mixture to enhance certain properties of concrete, such as the durability, workability, and strength. Because of its positive impacts on the environment and potential performance enhancements, blended cements are becoming popular in construction. Moreover,

https://doi.org/10.54389/URCO6216

compared to OPC-based concrete, the use of blended cements might cause changes in the behavior of the concrete due to the presence of SCMs. The SCMs may have an impact on the concrete's microstructure, hydration process, and creation of hydration products. Therefore, it is crucial to find out whether the correlations found for OPC-based concrete also apply to the concrete made with blended cements since the properties and performance of blended cements can differ from OPC-based concrete. In fact, it is possible that the relationships between specimen dimensions and tensile strength may be affected.

The main purpose of the present study was to investigate the potential relationships among tensile strength, specimen dimensions, and aggregate size in concrete made using blended cement. A secondary objective was to examine whether such relationships, if any, applicable to concrete manufactured using blended cements will be similar to those applicable to concrete made with OPC.

2 LITERATURE REVIEW

2.1 Tensile strength of concrete

Concrete is a substance with quasi-brittle properties. Its main advantage for use as a material of construction is its high compressive strength. However, tensile strength of concrete also needs to be considered in the design of some types of concrete structures. For example, concrete's tensile strength is a key characteristic used to evaluate the material's resistance to cracking. Tensile strength is also important for examining a structure's serviceability limit state as well as certain ultimate limit states. For instance, the value of tensile strength is required to determine the flexural capacity of structures without reinforcement or with limited reinforcement, the shear capacity of members lacking shear reinforcement, as well as in situations of bond failure and minimal reinforcement. (Słowik & Akram, 2021). Reinhardt (2013) identified factors affecting the tensile strength of concrete and it showed that, high cement strength and good adhesion are produced by a low water/cement ratio. In addition, aggregate type, concrete curing, temperature, specimen size and the effect of the load duration are significant factors as well.

2.2 Influence of specimen dimensions on tensile strength of concrete

Tensile strength tests reveal a size effect, - a reduction in ductility and nominal strength with increasing diameter of the specimen. Several researchers (Kadlecek et al. 2002, Bažant et al. 1991, Torrent 1997) investigated the size effect in pure concrete during splitting tensile tests on cylindrical specimens. They studied tensile strength change with varying diameter of cylindrical specimen (D) - from 2 cm (Bažant et al., 1991) to approximately 3 m (Hasegawa et al. 1985). Słowik and Akram (2021) conducted an experiment to examine the impact of cylindrical specimen length on the tensile splitting strength of concrete. Cylindrical specimens with 300 mm and 150 mm lengths and a diameter of 150 mm were employed in these experiments. Their results show that the length of cylindrical specimens influences the tensile strength of concrete estimated using splitting test. A 300 mm cylindrical specimen resulted in lower test result values (approximately 5%) for the tensile strength compared to a 150 mm cylindrical specimen. The influence of specimen dimensions on tensile strength of concrete was also examined by Malhotra (1970). On 276 specimens of various sizes and dimensions, the study used two indirect tension tests and one direct tension test. The results showed that the tensile strengths estimated by the direct and indirect tests can vary depending on the size of the specimen under test. Concrete cylinders with two distinct diameters (D=150 mm and D=50 mm) were investigated by Suchorzewski

& Tejchman (2018). They observed that the D=50 mm specimen had a 15% higher concrete splitting tensile strength than the D=150 mm specimen. Kanos et al. (2006) carried out a study on specimen size effect on concrete splitting tensile strength using a series of concrete specimens with three different diameters of 76mm, 101mm, and 152mm. The cylinder specimens had a diameter to height ratio of ½. The concrete cylinders were cast with two series of a maximum aggregate size of 5mm and 15mm and with cement class of 42.5. Each series of specimens showed a reducing trend in the splitting tensile strength with increasing cylinder diameter.

3 MATERIALS AND METHODS

3.1 Materials

The testing in the present study was conducted using 2 cement types: Ordinary Portland Cement (OPC) and a blended cement - Portland Composite Cement (PCC). In addition to standard steel moulds, PVC pipes also were utilized for specimen mould preparation in cases where the standard moulds did not conform to the required dimensions.

3.2 Specimen preparation

Cylinder moulds of different dimensions were used to get several different L/D (Length/Diameter) ratios.

- Selected cylinder lengths (L) – 300 mm, 150 mm, 125 mm, 100 mm, 75 mm
- Selected cylinder Diameters (D) – 150 mm, 110 mm, 90 mm, 75 mm

In cases where standard moulds were not available to accommodate these dimension combinations, moulds were fabricated using PVC pipes. Tests were conducted using 3 different mix ratio series.

- Series 1 - 1: 1.5: 3 (Cement:Sand:Coarse aggregates)
- Series 2 - 1: 1: 2 (Cement:Sand:Coarse aggregates)
- Series 3 - 1: 2: 4 (Cement:Sand:Coarse aggregates)

Figure 1. PVC pipe mould

3.3 Assessment of effects of mould deformations in PVC moulds for concrete specimen

In this study, PVC pipes were used to produce some of the cylindrical specimen moulds. Pipes were cut into selected lengths carefully. But there could be some imperfections in the circularity of the cross sections of these PVC pipes and it cannot be guaranteed that they are perfectly circular. Pipes can also be deformed slightly during demolding and reusing the same mould several times. Therefore, a 2-D finite element analysis was carried out using several different models to evaluate the potential impact of mould deformations on the splitting tensile strength of cylindrical concrete specimens.

- Perfect circular model: In order to represent the ideal conditions, an initial 2D model was created featuring a perfectly circular geometry with 150 mm diameter. This model was used as the baseline for the analyses. (Base Model)
- Deformed circular modals: Multiple models were created, introducing small deviations along with one axis leading to slightly elliptical cross sections to simulate deformed PVC pipe shapes as follows:

(a) 150 mm diameter circle with 6 mm elongation (+/- 3 mm on each side) – Model 1
(b) 150 mm diameter circle with 10 mm elongation (+/- 5 mm on each side) – Model 2
(c) 150 mm diameter circle with 12 mm elongation (+/- 6 mm on each side) – Model 3
(d) 150 mm diameter circle with 14 mm elongation (+/- 7 mm on each side) – Model 4

- Same material properties, boundary conditions and loads to simulate split cylinder test were applied on all the models.
- Prepomax v1.4.1 finite element simulations were conducted to analyse the stress distributions along the loading axis (along the vertical centrelines of the cylinder).
- Each stress distribution curve was compared with the perfectly shaped model outcomes to examine whether there was any significant influence of the small deformations on the stresses.

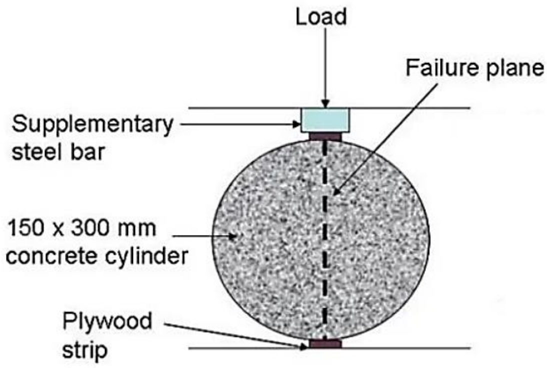

Figure 2: Test configuration

3.4 Split cylinder testing procedure

The split cylinder tensile test was conducted according to the ASTM standards (ASTM- C 496/C 496M) (Fig. 2). Three specimens of each dimension combination were tested in each of the 3 mix ratio series and the two cement types.

Apparatus

- Compression testing machine
- Supplementary Bearing Bar or Plate
- Bearing Strips

Calculations

The splitting tensile strength of the specimen is calculated using equation (1).

$$T = 2P/\pi DL \tag{1}$$

where:

T = splitting tensile strength; L = Length of specimen; D = diameter of specimen

P = load causing splitting of the specimen

3.5 Data Collection and Data Analysis

The dimensions of each specimen (length L and diameter D) and the tensile strength of each specimen obtained through the tests were recorded.

The data analysis was based on Buckingham's π theorem which is the basis for a dimensional analysis procedure used to examine the relationships between physical quantities based on their dimensions. It provides a method for determining dimensionless parameters that govern the behaviour of physical systems.

According to this theorem, if a quantity Q0 (a dependent variable) is totally determined by the values of a set of n independent dimensional variables, and the number of primary dimensions involved is k, then a suitable dimensionless Q0 will be completely determined by (n – k) dimensionless similarity parameters - often referred to as π-numbers.

Tensile strength of concrete (T) depends possibly on several parameters such as the mean compressive strength of concrete (fc,mean), strength of the cement used (fcement), length of the test specimen (L), diameter of the test specimen (D) and the aggregate size (a). If the same type of cement is used, then the fcement will be constant and should not be a variable. Then n = 4. Force and length can be considered to be the primary dimensions involved in this relationship. Then k = 2. According to Buckingham's π theorem the non-dimensionalized (normalized) T will depend on n-k = 2 non-dimensional parameters. The ratios L/D and a/D can be considered as these 2 non-dimensional parameters (π-numbers). The normalized tensile strength T can be taken as T/ fc,mean. Therefore, effectively, T/ fc,mean will depend on the ratios L/D, and a/D.

The mean compressive strength for each mixing ratio and cement type was determined by conducting compression tests on three standard size cylindrical specimens (150 mm x 300 mm). This test was done twice to improve reliability. Using the results, the average compressive strength values were calculated.

The resulting non-dimensional parameters were plotted in several different ways to check whether any relationships could be observed.

4 RESULTS AND DISCUSSION

4.1. Finite element analysis of possible influence of mould deformations on splitting tensile strength

Figures 3 to 7 show the normal stress distributions on a cross section along the diagonal along the loading axis for the different cross sections studied. These stresses were obtained using a 2-D finite element analysis. The external load was maintained at the same value for all cases. It can be seen that there are only minor differences between the maximum tensile stresses in the deformed models compared to the base model. The stress distribution curves are almost identical for all the models. It was concluded that minor imperfections in PVC pipe moulds will not exert a significant impact on the tensile strength results.

4.2. Mean compressive strength and split cylinder tensile strength results

As described above, 3 standard concrete cylinder specimens (150 mm diameter x 300 mm length) for each mix ratio and for each cement type were cast, cured, and tested after 28-days for cylinder compressive strength. This was done twice to improve reliability. The values obtained from the specimens were averaged and the results are presented in Table 1.

Max. Tensile Stress = 21.05 MPa

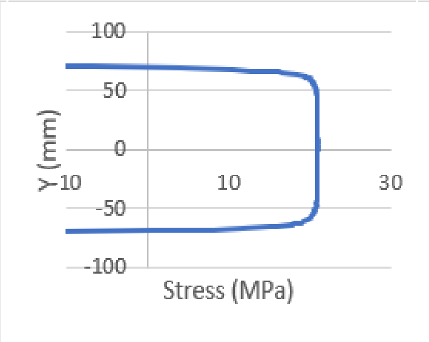

Figure 3: Stress distribution along the loading axis of the base model

Max. Tensile Stress = 21.03 MPa

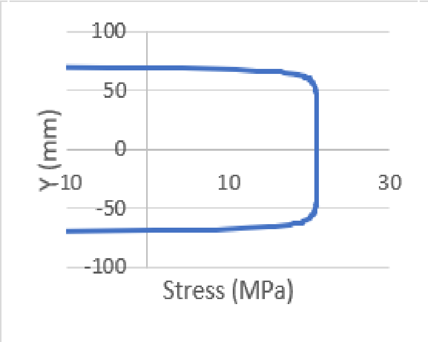

Figure 4: Stress distribution along the loading axis of the deformed model 1

Max. Tensile Stress = 21.02 MPa

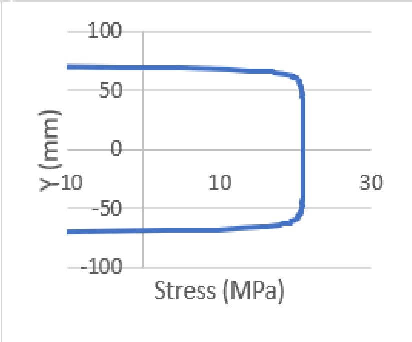

Figure 5: Stress distribution along the loading axis of the deformed model 2

Max. Tensile Stress = 21.01 MPa

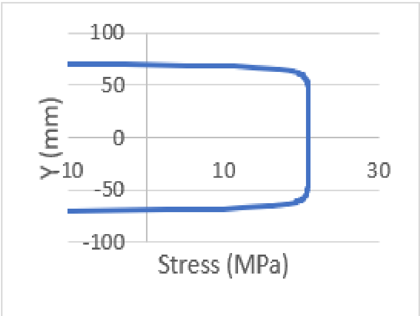

Figure 6: Stress distribution along the loading axis of the deformed model 3

Max. Tensile Stress = 21.00 MPa

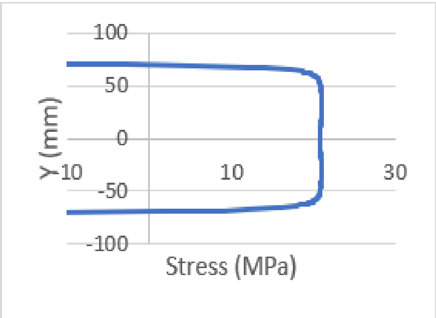

Figure 7: Stress distribution along the loading axis of the deformed model 4

Table 1: Mean compressive strengths of concrete mixes

Mix ratio	**Compressive strength (MPa)**	
	Cement OPC	**Cement PCC**
Series 1 (1: 1.5: 3)	25.6	24.7
Series 2 (1: 1: 2)	32.5	32.9
Series 3 (1: 2: 4)	16.0	16.2

Altogether 6 different concrete mixes were used in the tests [three mix ratios (series 1, 2, and 3) and two cement types (OPC and PCC)]. Using each of these 6 mixes cylindrical concrete specimens were cast corresponding to each of the different (diameter x length) combinations used in this study. In each case 3 specimens were cast. These specimens were cured, and at 28 days their dimensions were measured, and tested to determine the splitting tensile strength. The values from the 3 specimens corresponding to each mix were averaged. Results are presented in Table 2.

Table 2: Tensile Strength Results

D (mm)	L (mm)	Tensile strength (T) (MPa) [average of results from 3 specimens]					
		Series 1		Series 2		Series 3	
		OPC cement	PCC cement	OPC cement	PCC cement	OPC cement	PCC cement
150	300	2.28	2.16	3.21	2.70	2.16	1.48
110	300	2.64	2.43	2.86	2.57	1.56	1.63
90	300	2.66	2.51	3.27	3.26	1.85	2.07
75	300	2.64	2.12	3.31	3.10	2.03	1.70
150	150	2.39	2.38	2.35	2.81	1.43	1.15
110	150	2.93	2.58	2.25	2.34	1.92	1.80
90	150	2.64	2.60	3.24	3.14	1.78	2.10
75	150	3.02	2.80	3.52	2.49	1.80	2.12
150	125	2.27	2.37	3.34	2.53	1.47	1.62
110	125	2.86	3.18	3.15	3.02	2.05	1.97
90	125	3.24	2.88	3.18	3.37	2.01	1.98
75	125	3.20	2.58	3.32	3.37	2.11	1.88
150	100	2.08	2.20	2.79	2.74	1.62	1.50
110	100	2.91	2.41	2.90	2.87	2.17	2.21
90	100	2.74	2.64	2.83	3.36	1.89	1.78
75	100	3.37	3.01	3.30	3.56	2.21	2.19
150	75	2.43	2.32	3.06	2.85	1.44	1.70
110	75	2.73	2.46	3.24	2.64	2.02	2.03
90	75	2.57	3.15	3.16	3.76	2.02	2.12
75	75	3.14	2.76	3.07	3.50	2.12	1.88

4.3. Non–Dimensional Analysis

The main objective of this study was to examine correlations, if any, between the specimen dimensions and the tensile strength, and verify whether these relationships are similar for both Ordinary Portland cement (OPC) based concrete and blended cement (PCC) based concrete. The non-dimensional parameters were plotted as T/fc,mean vs L/D graphs (Fig. 8 and Fig. 9) allowing for a visual examination of potential relationships.

When considering the graphs in Fig.8 and Fig.9, in the range of L/D from 0.5 to 2.0, the T/fc,mean appears to have a slight increasing trend with increasing L/D values. The overall similarity in behaviour between PCC based concrete and OPC based concrete suggests that relationships between specimen dimensions and tensile strength in OPC-based concrete may also apply to PCC based concrete. However, the scatter in the plots might emphasize the need for additional data to draw firm conclusions.

Considering the non-dimensional analysis presented in section 3.5 above, another possibility could be suspected. It was argued that probably the non-dimensional parameter T/fc,mean could depend on the non-dimensional parameters L/D (= specimen length/diameter) and a/D (= aggregate size/specimen diameter). Therefore, it is possible that the scatter observed in Fig. 8 and Fig. 9 results from the influence of a/D. In an attempt to examine this possibility the results were re-plotted as

T/fc,mean vs L/D graphs with data points separated into groups corresponding to the a/D values.

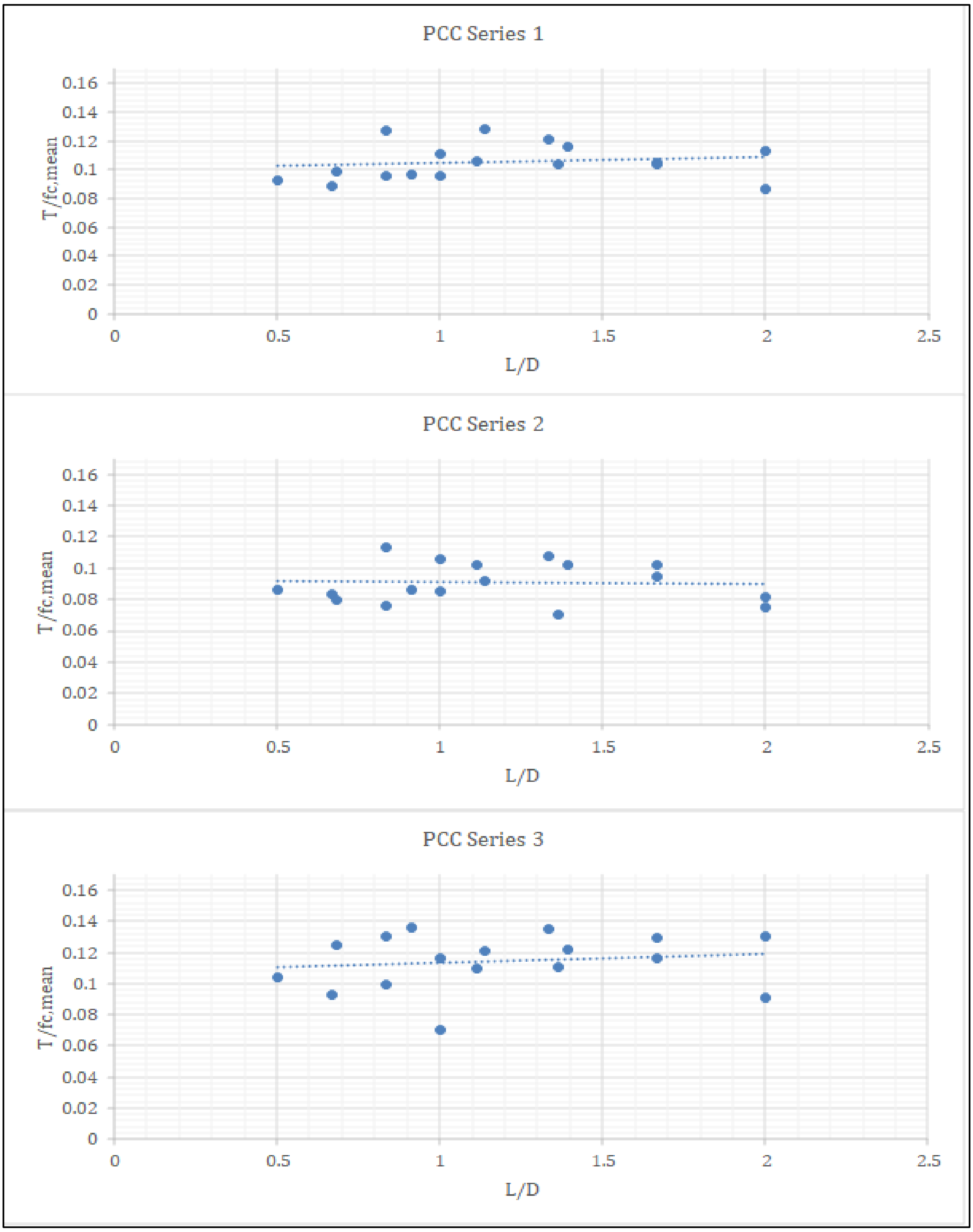

Figure 8: PCC based results

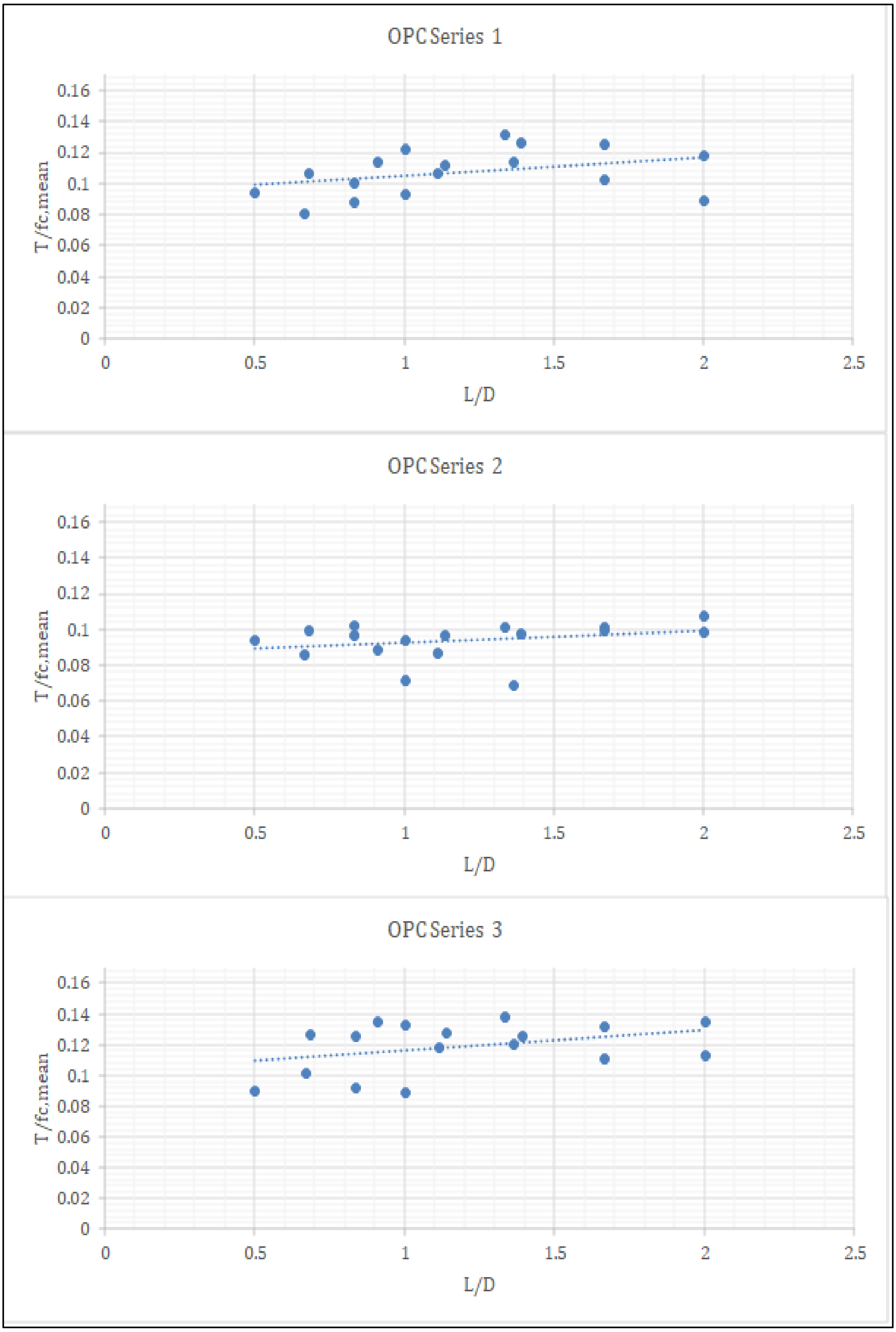

Figure 9: OPC based results

In this study the aggregate size – a - was maintained at a constant level by using the same aggregates for all the specimens. In the analysis, a nominal value of 25 mm was used for the aggregate size and the a/D ratios were calculated accordingly. They varied from 0.17 to 0.33 which comply with the requirement that they should be less than 1/3 as specified by Bungey et al. (2006). The results were plotted as a series of T/fc,mean vs L/D graphs with separate data points and curves for specific a/D values. (Fig. 10 and Fig. 11). In these graphs, all the series in both cement types show an increasing trend in T/fc,mean values with a/D values, indicating a correlation between these two parameters as well.

By plotting T/fc,mean against L/D for a constant a/D ratio, any scatter attributable to variations in a/D could be minimized. In Fig. 10 and Fig. 11 it is seen that T/fc,mean is more sensitive to changes in a/D than to changes in L/D. It is evident that for each a/D ratio, T/fc,mean varies only slightly with varying L/D values. It appears that this downward trend becomes more pronounced with increasing a/D ratios. Just as an illustration to highlight this point, two trend lines extracted from Fig. 11 are shown in Fig. 12. There is a slight downward trend in T/fc,mean with L/D for a given a/D ratio, but it is very small. The slight upward trend in T/fc,mean with increasing L/D values, previously observed in Fig. 8 and Fig. 9 seem to be the effect of changing a/D. This strongly suggests that T/fc,mean , for the most part, changes but only slightly with changing L/D for a given a/D.

Fig. 10 and Fig. 11 also illustrate that the inter-relationships among these parameters do not appear to be much influenced by the type of cement used in the production of concrete.

4.4. Nonlinear Regression Analysis

Since the results indicated, as explained above, that the non-dimensional parameter T/fc,mean is dependent on the ratios L/D and a/D, an attempt was made to employ nonlinear regression analysis to derive an approximate functional relationship showing, in a quantitative way, how T/fc,mean is related to the non-dimensional parameters L/D and a/D. However, this did not yield satisfactory results. The values of the co-efficients in the proposed non-linear expressions, when evaluated separately for each of the 6 different mixes, did not agree with one another. This might be due to the small number of data points available in each case. A functional relationship of the kind envisaged would have been useful as an approximate predictive tool. Moreover, a more complete set of data produced in a broader, more comprehensive study might be able to elicit a better result in this regard

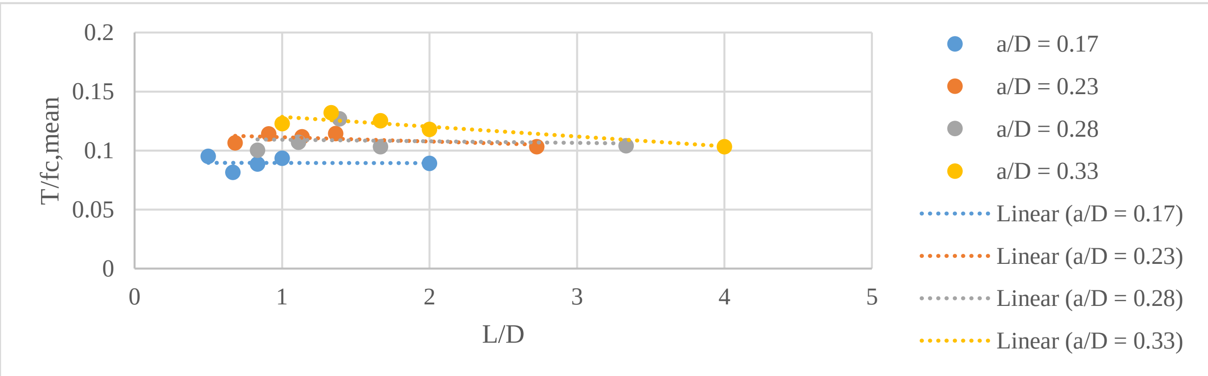

Figure 10: OPC series 1 results considering both L/D and a/D ratios

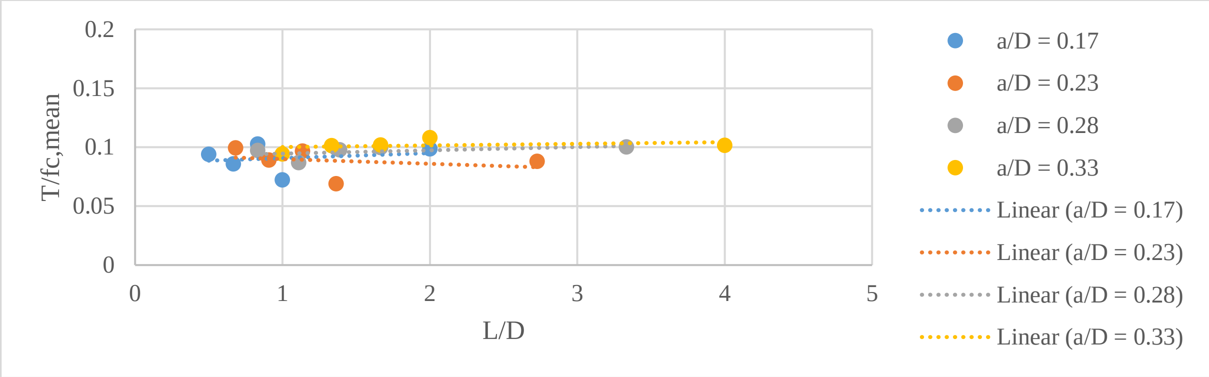

Figure 11: OPC series 2 results considering both L/D and a/D ratios

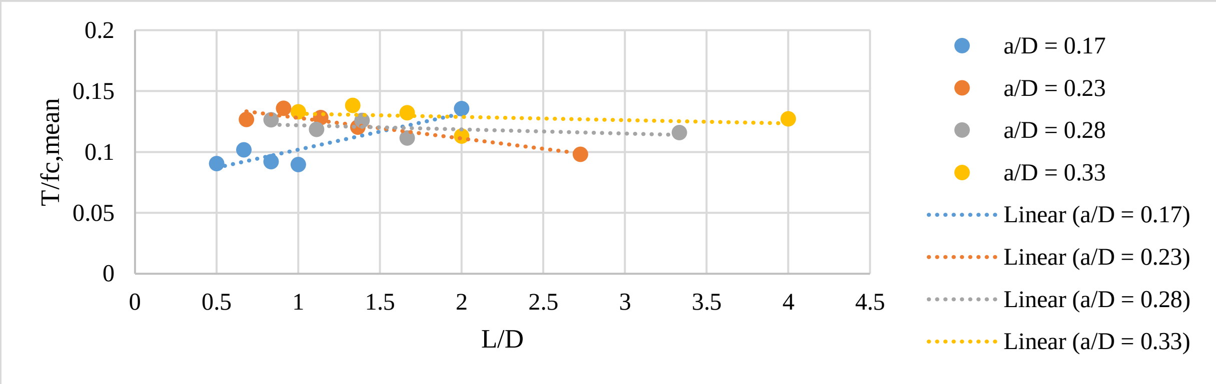

Figure 12: OPC series 3 results considering both L/D and a/D ratios

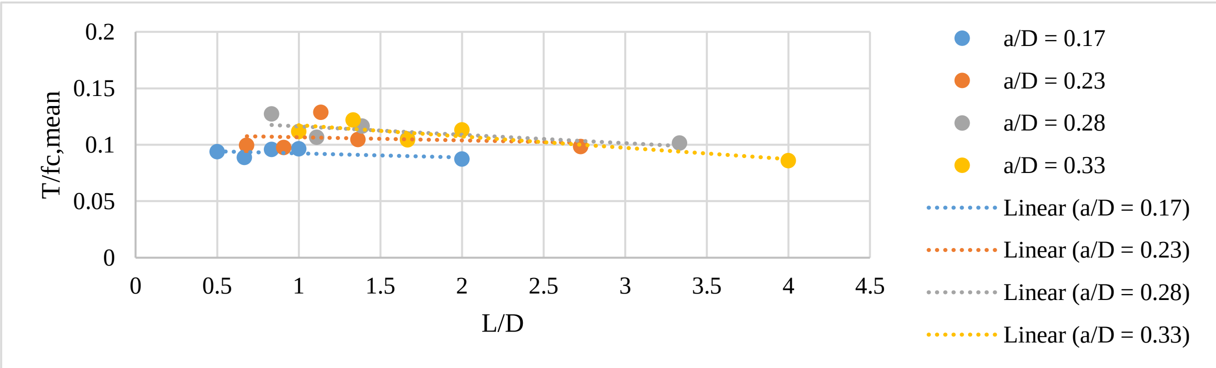

Figure 13: PCC series 1 results considering both L/D and a/D ratios

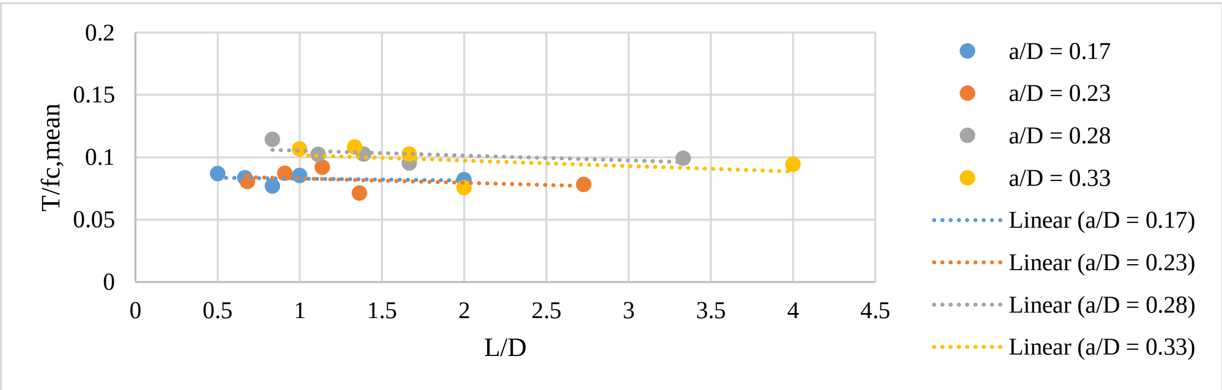

Figure 14: PCC series 2 results considering both L/D and a/D ratios

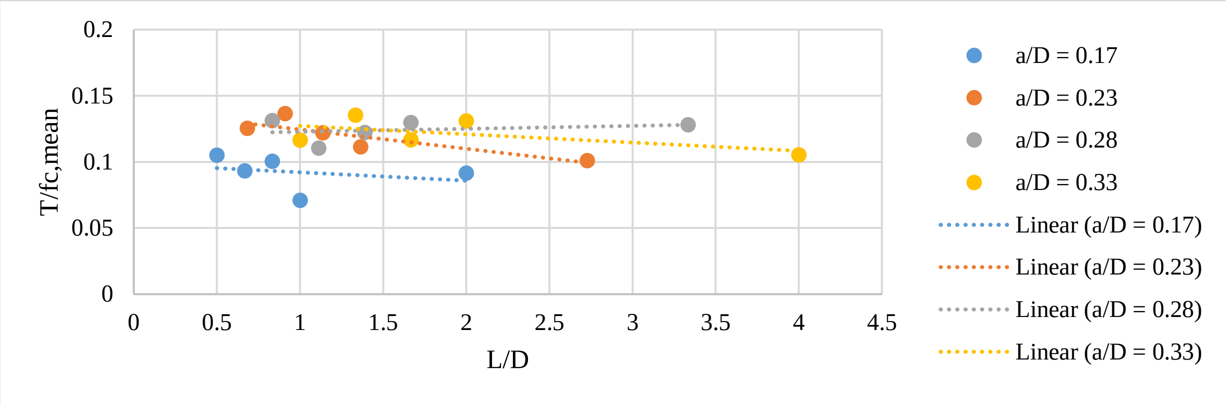

Figure 15: PCC series 3 results considering both L/D and a/D ratios

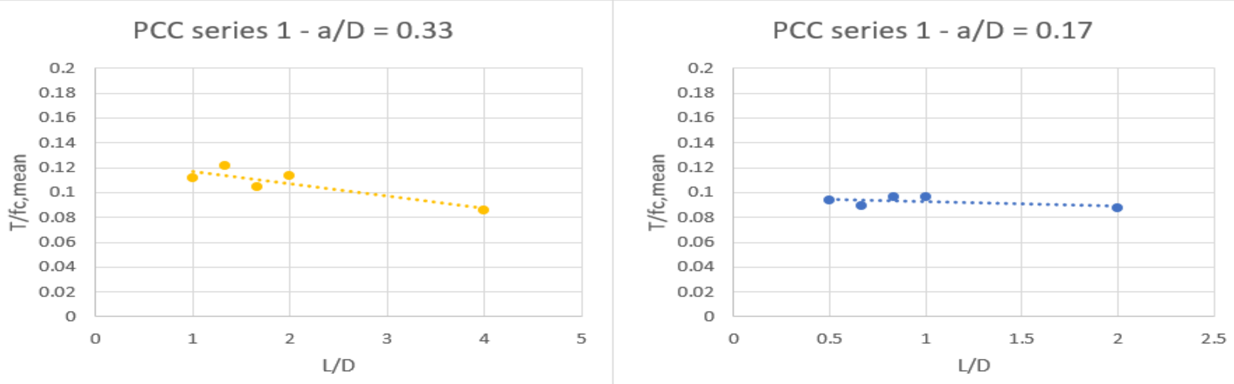

Figure 16: Two trend lines of two different a/D groups, extracted from PCC series 1 plot (Fig. 13)

There are several potential sources of error and scatter in the data. Variability in concrete composition, stemming from differences in raw materials, may contribute to scatter. In the testing phase, variations in sample preparation and curing conditions can introduce uncertainties. The limited dataset, especially with respect to L/D ranges also should be acknowledged as potential sources.

5 CONCLUSIONS

This study examined the relationship between specimen dimensions and the tensile strength of concrete. It expanded the scope beyond conventional OPC to include blended cement as well.

Analysis of the test data indicated a correlation between the ratio of tensile strength-to-mean compressive strength (T/fc,mean) and the ratios of specimen length to diameter (L/D) and aggregate size to specimen diameter (a/D). It was also noted that changes in a/D have a more pronounced impact on T/fc,mean than changes in L/D. The inconsistencies in the trends observed in previous research work described in section 2.2 above could be the result of ignoring the significance of the ratio a/D.

The comparative analysis between cement types exhibited similar behavior, showing that relationships established for OPC may hold true for blended cements (in the present case PCC) also. However, these are only preliminary conjectures based on limited tests. The extent of scatter in some of the data sets indicate a need for more comprehensive studies with enhanced range of data in order to reach definite conclusions with wider applicability.

6 ACKNOWLEDGEMENTS

The authors are grateful to SLIIT for providing the opportunity and resources to conduct this as a final year undergraduate research project. They also wish to thank two anonymous reviewers for helpful comments and suggestions.

REFERENCES

Bažant, Z.P. Kazemi, Hasegawa, & Mazars. (1991). Size Effect in Brazilian Split-Cylinder Tests: Measurements and Fracture Analysis. *ACI Materials Journal*, *88*(3). https://doi.org/10.14359/1987

Bungey, J.H., Millard, S.G., Grantham, M.G., (2006), *Testing of Concrete in Structures*, 4th ed., Taylor & Francis, London.

Kadleček, Vl., Modrý, S., & Kadleček, Vl. (2002). Size effect of test specimens on tensile splitting strength of concrete: General relation. *Materials and Structures*, *35*(1), 28. https://doi.org/10.1007/BF02482087

Kanos, A., Kanos, A., & Perdikaris, P. C. (2006). Size effect on concrete splitting tensile strength and modulus of elasticity in M. S. Konsta-Gdoutos (Ed.), *Measuring, Monitoring and Modeling Concrete Properties* (pp. 239–246). Springer Netherlands. https://doi.org/10.1007/978-1-4020-5104-3_29

Malhotra. (1970). Effect of Specimen Size on Tensile Strength of Concrete. *ACI Journal Proceedings*, *67*(6). https://doi.org/10.14359/7292

Reinhardt, H. W. (2013). Factors affecting the tensile properties of concrete. In *Understanding the Tensile Properties of Concrete* (pp. 19–51). Elsevier. https://doi.org/10.1533/9780857097538.1.19

Słowik, M., & Akram, A. (2021). Length Effect at Testing Splitting Tensile Strength of Concrete. *Materials*, *15*(1), 250. https://doi.org/10.3390/ma15010250

Suchorzewski, J., & Tejchman, J. (2018). Size effect in concrete under splitting tension. In G. Meschke, B. Pichler, & J. G. Rots, *Computational Modelling of Concrete Structures* (1st ed., pp. 437–445). CRC Press. https://doi.org/10.1201/9781315182964-54

Torrent, R. J. (1977). A general relation between tensile strength and specimen geometry for concrete-like materials. *Matériaux et Constructions*, *10*(4), 187–196. https://doi.org/10.1007/BF02478688