



Research Paper / Makale

A Numerical Approach to Estimate the Tensile Strength of Structural Lightweight Concrete

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Abstract: Since lightweight concrete has many advantages over traditional concrete, it is of great importance for the building industry to investigate more and examine its mechanical properties. It is considered that it will be very useful to use lightweight concretes in special concrete classes if they have sufficient strength properties. Structural lightweight concrete can be produced from different lightweight aggregates. Expanded clay aggregate, which is one of them, is thought to have an important place in the production of structural light concrete with its high reserve and easy availability. At the same time, structural lightweight concrete can improve the properties of structures such as earthquake resistance and thermal insulation. The aim of this study; a series of concrete specimens produced with different mixing ratios containing lightweight expanded clay aggregate is to develop a numerical model using the tensile strength test results in the literature. For this purpose, the studies on structural lightweight concrete have been investigated in detail in the literature. With this numerical model, it is hoped that the tensile strength can be easily calculated depending on the content of cement, aggregate, powder/filler, silica fume, water, lightweight expanded clay aggregate and superplasticizer. In this context, the parameters affecting tensile strength were determined. The effects of these parameters on tensile strength were interpreted with related graphics. In the numerical model developed in this study, tensile strength affected by the related parameters is included as output. As a result; with the numerical model developed using nonlinear statistical analysis, it is planned to develop a practical equation with high precision that can be easily used by application engineers.

Keywords: structural lightweight concrete, tensile strength, lightweight expanded clay aggregate, a numerical model

Yapısal Hafif Betonun Çekme Dayanımına Sayısal Bir Yaklaşım

Öz: Hafif betonun geleneksel betona göre birçok avantajı olduğundan dolayı daha çok araştırılması ve mekanik özelliklerinin incelenmesi inşaat sektörü açısından büyük bir önem taşımaktadır. Özel beton sınıfına giren hafif betonların yeterli dayanım özelliklerine sahip olması durumunda, yapılarda kullanımının çok faydalı olacağı düşünülmektedir. Yapısal hafif beton, farklı hafif agregalardan imal edilebilmektedir. Bunlardan biri olan geliştirilmiş kil agregasının (LECA), rezervinin çok fazla olması ve kolay elde edilebilirliği ile yapısal hafif beton üretiminde önemli bir yere sahip olduğu düşünülmektedir. Aynı zamanda yapısal hafif beton ile yapıların, depreme karşı dayanıklılık ve ısı yalıtımı gibi özelliklerinin de iyileştirilmesi sağlanabilmektedir. Bu çalışmanın amacı; LECA içeren farklı karışım oranları ile üretilen bir dizi beton numunenin, literatürdeki çekme dayanımı deney sonuçları kullanarak sayısal bir model geliştirmektir. Bu amaçla literatürde yapısal hafif beton üzerine yapılan çalışmalar detaylı bir şekilde incelenmiştir. Geliştirilen bu model ile çimento, agrega, bağlayıcı, silis dumanı, su, LECA ve katkı içeriğine bağlı olarak çekme dayanımının kolayca hesaplanabileceği umut edilmektedir. Bu kapsamda, çekme dayanımını etkileyen parametreler belirlenmiştir. Bu parametrelerin çekme dayanımına etkileri ilgili grafiklerle yorumlanmıştır. Bu çalışmada geliştirilen sayısal modelde, ilgili parametrelerin etkilediği çekme dayanımı çıktı olarak yer almaktadır. Sonuç olarak; doğrusal olmayan istatistiksel analiz kullanılarak geliştirilen sayısal model ile uygulama mühendisleri tarafından kolaylıkla kullanılabilecek pratik ve yüksek hassasiyetli denklem geliştirilmesi planlanmıştır.

Anahtar kelimeler: yapısal hafif beton, çekme dayanımı, geliştirilmiş kil agregası, sayısal model

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1. Introduction

Concrete, which is a good structural bearing, has disadvantages such as high unit weight and high thermal conductivity coefficient. By reducing the unit weight of conventional concrete, it is possible to reduce the structures by reducing the self-weight of the reinforced concrete factors. Lightweight concrete is generally classified according to both unit weight and strength. Lightweight concretes vary according to different standards. According to ASTM C330-69, concretes with unit weights not exceeding 1840 kg/m^3 and having a cylinder compressive strength of 28 days of more than 17 MPa are classified as lightweight concrete [1]. In TS 2511, the dry unit weight of less than 1900 kg/m^3 and BS16 class concrete is defined as lightweight concrete [2]. In DIN 1045, it is stated that the unit weight of lightweight concrete varies between $300\text{-}2000 \text{ kg/m}^3$ [3].

Lightweight aggregates that form lightweight concrete can be obtained as natural or artificial [4]. Substances such as pumice (pumice), volcanic tuff, perlite, vermiculite are naturally obtained light aggregates. The materials such as fly ash, blast furnace slag, expanded clay, expanded perlite are produced artificially and used as lightweight aggregate [5,6]. One of the most durable aggregates among artificial lightweight aggregates is expanded clay aggregate [7]. The expanded clay aggregate is thought to have an important place in the production of structural lightweight concrete, due to the appropriate raw material and technology, which enables the production of materials of desired grain size and properties. Expanded clays according to their commercial production and technical designations all over the world; It is also known as keramzite, lightweight expanded clay aggregate (LECA) [8]. When the previous studies in the literature are examined; Lo et al. (2008) examined the effect of LECA aggregates' water absorption capacity on the gap distribution at aggregate-cement paste interface [9]. Bartolini et al. (2010) examined the sound insulation performance of LECA with epoxy and concluded that LECA shows high-level sound insulation performance [10]. Self-compacting concrete specimens were prepared using LECA and lightweight concretes with compressive strength in the range of 37.4 MPa-60.8 MPa were obtained in Bogas et al. (2012) [11]. Costa et al. (2012) examined the shrinkage properties of lightweight concrete produced with LECA [12]. Uglyanitsa et al. (2014) investigated the presence and corrosion conditions of reinforced concrete produced with LECA [13]. Yang et al. (2014), examined the mix-design of lightweight concretes containing LECA and developed an empirical formula to calculate values such as compressive strength, dry unit weight [14]. Similarly; Tuğrul Tunç et al. (2018) examined the mix-design of lightweight concrete containing pumice aggregate and obtained a high accuracy formula to calculate the compressive strength [15]. Tunc et al. (2019) and Sağlam et al. (2019) developed equations that can easily and reliably calculate the compressive strength of lightweight concretes containing different lightweight aggregates [16,17].

Due to Turkey has been exposed to major earthquakes that have great financial and emotional damages, it was thought that the need to reduce the dead load of the building. This will be possible by using building materials produced with lightweight aggregates in buildings. The way to minimize the building load without reducing the strength characteristics of buildings is to produce lightweight concrete using lightweight aggregates. LECA, which is one of the lightweight aggregates, can be preferred in structural lightweight concrete production due to the abundant reserve in our country.

The present study aims to develop a numerical model by using the tensile strength test results of structural lightweight concrete containing LECA from previous studies. For this purpose, a detailed literature review was researched about structural lightweight concrete and experimental data were collected to be used in nonlinear statistical analysis. With the developed equation, it is aimed to calculate the tensile strength of structural lightweight concrete with high accuracy. Thus, both the preliminary mixture design of concrete and the tensile strength of the lightweight concrete can be determined without testing. Today, due to the increasing need for structural light concrete, it is expected to provide labor, time-saving and economic gain with the present study.

2. Materials and Statistical Method

2.1. Materials

According to ACI 213R-03; structural lightweight concrete, 28 days' minimum compressive strength 17 MPa, density between 1120-1960 kg/m³ or defined as the concrete produced with a light-normal aggregate combination [18]. As a special type of concrete structural lightweight concrete, especially in recent years has been used for structural purposes. Nowadays, structural lightweight concrete is generally used to reduce a dead load of a building and the weight of the reinforced concrete building factors to be used. However, it plays an active role especially in increasing the usage areas and openings of tall buildings [19]. Structural lightweight concrete; It is mainly used in the construction of walls, panels and blocks, in roof floors, bridge openings, pre-built concrete units. For this purpose, it can be preferred to produce structural lightweight concrete, especially to construct earthquake resistant structures [20]. Furthermore, lightweight concrete is preferred in skyscrapers, bridges, piers, platforms and many other structures. The Hagia Sophia Museum in Istanbul and the Maya Pyramids in Mexico are some of the magnificent antique structures built using lightweight concrete to date (Figure 1).



Figure 1. a) Maya Pyramids, b) Hagia Sophia Museum [21]

Clay, one of the oldest raw materials, has never lost its importance until today. When natural clays are heated above 1000 °C, they form a gas-filled porous structure due to the expansion of the gases in their structures. Thus, the expanded clay is formed [22]. Expanded clays are suddenly exposed to high temperatures in heated rotary furnaces. Clays heated between 1000-1300 °C according to the mineralogical structure of natural clay can produce a volume increase of 1.5-6 times their initial volume [5]. However, their density varies between approximately 320 and 960 kg/m³ [23]. Expanded clays are artificial material and are not found in the expanded state in nature. Every clay found in nature does not expand. The raw materials used to produce expanded clay are early sintered clay, sandy clay, clayey schist and shale [5]. Expanded clays provide good heat and sound insulation as well as lightened the structure. Owing to its robust sintered shell, it has the highest compressive strength among similar lightweight aggregates. Thus, according to the same

compressive strength class concrete, the structure is lightened by approximately 25%-35%. Expanded clay aggregates have many advantages compared to other lightweight aggregates with this aspect.

2.2. Statistical Method

The statistical program used in this study is an advanced analytical software developed by StatSoft (StatSoft Inc., USA) [24]. The program can successfully provide services such as data analysis, data management and data visualization. Numerical modeling and regression analysis based on various estimates can be performed with this program. Different versions are available. The program includes analytical and research graphs in addition to standard 2D and 3D graphs. It allows the search for outliers and data analysis. Different estimation methods can be tried with this program (Figure 2). In this study, nonlinear estimation based numerical analysis was performed.

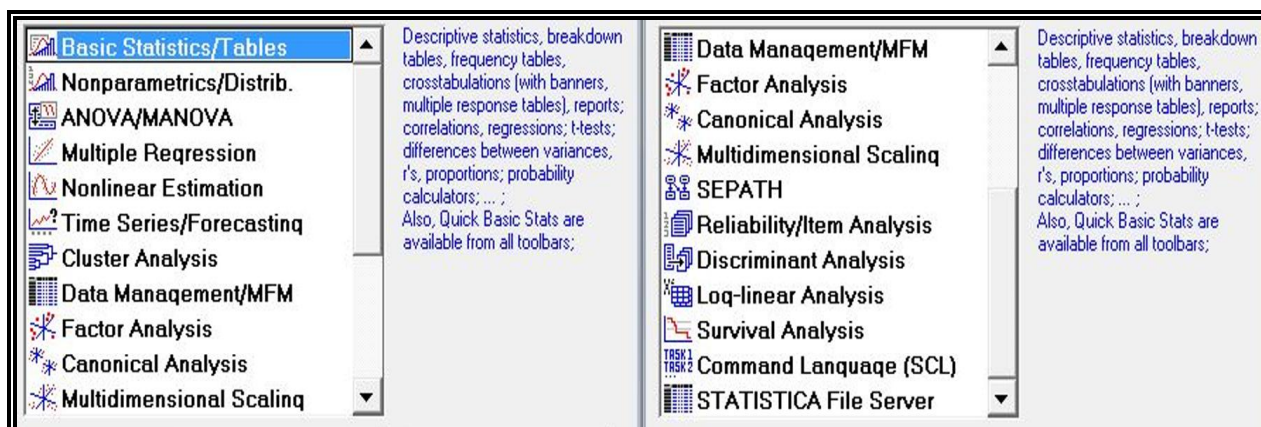


Figure 2. Different estimation methods developed with the software program

In this study, experimental data of previous studies investigating the tensile strength (f_t) of structural lightweight concrete produced using LECA aggregates were used. Mixture amounts of materials such as cement, aggregate, LECA, powder, superplasticizer, silica fume and water given in the previous studies were converted into dimensionless parameters. Using these data, regression analysis was performed using this program and a non-linear equation, Equation (1), was developed to calculate the tensile strength (f_t) of structural lightweight concrete. This equation was obtained by performing many analyzes in the program. Because the formula that gives the correlation coefficient R^2 closest to 1.0 is tried to be determined. In the program, " f_t/f_{mean} " output is defined as other dimensionless parameters are input. To calculate " f_t/f_{mean} " values consistent with experimental results, the coefficients of the relevant parameters were determined by the program (Table 1).

$$\frac{f_t}{f_{tort}} = -0.327 \times \frac{LECA}{TA} + 2.376 \times \frac{FA}{TA} + 2.609 \times \frac{CA}{TA} - 0.457 \times \frac{P}{C} + 1.737 \times \frac{SF}{C} - 3.384 \times \frac{W}{C} + 1.476 \times \frac{SA}{C} \quad (1)$$

where; f_t =tensile strength (MPa), f_{mean} =mean tensile strength (MPa), $LECA$ =lightweight expanded clay aggregate content (kg/m^3), FA =fine aggregate content (kg/m^3), CA =coarse aggregate content (kg/m^3), TA =total (fine + coarse) aggregate content (kg/m^3), P =powder content (kg/m^3), C =cement content (kg/m^3), SF =silica fume content (kg/m^3), W =water content (kg/m^3), SA =super plasticizer content (kg/m^3).

Table 1. The coefficients of the relevant dimensionless parameters obtained by the numerical analysis.

N=18 Estimate	Dep. Var: f_i Loss: (Observed-Predicted) ²						
	Final loss: 0.095658845 R=0.96886 Variance explained: 93.87%						
	x_1	x_2	x_3	x_4	x_5	x_6	x_7
	-0.327	2.376	2.609	-0.457	1.737	-3.384	1.476

The numerical $f_i/f_{i\text{mean}}$ values obtained from Equation (1) are presented in Table 2.

Table 2. Mixture design, experimental $f_i/f_{i\text{mean}}$ values from the previous studies and numerical $f_i/f_{i\text{mean}}$ values from this study.

Test number	The previous studies	LECA/TA	FA/TA	CA/TA	P/C	SF/C	W/C	SA/C	$f_i/f_{i\text{mean}}$ (experimental)	$f_i/f_{i\text{mean}}$ (numerical)
1	[25]	0.620	1.000	0.000	0.000	0.000	0.480	0.000	0.518	0.549
2		0.600	1.000	0.000	0.000	0.000	0.467	0.000	0.633	0.600
3		0.294	1.000	0.000	0.500	0.000	0.350	0.018	0.991	0.893
4	[26]	0.294	1.000	0.000	0.500	0.000	0.350	0.018	0.847	0.893
5		0.294	1.000	0.000	0.563	0.000	0.400	0.015	0.809	0.691
6		0.294	1.000	0.000	0.500	0.000	0.350	0.018	0.821	0.893
7		0.294	1.000	0.000	0.563	0.000	0.400	0.015	0.590	0.691
8		0.538	1.000	0.000	0.000	0.111	0.444	0.020	0.985	0.920
9	[27]	0.538	1.000	0.000	0.000	0.111	0.444	0.020	0.933	0.918
10		0.538	1.000	0.000	0.000	0.111	0.444	0.020	0.824	0.918
11		0.428	1.000	0.000	0.000	0.111	0.356	0.022	1.296	1.258
12		0.295	0.688	0.312	0.000	0.111	0.356	0.022	1.348	1.375
13		0.381	0.707	0.293	0.000	0.111	0.356	0.017	1.230	1.334
14		0.326	0.770	0.230	0.000	0.111	0.311	0.013	1.610	1.483
15		0.488	0.742	0.258	0.000	0.111	0.388	0.013	1.212	1.176
16		0.694	0.742	0.258	0.000	0.101	0.389	0.025	1.158	1.106
17		0.720	1.000	0.000	0.000	0.100	0.341	0.015	1.129	1.183
18		0.327	0.759	0.241	0.000	0.111	0.311	0.015	1.431	1.487

3. Results and Discussion

In the previous section, it was stated that Equation (1) was developed for the calculation of f_i . The statistical method in which this equation is developed is explained below. In this section, the reliability of this equation will be emphasized. The mean and standard deviation values of the relevant dimensionless parameters from the software program are presented in Table 3.

Various graphs were drawn and comments were made to demonstrate the safe availability of Equation (1). In this context, the relevant experimental " $f_i/f_{i\text{mean}}$ " values were compared with the numerical " $f_i/f_{i\text{mean}}$ " values calculated from Equation (1) (Figure 3). There was a minimum deviation of 1% and a maximum of 15% between experimental and numerical results. When all the results were examined, the approximate average deviation value was 6.5%. Thus, it can be said that the experimental results of previous studies and the numerical results of the present study are compatible with each other.

Table 3. The program outputs: mean and standard deviation values.

The variables	Mean	St. dev.	Min.	Max.
LECA/TA	0.442539	0.151296	0.294118	0.720155
FA/TA	0.911582	0.129783	0.687987	1.000000
CA/TA	0.088418	0.129783	0.000000	0.312010
P/C	0.145833	0.242536	0.000000	0.562500
SF/C	0.066722	0.054868	0.000000	0.111110
W/C	0.385336	0.051930	0.311110	0.480000
SA/C	0.015856	0.006662	0.000000	0.025250
f_t/f_{tmean}	1.020272	0.302964	0.518380	1.609850

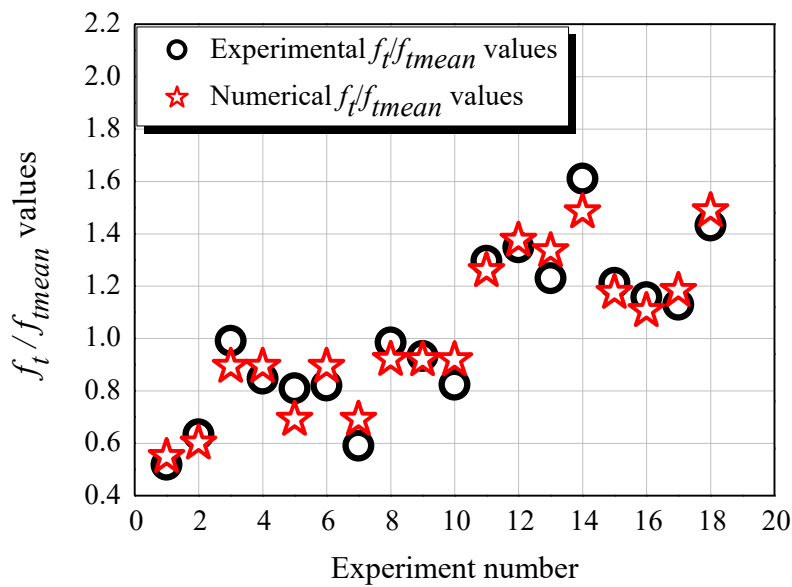


Figure 3. Variation of f_t/f_{tmean} with experiment number for the current study and previous studies

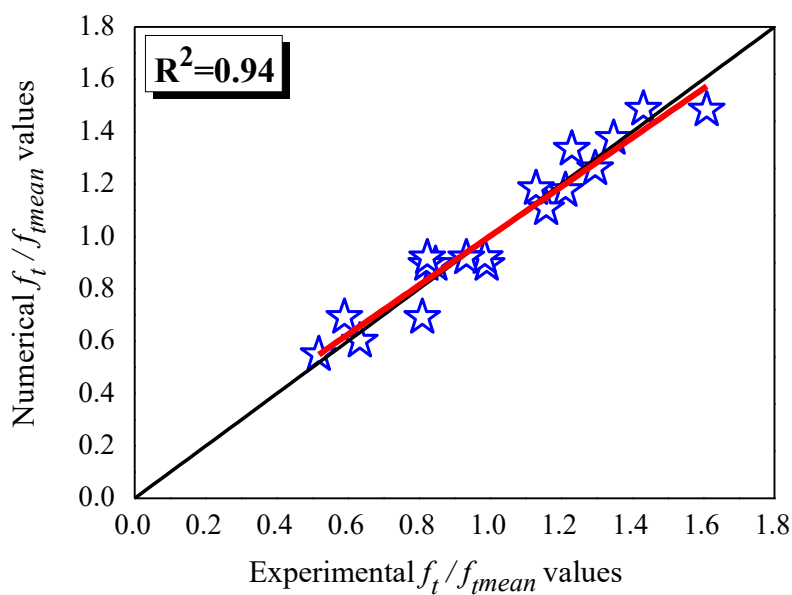


Figure 4. Comparison of experimental and numerical f_t/f_{tmean} values for the current study and previous studies

In Figure 4, the accuracy of Equation (1) is examined by regression analysis. The correlation coefficient was determined as $R^2=0.94$. Experimental results were plotted on the x axis and numerical results were plotted on the y axis. The data seem to be very close to 45° of the perfect line. This indicates that the numerical results are quite compatible with the experimental results. Furthermore, this indicates the availability of Equation (1).

Similarly, with the graph shown in Figure 5, the usability of Equation (1) was emphasized. Because Figure 7 shows the differences between experimental results and numerical results. The differences between -0.11 and +0.14 are observed. In other words, the residual values are very close to the zero axis.

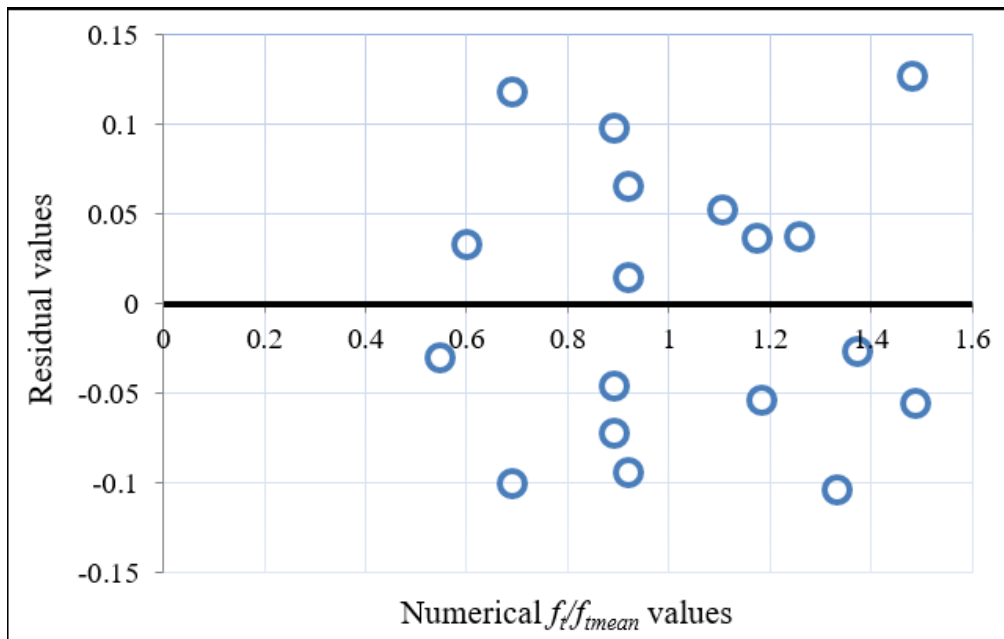


Figure 5. Comparison of numerical and residual f_t/f_{tmean} values for the current study and previous studies

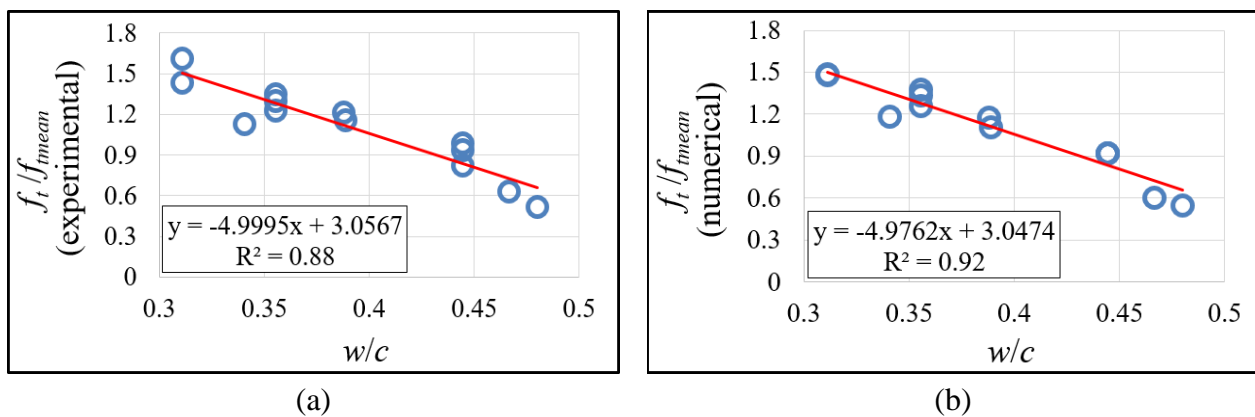


Figure 6. Variation of f_t/f_{tmean} with w/c : a) for the previous experimental studies b) for the current numerical study

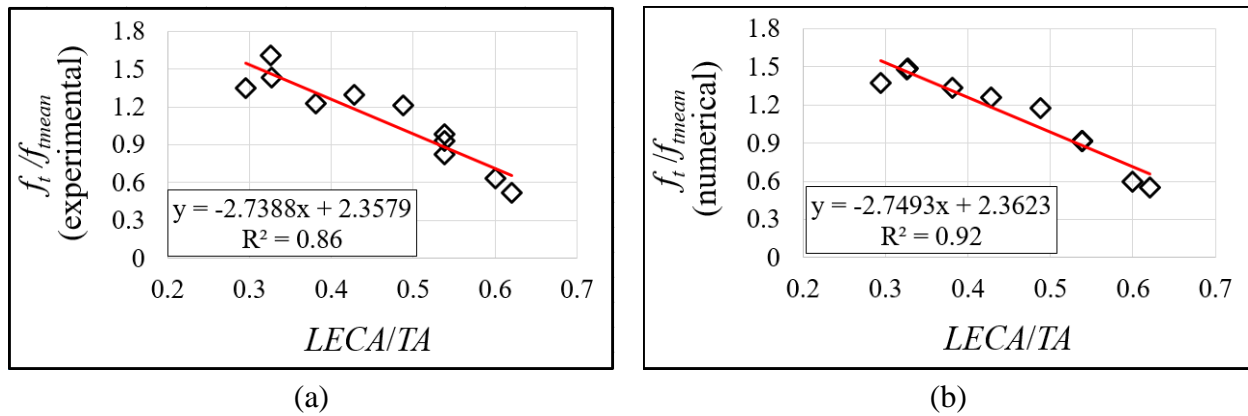


Figure 7. Variation of f_t/f_{mean} with $LECA/TA$: a) for the previous experimental studies b) for the current numerical study

Also, the effect of related dimensionless parameters on tensile strength was investigated in this study. It is known that concrete strength decreases as water cement ratio (w/c) ratio increases [28,29]. As shown in Figure 6, as the “ w/c ” increases, both experimental and numerical “ f_t/f_{mean} ” values decrease. The correlation coefficient for changing the numerical “ f_t/f_{mean} ” values with “ w/c ” was higher, $R^2=0.92$ (Figure 6b). This shows that the numerical results are consistent in this respect.

Since lightweight expanded clay aggregate (LECA) is a lightweight aggregate, it is a type of aggregate that reduces the strength when using it in concrete. When the results of this study are examined, it is seen that “ f_t/f_{mean} ” decreases as “ $LECA/TA$ ” increases (Figure 7). The correlation coefficient was higher ($R^2=0.92$) for the variation of numerical “ f_t/f_{mean} ” values with “ $LECA/TA$ ” (Figure 7b). In this respect, it can be said that the numerical results are compatible.

4. Conclusions

The conclusions of the current numerical study are summarized below:

- In this study, it is thought that the tensile strength results of concrete can be calculated easily and accurately with the developed equation by nonlinear statistical analysis.
- A numerical model has been developed which can be useful for literature and application engineers.
- It is seen that it is possible to design both the preliminary concrete mixture design and the tensile strength of lightweight concrete without any testing.
- It is expected to provide labor, time savings and economic gains with this study.
- The numerical results from this study were found to be consistent with the previous experimental results.

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