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# Formulation of mechanical properties of hybrid fiber alkali-activated concretes by data analysis

## *Hibrit lifli alkali aktivasyonlu betonların mekanik özelliklerinin veri analizi ile formüle edilmesi*

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# Formulation of Mechanical Properties of Hybrid Fiber Alkali-activated Concretes by Data Analysis

## *Highlights*

- *A total of 117 AAC and FAAC cube specimens were produced with steel and polyester fibers*
- *Compressive strength was predicted using non-destructive surface hardness and ultrasonic tests*
- *Existing empirical formulas showed high error rates up to 154% for alkali-activated concretes*
- *New regression-based formulas reduced error to as low as 2.81% for 7 days compressive strength*
- *Combined use of surface hardness and ultrasonic pulse velocity provided the best prediction accuracy*

## *Graphical Abstract*

*The compressive strength of hybrid fiber-reinforced alkali-activated concretes was predicted using non-destructive test methods and new empirical formulas with significantly reduced error rates were developed*

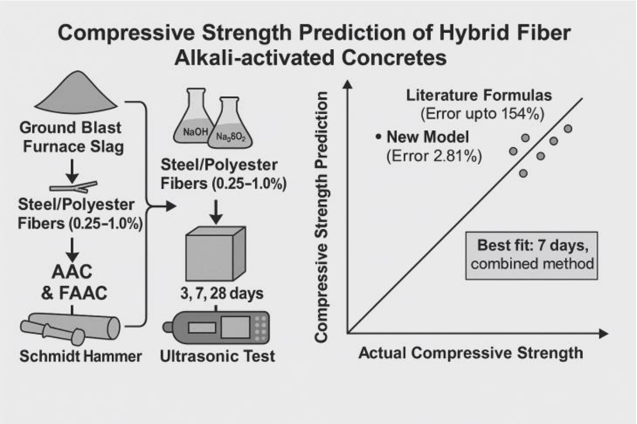


**Figure.** Graphical abstract of compressive strength prediction in fiber-reinforced alkali-activated concretes

## *Aim*

*In this study, the compressive strength of alkali-activated concretes reinforced with steel and polyester fibers was predicted using non-destructive test methods (Schmidt hammer and ultrasonic pulse velocity).*

## *Design & Methodology*

*Concrete specimens containing steel, polyester and hybrid fibers were produced by alkali activation using ground granulated blast furnace slag (GGBFS) and waste volcanic rock dust (RD) as binders. Surface hardness and ultrasonic pulse velocity were measured at three different curing periods (3, 7 and 28 days) and compressive strengths were determined both experimentally and using empirical formulas. New regression-based prediction models were developed and compared with those in the literature.*

## *Originality*

*In this study, the limitations of widely used empirical formulas for predicting the compressive strength of fiber-reinforced alkali-activated concretes using non-destructive test methods were revealed and original regression models with significantly lower error margins were developed for such systems.*

## *Findings*

*The newly developed regression models reduced this margin to as low as 2.81% while the compressive strength predictions made using literature-based empirical formulas yielded error rates ranging from 18% to 154%.*

## *Conclusion*

*This study demonstrated that the newly developed regression models for predicting compressive strength of alkali-activated concretes containing steel and polyester fibers using non-destructive testing methods provide significantly lower error rates compared to empirical formulas in the literature.*

## *Declaration of Ethical Standards*

*The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.*

# Formulation of Mechanical Properties of Hybrid Fiber Alkali-activated Concretes by Data Analysis

*Araştırma Makalesi / Research Article*

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**ABSTRACT**

In this study, ground blast furnace slag (GBFS) and waste volcanic rock dust (RD) produced in a natural stone processing plant were used as binders. The binders were activated with Sodium Hydroxide (NaOH) and Sodium Silicate ($Na_2SiO_3$) to produce two types of concrete: alkali-activated concrete without fibers (AAC) and alkali-activated concrete with fibers (FAAC). In the production of concrete, steel and polyester fibers were used separately and hybrid at 0.25%, 0.50%, 0.75% and 1.0% by volume and a total of 117 15x15x15 cm cube specimens were produced. The mechanical properties of the specimens were evaluated by concrete surface hardness, ultrasonic pulse velocity and concrete compressive strength tests at 3, 7 and 28 days. The results obtained using non-destructive test methods were matched with concrete compressive strength values using various empirical formulas. Calculated concrete compressive strength values and actual concrete compressive strength values were compared using data analysis method. As a result, it was observed that there was a very significant correlation between the experimental compressive strength and the combined method in which 7-day surface hardness and ultrasound transmission rate were used together to calculate the compressive strength.

**Keywords: Data analysis, fiber alkali activated concretes, mechanical properties, non-destructive testing, short curing time.**

# Hibrit Lifli Alkali Aktivasyonlu Betonların Mekanik Özelliklerinin Veri Analizi ile Formüle Edilmesi

**ÖZ**

Bu çalışmada, bir doğal taş işleme tesisinden atık olarak elde edilen volkanik kaya tozu (KT) ve öğütülmüş yüksek fırın cürufu (ÖYFC) bağlayıcı olarak kullanılmıştır. Bağlayıcılar Sodyum Hidroksit (NaOH) ve Sodyum Silikat (Na2SiO3) ile aktive edilerek iki tip beton üretilmiştir: alkalilerle aktive edilmiş lifsiz beton (AAB) ve alkalilerle aktive edilmiş lifli beton (LAAB). Beton üretiminde çelik ve polyester lifler hacimce %0,25, %0,50, %0,75 ve %1,0 oranlarında ayrı ayrı ve hibrit olarak kullanılmış ve toplam 117 adet 15x15x15 cm boyutlarında küp numune üretilmiştir. Numunelerin mekanik özellikleri beton yüzey sertliği, ultrasonik geçiş hızı ve 3, 7 ve 28 günlük beton basınç dayanımı testleri ile değerlendirilmiştir. Tahribatsız test yöntemleri kullanılarak elde edilen sonuçlar, çeşitli ampirik formüller kullanılarak beton basınç dayanımı değerleri ile eşleştirilmiştir. Hesaplanan beton basınç dayanımı değerleri ile gerçek beton basınç dayanımı değerleri veri analizi yöntemi kullanılarak karşılaştırılmıştır. Sonuç olarak, basınç dayanımını hesaplamak için 7 günlük yüzey sertliği ve ultrasonik geçiş hızının birlikte kullanıldığı birleşik yöntem ile deneysel basınç dayanımı arasında çok anlamlı bir korelasyon olduğu görülmüştür.

**Anahtar Kelimeler: Kısa kür süresi, lifli alkali aktivasyonlu betonlar, mekanik özellikler, tahribatsız test, veri analizi.**



## 1. INTRODUCTION

Traditional concrete cannot fulfill its function sufficiently in the rapidly developing world conditions. For this reason, natural and/or artificial materials such as red mud, rice husk ash, palm oil ash, fly ash, blast furnace slag, metakaolin which have aluminosilicate properties as a different binder activated with an activator such as sodium hydroxide, sodium silicate, potassium hydroxide, potassium silicate, etc. in the production of alkaline activated concrete are continuing rapidly. Alkali-activated concrete (AAC) is a polymer composite with an inorganic aluminosilicate content. It is more environmental building material than traditional concrete [1,2]. Alkaline activated concretes are environmentally friendly because of free cement as a binder, resulting in high energy savings and low carbon dioxide emissions. In addition, AAC has many advantegous in mechanical and durability properties [3-5]. AAC is a new generation of building material has superior properties compared to conventional concrete such as low permeability, high temperature resistance, fast curing, produced at low temperatures and improve the long-term shrinkage performance of mortars [6].

Their tensile strength is weak like conventional concrete despite all these superior properties of AAC. Fibers mainly steel and synthetic in various lengths and different shapes are used in order to improve the poor tensile properties of AAC. Many studies to improve the weaknesses of AAC which is developing as an alternative to traditional concrete, especially its tensile strength. The first study made on concretes produced using glass fiber was conducted in 1963. Subsequent studies continued with the use of different fiber types and investigating the properties of the concrete produced. It was revealed that

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steel fibers, which are discontinuously distributed in concrete, significantly reduce crack formation, increase the deformation capacity, toughness, impact and tensile strength of concrete and make it possible to obtain concretes with high ductility [7-14].

Structures above ground and underground are exposed to many natural and/or artificial affects especially earthquake during their lifetime. Many structural problems arise because of these effects. The main source of these problems is the concrete quality. There are many tests to determine the quality of concrete used in buildings around the world and in our country. These test methods are classified as destructive and non-destructive. Concrete coring is the most commonly used destructive method. Concrete test hammer and ultrasonic pulse velocity are the most commonly used methods in non-destructive [15-20]. Non-destructive methods are more preferable since destructive methods may damage the structure in some cases are costly and cannot be repeated. Non-destructive methods are also based on the principle of investigating both construction defects and geometrical-compositional characteristics of structures without damaging the structural element [21]. Non-destructive test methods are divided into two basic groups. The first group is based on the sound transmission properties of concrete. These experiments are based on the determination of the resonant frequency and the speed of sound transmission. Stress wave tests used to determine the thickness of concrete, the voids and cracks in it can also be placed in this category. The second group of experiments is based on surface hardness measurement. These experiments include Schmidt hammer, pull-off, crushing, maturity and combined methods. Some of these methods are not completely non-destructive and cause negligible damage on the concrete surface [22,23]. Ultrasonic pulse velocity and determination of concrete surface hardness with schmidt hammer which are among the non-destructive test methods are providing information about the compressive strength of concretes. In the literature, the compressive strength of concrete is estimated using empirical formulas proposed by using each of the non-destructive methods alone or in combination. However, since all these empirical formulas are given for conventional concrete, there is very limited information on their use in predicting the compressive strength of fibrous concrete produced by the alkali activation method. In this study, the empirical formulas used in the literature for conventional concrete and the new empirical formulas proposed in this study were compared with each other for the prediction of compressive strength of fiber concrete produced by alkali activation method. In addition, the compressive strengths of alkali-activated concretes produced without fibers and with different fiber ratios of steel and polyester fibers separately and hybrids were estimated.

In this study, new formulas for predicting the compressive strength of concrete by utilizing non-destructive testing methods are presented as a result of regression analysis in addition to the empirical formulas given in the literature. Non-destructive test results were subjected to regression analysis and separate formulas were obtained while determining the empirical formulas [24]. Thus, the compressive strengths of steel and polyester fiber substituted alkali-activated concretes were predicted by comparing the empirical formulas proposed in the literature for conventional concrete with the new empirical formulas proposed in this study.

## 2. MATERIAL and METHOD

### 2.1. Binder

Rock dust (RD) obtained as waste from the natural stone processing plant that cuts natural stones and produces coating products such as curbs, paving stones, tiles and ground blast furnace slag (GBFS) from Bolu cement factory were used as binders in the production of alkali-activated fiber concrete. XRF analysis was performed to determine the material properties of GBFS and RD (Table 1). XRD analysis was performed to determine the crystallographic structure of the binder materials (Figure 1).

**Table 1.** XRF analysis (Chemical and physical properties)

| Sample | $SiO_2$ (%) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | CaO (%) | MgO (%) | MnO (%) | $K_2O$ (%) | $Na_2O$ (%) | Density ($g/cm^3$) | Blaine ($cm^2/g$) |
|---|---|---|---|---|---|---|---|---|---|---|
| RD | 42.90 | 10.27 | 18.04 | 10.57 | 10.25 | 0.21 | 0.74 | 1.88 | 2.65 | 2351 |
| GBFS | 41.24 | 20.64 | 7.28 | 25.45 | 2.93 | 0.47 | 0.84 | 1.15 | 2.91 | 5384 |

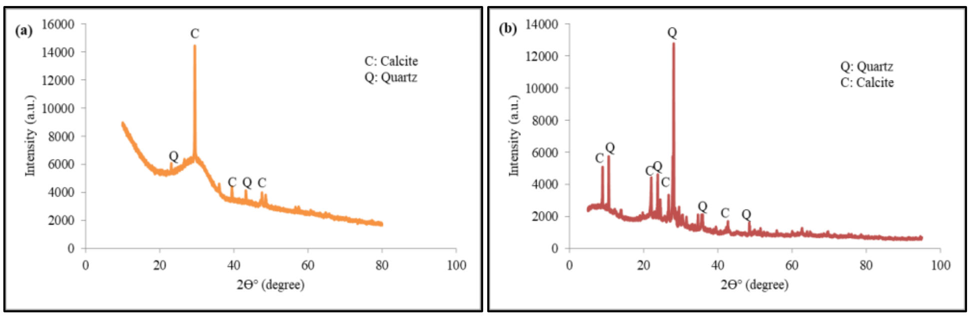


**Figure 1.** XRD patterns of (a) GBFS and (b) RD

### 2.2. Aggregates

Crushed sand in the range of 0-4 mm was used as fine aggregate, crushed stone I in the range of 4-11.2 mm and crushed stone II in the range of 11.2-22.4 mm was used as coarse aggregate in the study. In the granulometry curve obtained with the sieve analysis results, the granulometry curve of the samples showed a behavior very close to the B32 curve is the middle limit in TS 706 EN 12620+A1 [25]. Sieve analysis results were obtained as shown in Figure 2.

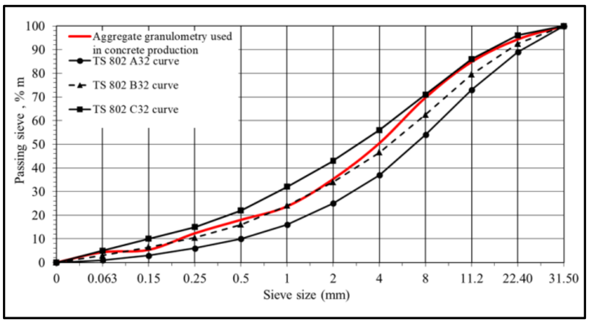


**Figure 2.** Granulometry curve of aggregates used in concrete mixtures

### 2.3. Fibers

Fibers used in FAAC production which are the long polymer fiber has a curved structure with a length of 50 mm and a rectangular cross-section with a cross-sectional area is approximately 0.45 mm$^2$ and the steel fiber is 50 mm long hooked end, with a diameter of 0,9 mm and a circular cross section. Technical properties of the fibers obtained from local producers are given in Table 2.

### 2.4. Alkaline Solution, Superplasticizer and Water

The solution was mixed with water to make 2 liters solution with 800 grams of solid sodium hydroxide at a solution concentration of 10 M. Plasticizer additive, modified polycarboxylate (PCE) is polymer based and has the appearance of light brown liquid. PCE is a liquid with a density of 1.10+0.02 kg/l and is a highly water-reducing/super plasticizing admixture developed for the ready-mixed concrete and precast industry, where early and final high strength and durability are required, to achieve excellent surface appearance. Drinking water was used in the production of AAC and FAAC and there are no unusual substances in it.

**Table 2.** Technical specifications of the fibers used

| Fiber Properties | Steel Fiber | Polyester Fiber |
|---|---|---|
| Length (mm) | 30-60 | 25-50 |
| Width (mm) | - | 0.9 |
| Thickness (mm) | - | 0.5 |
| Diameter (mm) | 0.9 | - |
| Specific mass (g/cm$^3$) | 7.87 | 1.36 |
| Tensile strength (MPa) | ~1100 | 400-800 |
| Modulus of elasticity (MPa) | 200000 | 17237 |
| Ultimate elongation (%) | < 2 | > 8 |

### 2.5. Test Methods

#### 2.5.1. Composite material production

The fibers used in the study were applied as % of the concrete volume and the amount of material in 1 m$^3$ concrete is given in Table 3.

The process applied in conventional concrete production was followed during the production of alkali-activated concrete. The dry mix was poured into the concrete mixer together with the binders in such a way that the aggregates had a saturated dry surface and mixed for about two minutes for a homogeneous mixture. Alkaline activators (NaOH and $Na_2SiO_3$) prepared the day before were added together with the superplasticizer.

**Table 3.** Mix proportion details of AAC and FAAC (1 m$^3$)

| Concrete Type | Binder (GBFS) (kg) | $Na_2SiO_3$ /NaOH | Fiber content (kg) | | SP (kg) | QW (kg) | Aggregate (kg) | | | Water (kg) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | ÇL | PYL | | 0-0.25 (mm) | 0.25-4 (mm) | 4-11.2 (mm) | 11.2-22.4 (mm) | |
| REFERENCE | 350 | 117/58 | - | - | 6 | 400 | 384.8 | 523.2 | 436.1 | 106 |
| SAAC/0.25 | 350 | 117/58 | 19.6 | - | 6 | 400 | 384.8 | 523.2 | 436.1 | 106 |
| SAAC/0.50 | 350 | 117/58 | 39.2 | - | 6 | 400 | 384.8 | 523.2 | 436.1 | 106 |
| SAAC /0.75 | 350 | 117/58 | 58.8 | - | 6 | 400 | 384.8 | 523.2 | 436.1 | 106 |
| SAAC /1.00 | 350 | 117/58 | 78.4 | - | 6 | 400 | 384.8 | 523.2 | 436.1 | 106 |
| PYAAC/0.25 | 350 | 117/58 | - | 3.4 | 6 | 400 | 384.8 | 523.2 | 436.1 | 106 |
| PYAAC /0.50 | 350 | 117/58 | - | 6.8 | 6 | 400 | 384.8 | 523.2 | 436.1 | 106 |
| PYAAC /0.75 | 350 | 117/58 | - | 10.2 | 6 | 400 | 384.8 | 523.2 | 436.1 | 106 |
| PYAAC /1.00 | 350 | 117/58 | - | 13.6 | 6 | 400 | 384.8 | 523.2 | 436.1 | 106 |
| HAAC/0.25 | 350 | 117/58 | 9.8 | 1.7 | 6 | 400 | 384.8 | 523.2 | 436.1 | 106 |
| HAAC /0.50 | 350 | 117/58 | 19.6 | 3.4 | 6 | 400 | 384.8 | 523.2 | 436.1 | 106 |
| HAAC /0.75 | 350 | 117/58 | 29.4 | 5.1 | 6 | 400 | 384.8 | 523.2 | 436.1 | 106 |
| HAAC /1.00 | 350 | 117/58 | 39.2 | 6.8 | 6 | 400 | 384.8 | 523.2 | 436.1 | 106 |

After mixing the alkaline activator and the dry mix for two minutes, the mixer was stopped and the fibers (according to the concrete class planned to be produced) and additional water were mixed for another two minutes. After the mixing was completed, the alkali activated concrete was casting into cube (15x15x15cm) molds (Figure 3).

**Figure 3.** Alkali activated concretes production process

All specimens were demolded after 24 hours and cured in water at a constant temperature of 20 ± 2 °C with a relative humidity above 95% until the designated testing ages (3, 7 and 28 days). Relative humidity in the curing environment was maintained above 95% to minimize moisture loss.

### 2.5.2. Determination of concrete surface hardness using schmidt hammer

Schmidt Hammer test, which is one of the non-destructive tests on hardened AAC and FAAC specimens, was performed on the end of 3, 7 and 28 days curing periods. N type Schmidt hammer was used in the experiment. The Schmidt hammer method was performed by reading the rebound number according to ASTM C805 at 12 different points on any surface not in the casting direction of 3 standard cube specimens of 13 different castings [26].

### 2.5.3. Ultrasonic pulse velocity test

The determination of ultrasonic pulse velocity was performed according to ASTM C597 by taking measurements from 5 different points on any two opposite surfaces of a standard cube sample, not in the casting direction [27].

### 2.5.4. Concrete compressive strength test

The compressive strength of the reference and fiber concrete specimens produced by the activation method at 3, 7 and 28 days were performed in accordance with the principles specified in ASTM C39 standard [28].

### 2.5.5. Determination of concrete compressive strength values using some empirical formulas

Empirical formulas have been used to determine the compressive strength of concrete using non-destructive testing methods in many studies. Kheder has been modeled the compressive strength of concrete with the results of Schmidt concrete test hammer using the formula given in Equation 1 (Equation R-Schmidt) in his study [29]. Qasrawi has been determined the compressive strength of concrete using the empirical formula given in Equation 2 (Equation V-Ultrasonic) in his study by utilizing ultrasonic pulse velocity data [29]. There are many formulas in the literature for the combined method in which the compressive strength of concrete is determined using both the concrete test hammer (schmidt) and the ultrasonic pulse velocity test results. In this study, the formula given in Equation 3 (Equation RV-Combined) was used because of its low mean squared error [22,31-34].

$$f_{cR} = 0.4030 \times R^{1.2083} \quad (1)$$

$$f_{cV} = 1.2 \times 10^{-5} \times V^{1.7447} \quad (2)$$

$$f_{cRV} = 0.745 \times R + 0.951 \times V - 0.544 \quad (3)$$

Where; $f_{cR}$, $f_{cV}$ and $f_{cRV}$ are concrete compressive strength (MPa), $R$ is the concrete surface hardness (rebound number), $V$ is the ultrasonic pulse velocity (km/s).

The mean square error (MSE) formula was calculated using Equation 4 to explain how statistical error values are calculated.

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left( f_{c,\exp,i} - f_{c,calc,i} \right)^2 \quad (4)$$

Where; $f_{c,exp,i}$ is the experimentally measured compressive strength (MPa), $f_{c,calc,i}$ is the calculated/predicted compressive strength (MPa) and $n$ is the number of samples.

In this study, in addition to the empirical formulas given above, new formulas for predicting the compressive strength of concrete by utilizing non-destructive testing methods are presented as a result of regression analysis. Non-destructive test results were subjected to regression analysis and separate formulas were obtained while determining the empirical formulas.

## 3. RESULTS and DISCUSSION

### 3.1. Mechanical Properties

The compressive strength of 3, 7 and 28-day concrete which macro synthetic and steel fiber and reference calculated by empirical formulas and results given by Table 4.

**Table 4.** Compressive strength values calculated experimentally and theoretically

| SAMPLES | | Experimentally compressive strength (MPa) | | | Calculated compressive strength (MPa) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Equation R (Schmidt) | | | Equation V (Ultrasonic) | | | Equation RV (Combined) | | |
| | | 3 days | 7 days | 28 days | 3 days | 7 days | 28 days | 3 days | 7 days | 28 days | 3 days | 7 days | 28 days |
| REFERENCE | | 4.29 | 10.77 | 38.87 | 25.15 | 25.25 | 33.19 | 11.38 | 21.08 | 28.78 | 24.78 | 25.92 | 32.45 |
| SFAAC-0.25 | | 3.90 | 10.31 | 36.88 | 24.36 | 24.75 | 33.61 | 9.96 | 19.26 | 28.86 | 24.00 | 25.37 | 32.75 |
| SFAAC -0.50 | | 4.82 | 12.78 | 44.18 | 23.47 | 25.15 | 34.65 | 13.30 | 21.04 | 30.25 | 23.73 | 25.85 | 33.61 |
| SFAAC -0.75 | | 3.49 | 5.04 | 40.98 | 23.76 | 25.74 | 32.46 | 8.62 | 13.03 | 28.14 | 23.36 | 25.42 | 31.87 |
| SFAAC -1.00 | | 3.37 | 5.96 | 35.22 | 22.49 | 26.04 | 31.74 | 8.77 | 13.58 | 28.01 | 22.41 | 25.72 | 31.34 |
| PYFAAC-0.25 | | 4.29 | 8.62 | 46.60 | 23.67 | 26.75 | 34.13 | 11.43 | 17.96 | 30.56 | 23.67 | 26.73 | 33.27 |
| PYFAAC-0.50 | | 5.73 | 14.97 | 49.64 | 23.18 | 25.05 | 37.83 | 14.65 | 23.28 | 31.00 | 23.67 | 25.98 | 35.91 |
| PYFAAC-0.75 | | 5.65 | 16.56 | 47.70 | 23.96 | 27.35 | 39.75 | 14.51 | 24.00 | 31.42 | 24.27 | 27.77 | 37.29 |
| PYFAAC-1.00 | | 5.92 | 16.09 | 48.45 | 25.74 | 26.14 | 38.15 | 16.07 | 23.14 | 31.24 | 25.78 | 26.80 | 36.16 |
| HFAAC-0.25 | | 4.11 | 12.53 | 47.73 | 23.18 | 25.55 | 35.29 | 13.41 | 21.32 | 29.99 | 23.54 | 26.17 | 34.04 |
| HFAAC-0.50 | | 6.37 | 18.38 | 53.63 | 23.37 | 26.24 | 36.02 | 16.75 | 25.21 | 31.79 | 24.06 | 27.07 | 34.71 |
| HFAAC-0.75 | | 6.82 | 20.88 | 56.58 | 24.45 | 27.75 | 36.55 | 17.64 | 25.63 | 31.40 | 24.98 | 28.22 | 35.06 |
| HFAAC-1.00 | | 6.17 | 19.71 | 54.22 | 25.05 | 26.85 | 35.71 | 14.93 | 24.81 | 29.95 | 25.14 | 27.48 | 34.34 |
| Statistical Property | Min. | 3.37 | 5.04 | 35.22 | 22.49 | 24.75 | 31.74 | 8.62 | 13.03 | 28.01 | 22.41 | 25.37 | 31.34 |
| | Max. | 6.82 | 20.88 | 56.58 | 25.74 | 27.75 | 39.75 | 17.64 | 25.63 | 31.79 | 25.78 | 28.22 | 37.29 |
| | Mean | 4.99 | 13.28 | 46.21 | 23.99 | 26.05 | 35.31 | 13.19 | 21.03 | 30.11 | 24.11 | 26.5 | 34.06 |
| | Std. | 1.17 | 5.05 | 6.72 | 0.92 | 0.92 | 2.35 | 2.96 | 4.12 | 1.3 | 0.89 | 0.92 | 1.76 |

### 3.2. Statistical Analysis

The graph showing the relationship between the theoretical compressive strength values calculated by the empirical formulas given in this study and the experimentally compressive strength values obtained from the uniaxial compressive strength test is given in Figure 4, Figure 5 and Figure 6 for all curing times (3, 7 and 28 days) respectively.

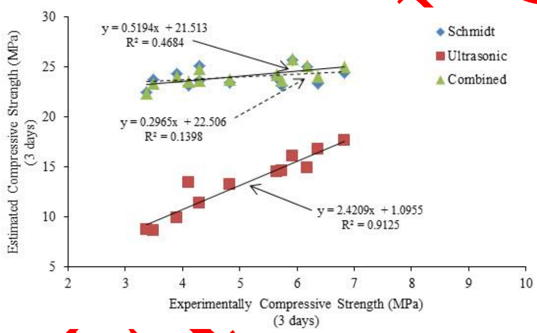


**Figure 4.** Relationship between theoretically and experimentally compressive strengths (3 days)

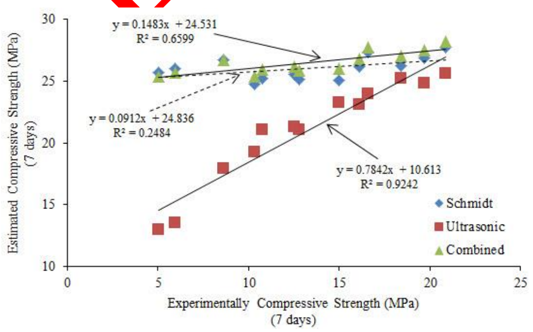


**Figure 5.** Relationship between theoretically and experimentally compressive strengths (7 days)

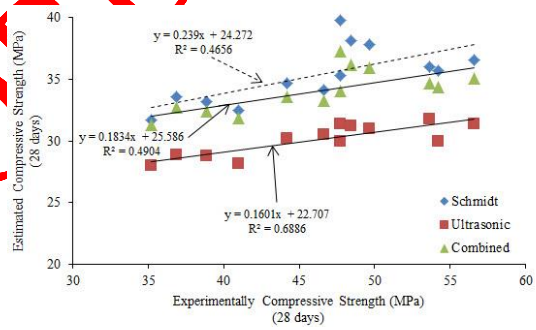


**Figure 6.** Relationship between theoretically and experimentally compressive strengths (28 days)

The average error percentages calculated between the experimental results and the compressive strength values obtained using empirical formulas are given in Table 5.

**Table 5.** Mean square error rates and correlations

| Curing time (day) | Mean error (%) | | | Correlation coefficients | | |
|---|---|---|---|---|---|---|
| | $f_{cR}$ | $f_{cV}$ | $f_{cRV}$ | $f_{cR}$ | $f_{cV}$ | $f_{cRV}$ |
| 3 | 20.72 | 153.43 | 24.10 | 0.468 | 0.912 | 0.139 |
| 7 | 81.70 | 18.42 | 81.75 | 0.248 | 0.924 | 0.659 |
| 28 | 64.98 | 80.70 | 73.80 | 0.465 | 0.688 | 0.490 |

When Table 5 is examined the average error percentages were quite high (between 18% and 154%) in the prediction of compressive strengths of reference and fibrous alkali-activated concretes with the empirical formulas given in the literature. The lowest average percentage error of 18.42% was obtained with the formula in Equation 2 using the ultrasonic pulse velocity. Thus, it was seen that the percentage error values were quite high considering the concrete compressive strength values and thus, the use of fiber alkali activated concrete in the prediction of compressive strengths would cause high error rates. The compressive strength values obtained for different curing times using the formulas recommended in the literature and the graphs matching the experimental compressive strength values are given in Figure 7, Figure 8 and Figure 9, respectively.

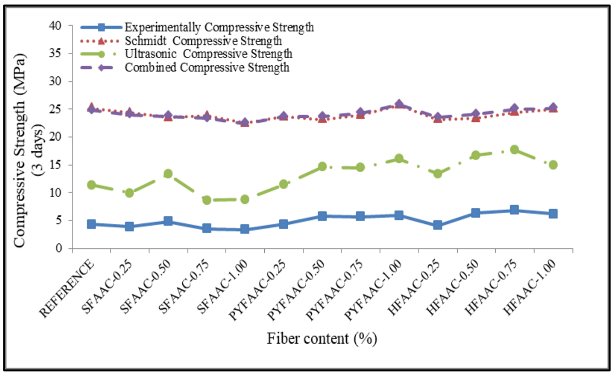


**Figure 7.** Matching graph of experimentally compressive strength and estimated compressive strengths (3 days)

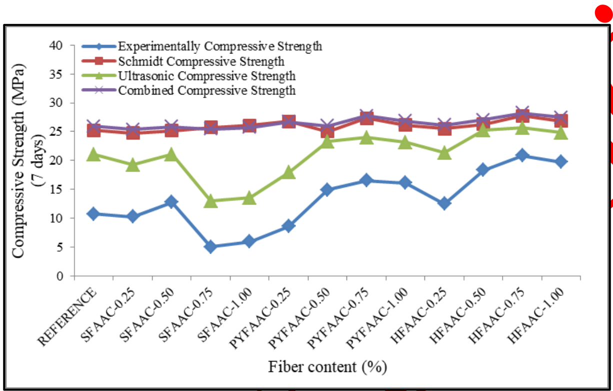


**Figure 8.** Matching graph of experimentally compressive strength and estimated compressive strengths (7 days)

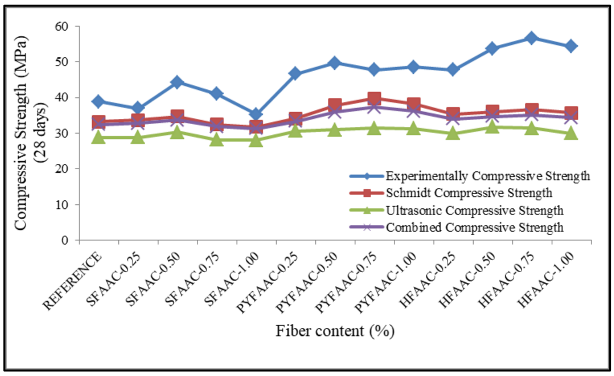


**Figure 9.** Matching graph of experimentally compressive strength and estimated compressive strengths (28 days)

### 3.3. New Prediction Models Development Based on Regression Analyses

This section presents the development of new prediction models for compressive strength estimation in fiber-reinforced alkali-activated concretes. The models were derived from the experimental dataset generated within the scope of this study aiming to overcome the limitations of existing empirical equations for such materials. The regression equations presented herein were developed directly from the compressive strength, Schmidt rebound number and ultrasonic pulse velocity data obtained in the experimental program of this study. All regression analyses were performed using IBM SPSS statistics 26 software. In this study, statistical analysis was carried out by using the non-destructive test results obtained at different curing times (3, 7 and 28 days) on samples prepared with different fiber types and fiber ratios (0.25%, 0.50%, 0.75% and 1.0%) with reference and the following empirical formulas were obtained. Prediction of compressive strength of reference and fiber alkali activated concretes using Schmidt hammer only;

$$f_{cR} = a + b * R \tag{5}$$

formula is used. Where; $f_{cR}$ is the compressive strength (MPa), $R$ is the rebound number, $a$ and $b$ are statistical constants. Statistical analysis results for different curing times are given in Table 6.

**Table 6.** Regression analysis results based on Schmidt hammer test data depending on curing times

| Curing time | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 3 days | | | 7 days | | | 28 days | | |
| r | $r^2$ | Adjusted $r^2$ | r | $r^2$ | Adjusted $r^2$ | r | $r^2$ | Adjusted $r^2$ |
| 0.374 | 0.140 | 0.062 | 0.498 | 0.248 | 0.179 | 0.685 | 0.469 | 0.421 |
| Constants | Coefficients | Standard Error | Constants | Coefficients | Standard Error | Constants | Coefficients | Standard Error |
| a | -8.706 | 10.236 | a | -72.373 | 45.035 | a | -37.368 | 26.815 |
| b | 0.466 | 0.348 | b | 2.719 | 1.429 | b | 2.063 | 0.661 |

Prediction of compressive strength of reference and fibrous alkali activated concretes using Ultrasound velocity only;

$$f_{cV} = a + b * V \quad (6)$$

formula is used. Where; $f_{cV}$ is the compressive strength (MPa), $V$ is the ultrasonic pulse velocity (km/s), $a$ and $b$ are statistical constants. Statistical analysis results for different curing times are given in Table 7.

**Table 7.** Regression analysis results based on ultrasonic pulse velocity test data depending on curing times

| Curing time | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 3 days | | | 7 days | | | 28 days | | |
| r | $r^2$ | Adjusted $r^2$ | r | $r^2$ | Adjusted $r^2$ | r | $r^2$ | Adjusted $r^2$ |
| 0.950 | 0.903 | 0.895 | 0.952 | 0.907 | 0.898 | 0.834 | 0.695 | 0.668 |
| Constants | Coefficients | Standard Error | Constants | Coefficients | Standard Error | Constants | Coefficients | Standard Error |
| a | -3.364 | 0.831 | a | -27.045 | 3.919 | a | -176.158 | 44.402 |
| b | 2.911 | 0.287 | b | 10.722 | 1.035 | b | 47.820 | 9.546 |

Both ultrasound velocity values and Schmidt's hammer and surface hardness results were used together to predict the compressive strength of reference and fibrous alkali-activated concretes;

$$f_{cRV} = a + b * R + c * V \quad (7)$$

formula is used. Where; $f_{cRV}$ is the compressive strength (MPa), $R$ is the rebound number, $V$ is the ultrasonic pulse velocity (km/s), $a$, $b$ and $c$ are statistical constants. Statistical analysis results for different curing times are given in Table 8.

**Table 8.** Regression analysis results based on combined method (Schmidt hammer + ultrasonic pulse velocity) depending on curing times

| Curing time | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 3 days | | | 7 days | | | 28 days | | |
| r | $r^2$ | Adjusted $r^2$ | r | $r^2$ | Adjusted $r^2$ | r | $r^2$ | Adjusted $r^2$ |
| 0.953 | 0.908 | 0.889 | 0.972 | 0.945 | 0.934 | 0.837 | 0.700 | 0.640 |
| Constants | Coefficients | Standard Error | Constants | Coefficients | Standard Error | Constants | Coefficients | Standard Error |
| a | -5.848 | 3.520 | a | -59.617 | 12.849 | a | -191.065 | 59.354 |
| b | 2.838 | 0.310 | b | 9.957 | 0.886 | b | 54.633 | 19.713 |
| c | 0.092 | 0.126 | c | 1.125 | 0.430 | c | -0.414 | 1.035 |

The graphs showing the relationships between the compressive strength values calculated with the empirical formulas obtained as a result of the regression analysis and the experimental compressive strengths are given in Figure 10, Figure 11 and Figure 12 for each curing period, respectively.

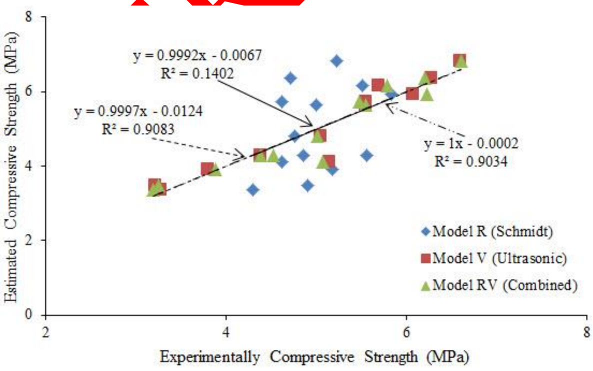


**Figure 10.** Relationship between calculated compressive strengths and experimentally compressive strengths (3 days)

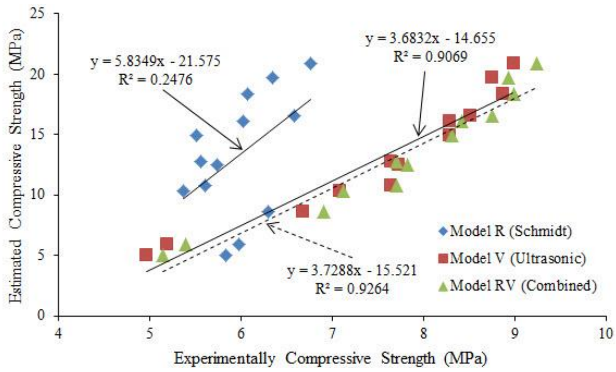


**Figure 11.** Relationship between calculated compressive strengths and experimentally compressive strengths (7 days)

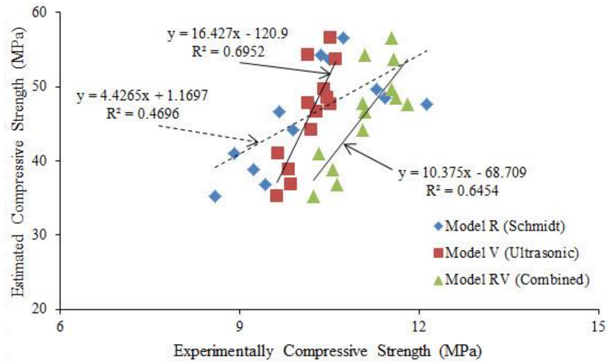


**Figure 12.** Relationship between calculated compressive strengths and experimentally compressive strengths (28 days)

The average error percentages calculated between the experimental results and the compressive strength values obtained using the empirical formulas developed are given in Table 9.

**Table 9.** Mean square error rates and correlations

| Curing time (day) | Mean error (%) | | | Correlation coefficients | | |
|---|---|---|---|---|---|---|
| | $f_{cR}$ | $f_{cV}$ | $f_{cRV}$ | $f_{cR}$ | $f_{cV}$ | $f_{cRV}$ |
| 3 | 62.53 | 4.95 | 4.67 | 0.140 | 0.903 | 0.908 |
| 7 | 50.24 | 4.76 | 2.81 | 0.247 | 0.906 | 0.926 |
| 28 | 31.46 | 16.62 | 16.33 | 0.469 | 0.695 | 0.645 |

When Table 9 is examined, the mean error percentages in the prediction of the compressive strengths of the reference and fibrous alkali-activated concretes with the empirical formulas developed in this study were between 2% and 63%. The lowest mean error percentage of 2.81% was obtained with the formula in Equation 6 which was suggested by using the ultrasonic pulse velocity and Schmidt hammer values together (Combined Method). The graphs where the compressive strength values calculated using the empirical formulas proposed in this study are matched with the experimentally compressive strength values for different curing times are given in Figure 13, Figure 14 and Figure 15, respectively.

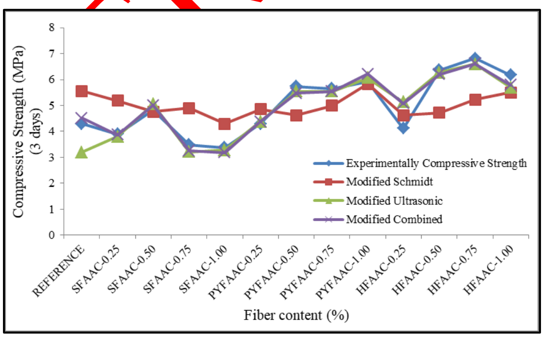


**Figure 13.** Matching graph of experimentally compressive strength and modified theoretically compressive strengths (3 days)

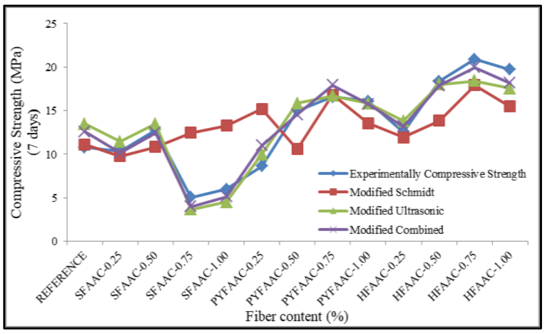


**Figure 14.** Matching graph of experimentally compressive strength and modified theoretically compressive strengths (7 days)

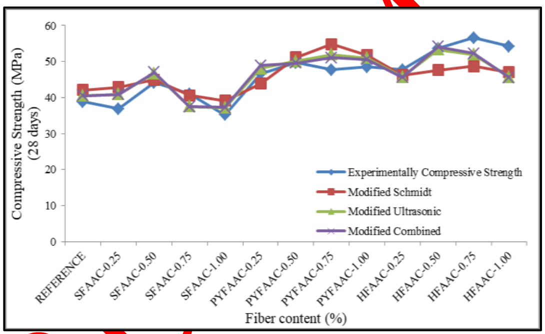


**Figure 15.** Matching graph of experimentally compressive strength and modified theoretically compressive strengths (28 days)

In addition, a comparative analysis of the mean error percentages and correlation coefficients (r) between the newly developed regression formulas (Equations 5–7) and the literature-based formulas (Equations 1–3) is presented graphically in Figure 16, Figure 17 and Figure 18, respectively.

The comparative analysis of the developed regression models for 3, 7 and 28-day curing periods revealed that the Equation V-Model V consistently achieved the highest correlation with experimental compressive strength values ($R^2 \geq 0.997$) across all ages while the Equation RV-Model RV and Equation R-Model R exhibited lower correlation coefficients, particularly at early ages ($R^2 = 0.516$ and $R^2 = 0.5642$ for 3 and 7 days, respectively). At 28 days, all models demonstrated strong correlations ($R^2 \geq 0.9149$) with the Equation R-Model R achieving a perfect fit ($R^2 = 1.0$) indicating that the predictive accuracy of the regression equations improved significantly with curing time.

The comparison of both approaches revealed that in the literature-based equations, UPV provided the lowest error for 7-day predictions while Schmidt showed relatively better performance at 3 and 28 days; in contrast, the combined R–V approach achieved the highest accuracy across all ages offering the lowest average error particularly at 7 days (2.81%) in the developed models.

Similarly, the compressive strength of high-temperature-treated concrete was successfully predicted using fuzzy logic and regression methods in the study conducted by Durmuş and Can [35].

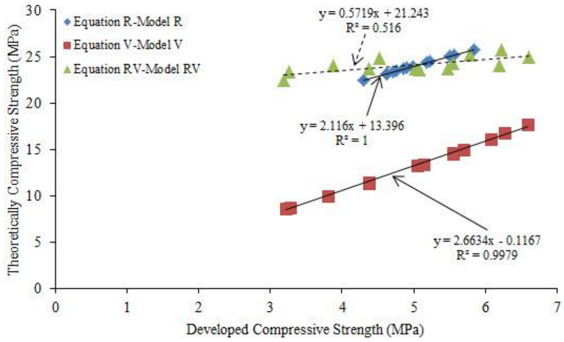


**Figure 16.** Relationship between theoretically compressive strengths and developed compressive strengths (3 days)

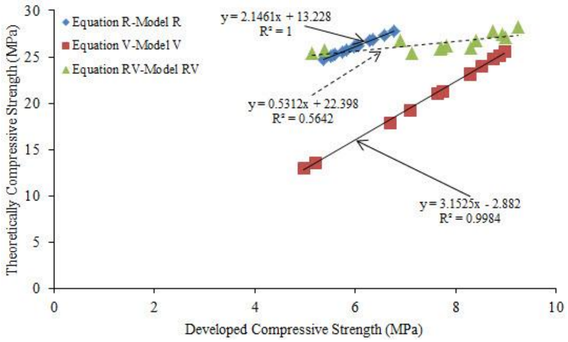


**Figure 17.** Relationship between theoretically compressive strengths and developed compressive strengths (7 days)

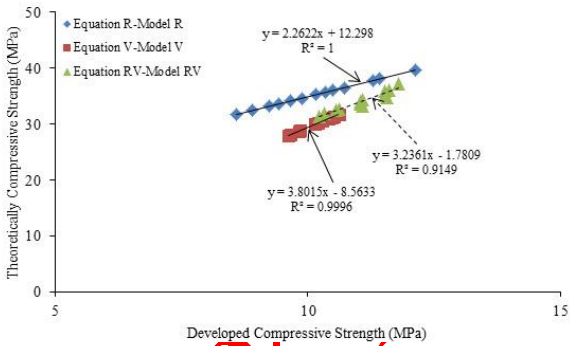


**Figure 18.** Relationship between theoretically compressive strengths and developed compressive strengths (28 days)

## 4. CONCLUSION

AAC and FAAC were produced by using rock dust, a quarry waste material with pozzolan properties, as binder by alkali activation method, the compressive strengths of concrete specimens obtained by using different ratios of fiber in concrete at different curing times were estimated by using non-destructive test methods in this study. Based on the data obtained from the experiments, the results obtained from concretes containing different ratios of fiber by volume and with different curing times are as follows;

- The error rates (between 18% and 154%) in concrete compressive strength estimation with empirical formulas in the literature given in Equations 1-3 are quite high,
- In the concrete compressive strength prediction obtained from the empirical formula (Model R) using only the surface hardness, the average error percentage was 31.46%, especially in the 28-day curing period of concrete,
- In the concrete compressive strength prediction obtained from the empirical formula (Model V) developed by using only the ultrasonic transmission rate data, the average error percentage was 4.95%, especially in the 3-day curing period which is the early age strength of concrete,
- In the concrete compressive strength prediction obtained from the empirical formula (Model RV) developed by using both surface hardness and ultrasound transmission rate data together, the average error percentage is very low (2.81%), especially in the 7-day curing period when the concrete gains 70-75% of its strength,
- It was concluded that the error rates between the empirical formulas proposed in the literature and the formulas developed in this study were significantly lower in the developed formulas when all curing times were taken into account and that the proposed empirical formulas can be used in the prediction of AAC and FAACs, especially in the prediction of 7-day concrete compressive strength.

## DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

## AUTHORS' CONTRIBUTIONS

**Yavuz Selim AKSÜT:** Research, methodology, writing - revising and editing.

**Şükrü YETGİN:** Supervision, funding.

## CONFLICT OF INTEREST

There is no conflict of interest in this study

## REFERENCES

[1] Almashhadani M.M., Canpolat O., Aygörmez Y., Uysal M. and Erdem S., "Mechanical and microstructural characterization of fiber reinforced fly ash based geopolymer composites", ***Construction and Building Materials***, 167: 505-513, (2018).

[2] Kenneth M.M.A., MacKenzie J.D. and Keyzers R.A., "Porous aluminosilicate inorganic polymers (geopolymers): a new class of environmentally benign heterogeneous solid acid catalysts", ***Applied Catalysis A: General***, 524: 173-181, (2016).

[3] Jamieson E., McLellan B., Riessen A. and Nikraz H., "Comparison of embodied energies of Ordinary Portland Cement with Bayer-derived geopolymer products", ***Journal of Cleaner Production***, 99: 112-118, (2015).

[4] Li Z. and Li S., “Carbonation resistance of fly ash and blast furnace slag based geopolymer concrete”, ***Construction and Building Materials***, 163: 668-680, (2018).

[5] Aksüt Y.S., Çullu M. and Yetgin Ş., “Optimal ratio of steel and polyester fibers on the mechanical behavior of alkali-activated concrete produced by industrial waste minerals”, ***Iranian Journal of Science and Technology, Transactions of Civil Engineering***, (2025).

[6] Duxson P., Provis J.L., Lukey G.C. and van Deventer J.S.J., “The role of inorganic polymer technology in the development of green concrete”, ***Cement and Concrete Research***, 37: 1590-1597, (2007).

[7] İpek M. and Aksu M., “The effect of different types of fiber on flexure strength and fracture toughness in SIFCON”, ***Construction and Building Materials***, 214: 207-218, (2019).

[8] Karilhaloo B.L., “***Fracture Mechanics and Structural Concrete***”, Longman Group Ltd., Essex, England, (1995).

[9] Khale D. and Chaudhary R., “Mechanism of geopolimerization and factors influencing its development: a review”, ***Materials Science***, 42: 729-746, (2007).

[10] Natali A., Manzi S. and Bignozzi M.C., “Novel fibre reinforced composite materials based on sustainable geopolymer matrix”, ***Procedia Engineering***, 21: 1124-1131, (2011).

[11] Ranjbar N., et al., “Mechanisms of interfacial bond in steel and polypropylene fiber reinforced geopolymer composites”, ***Composites Science and Technology***, 122: 73-81, (2016).

[12] Wang Y., Hu S. and He Z., “Mechanical and fracture properties of geopolymer concrete with basalt fiber using digital image correlation”, ***Theoretical and Applied Fracture Mechanics***, 112: 102909, (2021).

[13] Wang Z., Bai E., Huang H., Liu C. and Wang T., “Dynamic mechanical properties of carbon fiber reinforced geopolymer concrete at different ages”, ***Ceramics International***, 49: 834-846, (2023).

[14] Yıldız S., Bölükbaş Y. and Keleştemur O., “The effect of glass fiber reinforcement on the compressive and tensile strength of concrete”, ***Jornal of Polytechnic***, 13(3): 239–243, (2010).

[15] Cui L. and Fall M., “Mechanical and thermal properties of cemented tailings materials at early ages: influence of initial temperature, curing stress and drainage conditions”, ***Construction and Building Materials***, 125: 553-563, (2016).

[16] Erdoğan T.Y., “***Concrete***”, METU Development Foundation Publishing and Communication, Ankara, Turkey, (2003).

[17] Libos I.L.S. and Cui L., “Effects of curing time, cement content, and saturation state on mode-I fracture toughness of cemented paste backfill”, ***Engineering Fracture Mechanics***, 235: 107174, (2020).

[18] Libos I.L.S., Cui L. and Liu X., “Effect of curing temperature on time-dependent shear behavior and properties of polypropylene fiber-reinforced cemented paste backfill”, ***Construction and Building Materials***, 311: 125302, (2021).

[19] Mehta P.K., “***Concrete: Structure, Properties, and Materials***”, Prentice-Hall, Englewood, NJ, USA, (1986).

[20] Neville A.M., “***Properties of Concrete***”, Pearson Education Limited, England, (2006).

[21] Yazıcı S., Göktepe A.B., Altun S. and Karaman V., “An evaluation on TS-10465 and TS EN 12504-1 for determination of compressive strength of hardened concrete”, ***DEÜ Faculty of Engineering Journal of Science and Engineering***, 8(1): 119-128, (2006).

[22] Erdal M. and Şimşek O., “Investigation of the performance of some nondestructive test methods in determination of compressive strength of vacuum treated concrete”, ***Journal of Gazi University Faculty of Engineering and Architecture***, 21(1): 65-73, (2006).

[23] Yüksel I., “Determination of concrete strength by compound non-destructive concrete tests and its application in a reinforced concrete structure”, Master's Thesis, Yıldız Technical University, Institute of Science and Technology, Istanbul, (1995).

[24] Subaşı S., Çullu M., Bolat H., Emiroğlu M. and Erdal M., “Determination of engineering properties of fly ash substituted concretes by non-destructive test methods”, ***Engineering Sciences***, 5(3): 494-506, (2010).

[25] TS 706 EN 12620, “Concrete aggregates”, Turkish Standards Institute, Ankara, (2003).

[26] ASTM C805, “Standard test method for rebound number of hardened concrete”, ASTM, U.S.A., (2019).

[27] ASTM C597-22, “Standard test method for ultrasonic pulse velocity through concrete”, ASTM, U.S.A., (2023).

[28] ASTM C39-21, “Standard test method for compressive strength of cylindrical concrete specimens”, ASTM, U.S.A., (2021).

[29] Kheder G.F., “A two stage procedure for assessment of in-situ concrete strength using combined non-destructive testing”, ***Materials and Structures***, 32: 410-417, (1998).

[30] Qasrawi H.Y., “Concrete strength by combined nondestructive methods simply and reliable predicted”, ***Cement and Concrete Research***, 30: 739-746, (2000).

[31] Erdal M., “Determination of concrete compressive strength by some nondestructive test methods”, Master's Thesis, Gazi University, Institute of Science and Technology, Ankara, (2002).

[32] Kalaycı S., “***SPSS applied multivariate statistical techniques***”, Asil Publication Distribution Company, 3rd Edition, Ankara, (2008).

[33] Tanigawa Y., Baba K. and Mori H., “Estimation of concrete strength by combined nondestructive testing method”, ***ACI SP***, 82(1): 57-65, (1984).

[34] Şimşek B. and Uygunoğlu T., “Multi-response optimization of ultrasound velocity and dynamic modulus of elasticity of concrete containing polymeric wastes”, ***Jornal of Polytechnic***, 20(4): 1009–1017, (2017).

[35] Durmuş G. and Can Ö., “Prediction of compressive strength of high-temperature-treated admixture concrete using fuzzy logic and regression methods”, ***Jornal of Polytechnic***, 12(3): 195–200, (2009).