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Correlation Between Tensile and Compressive Strength of Concretes Incorporating Calcined Crude Kaolin and High Purity Metakaolin

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Abstract

In this study, an experimental program was conducted to evaluate the relation between splitting and compressive strength of high performance concretes modified with different types of calcined kaolins (CKs) and metakaolin (MK). CKs were obtained by heat treatment of crude Turkish kaolins while MK was obtained from high purity Czech kaolin. Four replacement levels from 0 to 20% of total cement content were used to evaluate the effectiveness of the mineral admixtures. Water to binder ratio of 0.4, total binder content of 350 kg/m^3, four types of CKs and one type MK were used in concrete mixture proportioning. Considering one control mix, a total of 21 concrete mixtures were cast. The compressive and tensile strength at 28 and 90 days of moist curing were measured and compared. In the experimental program, the cubic specimens having the dimension of 150 mm and the cylindrical specimens with the size of φ100x200 mm were used for the compressive and splitting tensile strength tests respectively. However, in order to correlate the data, the conversion coefficients were utilized to obtain the equivalent strengths of standard cylindrical specimens. The experimental results indicated that there are favorable strength enhancements at 28 and 90 days of curing. Moreover, the correlation of the data demonstrates that there is a relatively good agreement as compared with the literature approaches presented to analyze the relationship between splitting and compressive strength of concrete.

Keywords: Calcined Kaolin; Correlation; Metakaolin; Strength

Yüksek Saflıktaki Metakaolen ve Kalsine Ham Kaolen İçeren Betonların Çekme ve Basınç Dayanımları Arasındaki Korelasyon

Özet

Bu çalışmada farklı kalsine kaolen (KK) ve metakaolen (MK) katkıları ile oluşturulmuş yüksek performanslı betonların yarmada çekme ve basınç dayanımları arasındaki ilişkiyi değerlendirmek üzere bir deney programı yürütülmüştür. KK'ler ham Türkiye kaolenlerinin ısıl işlemi ile, MK ise yüksek saflıkta Çek kaoleninden elde edilmiştir. Mineral katkıların etkinliğini değerlendirmek için, toplam çimento içeriğinin % 0 ila % 20'si arasında dört ikame seviyesi kullanılmıştır. Beton karışımı hesaplarında su/bağlayıcı oranı 0.4, toplam bağlayıcı içeriği 350 kg/m^3, dört tip KK ve bir tip MK kullanılmıştır. Biri kontrol karışımı olmak üzere toplam 21 beton karışımı dökülmüştür. Islak kürleme uygulanan betonların 28 ve 90 günlük basınç ve çekme dayanımları ölçülmüş ve karşılaştırılmıştır. Deney programında, 150 mm boyutlu kübik numuneler ve ϕ100x200 mm boyutlu silindirik numuneler sırasıyla basınç ve yarmada çekme dayanım testleri için kullanılmıştır. Bununla birlikte, elde edilen verilerin korelasyonunu sağlamak için standart silindirik numunelerin eşdeğer dayanımlarını elde etmek amacıyla dönüşüm katsayıları kullanılmıştır. Deneysel sonuçlar, 28 ve 90 günlük kürlemede dayanımda iyileşme olduğunu göstermiştir. Bunun yanısıra, verilerin korelasyonu, betonun yarmada çekme ile basınç dayanımı arasındaki ilişkiyi analiz etmek için sunulan literatür yaklaşımlarıyla iyi bir uyum olduğunu göstermiştir.

Anahtar kelimeler: Kalsine Kaolen; Korelasyon; Metakaolen; Dayanım

1. Introduction

Since cement is one of the most consumed materials in the construction industry, the amount of carbon dioxide emitted to the atmosphere during production is considerably high [1]. Considering the effect of this undesirable situation, a number of studies have been carried out to produce alternative materials to replace a part of the cement in concrete. Metakaolin which is a mineral admixture like fly ash and silica fume has been used due to its satisfactory pozzolanic reactivity related to the properties of raw materials involved. [2, 3]. As a result of the fact that metakaolin can be used at different rates with different pozzolanic materials under various conditions, its effect on concrete properties have still been investigated to determine optimum values [4-6]. Metakaolin is different from the other mineral mixtures due to production process [7]. While mineral additives are either obtained naturally or are industrial wastes, metakaolin is obtained by treating the pure clay at about 450-650 ^{o}C for a specified time for complete removal of the bound water [8]. As a result of this process, an amorphous aluminosilicate is generated. The specific surface area of metakaolin is similar to silica fume and it is in the range from 5 to 25 m^2/g. While the density of the material is about 2,5 g/cm^3, an average grain size is less than 2 µm. The composition of metakaolin is approximately formed by 50-55% SiO_2 and 40-45% Al_2O_3 [9]. By using metakaolin in concrete mixtures, $Ca(OH)_2$, a by-product resulting from cement hydration reacts with metakaolin and the favorable secondary CSH gel structure is formed. By this way, durability characteristics of concrete is improved by consumption of the unwanted phase $Ca(OH)_2$.

Kaolin is an industrial raw material mainly composed of kaolinite minerals which is formed as a result of in situ degradation of alkaline magmatic rocks [10,11]. The chemical composition of kaolin is 46.54% SiO_2, 39.50% Al_2O_3 and 13.96% H_2O [12]. Turkey's kaolin deposit is around 100 million tonnes, and the operationally-visible reserves are around 35 million tons. Due to the fact that there are different geological formation conditions, economical feasibility, location, quality, origin and mineralogical-geochemical properties, there is a wide range of beneficiation field for this material. These are the basic factors affecting the exploitation of unprocessed kaolin [13]. While minor amount of the kaolins produced in Turkey is used in the cement sector, the major part is benefited in the ceramics manufacture, glass, filling, rubber-paint sectors etc. Through calcination process kaolin is converted to metakaolin. Metakaolin is also known as calcined kaolin which has broadly been studied since the mids of 1990‘s for improving the mechanical and durability properties of concrete [14].

In this study, an experimental program on the concretes that include different calcined crude kaolins and metakaolin as a partial replacement for cement was carried out and the correlations between compressive and splitting tensile strength of concrete mixtures were determined.

2. Materials and Mix Properties for Experimental Study

2.1. Materials

2.1.1. Cement

For preparing the concrete mixes for mechanical testing CEM I 42.5 R type portland cement was utilized. Specific gravity and Blaine fineness of the cement are 3.14 and 327 m^2/kg respectively. The chemical composition of the cement is shown in Table 1.

Table 1. Chemical composition of the cement

Chemical composition of the cement (%)								
CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	LOI
62.58	20.25	5.31	4.04	2.82	2.73	0.92	0.22	1.02

2.1.2. Calcined Kaolins and Commercial Metakolin

Kaolins utilized in this experimental study were obtained from deposits in Turkey. Four deposits which have different geological formations were focused in the study. Kaolins taken from different cities investigated in this study are designated as Balıkesir kaolin (DV and DC), Çanakkale kaolin (CC) and Bursa kaolin (BMK). Because of the fact that almost half of the kaolin deposits in Turkey are located in Balıkesir city, two kinds of kaolins (DV and DC) from different areas located in this city were examined.

On the other hand, kaolins taken from Bursa and Çanakkale cities were also investigated to understand the influence of mineralogy and chemical composition. The chemical properties and experimental codes of the kaolins utilized in this experimental investigation are illustrated in Table 2. To determine the convenient temperature for calcination process seven heat treatment levels (550, 600, 650, 700, 750, 800 and 850 ^{0}C) were implemented to the Turkish kaolin samples.

Commercial metakaolin (MK) which is a white material with a Dr Lange whiteness value of 87 was used as reference. Metakaolin has a specific surface area of 18000 m^2/kg and specific gravity of about 2.60. Physical and chemical properties of MK supplied from Czech Republic are also shown in Table2.

Table 2. Chemical, physical and mineralogical properties of the calcined Turkish kaolins and commercial metakaolin (MK)

	Item	DV	DC	BMK	CC	MK
Chemical properties	CaO (%)	2.22	3.07	2.42	1.86	0.5
	SiO_2 (%)	69.78	77.7	59.9	68.19	53
	Al_2O_3 (%)	24.16	16.04	29.32	25.58	43
	Fe_2O_3 (%)	0.69	1.01	0.43	1.32	1.2
	MgO (%)	0.89	0.78	1.07	0.95	0.4
	TiO_2 (%)	0.49	0.36	0.88	0.50	0.8
	LOI (%)	0.73	0.50	0.5	0.65	0.4
Physical properties	Specific gravity	2.60	2.64	2.67	2.55	2.60
	Fineness (cm^2/g)	73400	64500	74300	44500	180000

2.1.3. Aggregates

Fine sand used for production of concrete specimens is the mixture of crushed and natural river sand with specific gravities of 2.42 and 2.66 respectively. Besides, two kind of coarse aggregates namely, No I (4-16 mm) and No II (16-22 mm) were used. The grading of the aggregates was kept constant for concrete production. Figure 1 illustrates the gradation curves of the each aggregate and aggregate mixture in comparison to reference curves (A32, B32, C32).

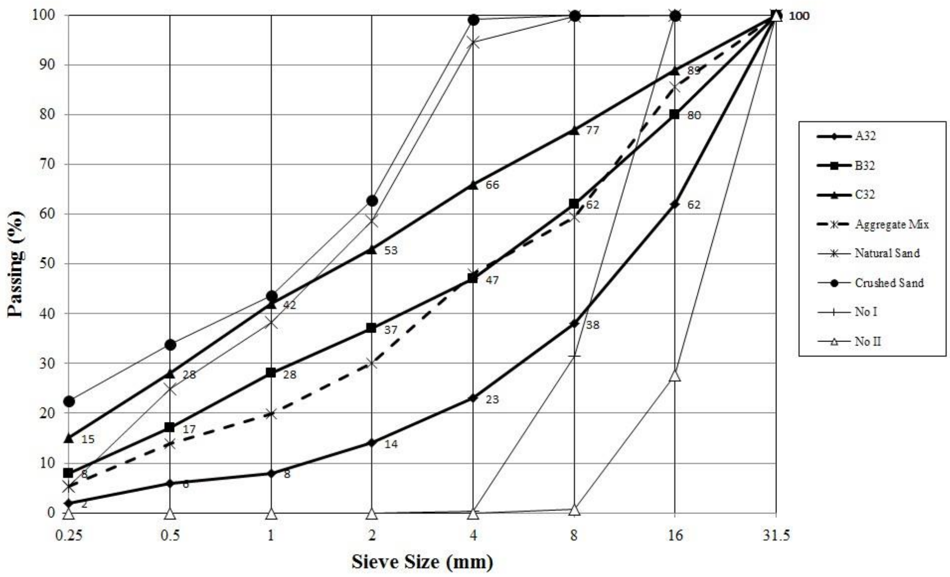


Figure 1. Aggregate grading curves

2.1.4. Superplasticizer

A commercially available sulphonated naphthalene formaldehyde-based superplasticizer was utilized to obtain a stable workability. The properties of the superplasticizer supplied by Grace Chemical Corp. are shown in Table 3.

Table 3. Properties of the superplasticizer

Color	Dark brown
State	Liquid
Specific gravity	1.19
Freezing point	-4 ^{o}C
Chloride content	None
Nitrate content	None

2.2. Mix Properties

Water/cementitious material (w/cm) ratio of concrete mixtures designed for experimental study was defined as 0.40. In order to evaluate the effectiveness of the mineral admixtures, four replacement levels varied between 0% and 20% of the total cement content were used. Metakaolin replaced with binder at levels of 5%, 10%, 15% and 20% by weight. In addition a control group was prepared to make comparison with admixture containing concretes. Therefore, 21 concrete mixtures having different properties were designed. The mix proportions of the all mixtures are given in Table 4. To define the mixtures, name of calcined kaolin and replacement level are used. For example, the concrete mixture containing metakaolin with 10% substitution was coded as MK10.

Table 4. Mix designations and mix proportions

Type of Calcined Kaolin	Replacement Level (%)	Mix ID	Materials kg/m^3							
			Cement	Calcined Kaolin	Water	No I (4-16 mm)	No II (16-22 mm)	Natural sand	Crushed Sand	SP^{f}
None	0	Control	350	0	140	695.5	397.4	794.9	99.4	3.5
DV^{a}	5	DV5	332.5	17.5	140	693.9	396.5	793.0	99.1	4.2
	10	DV10	315	35	140	692.0	395.4	790.9	98.9	5.3
	15	DV15	297.5	52.5	140	690.1	394.3	788.7	98.6	6.3
	20	DV20	280	70	140	688.5	393.4	786.8	98.4	7.4
DC^{b}	5	DC5	332.5	17.5	140	694.0	396.6	793.1	99.1	4.1
	10	DC10	315	35	140	692.2	395.5	791.1	98.9	5.0
	15	DC15	297.5	52.5	140	690.4	394.5	789.0	98.6	6.1
	20	DC20	280	70	140	688.9	393.6	787.3	98.4	7.2
CC^{c}	5	CC5	332.5	17.5	140	693.8	396.4	792.9	99.1	4.0
	10	CC10	315	35	140	691.7	395.3	790.6	98.8	4.8
	15	CC15	297.5	52.5	140	689.7	394.1	788.3	98.5	5.9
	20	CC20	280	70	140	688.0	393.1	786.3	98.3	7.0
BMK^{d}	5	BMK5	332.5	17.5	140	694.1	396.6	793.2	99.2	4.2
	10	BMK10	315	35	140	692.4	395.6	791.3	98.9	5.5
	15	BMK15	297.5	52.5	140	690.7	394.7	789.3	98.7	6.6
	20	BMK20	280	70	140	689.2	393.8	787.7	98.5	7.7
MK^{e}	5	MK5	332.5	17.5	140	693.9	396.5	793.0	99.1	6.5
	10	MK10	315	35	140	692.0	395.4	790.9	98.9	7.4
	15	MK15	297.5	52.5	140	690.1	394.3	788.7	98.6	8.1
	20	MK20	280	70	140	688.5	393.4	786.8	98.4	8.7

a: Calcined Balıkesir-Düvertepe kaolin, b:Calcined Balıkesir-Danaçayırı kaolin, c: Calcined Çanakkale-Çan kaolin, d: Calcined Bursa Mustafa Kemal Paşa kaolin, e: Commercial high reactivity metakaolin from Czech Republic, f: Superplasticiser

3. Test Methods

3.1. Compressive Strength

For determination of compressive strength of concretes, 150x150x150 mm cube samples were used according to ASTM C39 through a 3000 kN capacity testing machine [15]. The test was applied on the concrete specimens at the ages of 28 and 90 days to observe the compressive strength development. The compressive strength was computed from average of three specimens at each testing age.

3.2. Splitting Tensile Strength

*φ*100x200 mm cylinder concretes were utilized to define splitting tensile strength of concretes at 28 and 90 days as described by ASTM C496 [16]. The splitting tensile strength presented is the average of the values obtained from three cylinder samples.

4. Test Results

4.1. Compressive Strength Development

The compressive strength values of concretes at 28 and 90 days were monitored. The compressive strength of concrete that contains partially Turkish kaolin and commercially available metakaolin were presented in Table 5 and Figure 2. While the compressive strength of the control concrete samples ranged between 53-56 MPa, compressive strength of concrete specimens produced with CK and MK varied between 52-64 MPa and 56-67 MPa, respectively. When comparing the obtained results, it is seen that the strength values strongly depend on the duration of curing and the level of replacement.

Table 5. Compressive strength of the concretes, (MPa)

Mixtures	28 days	90 days
Control	53.5	56.2
DV5	56.4	58.5
DV10	52.9	58.7
DV15	60.5	62.3
DV20	55.7	60.5
DC5	57.6	59.6
DC10	56.0	62.0
DC15	58.8	64.1
DC20	56.0	63.0
CC5	56.3	58.3
CC10	54.4	60.3
CC15	57.5	62.7
CC20	55.8	59.1
BMK5	53.3	56.8
BMK10	52.6	58.9
BMK15	55.7	61.0
BMK20	53.3	60.0
MK5	58.3	60.1
MK10	56.7	64.0
MK15	61.8	66.5
MK20	61.9	66.9

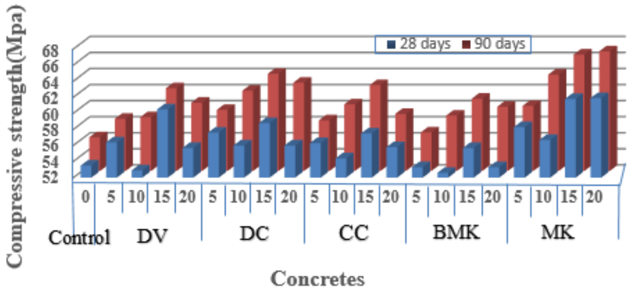


Figure 3. Compressive strengths of the plain and mineral admixed concretes at 28 and 90 days

4.2. Splitting Tensile Strength Development

Splitting tensile strength values of concretes measured at 28 and 90 days were presented in Table 6 and graphically illustrated in Figure 3. While the maximum splitting tensile strength values were obtained from MK incorporated concretes at 28 and 90 days as 4.28 and 4.68 MPa, splitting tensile strength values of control concrete were determined as 3.20 and 3.40 MPa and these values are the lowest results at both ages respectively.

Table 6. Splitting tensile strength of the concretes, (MPa)

Mixtures	28 days	90 days
Control	3.20	3.40
DV5	3.77	4.01
DV10	3.93	4.20
DV15	4.02	4.46
DV20	3.68	4.55
DC5	3.30	3.81
DC10	3.26	4.04
DC15	4.17	4.26
DC20	3.66	4.03
CC5	3.79	4.07
CC10	3.22	4.18
CC15	4.08	4.53
CC20	3.50	4.16
BMK5	3.31	3.94
BMK10	3.88	4.25
BMK15	3.81	3.96
BMK20	3.32	3.94
MK5	3.94	4.14
MK10	4.04	4.53
MK15	4.28	4.68
MK20	3.91	4.68

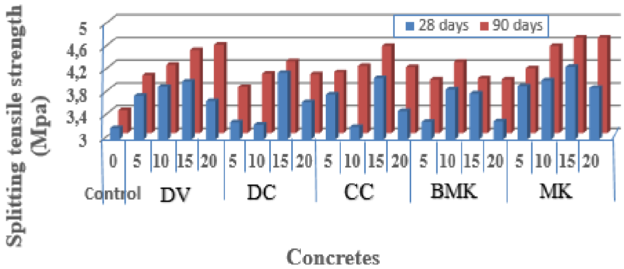
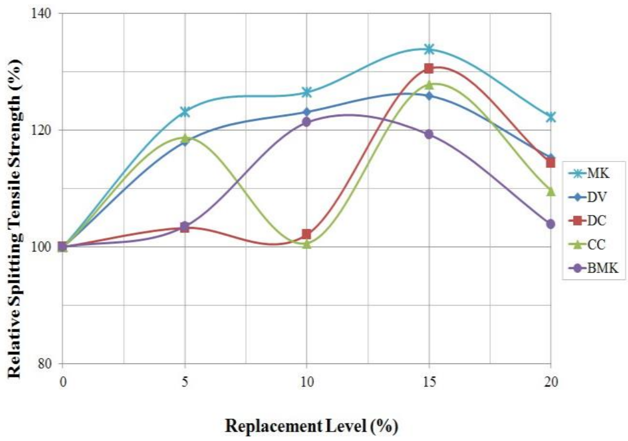
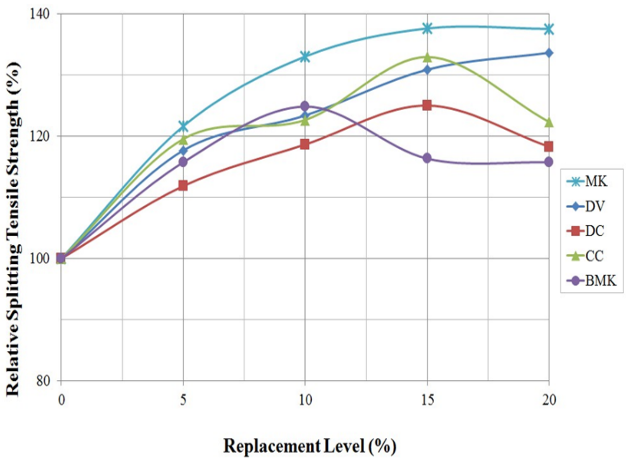


Figure 3. Splitting Tensile strengths of the plain and mineral admixed concretes at 28 and 90 days

It was concluded that best improvement was achieved for MK and CK incorporated concretes at 15% substitution level. However, it was realized that MK15 and MK20 had same values at 90 days. Besides, relative splitting tensile strength values were shown in Fig. 4.



a)



b)

Figure 4. Effect of replacement level on splitting tensile strength of the concretes at a) 28 days, b) 90 days ($F_{s,\text{plain concrete}}$= 100%).

5. Correlations between experimental data

Researchers generally need to correlate data to assess the relation between experimental results. All of the analyzed data are the experimental test results obtained at 28 and 90 days from current study. The correlation coefficient between the tensile and compressive strengths was found as 0.619. and it was illustrated in Fig 5. Concretes containing MK showed a more uniform tendency than control specimen and concretes containing CKs.

In order to take the size effect into account, the conversion from the cube sample (150x150x150) to the standard cylindrical sample (ϕ150x300) cylinder/cube conversion factor (K_f) is taken as 0.8. Hence, the corresponding compressive strength values for the cylinder samples are attained by using the compressive strengths obtained from the cube samples. Compressive strengths were converted using Eq. (1).

$$0.8\times f_{c,150\times150(cube)} = f_{c,\phi150\times300(cylinder)} \qquad \text{Eq.(1)}$$

After determining the compressive strengths, to attain the splitting tensile strengths of standard cylinder size samples, the other suitable coefficient was utilized on the ϕ100x200 mm size specimens values. İt was taken from literature as 0.95. The splitting tensile strengths for standard size cylinder samples were calculated using Eq. (2).

$$0.95\times f_{c,\phi100\times200(cylinder)} = f_{c,\phi150\times300(cylinder)} \qquad \text{Eq. (2)}$$

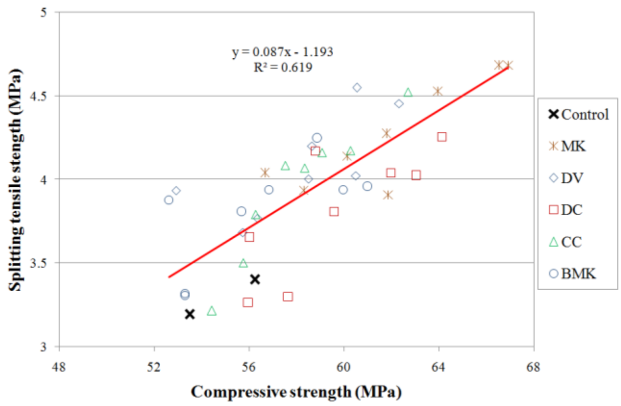
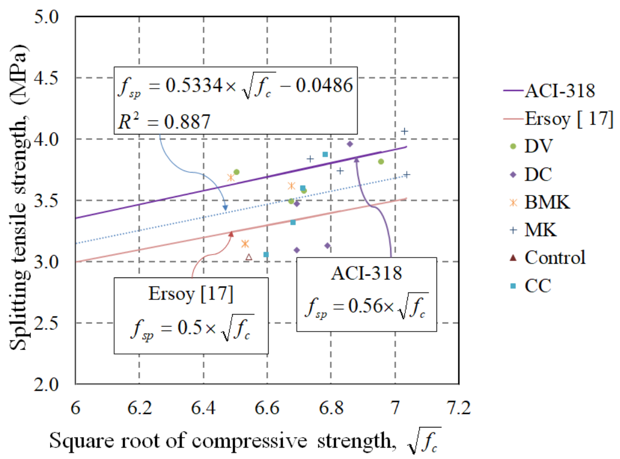
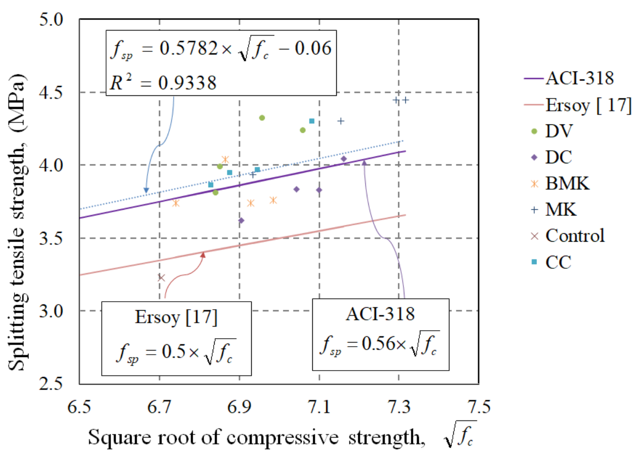


Figure 5. Correlation between compressive and splitting tensile strength of concretes using experimental data without conversion

In the design codes, for prediction of tensile strength of concrete, generally square root of compressive strength obtained from standard cylindrical specimen is used. In this study, a similar approach is adopted. Figure 6 indicates this correlation and the proposed models for 28 and 90 days of curing ages were annotated on Figure 6 as well. Moreover, in order to assess the performance of the proposed models two different models proposed by Ersoy [17] and ACI-318 [18] design code is demonstrated below.



a)



b)

Figure 6. Correlation between compressive and splitting tensile strength of concretes at a) 28 days b) 90 days, using an approach adopted in the literature

$$f_{sp} = a \times \sqrt{f_c}$$ where f_{sp} and f_c values are splitting and compressive strengths of ϕ150x300 mm standard cylindrical specimen

6. Conclusions

The following conclusions can be drawn from the study;

The enhancement capability of the calcined crude kaolins on the mechanical properties of the concretes investigated in this study is as good as that of high purity MK.

15% replacement level of MK or CKs was proved to be the best level for obtaining the highest strength gain. This can be attributed to the fact that by using this replacement level a critical balance was obtained between the cement content and mineral additives. Because, in order to obtain highest pozzolanic reactivity, the most proper microfilling and dilution effects, 15% replacement level provided the best performance for the water/binder ratio and the total binder content taken into account in this study.

Although, the sizes of cube and cylinder specimens used in this experimental study for compressive and splitting tensile tests were 150x150x150 mm and ϕ100x200 mm, respectively, conversion factors were used to get the values for standard cylinder size. This procedure was applied to determine the relation between compressive and splitting tensile strengths of concrete and compared with those presented in the literature. The coefficient of determination (R^2) between the tensile and compressive strengths for standard size concrete specimens at 28 days and at 90 days were obtained as 0.887 and 0.934 respectively. It means there is a strong correlation between these two parameters. By using the experimental data, two equation were obtained and it was compared with two equation taken from literature. İt is clear that the new equation is very similiar to the available ones.

But there are also two critical limitations of the new equations presented. First, when f_c value is assigned as zero the result gives a negative value and it is not a valid result. The equations presented have reasonable robustness with high compressive strength values of higher than 50 MPa.

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