

**UNIVERSITY OF GAZIANTEP
GRADUATE SCHOOL OF
NATURAL & APPLIED SCIENCES**



**EFFECT OF METAKAOLIN AND CALCINED KAOLIN
ON HARDENED PROPERTIES OF
SELF COMPACTING CONCRETE**

**M. Sc. THESIS
IN
CIVIL ENGINEERING**

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**Effect of Metakaolin and Calcined Kaolin on Hardened
Properties of
Self Compacting Concrete**

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**by
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June 2017**

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ABSTRACT

EFFECT OF METAKAOLIN AND CALCINED KAOLIN ON HARDENED PROPERTIES OF SELF COMPACTING CONCRETE

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M.Sc. in Civil Engineering

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In this thesis, commercially available high reactivity Czech metakaolin (MK) and calcined impure Turkish kaolin (CK) were used for production self-compacting concrete (SCC) and some hardened properties of these concretes have been investigated. Five types of SCC mixtures including control mixture were produced with 0%, 5% and 10% replacement level of metakaolin (MK) and calcined kaolin (CK) (MK5, MK10, CK5, CK10 and Control Mixture). Control mixture was produced with the aim of comparison. The SCC mixtures produced with high range water reducing admixture (HRWRA) with 0.35 water-to-binder ratio and 550 kg/m³ total binder content. After the standard curing process, compressive strength, water permeability, gas permeability, water absorption and sorptivity of SCCs were tested. Compressive strength test were applied to SCCs after 3, 7, 28, and 56 days curing periods and the highest strength values obtained from 10% replacement level of MK (MK10). When all of the other hardened properties of 28 and 56 days samples are examined, also the best performances were obtained from the MK 10 samples. Control specimens and MK10 specimens are compared after 56 curing days and this comparison shows that the MK10 samples have better performance of 63% water permeability, 60% gas permeability, 35% water absorption and 53% sorptivity. In conclusion, when the specified hardened properties of SCCs are examined, specimens containing MK show better results than all other samples. In addition, specimens containing CK show better results than control specimens.

Keywords: Self Compacting Concrete, Calcined Kaolin, Metakaolin, Hardened Properties

ÖZET
METAKAOLEN VE KALSİNE KAOLENİN KENDİLİĞİNDEN YERLEŞEN
BETONUN SERTLEŞMİŞ ÖZELLİKLERİNE ETKİSİ

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Bu tezde Çek Cumhuriyetinden temin edilmiş yüksek reaktivite değerlerine sahip metakaolen (MK) ve yerli saflaştırılmamış kalsine kaolin (KK) kullanılarak kendiliğinden yerleşen betonlar (KYB) üretilmiş ve bu betonların bazı sertleşmiş özellikleri incelenmiştir. Metakaolin ve kalsine kaolen ağırlıkça %0, %5 ve %10 oranlarında portland çimentosu ile yer değiştirilerek kontrol karışımı ile birlikte toplamda 5 karışım hazırlanmıştır (Konrol karışımı, MK5, MK10, KK5 ve KK10). Yüksek oranda su azaltıcı katkı maddesi kullanılan karışımlar, su bağlayıcı oranı 0.35 ve toplam bağlayıcı miktarı 550 kg/m^3 olacak şekilde üretilmiştir. Standart kür işlemi sonrasında KYB numunelerinin basınç dayanımları, basınçlı su geçirimsizlik oranları, gaz geçirimsizlikleri, su emme kapasitesiteleri ve kılcal su geçirimsizlikleri araştırılmıştır. Basınç dayanımı ölçümü için 3, 7, 28 ve 56 günlük basınç testleri uygulanmış ve en yüksek dayanım %10 oranında MK kullanılan KYB numunelerinden (MK10) elde edilmiştir. Tüm numunelerin 28 ve 56 günlük diğer sertleşmiş özellikleri incelendiğinde, yine en iyi performanslar MK 10 numunelerinden elde edilmiştir. 56 günlük kontrol numuneleri ile MK10 numuneleri karşılaştırıldığında, MK10 numuneleri basınçlı su işlemede %63, gaz geçirimsizliğinde %60, su emme kapasitesitesinde %35 ve kılcal su geçirimsizliğinde %53 daha iyi performans sergilemiştir. Sonuç olarak, KYB'lerin belirtilen sertleşmiş özellikleri incelendiğinde, MK içeren KYB numuneleri diğer tüm numunelerden daha iyi sonuçlar vermiştir. Ayrıca KK içeren KYB numuneleri kontrol amaçlı üretilen numunelerden daha iyi sonuçlar vermiştir.

Anahtar Kelimeler: Kendiliğinden Yerleşen Beton, Kalsine Kaolen, Metakaolen, Sertleşmiş Özellikler

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LIST OF SYMBOLS/ABBREVIATIONS

ACI	American Concrete Institute
ASR	Alkali-Silica Reactivity
ASTM	American Society for Testing Materials
CH	Calcium Hydroxide
C-S-H	Calcium Silicate Hydrate Gel
CVC	Conventionally Vibrated Concrete
DTA	Differential Thermal Analysis
E_c	Modulus of Elasticity
EN	European Norm
HRWRA	High Range Water Reducing Admixture
K	Permeability Coefficient
GGBFS	Ground-Granulated Blast-Furnace Slag
FA	Fly Ash
MK	Metakaolin
OPC	Ordinary Portland Cement
PC	Portland Cement
SCC	Self Compacting Concrete
SF	Silica Fume
TG	Thermogravimetric Analysis
VC	Vibrated Concrete
w/b	Water to Binder Ratio
WA	Water Absorption

CHAPTER 1

INTRODUCTION

1.1 Background

Self Compacting Concrete (SCC) is a special type high performance concrete that has high fluidity and workability properties due to its lower water to cement ratio which leads to rapid strength development and high durability performances. SCC fills the framework without any vibration process and it can be easily placed in the dense reinforcement. This concrete minimizes and prevents possible mistakes such as air gaps in concrete during the placement and compaction process. Also, SCC shows better performances in terms of segregation and bleeding. Because of these advantages, it becomes one of the most popular construction materials (Ghezal et al., 2002; Khayat et al., 2002; Felekoğlu et al., 2007; Carro-López et al., 2015; Kapoor et al., 2016). Widespread using of this material, canalized the researchers to concentrate on fresh and hardened properties of it (Khayat, 2000; Khayat et al., 2001; Felekoğlu et al., 2007; Carro-López et al., 2015). Filling ability, passing ability and segregation resistance are the principal fresh properties of SCC. Slump flow test, V-funnel test, J-ring test and Orimet test are used for determination of fiilling abilities of SCC. For determination of passing ability of SCC L-box test and J-ring tests are used and for determination of segregation resistance of SCC sieve stability test and penetration test are used (Schuter, 2005). Compressive and tensile strength, sorptivity, modulus of elasticity, creep and shrinkage, freeze-thaw resistance, permeability and water absorption are the main hardened properties of SCC. Scientists carried out many experimental studies for determination of these hardened properties (Sabău et al., 2012, Filho et al., 2010, Barluenga et al., 2015, Ulubeyli and Artir, 2017).

From the 90s to the present day, high-reactivity Metakaolin (MK) has become a research subject that attracts a great deal of attention (Caldarone et al., 1994; Caldarone and Gruber, 1995; Banthia and Yan, 1996; Gruber et al., 2001; Batis et al.,

2005; Güneyisi and Mermerdaş, 2007; Zhang et al., 2014; Wu et al., 2016). This material is used as cement replacement material for improving characteristic properties of concrete. MK is a thermally activated cementitious material that is a resultant product of the calcinations of kaolinitic clay (Siddique and Klaus, 2009; Mermerdaş, 2013). Normally, kaolin is quite stable, however during calcination process kaolin heated to 650-900 C° and it loses approximately 14% of its mass in bound hydroxylions and then MK is formed. The main reaction that occurs between MK and Calcium Hydroxide (CH) derived from cement hydration. Additional Calcium Silicate Hydrate (C-S-H) gel and crystalline products are formed during this reaction. Reactivity level of MK is the most significant and main factor in the hydration reaction. Chapelle test is used for determination of reactivity level of MK. (Kostuch et al., 1993; Asbridge et al., 1994).

Calcined kaolin (CK) is an another widely studied material after 1990's for improving the properties of concrete (Sabir et al., 2001; Ding and Li, 2002; Güneyisi and Mermerdaş, 2007; Kim et al., 2007; Yuan et al., 2013; Mallik et al., 2015). CK is used as cement replacement material for improving properties of SCCs at different replacement levels.

In this experimental study, hardened properties of SCCs those contains high-reactive Czech MK and commercially available Turkish CK were tested. With control specimens five types of SCC mixtures were produced with 0%, 5% and 10% replacement level of MK and CK (Control, MK5, MK10, CK5, and CK10). Moreover, commercially accessible metakaolin (MK) that has high reactivity value from Czech Republic was also used for comparison purpose. Compressive strength, water permeability, gas permeability, water absorption and sorptivity test were applied to SCC specimens. SCCs tested after 3, 7, 28, and 56 days, and the development of desired features of SCCs were observed.

1.2 Outline of the Thesis

This thesis consists of 5 chapters. The sections of thesis and contents of these sections are as follows:

Chapter 1 Introduction: Aim and objectives of the thesis were introduced with related studies in the first chapter.

Chapter 2 Literature Review: A detailed literature review and general background information about hardened and fresh properties of SCC were presented. In addition, detailed information about the effect of metakaolin on properties of SCC has been explained.

Chapter 3 Experimental Study: This chapter includes the information about the materials those are utilized in this study. The characteristics of cement, aggregates, superplasticizers, high reactivity Czech metakaolin (MK) and calcined impure Turkish kaolin (CK) presented in this section. In addition, details of mix proportions and applied test methods were given.

Chapter 4 Test Results and Discussions: In this part of study, results of compressive strength test, permeability tests, water absorption test and sorptivity test were presented. Moreover, evaluation, and discussion of test result were given.

Chapter 5 Conclusion: This chapter contains the summary of the conclusions obtained from experimental studies presented in this thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Self-Compacting Concrete

SCC is a kind of concrete that has high rate of fluidity feature and ability to consolidate by means of its own weight. When SCC settles into the formwork, external and internal vibrations are not required for compaction and placing (Ghezal, 2002; Carro-López et al., 2015; Kapoor et al., 2016). SCC minimizes and prevents possible mistakes such as air gaps in concrete during the placement and compaction process. In addition, SCC is a non-segregating concrete and by using this concrete the durability and strength about properties of concrete has been reached to the expected requirements of performance. The strengthening projects, heavily reinforced elements, aesthetic mold designs, narrow and deep sections that vibrators cannot be used in are some using areas of SCC (Kılınç, 2012).

SCC has several benefits and advantages over conventional concrete. They are:

- Improved constructability.
- Labor reduction.
- Improved structural integrity.
- Provides labor savings.
- Suitable for complex molds in terms of fluidity.
- Provides concrete production with very low void ratio for highly reinforced areas.
- Forms a smooth concrete surface.
- Provides more durable concrete production.
- Can be pumped more easily.
- No need for vibration and mechanical consolidation during placement.
- Decreasing noise levels those produced by mechanical vibrators.

- Forms a uniformly distributed concrete surface.
- Can be used for deep sections or long-span applications.

Test methods and procedures were established in the 1986. After 1986s, researchers concentrate on hardened and fresh properties of SCC (Khayat, 2000; Khayat et al., 2001; Felekoğlu et al., 2007; Filho et al., 2010, Barluenga et al., 2015, Ulubeyli and Artir, 2017).

2.1.1 Fresh Properties of Self-Compacting Concrete

Ability of filling, ability of passing and resistance of segregation are the main properties of SCC in fresh state. They are provided with highly effective water reducing agents (superplasticizers), those usually based on polycarboxylate ethers (Wüstholtz, 2003).

2.1.1.1 Filling Ability

Filling ability is the ability of filling a formwork and reaching all points of formwork completely under its own weight. Filing ability depends on flow speed of fresh concrete. Slump flow test is used to measure flow speed of concrete. This test indicates free, unlimited deformability and the ratio of deformation within a specified flow distance. V-funnel test, J-ring test and Orimet test can be used as alternative test methods for determination of filling ability of SCC (Schuter, 2005).

For proper filling ability, the following points should be taken into consideration (Kılınç, 2012):

- Increasing the deformation capacity of the cement paste by using superplasticizer additives and by balanced water / binder ratio.
- Reducing the friction between particles by using low coarse aggregate volume (high cement mortar content) and appropriate particle size distribution according to aggregate and cement used

2.1.1.2 Passing Ability

Passing ability is the property of concrete to overcome passing obstacles like heavily reinforcement and small openings, under its own weight. When SCC spreads into formwork, there is a risk of blockage in the following situations (Kılınç, 2012):

- If the maximum aggregate grain size too large,
- If the contents of coarse aggregates are too high.

The following points should be taken into consideration for proper passing ability of SCC (Kılınç, 2012):

- Increasing cohesion to reduce aggregate separation by using low water/binder ratio and increasing viscosity.
- Using appropriate form of coarse aggregate by using low coarse aggregate content and low maximum grain diameter of aggregate.

L-box test is utilized for investigation of the passing ability of SCC. This test measures the accessed height of newly poured SCC after passing through the specified spaces of steel bars and flowing within a specified flowing distance. By using this test reached height, the passing ability of SCC can be found. J-ring test also could be used for determination of passing ability of SCC (Schutter, 2005).

2.1.1.3 Segregation Resistance

In some cases components of fresh concrete separate from each other and cause segregation. Segregation prevents homogenous distribution of fresh concrete. Segregation is caused by the following reasons (Kılınç, 2012):

- Separation of the coarse aggregate from the main mass of concrete,
- Separation of the grout from the mix,
- Bleeding.

To prevent segregation of concrete the following precautions must be taken:

- Optimum quantity of water should be used for concrete mix to get enough cohesion.
- Field quality requirements should be provided and controlled for all phases of concrete from production of concrete to the final phase.
- In case of detecting of segregation, concrete must be mixed again to get an homogeneous concrete.
- To avoid segregation, chemical and mineral admixtures such as air entraining agent and pozzolanic materials should be used.
- Concrete casting should not be done at high distance. It should be done from nearest position.

Sieve stability test is used for investigation of the segregation resistance of SCC. 5 mm sieve is used in this test. The fraction of concrete that pass through this sieve measured and this measurement decides segregation resistance of concrete. Poor resistance of segregation means that the paste or mortar has a high potential of passing through the sieve. So the sieved portion of concrete considered as the indicator of stability of concrete. Penetration test could be use an alternative method for testing segregation resistance of SCC (Schutter, 2005).

2.1.2 Hardened Properties of SCC

Tensile and compressive strength, sorptivity, modulus of elasticity, creep, shrinkage, freeze-thaw resistance, permeability and water absorption are the main hardened properties of SCC. There have been many studies done on the hardened properties for determination of these properties of SCCs (Sabău et al., 2012, Filho et al., 2010, Barluenga et al., 2015, Ulubeyli and Artir, 2017).

2.1.2.1 Compressive Strength

Compressive strength is one of the most significant characteristics of hardened SCC that gives an idea about all the characteristics of concrete. It depends on components

of concrete and dosage of use of these components. In addition, quality of the components and quality control during production affect compressive strength of concrete.

C39/C39M standard by American Society for Testing Materials (ASTM) and EN 12390-4 standard by European Norm provide the test methods for compressive strength of concrete. 15cm x 15cm x 15cm Cube or 15cm x 30cm cylinder specimens are used for determination of compressive strength of concrete (ASTM, 2016; EN, 2000) (Figure 2.1). These specimens are tested with compression test machine after 7 days or 28 days curing. Compressive strength of concrete is formulated in Eqn (2.1).

$$f_c = \frac{P}{A} \quad (2.1)$$

Where;

f_c is compressive strength of concrete (MPa),

P is failure load (N),

A is area of specimen (mm^2).

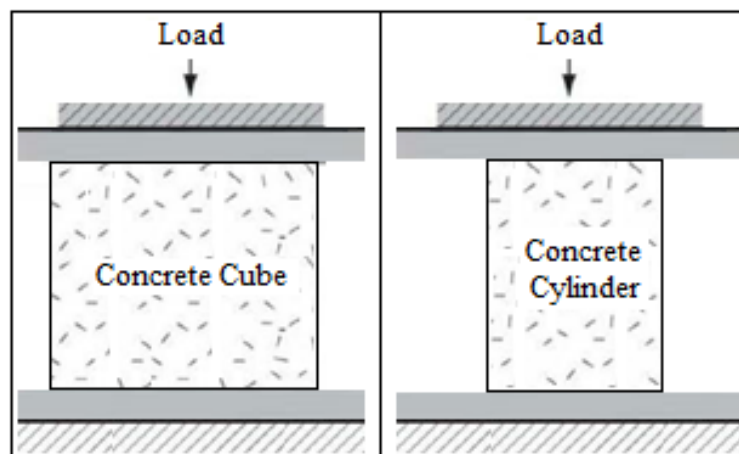


Figure 2. 1 Set up of compressive strength test for cylinder and cube concrete specimens.

2.1.2.2 Tensile Strength

Tensile strength of SCC is assessed with the indirect tensile strength. It is obtained by the splitting test results of cylinders specimens (Sabău et al., 2012) (Figure 2.2). C496 / C496M – 11 standard by ASTM provide the testing methodology of splitting tensile strength of 15cm x 30cm cylindrical concrete specimens (ASTM, 2004). Also, EN 12390-6 standard by European Norm provide the test method of Tensile splitting strength of concrete specimens (EN, 2000). Tensile strength is calculated according the formula shown in Eqn (2.2).

$$f_t = \frac{2P}{2\pi rL} \quad (2.2)$$

Where;

f_t is tensile strength of concrete (MPa),

P is compressive failure load (N),

r is the radius of the cylinder (mm),

L is the height of the cylinder (mm).

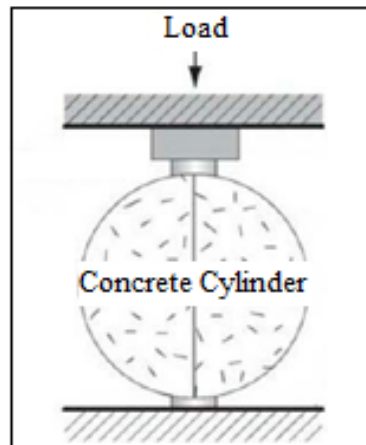


Figure 2. 2 Schematically representation of splitting test of cylinder concrete specimen.

2.1.2.3 Sorptivity

Sorptivity is the measurement of capacity of the material for absorbing or desorbing fluid by capillarity. The test of sorptivity measures the ratio of water that drowned into the voids of concrete (Mermerdaş, 2013). Concrete cubes are used in this test, and only the lowest 2-5 mm of the cubes is submerged. The test mechanism is shown in Figure 2.3.

Sorptivity is affected by concrete's surface condition so the test is only applied to the surface of the concrete (Leung et al., 2016). C1585-13 standard by ASTM provide the method of testing for sorptivity. Sorptivity is calculated by the formula given in Eqn (2.3) and Eqn (2.4).

$$I = \frac{\Delta W}{Ad} \quad (2.4)$$

$$S = I/\sqrt{t} \quad (2.3)$$

Where;

S is sorptivity ($\text{mm}/\text{min}^{0.5}$),

t is elapsed time in minute,

I is the Σ infiltration (mm) at time t,

ΔW (g) is difference of weights ($W_2 - W_1$; W_1 is oven dry weight of the cylinder, W_2 is weight of cylinder after half hour capillary suction of water),

A is surface area of the concrete sample that water penetrated in and

d is the density of water (Kumar, 2016).

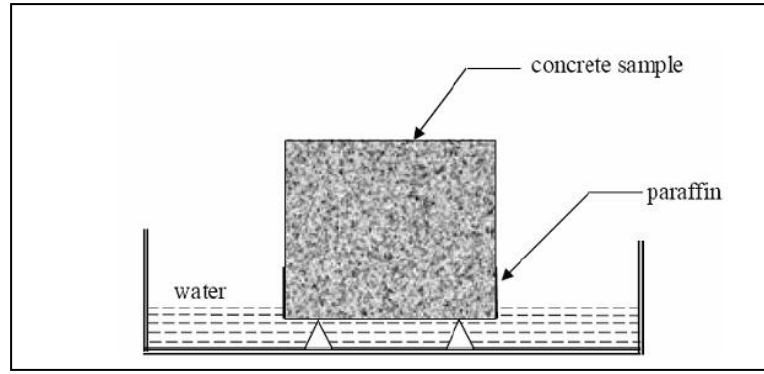


Figure 2. 3 Schematically representation of sorptivity test (Mermerdaş, 2013)

2.1.2.4 Modulus of Elasticity (E_c)

Modulus of elasticity (E) is the measurement of instantaneous elastic deformation. In addition, it is the ratio of normal stresses and strain below the proportional limit of a material. ASTM D695-15 standard provides the test method and calculation of E of concrete (ASTM, 2015a). E is calculated according to the American Concrete Institute (ACI 318-02) by using the formula shown in Eqn (2.5).

$$E_c = 4.73 * (f_c)^{0.5} \quad (2.5)$$

Where;

E_c is the modulus of elasticity of concrete (GPa),

f_c is the compressive strength of standard test cylinder (MPa).

SCC mixes that include higher paste content inversely have a lower E , because of contribution of aggregates to the over-all stiffness of concrete (Craeye et al., 2014). According to the studies done for determination of modulus of elasticity of SCC, E of some SCC mixes was lower than that of the vibrated concrete (VC) mixes with a similar compressive strength (Domone, 2007; Holschemacher and Klug, 2002; Brito-EuRam, 2005; Georgiadas et al., 2007).

2.1.2.5 Creep and Shrinkage

Creep and shrinkage of concrete are physical and time dependent characteristics of concrete (Mermerdaş, 2013). Creep and shrinkage cause progressive changes in

stresses and strains in reinforced and prestressed concrete structures (Hołowaty, 2015). Time related deformations of concrete are due to exposure of a sustained load as shown in Figure 2.4.

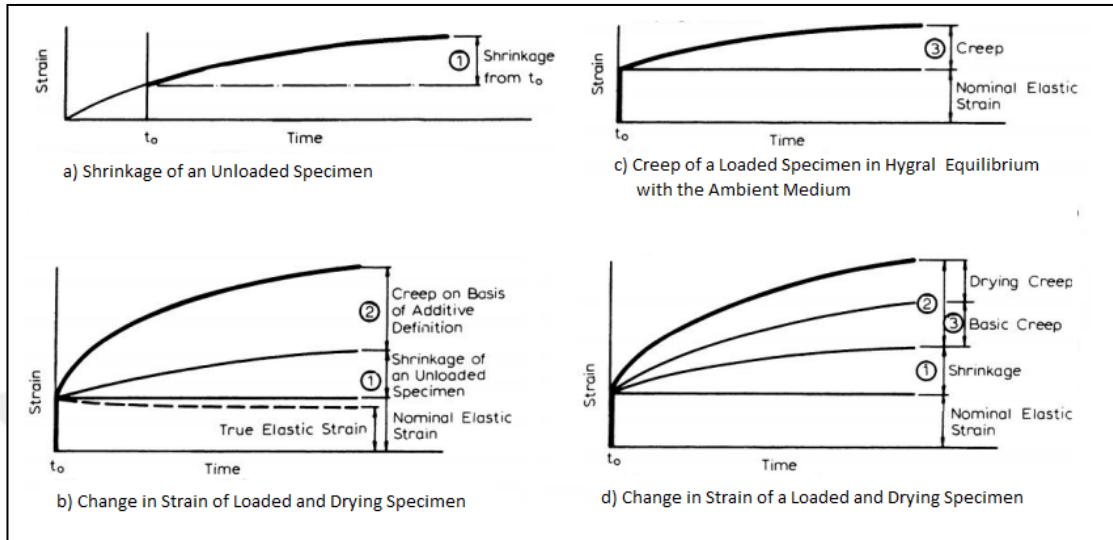


Figure 2. 4 Time related deformations of concrete under a sustained load (Neville, 2011).

Creep is the concrete deformations that caused by its own weight or additional loads and forces depending on time. Although the loads acting on the concrete are constant these deformations occur. The factors those affect creep are concrete mix proportions, properties of aggregates and cement, curing conditions and so on. ASTM C512 / C512M-15 standard provide the test methodology for creep of concrete in case compression (ASTM, 2015b).

Shrinkage is shortening of the concrete due to change in moisture of concrete. Drying conditions, water to cement ratio (w/c) and moisture conditions affect shrinkage. There are 4 type of shrinkage: autogenous, plastic, carbonation, and drying shrinkage. ASTM C157 / C157M-08 and RILEM CPC 9 standards provide the test methods for shrinkage of concrete (ASTM, 2014; Holt, 2001).

According to the study done by Persson (2001), creep and shrinkage of SCC didn't change in an important rate from the specified properties of normally compacted concrete. However, Leemann et al. (2011) used simple analytical composite models

for determination of shrinkage of SCC, and they reported that, these models confirm SCC has higher shrinkage than CVC due to their higher paste volume.

2.1.2.6 Freeze/Thaw Resistance

Unlike other liquids, water expands in volume when it freezes. Thus it causes pressure in the pores of the concrete. Due to the pressure expanding and cracking occur in pores when it exceeds the tensile strength of concrete. Relation between the numbers of cycles of freezing and thaw increase in percent volume is shown in Figure 2.5. Freeze and thaw cycles cause 4 type damage in concrete, they are surface scaling, pop-outs, D-cracking and internal damages (Harrison et al., 2001). ASTM C666 / C666M-15 standard provides the test method for rapid freezing and thawing in water (ASTM, 2015c).

Degree of saturation and the pore system of the hardened cement are the main factors that affect the resistance of concrete to freezing and thawing. Dry concrete is not going to affect from freezing and thawing and below some critical value of saturation concrete is highly resistant to frost. To avoid damages caused by freezing and thawing, concrete should be allowed to dry out before exposure winter conditions (Neville, 2011).

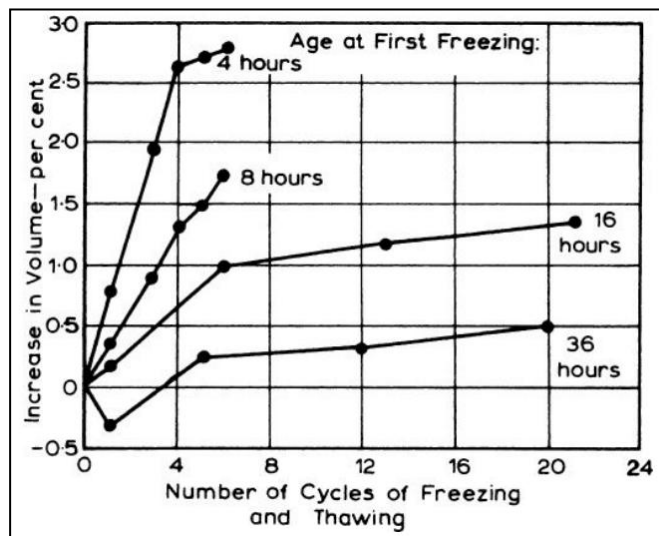


Figure 2. 5 Increase in volume of concrete subjected to freezing and thawing as a function of age at which first freezing starts (Neville, 2011).

2.1.2.7 Permeability and Water Absorption

Permeability and water absorption are the main water transport mechanisms in concrete. Low permeable concretes resist entrance of water and due to this property these concretes are not affected much affected from freezing and thawing. Travel of liquids and gasses through concrete is called as permeability. It has direct relationship with durability of concrete. It is necessary for concrete to be reliable and to withstand the conditions it has been designed for, to not to have trouble during its service life. Water cement ratio, compaction and curing of the concrete affect the permeability.

Testing concrete for permeability has not been generally standardized. In the test methods used to measure permeability, the steady-state flow of water through concrete that caused by a pressure differential is measured, and the equation of Darcy is used for calculation of the coefficient of permeability. The graph of permeability coefficient and water to cement ratio for cement pastes is given in Figure 2.6. U. S. Bureau of Reclamation test, Canadians test, German test and also Rapid Chloride Permeability Test (RCPT) are used for determination of water permeability of concrete (Neville, 2011). ASTM C1202-05 provides test method for RCPT (ASTM, 2005). In addition, Cembureau Method is used for measurement of the gas permeability and water absorption of concrete (RILEM, 1999). BS 1881-122 and ASTM C140 standards provide the methods' for determination of water absorption.

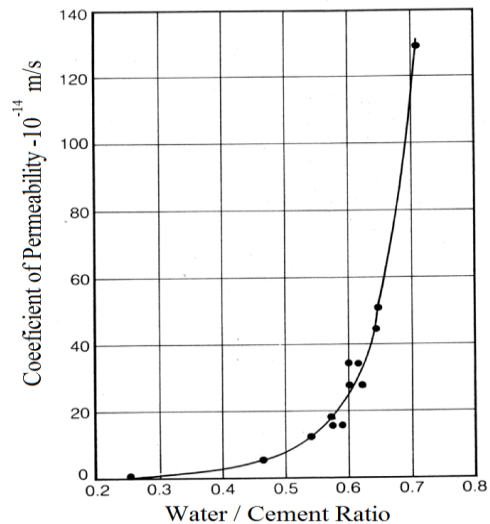


Figure 2. 6 The graph of permeability coefficient and water to cement ratio for mature cement pastes (Neville, 2011)

2.2 Metakaolin as a Supplementary Cementitious Material

Metakaolin (MK) is a thermally activated cementitious substance that is formed after the calcinations of kaolinitic clay (Siddique and Klaus, 2009; Mermerdaş, 2013). MK can also be obtained from lateritic soils (Ambroise et al., 1985). MK is used in many types of concrete for different purposes (Siddique and Klaus, 2009). They are:

- Precast concrete,
- High performance concrete,
- Lightweight concrete,
- Fiber cement concrete,
- High strength concrete,
- Glass fiber reinforced concrete.

2.2.1 Properties of Metakaolin

Physical and chemical characteristics of MK should confirm ASTM C-618 standard 'Class N Specifications for Natural and Calcined Pozzolans'. An example of physical characteristics of MK those are taken from an experimental study are shown in Table 2.1 (Siddique and Klaus, 2009). A typical chemical composition of MK according to

Ambroise et al. (1994) is given in Table 2.2.

Table 2. 1 Physical properties of MK (Siddique and Klaus, 2009)

Property	Value
	2.60
Specific Gravity	0.3 to 0.4
Bulk Density	g/cm ³
Physical Form	Powder
Color	Off-White
GE Brightness	79-82 Hunter
Mean Particle Size	L
	6 μm

Table 2. 2 Percentages of Chemical ingredients of MK (Ambroise et al., 1994)

Oxides	% by Weight
SiO ₂	51.52
Al ₂ O ₃	40.18
Fe ₂ O ₃	1.23
CaO	2.0
MgO	0.12
K ₂ O	0.53
SO ₃	0.0
TiO ₂	2.27
Na ₂ O	0.08
Loss on Ignition	2.01

2.2.2 Advantages of Metakaolin Usage

The use of MK in concrete has many advantages over concrete. These advantages are listed below (Siddique and Klaus, 2009):

- Enhanced compressive and tensile strengths,

- Lower permeability values,
- Higher resistance to chemical attack,
- Higher durability,
- Low effects of alkali-silica reactions (ASR),
- Lower shrinkage,
- Improved workability of concrete and better finishing surface of concrete,
- Low efflorescence potential,
- Enhanced finish ability, color and appearance.

2.2.3. Formation of Metakaolin and its Reaction Mechanism

MK is a thermally activated cementitious material that is obtained by the calcinations of kaolinite (Mermerdaş, 2013). Kaolinite (Figure 2.7) is a clay mineral and its chemical composition can be formulated as $\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$ (hydrated aluminum disilicate). It is one of the silicate mineral that has a layered structure (Figure 2.8).

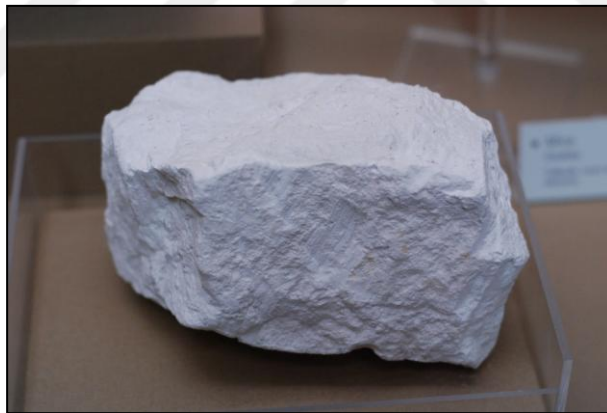


Figure 2. 7 Kaolinite

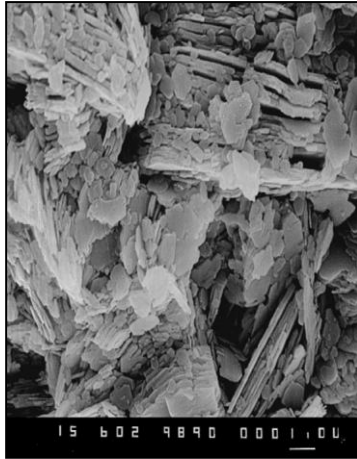


Figure 2. 8 Layered structure of kaolin (Rashad, 2013)

Kaolinite-rich rocks (contain %40-70 kaolinite) are known as kaolin. In the state of nature, kaolin is quite stable, however during calcination process kaolin heated to 650-900 C° and it loses approximately 14% of its mass in bound hydroxylions. This process causes breakage of structure of kaolin so that the alumina and silica layers in kaolin lose their long-range order. MK ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) is formed after this dehydroxylation stage (Rashad, 2013).

The main reaction occurs between MK and Calcium Hydroxide (CH) derived from cement hydration. Additional cemented Calcium Silicate Hydrate (C-S-H) gel and crystalline products are formed during this reaction. The MK/CH ratio and temperature of reaction affect the formation of crystalline products (Siddique and Klaus, 2009).

Reactivity level of MK is the most significant factor in the hydration reaction. Chapelle Test is used for determination of reactivity level of MK, and this level is uttered as the ratio of CH per gram of pozzolans (Kostuch et al., 1993; Asbridge et al., 1994).

Thermogravimetric analysis (TG) and differential thermal analysis (DTA) could be utilized for determination of quantity of Calcium Hydroxide in hardened concrete. The reactivity rate of pozzolans could also be evaluated by chemical determination of unreacted pozzolan in hydrated Portland cement (PC)-pozzolan pastes (Siddique and Klaus, 2009). According study of Kostuch et al. (1993), 20% replacement of

cement by MK was required to fully remove all the CH in concrete at 28 days. On the other hand, according study of Oriol and Pera (1995) it is reported that 30-40% MK is needed for removing all of the CH in MK-PC paste at a W-B (Water to binder) ratio of 0.5 in the case of curing in lime-saturated water for period of 28 days.

2.2.4 Effect of MK on the fresh properties of concrete

Metakaolin has a great affect in terms of improvement in the constructability and workability, also it saves energy and time on finishing and pumping of fresh concrete, when it is used with proper amount of superplasticizers (Shekarchi et al., 2010). According to experimental studies of Brooks et al. (2000), a 30% decreasing of slump and a 20% setting times retardation were observed when using 15% MK in concrete. Shekarchi et al. (2010) pointed that using MK has an accelerating effect for the initial setting time of concrete; but it is not going to affect the final set time. Moulin et al. (2001) observed that using 20% of different types of MK cause retardation in a range of 0–95% in initial setting time and 14–64% for final setting time. The inconsistencies are due to fineness of different kind of MKs, the usage percentages and performance of different plasticizers those are used in different tests.

Badogiannis et al. (2005) and Batis et al. (2005) tried to explain the water need and setting times of MK included cements in their experimental studies. Badogiannis et al. (2005) used four different types of MKs (MK1, MK2, MK3 and MK4) those obtained from poor Greek kaolins and a commercially available MK (MKC) of high purity. The authors have reached the these results; blended cements with MK needed substantially more water than the pure cement and the MK content affected both setting times of blended cements with MK. According this study, cements with 10% MK has similar setting times to that pure cement and cements with 20% MK content caused a delay in the setting time. Water demand and setting times of blended cements with MK those obtained from the study of Badogiannis et al. (2005) are shown in Table 2.3.

In the study of Batis et al. (2005) MK that was derived from poor Greek kaolin that has low kaolinitic clay capacity was used and it was reported that increasing the

amount of the MK causes a more demand of the water. Pure cement that includes 10% MK (MK-10) had the lower water demand than the normally blended cements. The both setting times of MK cements is higher than those of pure cement. The results of the study of Batis et al. (2005) are shown in Table 2.4.

Table 2. 3 Setting times and water needs of cements with MK (Badogiannis et al., 2005)

Sample	Metakaolin (% mass)	Water Demand (% mass)	Setting Time (min)	
			<i>Initial</i>	<i>Final</i>
PC	-	27.5	105	140
MK1-10	10	29.0	75	130
MK2-10	10	29.0	85	130
MK3-10	10	32.0	105	160
MK4-10	10	32.5	155	180
MKC-10	10	31.0	95	130
MK1-20	20	32.0	105	160
MK2-20	20	31.5	110	165
MK3-20	20	38.5	120	160
MK4-20	20	41.0	205	230
MKC-20	20	37.5	140	170

Table 2. 4 Setting times and water need of cements with MK (Batis, 2005)

Sample	Metakaolin (% mass)	Water Demand (% mass)	Setting Time (min)	
			<i>Initial</i>	<i>Final</i>
PC	-	27.5	105	140
MK-10	10	32.5	155	180
MK-20	20	41.0	205	230
MKC-20	20	37.5	140	170

2.2.5 Effect of MK on the hardened characteristics of concrete

Hardened characteristics of concrete are determined by determination of pore size distribution, water absorption, sorptivity, compressive strength, tensile strength,

bending strength, corrosion resistance, creep resistance, shrinkage resistance etc. of the concrete samples.

2.2.5.1 Pore size distribution

Pore size distribution is one of the most significant effects of the additional cementitious materials (Mermerdaş, 2013). Bredy et al. (1989) used different percentages of MK in cement pastes and tried to determine pore size distribution of these mortars. They observed the porosity of the pastes was decreased when MK content was below 20% but above 30% content porosity was increased. This increase caused by increasing water to binder ratio. Khatib and Wild (1996) conducted a study for determination of the porosity and pore size distribution of cured Ordinary Portland Cement with metakaolin paste. It is written that the MK cause refinement of the pore structure and increase in MK content cause decreasing of threshold value of paste. Frías and Cabrera (2000) conducted a study for investigation of the effectiveness of metakaolin over the pore size distribution of cement pastes containing 0%, 10%, 15%, 20% and 25% of MK. They reported that the pastes of MK mixtures used in experiment have greater porosity values than the Ordinary Portland Cement (OPC) paste and a rise about 16% was observed.

2.2.5.2 Sorptivity and water absorption

According to the study of Khatib and Mangat (1995), sorptivity coefficients those belong to highest points of concrete cube could be much greater than coefficients taken from lowest points of the cube and carbonation affects the sorptivity of concrete. Dias (2000) reported that carbonation of the free zone cause a reduction in sorptivity. In the study of Courard et al. (2003), it is showed that the increase of MK percentage in concrete cause an increase of water absorption (WA) at 28 days and 14 months periods. Also, Khatib and Clay (2004) noted that the higher MK content cause higher water absorption (WA) capacity of concrete mixtures for all curing times (Figure 2.9).

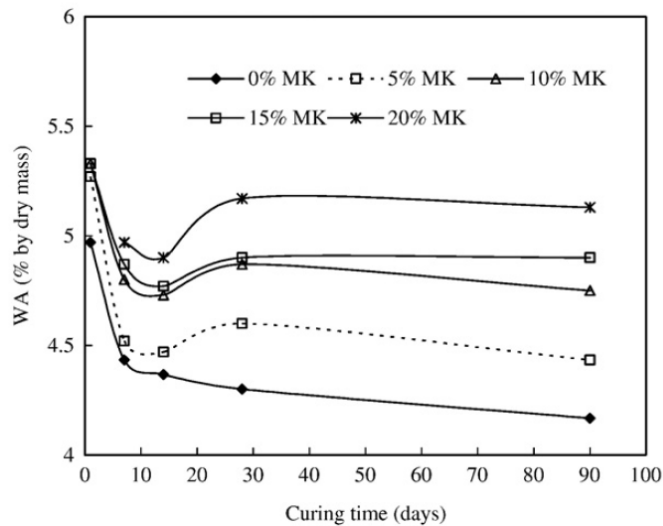


Figure 2. 9 Water absorption-curing time graph of MK including concrete (Khatib and Clay, 2004).

2.2.5.3 Compressive strength

Compressive strength values of concrete increase when MK used as cement replacement material (Brooks and Johari 2001). The compressive strength results of Brooks and Johari (2001) showed that maximum strength value obtained with %20 MK replacement (Table 2.5). Wild et al. (1996) obtained optimum replacement level of MK that gives the highest long term strength enhancements as 20%. On the other hand, Li and Ding (2003) found that the optimum replacement level with 10% MK content.

Table 2. 5 Compressive strength of MK including concretes (Brooks and Johari 2001).

Concrete mixes	Compressive strength (MPa)
OPC	78.0
MK5	91.5
MK10	104.0
MK15	103.5

In the study of Badogiannis et al. (2005) the compressive strength of concrete including MK was tried to explain up to 180 days. Five types of metakaolins: MK1, MK2, MK3, MK4 obtained from Greek kaolins and commercial metakaolin (MKC)

were used in this study. The authors reported that MK had great effect in terms of cement strength after 2 days, especially at 28 and 180 days. They proved that using 10% MK content in concrete gives better results than using %20 MK content.

According to the study of Güneyisi et al. (2012), concretes were produced with cement and 5-15% MK. It is indicated that MK including concretes have higher strength than that of normal concretes at two different water-to-cementitious material ratios (0.25 and 0.35). The result of the study is shown in Figure 2.10.

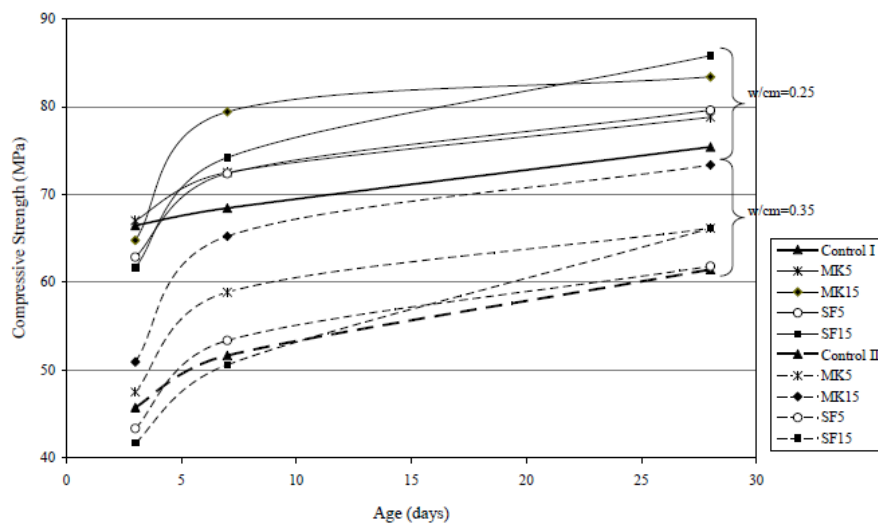


Figure 2. 10 Effect of SK and MK on compressive strength (Güneyisi et al. 2012),

2.2.5.4 Tensile and bending strength

For investigation of tensile and bending strength of MK including concretes Qian and Li (2001) conducted a study. They used four different percentages of MK (0%, 5%, 10%, and 15%) as cement replacement material. At the end the study it was observed that the tensile and bending strength of concrete were increased depending on the increasing level of MK replacement. The result of their study is shown in Table 2.6.

Table 2. 6 Tensile and bending strength of concrete specimens include MK (Qian and Li, 2001)

Metakaolin Content (% mass)		<i>0%</i>	<i>5%</i>	<i>10%</i>	<i>15%</i>
Strength Type	Tensile strength (MPa)	3.35	3.58	3.88	4.29
	Bending strength (MPa)	4.65	4.74	6.16	6.40

Courard et al. (2003) studied the impact of MK on the bending strength of cement paste. In this study cement was replaced with 5–20% of MK. It is stated that replacement of cement with MK caused decreasing of the bending strength after 72 hours curing period. However, after 28 day mortar containing MK gives higher strength (Figure 2.11). Karaoğlu et al. (2012), produced concretes with 5% and 15% replacement level of MK. The highest splitting tensile strengths were obtained for specimens those include 15% replacement of silica fume (SF) and MK. The splitting tensile strength results of the study were presented in Figure 2.12.

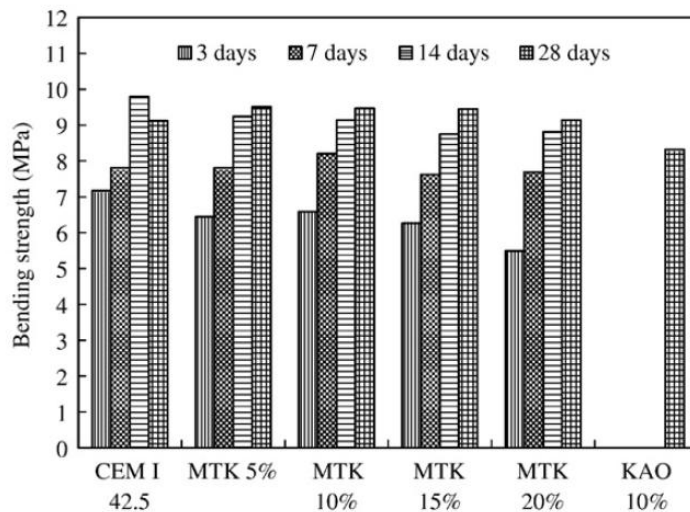


Figure 2. 11 Bending strength of mortar containing MK and kaolin Courard et al. (2003)

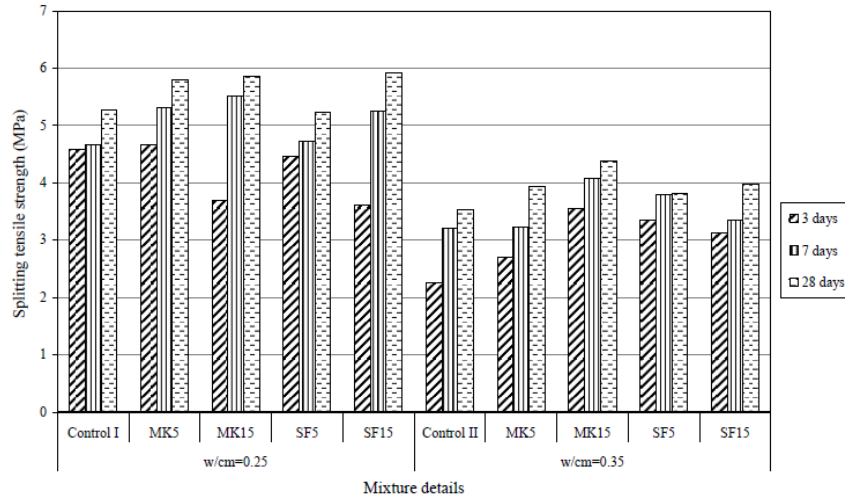


Figure 2. 12 Effect of SF and MK on splitting tensile strength Karaoğlu et al. (2012)

2.2.5.5 Creep, Shrinkage and Corrosion resistance

When MK is used at certain percentages has positive effect in terms of corrosion resistance concrete. Batis et al., 2005 reported that when MK used as sand and cement replacement material up to 20% and 10% respectively, an improvement of the corrosion behavior of paste concrete samples was observed.

Brooks and Johari (2001) conduct an experimental study for investigating of the effect of MK on the creep and shrinkage, time dependent properties of concrete. They produced concrete mixtures including 0%, 5%, 10%, and 15% of MK. This study showed that at early days, as the usage percentage of MK increased the autogenous shrinkage was reduced whereas at long-term, increasing of MK content caused increase of autogeneous shrinkage. The total shrinkage of drying concrete samples after 24 hour is shown in Figure 2.13. The use of MK reduced the total and basic creep of concrete and increasing of MK content caused higher reduction in creep. In terms of basic creep, approximations for low percentages of MK were acceptable however, for high percentages, creep was unpredictable. The 200-day specific drying creep, variation between the basic creep and total creep, was also decreased for MK including concretes. The influence of MK on total creep of concrete is shown in Figure 2.14.

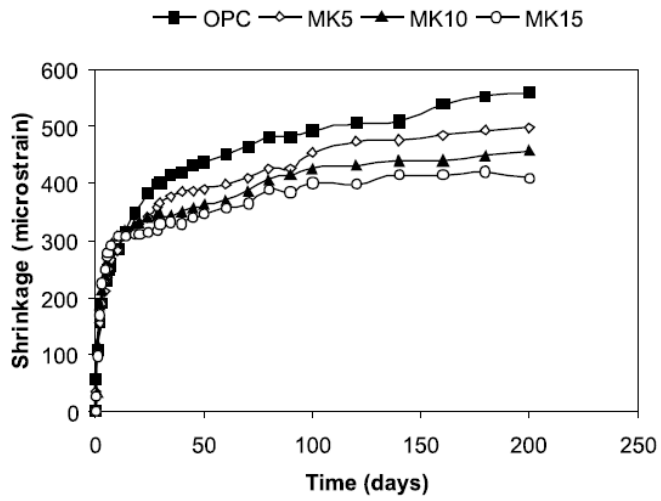


Figure 2. 13 The drying shrinkages of concrete samples (Brooks and Johari, 2001)

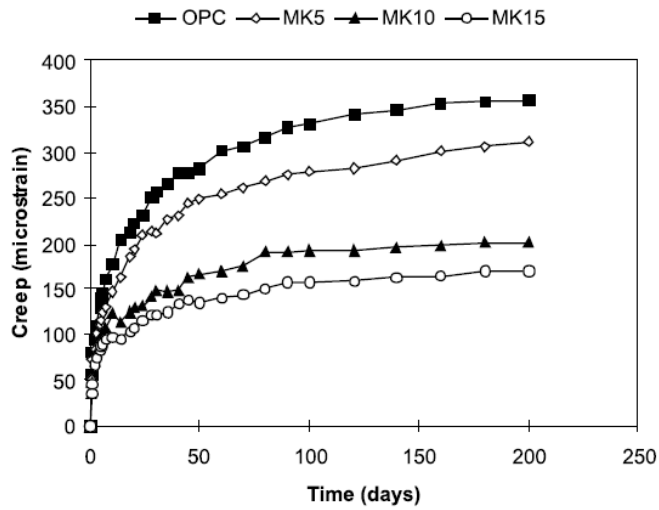


Figure 2. 14 Influence of MK on total creep of concrete (Brooks and Johari, 2001)

CHAPTER 3

EXPERIMENTAL STUDY

In the experimental study, kaolin-free self compacting concretes (SCC) and self compacting concretes incorporating calcined impure kaolins (CK) were produced for determination of the hardened properties of the SCC. In addition, SCC incorporation high reactivity metakaolin (MK) was produced for comparison purposes.

3.1 Materials

3.1.1 Cement

PC 42.5R (CEM I 42.5R) type cement was used for production of different type of SCCs. The specific gravity of cement is 3.13 and its Blaine fineness of 3380 cm²/g. The technical details and chemical composition of the cement are respectively tabulated in Table 3.1 and Table 3.2.

Table 3. 1 Technical details of CEM I 42.5R

Property	Unit	Normative Value	Average Value
Water Demand	%	N/A	28.4-30.0
Initial Setting Time	min	≥ 60	100-180
Compressive Strength (2 days)	MPa	≥ 20	27.5-33.5
Compressive Strength (28 days)	MPa	≥ 42.5, ≤ 62.5	54.0-59.0

Table 3. 2 Chemical composition of the CEM I 42.5R

Chemical composition of the cement (%)								
CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	SO ₃	K ₂ O	Na ₂ O	LOI
63.6	19.49	4.54	3.38	2.63	2.43	0.72	0.22	2.99

3.1.2 Calcined kaolins and metakaolin

Turkish kaolin used in the present study was obtained from a quarry located in Balıkesir province (Sındırgı district – Düvertepe village). This kaolin was subjected to 3 hours calcination process before being used in experimental study. Powdery white Metakaolin (MK) utilized in the study was obtained from the Czech Republic. It has a Dr Lange whiteness value of 87 and a specific gravity of about 2.60. Its specific surface area (Nitrogen BET Surface Area) is 18000cm²/g. Chemical, physical and mineralogical properties of calcined impure kaolin (CK) and commercially available Czech metakaolin are given in Table 3.3.

Table 3. 3 Chemical, physical and mineralogical properties of the calcined Turkish kaolins and Czech metakaolin

	Compound	CK	MK
Chemical Properties (%)	CaO	2.22	0.5
	SiO ₂	69.78	53
	Al ₂ O ₃	24.16	43
	Fe ₂ O ₃	0.69	1.2
	MgO	0.89	0.4
	TiO ₂	0.48	0.8
	LOI	0.73	0.4
	Physical Properties	Specific Gravity	2.6
Fineness (cm ² /g)		7430*	18000*

*BET (Brunauer–Emmett–Teller) nitrogen adsorption method

3.1.3. Aggregates

Fine and coarse aggregates utilized in this experimental study were obtained from regional limestone quarry. The gradation of aggregates is closed to Fuller's curve as shown in Figure 3.1. The characteristics of the fine and coarse aggregates are tabulated below (Table 3.4).

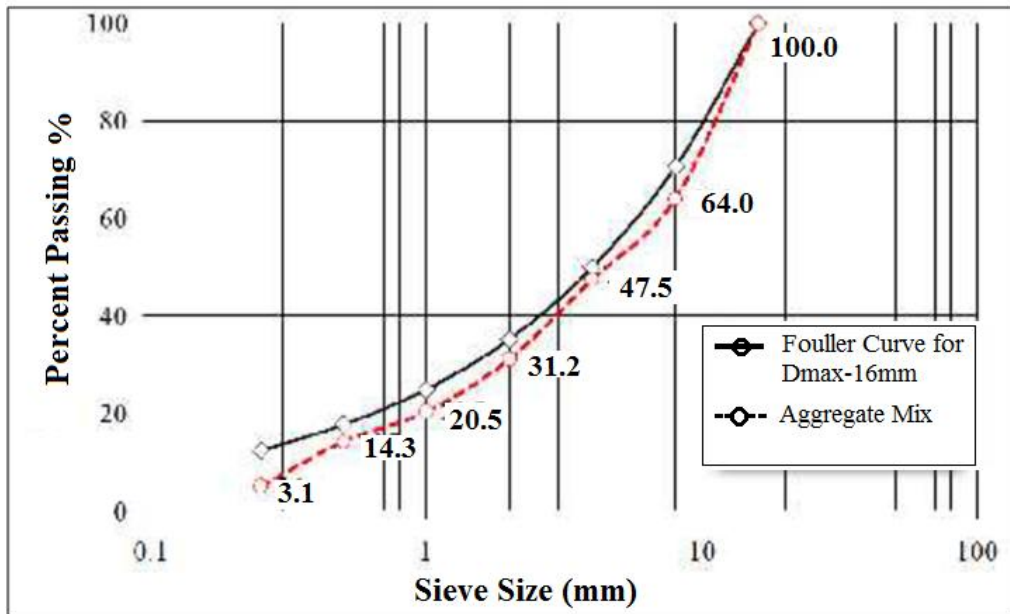


Figure 3. 1 Aggregate grading curves

Table 3. 4 The characteristics of the aggregates used in study

Property	Fine Aggregate	Coarse Aggregate
Fineness Modulus	3.38	5.68
Specific Gravity	2.45	2.72
Water Absortion (%)	0.95	0.45

3.1.4. Superplasticizer

A high range water reducing admixture (HRWRA) that has a specific gravity of 1.07 and pH value of 5.7 was utilized in experimental study to get a consistent workability for SCC mixtures. HRWRA is used in the study is polycarboxylic ether type water reducing admixture commonly used in SCC production.

3.2 Mix Proportions

In this study, SCC mixtures with W/B ratio of 0.35 and binder replacement levels 0%, 5% and 10% were produced. The total binder content was 550 kg for 1 m³ mixture. Portland cement (PC) and thermally treated kaolins, MK and CK, were utilized in experiments. Control mixtures were produced only with Portland cement. Details of the mixes of SCCs are given in Table 3.5. The concretes were produced to provide a slump flow diameter of 700±20 mm. These properties were obtained by

using HRWRA at different percentages.

Table 3. 5 Information of the mix proportions of SCCs

Type of Calcined Kaolin	Replacement Level (%)	Mix ID	Cement	Calcined Kaolin	Water	Coarse Aggregate	Sand	HRWRA
None	0	Control	550	0	192.5	790.9	750.6	7.43
MK	5	MK5	522.5	27.5	192.5	787.4	747.2	8.25
	10	MK10	495	55	192.5	783.4	743.5	9.35
CK	5	CK5	522.5	27.5	192.5	787.4	747.2	8.25
	10	CK10	495	55	192.5	783.4	743.5	9.35

3.3 Test Methods

3.3.1 Compressive strength

Compressive strength test applied 15x15x15 cm cube specimens according to ASTM C39 / C39M-16b (ASTM, 2016) standard and the test machine has 3000 kN loading capacity. Cube specimens tested at the ages of 3, 7, 28, and 56 days for determination of compressive strength developments. Three samples were tested and the results obtained by averaging three compressive strength result for each age.

3.3.2 Water permeability

Water permeability test applied the concrete specimens according TS EN 12390-8 (TS, 2002) standard. After being placed in the test machine, the specimens were exposed to a downward water pressure 500 ± 50 KPa for 72 ± 2 hours. After 72 ± 2 hours of pressure application, the test specimens are split in half perpendicular to water applied surface and the highest penetration depth of water is measured in mm. During the experiment, unpressurized surfaces of test sample were observed at certain intervals and the presence of water on the surfaces recorded. Permeability test arrangement and the photograph of the water permeability test equipment are respectively figured in Figure 3.2 and Figure 3.3.

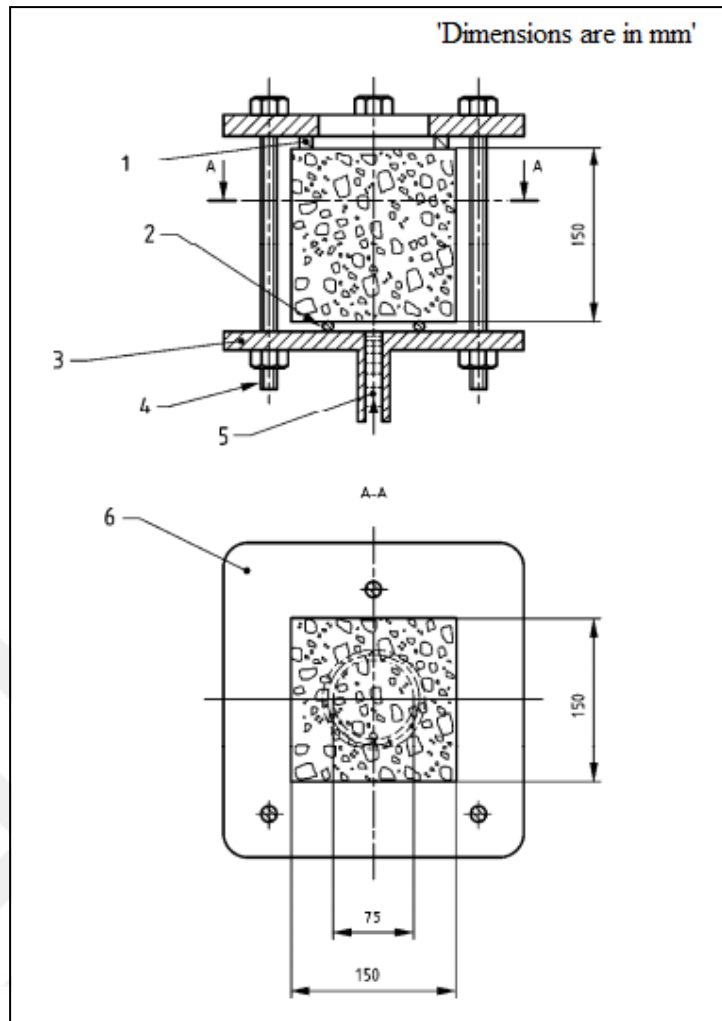


Figure 3. 2 Permeability test arrangement (1 Packing Piece, 2 Sealing ring, 3 Screwed on plate, 4 Screw-threaded rod, 5 Water under pressure, Screwed on plate) (TS, 2002)

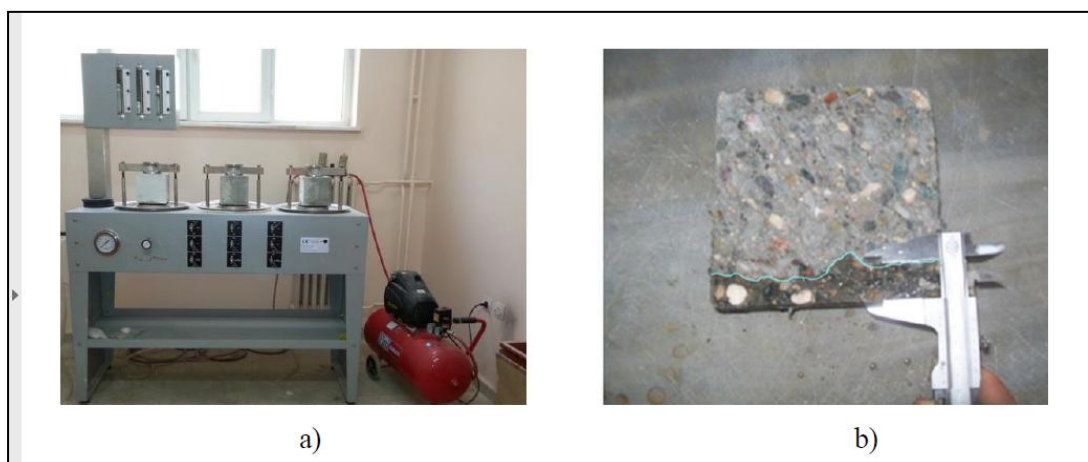


Figure 3. 3 Water permeability test: a) device and b) measurement of penetration depth.

3.3.3 Gas Permeability

Cembureau Method is utilised for measurement of the gas permeability of the concrete specimens (RILEM, 1999). Experimental study was performed in a room with a controlled temperature of $20^{\circ}\text{C} \pm 2^{\circ}\text{C}$ without excessive air circulation close to the test apparatus. The test specimens had a thickness of $50 \text{ mm} \pm 1 \text{ mm}$ and a diameter of $150 \text{ mm} \pm 1 \text{ mm}$. For characterization of concrete three test specimens were used. After applying the test procedures, average flow rates evaluated for each specimen and then gas permeability coefficient K_i was calculated according formula given in Eqn (3.1). Mean coefficient value obtained from three values of K_i . Set-up of gas permeability test is shown in Figure 3.4 and Figure 3.5 and also schematic representation of concrete specimen that is placed in permeameter cell shown in Figure 3.6.

$$K_i = \frac{2P_a Q_i L \mu}{A(P_i^2 - P_a^2)} \quad (3.1)$$

Where, K_i is coefficient of gas permeability (m^2), P_i is inlet gas pressure (N/m^2), P_a is outlet gas pressure (N/m^2), A is cross-sectional area of the sample (m^2), L is height of sample (m), μ is viscosity of oxygen ($2.02 \times 10^{-5} \text{ Nsn}/\text{m}^2$) and Q_i is rate of flow of air bubble (m^3/sn).

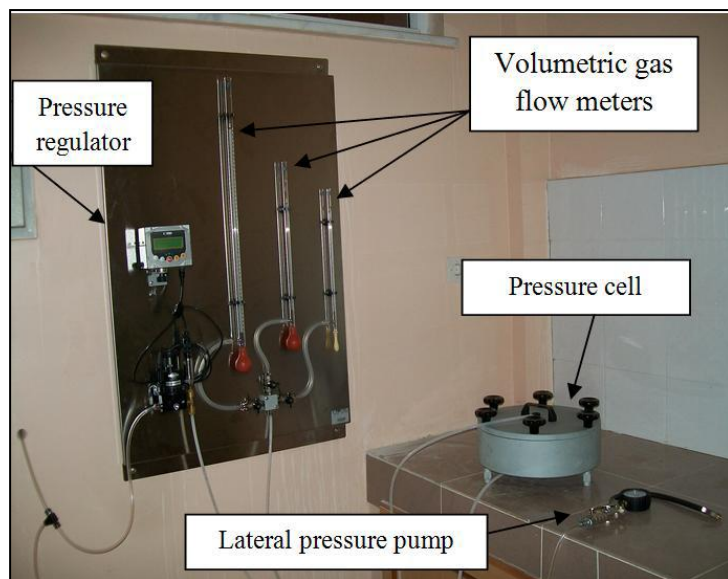


Figure 3. 4 Set-up of gas permeability test.

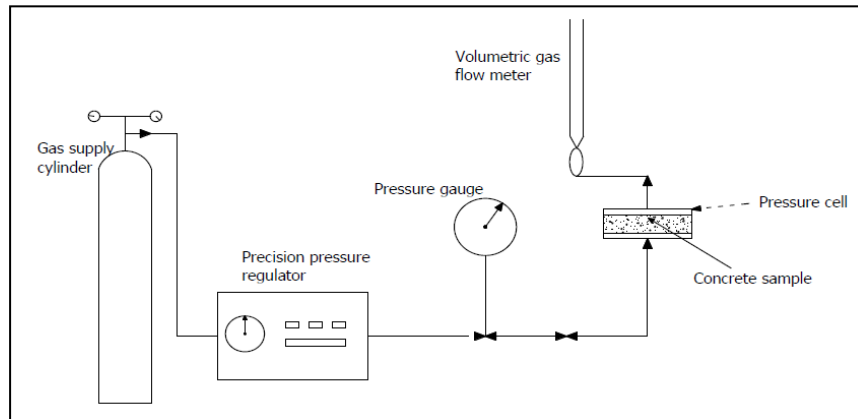


Figure 3. 5 Layout of the experimental gas permeability test.

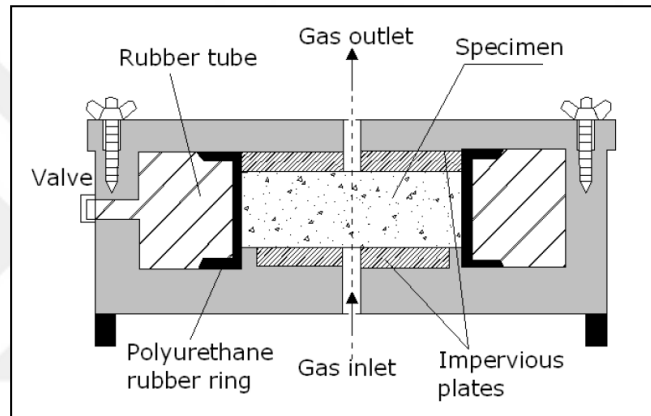


Figure 3. 6 Schematic representation of concrete specimen that is placed in permeameter cell

3.3.4 Water absorption

Water absorption test was applied to SCC specimens according to BS 1881 (Part 122) standard (BS, 1983). Three concrete specimens were placed in the drying oven so that each one is not less than 25 mm from any heating surface or from each other. After 72 ± 2 hours, specimens were removed from the oven, and next they were cooled at 24 degree for 24 ± 0.5 h in the dry airtight vessel. All specimens were weighed and immersed in water filled tank for 30 ± 0.5 min. At the end of the specified time they were removed from the water, dried with a dry towel and weighed again.

3.3.5 Sorptivity

To perform the sorptivity test, three samples with dimensions of $\text{Ø}100 \times 50$ mm were used. Test samples were dried at 50°C until getting constant mass. Afterward specimens were cooled in a closed vessel at room temperature. Paraffin was used for coating of sides of specimens. Afterwards, specimens were placed in the experimental setup such that lower part of the sample up to 5 mm was in contact with water as shown in Figure 3.7. Specimens were weighed at specific time intervals until 1 hour. For each time, absorbed water volume was found. The results are plotted versus the square root of time. The sorptivity coefficients of concrete were found as the slope of the best fit line. For each test, the average values of three specimens were calculated. The sorptivity test was done at the ages of 28 and 56 days.

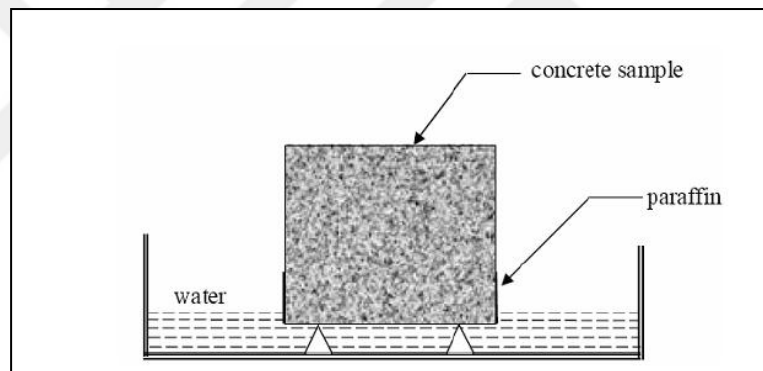


Figure 3. 7 Sorptivity test set-up

3.4 Cost Analysis

Cement, water, aggregates, chemical admixtures and mineral admixtures are the main components of concrete. When cost analysis of concrete is carried out, the usage quantities and prices of these components are taken into account.

In this study, five types of SCC mixtures including control mixture were produced with 0%, 5% and 10% replacement level of MK and CK (Control, MK5, MK10, CK5, and CK10). Control mixture contains only PC (CEM I 42.5R) and other

mixtures were produced by using PC and MK/CK. The amounts of water used in the entire mixtures were equal. Sikament® 98 was used in this study as HRWRA.

The cost analysis was performed for the Control, MK5, MK10, CK5, and CK10 mixtures. Firstly, the price and quantity of each material were determined for calculation of total cost of 1 m³ SCCs. Then the total costs of mixtures were compared with control mixture. As it is seen in the Table 3.6, the costs of 1m³ of mixtures are range between 272 TL to 317 TL and the costs of MK5, MK10, CK5 and CK10 mixtures are higher than that of Control mixture by 8%, 15.9%, 4% and 8%, respectively. The highest cost was obtained for %10 MK incorporated SCC as 317.58 TL. It is observed that as the amount of MK or CK used in the mixtures increased, the total costs increased. In Figure 3.8, the total costs of mixtures were illustrated.

Table 3. 6 Cost of 1 m³ SCCs produced with a) only PC (Control Sample) b) 95% PC and 5% MK c) 90% PC and 10% MK d) 95% PC and 5% CK e) 90% PC and 10% CK 0.17

a)

	Type of Ingredients	Unit Price (TL)	Total Usage (kg or lt)	Total Price (TL)
Control Sample	Cement CEM I 42.5R (kg)	0.31	550	170.50
	Water (lt)	0.003	192.5	0.58
	Coarse Aggregate (kg)	0.055	790.9	43.50
	Sand (kg)	0.055	750.6	41.28
	HRWRA Sikament® 98 (kg)	2.25	7.43	16.17
	Czech Metakaolin (kg)	1.065	0	0.00
	Turkish Kaolin (kg)	0.71	0	0.00
				Cost of SCC per 1m ³

b)

	Type of Ingredients	Unit Price (TL)	Total Usage (kg or lt)	Total Price (TL)
MK5	Cement CEM I 42.5R (kg)	0.31	522.5	161.98
	Water (lt)	0.003	192.5	0.58
	Coarse Aggregate (kg)	0.055	787.4	43.31
	Sand (kg)	0.055	747.2	41.10
	HRWRA Sikament® 98 (kg)	2.25	8.25	18.56
	Czech Metakaolin (kg)	1.065	27.5	29.29

Turkish Kaolin (kg)	0.71	0	0.00
Cost of SCC per 1m ³			294.8

c)

	Type of Ingredients	Unit Price (TL)	Total Usage (kg or lt)	Total Price (TL)
MK10	Cement CEM I 42.5R (kg)	0.31	495	153.45
	Water (lt)	0.003	192.5	0.58
	Coarse Aggregate (kg)	0.055	783.4	43.09
	Sand (kg)	0.055	743.5	40.89
	HRWRA Sikament® 98 (kg)	2.25	9.35	21.03
	Czech Metakaolin (kg)	1.065	55	58.58
	Turkish Kaolin (kg)	0.71	0	0.00
	Cost of SCC per 1m ³			317.58

d)

	Type of Ingredients	Unit Price (TL)	Total Usage (kg or lt)	Total Price (TL)
CK5	Cement CEM I 42.5R (kg)	0.31	522.5	161.98
	Water (lt)	0.003	192.5	0.58
	Coarse Aggregate (kg)	0.055	787.4	43.31
	Sand (kg)	0.055	747.2	41.10
	HRWRA Sikament® 98 (kg)	2.25	8.25	18.56
	Czech Metakaolin (kg)	1.065	0	0.00
	Turkish Kaolin (kg)	0.71	27.5	19.53
	Cost of SCC per 1m ³			285.04

e)

	Type of Ingredients	Unit Price (TL)	Total Usage (kg or lt)	Total Price (TL)
CK10	Cement CEM I 42.5R (kg)	0.31	495	153.45
	Water (lt)	0.003	192.5	0.58
	Coarse Aggregate (kg)	0.055	783.4	43.09
	Sand (kg)	0.055	743.5	40.89
	HRWRA Sikament® 98 (kg)	2.25	9.35	21.03
	Czech Metakaolin (kg)	1.065	0	0.00
	Turkish Kaolin (kg)	0.71	55	39.05
	Cost of SCC per 1m ³			298.11

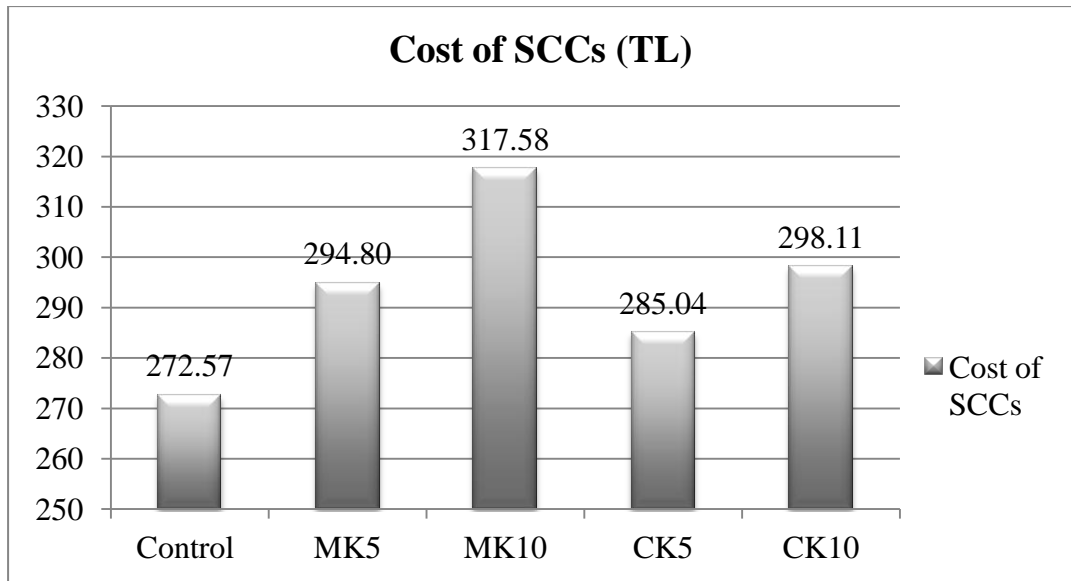


Figure 3. 8 Cost of 1 m³ of SCCs

CHAPTER 4

TEST RESULTS AND DISCUSSIONS

4.1 Results of Compressive Strength Test

Age-related compressive strength of the SCCs produced with calcined Turkish kaolins (CK) and the Czech metakaolin (MK) are given in Table 4.1 and graphically presented in Figure 4.1. There are 5 mixture types in total: Control mixture, MK5, MK10, CK5 and CK10. The increase in compressive strength of concrete is due to both microfilling and hydration of mineral admixture with Portlandite (Siddique et al., 2009; Badogiannis et al., 2005; Shvarzman et al., 2003; Mermerdaş et al., 2013; Mermerdaş et al., 2012). Control mixtures, SCCs without MK or CK, gain their strength with hydration of PC, however MK or CK used SCCs gain their strength with both hydration of PC and pozzolanic reactions of MK or CK. According to the Table 4.1, the compressive strength of control mixture ranged between 62.2 and 70.2 MPa. MK and CK used SCC mixtures have compressive strength values of 60.2-83.5 MPa and 59.8-77.8, respectively.

When 3-day compressive strength values of all mixtures are examined, they seem to be close all together with the exception of CK10. The strength value of control mixture is slightly higher than all and strength performance of MK replacement SCCs are slightly higher than CK replacement SCCs for this time period. As the cure time elongates, the values of compressive strength are better understood.

When the mixing percentages of the same type of concrete are compared MK10 mixtures have better compressive strength performance than MK5 mixtures for all curing periods except 3 day curing period. For SCCs containing CK, CK5 mixtures show better performances for 3 and 7 day curing periods however CK10 mixtures show better performance for 28 and 56 day curing periods.

After 56 days, the highest compressive strength result (83.5 MPa) is achieved with 10% MK incorporating SCCs. Second best performance (78.4 MPa) obtained with 5% MK incorporating SCCs. CK incorporating SSCs and control mixtures have lower compressive strength values than MK incorporating SSCs because of fineness level and reactivity level of MK. Inclusion of MK cause improvement of the compressive strength of concrete at all time intervals. In addition, all MK and CK incorporating SSCs showed better performance than control mixture.

Table 4. 1 Compressive strength (MPa) of the SCC mixes

Mixture	Replacement Level (%)	Age (Days)			
		3	7	28	56
Control	0	62.2	65.4	68.6	70.2
MK5	5	60.2	64.1	75.7	78.4
MK10	10	58.7	67.4	78.5	83.5
CK5	5	59.8	65.6	70.6	74.8
CK10	10	53.8	63.9	74.1	77.8

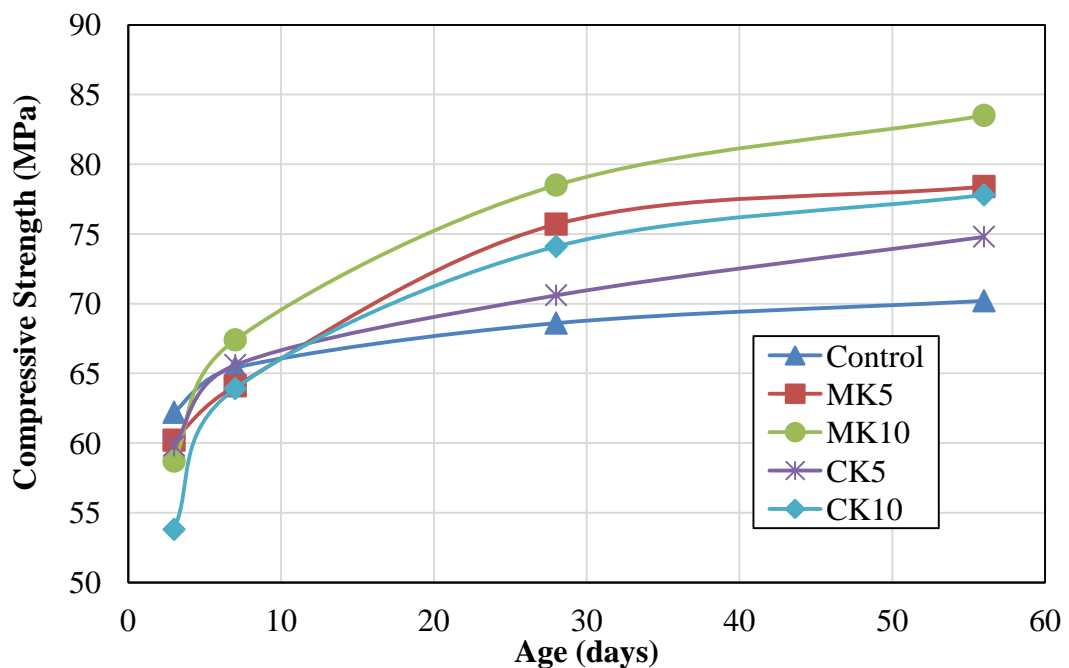


Figure 4. 1 Graphically representation of Compressive strength (MPa) of the SCC mixtures

4.2 Results of Gas Permeability Test

The apparent gas permeability coefficients (K) of the SCCs those produced Turkish kaolins (CK) and the Czech metakaolin (MK) and control mixtures were measured at 28 and 56 days and shown in Table 4.2 and graphically represented in Figure 4.2. The lowest gas permeability coefficients at 28 and 56 days were obtained at 10% MK containing SCCs as $0.952 \times 10^{-16} \text{ m}^2$ and $0.463 \times 10^{-16} \text{ m}^2$, respectively. For the same test periods, the variation of the K coefficients of CK incorporated SCCs were observed in the range of 1.28×10^{-16} - $0.558 \times 10^{-16} \text{ m}^2$. In addition, the highest K values were observed at control mixtures as $1.32 \times 10^{-16} \text{ m}^2$ and $1.16 \times 10^{-16} \text{ m}^2$ at 28 and 56 days, respectively. According table 4.2 increase of the replacement level and measurement period causes decreasing of gas permeability coefficients of MK and CK incorporated SCCs. For the same replacement levels and periods, MK included SCCs have lower K values than CK included SCCs. For instance, at 28 days and 5% replacement level, K values of MK5 and CK5 are $1.15 \times 10^{-16} \text{ m}^2$ and $1.28 \times 10^{-16} \text{ m}^2$.

Table 4. 2 Apparent gas permeability of SCC mixtures ($K \times 10^{-16} \text{ m}^2$)

Mixture	Replacement Level (%)	Age (Days)	
		28	56
Control	0	1.32	1.16
MK5	5	1.15	0.756
MK10	10	0.952	0.463
CK5	5	1.28	0.873
CK10	10	1.12	0.558

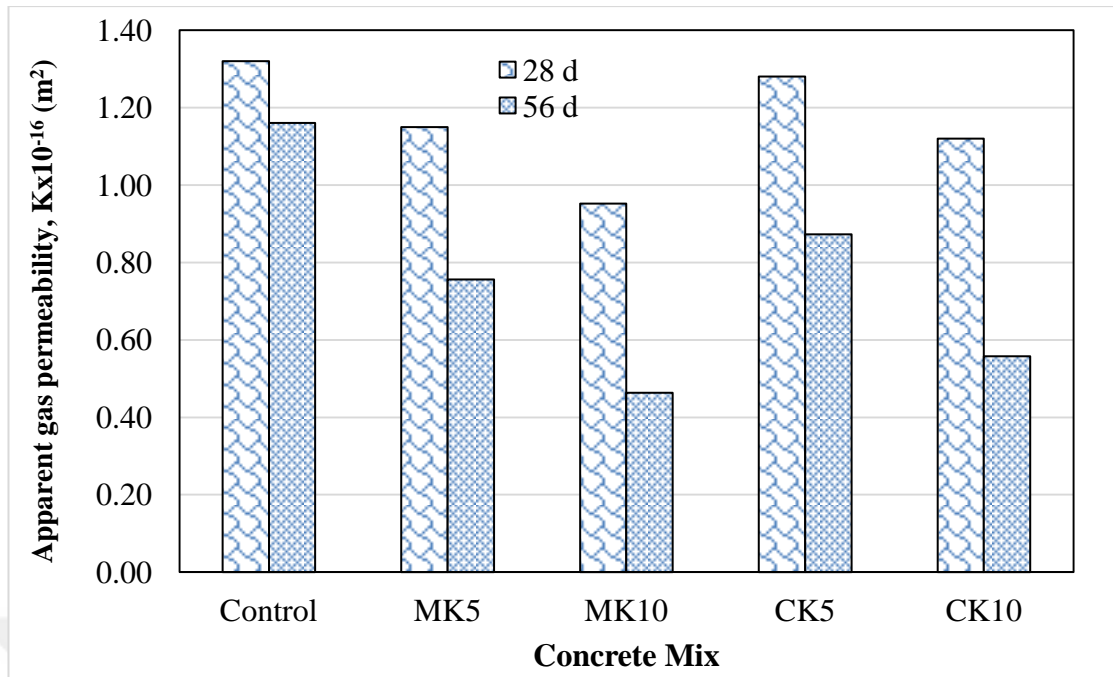


Figure 4. 2 Apparent gas permeability of SCC mixtures

4.3 Results of Water Permeability Test

Permeability of the concrete is the state with which liquids or gasses could travel through in concrete as a result of factors like differential pressure and depth. The results of water permeability test that applied to plain (Control) and mineral admixed SCCs are tabulated in Table 4.3 and graphically demonstrated in Figure 4.3. According to test results the use of MK and CK as mineral additive and cement replacement materials has significantly reduced water permeability of self compacting concrete, depending on replacement level. The lowest penetration depths obtained with 10% MK containing SCCs (MK10) as 6 mm and 3.5 mm at 28 and 56 days whereas the highest depths obtained with control SCCs as 12 mm and 9.5 mm at 28 and 56 days, respectively. The results indicates that the use of 10% MK with portland cement in SCC causes 50-63% reduction in water permeability..

MK and CK incorporated SCCs shows better water permeability performance at later ages because of formation of additional C-S-H gels as a result of pozzolanic reaction. Subsequently formed C-S-H gels lead increasing in the volume of concrete and decreasing the volume of capillary pore system and thus it becomes difficult for liquid water and dissolved ions to move through the pore system. Therefore, the

lowest water permeability values for all the mixtures (Control, MK5, MK10, CK5, CK10) were obtained at the end of 56 days.

Table 4. 3 Water penetration depths (mm) of SCC mixes

Mixture	Replacement Level (%)	Age (Days)	
		28	56
Control	0	12	9.5
MK5	5	8	6
MK10	10	6	3.5
CK5	5	11	9
CK10	10	9.5	6.5

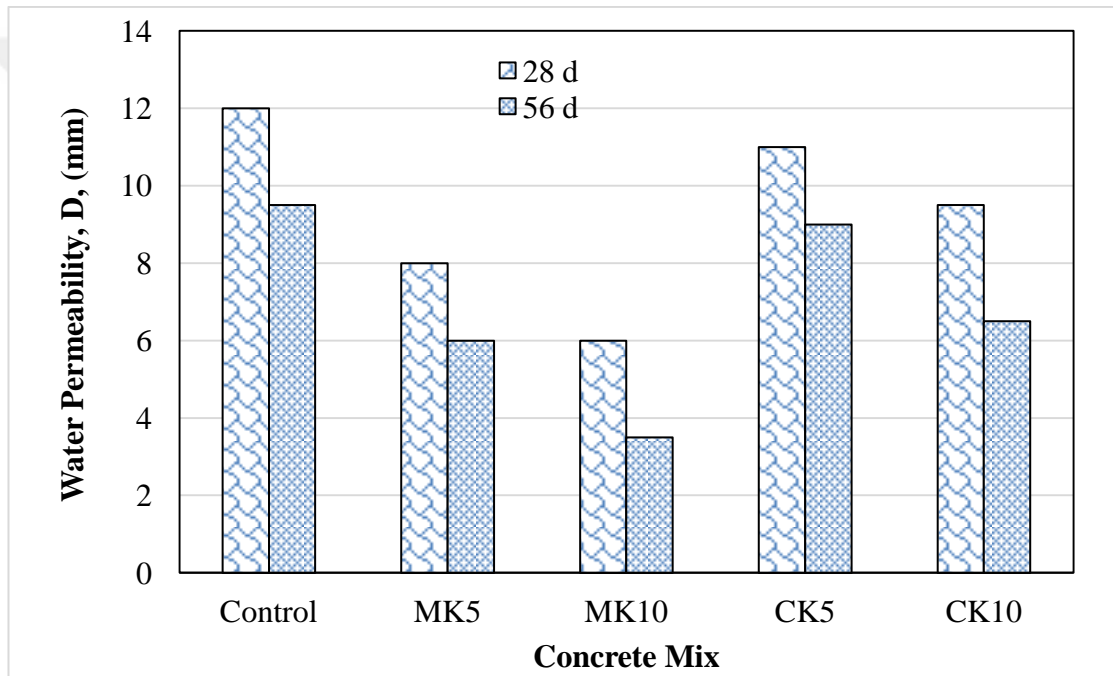


Figure 4. 3 Water penetration depths (mm) of SCC mixes

4.4 Results of Water Absorption Test

Water absorption ratio is one of the most crucial factor that is affecting the durability properties of concrete. Water permeability ratio of concrete depends on the structure and proportion of the pores those located in the concrete. The less absorption of water leads to less permeability of concrete and thus it means more durable concrete. The main factors in the significant and proportional changes in absorption values include usage percentage and particle size of MK and CK in SCC and duration of

curing period of specimens. After experimental work the water absorption values of five types of SCCs (Control, MK5, MK10, CK5, and CK10) were obtained. The results tabulated in Table 4.4 and visualized in Figure 4.4.

When the results of all concrete samples are taken into account the 10% MK containing SCCs have the least water absorption values as %2.8 and %1.8 by weight for 28 and 56 days. The water absorption values of MK, CK and Control SSCs are ranged between 1.8-3.3%, 2-3.5% and 2.8-3.6%, respectively by weight. 5% CK containing SCC absorbed less water than the control sample with a slight difference for 28 days period; however it absorbed more water than the control sample for 56 days period. The results of 10% CK, %10MK and %5MK containing SCCs have lower water absorption values in both periods of 28 and 56 days. Therefore, there may be an experimental mistake for 5% CK containing SCCs. The lowest values were obtained from the control samples in both curing periods with the exception of 56 days CK5 sample.

Table 4. 4 Water absorption values of SCCs (% by weight)

Mixture	Replacement Level (%)	Age (Days)	
		28	56
Control	0	3.6	2.8
MK5	5	3.3	2.5
MK10	10	2.8	1.8
CK5	5	3.5	2.95
CK10	10	3	2

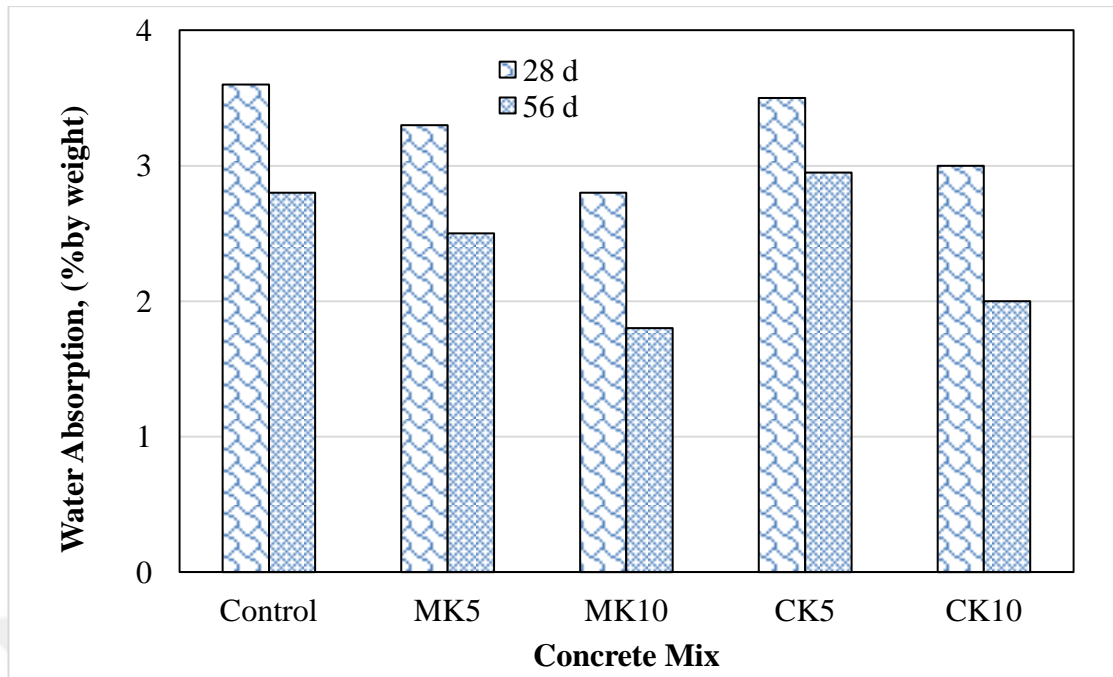


Figure 4. 4 Water absorption values of SCCs (% by weight)

4.5 Results of Water Sorptivity Test

Sorptivity is an index of water transport into unsaturated concrete masses and it is one of the signs of concrete durability. Sorptivity of concrete specimens were calculated according the equations specified in the second part (Eqn (2.3) and Eqn (2.4)). The water sorptivity coefficients (S) of the five types of SCCs (Control, MK5, MK10, CK5, and CK10) and thermally treated kaolin incorporating concretes are shown in Table 4.5 and graphically represented in Figure 4.5. The lowest sorptivity coefficients ($0.082 \text{ mm/min}^{1/2}$ and $0.048 \text{ mm/min}^{1/2}$) obtained with SCCs those contain %10 MK at both ages. According the results, when the MK and CK ratios are increased from 5% to 10%, better results were obtained. For example, 28 days sorptivity coefficients MK5 and CK5 are $0.0955 \text{ mm/min}^{1/2}$ and $0.121 \text{ mm/min}^{1/2}$, on the other hand the coefficients of MK10 and CK10 are $0.082 \text{ mm/min}^{1/2}$ and $0.111 \text{ mm/min}^{1/2}$. The SCC with 5% replacement MK has 21% lower sorptivity coefficient than SCC with 5% replacement CK for 28 days curing period. In addition, MK5 has %20 lower sorptivity coefficient than CK5 for 56 days curing period. According to the previous comparison the sorptivity ratios between the same percentage of MK and CK at different times are almost the same. The most undesirable and the highest coefficients obtained with Control SCCs as 0.133

mm/min^{1/2} and 0.102 mm/min^{1/2} for 28 and 56 days.

Khatib and Clay (2004) studied the water sorptivity properties of the MK incorporated concrete. They reported that use of MK with cement has positive effect on the reduction of the sorptivity.

Table 4. 5 28 and 56 days sorptivity coefficients (mm/min^{1/2}) of SCCs

Mixture	Replacement Level (%)	Age (Days)	
		28	56
Control	0	0.133	0.102
MK5	5	0.0955	0.061
MK10	10	0.082	0.048
CK5	5	0.121	0.076
CK10	10	0.111	0.058

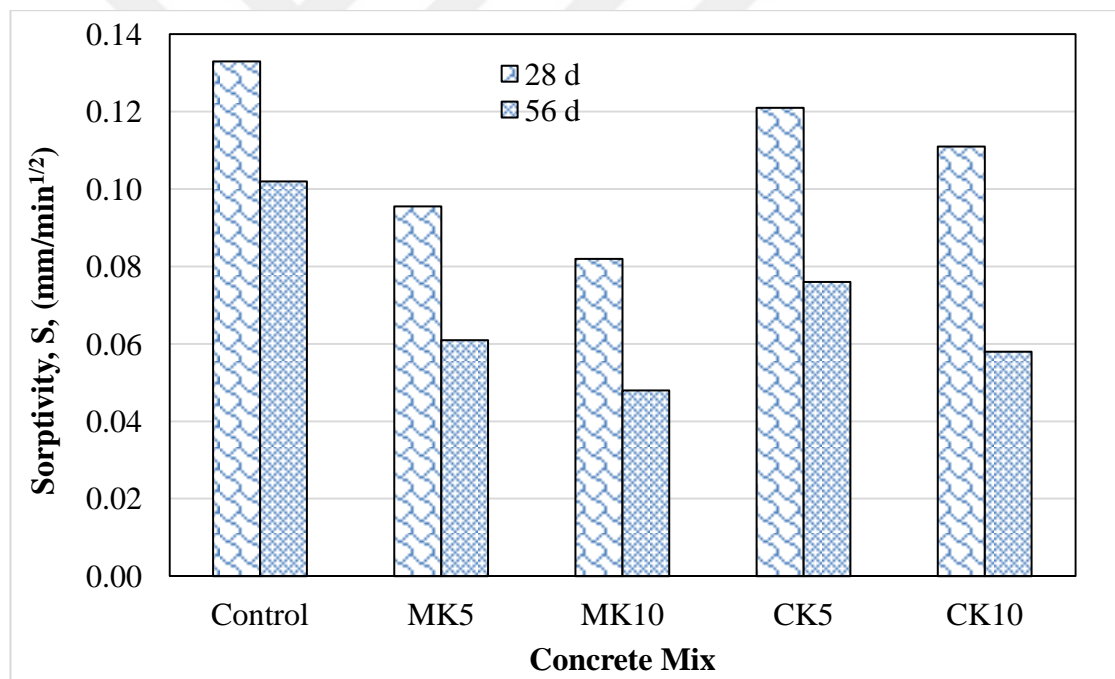


Figure 4. 5 28 and 56 days sorptivity coefficients (mm/min^{1/2}) of SCCs

CHAPTER 5

CONCLUSION

In this experimental study, the effect of high reactivity Czech metakaolin and calcined impure Turkish kaolin on hardened properties of SCC is tried to explain. The conclusions below can be drawn from the findings presented in this experimental study.

- At the end of the compressive strength tests, it was seen that the use of MK and CK improve the compressive strength properties of SCC. After 3 days curing period the strength values of MK5, MK10, CK5 and CK10 were lower than control SCC. The strength improvements were observed after 7 days curing period and reached the maximum levels at 56 days. The best strength values for all the SCC mixtures (MK5, MK10, CK5 and CK10) were obtained at the end of the 56 days. %10 MK modified SCCs (MK10) show the highest strength performance as 83.5 MPa. The optimum replacement levels of MK and CK were found as 10% in terms of SCC strength development. The ranking of the best strength values are as follows: MK10, MK5, CK10 and CK5.
- The use of MK and CK in SCC provided noticeable enhancement in gas permeability of SCCs at 28 and 56 days. The lowest and best gas permeability values were obtained from %10 MK incorporated SCCs as $0.463 \times 10^{-16} \text{ m}^2$. The optimum replacement levels of MK and CK was found as %10 in term of gas permeability. Control SCCs have the highest gas permeability coefficients.
- The lowest water penetration depth was obtained for %10 MK incorporated SCC at 28 days as 6 mm and at 56 days as 3.5 mm. The highest for control SCC as 12 mm at 28 days. %10 replacement levels of MK and CK proved to

be the most effective substitution levels. MK and CK used SCCs have lower water penetration performances than control SCCs for 28 and 56 days.

- The lowest and best water absorption value obtained from %10 MK incorporated concrete as 1.8 % by weight at 56 days. Control SCCs have highest water penetration depths for both 28 and 56 days. %5 replacement levels of MK and CK in SCC showed lower performance than %10 replacement levels.
- Sorptivity test results show that 5% and 10% replacement of MK and CK lead to decrease of sorptivity coefficients of SCCs at 28 and 56 days. The lowest sorptivity coefficients ($0.082\text{mm}/\text{min}^{1/2}$ and $0.048\text{mm}/\text{min}^{1/2}$) obtained with SCCs those contain %10 MK at both ages. Control SCCs have the highest and the most undesirable sorptivity coefficients as $0.133\text{mm}/\text{min}^{1/2}$ and $0.102\text{mm}/\text{min}^{1/2}$ for 28 and 56 days, respectively. 10% replacement levels of MK and CK were found as optimum level in terms of sorptivity.
- According performed cost analysis, MK included SCCs have the highest costs because of the high unit price of MK. In addition MK and CK incorporated SCCs have higher cost than the Control mixture.

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