ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

MECHANICAL AND DURABILITY PROPERTIES OF ALKALI ACTIVATED SLAG CONCRETE

M.Sc. THESIS

Cansu ÇOLAK

Department of Civil Engineering

Structure Engineering Programme

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

ALKALİLER İLE AKTİVE EDİLEN BETONLARIN MEKANİK VE DURABİLİTE ÖZELLİKLERİ

YÜKSEK LİSANS TEZİ

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Cansu Çolak, a M.Sc. student of İTU Graduate School of Science Engineering and Technology student ID 501151009, successfully defended the thesis entitled "MACHANICAL AND DURABILITY PROPERTIES OF ALKALI ACTIVATED SLAG CONCRETE", which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To all women who have to stay strong,

FOREWORD

To adapt in changing environment and create a footprint in sustainable studies, alkali acitated slag concrete was studied in this master's thesis. Replacement of cement with granulated blast furnace slag and analysis of mechanical and durability properties of alkali activated slag concrete were aimed for this study.

I would like to express my deepest appreciation and thanks to my advisor Assoc. Prof. Dr. Özkan ŞENGÜL who always responses to my every question and has inspired me for this field during my bachelor degree. Without his guidance and support, this research could not be completed.

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June 2018 Cansu ÇOLAK

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ABBREVIATIONS

AASC : Alkali Activated Slag Concrete
ASTM : American Society for Testing Materials
GBFS : Granulated Blast Furnace Slag
LOI : Loss on Ignition
MPa : Mega Pascal (N/mm^2)
PC : Portland Cement Concrete
TS EN : Turkish Standart European Norm

SYMBOLS

A	: Cross section area
D	: Unit weight of fresh concrete
$\mathbf{F_c}$	: Maximum load
$\mathbf{I_0}$	: Current that after immediately voltage is applied
$\mathbf{I_t}$	: Current that t minutes voltage is applied
K	: Coefficient of capillary absorption
L	: Length
M	: Weight
q	: Amount of water that absorbed from unit area
Q	: Charge passed
R	: Resistance
$\mathbf{S_w}$	: Water absorption by weight
t	: Time
V	: Volume
$\mathbf{W_f}$	: Final weight of specimen
$\mathbf{W_i}$	: Initial weight of specimen
$\rho_{concrete}$	: Electrical resistivity of concrete
σ_c	: Compressive strength

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MECHANICAL AND DURABILITY PROPERTIES OF ALKALI ACTIVATED SLAG CONCRETE

SUMMARY

In this study, to obtain sustainable concrete alkali activated slag concrete was researched. Portland cement has a significant role about CO_2 emission. To reduce this emission, Portland cement was replaced with granulated blast furnace slag. On the other hand, due to the slow reaction of pozzolans, alkali actviators are used to accelerate strength gaining. In this research, to activate slag, sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) were used.

NaOH which is in bead form, was prepared solution with water. The other Na_2SiO_3 was used in a solution form. Four different concrete mix series were prepared. Each series had three different water/binder ratios and these are 0.36, 0.50 and 0.65. The first series was reference concrete and they were produced to compare the results of alkali activated slag concrete. In alkali activated slag concrete, NaOH solution molarity was constant, and 8 M. The Na_2SiO_3/NaOH ratio of second series is 2.5, third series is 1 and fourth series is 4. 12 cylindrical specimens were obtained for each production. In addition, all specimens were cured at 20 ± 2ºC in the saturated lime water during 28 days.

For fresh concrete state, slump test and unit weight test were applied. Also, the real air content was calculated from the real unit weight. To identify the workability, alkali activated slag concretes show S4 and S5 classes, the reference concretes show S4 class. However, while molding process of alkali activated slag concretes, setting was observed quickly and loss of concrete consistency was occurred.

28^{th} day compressive strength and modulus of elasticity were obtained to analyze mechanical properties of specimens. Compressive strength results show that water/binder ratio is a determinative property. The highest compressive strength results were obtained from AASC specimens. Also, 0.36 water/binder ratio shows linear trend with the increment of Na_2SiO_3/NaOH ratios. 0.50 and 0.65 water/binder ratio specimens show the lowest compressive strength when Na_2SiO_3/NaOH ratio is 2.5. Beside that, modulus of elasticity shows reverse results of compressive strength results.

To identify durability properties, water absorption, capillary water absorption, rapid chloride penetration and electrical resistivity tests were applied. For water and capillary water absorption test results show that reference concretes show the lowest permeability properties. Results of rapid chloride test show similar results like water

absorption results, in an other saying 0.36 water/binder ratio specimens show lower chloride penetration potential. In addition, two point electrical resistivity test was applied and results show similarity with chloride penetration results.

After the durability tests, it has been understood that water/binder ratio is the determinative factor for the results. The reason of this is air voids in the inner structure of geopolymer mixes. Also, durability properties depend on both source and chemical composition of alkali activators, mixing and cure properties.

The cost analyses of mixes were investigated. The reference concrete mixes are more economical than alkali activated slag concrete mixes. The reason of this is, used alkali activators made the cost increased.

ALKALİLER İLE AKTİVE EDİLEN CÜRUF BETONLARININ MEKANİK VE DURABİLİTE ÖZELLİKLERİ

ÖZET

Bu çalışmada, CO_2 salınımında büyük bir role sahip olan çimentonun betonda mineral katkı ile yer değiştirilmesiyle elde edilen betonların mekanik ve durabilite özellikleri incelenmiştir. Bağlayıcı malzeme olarak öğütülmüş yüksek fırın cürufu kullanılmıştır. Puzolanik reaksiyonların yavaş gerçekleşmesi, bu sebeple de betonun geç yaşlarındaki dayanımına katkı sağladığı bilindiği için, bu aşamayı hızlandırmak için alkali aktivatörler kullanılmştır. Sodyum hidroksit (NaOH) ve sodium silikat (Na_2SiO_3) kullanılan alkali aktivatörlerdir.

Beton üretimine boncuk formundaki NaOH suda çözülerek ve sıvı formdaki Na_2SiO_3 su eklendikten sonra karışıma eklenmiştir. Beton üretimleri 4$\pm$2 dakikada tamamlanmıştır. Yeterli işlenebilirlik için gerektiğinde bağlayıcı ağırlığının %1 ile %3'ü arasında süperakışkanlaştırıcı katkı kullanılmıştır. Her bir seri beton üretimlerinde her su/bağlayıcı oranı için 12 adet silindir numune üretilmiştir. Silndir numune boyutları; çap 10 cm, yükseklik 20 cm'dir. Bütün numuneler 28 gün boyunca 20$\pm$2ºC'de kirece doygun suda bekletilmiştir.

Taze haldeki beton üretimlerinde birim ağırlık ve çökme deneyi yapılmıştır. Sertleşmiş beton numuneleri için ise, 28 günlük basınç dayanımı, elastisite modülü tayini, su emme, kılcal geçirimlilik, hızlı klor geçirimliliği ve iki noktalı elektriksel özdirenç deneyleri yapılmıştır.

Taze beton deneylerinden birim ağırlık deneyi TS EN 12350-6 (2010), çökme deneyi TS EN 12350-2 (2010) standardına uygun olarak yapılmıştır. Beton karışım hesaplarından tayin edilen teorik birim ağırlık ve deneylerden elde edilen gerçek birim ağırlık değerleri sonucunda beton içerisindeki gerçek hava miktarı hesaplanmıştır. Üretilen betonlardan yeterli işlenebilirliği elde etmek için yapılan çökme deneyinde ise, referans betonlar ve Na_2SiO_3/NaOH oranı 2,5 olan ikinci seri üretimler S4 sınıfı, Na_2SiO_3/NaOH oranı 1 olan üçüncü seri ve Na_2SiO_3/NaOH oranı 4 olan dördüncü seri üretimler ise S5 sınıfı olarak belirlenmiştir. Üretimden 30 dakika sonra alkaliler ile aktive edilen betonların çok hızlı kıvam kaybettikleri gözlemlenmiştir.

Sertleşmiş beton numunelerine uygulanan mekanik deneylerden basınç dayanımı deneyi TS EN 12390-3 (2010) standardına göre, 28 günlük numuneler üzerinde yapılmıştır. Deney sonuçlarına göre numunelerin basınç dayanımları üzerinde su/bağlayıcı oranının en önemli etken olduğu görülmüştür. En yüksek basınç dayanımı 60 MPa olarak 0,65 su/bağlayıcı oranında Na_2SiO_3/NaOH oranı 4 olan numunelerde elde edilmiştir. Su/bağlayıcı oranı 0,50 ve 0,65 olan numunelerde Na_2SiO_3/NaOH oranı 2,5 olan numunelerde kendi serileri içinde en düşük basınç dayanımları gözlemlenmiştir. Bütün numuneler içerisinde en düşük basınç dayanamı

ise 0,65 su/bağlayıcı oranında Na_2SiO_3/NaOH oranı 2,5 olduğunda 10 MPa olarak elde edilmiştir. Buna ek olarak, su/bağlayıcı oranı 0,35 olan numunelerde basınç dayanımı artışı Na_2SiO_3/NaOH oranının artışı ile lineer eğilim gösterirken, su/bağlayıcı oranı 0,50 ve 0,65 olan numunelerde eğilim lineer özellik göstermemektedir.

Diğer bir mekanik özellik olan elastisite modülü deneyi ise silindir numunelerinin basınç dayanımlarının %30'una kadar yüklenip burdan elde edilen verilerle çizilen grafiğin lineer elastik bölgesinin eğimi ile belirlenmiştir. Elde edilen en büyük elastisite modülü 36 GPa olup, su/bağlayıcı oranı 0,36 olan referans betonlarına elde edilmiştir. 0,36 ve 0,50 su/bağlayıcı oranlarında en düşük elastisite modülleri Na_2SiO_3/NaOH oranı 2,5 olduğunda elde edilmiş ve bu değerler sırasıyla 22,8 ve 17,2 GPa'dır. Elde edilen sonuçlarda, basınç dayanımları ve elastisite modülleri arasında pozitif artış gösteren lineer bir eğilim elde edilememiştir.

Durabilite özelliklerini belirlemek için yapılan su emme deneyi TS EN 12390-7 (2010) standardına göre yapılmıştır. Numuneler 24 saat 105ºC etüvde daha sonra ise 3 gün boyunca suda bekletilmiştir. Numunelerin kuru ve suya doygun ağırlıkları elde edilip ağırlıkça yüzde su emmeleri hesaplanmıştır. Sonuçlara göre, en düşük su emme su/bağlayıcı oranı 0,36 olan referans betonunda %0,3 olarak gözlemlenmiştir. Diğer en düşük su/bağlayıcı oranı %2 olarak su/bağlayıcı oranı 0,36 olan alkalilerle active edilen betonlarda gözlemlenmiştir. Diğer bir deyişle, betonların su geçirimliliğinde de belirleyici özellik basınç dayanımlarında olduğu gibi burada da su/bağlayıcı oranı olmuştur. Su/bağlayıcı oranı 0,50 ve 0,65 olan numunelerde tüm Na_2SiO_3/NaOH oranlarında %4 olarak gözlemlenmiştir.

İkinci durabilite deneyi olan kılcal su emme deneyi ise TS EN 772-11 (2012) standardına uygun olarak yapılmıştır. Silindir numuneler düşey doğrultuda ortadan ikiye bölünerek yükseklikleri 10 cm, çapları 10 cm olan numuneler elde edilip 105ºC'de 24 saat etüvde bekletilmiştir. Kesim yüzeyleri suyla temas edecek şekilde alt yanal yüzeyleri su geçirimsizlik için parafinle kaplanmıştır. 144 dakika boyunca süren deneyde, ağırlık farkları ölçülerek kılcal su emme katsayısı hesaplanmıştır. En düşük kılcallık katsayısı su/bağlayıcı oranı 0,36 olan referans betonunda $0{,}01x10^{-6}$ cm^2/s olarak elde edilmiştir. En yüksek kılcallık katsayısı ise su/bağlayıcı oranı 0,50 ve Na_2SiO_3/NaOH oranı 4 olan betonda $41{,}7x10^{-6}$ cm^2/s olarak elde edilmiştir.

Üçüncü durabilite deneyi olan hızlı klor geçirimliliği deneyi ASTM C 1202-12 standardına göre yapılmıştır. Çapı 100 mm, yüksekliği 50±3 mm olan silindir numunelerin çevreleri geçirimsizlik için poliüretan malzeme ile kaplanmıştır. Numuneler deneyden önce, 3 saat boyunca hava vakumu sonrasında ise vakum haznesi su ile doldurularak 1 saat boyunca numunelere vakum etkisinde su emmeleri sağlanmıştır. Vakum işlemi sonrasında numuneler, deney başlayıncaya kadar suda bekletilmiştir. Hızlı klor geçirimliliği deneyinde hücrelerden biri %3 oranında NaCl çözeltisi ile, diğer ise 0,3 N NaOH ile doldurulmuştur. Bu iki hücre arasına yerleştirilen numuneye 60 V potansiyel fark uygulanıp 6 saat boyunca her yarım saatte bir olmak üzere akım okunmuştur. Deney sonunda akım zaman grafiği çizilip altında kalan alan hesaplanarak elektrik miktarı coloumb cinsinden hesaplanmıştır. Deney sonucunda elde edilen verilere göre, klor geçirimliliğini etkileyen faktörün su/bağlayıcı oranı olduğu gözlemlenmiştir.

Durabilite deneylerinden sonuncu deney olan iki elektrot yöntemi ile elektriksel özdirenç deneyi yapılmıştır. Elektriksel özdirençler ölçülürken, numuneler yüzey kuru suya doygun yapıda olup iki çelik plaka arasına yerleştirilerek okumalar alınmıştır. Deney sonuçları, hızlı klor geçirimliliği sonuçları ile paralellik göstermiştir.

Durabilite deneylerinde sonuçları etkileyen faktörün su/bağlayıcı oranı olduğu anlaşılmıştır. Alkali aktivatör oranlarının değişmesinin durabilite sonuçları üzerinde çok etkili bir farklılık göstermediği anlaşılmıştır. Durabilite özellikleri betonun iç yapısına bağlı olduğu için, iç yapısında oluşan boşluklar geopolimer karışımların geçirimlilik özellerini arttırmış olmaktadır. Bunun sebepleri ise, kullanılan alkali aktivatörlerin kimyasal özellikleri, beton karışım oranları ve kür koşulları olabilir.

Yapılan maliyet analizlerinde ise, alkalilerle aktive edilen betonların maliyetinin, referans betonlarının yaklaşık olarak 8 katı olduğu belirlenmiştir. Bunun sebebi ise kullanılan alkali aktivatörlerin birim fiyatlarının yüksek olmasıdır.

1. INTRODUCTION

Concrete is a composite material whose components are aggregates, cement, water and admixtures, which can be used if it is necessary. While technology is being developed, caring the natural sources and environmental sustainability are coming out as significant aims. Cement is a fundamental binder component for concrete, therefore environmental effects of cement production have an important role on concrete.

Cement production requires high amount of natural sources, energy, heat and CO_2 emissions which occur during production (Stajanča& Eštoková, 2012). According to the ERMCO (2016) statistics, 123 millions of m^3 concrete were produced and 63.7 millions of ton cement were consumed in Turkey in 2015 (p.10). In the construction industry, to reduce the air pollution, which occurs due to the cement production, Portland cement can be replaced with alternative binders. Limestone is the component of clinker which is the main responsible constituent of CO_2 emission. Kajaste and Hurme (2016) explain that in Turkey, 708 kg CO_2/t cement specific emission released in 2011. Also, studies show that, when mineral admixtures are used in cement production to obtain blended cement, CO_2 emissions decreased nearly 50%, and total kg CO_2/t was 392 in 2011, Turkey. To decrease the carbon footprint of cement, alternative binders can be used, such as supplementary cementitious materials, which are also named as pozzolans in cement production, or as a main binder. Thanks to the usage of pozzolans instead of the Portland cement, the ratio of CO_2 emissions can be decreased.

Concrete, which is widely used as a building material, should provide three main properties. The first one is workability, which is for fresh concrete, and strength and durability, which are hardened concrete properties. In addition, popular demand in concrete technology is to ensure high strength and durability and also both, low cost and environmental damage. Geopolymer concrete is one of the choices to obtain all these properties.

Weerdt (2011) assumes that according to Davidovits research, prefix geo comes from Greek language and it means earth. The reason of the usage of this prefix is, alumnium and silicon oxide which formed geopolymers are the most common components in the earth's shell. Duxson et al. (2007) explain that "geopolymer" term is used to define amorphous materials, which are final products of crystalline reactions. Also, geopolymer is not the only term for these materials, in addition alkali-activated concrete, geocement, alkali bonded ceramic, hydroceramic, soil-cement, low-temperature aluminosilicate glass and inorganic polymer concrete can also be used. According to Weerdt (2011) if reactive aluminosilicate components exist in the binder and activated with alkali activators, amorphous inner structure is formed in three dimensions. Therefore, they have excellent mechanical and durability properties (such as acid and heat resistances).

Aim of this research study is to obtain environmental friendly concrete and observe both durability and mechanical properties of alkali activated slag concrete.

1.1 Pozzolans

According to the ASTM C125-18 (2018), pozzolans are supplementary cementitious materials which contain siliceous or siliceous and aluminous materials and have less or no bindig properties but with calcium hydroxide, water and proper temperature they show bindig properties.

Pozzolan is named from a town of Italy, called Pozzuoli which is near Naples. Romans discovered that pozzolans are hydrolic binders, because they possess cementitious properties with slaked lime and ordinary water (Erdoğan, 2003).

Pozzolans are divided into two groups. These are natural pozzolans and artificial pozzolans. Natural pozzolans are mostly volcanic origined materials, as an example volcanic ash, tuffs, pumicite and such. Artificial pozzolans are industrial by-products such as fly ash, silica fume and granulated blast furnace slag.

1.1.1 History of usage of pozzolans

Usage of pozzolans can be traced back to neolithic age. Shi (2011) explains that, the first usage of pozzolan and lime was observed in 7000 BC. Roman concrete (also known as opus caementicium) and Greek concrete (which is known as emplechton) are also lime and pozzolan combined binders. Until the invention of Portland cement, this pozzolan-lime binder was the only binding material. However, due to the slow strength gaining mechanism of pozzolan binders, Portland cement took its place.

1.1.2 Pozzolanic activity and reaction

Pozzolanic activity shows the degree of reaction with slaked lime and amount of binding capacity when it is replaced with cement. Pozzolans should be sufficiently fine, amorf and include enough amount of siliceous, aluminous and iron oxide to have pozzolanic activity (Erdoğan, 2003).

Strength gaining with pozzolans are related with lime concentration. Pozzolans react with lime, which comes from the C_3S and C_2S hydration reactions. Strength development in pozzolanic concrete depends on both water/binder ratio and pozzolan/lime ratio. In addition, lime hardens with CO_2 because it is an air binder material. This hardening mechanism is called as carbonation. Massazza (1998) assumes that chemical and mineralogical properties, fineness of pozzolans, curing type and conditions, lime concentration and temperature affect the reactivity of hardening. Also, gypsum (Na_2SO_4) and $CaCl_2$ chemicals have activator roles and also affect the concentration of lime positively.

Massazza (1998) claims that, hydration products of pozzolan-lime combination and Portland cement have similarities because the chemical compound of these two binders are similar. In fact, different natural pozzolans have similar chemical compounds, so final hydration products are same such as aluminates and silicate hydrates. These final products are calcium silicate hydrate (CSH) and different forms of hexagonal aluminates. These products can also be formed when only pozzolans react with water or react with limewater. Other researches show that, because pozzolanic hydration mechanism is slower, the final products can be diversified like, carboaluminate, gehlenite hydrate and types of hydrogarnet if the duration time of reaction is increased.

1.2 Granulated Blast Furnace Slag

Granulated Blast Furnace Slag (GBFS) can be used for either replacement of cement in concrete or production of blended cement. The first usage of GBFS as an additive cement was in Germany in 1892 and in USA in 1896. GBFS was used in concrete as a supplementary cementitious material in the late 1950s (Virgalitte et al., 1995).

1.2.1 Production of granulated blast furnace slag

GBFS is a by-product of iron production. Erdoğan (2003) states that, hematite (Fe_2O_3) and magnetite (Fe_3O_4) are iron ores in nature. These ores contain small amount of silica, alumina, sulfur, phosphorus and manganese. To obtain iron from the iron ores, iron ores should be heated at up to 1600 ºC in the blast furnaces and thanks to this process, oxygen and other unfamiliar materials are removed. In the blast furnaces, coke are used as a fuel, in this way carbon (coming from coking coal) and oxygen (coming from iron oxides) are coming together and carbon monoxide and carbon dioxide gases occur. Except these gases, molten iron and molten CaO, SiO_2, Al_2O_3, MgO, MnO and S compounds are formed. The density of iron is heavier than unfamiliar compounds, because of this, iron remains in the below part and molten compounds remain above of it and this upper part is called as blast furnace slag.

Tokyay and Erdoğdu (2009) explain that blast furnace slag, because of its heavy structure, remains over the pig iron during this process and it is formed at 1400-1600ºC. These production mechanisms are shown in Figure 1.1. When blast furnace slag is cooled slowly, it forms a crystal structure, conversely when this cooling process actualizes quickly, it forms an amorphous structure. Moreover, this type of slag is called a granulated blast furnace slag. Name of the slag type can be determined by cooling processes. These are; air cooled slag, expanded slag and granulated slag. According to the Indian Minerals Yearbook (2014), if liquefied by heat slag remains in a hole to be cooled by air in a slow pace, it is classified as an air cooled slag. If molten slag is extinguished by high pressure water jets, cooled slag has an amorphous structure and it is classified as a granulated slag. Lastly, when cooling process for liquefied slag is made water or both water and steam, expanded slag is occurred. Because of the compressed air which is applied during the cooling process, porosity of slag increases, so expanded slag may be used as a lightweight aggregate.

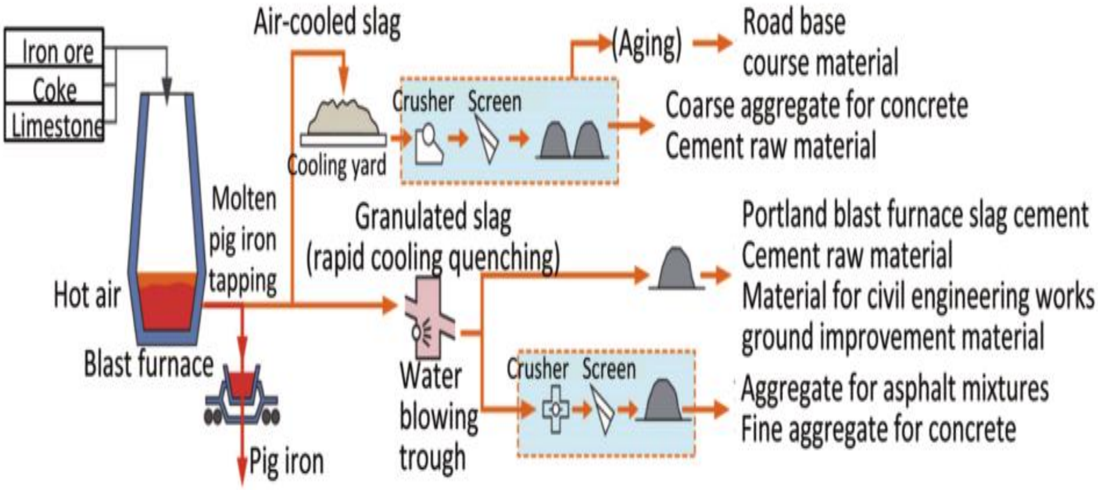

Figure 1.1 : Production of blast furnace slag (Miyamato, et.al., 2015).

1.2.2 Chemical compositon and hydration mechanism of GBFS

The chemical composition of slag depends on obtainability of raw materials compounds. Usage of different sources for production of GBFS, results in different chemical compounds, which shows differences for countries (Table1.1). The major components of GBFS are; CaO, SiO_2 and Al_2O_3. In addition, GBFS and portland cement have the same components and Table 1.2 shows the comparison between portland cement and GBFS chemical compositions.

Hewlett (2003) claims that hydrolic binder properties of GBFS depend on the increment of CaO/SiO_2 ratio. However, if this ratio exceeds limit value, granulation can be difficult. On the other hand, when constant CaO/SiO_2 ratio is obtained, the increment of Al_2O_3 increases the slag activity. Other oxide compositions of GBFS such as Fe_2O_3 and MnO affect the strength properties of slag negatively. Unless MgO ratio exceeds 10%, no negative results can be shown for strength properties of GBFS.

Table 1.1 : Chemical composition of GBFS, % (Erdoğan, 2003).

Chemical Compounds	USA and Canada	South Africa	Australia	Turkey
CaO	29-50	30-40	39-44	34-41
SiO_2	30-40	30-36	33-37	34-36

Table 1.1 (continued): Chemical composition of GBFS, % (Erdoğan, 2003).

Chemical Compounds	USA and Canada	South Africa	Australia	Turkey
Al_2O_3	7-18	9-16	15-18	13-19
Fe_2O_3	0.1-1.5	-	0-0.7	0.3-2.5
MgO	0-19	8-21	1-3	3.5-7
MnO	0.2-1.5	-	0.3-1.5	1.0-2.5
S	0-2.0	1.0-1.6	0.6-0.8	1-2

Hydration mechanism of GBFS shows similarities with Portland cement, but reaction rate of GBFS and water is slower than Portland cement. When GBFS and Portland cement are used in concrete together, hydration mechanism comes true with few steps. First step is materialized between slag and alkali hydroxides which come from cement. For second step, after cement hydration, calcium hydroxide occurs and this component and slag react strongly. Reactions between portland cement, GBFS and water are summarized in equation 1.1. When only slag is used in concrete, slag and water react at a slow pace as a result strength gaining speed is getting slower. However only slag and water reactions can not have an important role on strength gaining.

$$\text{Portland cement + water} \longrightarrow \text{C-S-H} + Ca(OH)_2$$
$$\text{NaOH or KOH} \qquad (1.1)$$
$$\text{GBFS + water} + Ca(OH)_2 \longrightarrow \text{C-(N,K)-S-H}$$

Table 1.2 : Chemical composition of Portland Cement and GBFS (Lewis et al., 2003).

Chemical components	Portland Cement (%)	GBFS (%)
CaO	54	40
SiO_2	21	36

Table 1.2 (continued): Chemical composition of Portland Cement and GBFS (Lewis et al., 2003).

Chemical components	Portland Cement (%)	GBFS (%)
Al_2O_3	6	10
Fe_2O_3	3	0.5
MgO	1.5	8
SO_3	2	0.2
K_2O	0.8	0.7
Na_2O	0.5	0.4

Tokyay and Erdoğdu (2009) suggest that beginning of GBFS own hydration starts with dissolving in water partially. With this dissolving, calcium silicate hydrate (C-S-H), hydrated aluminates and hydrated silica aluminates subside. After the precipitation of C-S-H, lime concentration of solution increases. After the hydration reactions, C-S-H, C_2ASH and $C_4AH_{13\text{-}19}$ components are formed. In addition, to accelarate the reaction between GBFS and water, activators can be used. These activators can be alkali (such as sodium silicate, lime, sodium hydroxide, carbonate and so on) and sulfate activators (such as plaster and anhydride, etc.). After usage of these activators C_4AH_{19}, C_4ASH_8 and ettringite occur as final products.

1.2.3 Activation of GBFS

Al-Otaibi (2002) explains that activation of GBFS depends on type and fineness of slag, activator type, modulus of Na_2SiO_3 and curing conditions.

Al-Otaibi (2002) assumes that the reason why slag type affects the GBFS activation is, when GBFS has high alumna content, early strength and quick setting can occur. On the other hand, Fe_2O_3 content affects GBFS activation negatively. In addition, inner structure such as being amorphous or crystalline also affect the GBFS activation, such as; amorphous structure gives reactivity properties to slag but crystalline form has no siginificant role in reactivity.

Talling and Brandstetr (1989) explain that when fineness of GBFS increases, specific surface area increases and this helps for development of strength gaining and decrease the setting time.

Activator type such as aluminates, silicates, weak acid salts, strong acid salts, alkalies and alumina silicates affect reaction of GBFS differently. Al-Otaibi (2002) claims that not only types of activators but also usage of them also affect GBFS activation. For instance, these alkalies can be added in concrete mix in three forms. The first one is solution form, the second one is solid form and it is crushed with slag and the last form is again solid form and it is added in concrete mix such as a constituent. It has been understood that usage of the solid form of the alkalies can affect strength negatively and it causes variety in the results. The reason of this is that, during stocking the solid alkalies can loose their humidity. Dissolution in concrete mix may not be efficient.

Al-Otaibi (2002) mentions that modulus of Na_2SiO_3 (SiO_2/NaO) which is also known by silica modulus (M_s) has significant role, because SiO_2 has a resposibility to create silica gel which helps the concrete to gain strength. By this way, the higher M_s can give us higher strength, but there is a limitation for M_s value. Higher Ms requires both SiO_2 and Na_2O, so increment of Na_2O accelarates the setting time which is not required. Because of this Ms value is limited in between 1 to 1.5 (Wang et al., 1994)

Effective curing has a significant role for gaining strength and creates impermeable concrete which is needed for effective durability. For example, under high temperature and pressure, NaOH activated slag concrete shows the highest compressive strength (Kutti et al., 1982).

1.2.4 Effect of GBFS on fresh concrete properties

Tokyay and Erdoğdu (2009) explain that workability of GBFS concrete shows more satisfactory values then traditional concrete. When slag and clinker are compared, slag has less specific weight and surface roughness, and these two factors help us to obtain more cement paste by volume. Thanks to this, workability of slag binder concrete increases.

Due to the slow hydration pace of pozzolans, setting time of slag concrete is longer than traditional one. It can lead a problem for hot weather casting, if chemical admixtures are not used. In addition, for slag concrete, bleeding ratio shows higher values than traditional concrete (Tokyay & Erdoğdu, 2009).

Heat of hydration can show reduction if slag has been chosen as a binder. This is because cement is responsible for the heat of hydration due to its exothermic chemical reaction. If cement is replaced by slag, heat of hydration will decrase.

1.2.5 Effect of GBFS on hardened concrete

Strength gaining of slag concrete shows lower speed due to the slow pozzolanic reaction. Early age strengths can show a higher result in traditional concrete, on the other hand after 28th day strength values for slag concrete can show higher results in compressive strength. Also this late strength gaining mechanism is the same for modulus of elasticity.

Cement is the responsible component in concrete for shrinkage, researches show that there is no any remarkable difference about shrinkage between Portland cement concrete and slag concrete (Wainwright, 1995)

Tokyay and Erdoğdu (2009) explain that for creep results, the important ratio is stress over strength, and this ratio is independent from components of concete. Therefore, slag concrete and Portland cement conrete have no differences on creep property.

Tokyay and Erdoğdu (2009) assume that thermal expansion and conductivity also depend on source and properties of aggregates and therefore using slag as a binder has no effect on this property.

1.3 Alkali Activators

Glukhovsky et al. (1980) explain that alkali activators can be classified such as:

Caustic alkalies: MOH

Non-silicate weak acid salts: M_2CO_3, M_2SO_3, M_3PO_4, MF

Silicates: $M_2O.\ nSiO_2$

Aluminates: $M_2O.\ nAl_2O_3$

Alumina silicates: $M_2O.\ Al_2O_3.\ (2\text{-}6)SiO_2$

Non-silicate strong acid salts: M_2SO_4

Most widely used alkali activators from above are, sodium hydroxide (NaOH), sodium carbonate (Na_2CO_3) and sodium silicate ($Na_2O.\ nSiO_2$), because they can be obtained more easily and economically. Moreover, potassium compounds have same reaction mechanism with sodium compounds. However, potassium chemicals are preferred to use only in laboratory studies due to the their uneasy accessibilities and high costs (Shi, Krivenko& Roy, 2006).

Although, alkali activators have some benefits for GBFS hydration rate, there can be some disadvantages. Luukkonen et al. (2018) claim that, both type of the alkali activators and the form of the alkali activators affect the reaction. For example, when NaOH is used in a solid form, corrosion can be a risk for AASC, and when CO2 penetrates inside the surface, NaOH forms to Na_2CO_3.

1.3.1 Historical development of usage of alkali activators

The first edition about alkali activated slag concrete was published in 1908 by Kühl. Kühl (1908) claims that GBFS and lime can be activated with caustic alkalies such as sodium sulfate or sodium carbonate. Thanks to this activators, binder mechanism can be faster. Provis and Bernal (2014) explain that, Purdon published about slag activation with different alkali activators in 1940 and he intended to make a profit with this study and it called Purdocement. Because of the financial problems of Purdocement was stopped in 1957. A few decades later, low and high calcium binding system was developed to obtain long term durability for alkali activated products in Kiev. After other researches, geopolymer term was used first in 1979 by Davidovits. This research was about alkali activators and natural pozzolans such as metakaolin, and after this research, popularity of this subject increased. Especially between 1980s and 1990s, scientific researches and commercial advances about geopolymers were increased.

Glukhovsky (1994) assumes that studying on different binding mechanisms, and investigations on ancient Roman, Greek and Egyption architectures help to develop alternatives of Portland cement. Provis (n.d.) explains that research about alkali activated materials have started in Western Europe, then it has spread to eastwards. Soviet Union and China have become the part of this investigation because of cement scarcity. In Soviet Union, investigation of Glukhovsky has led on development of alkali activated materials. After 1980s, publishments of Roy highlighted these researches. In France, Davidovits patented his alkali activated works and, "geopolymer" term was used firstly, in 1980s by him. At that time, in Unites States Army researched about role of alkali activated materials in military places and wanted to apply these materials to repair the concrete cracks in 1985.

1.3.2 Mechanism of GBFS and alkali activators

GBFS is the important binder among the pozzolans because of its chemical compound. Table 1.2 presents that GBFS has high amount of CaO and low amount of Al_2O_3. Gao (2017) explains that, slag and alkali mechanism start with first alkali damages on raw materials then increment of reaction products. Figure 1.2 shows slag and alkali materials reaction steps. Step A presents the beginning of slag and alkalies meeting and when slag and alkali activators come across, H^+ interchanges with Ca^{+2} and Na^+. The action of Ca^{+2} taking away leads to give harm to the amorphous structure of slag. Beside that, removing Na^+ also gives damage to the amorphous structure but Ca^{+2} positive charge is higher than Na^+, because of this dissolving of Ca^{+2} gives more damages to the inner structure. In step B, the main slag bonds start to be destroyed by alkalies such as Al-O-Si, Ca-O, Si-O-Si, Mg-O, Al-O-Al bonds. In the third step C represents that when main bonds (like Ca-O) are damaged the whole amorphpous structure begins to be ruined. The last step D shows that, reaction products start to be developed near the surface of slag particles.

To sum up, the first step of alkali activators and GBFS is translocation of ions, then initial bonds such as Ca-O and T-O destruction and amorphous structure is begun to be destroyed. The last part is, final products of this reaction is begun to cover the surfaces of slag particles. In other words, hydration products begun to cover the slag particles from the surface like cement hydration products.

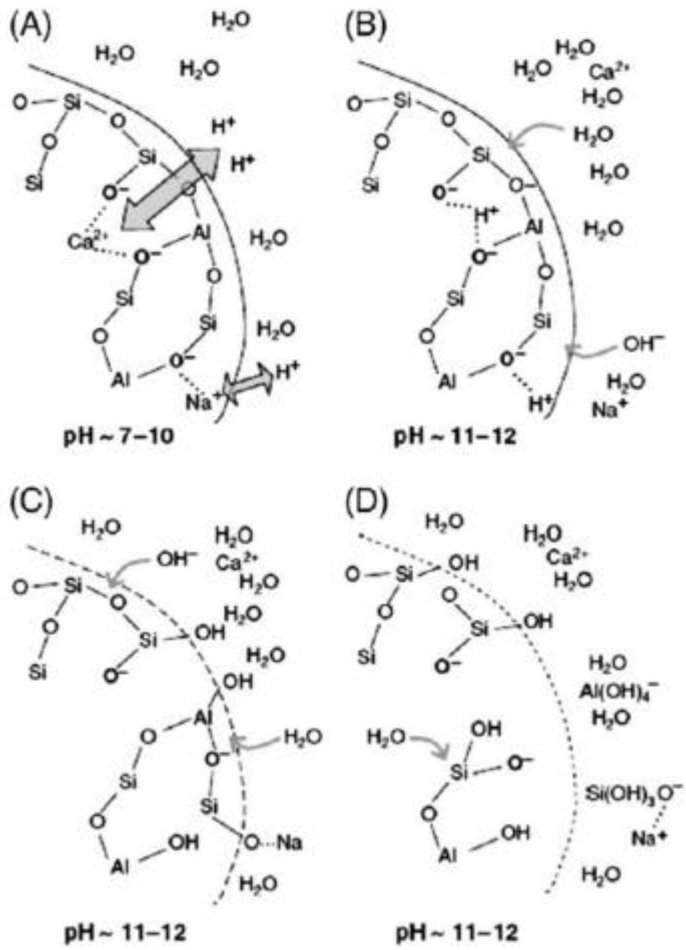

Figure 1.2 : Dissolution of Ca-Si chemicals (Duxon and Provis, 2008).

1.3.3 Alkali activators: sodium hydroxide

Sodium hydroxide is also known with its most common name; caustic soda. The flake and bead type caustic soda can be used in AASC. Shi et al. (2006) explain that, flake and bead type NaOH are produced from cooling process of liquefied caustic soda. During this process, all water inside the caustic soda is turned from liquid into vapor. To obtain flake caustic soda, this molten part falls away from a surface in thin pieces, then they are ground, eliminated and wrapped. At the same time to obtain bead form of caustic soda, supplying liquefied solution into a prilling tower; then spherical beads are obtained. Only the process cycles are different for these two types of caustic soda, but their chemical composition are same.

To include caustic soda in concrete, a solution has to be prepared. While preparing this solution, caustic soda is dissolved in water and this process is an exothermic process. Temperature of final solution respects to the NaOH percentage is shown in Figure 1.3. Shi et al. (2006) suggest that while preparing this solution some precautions must be taken. First one is, water of the solution should be not cold or hot, it should be warm (30-40ºC). The second one is, after adding water into the caustic soda, swashing should be done to prevent insoluble residue inside the solution.

Caustic soda solution is used in concrete to activate pozzolan fast, however compressive strength shows reduction after 7 to 14 days of hydration mechanism start (Shi, et al., 2006). Other things that needed to be careful is about the preparing solution. Beacause of high final temperature of solution, while adding this boiling solution into the concrete, splashing can come true.

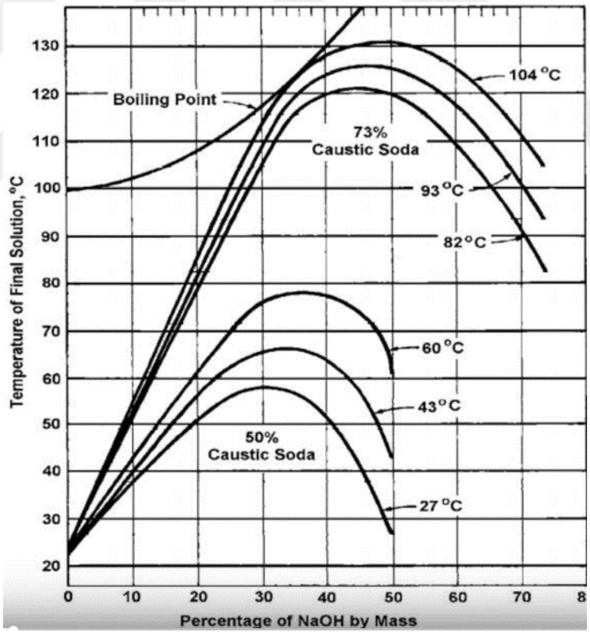

Figure 1.3 : Temperature of NaOH solution (The Dow Chemical Company, 1993).

1.3.4 Alkali activators: sodium carbonate

The widespread name of sodium carbonate is soda ash. The trading soda ash is defined by sodium oxide (Na_2O) percentage. For example, 40% trading soda means that it includes 40% Na_2O. The source of soda ash is supplied from some marine plants or some rocks (Elibol, 2012).

Shi et al. (2006) explain that after the reaction of water and Na_2CO_3, sodium carbonate monohydrate ($Na_2CO_3.H_2O$), sodium carbonate heptahydrate ($Na_2CO_3.7H_2O$) or sodium carbonate decahydrate ($Na_2CO_3.10H_2O$) are obtained. The reason of these different final products is the concentration and temperature of the solution. The solvability of this solution depends on the temperature. Figure 1.4 shows that until 35.4ºC solubility of the solution increases, but after this critic temperature if the heat continues to increase, the solubility shows decrease.

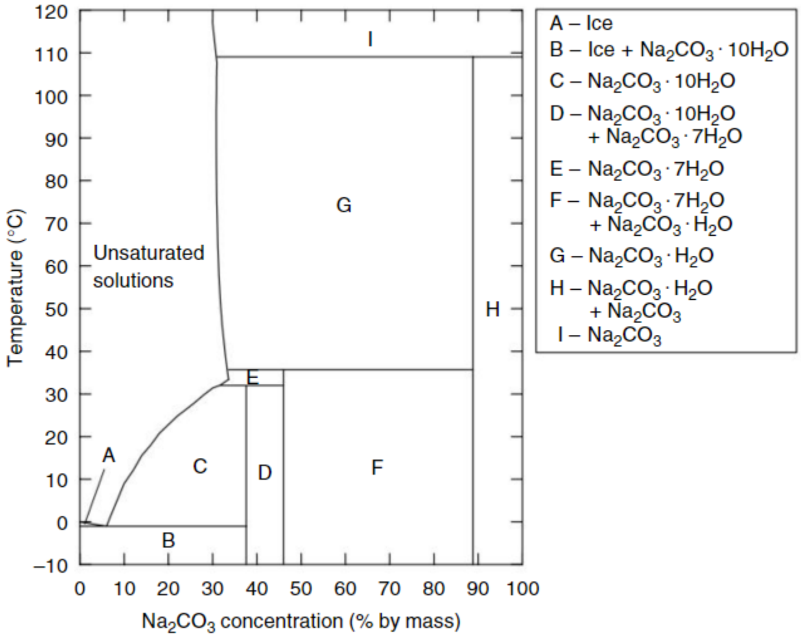

Figure 1.4 : Soda ash concentration and temperature relation (Shi et al., 2006).

Odler et al. (1976) say that although soda ash is a kind of accelerator in concrete, when the dosage is above to the optimum value, it acts as a retarder in the concrete mixture.

1.3.5 Alkali activators: sodium silicate

Sodium silicate chemical formula is $Na_2O.nSiO_2$ and the common name of this product is waterglass. Shi et al. (2006) claim that n can be between 0.4-4.0 range. In addition, for liquid sodium silicate the ration of SiO_2 to Na_2O should be between 1.60 to 3.85. If this ratio is below 2.85, the liquid solution is alkali, if it is above the 2.85, the liquid solution is neutral. The production of the waterglass has a few steps. Firstly, sand and soda ash are placed in the furnace at 1400ºC. After this combustion process, 50% caustic soda is used as a dissolver into the mixture, then ratio and solid accuracy is done. Afterwards it is divided into two grops: liquid silicate storage and granular meta silicate which is obtained after drying process.

The effectiveness of this solution can be identified with modulus of the solution and sum of SiO_2 and MeO_2. Sum of these two chemical can be analysed of residue forms with an acid titration, however modulus of the solution can be estimated either with a calibration chart or the empirical formula in 1.2 (Shi et al., 2006).

$$n= 55.16(\rho-1)N-2.28 \tag{1.2}$$

where,

ρ: density of the liquid solidum silicate

N: Normality of alkali in the solution

When sodium silicate is used as an accelerator in concrete or mortar, strength development occurs. According to Brough & Atkinson (2002), final products of hydration are not in crystalized form, and they are spread uniformly in cement phase.

1.4 Previous Studies on AASC

Previous studies on AASC and its progress are briefly explained below. Research about mechanical and durability properties are explained.

1.4.1 Mechanical studies of AASC

Examples of AASC specimens can achieve up to 60 MPa compressive strength in one day and after one year, increment of compressive strength can exceed 100 MPa (Pu, et al., 1988). The reasons of these higher compressive strength results can be explained by the fast hydration process of AASC (due to the high pH values of concrete) and intensive and homogeneous structure of interfacial transition zone (ITZ) of AASC (Bernal, et al., 2011).

Not only internal structure, but also curing conditions are highly effective on compressive strengths. Bakharev et al. (1999) explain that heat cured specimens showed higher early strength than room temperature cured ones. On the other hand, compressive strength shows decrease at later ages. The reason of this reduction is quick hydration process during the heat cured AASC specimens. When curing is obtained in high temperatures, hydration products are aligned around slag particles. This step causes inhomogeneity inside the internal structure and while hydration products are remaining near the slag particles, they leave their initial locations and this causes voids. In addition, during this substitution, concentrated precipitates are formed and these are acting as a barrier for ion diffusion.

1.4.2 Durability assessment of AASC

Permeability of concrete affects the durability properties. Law et al. (2012) claim that Portland cement has an important role for impermeable concrete, and at later ages degradation due to the harmful chemicals affect PC more than AASC. Besides, AASC and blended cement concretes can show similar permeable properties.

Salihpaşaoğlu (2017) indicates that leaky alkalies from AASC can react with CO_2 from air and it can cause florescence.

Bakharev et al. (2001) search that the probability of alkali aggregate reaction (AAR) in AASC is higher than PC. Because this is potential alkali amounts are very high which increases the risk of AAR.

Bakharev et al. (2003) indicate that PC specimens can not resist acid attack due to their high calcium content. When calcium compound, of AASC and PC are compared, it can be understood than AASC has low calcium content and more impermeable structure. Due to these reasons, resistance of acid attack on AASC is higher than.

For chloride penetration, matrix of concrete should have porous structure and when suitable conditions occur, chloride ions start to transport. Ismail et al. (2013) present that AASC decelerates transportation of chloride ions. Because gel structure, which occurs at the end of the hydration process, makes the chloride binding capacity increased.

2. EXPERIMENTAL STUDIES

All experimental studies were carried out in İstanbul Technical University, Building Materials Laboratory. 12 different concrete mixes were producted for this study.

2.1 Materials and Properties

2.1.1 Cement

The Portland cement which was used in this study complies TS EN 197-1 (2012) standard. Cement type is CEM I 42.5 R. This Portland cement was supplied from Akçansa Çimento Sanayi ve Tic. A.Ş. Chemical composition of the cement is given in Table 2.1 and physical properties of cement is given in Table 2.2.

Table 2.1 : Chemical analysis of cement.

Chemical Analysis	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI
(%)	19.71	5.20	3.73	62.91	2.54	2.72	0.25	0.90	0.96

Table 2.2 : Physical properties of cement.

<table>
<tr><td colspan="2">Physical Properties</td><td>Results</td></tr>
<tr><td colspan="2">Specific Weight (g/cm^3)</td><td>3.10</td></tr>
<tr><td rowspan="2">Fineness</td><td>Residue retaining part from 200 µm sieve (%)</td><td>0</td></tr>
<tr><td>Residue retaining part from 90 µm sieve (%)</td><td>2</td></tr>
</table>

2.1.2 Granulated blast furnace slag

Granulated blast furnace slag which was used in all experimental studies was obtained from Kardemir Karabük Demir Çelik Sanayi ve Tic. A.Ş. GBFS bags were protected from water and environmental moisture with plastic bags. The physical properties of GBFS were obtained. Specific weight of GBFS is 2.97 g/cm^3 and the specific surface area in Blaine is 5500 cm^2/g. The chemical composition of GBFS is given in Table 2.3.

Table 2.3 : Chemical analysis of GBFS.

Chemical Analysis	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Cl^-	LOI
(%)	43,5	1,2	11,3	29,2	10,3	1,3	1,1	0,35	0,01	1,9

2.1.3 Water

The water which was used in all experimental studies and during the curing process was from İstanbul Water and Sewerage Administration and the water was potable water. The water in which used in concrete production and curing process was compatible with TS EN 1008 (2003).

2.1.4 Alkali activators

The selected alkali activators are sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). These were used in AASC together. During the experimental studies, chemicals were conserved in their plastic containers.

2.1.4.1 Sodium hydroxide

Sodium hydroxide (NaOH) was used during the AASC production. The type of NaOH was in bead form. Before adding this chemical in the concrete mix, a solution was prepared with water. The dissolving process of NaOH which is one of the strong bases is exothermic. The flake form of NaOH was white and odorless. The molecular weight of this chemical is 39.99 g/mol and the density of this chemical is 2.15 g/cm^3 at room temperature.

2.1.4.2 Sodium silicate

Sodium silicate (Na_2SiO_3) which was used all productions of AASC specimens is in solution form. The solution is colorless and odorless. The molecular weight of this chemical is 184.04 g/mol and its density is 1.35 g/cm^3 at room temperature and this sodium silicate solution is 47-50º Baumé (hydrometer scale for specific gravity of liquids).

2.1.5 Aggregates

The types of aggregates which were used during the experimental studies are natural sand, crushed sand, crushed stone I and crushed stone II. The source of the crushed stone I, crushed stone II and crushed sand is limestone. The density of the aggregates is given in Table 2.4. The sieve analysis of these 4 different aggregates was done with respect to TS EN 933-1 (2012). The particle size distribution of aggregates is given in Table 2.5. Aggregate mixture ratios, final mix of aggregate particle size distribution and reference aggregate lines (A32, B32 and C32) are also given in Figure 2.1.

Table 2.4 : Specific weight of aggregates.

Aggregates	Specific Weight (g/cm^3)
Natural Sand	2.62
Crushed Sand	2.71
Crushed Stone I	2.70
Crushed Stone II	2.74

According to Table 2.4 and Table 2.5, aggregates properties and proportions were determined to perform the concrete mix design. Thanks to reference aggregate size distributions, aggregate gradation was optimized.

Table 2.5 : The particle size distribution of aggregates.

Sieve Openings (mm)	Aggregates			
	Natural Sand	Crushed Sand	Crushed Stone I	Crushed Stone II
31.5	100	100	100	100
16	100	100	100	36
8	100	100	64	0
4	100	84	3	0
2	93.7	51	0	0
1	75.7	35	0	0
0.5	54.8	18	0	0
0.25	8.8	11	0	0

Respect to the sieve analysis of aggregates, A32-B32-C32 reference lines were used. The particle size distribution of reference lines are given in Table 2.6.

Table 2.6: The particle size distribution of reference aggregates.

References	Sieve Openings (mm)							
	31.5	16	8	4	2	1	0.5	0.25
A32	100	62	38	23	14	8	5	2
B32	100	80	62	47	37	28	18	8
C32	100	89	77	65	53	42	28	15

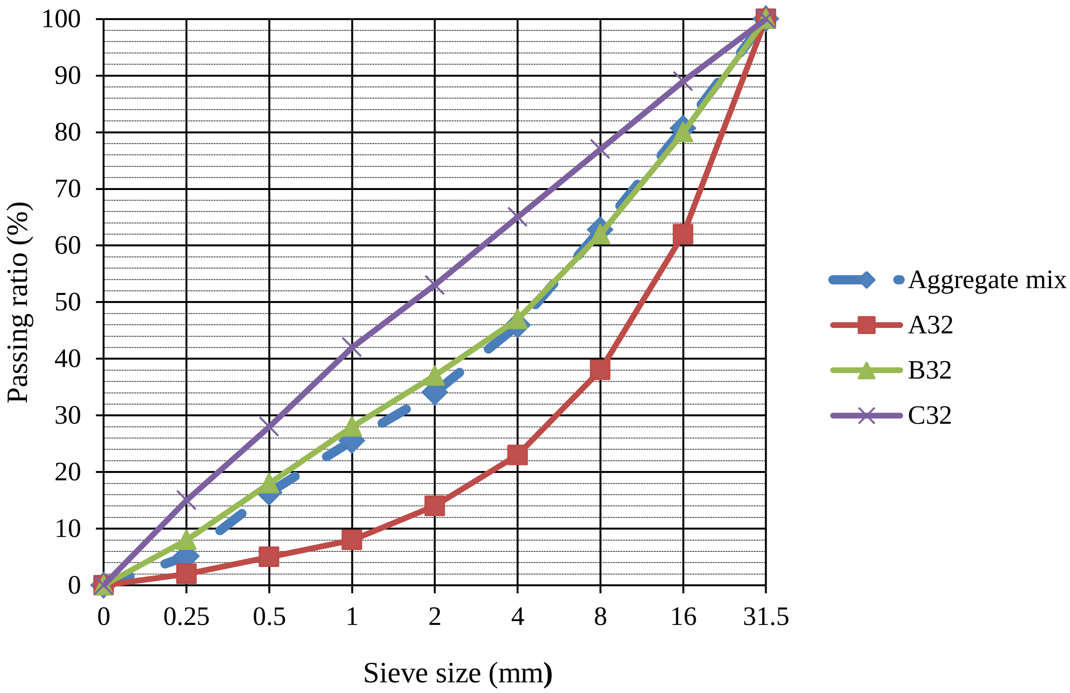

Figure 2.1 : Mix aggregate particle size distribution.

2.1.6 Chemical Admixture

Superplasticizer was used in concrete production. This chemical admixture was used in fresh concrete to increase workability and final compressive strength, to decrease concrete mix water and permeability. This superplasticizer was obtained from Pascal Yapı Kimyasalları San. Tic. A.Ş.. The physical and chemical properties are given in Table 2.7.

Table 2.7: Technical properties of superplasticizer.

Color	Brown
Chemical properties	Polycarboxylate solution
pH	5.0 $\pm$1
Specific weight (g/cm^3)	1.08$\pm$0.02
Total Cl$^-$ ratio (%)	< 0.1%
Alkali content (%)	< 0.1 %

2.2 Mixtures

In experimental studies, twelve different concrete mixtures were prepared. Three different water/binder ratios were determined, and these are 0.36, 0.50 and 0.65. Three of these mixtures are reference concrete with different water/cement (w/c) ratios. The reference Portland cement concrete specimens (PC) were produced for comparison. During the PC production only Portland Cement 42.5 R was used as a binder and no alkali activators were used. On the other hand, the other has different water/binder (w/b) and Na_2SiO_3/NaOH ratios. Molarity of NaOH is constant for all AASC specimens and the value is 8 M. GBFS was used as a binder and both NaOH and Na_2SiO_3 were used as alkali activators to produce AASC.

Alkali activators were added in concrete mixes as a solution form. Beads form of NaOH was solved in water and prepared 8 M solution, then both solution form of Na_2SiO_3 and NaOH were added in concrete mix. After this step, if it was necessary, superplasticizer was used to obtain workability.

The naming of the reference specimens start with RC letters, then number refers to their w/c ratio. For example, for three reference concretes RC0.36, RC0.50 and RC0.65 were given as specimen codes. The first set of AASC was entitled with AASC letters then w/b ratio and Na_2SiO_3/NaOH ratio were given. In addition, Na_2SiO_3/NaOH ratio of the first set of AASC is 2.5. For instance, the name of the first AASC series are AASC0.36/2.5, AASC0.50/2.5 and AASC0.65/2.5. Na_2SiO_3/NaOH ratio of the second set of AASC is 1, so the name of the second sets are AASC0.36/1, AASC0.50/1 and AASC0.65/1. The third and the last series of AASC were named like, AASC0.36/4, AASC0.50/4 and AASC0.65/4, because the ratio of Na_2SiO_3/NaOH is 4.

2.2.1 Concrete mix proportions

12 different concrete mix designs are given in this section. Reference Portland cement concrete (RC) actual mix proportions of each component for $1m^3$ concrete production are given in Table 2.8.

Table 2.8 : RC mix proportions for $1m^3$.

Components		RC 0.36	RC 0.50	RC 0.65
Cement (kg)		585	460	336
Water (kg)		210	230	220
Superplasticizer (kg)		9	10	1.7
Aggregates	Natural Sand (kg)	315	325	352
	Crushed Sand (kg)	490	505	546
	Crushed Stone I (kg)	325	335	363
	Crushed Stone II (kg)	345	552	552
w/c		0.36	0.50	0.65

For the first series of AASC, actual mix proportions of each component for $1m^3$ concrete production are given in Table 2.9.

Table 2.9 : The first series of AASC mix proportions for $1m^3$.

Components	AASC0.36/2.5	AASC0.50/2.5	AASC0.65/2.5
GBFS (kg)	501	501	336
Water (kg)	47	120	131
Na(OH) (kg)	36	36	24
Water (for NaOH solution) (kg)	67	67	45
Na_2SiO_3 solution (kg)	87	87	58

Table 2.9 (continued): The first series of AASC mix proportions for 1m^3.

Water part of Na_2SiO_3 solution (kg)		64	64	43
Superplasticizer (kg)		8	7	5
Aggregates	Natural Sand (kg)	296	258	319
	Crushed Sand (kg)	459	401	495
	Crushed Stone I (kg)	305	266	329
	Crushed Stone II (kg)	464	405	501
w/c		0.36	0.50	0.65

For the second series of AASC, actual mix proportions of each component for 1m^3 concrete production are given in Table 2.10.

Table 2.10 : The second series of AASC mix proportions for 1m^3.

Components	AASC0.36/1	AASC0.50/1	AASC0.65/1
GBFS (kg)	530	501	336
Water (kg)	0	15	60
Na(OH) (kg)	63	61	41
Water (for NaOH solution) (kg)	145	191	128
Na_2SiO_3 solution (kg)	63	61	41
Water part of Na_2SiO_3 solution (kg)	46	45	30
Superplasticizer (kg)	5	0	0

Table 2.10 (continued): The second series of AASC mix proportions for 1m^3.

Aggregates	Natural Sand (kg)	289	266	324
	Crushed Sand (kg)	448	412	503
	Crushed Stone I (kg)	298	274	334
	Crushed Stone II (kg)	453	417	509
w/c		0.36	0.50	0.65

For the third series of AASC, actual mix proportions of each component for 1m^3 concrete production are given in Table 2.11.

Table 2.11 : The third series of AASC mix proportions for 1m^3.

Components		AASC0.36/4	AASC0.50/4	AASC0.65/4
GBFS (kg)		501	501	336
Water (kg)		31	101	118
Na(OH) (kg)		24	24	17
Water (for NaOH solution) (kg)		76	76	51
Na_2SiO_3 solution (kg)		98	98	66
Water part of Na_2SiO_3 solution (kg)		73	73	49
Aggregates	Natural Sand (kg)	293	260	321
	Crushed Sand (kg)	455	404	498
	Crushed Stone I (kg)	302	268	331
	Crushed Stone II (kg)	460	408	503
w/c		0.36	0.50	0.65

2.2.2 Sample Production

12 different concrete mix was produced in concrete mixer whose volume capacity is 50 l. Production stage started with aggregates. Firstly, coarse then fine aggregates were put in the mixer, then 1-2 minutes aggregates were mixed. After the aggregates, cement, water and alkalines were added. After 5 minutes of mixing, if it was necessary, superplasticizer was added.

Cylindrical specimens (diameter: 10 cm, height: 20 cm) were used for each type of production. Twelve cylindrical specimens were produced, so at the end 120 cylindrical specimens were obtained. Whole specimens were cured in saturated lime water during 28 days.

2.3 Experiments

2.3.1 Fresh concrete experiments

Fresh concrete experiments were applied the concrete which had not set yet. Unit weight and slump test were applied.

2.3.1.1 Unit weight experiment

Unit weight experiment was done for fresh state concrete with respect to TS EN 12350-6 (2010). Fresh state concrete was filled in steel container and the volume of this container was 7 L. Before this experiment, tare weight of container was estimated with 0.1g sensitivity scale. Fresh concrete was casted in stages in the container. After filling process was finished, to get the compaction, container was placed on the vibratory table unit, then vibration was started.

To obtain the unit weight of fresh concrete, in equation 2.1 can be used.

$$D = \frac{M_2 - M_1}{V} \tag{2.1}$$

where, D: Unit weight of fresh concrete (kg/m^3)

M_1: Weight of the steel container (kg)

M_2: Weight of the both concrete and the container (kg)

V: Volume of the steel container (m^3)

2.3.1.2 Slump test

Slump test for concrete was applied with respect to TS EN 12350-2 (2010). This slump test is applied to obtain the workability of concrete. Firstly, the internal surface of slump cone was wetted. Then the cone was filled with fresh concrete mix in 3 equal layers. After filling the cone, each layer was tamped down 25 times with a tamping rod. Lifting up the cone from the fresh concrete vertically and it is put near the concrete in reverse form. Finally, difference between the height of the cone and the top point of the concrete was measured (Figure 2.2).

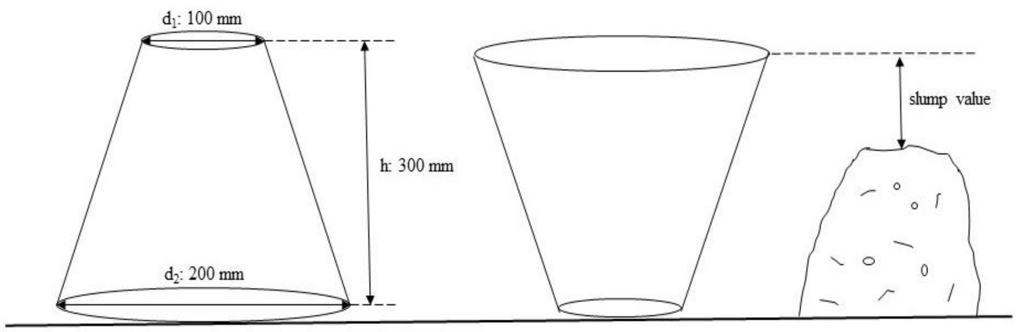

Figure 2.2: Slump value measurement.

2.3.2 Hardened concrete experiments

After demolding, specimens were cured in saturated limewater for 28 days. On the 28th day, both mechanical and durability experiments were made on the specimens.

2.3.2.1 Compressive strength test

Compressive strength tests were performed on 100 mm (diameter) and 200 mm (height) specimens. This compressive strength was done with respect to TS EN 12390-3 (2010). Before this test, capping for cylindrical concrete specimens was completed. For this test 500 ton capacity compression testing machine was used. The compressive strength of specimens was calculated with respect to in equation 2.2.

$$\sigma_C = \frac{\mathbf{F_C}}{\mathbf{A}} \qquad (2.2)$$

where, σ_c: Compressive strength (MPa)

F_C: Maximum load (N)

A: Cross section area (mm^2)

2.3.2.2 Measurement of the modulus of elasticity

Modulus of elasticity of cylindrical concrete specimens (100 mm diameter and 200 mm height) was obtained. The followed path, while obtaining the modulus of elasticity is first determining the compressive strength of specimen, then gauge frame was attached to the cylindrical specimen. Constant loading rate was determined and the test was started. To obtain the value of the modulus of elasticity, 30% of maximum stress was determined and the linear-elastic part of graph was used to obtain the slope**.**

2.3.2.3 Water absorption of concrete

Water absorption of concrete by weight was done with respect to TS EN 12390-7 (2010). 200 mm height and 100 mm diameter cylindrical specimens were cut in half, specimens were put in the oven at 105 º C for 24 hours, and their initial weights were determined. After this step, 100 mm height and 100 mm diameter specimens were placed in water during 3 days. After this, final weights were determined and at the end water absorption by weight was determined by 2.4 equation.

$$S_W = \frac{W_i - W_f}{W_i} \times 100 \tag{2.4}$$

where, S_W: Water absorption by weight (%)

W_i: Initial weight of specimen (gr)

W_f: Final weight of specimen (gr)

2.3.2.4 Capillary water absorption

Capillary water absorption for concrete specimens was done with respect to TS EN 772-11 (2012). Cylindrical specimens (100 mm diameter and 200 mm height) were cut in half and their heights were 100 mm. Before the test, specimens were put in the oven at 105ºC during 24 hours. Specimens in contact with water covered with paraffin to obtain non wettable faces, so specimens were exposed to water with only one side, which was the cut surface of the concrete. The change in weight was recorded for 144 minutes. The rate of weight change and the square root of time were obtained and the graph was drawn with respect these two parameters. Capillary water absorption test is shown in Figure 2.3.

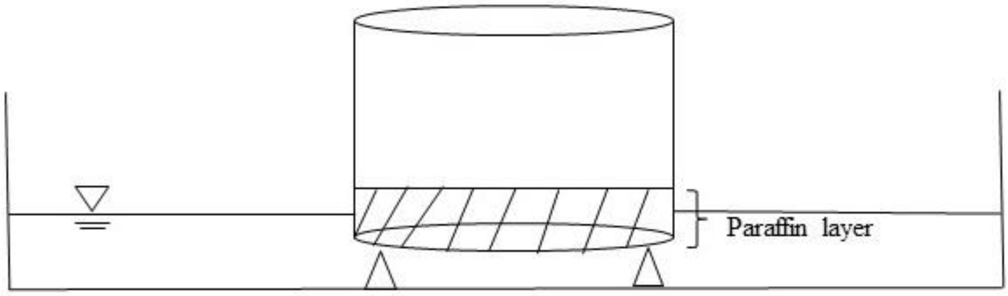

Figure 2.3 : Capillary absorption of water.

The capillary water absorption coefficient can be calculated with equation 2.5.

$$\mathbf{q^2 = Kxt} \tag{2.5}$$

where, q: amount of water that absorbed from unit area (cm^3/cm^2)

K: coefficient of capillary absorption (cm^2/s)

t: time (s)

2.3.2.5 Rapid chloride penetration test

Rapid chloride penetration test was done with respect to ASTM C 1202-12. 50 mm thickness and 100 mm diameter specimens were prepared. At the end of the 28^{th} day of concrete specimens, their surfaces except their top and bottom surfaces were covered with waterproof polyurethane adhesive. Specimens were vacuumed by air with 3 hours, then during one hour water vacuuming were applied. After this preparation process, A potential of 60 V was applied as a DC. Two cell containers were filled with solution. One of them was filled with 3% NaCl solution and this cell was going to be connected with negative terminal of power supply and the other cell was filled with 0.3N of NaOH solution, and this part was going to be connected with positive terminal of power supply. After starting the test, current was recorded every 30 minutes, and test was continued during 6 hours. Passed charged was calculated with equation 2.6.

$$\mathbf{Q} = \mathbf{900}(\mathbf{I_0} + \mathbf{2I_{30}} + \mathbf{2I_{60}} + \cdots + \mathbf{2I_{300}} + \mathbf{2I_{330}} + \mathbf{I_{360}}) \qquad (2.6)$$

where, Q: charge passed (coulombs)

I_0: current that after immediately voltage is applied

I_t: current that t minutes voltage is applied

Passing charge and chloride penetration relationship is given in Table 2.12.

Table 2.12 : Passing charge and chloride penetration relation.

Passing Charge (coulombs)	Chloride Penetration
>4000	High
2000-4000	Medium
1000-2000	Low
100-1000	Very Low
<100	Negligible

2.3.2.6 Electrical resistivity

Two electrode method was used for identifying the electrical resistivity of concrete specimens. The concrete sample was placed between two parallel electrodes and the experimental setup is given in Figure 2.5. Thanks to this experiment, corrosion risks of these specimens can be identified.

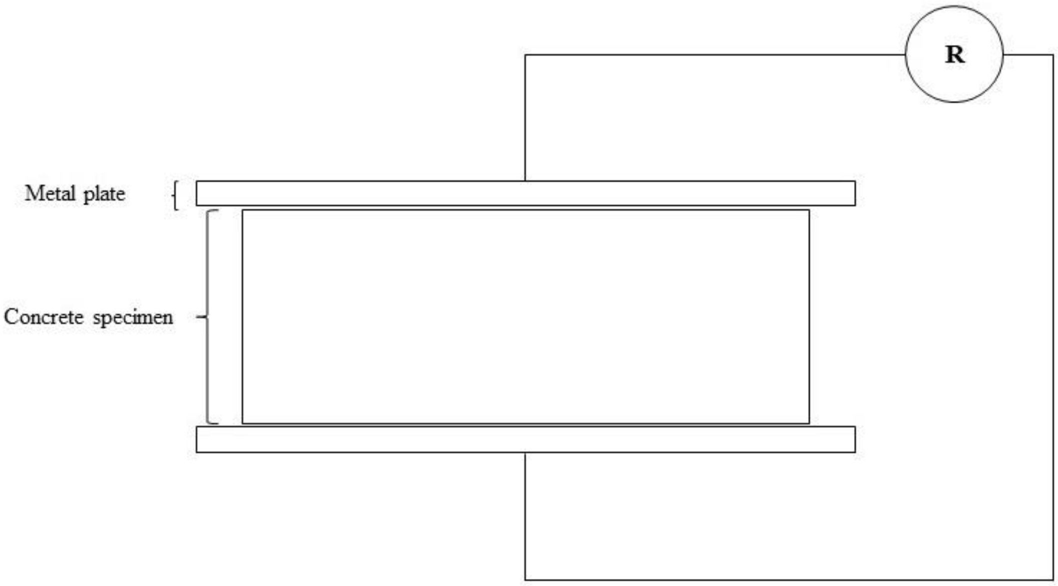

Figure 2.4 : Two electrode method for electrical resistivity.

Concrete specimen was placed between two metal plates and the resistance of alternative current is measured. Electrical resistivity of concrete is calculated with 2.7 equation.

$$\rho_{\text{concrete}} = \text{Rx}\frac{\text{A}}{\text{L}} \tag{2.7}$$

where, $\rho_{concrete}$: electrical resistivity of concrete

R: resistance

A: cross section area of concrete

L: length of the specimen

3. RESULTS AND DISCUSSION

3.1 General

In this chapter, the results of fresh concrete experiments and hardened concrete which are both mechanical and durability experiments are presented. Reasons of these results are also discussed in this chapter.

3.2 Results of Fresh Concrete Experiments

Theoric and real unit weights and slump values of fresh concrete are given in Table 3.1. Real air content of 12 different mixes were obtained by calculation. Air content of reference mixes have the lowest values.

Table 3.1 : Results of fresh concrete experiments.

	Types of Concrete Mix											
	PC			AASC								
	0.36	0.50	0.65	0.36/1	0.50/1	0.65/1	0.36/2.5	0.50/2.5	0.65/2.5	0.36/4	0.50/4	0.65/4
Theoric Unit Weight (kg/m^3)	2453	2366	2369	2336	2243	2306	2334	2212	2286	2313	2213	2290
Real Unit Weight (kg/m^3)	2441	2354	2360	2329	2218	2284	2320	2202	2271	2296	2200	2259

Table 3.1 (continued): Results of fresh concrete experiments.

	Types of Concrete Mix											
	PC			AASC								
	0.36	0.50	0.65	0.36/21	0.50/1	0.65/1	0.36/2.5	0.50/2.5	0.65/2.5	0.36/4	0.50/4	0.65/4
Slump Value (cm)	19	17	18	21	24	25	21	20	22	23	25	27
Real Air content (%)	0.5	0.6	0.4	0,6	1	1	1,1	0,8	0,9	0.7	0.7	1.3

3.3 Results of Mechanical Experiments

In this chapter both compressive strength and modulus of elasticity of concrete results are given. The relationship between these values are also studied.

3.3.1 Results of compressive strength

28th day of compressive strength of the concrete specimens were given in Table 3.2 and comparative compressive strength results were given in Figure 3.1. Three specimens were tested for each type of mixes and the average compressive strength values are given.

Table 3.2 : Compressive strength of cylindirical specimens.

Mix Code	Cylindrical compressive strength of concrete (MPa)
RC 0.36	51
RC 0.50	47
RC 0.65	30

Table 3.2 (continued): Compressive strength of cylindirical specimens.

AASC 0.36/1	57
AASC 0.50/1	43
AASC 0.65/1	42
AASC 0.36/2.5	53
AASC 0.50/2.5	26
AASC 0.65/2.5	10
AASC 0.36/4	60
AASC 0.50/4	32
AASC 0.65/4	22

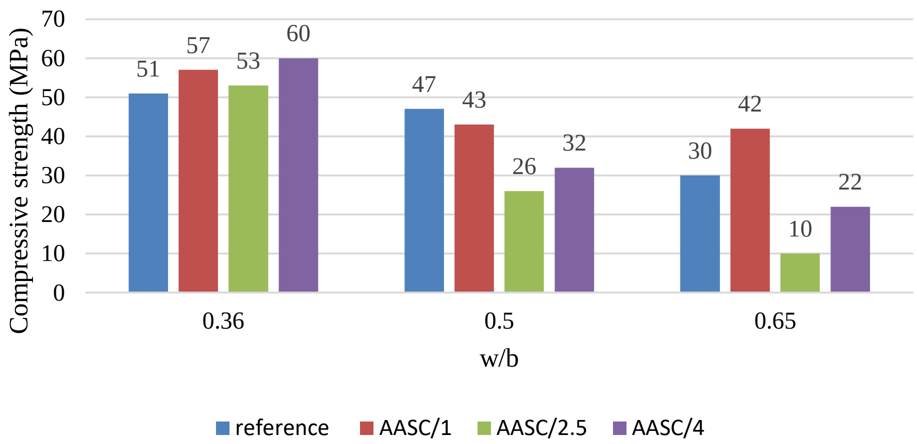

Figure 3.1 : Comparatively compressive strength results of concrete mix.

3.3.2 Results of modulus of elasticity

28th day modulus of elasiticity values are given in Table 3.3. Comparatively results are given in Figure 3.2.

Table 3.3 : Results of modulus of elasticity values.

Mix Code	Modulus of Elasticity (GPa)
RC 0.36	36.9
RC 0.50	32.3
RC 0.65	32.6
AASC 0.36/1	29.6
AASC 0.50/1	21.9
AASC 0.65/1	26.3
AASC 0.36/2.5	22.8
AASC 0.50/2.5	17.2
AASC 0.65/2.5	27.3
AASC 0.36/4	29.9
AASC 0.50/4	18.0
AASC 0.65/4	18.6

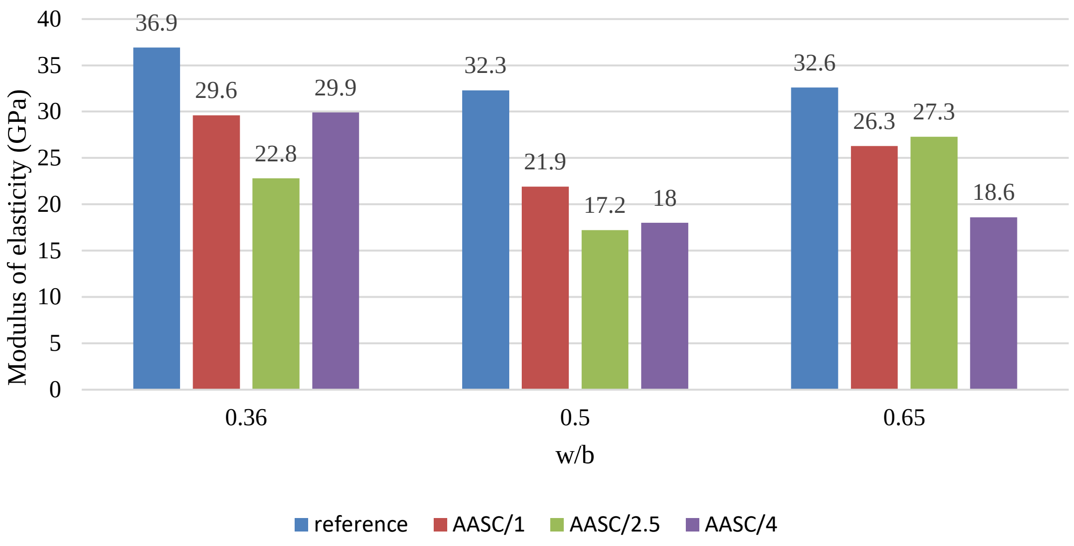

Figure 3.2 : Comparatively modulus of elasticity results.

3.4 Results of Durability Experiments

In this chapter, results of durability experiments are presented. Water absorption, capillary water absorption, rapid chloride penetration and electrical resistivity tests were obtained for durability properties of specimens.

3.4.1 Results of water absorption of concrete

28th day water absoption percentages are given in Table 3.4 and Figure 3.3 with respect to their water/binder ratio. For this experiment, weight of water absorbed was calculated.

Table 3.4 : Water absorption percentages.

Water Absorption (%)	Mix Type											
	R0.36	R0.50	R0.65	AASC0.36/1	AASC0.50/1	AASC0.65/1	AASC0.36 /2.5	AASC0.50/2.5	AASC0.65/2.5	AASC0.36/4	AASC0.5/4	AASC0.65/4
	0.3	3	4	2	4	4	2	4	5	2	4	4

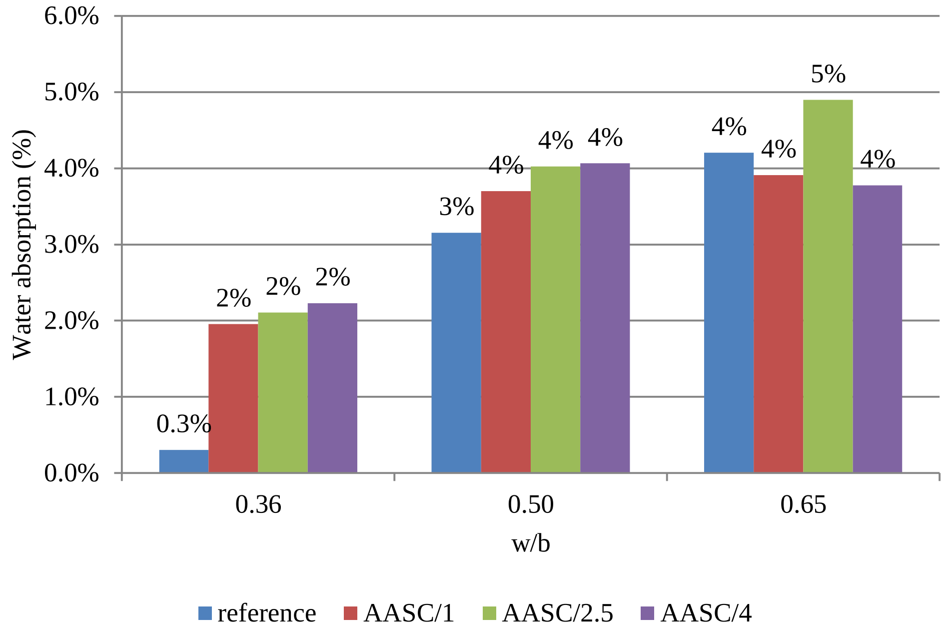

Figure 3.3: Comparatively water absorption results.

3.4.2 Capillarity results

28th day capillarity results are given in Table 3.5 and Figure 3.4. To characterize porous internal structure, sorptivity coefficient was calculated.

Table 3.5: Coefficient of capillary water absorption.

	Mix Type											
Sorptivity Coefficient (cm^2/s) ($x10^{-6}$)	R0.36	R0.50	R0.65	AASC0.36/1	AASC0.50/1	AASC0.65/1	AASC0.36/2.5	AASC0.50/2.5	AASC0.65/2.5	AASC0.36/4	AASC0.50/4	AASC0.65/4
	0.01	1.22	1.22	2	16	5	1.22	28.9	57.8	1.17	41.7	32.2

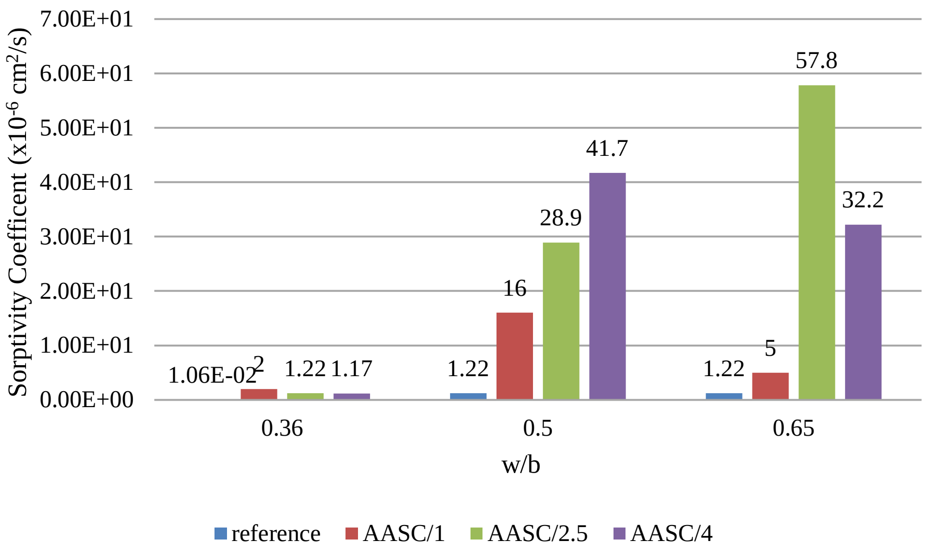

Figure 3.4: Comparatively coefficient of capillary water absorption results.

3.4.3 Results of chloride penetration test

28th day rapid chloride penetration test results are given in Table 3.6 and Figure 3.5. Concrete resistivity of chloride ion permeability was obtained respect to this test.

Table 3.6 : Passing charge amount.

Water/binder ratio	Mixture Code	Passing charge (coloumbs)
0.36	RC	1572
	AASC/1	1553
	AASC/2.5	1961
	AASC/4	1739
0.50	RC	3105
	AASC/1	3396
	AASC/2.5	3151
	AASC/4	4295
0.65	RC	3749
	AASC/1	4295
	AASC/2.5	3599
	AASC/4	8408

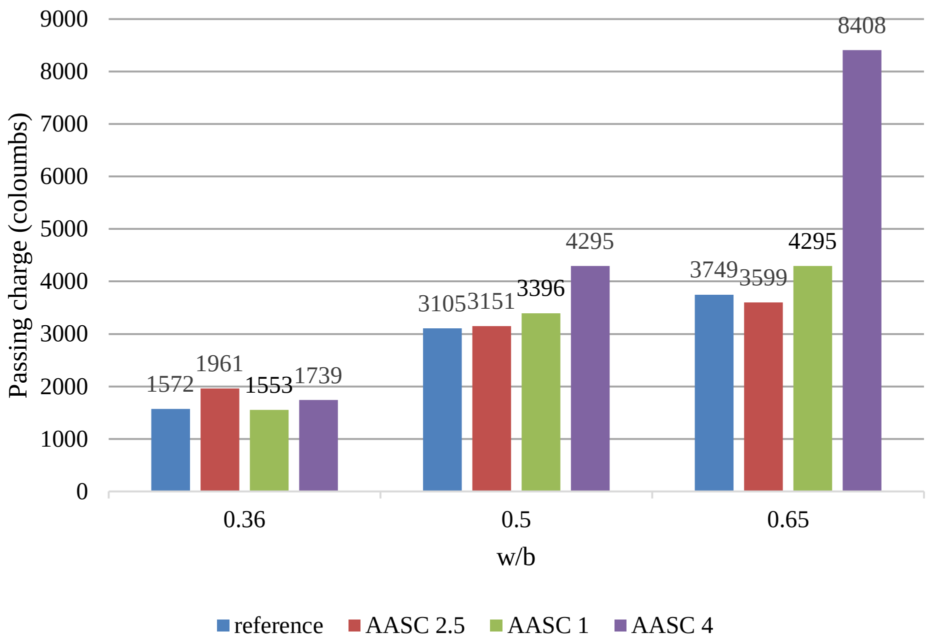

Figure 3.5 : Chloride permeability of PC and AASC**.**

3.4.4 Electrical resistivity

For concrete mixes which have different w/b ratio and Na_2SiO_3/NaOH ratio, the electirical resistivities with two electrode method are given in Table 3.7 and Figure 3.6.

Table 3.7 : Electrical resistivity of PC and AASC.

Water/binder ratio	Mixture Code	Electrical Resistivity (kΩ.cm)
0.36	RC	15.6
	AASC/1	16.7
	AASC/2.5	11.2
	AASC/4	13.5
0.50	RC	10.3
	AASC/1	7.9
	AASC/2.5	8.1
	AASC/4	4.1
0.65	RC	6.9
	AASC/1	6.7
	AASC/2.5	6.8
	AASC/4	4.5

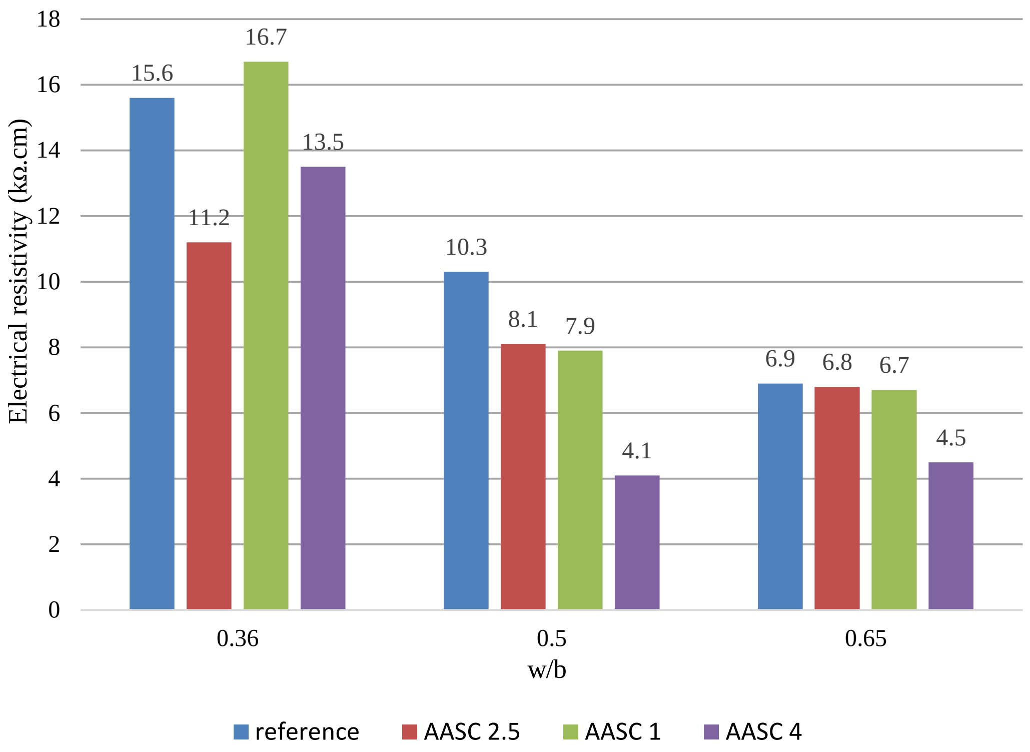

Figure 3.6: Electrical resistivity of PC and AASC.

3.5 Discussion

3.5.1 Workability results

Slump values of PC and AASC specimens are given in Figure 3.7. Slump values of AASC show higher values than PC, although with the same w/b, PC specimens show the lowest slump value. The reason of this is the better dispersion of GBFS particles. During the production of PC mixes, workability was tried to keep constant. In addtition, mixes of AASC show an upward trend. At nearly 30 minutes later after producing of AASC mixes, the loss of workability occurred. Teixeira-Pinto et al. (2002) explain that increase in molding time make the inner temperature of mixes increased so workability decrease can be observed. However, after casting mixes into the molds and vibrated them, no segregation was observed. Figure 3.7 shows that, maximum slump value is 27 cm when w/b is 0.65 and $Na_2SiO_3/NaOH$ is 4 for AASC and the minimum slump value is 20 cm when w/b is 0.50 and $Na_2SiO_3/NaOH$ is 2.5 for AASC.

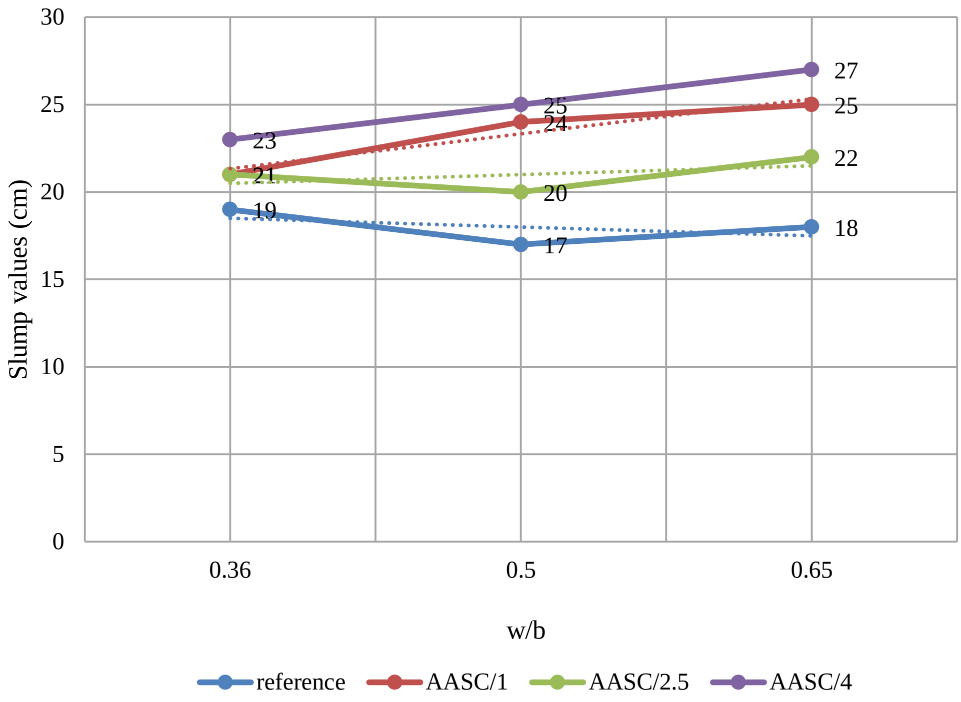

Figure 3.7 : The effect of w/b and Na2SiO3/NaOH ratios slump test.

3.5.2 Mechanical results

$Na_2SiO_3/NaOH$ ratio and compressive strength results are given in Figure 3.8. This graph presents that for these mixtures, water/binder ratio becomes a significant property for obtaining compressive strength. Beside that, when w/b is 0.36, increment of $Na_2SiO_3/NaOH$ ratio affects positively for compressive strength. On the other hand, when w/b is 0.50 or 0.65 and $Na_2SiO_3/NaOH$ ratio is 2.5, the lowest compressive strength is obtained. Also, irregular tendencies are observed for 0.5 and 0.65 w/b raitos.

When w/b is 0.36, all of the specimens yield compressive strength values higher than 50 MPa compressive strength. This means that, all of 0.36 w/b mixes can be load-bearing concrete. In addition, for 0.36 w/b, AASC have higher compressive strength than PC and the maximum compressive strength is 60 MPa which is obtained from AASC 0.36/4 and this value is 17.6% higher than RC 0.36.

When w/b is 0.50, the maximum compressive strength is 47 MPa which is obtained from RC 0.50. The maximum compressive strength is 84.6% higher than the lowest compressive strength which is obtained from AASC 0.50/2.5.

When w/b is 0.65, the maximum compressive strength is 42 MPa which is obtained from AASC 0.65/4.

General trend explains that, 0.36 w/b gives highest compressive strength values than other mixes.

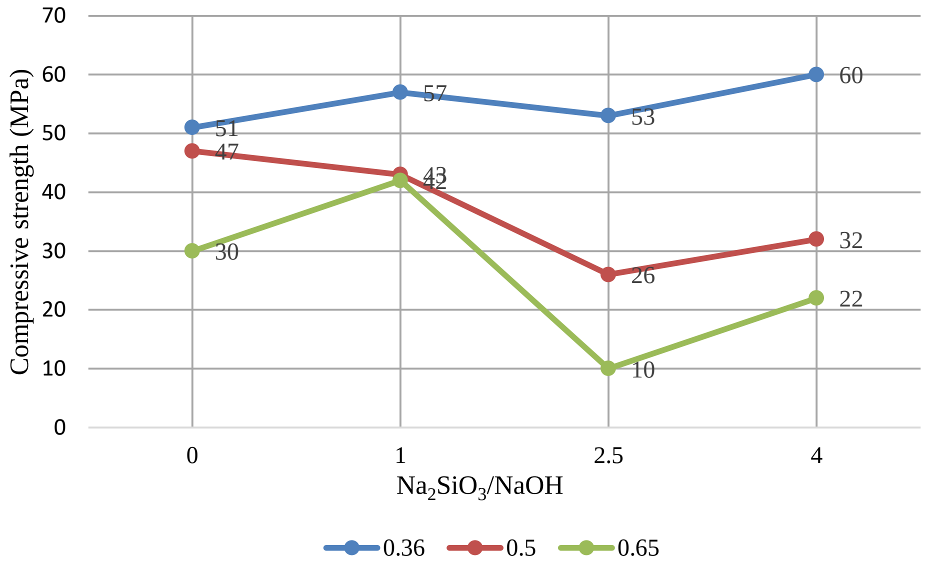

Figure 3.8 : Compressive strengths are in compliance with Na_2SiO_3/NaOH.

Relationships between modulus of elasticity and Na_2SiO_3/NaOH ratio are given in Figure 3.9. The trends between modulus of elasticity and compressive strength are approximately opposite. For example, when w/b ratio is 0.65 and Na_2SiO_3/NaOH ratio is 2.5, 10 MPa compressive strength which is the lowest value has been obtained, on the other hand 27.3 GPa modulus of elasticity which is the second highest value has been obtained between AASC specimens.

According to Puertas et al. (2011), C-S-H gels which are formed of Portland cement hydration, on the other hand C-A-S-H gels are formed of alkali activated slag hydration. Chain lengths of C-S-H and C-A-S-H are different, which may affect the elastic modulus obtained. Thomas et al. (2003) explain that C-S-H gel has a crystal structure and Ca-O polyhedral layer is ribbed on continuous silicate chains so it can be understood that C-S-H has a chain structure. According to Puertas et al. (2011) and Thomas et al. (2003), for perfect tobermorite C-S-H chain length is between 1.1 and 1.4 nm, but when Al is included in this chain, chain length reduced. Chain length is affected by packing factor. Packing factor of C-S-H gel is around 0.68, 0.77 and

0.9, however packing factor of C-A-S-H is around 0.63, 0.68, 0.79. This difference may affect mechanical properties.

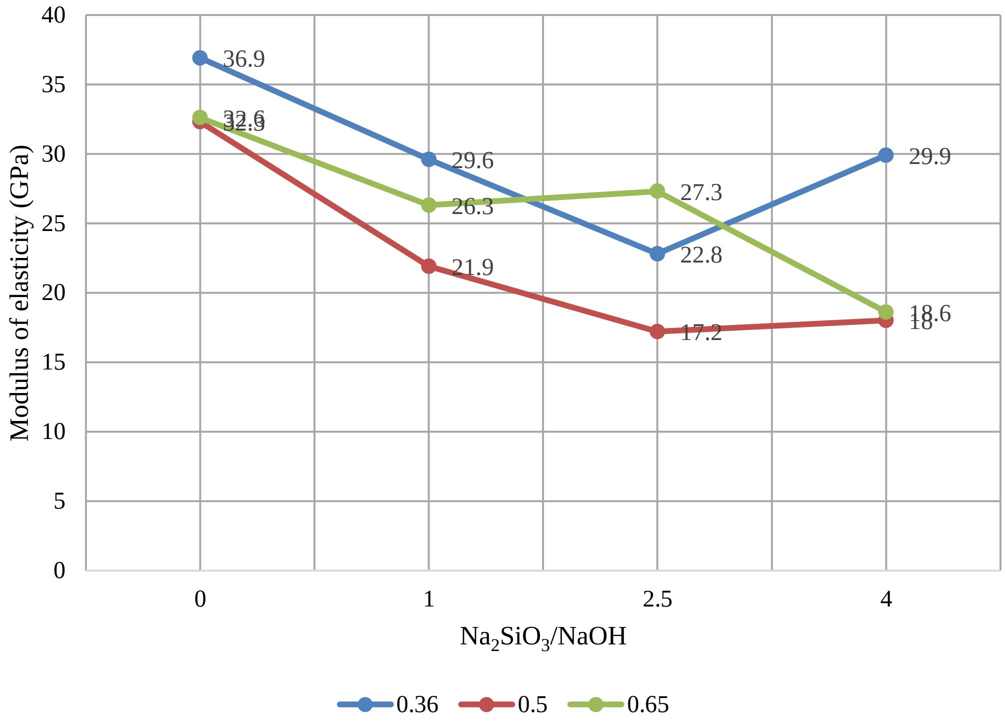

Figure 3.9 : Modulus of elasticity results are in compliance with Na_2SiO_3/NaOH.

3.5.3 Durability results

The first durability test, water absorption has a significant role to identify the permeability which affects durability. Also, microstructure mechanism affects all these durability properties. Valcke et al. (2012) research that, durability results show that, w/b ratio is a determinative property and this is related to larger pore structure of connected air voids and microcracks of AASC and high capillary suction force of dense geopolymer paste. Also, De Gutierrez et al. (2003) and Olivia et al. (2008) explain that geopolymers have lower permeability than cement based materials. According to Valcke et al. (2012), because of the change of the durability results, general statements can not be obtained for durability of geopolymer concrete. The reasons of these variations may be the source of the chemicals or differents mix designs and curing procedures.

According to rapid chloride penetration test results, when w/b ratio increases, chloride penetration also increases and alkali activator ratio does not affect this property. In addition, electrical resistivity results which is the non-destructive test are in the same tendency with chloride penetration. While w/b ratio is increasing, electrical resistivity decrease.

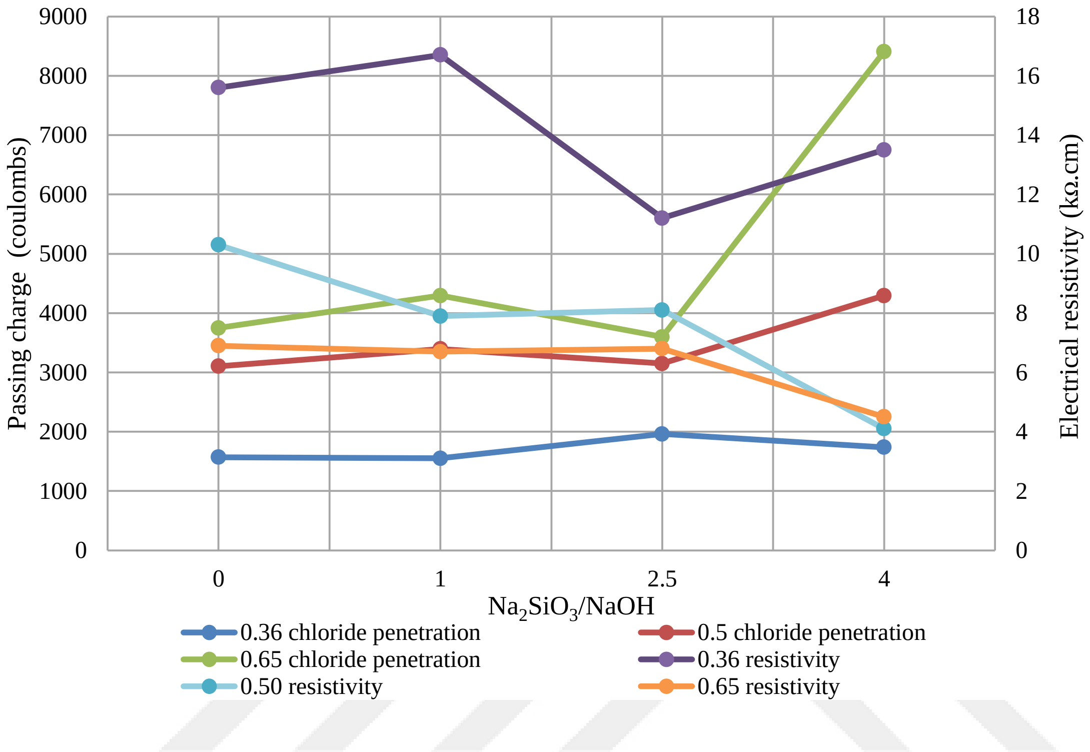

Figure 3.10 : Chloride penetration and electrical resistivity of PC and AASC.

4. COST ANALYSES

While analyzing the costs of productions, unit prices are obtained from 2017 Unit Price List which is published from Environment and Urban Planning Ministry of Turkey. The example of unit cost calculation is given in Table 4.1. The unit prices which are obtained from Environment and Urban Planning Ministry of Turkey, are multiplied with quantities of the components in concrete.

Table 4.1 : Cost analysis for 1 m^3 RC0.36 cocnrete mix.

Item Number	Drefinition	Unit	Price (TL)	Quantity	Price (TL)
04.008/2C	Portland Cement (CEM I 42.5 R)	ton	176.00	0.59	103.84
04.031	Su	m^3	5.60	0.21	1.18
04.001/051	Crushed Stone II	m^3	26.50	0.13	3.45
04.001/051	Crushed Stone I	m^3	26.50	0.12	3.18
-	Crushed Sand	ton	33	0.49	16.17
04.007/A	Sand	kg	0.24	315	75.60
04.613/1A3 (2011)	Superplasticizer	kg	2.35	9	21.15
				TOTAL PRICE (TL)	224.57

Cost analyses of 12 mixes are given comparatively in Table 4.2. After the cost analyses of concrete mixes, it is understood that reference concrete mixes are more ecomonical than AASC. The reason of this is not the change of the binder, using chemicals as activators make this price difference high.

Table 4.2 : Comparatively cost analyses of concrete mixes.

Concrete Mix	Unit Cost (TL)
RC 0.36	224.57
RC 0.50	210.37
RC 0.65	176.45
AASC 0.36/2.5	1734.25
AASC 0.50/2.5	1720.44
AASC 0.65/2.5	1195.09
AASC 0.36/1	2017.21
AASC 0.50/1	1995.73
AASC 0.65/1	1387.95
AASC 0.36/4	1562.06
AASC 0.50/4	1551.75
AASC 0.65/4	783.67

5. CONCLUSIONS

The conclusions of alkali activated slag concrete were summarized as folow. For fresh concrete test results, PC showed similar slump values, however for the constant Na_2SiO_3/NaOH ratio, slump value increased with w/b increment.

The highest compressive strength was obtained from AASC. However, this high result was not obtained for every AASC respects to different w/b ratios. The optimum mechanical properties of AASC were obtained when w/b was 0.36. Elastic modulus showed negative trend with compressive strength. The highest elastic modulus was obtained from PC.

For water absorption and capillary water absorption results, reference concrete specimens had lower water permeability. For rapid chloride penetration and electrical resistivity tests, w/b ratio was determinative property like other durability test results and reference concrete specimens had lower chloride permeability. According to cost analyses, for 1 m^3 mixes, Portland cement concrete mixes are more economical than alkali activated slag concrete mixes.

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APPENDICES

APPENDIX A: Cost analyses

APPENDIX A

Table A.1 : Cost analysis for 1 m^3 RC0.50 cocnrete mix.

Item Number	Drefinition	Unit	Price (TL)	Quantity	Price (TL)
04.008/2C	Portland Cement (CEM I 42.5 R)	ton	176.00	0.50	88.00
04.031	Su	m^3	5.60	0.25	1.40
04.001/051	Crushed Stone II	m^3	26.50	0.18	4.77
04.001/051	Crushed Stone I	m^3	26.50	0.12	3.18
-	Crushed Sand	ton	33	0.48	15.84
04.007/A	Sand	kg	0.24	307	73.68
04.613/1A3 (2011)	Superplasticizer	kg	2.35	10	23.50
				TOTAL PRICE (TL)	210.37

Table A.2 : Cost analysis for 1 m^3 RC0.65 cocnrete mix.

Item Number	Drefinition	Unit	Price (TL)	Quantity	Price (TL)
04.008/2C	Portland Cement (CEM I 42.5 R)	ton	176.00	0.34	59.84
04.031	Su	m^3	5.60	0.22	1.23
04.001/051	Crushed Stone II	m^3	26.50	0.20	5.30
04.001/051	Crushed Stone I	m^3	26.50	0.13	3.45
-	Crushed Sand	ton	33	0.55	18.15
04.007/A	Sand	kg	0.24	352	84.48
04.613/1A3 (2011)	Superplasticizer	kg	2.35	1.70	4.00
				TOTAL PRICE (TL)	176.45

Table A.3 : Cost analysis for 1 m^3 AASC0.36/2.5 cocnrete mix.

Item Number	Drefinition	Unit	Price (TL)	Quantity	Price (TL)
04.011 (2011)	GBFS	ton	81.00	0.50	40.50
04.031	Su	m^3	5.60	0.11	0.62
04.001/051	Crushed Stone II	m^3	26.50	0.17	4.51
04.001/051	Crushed Stone I	m^3	26.50	0.11	2.92
-	Crushed Sand	ton	33	0.46	15.18
04.007/A	Sand	kg	0.24	296	71.04
04.613/1A3 (2011)	Superplasticizer	kg	2.35	8	18.80
-	NaOH	kg	21.30	36	766.80
-	Na_2SiO_3	L	12.63	64.44	813.88
				TOTAL PRICE (TL)	1734.25

Table A.4 : Cost analysis for 1 m^3 AASC0.50/2.5 cocnrete mix.

Item Number	Drefinition	Unit	Price (TL)	Quantity	Price (TL)
04.011 (2011)	GBFS	ton	81.00	0.50	40.50
04.031	Su	m^3	5.60	0.19	1.06
04.001/051	Crushed Stone II	m^3	26.50	0.15	3.98
04.001/051	Crushed Stone I	m^3	26.50	0.10	2.65
-	Crushed Sand	ton	33	0.40	13.20
04.007/A	Sand	kg	0.24	258	61.92
04.613/1A3 (2011)	Superplasticizer	kg	2.35	7	16.45

Table A.4 (continued): Cost analysis for 1 m^3 AASC0.50/2.5 concrete mix.

-	NaOH	kg	21.30	36	766.80
-	Na_2SiO_3	L	12.63	64.44	813.88
				TOTAL PRICE (TL)	1720.44

Table A.5 : Cost analysis for 1 m^3 AASC0.65/2.5 concrete mix.

Item Number	Drefinition	Unit	Price (TL)	Quantity	Price (TL)
04.011 (2011)	GBFS	ton	81.00	0.34	27.54
04.031	Su	m^3	5.60	0.18	1.01
04.001/051	Crushed Stone II	m^3	26.50	0.18	4.77
04.001/051	Crushed Stone I	m^3	26.50	0.12	3.18
-	Crushed Sand	ton	33	0.50	16.50
04.007/A	Sand	kg	0.24	319	76.56
04.613/1A3 (2011)	Superplasticizer	kg	2.35	5	11.75
-	NaOH	kg	21.30	24	511.20
-	Na_2SiO_3	L	12.63	42.96	542.58
				TOTAL PRICE (TL)	1195.09

Table A.6 : Cost analysis for 1 m^3 AASC0.36/1 concrete mix.

Item Number	Drefinition	Unit	Price (TL)	Quantity	Price (TL)
04.011 (2011)	GBFS	ton	81.00	0.53	42.93
04.031	Su	m^3	5.60	0.15	0.84
04.001/051	Crushed Stone II	m^3	26.50	0.17	4.51
04.001/051	Crushed Stone I	m^3	26.50	0.11	2.92

Table A.6 (continued): Cost analysis for 1 m^3 AASC0.36/1 concrete mix.

-	Crushed Sand	ton	33	0.45	14.85
04.007/A	Sand	kg	0.24	289	69.36
04.613/1A3 (2011)	Superplasticizer	kg	2.35	5	11.75
-	NaOH	kg	21.30	61	1299.30
-	Na_2SiO_3	L	12.63	45.19	570.75
				TOTAL PRICE (TL)	2017.21

Table A.7 : Cost analysis for 1 m^3 AASC0.50/1 concrete mix.

Item Number	Drefinition	Unit	Price (TL)	Quantity	Price (TL)
04.011 (2011)	GBFS	ton	81.00	0.50	40.50
04.031	Su	m^3	5.60	0.21	1.18
04.001/051	Crushed Stone II	m^3	26.50	0.15	3.98
04.001/051	Crushed Stone I	m^3	26.50	0.10	2.65
-	Crushed Sand	ton	33	0.41	13.53
04.007/A	Sand	kg	0.24	266	63.84
-	NaOH	kg	21.30	61	1299.30
-	Na_2SiO_3	L	12.63	45.19	570.75
				TOTAL PRICE (TL)	1995.73

Table A.8 : Cost analysis for 1 m^3 AASC0.65/1 concrete mix.

Item Number	Drefinition	Unit	Price (TL)	Quantity	Price (TL)
04.011 (2011)	GBFS	ton	81.00	0.34	27.54
04.031	Su	m^3	5.60	0.19	1.06
04.001/051	Crushed Stone II	m^3	26.50	0.19	5.04

Table A.8 (continued): Cost analysis for 1 m^3 AASC0.65/1 cocnrete mix.

04.001/051	Crushed Stone I	m^3	26.50	0.12	3.18
-	Crushed Sand	ton	33	0.50	16.50
04.007/A	Sand	kg	0.24	324	77.76
-	NaOH	kg	21.30	41	873.30
-	Na_2SiO_3	L	12.63	30.37	383.57
TOTAL PRICE (TL)					1387.95

Table A.9 : Cost analysis for 1 m^3 AASC0.36/4 concrete mix.

Item Number	Drefinition	Unit	Price (TL)	Quantity	Price (TL)
04.011 (2011)	GBFS	ton	81.00	0.50	40.50
04.031	Su	m^3	5.60	0.11	0.62
04.001/051	Crushed Stone II	m^3	26.50	0.17	4.51
04.001/051	Crushed Stone I	m^3	26.50	0.11	2.92
-	Crushed Sand	ton	33	0.46	15.18
04.007/A	Sand	kg	0.24	293	70.32
-	NaOH	kg	21.30	24	511.20
-	Na_2SiO_3	L	12.63	72.59	916.81
TOTAL PRICE (TL)					1562.06

Table A.10 : Cost analysis for 1 m^3 AASC0.50/4 concrete mix.

Item Number	Drefinition	Unit	Price (TL)	Quantity	Price (TL)
04.011 (2011)	GBFS	ton	81.00	0.50	40.50
04.031	Su	m^3	5.60	0.18	1.01
04.001/051	Crushed Stone II	m^3	26.50	0.15	3.98
04.001/051	Crushed Stone I	m^3	26.50	0.10	2.65

Table A.10 (continued): Cost analysis for 1 m^3 AASC0.50/4 concrete mix.

-	Crushed Sand	ton	33	0.40	13.20
04.007/A	Sand	kg	0.24	260	62.40
-	NaOH	kg	21.30	24	511.20
-	Na_2SiO_3	L	12.63	72.59	916.81
				TOTAL PRICE (TL)	1551.75

Table A.11 : Cost analysis for 1 m^3 AASC0.65/4 concrete mix.

Item Number	Drefinition	Unit	Price (TL)	Quantity	Price (TL)
04.011 (2011)	GBFS	ton	81.00	0.34	27.54
04.031	Su	m^3	5.60	0.17	0.95
04.001/051	Crushed Stone II	m^3	26.50	0.18	4.77
04.001/051	Crushed Stone I	m^3	26.50	0.12	3.18
-	Crushed Sand	ton	33	0.50	16.50
04.007/A	Sand	kg	0.24	321	77.04
-	NaOH	kg	21.30	17	36.21
-	Na_2SiO_3	L	12.63	48.89	617.48
				TOTAL PRICE (TL)	783.67

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