EFFECT OF COATING MATERIALS AND MIXTURE CONSTITUENTS ON THE PERMEABILITY OF CONCRETE

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ABSTRACT

EFFECT OF COATING MATERIALS AND MIXTURE CONSTITUENTS ON THE PERMEABILITY OF CONCRETE

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The improvement in the impermeability of concrete was studied using different methods. The main aim was to investigate impermeability improvement of concrete and to compare these methods. Two different methods were examined to investigate and compare impermeability and strength improvement of concrete by using two different sets of concrete specimens. These methods included the application of coating materials to concrete and the production of concrete using different constituent amounts and types. The first set of concrete specimens was prepared by applying two different coating materials (a coating material including both powder and liquid components; and a coating material including only a liquid component) on reference concrete specimens separately. The second set of concrete specimens was prepared using different proportions of concrete constituents such as cement, water, steel and plastic fibers, mineral and chemical concrete admixtures.

Various tests were conducted on both sets of concrete specimens in order to compare the permeability of concrete specimens. However, some of these tests were not applied on all of the specimens because of test and material specifications. The tests were used to evaluate compressive strength, water absorption, chloride ion penetration and depth of water penetration under pressure. These test methods were carried out on concrete cube specimens and concrete cores taken from those specimens according to the relevant standards.

It was found that the permeability of the concrete specimens decreased significantly when the coating material which was composed of the combination of powder and liquid components was applied on concrete specimens. However, permeability did not decrease significantly for concrete specimens coated with the coating material composed of only a liquid component. Significant improvement in the impermeability of the concrete specimens was observed when the amount of cement was increased, the water-to-cement ratio was decreased, mineral admixtures (silica fume and fly ash) and plasticizers were used. This improvement was associated with densification of the concrete microstructure and reduction in capillary pores as a result of pozzolanic reaction and due to reduction in water-to-cement ratio. Coating materials were determined to be effective for concretes with high permeability prior to coating whereas their effect was less significant for lower-initial permeability concretes. Moreover, the effect of coating materials on permeability differed depending on their chemical compositions. The effect of using steel fibers and plastic fibers for the improvement of concrete impermeability was found to be insignificant.

Keywords: Concrete, Permeability, Coating Materials, Pozzolanic Reactions

ÖZ

KAPLAMA MALZEMELERİ VE KARIŞIM BİLEŞENLERİNİN BETON GEÇİRİMLİLİĞİ ÜZERİNDEKİ ETKİSİ

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Farklı yöntemler kullanılarak beton geçirimsizliğinin geliştirilmesine çalışıldı. Temel amaç beton için geçirimsizlik geliştirilmesini incelemek ve bu yöntemleri karşılaştırmaktı. Beton geçirimsizliği ve dayanımı gelişimini incelemek ve karşılaştırmak için iki farklı yöntem iki farklı beton numune seti vasıtasıyla araştırıldı. Bu yöntemler, betona kaplama malzemesi uygulanmasını ve farklı beton bileşen miktarları ve çeşitleri kullanarak beton üretimini içerdi. İlk beton numunesi seti referans beton numuneleri üzerine ayrı ayrı iki farklı kaplama malzemesi (toz ve sıvı bileşen kombinasyonu içeren kaplama malzemesi; ve sadece sıvı bileşen içeren kaplama malzemesi) uygulanarak üretildi. İkinci beton numunesi seti, çimento, su, çelik ve plastik fiber, kimyasal ve mineral katkıların farklı oranlada kullanılmasıyla hazırlandı.

Beton numunelerinin geçirimliliğini karşılaştırmak için her iki beton numunesi seti üzerinde farklı deneyler uygulandı. Bununla birlikte, bu deneylerin bir kısmı deney ve numune özellikleri nedeniyle tüm numuneler üzerinde uygulanmadı. Bu deneyler basınç dayanımını, su emmesini, klor iyonu penetrasyonunu ve basınç altında su işleme derinliğini değerlendirmek için kullanıldı. Bu deney yöntemleri, beton küp numuneleri ve bu numunelerden alınan karot numuneler üzerinde ilgili deney standartlarına göre uygulandı.

Beton numuneleri üzerine toz ve sıvı bileşen kombinasyonuna sahip kaplama malzemesi uygulandığında bu numunelerin geçirimliliğinin önemli miktarda azaldığı saptandı. Bununla birlikte, sadece sıvı bileşen içeren kaplama malzemesi ile kaplanmış beton numuneleri için beton geçirimliliğinin önemli miktarda azalmadığı saptandı. Çimento miktarı arttırılarak, su/çimento oranı düşürülerek, mineral katkılar (silis dumanı ve uçucu kül) ve akışkanlaştırıcı kullanılarak üretilen beton numunelerinin beton geçirimsizliğinde önemli bir gelişme olduğu saptandı. Bu gelişme puzolanik reaksiyonlar ve su/çimento oranındaki azalma sonucunda oluşan beton mikroyapısı sıkılaştırması ve kapiller boşluklardaki azalma ile ilişkilendirildi. Kaplama malzemelerinin, ilk geçirimliliği düşük olan betonlar için az önemli olmakla birlikte, geçirimliliği yüksek betonlar için etkili olduğu belirlendi. Buna ek olarak, kaplama malzemelerinin geçirimlilik üzerindeki etkilerinin kimyasal özelliklerine göre değiştiği belirlendi. Beton üretiminde çelik ve plastik fiberlerin kullanılmasının beton geçirimsizliği geliştirilmesi üzerindeki etkisinin çok önemli olmadığı saptandı.

Anahtar Kelimeler: Beton, Geçirimlilik, Kaplama Malzemeleri, Puzolanik Reaksiyonlar.

To My Family...

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CHAPTER 1

INTRODUCTION

1.1 Background

“Concrete is a composite material that consists essentially of a binding medium within which are embedded particles or fragments of aggregate, usually a combination of fine aggregate and coarse aggregate”. “In Portland-cement concrete, the binder is a mixture of Portland cement and water, with or without admixtures” (ACI 116R).

The durability of concrete is considered to be an important parameter of the service life of concrete. That is, in addition to compressive strength, durability should be taken into account in the concrete production process. The continuation of their intended functions is essential for concrete structures. Namely, these structures should maintain their required strength and serviceability during the specified service life. In other words, concrete must be able to withstand the inner and outer deterioration processes. This property for concrete is named “durability of concrete” (Neville, 2000). ACI Committee 201 states durability of concrete as its resistance to weathering mechanisms, abrasion, chemical mechanisms and to any deterioration mechanism. Durability of construction materials is important because of their positive implications for socioeconomic and ecological prospects (Mehta, 1986). The durability of concrete becomes more important especially for concrete structures which are built in harsh environments where there is risk of chemical or physical attack.

The durability of concrete is mostly considered to be related with the permeability of concrete which refers to the ease of fluid entrance into and movement through concrete (Neville, 2000). The improvement of the impermeability of concrete is required to prevent alkali-silica reaction as well as other deterioration mechanisms. In this way, improving the impermeability of concrete in the concrete production phase by adjusting concrete constituent amounts and improving the impermeability of concrete structures after they are built by applying a coating material to hardening concrete offer two alternatives to resist deterioration of concrete. As a result, research is needed to compare impermeability improvement methods.

1.2 Aim and Objectives

Objectives of the study were:

a) To compare methods to reduce water permeability of concrete including application of two different coating materials on hardened concrete and changing concrete mixture constituents and types.

b) To investigate the effectiveness of coating materials in reducing permeability for concretes with changing concrete constituents.

c) To search for the correlation between concrete permeability and compressive strength.

Two different sets of concrete specimens were prepared in the laboratory.

a) The first set of specimens was prepared by applying one of two different coating materials (combination of powder and liquid; and liquid-only) on to hardened concrete specimens.

b) The second set of concrete specimens was produced by changing the concrete constituents which consisted mainly of changing the water-to-cementitious material ratio and adding mineral admixtures (silica fume and fly ash).

In the chapters of the study following items were explained:

In Chapter 2, a review of literature on concrete durability and concrete permeability is presented.

In Chapter 3, experimental phases of the research are explained.

In Chapter 4, results of the concrete permeability tests and discussions of these results are given.

In Chapter 5, conclusions derived from the findings of the study are provided.

CHAPTER 2

LITERATURE REVIEW

2.1 Durability and Permeability of Concrete

Durability is the capacity of concrete to resist chemical attack, weathering action, abrasion and service conditions. It is a complex issue and degradation of concrete can involve some mechanisms related with transport of substances into and out of concrete and their impacts on the concrete (ACI 116R).

Concrete becomes vulnerable to various exposures if some precautions are not taken. Three major components of reinforced concrete are aggregate, paste, and steel reinforcement and their adverse performance can lead to deterioration of concrete. W/C is considered as the single parameter that has the largest impact on durability characteristics of concrete. Decrease in w/c results in decrease in porosity of the paste making concrete less permeable. Requirements of concrete for use in special conditions are given in Table 2.1. The permeability of concrete is an important parameter for durability as it controls entry of moisture and aggressive chemicals. Moreover, low w/c increases the strength of concrete and improves its resistance to cracking resulting from the internal stresses (Mindess et al. 2003).

Table 2.1 Requirements for special exposure conditions (ACI 318R)

Exposure Condition	Maximum cementitious material ratio, by weight, normal weight concrete	Minimum fc, normal weight and lightweight concrete, MPa
Concrete intended to have low permeability when exposed to water	0.50	27.6
Concrete exposed to freezing and thawing in a moist condition or to deicing chemicals	0.45	31.0
For corrosion protection of reinforcement in concrete exposed to chlorides from deicing chemicals, salt, salt water, brackish water, sea water, or spray from these sources	0.40	34.5

2.2 Hydration of Portland Cement

Chemical and physical processes between cement and water are the main determinants for the setting and hardening of concrete. The principal hydration product is a calcium silicate hydrate, C-S-H (Mindess et al. 2003). Hydration reactions of the two main calcium silicates in Portland cement are given in Table 2.2.

Table 2.2 Hydration reactions for two calcium silicates (Mindess et al. 2003)

$2\ C_3S$ +	$11\ H$ $\longrightarrow$	$C_3S_2H_8$ +	$3CH$
Tricalcium silicate	Water	C-S-H	Calcium hydroxide
$2\ C_2S$ +	$9H$ $\longrightarrow$	$C_3\ S_2H_2$ +	CH
Dicalcium silicate	Water	C-S-H	Calcium hydroxide

2.2.1 Microstructure of Hydrated Cement Pastes

Sequence of structure formation (see Table 2.3) as hydration proceeds is important for the microstructural development of concrete. In that process, water separating individual cement grains in the fluid paste is replaced with solid hydration products forming a continuous matrix and binding residual cement grains (Mindess et al. 2003).

Table 2.3 Sequence of hydration of the calcium silicates (Mindess et al. 2003).

Reaction Stage	**Kinetics of Reaction**	**Chemical Process**	**Relevance to Concrete Properties**
1-Initial hydrolysis	Chemical control; rapid	Initial hydrolysis; dissolution of ions	-
2-Induction Period	Nucleation control; slow	Continued dissolution of ions	Determines initial set
3-Acceleration	Chemical control; rapid	Initial formation of hydration products	Determines final set and rate of initial hardening
4-Deceleration	Chemical and diffusion control; slow	Continued formation of hydration of products	Determines rate of early strength gain
5-Steady state	Diffusion control; slow	Slow formation of hydration products	Determines rate of later strength gain

Porosity is an important component of the microstructure. An important aspect of microstructural development is the decrease in porosity during hydration. All the hydration products of the cement compounds have lower specific gravities and larger specific volumes than the cement compounds themselves (Mindess et al. 2003). Main compounds and usual composition for Portland cement are given below in Table 2.4 and Table 2.5.

Table 2.4 Main compounds of Portland cement (Neville, 2000)

Name of Compound	Oxide composition	Abbreviation
Tricalcium silicate	$3CaO.SiO_2$	C_3S
Dicalcium silicate	$2CaO.SiO_2$	C_2S
Tricalcium aluminate	$3CaO.Al_2O_3$	C_3A
Tetracalcium aluminoferrite	$4CaO.Al_2O_3.Fe_2O_3$	C_4AF

Table 2.5 Usual composition limits of Portland cement (Neville, 2000)

Oxide	**Content (%)**
CaO	60-67
SiO_2	17-25
Al_2O_3	3-8
Fe_2O_3	0.5-6.0
MgO	0.5-4.0
Alkalis (Na_2O equivalent)	0.3-1.2
SO_3	2.0-3.5

Pores in concrete are important for the permeability. Two of the different types of pores are capillary pores and gel pores. Capillary pores are "remnants of water-filled space between the partially hydrated cement grains". The gel pores are "intrinsic parts of the C-S-H". The sizes of these pores are given in Table 2.6 (Mindess et al. 2003).

Table 2.6 Pore size classification in hydrated cement paste (Mindess et al. 2003)

Designation	**Diameter**	**Description**
Capillary Pores	10,000-50 nm (10-0.05 μm)	Large capillaries (macropores)
	50-10 nm	Medium capillaries (large mesopores)
Gel Pores	10-2.5 nm	Small isolated capillaries (small mesopores)
	2.5-0.5 nm	Micropores
	< 0.5 nm	Interlayer spaces

The pore system within the bulk of the hardened cement paste and the interface between the cement paste and the aggregate are important for permeability of concrete. The permeability of concrete is affected by its porosity as well as size, distribution, continuity, shape and tortuosity of the pores. Flow of water through the capillary pores occurs more easily than through the much smaller gel pores. That is, permeability of hardened paste is controlled by capillary porosity in concrete (Neville, 2000).

2.3 Causes of Inadequate Durability of Concrete

Negative chemical and physical events that have negative effects on the durability of concrete are decomposition of calcium hydroxide in concrete and development of efflorescence on concrete surface, sulfate attack, sea water attack, acid attack, carbonation, alkali-aggregate reaction, corrosion of reinforcing steel in concrete, freezing-thawing effect and peeling of concrete surface (Erdoğan, 2003).

Deterioration of concrete is a manifestation of inadequate durability of concrete structures. This deterioration can be due either to external factors or internal factors and those factors can be physical, chemical, or mechanical. The mechanical ways of deterioration include impact, abrasion, erosion or cavitation. The chemical mechanisms include the alkali-silica and alkali-carbonate reactions. External chemical attacks are generally caused by the action of aggressive ions (chlorides, sulfates etc.) and carbon dioxide. Moreover a lot of natural and industrial liquids and gases lead to chemical attacks. The physical causes of deterioration of concrete structures include expansion of aggregate and of the hardened cement paste due to fluctuations in temperature. An important cause of the damage is alternating freezing and thawing of concrete and the associated action of de-icing salts. Except for the mechanical damage to concrete structures, all the adverse effects on durability involve the transport of fluids through the concrete. That's why the transport of fluids should be examined and analyzed in order to clarify the durability concerns of concrete structures (Neville, 2000).

2.3.1 Transport of Fluids in Concrete

There are three fluids which are related with durability. These are water, pure or carrying aggressive ions, carbon dioxide and oxygen. The movement of these fluids can differ but their transportation in concrete depends mainly on the structure of the hydrated cement paste. The durability of concrete mostly depends on the ease with which fluids, both liquids and gases, can enter into, and move through the concrete. This mechanism is defined as the permeability of concrete. In other words, the permeability can be stated as flow through a porous medium. Movement of some fluids through concrete can also take place by diffusion and sorption. However "permeability" is used as a general term to define the movement of fluids into and through concrete (Neville, 2000).

Transport properties of hardened concrete have an important role on the ingress of potentially deleterious and harmful materials. The resistance of hardened cement paste to chemical and physical impacts is related with the composition and microstructural properties of the paste and also environmental conditions around the concrete structures during both the fresh and hardened concrete phases. That is, the transport properties of concrete (diffusity, permeability, and sorptivity) are important factors (Young, 1988 cited in Arjunan, 2000).

Low permeability concrete possesses high strength and it is resistant to the ingress of water and salt solutions. As chloride, oxygen and moisture reaches steel easily, the corrosion of reinforcing steel takes place earlier and easier in the case of porous surrounding concrete. That is, measurement of the permeability of concrete contributes to detection of durability problems which will in turn lead to timely and cost-effective protection of concrete structures (Canadian Strategic Highway Research Program, 1995).

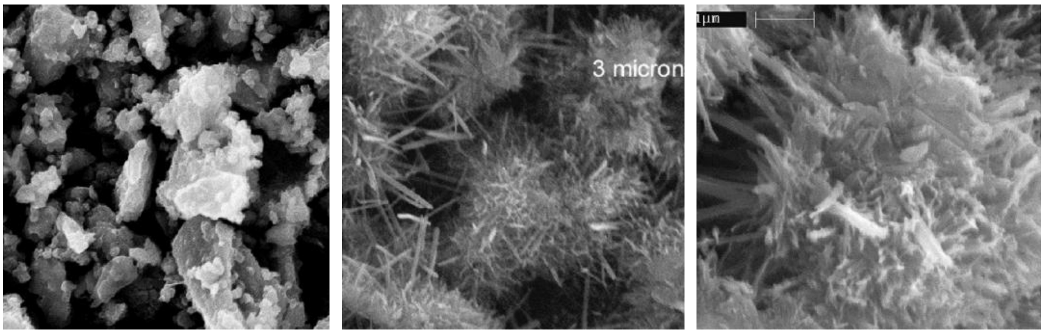
High performance concrete provides improved durability under severe conditions, improved properties at early ages and enhanced mechanical properties. These concretes may contain materials such as fly ash, silica fume, ground, granulated slags, fibers and chemical admixtures. Service life will be increased and life-cost may be reduced with higher durability of concretes (Strategic Highway Research Program, 1993). Criteria for high performance concrete are given in Table 2.7.

Table 2.7 Criteria for HPC (High Performance Concrete) (SHRP, 1993)

Category of HPC	Minimum Compressive Strength	Maximum Water/Cement Ratio	Minimum Frost Durability Factor
Very early strength (VES)			
Option A (with Type III cement)	14 MPa in 6 hours	0.40	80 %
Option B (with PBC-XT cement)	17.5 MPa in 4 hours	0.29	80 %
High early strength (HES) (with Type III cement)	35 MPa in 24 hours	0.35	80 %
Very high strength (VHS) (with Type I cement)	70 MPa in 28 days	0.35	80 %

2.3.2 Porosity and Permeability in Concrete

Porosity is the proportion of the total volume of concrete occupied by pores. In the case of high porosity and interconnected pores, permeability of concrete increases and transport of fluids becomes easy (Neville, 2000). Concrete behavior is closely related with water which is needed for hydration but at the same time occupies space in the concrete. Hydration of Portland cement is shown at different size scales in Figure 2.1. Porosity of the hardened cement paste is an important parameter affecting concrete strength and durability. Filling degree of void spaces between and among the cement grains by the hydration products mostly determines this porosity property (Hover, 2011).



a) b) c)

Figure 2.1 Portland cement a) Unhydrated particles-magnification 2000x; b) Multiple particles of partially hydrated-magnification 4000x; c) Single particle of hydrated cement- magnification 11000x) (SEM photos by E. Soroos and K. Hover cited in Hover, 2011)

Hydration products and “degree of hydration” and pore space volume to be filled are important for the permeability of concrete. On the other hand, higher w/c means more water is available to maintain hydration but at the same time inter-particle pore space will be greater which will require high degree of hydration. Thus, lower w/c needs to be provided for high performance concrete. The higher the w/c is, the higher the permeability and the lower the compressive strength (see Figure 2.2) (Hover, 2011).

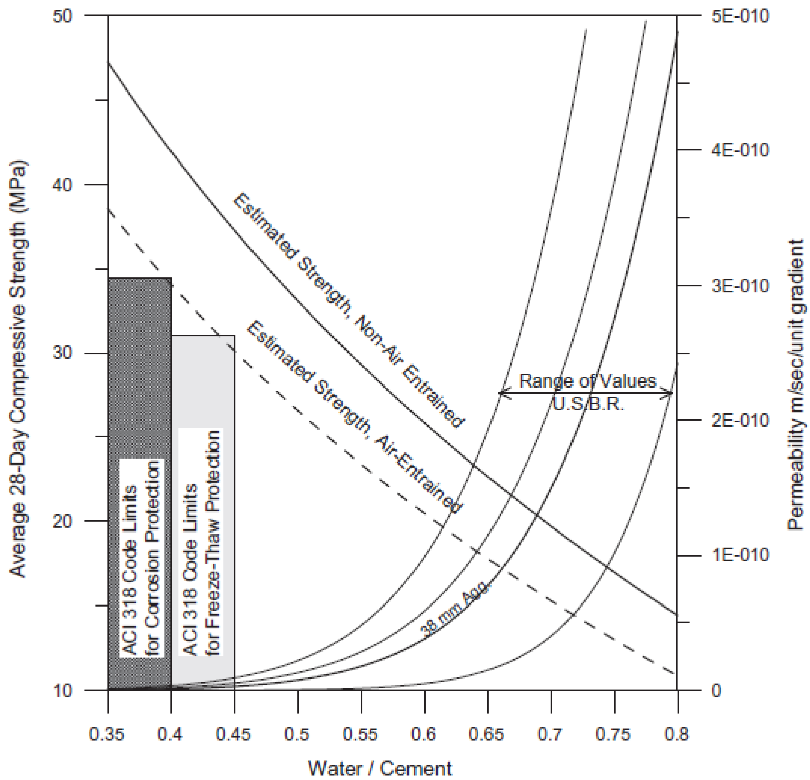


Figure 2.2 Relations among w/cm, average 28-day compressive strength and permeability (ACI 318 Building code requirements and USBR data cited in Hover, 2011).

The initial microstructural development of concrete is important for minimizing harmful effects. The porosity and the pore structures of cement paste are two major factors controlling the chemical resistance of concrete. Porosity and permeability are, in turn, mainly controlled by water content of a cement paste. It is also important to consider the development of the cement paste structure beginning with the fresh state, mixing, placing, consolidation, and through the curing period (Roy, 1986 cited in Arjunan, 2000).

2.4 Deterioration Mechanism of Concrete

Deterioration of concrete is a complex issue and it may have various reasons (see Table 2.8). The resistance of concrete to attack depends on the specific nature of chemical involved, the w/c of concrete, temperature of the aggressive solution, the permeability of the concrete, consolidation degree of the concrete, the type of the cement used in concrete, the degree of corrosion of the reinforcing steel and the level of wetting-drying of the chemical on the concrete (ACI 201.1R cited in EM 1110-2-2002, 2002).

Table 2.8 Causes of distress and deterioration of concrete (EM-1110-2-2002)

Accidental Loadings
Chemical Reactions
Acid attack
Aggressive water attack
Alkali-carbonate rock reaction
Alkali-silica reaction
Miscellaneous chemical attack
Sulfate attack
Construction Errors
Corrosion of Embedded Metals
Design Errors
Inadequate structural design
Poor design details
Erosion
Abrasion
Cavitation
Freezing and Thawing
Settlement and Movement
Shrinkage
Plastic
Drying
Temperature Changes
Internally generated
Externally generated
Fire
Weathering

Chemical reactions for concrete may be classified as external chemicals attacking the concrete such as acid attack, aggressive water attack, sulfate attack and internal chemical reactions between the constituents of the concrete such as alkali-silica reaction and alkali-carbonate rock reactions (EM 1110-2-2002). Factors that affect chemical attack on concrete structures are given in Table 2.9.

Table 2.9 Factors influencing chemical attack on concrete (ACI 201.2R)

	Factors that accelerate or aggravate attack		**Factors that mitigate or delay attack**
1.	**High porosity due to:**	**1.**	**Dense concrete achieved by:**
i.	High water absorption	i.	Proper mixture proportioning
ii.	Permeability	ii.	Reduced unit water content
iii.	Voids	iii.	Increased cementitious material content
		iv.	Air entrainment
		v.	Adequate consolidation
		vi.	Effective curing
2.	**Cracks and separations due to:**	**2.**	**Reduced tensile stress in concrete by:**
i.	Stress concentrations	i.	Using tensile reinforcement of adequate size, correctly located
ii.	Thermal shock	ii.	Inclusion of pozzolan (to reduce temperature rise)
		iii.	Provision of adequate contraction joints
3.	**Leaching and liquid penetration due to:**	**3.**	**Structural Design**
i.	Flowing liquid	i.	To minimize areas of contact and turbulence
ii.	Ponding	ii.	Provision of membranes and protective-barrier system(s) to reduce penetration
iii.	Hydraulic pressure		

2.5 Methods to Mitigate Deterioration of Concrete

The methods to produce impermeable concrete are using a finer cement, using low water/cement ratio, using water free of deleterious compounds, using low-permeability aggregates, using a good aggregate gradation, using additives which reduce water/cement ratio or which prevent water entry into concrete (Erdoğan, 2003).

2.5.1 Coating of Concrete

Coating of concrete, which is to apply material to a surface by brushing, spraying etc. to protect and seal the substrate, is considered as a preventative method against permeation of water and chemicals into concrete (ACI 116R).

Water penetration into concrete takes place because of hydrostatic pressure, capillary action, wind-driven rain, moisture vapor pressure or any combination of those. Leakage into structure, freezing-and-thawing deterioration and corrosion of reinforcement in the concrete structures are augmented by water penetration into concrete. That is, preventing water penetration should be considered to establish a protection system for concrete structures (ACI 546R). Surface treatment types and their properties are given in Table 2.10.

Table 2.10 Summary of surface treatments (ACI 546R)

Types	Generic classifications	Installation Requirements	Durability characteristics	Performance characteristics
Sealers	Boiled linseed oil Sprayed Approximately 10 °C or above	Clean, dry and sound surface Poor resistance to UV radiation	Improves resistance to freezing and thawing Frequent applications required	Darkens concrete slightly Does not bridge cracks
	Alkyl-alkoxy-silane Siloxanes	Surface free of pretreatments Sprayed, brushed, or rolled Ventilation required	Improves resistance to freezing and thawing Reduces salt penetration Reduces rate of corrosion	Improved resistance to water absorption and reinforcement corrosion Does not bridge cracks
	High-molecular-weight methacrylate	Clean, dry and sound surface Sprayed, brushed or rolled	Variable UV radiation resistance Prevents moisture from penetrating cracks	Seal cracks
Coatings	Epoxy Urethane or neoprane membrane/epoxy top coat system Rubberized asphaltic top coat system Urethane Membrane/urethane top	Clean, dry and sound surface Sprayed, brushed, rolled, or squeegeed Approximately 10 °C and above Ventilation required Level surface typically required	Generally improves resistance to freezing and thawing Fair to good abrasion resistance Variable UV radiation resistance	Generally good resistance to water absorption Unknown resistance to reinforcement corrosion Bridges small cracks
Overlays	Concrete Polymer concrete Polymer-modified concrete	Clean, sound and roughened surface Hand or machine applied Generally above freezing Ventilation may be required	Improves resistance to freezing and thawing Excellent abrasion resistance	May add weight Architectural finish is possible Protects structural concrete and reinforcement May improve structural capacity

Protective barriers (see Table 2.11) are used to protect concrete against degradation by chemicals and to prevent concrete staining. First, they have to resist permeation and diffusion of chemicals and they also have to be resistant to cracking, swelling, and dissolution. Second, they have to possess sufficient abrasion resistance during service. Third, the adhesive bond strength should be at least equal to the tensile strength of the concrete (ACI 201.2R).

Table 2.11 Protective barrier systems-general categories (ACI 515.1R cited in ACI 201.2R)

Severity of chemical environment	Total nominal thickness range	Typical protective barrier systems	Typical but not exclusive uses of protective systems in order of severity
Mild	Under 1mm	Polyvinyl butryal, polyurethane, epoxy, acrylic, styrene acrylic copolymer asphalt, coal tar, chlorinated rubber, vinyl, neoprane, coal-tar epoxy, coal-tar urethane	Protection against deicing salts Improve freezing-thawing resitance Prevent staining of concrete Use for high-purity water service Protect concrete in contact with chemical solutions having a pH as low as 4, depending on chemical
Intermediate	3 to 9 mm	Sand-filled epoxy, sand-filled polyester, sand-filled polyurethane, bituminous materials	Protect concrete from abrasion and intermittent exposure to dilute acids in chemical, dairy, and food-processing plants
Severe	1/2 to 6 mm	Glass-reinforced epoxy, glass reinforced polyester, procured neoprene sheet, plasticized polyvinyl chloride sheet	Protect concrete tanks and floors during continuous exposure to dilute material (pH is below 3), organic acids, salt solutions, strong alkalies
Severe	1/2 to 7 mm and over 250 6mm	Composite systems: a) Sand-filled epoxy system topcoated with pigmented but unfilled epoxy b) Asphalt membrane covered with acid-proof brick using chemical-resistant mortar	Protect concrete tanks during continuous or intermittent immersion, exposure to water, dilute acids, strong alkalies, and salt solutions Protect concrete from concentrated acids or combinations of acids and solvents.

Water, atmospheric pollutants and chloride ions are three major parameters influencing the long-term concrete performance. Water affects freeze-thaw durability, transport of chloride ions and atmospheric pollutants and contributes electrolytic continuity within the concrete material. The method for protection of existing concrete structures is to cut off the transportation path of aggressive materials and this is carried out by using surface coatings effectively and economically (Swamy and Tanikawa, 1993).

2.5.2 Effects of Mineral Admixtures on the Permeability of Concrete

Silica fume is mainly used because of its contribution to improve concrete strength and concrete durability. Concrete durability improvement is achieved by reducing aggressive fluid transport through the pore structure, reducing the rate of chloride-ion ingress, improving resistance to deleterious effects of alkali-silicate reaction and improving resistance to freezing and thawing. Deterioration mechanism of concrete is mostly affected by transport properties of materials, transport of gas, liquid and detrimental liquids. The improved durability characteristics of silica fume concrete are mostly provided by the low permeability of these concretes (ACI 234R).

Silica fume is used as a mineral admixture which results a denser pore structure in concrete. This reduction in permeability and improvement of durability is achieved by pore size refinement, $Ca(OH)_2$ amount reduction and cement paste-aggregate interfacial zone pore refinement. Pozzolanic reaction between silica fume and calcium hydroxide leads to densification in interfacial transition zone. Pozzolanic materials generally combine with hydrated calcium hydroxide ($Ca(OH)_2$) and form hydrated calcium silicate (C-S-H) which causes strength development of hydrated cement paste (Song et al., 2010).

Silica fume usage in concrete leads to a reduction in water permeability depending on silica fume dosage and mixture composition. The low permeability of silica fume concrete is the main determinant for its improved durability in the aggressive environment conditions (ACI 234R).

Concrete containing fly ash reaction products contribute to fill pores when the concrete is properly cured. Thus concrete permeability to water and chemicals is lowered (Manmohan and Mehta, 1981 cited in ACI 2322R).

Poon et al. (2006) carried out tests to determine and to compare compressive strength, chloride penetrability and porosity of control specimens, metakaolin-containing specimens and silica fume-containing specimens for 0.30 and 0.50 water/binder ratios, respectively. For both ratios, improvement was achieved for all of the three parameters for metakaolin and silica fume-containing concretes which were associated with strength and durability improvement due to admixture additions.

2.6 Determination of Chloride Penetrability into Concrete

Corrosion of reinforcing steel because of chloride ingress is considered as an important deterioration mechanism in reinforced concrete. Transport of chloride ions is related with a few mechanisms including diffusion, migration in an electric field, water permeation because of a pressure gradient and absorption because of capillary action. Chloride ion transport through concrete is affected by the pore structure within concrete and the interaction between the ions and the pore walls. Moreover, water/cement ratio, presence of supplementary cementing materials and concrete age are parameters influencing the pore structure (Neithalath and Jain, 2010).

CHAPTER 3

EXPERIMENTAL PHASE

The aim of this research program was to investigate and compare two methods for the improvement of the impermeability of concrete structures. The first method was to use coating materials on hardened concrete and the second was to produce concrete with different concrete constituent amounts and types. One set of concrete specimens was prepared for each method and tests were carried out on these specimens.

For the first set of concrete specimens, permeability of concrete which were produced with standard concrete constituent amounts with and without two different coating materials (coating material 1 and coating material 2) were examined respectively. Coating material 1 (composed of powder and liquid components) was being planned for structures exposed to water pressure and coating material 2 (composed of a liquid component only) was thought to be used on parts of structures which are above the water surface and which are not exposed to hydraulic pressure as are structures in the water.

For the second set of concrete specimens, permeability of any concrete produced using different concrete constituent types and amounts (with different components such as chemical additives [air entraining, plasticizers and other admixtures], silica fume, fly ash, steel and plastic fibers etc.) were examined.

3.1 Preparation of Concrete Specimens

The experiments were conducted on two sets of specimens. For each set, different experiments were carried out. For the first set of specimens, a concrete mixture was proportioned and a sufficient number of specimens (cube specimens with dimensions 150x150x150 mm) were cast for the tests. Two different types of coating materials (named coating material 1 and coating material 2) were applied on the concrete specimens and tests were carried out with and without those materials. The main aim was to identify the effects of each coating material on the permeability of concrete.

For the second set of specimens, four different concretes (concrete 1, concrete 2, concrete 3 and concrete 4) with different compositions were prepared (see Table 3.1). Again concrete specimens (cube specimens with dimensions of 150x150x150mm) were prepared and concrete cores were taken from cube specimens at each phase.

Table 3.1 Concrete constituents

Concrete Explanation	Concrete ID	Cementitious Material (kg/m³)	Silica Fume (wt. % of cementitious material)	Fly Ash (wt. % of cementitious material)	Water (kg/m³)	W/C	Fine Aggregate (kg/m³)	1st Coarse Aggregate (kg/m³)	2nd Coarse Aggregate (kg/m³)	Plasticizer (wt. % of cementitious material)	Air Entraining Material (wt. % of cementitious material)	Steel Fibers (wt % of cementitious material)	Plastic Fibers (kg/m³)
Concrete 1	C1	450	15	20	150	0.33	845	423	423	2 (Hyper)	-		
Concrete 2	C2	450	10	20	172	0.38	800	400	400	2	0.05		
Concrete 3	C3	450	-	-	161	0.36	822	411	411	2	0.05	6	
Concrete 4	C4	450	-	-	172	0.38	827	413	413	2	0.05		2.3
Reference Concrete	REF	300	-	-	190	0.63	750	563	563	-	-		

3.2 Concrete Constituent Materials

3.2.1 Cement

Cem I 42.5 N cement was used in the concrete production process. The constituents for this cement was given in Table 3.2

Table 3.2 Composition of Cem I 42.5 N Portland cement (Şahin, 2012)

Chemical Requirements	**Test Results (%)**	**Standards**	**Standards** TS EN 197-1
Total SiO_2	19.47		
Insoluble Residue	0.33	Max: 5.00	
Fe_2O_3	3.15		
Al_2O_3	4.72		
CaO	65.57		
MgO	1.44		
SO_3	2.50	Max: 3.50	
Loss of Ignition	2.70	Max: 5.00	
Na_2O	0.0906		
K_2O	0.4230		
Cl	0.0089	Max: 0.10	
Free Lime (CaO)	0.25		
Physical Requirements	0.09		
Specific Gravity	3.14		
Setting Time (minute)			
Initial	170	Minimum: 60	
Final	250		
Soundness (mm)	0.5	Maximum: 10.0	
Fineness			
Specific Surface (Blaine) (cm^2/g)	3176		
Residue on 200 mic. sieve (%)	0.0		
Residue on 90 mic. sieve (%)	1.0		
Residue on 45 mic. sieve (%)	15.0		
Compressive Strength (MPa)			TS EN 196-1
2 day	24.4	Minimum: 10	
7 day	40.1		
28 day	53.5	Min:42.5 Max:62.5	

3.2.2 Aggregates

Three different aggregate sizes (see Table 3.3) were used in concrete production process.

Table 3.3 Aggregate properties (DSİ Quality Control Laboratories, 2009)

Aggregate Type	**Range for Aggregate Sizes (mm)**	**Specific Gravity**	**Water Absorption (%)**	**Relevant Standards**
Coarse-1	12-22	2.70	0.1	ASTM C 127
Coarse-2	4-12	2.71	0.1	ASTM C 127
Fine	0-4	2.61	1.9	ASTM C 128

3.2.3 Water

Tap water in the laboratory was used in concrete production.

3.2.4 Fly Ash

Properties of the fly ash used in concrete 1 and concrete 2 are given below (see Table 3.4).

Table 3.4 Fly ash constituent amounts (Özel, 2012)

Name of Experiment	**Measurement Results**	**TS EN 450-1 Standard Limit**	**Test Method**
Loss On Ignition (%)	1.86	Category A / Max 5.0 Category B / 2.0 < < 7.0 Category C / 4.0 < < 9.0	TS EN 196-2
SO_2 (%)	0.30	Max 3.0	TS EN 196-2
Reactive CaO (%)	2.07	Max 10.0	TS EN 197-1

Table 3.4 (continued)			
Name of Experiment	**Measurement Results**	**TS EN 450-1 Standard Limit**	**Test Method**
Free CaO (%)	0.11	Max. 2.5	TS EN 451-1
Cl (%)	0.0077	Max. 0.1	TS EN 196-21
Density (kg/m³)	2300		Using Digital Pycnometer
Retained on 45 μm sieve (%)	15.1	Type N-Max. 40.0 Type S- Max. 12.0	TS EN 451-2:2000
28 Day Activity Index (%)	80.2	Min. 75	TS EN 450-1:2008
90 Day Activity Index (%)	91.5	Min. 85	TS EN 450-1:2008

3.2.5 Silica Fume

The properties of the silica fume used in concrete 1 and concrete 2 are given below (see Table 3.5).

Table 3.5 Silica fume constituent amounts (Sarıcaoğlu, 2012)

	Analysis (%)	**Requirement**	**Standard**
SiO_2	91.97	> 85.0 %	ASTM C 618, C1240/95
Cl	0.06	< 0.3 %	
Fe_2O_3	1.32		
Al_2O_3	0.62		
Na_2O	0.49		
K_2O	1.49		
MgO	1.25		
CaO	0.31	< 1.0 %	
SO_3	0.35	< 2.0 %	
H_2O	0.22		
L.O.I	1.33	< 5.0 %	
Bulk Density (kg/m3)	605.33		
Particles> 0.045mm (%)	1.24	< 40 %	
Specific Surface	21.08	> 15.00m^2/g	
Metallic Si	0.07	< 0.4 %	
Activity Index	131.50	> 95 %	

3.2.6 Water-reducing concrete admixtures

A water reducing and super plasticizer conforming to ASTM C494 Type F were used in concrete 2, concrete 3 and concrete 4.

A high range water reducing admixture conforming to ASTM 494C/ ASTM 494M was used in concrete 1.

3.2.7 Air entraining admixture

An air entraining admixture conforming to ASTM C 260 was used in concrete 2, concrete 3 and concrete 4.

3.2.8 Steel Fibres

The properties of the steel fibres used in concrete 3 are given below in Table 3.6.

Table 3.6 Steel fiber properties (Bekaert, 2012)

Physical Properties	
Materials	Cold drawn wire fibre with hooked ends and glued in bundles
Length	60 mm
Diameter	0.75 mm
Performance Class	80
Aspect Ratio (l/d)	80
Tensile Strength	1050 N/mm^2
Compliance	EN 10016-2-C9D

3.2.9 Plastic Fibres

The properties of the plastic fibres used in concrete 4 are given below in Table 3.7.

Table 3.7 Plastic fiber properties (Forta, 2012)

Physical Properties	
Materials	Virgin Copolymer /Polypropylene
Form	Monofilament/Fibrillated Fibre System
Specific Gravity	0.91
Tensile Strength	570-660 MPa
Length	54 mm, 38 mm
Compliance	ASTM C 116

3.3 Coating Materials Applied to Concrete Specimens

Coating material 1 and coating material 2 were applied to the reference concrete specimens separately in the test process.

3.3.1 Coating Material 1

Coating material 1 has two components and it is a polymer-modified cementitious coating. These components are mixed to form a coating against water ingress. Then it is applied to form a waterproof and flexible membrane by using a brush or roller. The powder component of the material is composed of specially selected cements, silica and reactive fillers. The liquid component is composed of blended acrylic copolymers and wetting agents (Coating material 1, 2012).

a)

b)

Figure 3.1 a) Preparation of coating material 1; b) application of coating material 1 on concrete cores

Mixing of the powder and liquid components is carried out by using a slow speed drill fitted with a suitable paddle as shown in Figure 3.1. Mixing is carried out and application of this mixture is recommended to end within 1 hour. A minimum of 1 mm coating thickness (1.8 kg/m²) is recommended by the manufacturer. The coating is stated to be resistant to up to water pressure of 7 bars (70 meter head) (Coating material 1, 2012).

3.3.2 Coating Material 2

It is used as a water repellent for concrete, clinker masonry, and ceramic tiles. It is also used for protection against the ingress of water and water-soluble pollutants. It is a clear, colorless and frost-resistant liquid based on monomeric alkyltrialkoxysilane (Coating material 2, 2012).

Figure 3.2 Application of coating material 2 to concrete cores

It is suited for rendering mineral construction materials water repellent and it is resistant to alkaline environments. Its manufacturer states that it forms water vapour permeable, colourless layer on the concrete surface. It reduces the uptake of water and soluble salts (e.g. chlorides). Approximate consumption for concrete is stated as minimum 150 g/m². A curing time of 28 days is recommended for concrete before application and application should be carried out on air-dry and clean surfaces (Coating material 2, 2012).

3.4 Tests Performed

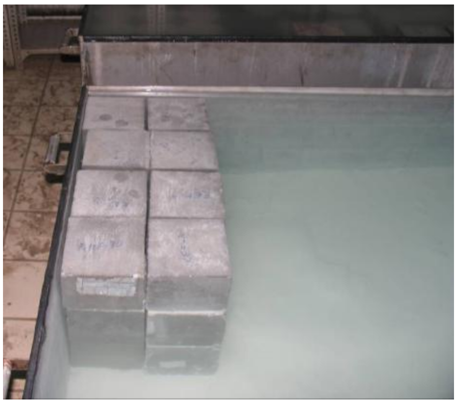
All tests were carried out according to TS EN (Turkish Standards European Norms) and ASTM (American Society for Testing and Materials) Standards. The results of these tests for different sets were compared with each other considering permeability and compressive strength values to achieve a less permeable concrete structure.

Tests performed included concrete compressive strength test, water absorption test, chloride ion penetration test and water penetration test under pressure. Tests, along with the corresponding specimen sets (see Table 3.8), were organized considering related standards and required conditions.

Table 3.8 Tests conducted on the different specimen sets

Test Chart				
Specimens	**Tests**			
	Compressive Strength Test	**Water Absorption Test**	**Chloride Ion Penetration Test**	**Water Penetration Test**
Standard	TS EN 12390-3	TS 3624	ASTM C 1202	TS EN 12390-8
Specimen Set-1				
Reference Concrete	+	+	+	+
Reference Concrete + Coating Material 1 (Combination of Powder and Liquid Component)	-	+	+	+
Reference Concrete + Coating Material 2 (Liquid Component)	-	+	+	-
Specimen Set 2				
Concrete 1 (C-1)	+	+	+	+
Concrete 2 (C-2)	+	+	+	+
Concrete 3 (C-3)	+	+	+	+
Concrete 4 (C-4)	+	+	+	+

+	**Test was carried out**
-	**Test was not carried out**



a)

b)

c)

d)

Figure 3.3 a) Concrete cube curing; b) Coring; c) Concrete cores; d) Cutting of cores

3.4.1 Concrete Compressive Strength Tests

Concrete compressive strength tests were carried out for reference concrete specimens and four different types of concrete specimens (150x150x150 mm) according to TS EN 12390-3. For reference concrete specimens, these tests were carried out after 28 days of curing period. For the four different concrete types these tests were carried out after 28 days, 90 days and 365 days of curing. The relation between concrete compressive strength and concrete permeability was investigated. Also the effects of concrete constituents and strength development based on concrete age were examined especially to clarify the effects of their constituents. This point was not examined for the reference concrete since it did not include any additive materials.

3.4.2 Concrete Water Absorption Tests

This test was carried out according to TS 3624. Concrete cores were taken for two different concrete specimen sets (TS EN 12504-1). For the first set, cores were taken from reference concrete specimens, they were cut and two different coating materials were applied on all of their surfaces. These specimens were submerged in water. For the second set of specimens, concrete cores were taken from four different types of concretes at an age of 365 days. They were cut and submerged in water. Water absorptions were reported.

Water absorption rate for hardened concrete was found by calculating the ratio of weight increase in hardened concrete to dry weight of concrete. Concrete specimens having mass greater than 800 g were submerged in water for 24 hours before weighing for wet weights.

Water absorption was calculated as follows:

Absorption (%) = ([B-A]/A) x 100

where:

B: Weight after 24 hours in water (g)

A: Dry Weight (g)

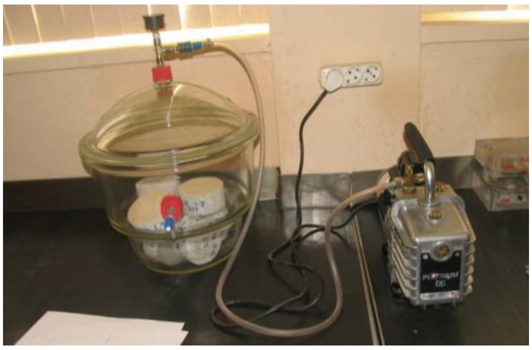
a) b)

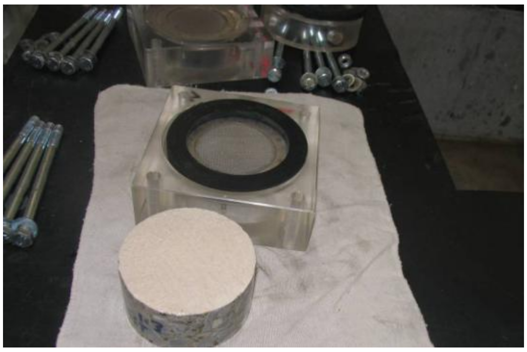
Figure 3.4 a) Application of coating material 1; b) Water absorption tests

3.4.3 Chloride Ion Penetration Tests

This test was carried out according to ASTM C 1202. Concrete cores were taken from concrete cubes for two different concrete specimen sets (TS EN 12504-1). For the first set of specimens, cores were taken from reference concrete cube specimens and they were cut. Reference core specimens were left uncoated. Two different coating materials were applied on other core specimens separately. For the second set, concrete cores were taken from four different types of concrete cube specimens. They were cut and prepared for the test. These specimens were placed into the chloride ion penetration equipment to carry out the chloride ion penetration at an age of 365 days.

In this test method, resistance of concrete to the penetration of chloride ions was determined by measuring electrical conductance of concrete. Electrical current passed through 51-mm thick slices of 102-mm nominal diameter cores was measured over a 6 hour period. A 60 V potential difference was maintained across the ends of the specimen. One end was immersed in sodium chloride solution and other end was immersed in sodium hydroxide solution. Finally, the total charge passed, in Coulombs, was found and related to the specimen resistance to chloride ion penetration using the guidelines in ASTM C 1202.





a) b)

c) d)

Figure 3.5 a) Conditioning of cores; b) Placement of concrete cores into test cells; c) Placement of solutions; d) Application of electrical potential for chloride ion penetration test phases

3.4.4 Depth of Penetration of Water under Pressure Tests

This test was carried out according to TS EN 12390-8. Concrete cube specimens were separated into two different sets. For the first set, one side of concrete cubes was covered with coating material 1 (combination of powder and liquid component) and the water permeability tests were performed on the concrete cubes. For the second set, four different types of concrete cubes (concrete 1, concrete 2, concrete 3 and concrete 4) were tested at an age of 28 days. Coating material 2 (liquid only) was not used in this test because of its inadequate pressure resistance.

In this test, the depth of penetration of water under pressure into hardened concrete was determined. Pressurized water was applied to the surface of hardened concrete and then that specimen was split and depth of penetration of the waterfront was measured. Cubic concrete specimens with 150x150x150 mm dimensions and older than 28 days were placed into the test apparatus. Then a water pressure of 500 ± 50 kPa was applied for 72 ± 2 hours. The specimen was split and the maximum depth of penetration under the test area was measured. Tap water was used in this test.

a) b)

Figure 3.6 a) Application of water pressure to cube specimens; b) Wetted-front after water penetration test

CHAPTER 4

RESULTS AND DISCUSSION

Test results as a whole stated the effects of different coating materials and different concrete constituents on the permeability properties of the concrete.

4.1 Concrete Compressive Strength Test Results

Table 4.1 and see Figure 4.1 show the compressive strength progress for 28 days, 90 days and 365 days for four different concrete types. Also air contents and slump values for fresh concrete phase were measured in order to examine fresh concrete properties and concrete compressive strength relation.

Table 4.1 Concrete compressive strength test results (cube specimens of 150x150x150 mm) and fresh concrete properties

Concrete Id.	**28-day compressive strength value (MPa)**	**90-day compressive strength value (MPa)**	**365-day compressive strength value (MPa)**	**Air Content of Fresh Concrete (%)**	**Slump Value (cm)**
C1	64.2	76.1	86.0	3.6	27.0
C2	38.0	47.4	76.0	7.0	17.0
C3	56.3	56.5	62.0	7.0	18.5
C4	44.4	49.8	52.0	8.0	17.0
REF	34.3	-	-	2.0	18.0

Concrete 1 and Concrete 2 contained silica fume, fly ash and chemical admixtures such as plasticizers and air entraining admixtures. Concrete 3 contained steel fibers and concrete 4 contained plastic fibers with chemical admixtures. Reference concrete did not contain any mineral and chemical admixtures. Compressive strength values increased significantly especially for Concrete 1 (86 MPa) and Concrete 2 (76 MPa) for 365 days.

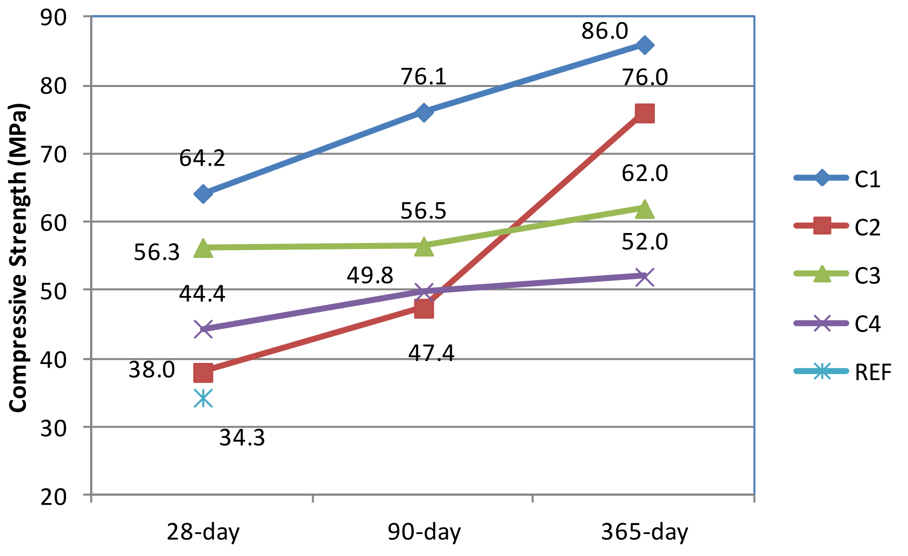


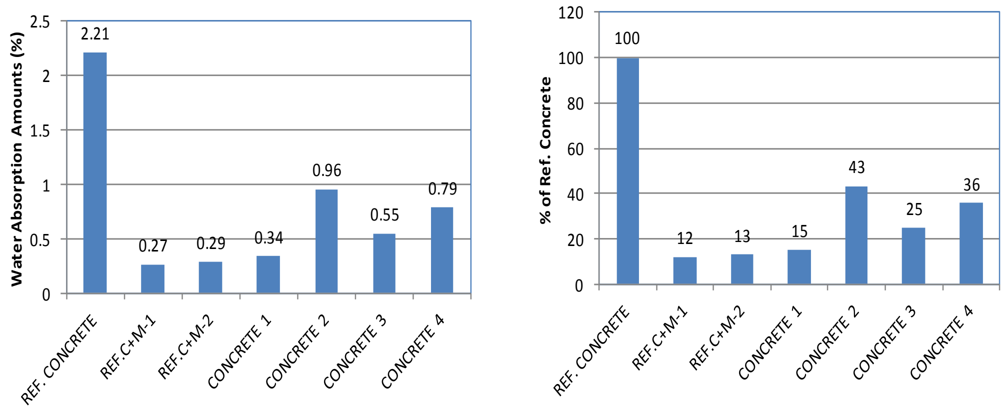
Figure 4.1 Concrete compressive strength development trends for the different concrete mixtures

4.2 Concrete Water Absorption Test Results

Table 4.2 and Figure 4.2 show significant decrease in water absorption rates for increased concrete constituent properties and concrete specimens coated with coating materials when compared with the reference specimens.

Table 4.2 Water absorption amounts for different coating materials and different concrete types

Specimen Id.	Water Absorption (%)	Percentage of Reference Concrete (%)
First Set of Specimens		
Ref. Concrete	2.21	100
Ref.C+M-1	0.27	12
Ref.C+M-2	0.29	13
Second Set of Specimens		
Concrete 1	0.34	15
Concrete 2	0.96	43
Concrete 3	0.55	25
Concrete 4	0.79	36



a) b)

Figure 4.2 a) Water absorption amounts for the different mixtures; b) Water absorption comparisons

It was found that both coating materials and concrete 1 showed significant improvement in resistance to water absorption compared to reference concretes. Relation between compressive strength and water absorption amounts is given in Figure 4.3.

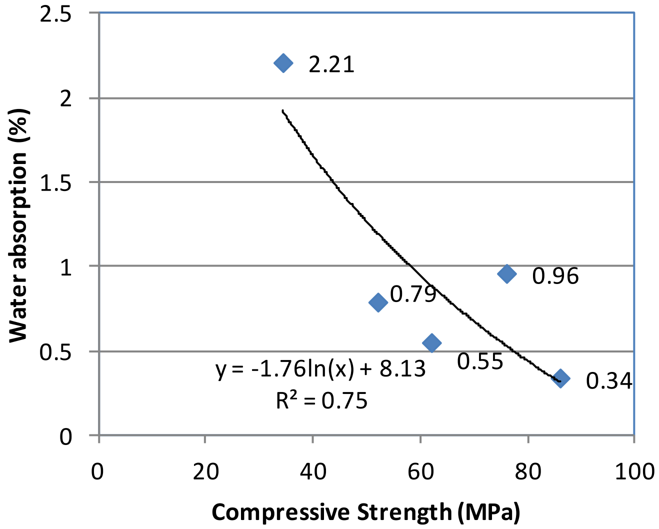


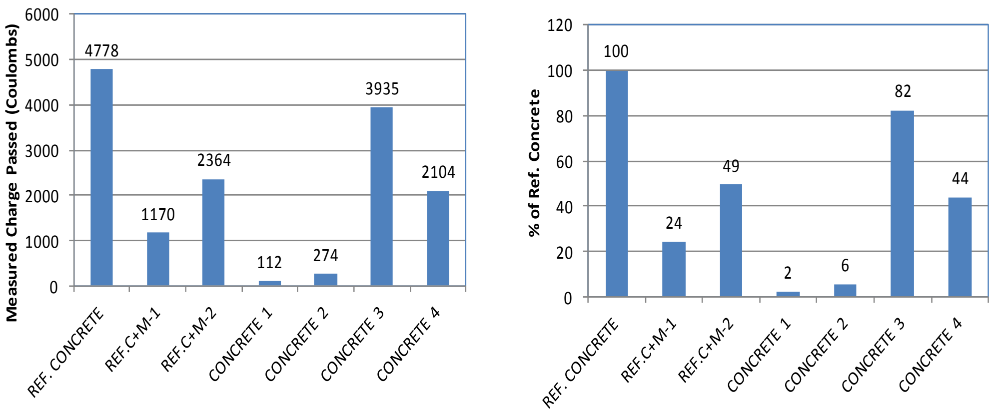
Figure 4.3 Relation between compressive strength and water absorption

4.3 Chloride Ion Penetration Test Results

Table 4.3 and Figure 4.4 show significant decrease in chloride ion penetration values for increased concrete constituent properties including lower w/c ratio, silica fume, fly ash and coating materials applied concrete specimen when compared with reference specimen. Evaluation of the results was carried out according to Table 4.4.

Table 4.3 Chloride ion penetration test results for the two coating materials and different concrete types

Specimen Id.	Measured Charge Passed (Coulombs)	Percentage of Reference Concrete (%)
First Set of Specimens		
Ref. Concrete	4778	100
Ref.C+M-1	1170	24
Ref.C+M-2	2364	49
Second Set of Specimens		
Concrete 1	112	2
Concrete 2	274	6
Concrete 3	3935	82
Concrete 4	2104	44



a) b)

Figure 4.4 a) Results for chloride ion penetration tests for the two coating materials and different concrete types; b) Comparisons of the results with reference concrete

Table 4.4 Recommendation for assessing chloride ion (ASTM C 1202)

Chloride Ion Penetrability Based On Charge Passed	
Charge Passed (Coulombs)	Chloride Ion Penetrability
> 4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
< 100	Negligible

Chloride ion penetration test results showed that chloride ion penetration through concrete coated with coating material 1 was low and it was moderate for concrete coated with coating material 2. For concrete 1 and concrete 2, chloride ion penetration was almost negligible whereas these amounts for concrete 3 and concrete 4 were high. This was associated with plastic fibers in concrete 4 and especially steel fibers for concrete 3. Compressive strength and chloride ion penetration relation for different concretes is given in Figure 4.5.

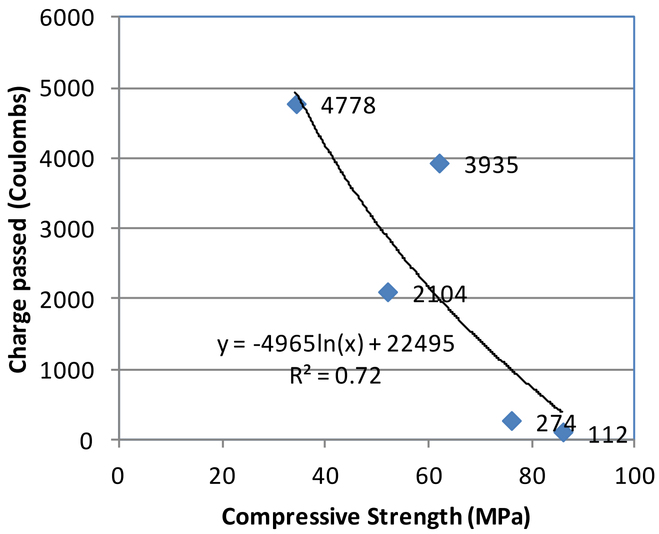


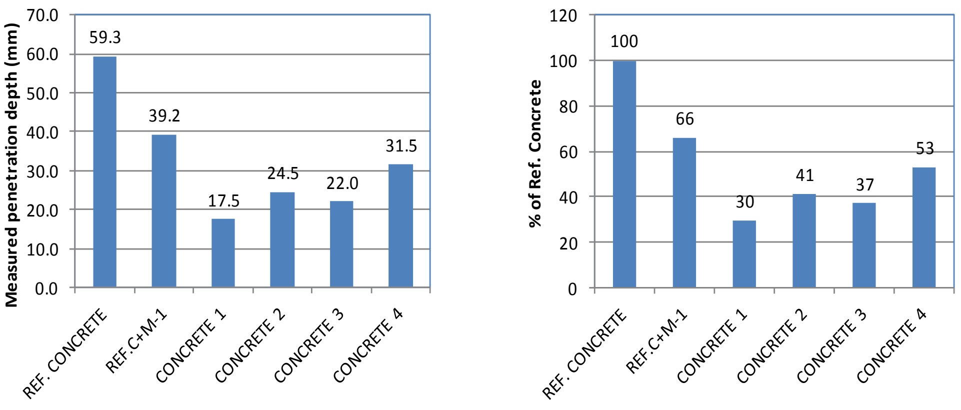
Figure 4.5 Compressive strength and chloride ion penetration relation

4.4 Depth of Penetration of Water under Pressure Test Results

Table 4.5 and Figure 4.6 show significant decrease in water penetration for four different concretes and for concrete coated with coating material 1 when compared with reference specimens.

Table 4.5 Results of depth of water penetration under pressure tests

Specimen Id.	Measured Penetration Depth Value (mm)	Percentage of Reference Concrete (%)
First Set of Specimens		
Ref. Concrete	59.3	100
Ref.C+M-1	39.2	66
Ref.C+M-2		
Second Set of Specimens		
Concrete 1	17.5	30
Concrete 2	24.5	41
Concrete 3	22.0	37
Concrete 4	31.5	53



a) b)

Figure 4.6 a) Results for depth of water penetration values under pressure; b) Comparisons of the results with reference concrete

Results of water penetration under pressure test showed an improvement in resistance to water penetration with Coating material 2 and other four different concrete types. Improvement with Coating material 2 was smaller than with the other four types of concretes. Compressive strength and depth of penetration of water under pressure relation is given in Figure 4.7.

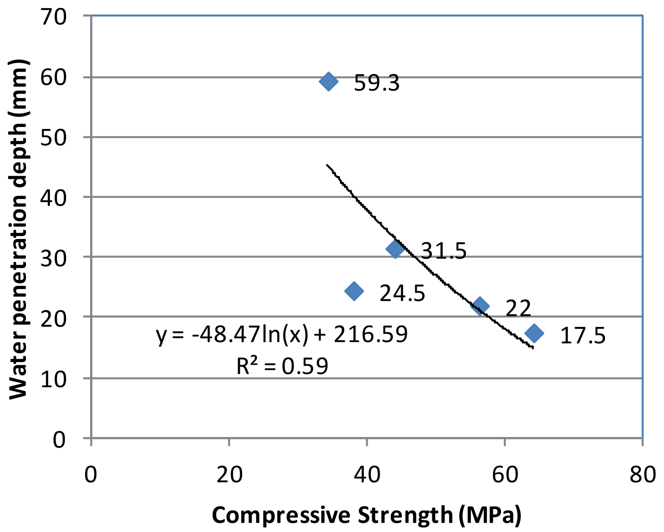


Figure 4.7 Compressive strength and water penetration depth relation

4.5 Discussion of Test Results

Compressive strength test results for reference concrete and for the four different types of concrete showed that, decrease in water-to-cementitious material ratio and addition of mineral admixtures led to significant increases in compressive strength. Silica fume and fly ash use in concrete also resulted in significant compressive strength development over time. A positive correlation was obtained between concrete compressive strength and concrete impermeability for four different concrete types. As an exception, Concrete 2 which contained mineral admixtures had lower water penetration depth results despite having relatively low 28-day compressive strength values for 28 days.

In the literature, it is stated that decrease in water-to-cementitious material ratio leads to increase in compressive strength. The results were consistent with this statement. Moreover, for the use of mineral admixtures such as silica fume and fly ash in concrete, it is stated that they result in a denser microstructure and an improvement over time in compressive strength values in the case of extending curing conditions as a result of pozzolanic reactions with calcium hydroxide (ACI 234R; Song et al., 2011). This is also consistent with the test results which showed increases in compressive strength values compared to reference concrete specimens. Also significant improvement in strength was detected for concrete including silica fume and fly ash over time from 28 days to 90 and 365 days.

Significant decreases in water absorption and chloride ion penetration observed when coating material 1 was used. For coating material 2, water absorption decreased significantly but chloride ion penetration decreased moderately. Water penetration under pressure test results showed moderate decrease for concrete coated with coating material 1. The results were consistent with the literature review information about coating materials in general (ACI 201.2R-01; ACI 546.R04; Swamy and Tanikawa, 1993). However the resistance of coating material 2 to chloride ion penetration was found to be moderate.

Significant improvement in resistance to water absorption, chloride ion penetration, and water penetration was found for concrete 1. This was associated with the improvement in impermeability because of decrease in water/cementitious material ratio and addition of silica fume and fly ash (ACI 234 2R; Erdoğan, 2003; Hover, 2011; Neithalath and Jain, 2010). This reduction in permeability was thought to result from pore size refinement, reduction in capillary pores, $Ca(OH)_2$ reduction, extra C-S-H formation, and cement paste-aggregate interfacial refinement as a result of pozzolanic reaction between mineral admixtures (silica fume and fly ash) and calcium hydroxide ($Ca(OH)_2$). For concrete 2, improvement in resistance to water absorption and resistance to water penetration was lower than for concrete 1. However, especially improvement in resistance to chloride penetration was higher for concrete 1 and concrete 2 than resistance of coating materials. For concrete 3 with steel fibers, resistance to chloride ion was very low which can be associated with the electrical conductivity of steel fibers and water penetration was moderate. For concrete 4, resistance to water absorption, chloride ion penetration and water penetration were moderate. These results were associated with negative effects of fiber during placing and mixing processes during concrete production. These problems in turn may have led to heterogeneity and weakening of the concrete microstructure.

Errors in the test results were minimized by increasing the numbers of test specimens. Moreover, probable damages causing errors in the results were minimized during the coring process for test specimens and also errors were minimized because of application of the same testing processes for all types of specimens. Increase in the test time and pressure used in the water penetration test to provide a better comparison for reference concrete and reference concrete coated with coating material may result in certain errors for the comparisons with other four concrete mixtures.

Test results as a whole revealed an improvement in impermeability after application of the two coating materials on to concrete specimens and adjustments of the concrete constituents. When test results were analyzed, improvements due to coating materials applications were associated with the outer layer resistance to permeation of water and chloride ions. Improvement due to changes in the constituent of concrete types was associated with improvement in the microstructure of concrete and improvement in hydration process which in turn resulted in the improvement in impermeability of concrete (EM 1110-2-2002; Neville, 2000; Roy, 1986 cited in Arjunan, 2000).

Application of coating materials to the concretes which are not impermeable was found to be effective of course based on the coating material characteristics. However, the analyses of concretes having lower water-to-cementitious material ratio and containing mineral admixtures such as silica fume and fly ash showed lower permeability values than concretes coated with coating materials. This result proved that, application of proper coating material on hardened concretes makes sense only for concretes with high permeability.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study has been carried out to examine the effects of coating materials and mixture constituents on the permeability of concrete. Coating material application on hardened concrete was analyzed for concretes having different permeability properties. Also, the effect of using mineral admixtures such as silica fume and fly ash; and effect of water-to-cementitious material ratio; effect of using steel and plastic fibers on impermeability improvement of concrete were examined.

The following conclusions were drawn:

- Coating material application to hardened concrete significantly decreased permeability of concrete specimens. Moreover, the properties of concrete and their constituents were found to be important when evaluating the effect of the coating materials. Coating materials were found to be less effective for concretes which were almost impermeable.

- Coating material application to hardened concretes could be considered as a prevention method for concrete having high permeability.

- Effectiveness of coating materials was found to vary with their chemical and physical characteristics.

- Water-to-cementitious material ratio, silica fume and fly ash contents of concrete were found to be the major factors affecting permeability of the concrete. Concrete permeability had a tendency to decrease when water to cementitious material ratio decreased and silica fume and fly ash was used in concrete. This result was associated with reduction in capillary pores due to low water/cement ratio and pozzolanic reaction between mineral admixtures and calcium hydroxide. Moreover, the use of plasticizers was required for low water/cementitious material ratios to prepare the concrete in order to hold slump values over 15 cm to make these concretes workable.

- Significant improvement was obtained for compressive strength development for concretes containing silica fume and fly ash over time from 28 days to 365 day.

- Positive correlation was found between concrete compressive strength and concrete impermeability.

- Although water-to-cementitious ratio was decreased in important amounts, permeability of concrete containing steel fibers did not decrease in significant amounts. This was considered to be a result of negative effects of steel fibers in mixing, placing and hydration process of cementitious material in fresh concrete phase. Especially chloride ion penetration was high for this concrete which was related to conductivity of steel fibers.

- Permeability of concrete containing plastic fibers did not decrease significantly. This was associated with the problems about plastic fiber during mixing and placing fresh concrete which in turn resulted in heterogeneous distribution of fibers in concrete.

5.2 Recommendations

- Application of coating materials should be carried out considering material amounts, application methods, climatic conditions for application, workmanship, and concrete conditions.

- Resistance of coating materials to outside effects, their long-term sustainability and their adhesion characteristics to concrete surface should be considered and evaluated in detail.

- Admixtures which are used to reduce w/c and to offer higher slump values should be investigated for their negative impacts on the concrete and they should be used in reliable amounts and reliable ways.

- Different cement types should be used to examine their effects on concrete permeability.

- Impermeability improvement methods should be carried out considering importance of concrete structures, usage aim of the structure and practical applicability of the method.

REFERENCES

1. ACI 116.R. Cement and Concrete Terminology. Detroit: American Concrete Institute; 2005.

2. ACI 201.2R. Guide to Durable Concrete. Detroit: American Concrete Institute; 2001.

3. ACI 232.2R. Use of Fly Ash in Concrete. Detroit: American Concrete Institute; 2003.

4. ACI 234.R. Guide for the Use of Silica Fume in Concrete. Detroit: American Concrete Institute; 2006.

5. ACI 318R. Building Code Requirements for Structural Concrete Commentary, 2005.

6. ACI 546.R. Concrete Repair Guide. Detroit: American Concrete Institute; 2004.

7. Arjunan P., (2000), Ph.D. Thesis, "Detailed Characterization of Current North American Portland Cements and Clinkers and The Implications For The Durability of Modern Concrete'', The Graduate School Intercollege Graduate Program In Materials, The Pennsylvania State University, U.S.

8. ASTM C 1202-05. Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration (2005)

9. Bekaert, 2012. Dramix 80/60 Available at < http://pdf.directindustry.com/pdf/bekaert/dramix-rc-80-60-bn/5919-56674.html> (Accessed 5 January 2012)

10. BASF, 2012, Full range water reducer admixture. Available at < http://www.basf-admixtures.com/SiteCollectionDocuments/Data%20Sheets/HRWR/PRE-DAT-0055%20Glenium%203030NS%20062710_WEB.pdf> (Accessed 14 January 2012)

11. Canadian Strategic Highway Research, 1995. Concrete Durability Technical Brief # 5 (online). Available at< http://www.cshrp.org/products/csbf-e5.pdf> (Accessed 25 November 2011).

12. Coating Material 1. Available at <http://www.basf-yks.com.tr/TR/urunler/yapi_sistemleri/suyalitim/masterseal_525/Pages/default.aspx> (Accessed 10 January 2012)

13. Coating Material 2. Available at <http://www.basf-yks.com.tr/TR/urunler/yapi_sistemleri/mimariyuzeykoruyucular/protectosil_bhn/Pages/default.aspx> (Accessed 10 January 2012)

14. DSİ (State Hydraulic Works) Technical Research and Quality Control Department Concrete-Material Laboratory Equipment and Technical Specifications, 2009. Ankara, Turkey.

15. EM 1110-2-2002, Evaluation and Repair of Concrete Structures Chapter 3: Causes of Distress and Deterioration of Concrete. US Army Corps of Engineers.

16. Erdoğan, T.Y., 2003. Concrete. Ankara: METU Press.

17. Forta Ferro, 2012. Macrofiber Concrete Reinforcement Available at < http://www.forta-ferro.com/products/macrofibers/forta-ferro/> (Accessed 10 January 2012)

18. Hover, K.C., The influence of water on the performance of concrete. Construction and Building Materials, 25, (2011) 3003–3013.

19. Mehta, P.K., Concrete: structure, properties and materials, Prentice-Hall, Englewood Cliffs, NJ, 1986, pp 18-36, 111-128, 252.

20. Mindess, S., Young, J.F. and Darwin, D. 2003. Concrete. 2nd Edition. Pearson Education, Inc. NJ, USA.

21. Neithalath, N. and Jain, J. 2010. Relating rapid chloride transport parameters of concretes to microstructural features extracted from electrical impedance. Cement and Concrete Research, 40 (2010) 1041–1051.

22. Neville, A.M., Properties of Concrete, Harlow, England; New York: Prentice Hall/Pearson Education, 2000, pp.8, 10, 482-485.

23. Özel, N., 2012 BASF Construction Chemicals Region Director. Test Report for Sugözü Energy Plant Fly Ash, 2009. TÇMB Independent Quality Control Testing Laboratories. (Personal communication 20 January 2012).

24. Poon, C.S., Kou, S.C. and Lam, L., 2006. Compressive strength, chloride diffusivity and pore structure of high performance metakaolin and silica fume concrete. Construction and Building Materials (e-journal) 20 (2006) 858–865. Available through Web of Science Database (Accessed 12 May 2011).

25. Sarıcaoğlu, H. Oyak Ready Mixed Concrete, Ankara. Certificate of Analysis for Silica, 2001. Finnfjord Smeltevertk A/S, Norway (Personal communication 25 January 2012).

26. Sika, 2012. Water Reducers Available at < http://www.tekkonengineering.com.tr/pdf/Sikament-FFN_EN_01072003.pdf> (Accessed 8 January 2012)

27. Sika, 2012. Air Entraining Admixtures Available at < http://us01.webdms.sika.com/fileshow.do?documentID=37> (Accessed 14 January 2012)

28. Song H., Pack, S., Nam, S., Jang, J. and Saraswathy, V., 2010. Estimation of the permeability of silica fume cement concrete Construction and Building Materials (e-journal) 24 (2010) 315–321. (Accessed 16 June 2011)

29. Strategic Highway Research Program (SHRP), National Research Council. 1993 Mechanical Behavior of High Performance Concrete Volume 2, Production of High Performance Concrete (online). Washington DC. Available at < http://onlinepubs.trb.org/onlinepubs/shrp/SHRP-C-362.pdf> (Accessed 26 November 2011).

30. Swamy, R.N. and Tanikawa, S. An external surface coating to protect concrete and steel from aggressive environments. Materials and Structures, 26 1993, 465-478.

31. Şahin, T. 2012. Limak Cement Şanlıurfa Quality Control Chief. Analysis Report for CEM I 42,5 N Portland Cement (Personal communication, 25 January 2012).

32. TS 3624, 1981. Test Method for Determination the Specific Gravity the Absorbtion Water and The Void Ratio In Hardened Concrete. Turkish Standard.

33. TS EN 12390-3, 2003. Testing hardened concrete - Part 3 : Compressive strength of test specimens. Turkish Standard

34. TS EN 12504-1, Concrete – Concrete tests in structure – Part 1: Core specimens, taking cores, testing and determination of compressive strength. Turkish Standard.

35. TS EN 12390-8, 2002. Testing hardened concrete - Part 8: Depth of penetration of water under pressure. Turkish Standard.

APPENDIX A

COMPRESSIVE STRENGTH TEST RESULTS

Table A.1 Concrete compressive strength values

Specimen Id.	Specimen Age (days)	Compressive Strength (MPa)
CONCRETE 1		
C.1-1	28	64.5
C.1-2	28	63.9
C.1.Average		**64.2**
C.1-3	90	75.3
C.1-4	90	77.0
C.1.Average		**76.1**
C.1-5	365	**86.0**
CONCRETE 2		
C.2-1	28	39.0
C.2-2	28	37.1
C.2.Average		**38.0**
C.2-3	90	48.6
C.2-4	90	46.1
C.2.Average		**47.4**
C.2-5	365	**76.0**
CONCRETE 3		
C.3-1	28	55.6
C.3-2	28	57.0
C.3.Average		**56.3**
C.3-3	90	52.0
C.3-4	90	61.0
C.3.Average		**56.5**
C.3-5	365	**62.0**
CONCRETE 4		
C.4-1	28	44.0
C.4-2	28	44.8
C.4.Average		**44.4**
C.4-3	90	50.0
C.4-4	90	49.5
C.4.Average		**49.8**
C.4-5	365	**52.0**

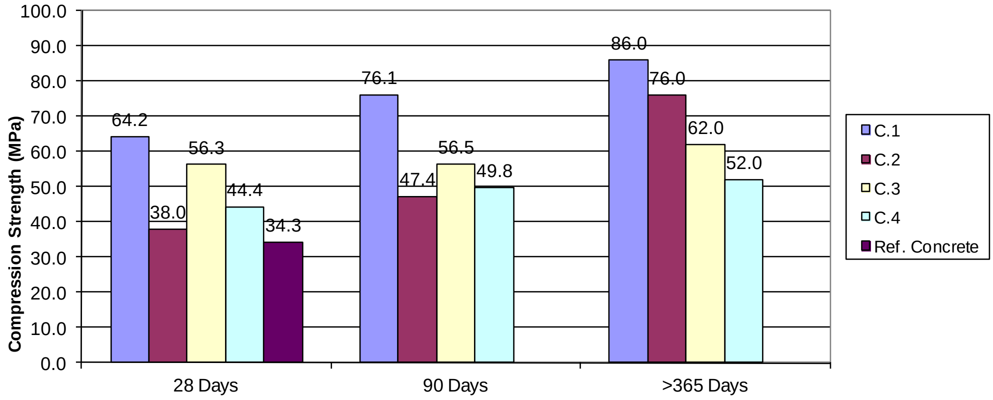


Figure A.1 Concrete compressive strength values for different concrete types (150x150x150 mm)

APPENDIX B

WATER ABSORPTION TEST RESULTS

Table B.1 Water absorption test results for reference concrete specimens and reference concrete specimens coated with two different coating materials

Specimen Id.	Initial Mass of Specimen (g)	Mass of Specimen after 24 Hours (g)	Mass of Specimen after 48 Hours (g)	Water Absorption Amounts	%
REF. CONCRETE					
REF.C-1	918.1	936.0	937.6	0.021	2.12
REF.C-2	922.2	941.5	943.4	0.023	2.30
REF.C-3	913.8	932.6	934.1	0.022	2.22
REF.C-Average					**2.21**
REF.C+ Coating Material 1					
REF.C+CM1-1	995.5	997.6	998.0	0.003	0.25
REF.C+CM1-2	992.9	995.1	995.7	0.003	0.28
REF.C+CM1-3	1009.1	1011.1	1011.8	0.003	0.27
REF.C+CM1-Average					**0.27**
REF+ Coating Material 2					
REF.C+CM2-1	909.5	911.2	912.2	0.003	0.30
REF.C+CM2-2	934.5	936.3	937.2	0.003	0.29
REF.C+CM2-3	913.9	915.7	916.5	0.003	0.28
REF.C+CM2-Average					**0.29**

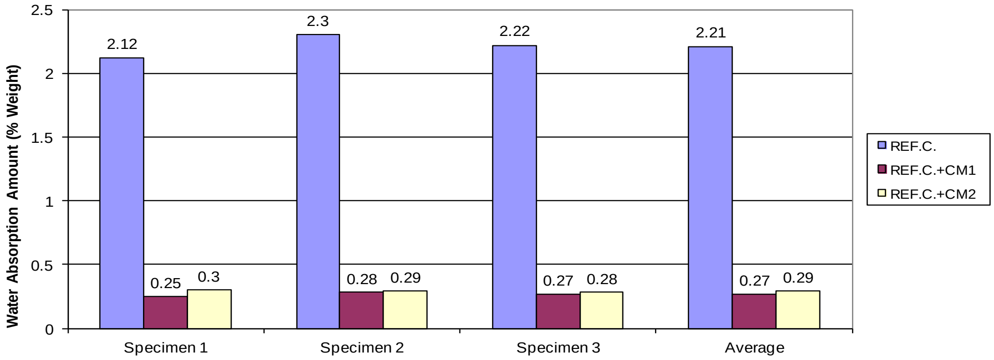


Figure B.1 Water absorption comparisons for reference concretes and reference concrete specimens coated with two different coating materials applied

Table B.2 Water absorption results for 4 different types of concrete specimen types and coating material 2.

Specimen Id.	Initial Mass of Specimen (g)	Mass of Specimen after 24 Hours (g)	Mass of Specimen after 48 Hours (g)	Water Absorption Amounts	%
CONCRETE1					
C.1-1	939.9	942.5	943.0	0.003	0.33
C.1-2	933.1	935.9	936.4	0.004	0.35
C.1.Average					**0.34**
CONCRETE2					
C.2-1	848.5	854.8	856.2	0.009	0.91
C.2-2	851.6	858.6	860.2	0.01	1.01
C.2.Average					**0.96**
CONCRETE3					
C.3-1	892.7	896.5	897.2	0.005	0.5
C.3-2	885.2	889.5	890.5	0.006	0.6
C.3.Average					**0.55**
CONCRETE4					
C.4-1	861.6	866.9	868.1	0.008	0.75
C.4-2	861.2	866.9	868.3	0.008	0.82
C.4.AV.					**0.79**
COATING MATERIAL1					
CM.1-1	640.6	644.1	647.3	0.01	1.05
CM.1-2	655.5	658.6	661.1	0.009	0.85
CM.1.Average					**0.95**

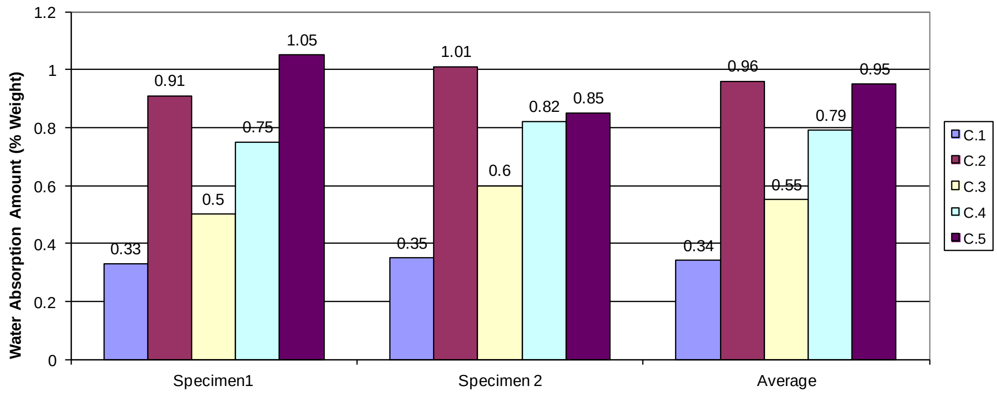


Figure B.2 Water absorption amounts for different concrete types

APPENDIX C

RAPID CHLORIDE ION PENETRATION TEST RESULTS

Table C.1 Chloride ion penetration test results for reference concretes and coating materials applied ref. concretes

Specimen Id.	Maximum Temperature (°C)	Measured Charge Passed, (Coulombs)
REF. CONCRETE		
REF.C-1	-	4215.0
REF.C-2	51	5930.0
REF.C-3	37	3250.0
REF.C-4	47	5263.0
REF.C-5	43	4787.0
REF.C-6	47	5223.0
REF.C-Average		**4778.0**
REF.C+Coating Material 1		
REF.C+CM1-1	30	1231.0
REF.C+CM1-2	22	801.0
REF.C+CM1-3	32	1754.0
REF.C+CM1-4	26	892.0
REF.C+CM1-Average		**1169.5**
REF.C+Coating Material 2		
REF.C+CM2-1	34	2216.0
REF.C+CM2-2	38	2511.0
REF.C+CM2-Average		**2363.5**

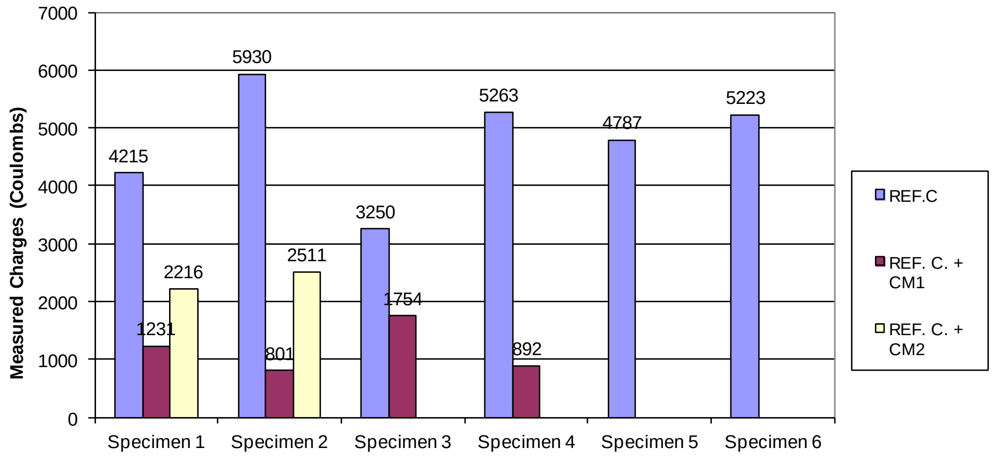


Figure C.1 Chloride ion penetration values for Ref.C. and coating materials

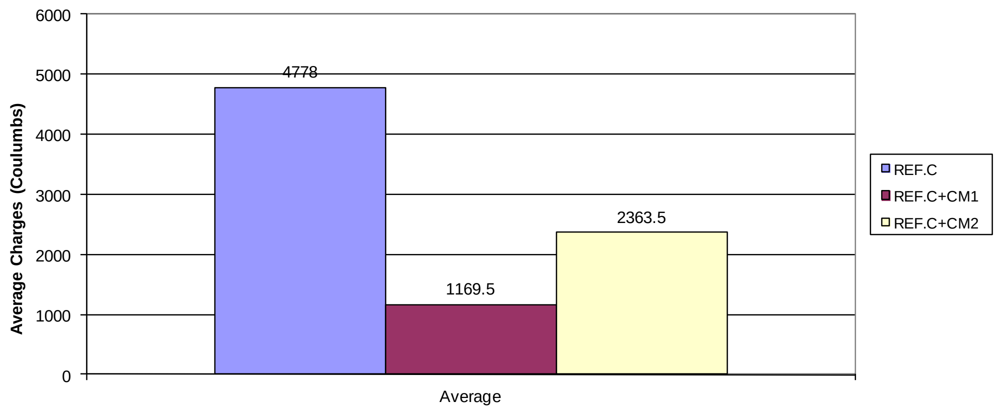


Figure C.2 Chloride penetration average values

Table C.2 Chloride ion penetration test results for different types of concretes

Specimen Id.	Maximum Temperature (C)	Measured Charge Passed, (Coulombs)
CONCRETE1		
C.1-1	23	112
C.1-2	22	112
C.1.Average		**112**
CONCRETE2		
C.2-1	21	271
C.2-2	23	277
C.2.Average		**274**
CONCRETE3		
C.3-1	36	2929
C.3-2	45	4941
C.3.Average		**3935**
CONCRETE4		
C.4-1	34	2210
C.4-2	31	1998
C.4.Average		**2104**

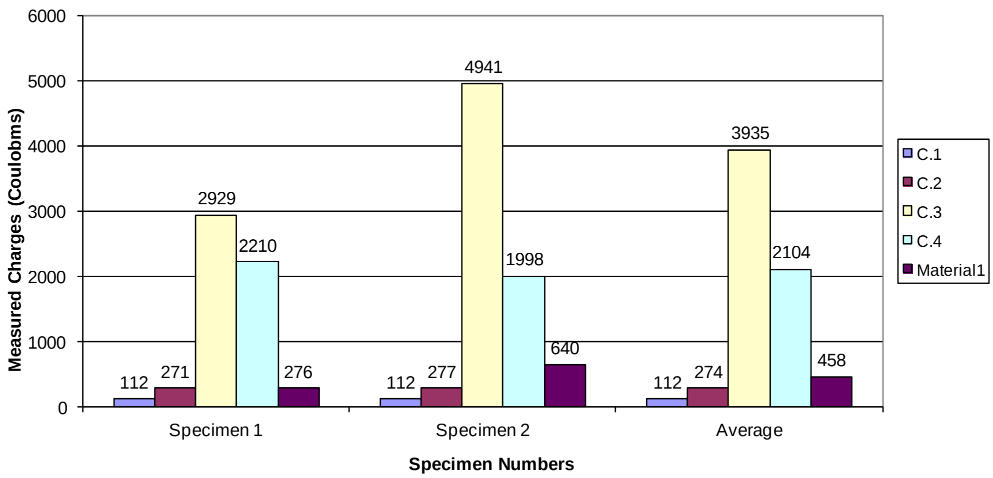


Figure C.3 Chloride ion penetration values for different concretes

APPENDIX D

DEPTH OF PENETRATION TEST RESULTS

Table D.1 Depth of penetration of water under pressure for ref. concrete specimen and coating material applied ref. concrete specimen

Specimen Id.	Applied Water Pressure, (bar)	Specimen Age (days)	Test Period (days)	Measured Penetration Depth Value, (mm)
REF. CONCRETE				
REF.C-1	7	65	7	60.0
REF.C-2	7	65	7	32.0
REF.C-3	7	64	7	42.0
REF.C-4	6	97	7	77.0
REF.C-5	6	97	7	95.0
REF.C-6	6	96	7	50.0
REF.C-Average				**59.3**
REF.C+ Coating Material 1				
REF.C+CM1-1	7	65	7	44.0
REF.C+CM1-2	7	59	7	27.0
REF.C+CM1-3	7	64	7	47.0
REF.C+CM1-4	6	97	7	17.0
REF.C+CM1-5	6	96	7	32.0
REF.C+CM1-6	6	91	7	32.0
REF.C+CM1-Average				**33.2**

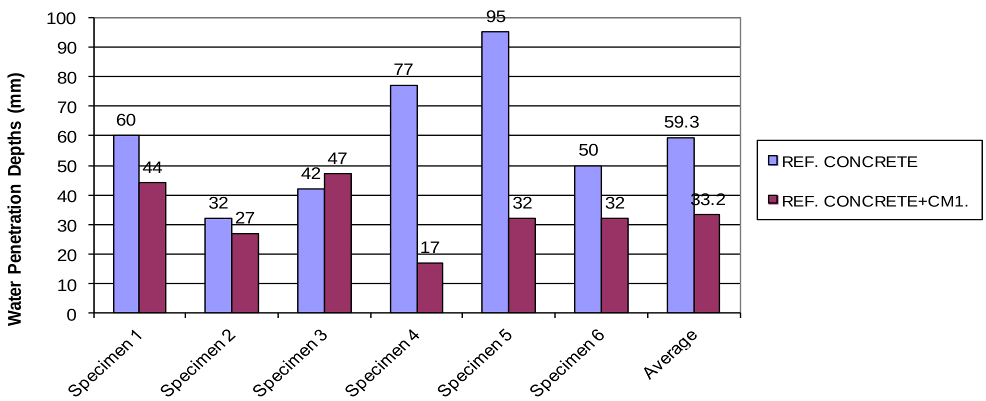


Figure D.1 Water penetration depth under pressure test results for ref. concrete and coating material 1 applied ref. concrete

Table D.2 Depth of penetration under pressure test results for 4 different types of concrete specimens

Specimen Id.	Applied Water Pressure, (bar)	Specimen Age (days)	Test Period (days)	Measured Penetration Depth Value, (mm)
CONCRETE1				
C.1-1	5	31	3	15.0
C.1-2	5	31	3	20.0
C.1.Average				**17.5**
CONCRETE2				
C.2-1	5	32	3	26.0
C.2-2	5	32	3	23.0
C.2.Average				**24.5**
CONCRETE3				
C.3-1	5	32	3	25.0
C.3-2	5	32	3	19.0
C.3.Average				**22.0**
CONCRETE4				
C.4-1	5	31	3	35.0
C.4-2	5	31	3	28.0
C.4.Average				**31.5**

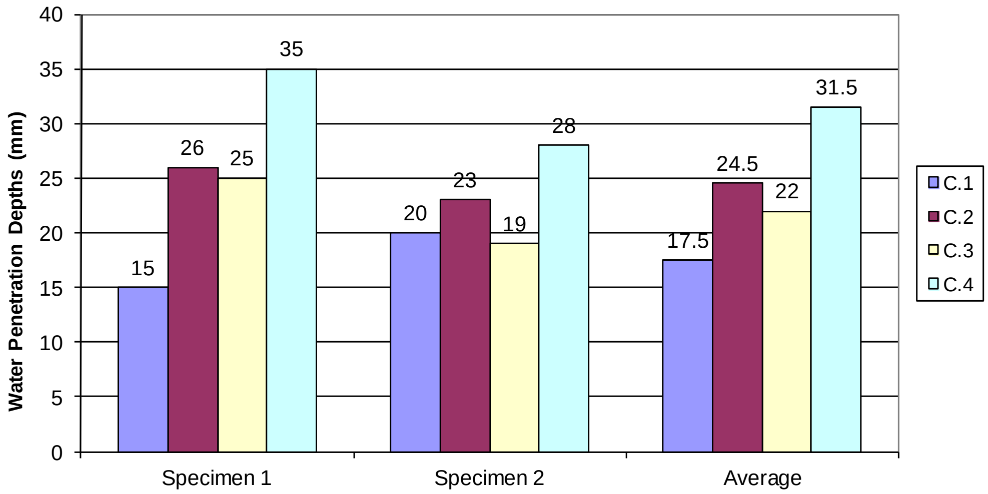


Figure D.2 Water penetration depth test results for different concrete types