THE EFFECT OF A MODIFIED ZEOLITE ADDITIVE AS A CEMENT AND CONCRETE IMPROVER

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DECLARATION

I declare that this dissertation is my own work. It is being submitted for the degree of Masters of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any University.

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ABSTRACT

This dissertation presents a study that investigated the potential of a modified zeolite additive known as PowerCem to improve the properties of cement mortar and concrete. Improvement of the characteristics of cement mortars and concrete is of interest to various researchers and practitioners in the field of construction materials engineering. The product, a blend of selected alkaloids and zeolite, is commercially available and effectively used in soil stabilization for road construction. However, its influence and effectiveness on the properties of cementitious systems has not been explored. The emphasis of this study was on improvement of the strength and durability properties of cement mortar and concrete using PowerCem (PWC) additive. Tests carried out on mortar samples include flow, flexural strength, compressive strength, oxygen permeability, sorptivity, porosity, resistance to sulphate attack, and resistance to alkali silica reaction. Tests carried out on concrete samples include workability, split tensile strength, compressive strength, oxygen permeability, sorptivity, porosity, and carbonation. The hydration behaviour of sample pastes were observed using differential thermal analysis (DTA) and thermogravimetric analysis (TGA). Improvement of strength and durability properties of cement mortar and concrete was observed when PWC additive was used at optimum proportions. In conclusion, PWC additive showed the potential to effectively improve mortar, concrete strength and durability properties when used at optimum proportions between 0.4 % and 0.6 %.

STATEMENT OF ACHIEVEMENT

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DEDICATION

This dissertation is dedicated to God Almighty, who preserved my life till this day, who gave me grace, strength when I was weak and the ability to successfully complete this degree. I reverence you O Lord, my God.

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CHAPTER ONE

1.0 GENERAL INTRODUCTION

In this study, the use of PowerCem, a synthetic zeolite additive, as a potential cement and concrete improver is investigated. Cement as a binder is a vital constituent of concrete, the most widely used construction material. Performance of concrete determines its suitability for construction and this quality is influenced by several factors among which are the types of binder used. There is ongoing interest and effort by many researchers towards the quality and performance of concrete by improving its durability, strength, and workability without increasing the cost of construction. This interest has led to a series of studies investigating the use of extenders or mineral admixtures also known as pozzolans, to improve concrete properties.

A wide variety of siliceous and aluminous materials are used for producing pozzolans and investigations have shown that these pozzolans improve concrete properties. Widely investigated pozzolans include fly ash, volcanic ash, silica fume and slag powder (Naiqian *et al.*, 1988; Palomo *et al.*, 1999; Canpolat *et al.*, 2004; Ekolu *et al.*, 2006). There has been little effort, however, devoted to the research on the use of artificially modified Pozzolans. Natural zeolite, an extender, has been investigated for use as cement and concrete improver by some researchers (Poon *et al.*, 1999; Perraki *et al.*, 2003).

Natural zeolite contains large quantities of reactive S_iO_2 and Al_2O_3 (Poon *et al.*, 1999). Similar to other pozzolanic materials, zeolite substitution can improve the strength of concrete by pozzolanic reaction with $Ca(OH)_2$, can prevent undesirable expansion due to alkali- aggregate reaction, reduce the porosity of the blended cement paste and improve the interfacial microstructure properties between the blended cement paste and the aggregate in the produced concrete (Feng *et al.*, 1990; Poon *et al.*, 1999; Canpolat *et al.*, 2004). It has been observed (Poon *et al.*, 1999) that pozzolanic activity of natural zeolite is higher than that of fly ash but lower than that of silica fume. This gives natural zeolite blended mortars and concrete a higher early strength compared to fly ash blended mortars and concrete. Typical oxide compositions of zeolites are shown in Table 1.1.

Table 1.1 Typical oxide composition of natural zeolites (Yan *et al.,* 1996)

Oxides	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	Na_2O	K_2O	MnO
%	65.7-69	11.9-14.3	0.7-3.4	0.7-2.6	0.4-1.3	1.5-3.5	1.7-3.8	0.04-4.9

According to Quanlin and Naiqian (2005), the effect of natural zeolite can be improved if it is modified, such that the cation exchange of the modified product is greatly increased. Due to its large surface area and water adsorption ability, more water and superplasticizer will be needed to maintain slump. The modified zeolite can have the advantage of enhancing cement mortars and concrete properties better and also reduce the dosage of zeolite additive that will be needed. In this study, PowerCem (PWC), a product containing a blend of selected alkaloids and natural zeolite is the focus of investigation into the effect of modified zeolite on cement properties.

1.1 BACKGROUND

PowerCem is the proprietary name of fine grain sized, carefully selected alkaloids, earth alkaloids and synthetic zeolite complemented with complex activator giving it its unique properties. It is manufactured and processed in the Netherlands according to ISO 9001 and 14002. It is claimed that the product modifies the dynamics and chemistry of the cement hydration process and enhances the crystallization process by forming long needle-like crystalline structures and calcium hydroxide besides dicalcium and tricalcium silicate. However, the reaction also produces other hydrates which effectively fill the pores in mortar or concrete (TNO-BCR-REPORT, 2004).

The selected alkaline and earth-alkaline substances in relation to special selected (synthetical) zeolites are free to react with the available calcium hydroxide, which is present in the pores and forms further calcium silicate and calcium aluminate hydrates. The pores are finally completely filled and contribute significantly to the durability of the PWC concrete. PWC comprises various chemical constituents that are readily available. The blending of these constituents gives a product that has significant benefits when mixed with cementitious binders. The chemical constituents are chosen based on their scientifically proven ability to improve the chemical composition of hydraulically bound material. PWC is environmentally friendly material (PowerCem, 2007). This was confirmed and reported by Dutch accredited laboratoria after investigating the leaching behavior of composite materials for a simulated period of 100 years. Composite materials stabilized/solidified using PWC treated materials have successfully passed the Dutch environmental tests.

PWC differs from the other cement additives like fly ash, slag powder and volcanic ash in that the quantity needed in mortar and concrete rarely exceeds 3 % of the weight of cement. In addition, while it generally costs more than ordinary Portland cement, its use in mortar and concrete would be based primarily on performance enhancement rather than economic benefit.

1.2 OBJECTIVES

The primary aim of this research was to produce cement mortar and concrete using PWC as additive to cement at different proportions and investigate its effect on the fresh and hardened properties of cement mortar and concrete. The study is guided by the following research issues:

- **Effect of PWC on the fresh properties of mortar and concrete**: The fresh property investigated was workability. Flow test and slump test were carried out on mortar and concrete samples respectively. Mortar and concrete samples were prepared with and without PWC additive.

- **Effect of PWC on hardened properties of mortar and concrete**: Mortar and concrete samples were allowed to harden and cure for different test ages. The investigations performed on hardened mortar and concrete samples were classified under strength and durability tests. Procedure followed for each test performed is described in Chapter Three. Tests results were analyzed and conclusions were drawn on the effect of PWC on hardened properties of mortar and concrete.

- **Extent to which PWC affects the hydration behaviour of cement:** The hydration behaviour of cement as a result of the presence of PWC was studied through differential thermal analysis (DTA) and thermogravimetric analysis (TGA).

- **The optimum dosages for use of the product in cementitious systems:** Results from the various tests were analyzed, and conclusions were drawn on the optimum dosages for use of the product in cementitious systems.

1.3 SCOPE AND LIMITATIONS OF THE STUDY

The study did investigate cement mortar and concrete properties by considering their fresh mixture characteristics, engineering properties, and durability. The main focus was to determine PWC’s influence on mortar and concrete properties, the optimal dosages and whether it is suitable for use in concrete. Properties investigated are workability, compressive strength, flexural strength, oxygen permeability, sorptivity, resistance to sulphate attack, resistance to alkali silica reaction, and carbonation. Thermal analysis was conducted on paste samples to study their hydration behaviour.

Report (PowerCem, 2007) showed that PowerCem is generally used together with cement in dosages ranging from 0.18 kg to 5 kg per m^3 of concrete. In a study by Lucas and Seth (2007), percentage proportions of up to 2.5 % and 5 % PowerCem were used to replace cement. It was observed that the concrete mixture with 2.5 %

PowerCem was of a higher quality than 5 % proportion in terms of strength and durability. Based on this information, lower percentage proportions of PowerCem up to maximum proportion of 2.5 %, of weight of cement were used for this study. A comparison was made in this study of concrete with PowerCem additive and concrete with Fly ash (FA). Fly ash was considered for comparison since it is the most commonly used extender (supplementary cementing material). Portland cement, CEM 1 42.5N (OPC) was used throughout the investigation.

1.4 TESTING MATRICES

The investigation was carried out in two phases; the first phase dealt with mortar tests and the second phase dealt with concrete tests. PWC was used in the following proportions of cement weight for mortar tests: 0.4 %, 0.6 %, 0.8 %, 1.0 %, and 2.5 %. The tests that were carried out on mortar samples were: flow, compressive strength, flexural strength, internal sulphate resistance, external sulphate resistance, alkali silica reaction, oxygen permeability, sorptivity, and porosity tests. Water/cement (W/C) ratios of 0.4, 0.485, and 0.49 were used for alkali silica reaction, external sulphate resistance, and internal sulphate resistance tests respectively, while 0.5 W/C ratio was used for the remaining tests. Pulverized paste samples passing through the 90 μm sieve was used for thermal analysis.

Concrete mixes contained additives in the following proportions: 0.6 % PWC, 1.0 % PWC, 30 % FA, 0.6 % PWC + 30 % FA, 1.0 % PWC + 30 % FA, and 40 % OPC + 59 % FA + 1 % PWC. The proportions were based on the quantity of cement in the mix. Tests carried out on concrete samples are slump, compressive strength, split tensile strength, oxygen permeability, sorptivity, porosity, and carbonation tests. 0.5 W/C ratio was used for all tests. A testing matrix drawn for each phase is shown in Appendix A (Table A-1 and A-2).

A review of the existing literature has been done in Chapter 2 followed in Chapter 3 by description of the materials and experimental methods. The results are analyzed and discussed in Chapter 4. Chapter 5 presents the conclusions and recommendations, followed by the list of references. The detailed experimental results are recorded in Appendix A, while picture sequences for samples and equipment are presented in Appendix B and Appendix C respectively.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 INTRODUCTION

Concrete is a composite material or an artificial rock that consists essentially of fragments of aggregates (fine and coarse aggregate), that are bonded together by a binding material in the presence of water. It is the most widely used construction material. Components of concrete are aggregate, cement, and water. Mortar is the mixture consisting of fine aggregate (sand), cement and water; the difference from concrete being the absence of coarse aggregate in mortar.

Aggregate is the granular material, such as sand, gravel, crushed stone and demolition waste that is used with cementing medium to produce either concrete or mortar. This can be in form of fine or coarse aggregate. Aggregate particles smaller than 4.75 mm but larger than 75 μm (No.200 sieve) are referred to as fine aggregates, while those larger than 4.75 mm are generally referred to as coarse aggregates.

Cements are adhesive materials which have the ability of bonding particles of solid matter into a compact whole (Soroka, 1979). This broad definition encompasses a wide variety of adhesive materials, but for engineering purposes it is restricted to calcareous cements that contain compounds of lime as their main principal constituent. The main raw materials used in producing Portland cement are oxides: lime (CaO), produced by heating calcium carbonate, silica (SiO_2), found in natural rocks and minerals, alumina (Al_2O_3), found in clay minerals, and ferric (Fe_2O_3), found in clays. Table 2.1 shows the composition of South African Portland cement clinker. Cement as a binder is a vital element in concrete. The quality of concrete depends on the cement or binder, the aggregate, the mix design and the workmanship involved in making, placing and subsequent curing. The performance of cement used in concrete is influenced by its chemical composition.

Table 2.1 Composition of South African Portland cement clinker (Addis, 2001)

Oxides	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	$Na_2O + 0.658\ K_2O$
% by mass in cement	63-68	19-24	4-7	1-4	0.5-3.5	0.2-0.8

2.1.1 Compounds composition of cement

There are four main compounds present in cement clinker namely: tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF). These compounds are formed from the following oxide reactions under equilibrium conditions (Bogue, 1947):

- Fe_2O_3 reacts with Al_2O_3 and CaO to produce $4CaO.Al_2O_3.Fe_2O_3$ (C_4AF)
- The remaining Al_2O_3 reacts with CaO to produce $3CaO.Al_2O_3$ (C_3A)
- The remaining CaO reacts with SiO_2 to first form $2CaO.SiO_2$ (C_2S) and the calcium oxide left over react further with C_2S to produce $3CaO.SiO_2$ (C_3S). Any CaO that is still uncombined at this point remains as CaO in the cement.

In addition, cement clinker also consists of minor compounds such as MgO, TiO_2, K_2O, and Na_2O which are usually present in small quantities. K_2O and Na_2O, referred to as alkalis are also of interest because they are found to react with some aggregates and cause disintegration of concrete (Neville, 1981). The quantity of these alkalis in cement is therefore important.

C_3S is more reactive than C_2S under hydraulic condition and therefore dominates the first four weeks of hydration after which C_2S starts (Javed and Kenneth, 1985). C_3S and C_2S are the chemical compounds which mostly determine the physical engineering properties of the concrete. C_3A and gypsum have important influence on durability. Table 2.2 shows the typical compound composition of South African Ordinary Portland cements.

Table 2.2 Compound composition of South African Ordinary Portland cements (Addis, 2001)

Compound	Formula	Abbreviation	% by mass in cement
Tricalcium silicate	$3CaO.SiO_2$	C_3S	45-65
Dicalcium silicate	$2CaO.SiO_2$	C_2S	10-35
Tricalcium aluminate	$3CaO.Al_2O_3$	C_3A	4-10
Tetracalcium aluminoferrite	$4CaO.Al_2O_3.Fe_2O_3$	C_4AF	5-10
Magnesia	MgO	M	0.3-4.0
Gypsum	Raw material	-	3.5-7
Free lime	CaO	-	0.3-2.5

2.1.2 Hydration of cement

Hydration is the reaction of cement compounds (C_3S and C_2S) with water to give calcium hydroxide and calcium silicate hydrate as products. Hydration of calcium aluminate in the presence of gypsum gives ettringite product and monosulphate on further hydration. Gypsum is added to cement to extend setting time, hydration processes of the different compounds are shown in equations (2.1) to (2.4). The reactions are exothermic in nature.

For tricalcium silicate,

$$\underbrace{2(3CaO.SiO_2)}_{C_3S}+\underbrace{6H_2O}_{H}\rightarrow\underbrace{3CaO.2SiO_2.3H_2O}_{C-S-H}+\underbrace{3Ca(OH)_2}_{C-H}\text{------------------------ }(2.1)$$

For dicalcium silicate,

$$\underbrace{2(2CaO.SiO_2)}_{C_2S}+\underbrace{4H_2O}_{H}\rightarrow\underbrace{3CaO.2SiO_2.3H_2O}_{C-S-H}+\underbrace{Ca(OH)_2}_{C-H}\text{------------------------- }(2.2)$$

For tricalcium aluminate,

$$\underbrace{3CaO.Al_2O_3}_{C_3A}+\underbrace{3CaSO_4.31H_2O}_{C_3\bar{S}H}\rightarrow\underbrace{3CaO.Al_2O_3.3CaSO_4.31H_2O}_{Ettringite}\text{------------------- }(2.3)$$

$$\underbrace{3CaO.Al_2O_3}_{C_3A} + \underbrace{6H_2O}_{H} \rightarrow \underbrace{3CaO.Al_2O_{3.}6H_2O}_{monosulphate} \text{ --- } (2.4)$$

From (2.4), monosulphate is the final hydration product of C_3A.

The setting and hardening of cement paste is brought about by the formation of C-S-H gel during hydration (Soroka, 1979), this C-S-H fills the space between the cement grains and therefore causes the stiffening of the paste and subsequent hardening. As hydration continues, more C-S-H gel will be formed and this will fill the capillary pores, decrease the porosity and increase strength. The presence of $Ca(OH)_2$ causes high alkalinity of pore solution but makes concrete sensitive to acid attack. One way of utilizing the unreacted $Ca(OH)_2$ and improving the quality and characteristics of concrete is by pozzolanic reaction.

Ettringite formation explains the concept of dormant period during cement hydration. The ettringite forms a layer around the grain of C_3A and stops hydration for a period (dormant period). As a result of volume change, the layer will burst due to expansion and hydration will continue. The process will be repeated until there is no sufficient sulphate to form ettringite. The ettringite will be converted to monosulphate and hydration continues until the stable hydrate is formed (Soroka, 1979). If the concrete is exposed to sulphate solution after hardening, delayed ettringite can be formed. This is referred to as delayed ettringite formation (DEF) that leads to cracking and expansion of concrete and aids deterioration of concrete structures. The fourth compound, C_4AF reacts with gypsum to form iron-substituted ettringite (Sha *et al.*, 1999).

The effect of extenders on concrete can be better understood if their effect on cement hydration is known. The process of hydration at different temperatures becomes more complicated when additives are added (Singh *et al.*, 1994). With the C-S-H gel being nearly amorphous, hydration behaviour of cement-water systems will not be effectively detected by analytical method other than DTA and TGA (Javed and Kenneth, 1985).

There are a few studies that have been conducted to assess cement hydration of plain and blended cement (Javed and Kenneth, 1985; Singh *et al*., 1994; Sha *et al*., 1999; Sharma and Pandey, 1999; Perraki *et al*., 2003). The most commonly used methods of analysis are: X-ray diffraction (XRD), differential thermal analysis (DTA), thermogravimetric analysis (TGA), differential thermogravimetry (DTG), fourier transform infrared spectroscopy (FTIR) and differential scanning calorimeter (DSC).

A hydration study was carried out by Javed and Kenneth (1985) on pastes of mine tailing cement and ordinary Portland cement (OPC), pastes of both cement were prepared by mixing with deionised water at 0.49 W/C ratio. The results from DTA and TGA showed that tailing cement exhibited better hydration behaviour than ordinary cement alone in terms of bound-water, free calcium hydroxide and degree of hydration when cured under identical conditions. Mine tailing cement used was produced from raw taconite and copper-nickel tailings of Minnesota, U.S.A. The better behaviour is attributed to its higher C_3S content, which hydrates faster and contributes much to strength development.

Addition of limestone and lime sludge to concrete has been shown in a study by Sharma and Pandey (1999) to accelerate hydration of ordinary Portland cement and increase the amount of $Ca(OH)_2$ that is liberated, but formation of ettringite takes long, continuing up to 28 days of hydration. Also, addition of lime sludge improves hydration of OPC better than limestone addition alone for the same replacement level of 10 %. The study was conducted using concrete samples of 0.4 W/C ratio. The concrete samples with or without 10 % additives were allowed to hydrate in plastic vials at $27 \pm 2\ ^{o}C$ and analyzed using XRD and DTA.

DSC was used by Sha *et al.* (1999) to investigate the thermal behaviour of hydration products in ordinary Portland cement. The results showed that the three major endothermic peaks 1, 2, and 3 in the DSC curves are as a result of loss of water from calcium silicate hydrate, de-hydroxylation of calcium hydroxide and de-carbonation of calcium carbonate respectively. The endothermic peaks are shown in Figure 2.1.

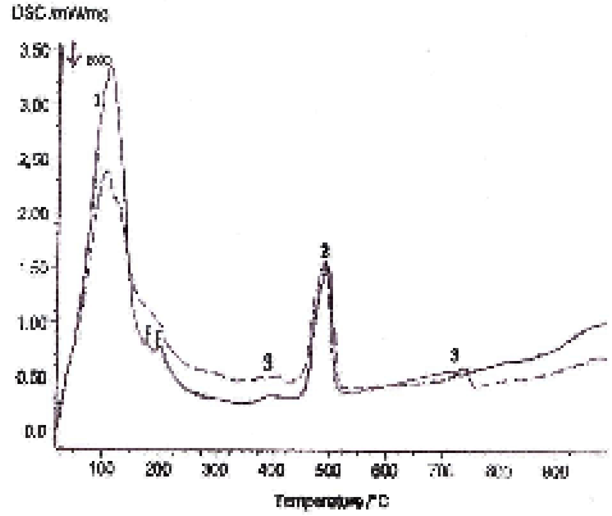

Figure 2.1: DSC curves of hydrated ordinary Portland cement at the ages of 17 (solid line) and 45 (dashed line) days. E = ettringite; F = iron-substituted ettringite; S = Fe_2O_3 solid solution (Sha *et al.,* 1999).

Perraki *et al.* (2003) studied the hydration of cement-zeolite pastes using XRD, FTIR and TG-DTG. XRD and FTIR were applied to identify the hydrated compounds while TG-DTG was used to determine the content of $Ca(OH)_2$ in the paste. The results showed a remarkable decrease of the $Ca(OH)_2$ content, especially in the sample incorporating 10 % zeolite. This effect was proportional to the age of hydration. This showed that natural zeolite used are pozzolanic materials that contribute to the consumption of $Ca(OH)_2$ formed during the hydration of Portland cement and formation of cement-like hydrated products. Further increase in zeolite content beyond 10 % did not seem to enhance the pozzolanic reaction and slight decrease of $Ca(OH)_2$ content observed was mainly due to the dilution effect on cement.

2.2 CEMENT EXTENDERS

Cement extenders are also referred to as pozzolans. A pozzolan (cement extender) is defined, according to Kumar *et al*. (1993) as a “siliceous or siliceous and aluminous material, which in itself possesses little or no cementing property but will, in a finely divided form and in the presence of moisture, chemically reacts with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties”. According to Habert *et al*. (2008) natural pozzolans (extenders), used as an admixture for the production of pozzolanic cements, are pyroclastic rocks rich in siliceous or siliceous and aluminous volcanic glass. The origin of the pozzolanic activity lies in the high content of reactive silica in extenders. Natural pozzolans are naturally occurring such as volcanic ash, zeolite e.t.c, while artificial extenders (fly ash, slag, silica fume) are by-products of manufacturing processes. The most commonly used cement extenders are discussed:

2.2.1 Fly ash

Fly ash is the ash precipitated electro-statically from the exhaust fumes of coal-fired power stations. It is the most common artificial pozzolan (Neville, 1981). The use of fly ash in concrete has been recognized to have the following benefits (Craig, 1994): Improved workability, lower heat of hydration, lower cost of concrete, improved resistance to sulfate attack, improved resistance to alkali-silica reaction, higher long-term strength, opportunity for higher strength concrete, equal freeze-thaw durability, lower shrinkage characteristics, lower porosity and improved impermeability. The major elements in fly ash, just like other pozzolans, are SiO_2, Al_2O_3, and Fe_2O_3. Fly ash is classified, based on quantities of these elements, into classes F and C with class F requiring a minimum total of 70 % of these elements in the ash while class C requires a minimum of 50 % (Craig, 1994). It is recognized that class C fly ash has a higher content of CaO than class F fly ash. This therefore, makes class C more reactive than class F fly ash. Fly ash, regardless of the class, has almost the same fineness as cement and is sometimes finer, making the silica readily available for reaction (Neville, 1981). Generally, FA proportion of 30 % has been successfully used in South Africa for producing blended cement (Addis, 2001).

2.2.2 Slag

Ground granulated blast furnace slag (GGBS), according to ASTM C 125 is "the glassy, granular material formed when molten blast-furnace slag produced as a by-product of iron production is rapidly chilled by immersion in water". This material is both cementitious and pozzolanic, in that it is self-cementing and does not necessarily require external supply of calcium hydroxide to form cementitious products. However, the cementitious products formed and the rates of formation are insufficient for structural purposes when GGBS is used on its own. When used together with Portland cement, the hydration process of GGBS is accelerated due to the presence of calcium hydroxide and gypsum (Perraki *et al.*, 2003). Using Slag as a separate ingredient in concrete has the following advantages according to Lewis (1981) and Addis (2001): higher ultimate strengths with a tendency toward lower early strengths, higher ratio of flexural to compressive strengths, improved refractory properties, lower coefficients of variation in strengths, improved resistance to sulfates and seawater, lower expansion from alkali-silica reaction, lower temperature rise due to lower heat of hydration, better finish and lighter color, equivalent durability in freezing and thawing, decreased porosity and reduced chloride penetration. Typical proportion of GGBS in blended cement, which has been extensively and successfully used in South Africa is 50 % (Addis, 2001).

2.2.3 Silica fume

Silica fume is a by-product from the manufacture of silicon or ferrosilicon alloys by the reduction of silica with carbon in an electric furnace. The gases produced are condensed into an extremely fine powder with high silica content, hence, the term condensed silica fume (CSF) (Greensmith, 2005). The most active material in silica fume is SiO_2. It is stated in Addis (1994) that, “the extremely small CSF particles in the mixing water act as nuclei for the formation of calcium silicate hydrate which would otherwise form only on the cement grains”. Consequently, more homogeneous microstructure with greater strength and lower permeability is developed.

The normal ratio of Portland cement (PC) to CSF is between 95:5 and 90:10. Effects of CSF on concrete are reduction in workability; therefore, more water is needed to maintain given slump or chemical admixtures must be used for CSF dispersion, increase cohesiveness of concrete mix, reduction in bleeding of fresh concrete, no change in setting times, develop early strength at rate similar to or higher than Portland cement only, reduction in concrete permeability and increase concrete strength at the range of 15 to 20 % at 28 days with 10 % replacement of OPC with CSF (Addis, 1994).

The usage of FA and GGBS must be guided by the following precautions according to Addis (1994): The W/C ratio for given 28 days strength should be reduced, they are not suitable for concrete floor slabs where sawing of joint has to be done at an early age due to slower rate of reaction, effective moist curing of the concrete is essential for strength development and impermeability, striking of formwork and removal of props may be delayed and finally, use of these pozzolans should be avoided for thin application like plastering and floor screed to prevent drying out. While CSF usage is guided by: Plasticizing admixture can be added to compensate for the reduced workability, the surface of the concrete slab cast should be kept moist to prevent plastic-shrinkage due to low bleeding capacity of CSF concrete and batching should be done with care because amounts of CSF is relatively small. Dispersants are essential for CSF.

2.2.4 Zeolite

Natural zeolites are hydrated aluminosilicate minerals containing alkaline and alkaline-earth metals, formed by the alteration of volcanic ash which is mainly an amorphous, siliceous material (Fragoulis *et al*., 1997). The amount of dissolved SiO_2 in zeolites is 3 to 7 times higher than that in other pozzolans (Naiqian, 1993). This makes it capable of absorbing more lime than ordinary tuffs and some other glassy mixtures and results in the formation of higher amounts of hydration products which are responsible for strength development. The structure of the zeolite minerals is characterized by a large number of channels and cavities which exhibit a high surface area (Fragoulis *et al*., 1997).

The most commonly investigated and used zeolites are those common in the sedimentary zeolite (tuff) deposits widespread all over the world, namely, clinoptilolite, mordenite, phillipsite and chabazite (Fragoulis *et al*., 1997; Yilmaz *et al*., 2007; Caputo *et al*., 2008). Albayraka *et al*. (2007) showed that when zeolite was used as a component of autoclaved aerated concrete to replace quartzite, the resulting strength was similar to conventional autoclaved aerated concrete. The zeolite was also observed to provide thermal conductivity values similar to those of conventional autoclaved aerated concrete at the same bulk density.

Burriesci *et al.* (1985), in their study, showed that zeolites derived from pumice (from the large local quarry of Lipari) by hydrothermal synthesis showed high pozzolanic activity at variance to those based on tuff. It was reported (Burriesci *et al.,* 1985) that the proposed cement formulation, containing 10-20 % zeolite lead to a low free CaO content at setting of the concrete when examined by Fratini test. The zeolites also improved the Blaine fineness value, flexural and compression strength, but further zeolite addition was observed not to lead to further gains in flexural and compression strength but instead acted inert.

The effect of zeolitic tuff (clinoptilolite), on the properties of cement was examined by Yilmaz *et al*. (2007). Clinoptilolite is one of the most common zeolite minerals found in nature. It was concluded (Yilmaz *et al*., 2007) that the clinoptilolite blend decreases the specific gravity of cements but the water demand of clinoptilolite blended cements increases due to microspores inherently found in their structures. Plasticity time of cement mortars was also found to increase depending on clinoptilolite blend ratios while the early strengths in clinoptilolite blended cements developed in relative to the Blaine fineness values. The final strengths were found to develop depending on the CH amount in the medium. Blaine fineness values of blended cements decreased with increasing blend ratios. Blended cements were produced by replacing OPC with 5 %, 10 %, 20 %, and 40 % clinoptilolite. Mortar samples were produced with W/C ratio of 0.5.

Investigations conducted by Caputo *et al*. (2008) to study the effect of zeolite structure on the pozzolanic activity of zeolites using two synthetic Na-zeolites A and X (X is more slightly siliceous than A) with a Si/Al ratio equal to 1–1.2, showed that the pozzolanic action of both zeolites involved the following steps: (a) cation exchange, (b) dissolution and/or breakdown, (c) possible formation of a transient alumino-silicate gel, and (d) precipitation of hydrated calcium silicates and aluminates from solution. The study showed that zeolite A reacted more readily than zeolite X, but the latter, being slightly more siliceous, contributed to greater development of the mechanical resistances of the cement pastes at short curing times.

Also, a review done by Caputo *et al*. (2008) indicated that natural zeolites are excellent pozzolanic materials which often behave better than glass of identical composition. Zeolite reactivity is related to its large external specific surface and metastability which favor its dissolution into the saturated lime solution and the subsequent precipitation of CSH (hydrated calcium silicate) and CAH (hydrated calcium aluminate) phases. The replacement of Portland clinker by zeolitic tuff, therefore, reduces workability and increases water demand although this effect may be overcome by using a superplasticizer. The replacement of Portland clinker by zeolitic tuff is also found to reduce the alkali level of the blend minimizing the risk of alkali-silica reaction which would result in undesired expansion and cracking of concrete. Typical compositions of South African extenders are shown in Table 2.3.

Table 2.3: Typical composition of South African cement extenders (Addis, 2001)

Oxides	% by mass in GGBS	% by mass in FA	% by mass in CSF
SiO_2	34-40	45-50	92
Al_2O_3	11-16	25-30	1.5
CaO	32-37	4-8	0.6
FeO	0.3-0.6	9-11	-
MgO	10-13	2-4	0.6
Fe_2O_3	-	-	1.2

2.3 POZZOLANIC REACTION: EFFECT ON CONCRETE PROPERTIES

The reaction between a pozzolan and calcium hydroxide is called a pozzolanic reaction. The differences between a hydration reaction and a pozzolanic reaction are (Kumar *et al*., 1993):

- A pozzolanic reaction is slower and therefore the rates of heat liberation and strength development are slower than a hydration reaction.
- Pozzolanic reaction is lime-consuming instead of lime- producing as is with the case of hydration reaction.
- The pozzolanic reaction product is efficient in filling up capillary spaces, thus improving the strength and impermeability of the system than hydration reaction.

Equations (2.5) and (2.6) show the differences.

Hydration reaction:

$C_3S + H \xrightarrow{fast} C - S - H + CH$ -- (2.5)

Pozzolanic reaction:

$Pozzolan + CH + H \xrightarrow{slow} C - S - H$ --- (2.6)

2.3.1 Effect on fresh concrete properties

The effect of pozzolans on Portland cement depends on the type of pozzolan and its replacement proportion. General effects of common pozzolans on fresh concrete properties are stated in Table 2.4.

Table 2.4: General effects of common pozzolans on fresh concrete properties (Addis, 2001).

Extenders	Effects on fresh concrete properties
GGBS	May improve workability slightly. Retards setting slightly. Exhibits low heat of hydration.
FA	Improves workability and reduces water requirement for a given slump. Slightly retards setting. Exhibits low heat of hydration.
CSF	Reduces workability. Increases cohesiveness. Reduces bleeding significantly. Exhibits low heat of hydration.

2.3.2 Effect on heat of hydration

A pozzolanic reaction being a slow reaction exhibits low heat of hydration compared to a hydration reaction. Figure 2.2 shows the relation between the heat of hydration and the pozzolan content in cement. The graph indicates that there is a decrease in the heat of hydration with increase in proportion of pozzolan incorporated in cement. The slow hydration and rate of heat development makes pozzolan useful in mass concrete construction (Neville, 1981).

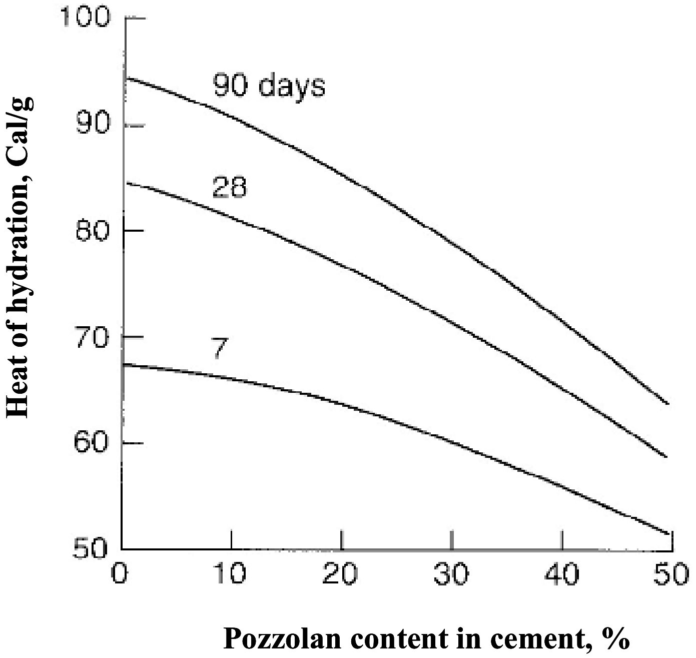

Figure 2.2: The relation between heat of hydration and the pozzolan content in cement (Kumar *et al*, 1993).

2.3.3 Effect on concrete strength development

The strength development of pozzolan concrete is generally slower than that of Portland cement concrete during the early stages of hydration because of the slow pozzolanic reaction. Hydration of Portland cement occurs to produce CH, while extenders have to wait for CH production from Portland cement before pozzolanic reaction can take place. However, late strength is enhanced due to the pore refinement associated with the pozzolanic reaction (Kumar *et al.*, 1993), the increase in C-S-H and the consumption of calcium hydroxide.

2.3.4 Effect on concrete durability

The process of pore-size and grain-size refinement due to pozzolanic reaction strengthens the cement paste at the interfacial zone. This increases the impermeability of the concrete matrix and improves its durability. Reduction of concrete permeability and calcium hydroxide content due to pozzolanic reaction enhance concrete resistance to ingress of moisture and dangerous chemical agents. According to Kumar *et al*., (1993), combinations of high-alkali Portland cement with pozzolan enhance reduction in expansion due to alkali-aggregate reaction. Some pozzolans have high alkali content, which may be harmless if these alkalis are insoluble in the high-PH environment of Portland cement concrete. Some pozzolans have been reported to promote resistance to alkali-silica reaction (Ekolu *et al*., 2006).

2.4 PROPERTIES OF FRESH CONCRETE

The engineering properties of concrete can be divided to two, namely: properties of fresh concrete and properties of hardened concrete. The properties of fresh concrete are those that affect concrete's ability to transport, handle, place and finish. For hardened concrete to be strong and durable, fresh concrete must satisfy the following:

- It must be easily mixed and transported.
- It must be uniform throughout a batch and between batches.
- It must flow adequately to fill casting forms.
- It must be easy to be compacted fully without excessive energy.
- It must not segregate during placement and compaction.
- It must be able to be finished properly, either by trowelling or within the formwork.

The properties of fresh concrete that influence the overall strength and durability are: workability, segregation, and bleeding.

2.4.1 Workability

Workability relates to the consistency of concrete and can be defined as the ability of concrete to flow freely in formwork without segregation. The more workable concrete is the easier for it to be transported, placed and finished without segregation. The level of concrete workability needed depends on the type of structure, placement and compaction. Concrete that needs to be placed in a high reinforced congested area has to be more workable than in the case of mass concrete. Compaction helps in eliminating entrapped air and to overcome the friction between individual particles in the concrete.

The main factor affecting concrete workability is the water content of the mix. Other factors are: aggregate size and characteristics, cement content, cement type, and admixture. The higher the water content, the higher the concrete consistency. Concrete mixtures with high consistency are vulnerable to segregation (non-uniform mix) and bleeding (appearance of water on the surface of the concrete after consolidation), while mixtures with too low a consistency will be difficult to place and compact. Highly wet mixes can lead to separation of coarse aggregate from the rest of concrete (Kumar *et al*., 1993). Consistency of a dry mix can be improved by adding water-reducing admixture. The workability of mortar can be assessed through flow test while the most universal method of assessing concrete workability is by measuring its consistency through slump test. These two tests are used in this study.

2.4.2 Segregation

Segregation is the separation of concrete constituents within the mix so that their distribution is no longer uniform, which can be due to differences in the specific weights of the constituents (Soroka, 1979). This can be aggravated by careless handling and the use of inadequate methods of transporting and placing. Placing concrete at a high distance and velocity may result in segregation. Factors contributing to segregation are (Donahue, 2004): large maximum particle size (>25 mm), large proportion of large aggregate, high specific gravity of coarse aggregate, decreased amount of fines (sand or cement), increased irregular shape or rough texture, and mixes that are too wet or too dry. Segregation can be partly overcome by careful handling.

2.4.3 Bleeding

Bleeding is a form of segregation which involves the rise of water onto the surface of cast concrete as the solid materials settle to the bottom. Mild bleeding is normal for good concrete, it prevents drying out, prior to complete hydration but excessive bleeding is deleterious to the concrete structure.

Concrete becomes porous, weak and non-durable, as a result of excessive bleeding. A weak wearing surface will be formed if bleed water is re-mixed during finishing (Neville, 1981). Bleeding water may accumulate beneath large aggregate or underneath reinforcing steel, generating weak zones and reducing bond. Plastic shrinkage may also result if the bleeding water evaporates more than bleeding rates, rapidly such as in hot or dry weather. In this case, paste at the surface does not adequately hydrate causing dusting and reduced durability of the wearing surface (Donahue, 2004). Laitance is the external manifestation of bleeding, which is caused by rising of water in the internal channel within concrete, carrying along cement and fine particles in concrete and depositing them in the form of scum on the concrete surface (Kumar *et al*., 1993), resulting in weak, porous and soft surface that is prone to dusting.

Bleeding can be reduced by modifying the mix in the following ways:

- Increasing the cement fineness or using pozzolans or other finely divided extenders.
- Increasing the rate of hydration by using cements with high alkali contents or high C_3A contents.
- Using air entrainment admixture (quite effective).

- Reducing the water content (provided adequate workability is maintained).

2.5 PROPERTIES OF HARDENED CONCRETE

2.5.1 TENSILE AND COMPRESSIVE STRENGTH

The strength of hardened mortar and concrete is an important parameter for concrete design; it indicates the concrete's ability to resist stress. Strength is considered as the foremost property of concrete, but in some practical cases other properties like durability and impermeability may be more important even though strength indicates the overall view of concrete quality and most other properties improve with strength. The strength of mortar has important influence on concrete strength. Hydration reactions that occur when water is added to cement, result in the formation of calcium silicate hydrate (CSH) gel, which is responsible for strength development in mortar and concrete.

Different forms of strength measurements can be determined by subjecting the concrete to compressive, tensile and shear tests. Out of these aforementioned tests, compressive strength is the most commonly used concrete design parameter. According to Addis, (1994) the relationship between tensile and compressive strength does not have a specific pattern, because the factors affecting strength do not affect tensile and compressive strength to the same degree. Both tensile and compressive strength tests were conducted in this study to assess the trend of effect of PWC additive on the two parameters.

Investigations have shown that natural zeolite enhances late compressive strength of concrete when used as a partial substitute to OPC, slightly reducing the early strength (Poon *et al*., 1999; Canpolat *et al*., 2004; Quanlin and Naiqian, 2005). This behavior is similar to other pozzolans like slag and fly ash (Vagelis, 2000; Targana *et al*., 2002; Toutanji *et al*., 2004) but contrary to silica fume and bentonite, which increase early strength. These varied effects are attributed to the slow pozzolanic reactions of fly ash, slag, and zeolite at early ages and large pozzolanic contribution of bentonite and silica fume at these early ages (Targana *et al*., 2002; Toutanji *et al*., 2004).

Research carried out by Poon *et al.* (1999), found the pozzolanic reactivity of zeolite to be higher than that of fly ash but lower than that of silica fume. This shows that zeolite concrete may have higher early strength than fly ash concrete. However, it was observed by Quanlin and Naiqian (2005) that since natural zeolite has great surface area, high water absorption ability, needs more water or superplasticizer to maintain slump, and also causes decrease in early strength when used at high percentage proportions, modification of zeolite is needed such that the cation exchange of the modified product is increased and this will give better results when used as cement improver.

In a study by Yan *et al.* (1996), it was shown that use of zeolites as conversion-preventing additives for inhibition of hydrogarnet formation in high alumina cement can effectively prevent strength reduction in high alumina cement mortars when used in quantities between 12 to 50 % by mass of high alumina cement. Also, the modified zeolite derived from immersion of natural zeolite in 2N NH_4Cl solution, according to Quanlin and Naiqian (2005) gave the same effect on concrete strength as natural zeolite with less than 5 % dosage of modified zeolite used. Generally, the strength of any concrete is based on the mortar matrix, the bond between mortar and coarse aggregate, the strength of coarse aggregate, and the presence of microcracks and pores in concrete. Therefore, the factors that affect mortar's strength will invariably affect concrete strength. Some of the factors influencing concrete strength which are relevant to this investigation are discussed in detail below:

2.5.1.1 Influence of porosity

There is an inverse relationship between porosity and strength of concrete (Soroka, 1979; Kumar, 1993; Addis, 1994; Neville, 1981). This relationship can be expressed as shown below:

$S = S_o e^{-kp}$

where:

S = Strength of concrete at given porosity p

S_o = Strength of the concrete at zero porosity

k = Constant, which depends on the type of cement, age of the sample, and other factors

This relationship is not only observed in mortar and concrete but also in other materials like iron, sintered alumina, plaster of paris and zirconia. Figures 2.3 and 2.4 show the typical results for the various materials. This general pattern establishes the fact that porosity is an important factor that affects the strength of materials and it explains why concrete of low porosity has high strength.

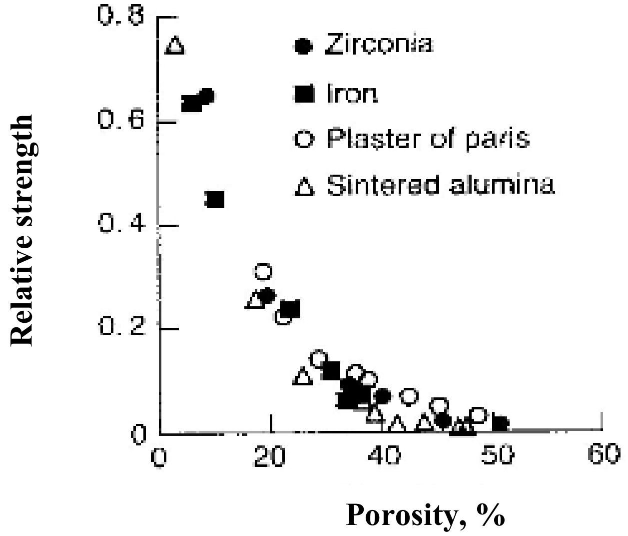

Figure 2.3: Porosity-strength relation in zirconia, iron, plaster of Paris and sintered alumina (Kumar *et al.*, 1993).

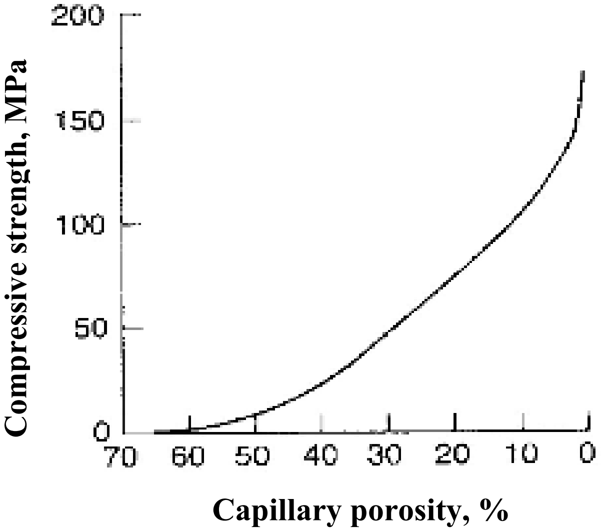

Figure 2.4: Porosity-strength relation in normally cured cements, autoclaved cements and aggregates (Kumar *et al.*, 1993).

Kumar *et al.* (1993) recorded that the strength of the interfacial transition zone at any point depends on volume and size of voids present. A contrary opinion was observed by Hearn *et al.* (1994) who recorded that the effect of porosity on concrete strength is mostly based on the volume of pores not the pore size or continuity. Overall, it can be seen that the presence of pores and cracks contribute to the overall porosity of the concrete and affect the strength of concrete.

2.5.1.2 Influence of paste-aggregate bond

The strength of mortars and concrete is significantly influenced by the bond between the paste matrix and the aggregates. Since the bond strength between paste and aggregate is less than the paste strength, failure tends to commence from the paste-aggregate interface than the paste itself.

At initial stage of hydration, the volume and size of voids at the interfacial zone is greater than that in bulk mortar. However, as hydration increases, the volume and size of voids decreases at the interfacial zone due to infilling by C-S-H gel and reduction of the concentration of $Ca(OH)_2$ at the interfacial zone. $Ca(OH)_2$ reduces adhesion capacity at the zone. Reduction in the volume and size of void results in dense concrete and increased strength. The presence of microcracks at the interfacial zone results in low concrete strength. The following factors affect the presence of microcracks at the interfacial zone: aggregate size and grading, water/cement ratio, cement content, degree of hydration, curing condition, and degree of consolidation of fresh concrete.

2.5.1.3 Influence of water/cement ratio

Water/Cement ratio is considered as the most important factor affecting concrete strength because it affects the porosity of the hardened paste as hydration progresses. The strength of concrete is a function of the strength of paste and the strength of aggregate-paste bond. Both factors are affected by the water/cement ratio of the mixture. The quantity of water used in a cement paste mixture has an overall effect on volume, since the volume of the wet paste is the sum of the volume of the anhydrous cement and the mixing water. The quantity of water used also affects the flow or rheology of the mixture as well as cohesion between paste and aggregate. As a result, it influences the overall strength of concrete.

According to Abram's law, if the effect of aggregate on strength is ignored and the same degree of hydration and compaction are undergone, concrete strengths are determined solely by the W/C ratio. The law gives the following expression:

$$S= A/B^{w}$$

where:

w = W/C ratio

S= Strength

A and B are constants which depend on the properties of aggregate (Neville, 1981). This law is valid on the basis of full compaction of concrete. Figure 2.5 shows the relation between W/C ratio and compressive strength. Neville (1981) reported that below a certain W/C ratio value, the expected increase in strength does not occur, because limited water is available for complete hydration and therefore it results in reduction in strength. On the other hand, increase in W/C ratio beyond certain value results in increase in porosity and weakening of the concrete matrix. In order to eliminate experimental bias as much as possible in this study, the same W/C ratio was used for all the mixes.

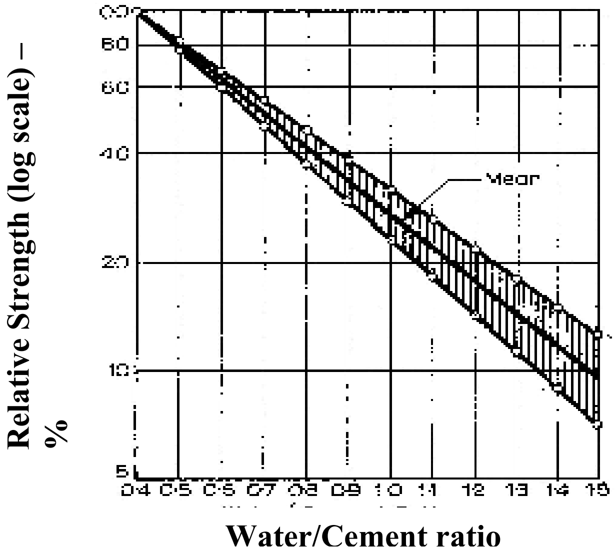

Figure 2.5: Relation between logarithm of strength and W/C ratio (Neville, 1981).

2.5.1.4 Influence of chemical admixtures

Chemical admixture was defined by Kumar *et al.* (1993) as “materials other than aggregates, cements, and water, which are added to the concrete batch, immediately before or during mixing”. These materials have an effect on the setting and hardening, rate of hydration, capillary porosity, density, microscopic structure, durability, and overall strength of concrete. The influence of admixtures on strength varies, depending on the chemical composition of the cement and the type of admixture. Examples of chemical admixtures that affect strength are: retarders, accelerators, water reducing agents (WRA), air entraining admixtures, and extenders. Retarders are used to temporary inhibit setting. They reduce the rate of cement hydration and rate of strength gain at early ages but generally do not adversely affect ultimate strength. Most retarders are based on sugars or soluble salts of zinc.

Accelerators increase the rate of hydration and rate of strength gain during the early ages. Examples of accelerators are calcium chloride ($CaCl_2$) and sodium chloride ($NaCl$). Chloride based accelerators are no longer used in reinforced concrete, as they cause steel corrosion.

WRA are surfactants, they develop charges at cement particle surface for repulsion of water molecules, leading to high workability. In application, WRA may be added to increase workability for a given mix or reduce W/C ratio while maintaining the same workability.

Air entrainment is used to incorporate voids in concrete matrix. Entrained air is applied for freeze-thaw resistance, usually done for concretes in cold climates, during severe winter. Percentage range of 5 to 8 % of air entrainment should be used in concrete, to minimize adverse effects on concrete strength, and durability.

Extenders, when used as a partial replacement to cement, usually exhibit reduction in early strength and improvement of ultimate strength. They also increase tensile strength of concrete (Kumar *et al*., 1993).

2.5.1.5 Influence of degree of hydration

According to Soroka (1979), degree of hydration can be considered as a measure of the amount of water required to cover the surface of the CSH gel with a mono-molecular layer (V_m) as a proportion of the original mixing water (W_o), that is V_m/W_o

measures the degree of hydration. Figure 2.6 shows the relation between the compressive strength of cement paste and V_m/W_o.

During hydration process, C-S-H gel is formed and the layer encapsulates the hydrating cement grains. This activity is responsible for strength development. The degree of hydration depends on the density and thickness of the C-S-H gel formed. The more dense and thicker the C-S-H gel layer gets, the lower the subsequent rate of hydration. In turn, these events have a bearing on the overall degree of hydration. As discussed in earlier Section 2.1.2, C-S-H is formed from chemical compounds of the cement, particularly C_3S and C_2S.

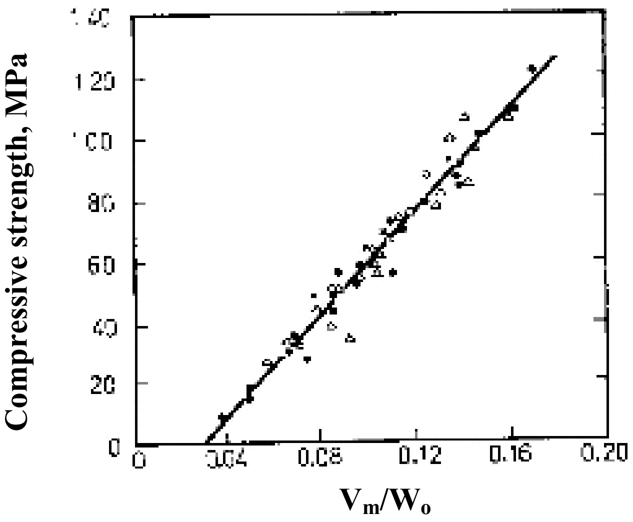

Figure 2.6: Compressive strength of cement paste plotted against V_m/W_o (Soroka, 1979).

The significance of the degree of hydration can also be considered by its effect on capillary porosity. Capillary porosity decreases with increase in the degree of hydration resulting in an increase in strength. Factors that affect degree of hydration are: age of paste, type of cement characterized by compound composition and fineness, admixtures, and temperature of curing. In this study, the same type of

Portland cement, curing temperature and testing ages were used for all the mixes, therefore the degree of hydration was solely affected by the different percentages of additive used.

2.5.2 CONCRETE DURABILITY

The durability of concrete is defined as its ability to be serviceable and withstand environmental conditions without major deterioration throughout its design period. The environmental effect can be as a result of natural occurrences, weathering, abrasion, exposure to high temperature, ingress of chemicals, and gases. Serviceability can be affected by internal causes like alkali-aggregate reaction, sulphate attack, and other damage mechanisms, volume changes within the concrete components, and permeability. Durable concrete must be dense and impermeable to liquids and gases. It should possess high intrinsic resistance to external penetration of ionic species such as sulphates and chloride (Osborne, 1999).

Durability of concrete is of great concern to researchers because it determines length of the life of concrete structures. Many structural failures can be traced to concrete of poor durability. Enhancing concrete durability has been widely discussed in a number of publications (Tarun *et al*., 1994; Osborne, 1999; Bai *et al*., 2002; Canan, 2003; Courard *et al*., 2003; Tsivilisa *et al*., 2003). One of the important factors that have gained attention of researchers in improving concrete durability is the use of cement extenders or pozzolans in concrete mixtures.

It was reported by Ha-Won and Seung-Jun (2007), that the durability of concrete is directly related to the type, size, and quantity of pores present. Due to pore refinement caused by addition of most cement extenders in concrete, decrease in final permeability, reduction in sorptivity, higher resistance to sulphate attack, and reduction in carbonation depth of blended samples have been reported (Banthia, 1989). The important properties of concrete that affect its durability are: permeability and sorptivity, sulphate attack, alkali-aggregate reaction, and carbonation. These are discussed in detail below:

2.5.2.1 Permeability and sorptivity

Permeability and sorptivity are both porosity related properties but they differ in function. Sorptivity measures the volume of open pores accessible to water by capillary suction while permeability measures the rate of flow of water through continuous pores at a given pressure and temperature (Soroka, 1979). Porosity of concrete allows the movement/transport of water and other substances, which may then cause deterioration of the structure. The transportation of substance into concrete is aided by pore structure of the concrete, exposure condition, and characteristics of diffusing substances (Gonen and Yaziioglu, 2007).

Permeability is considered as a major property of concrete for determining its durability (Banthia, 1989; Tarun *et al*., 1994; Ha-Won and Seung-Jun, 2007). Highly permeable concrete is vulnerable to damaging attacks like frost damage and reinforcement steel attack by corrosive agents. Several recent studies have shown that concrete permeability and sorptivity can be improved by incorporating cement extenders in mortar and concrete mix.

Tarun *et al.* (1994), observed that 50 % fly ash concrete mixture reduced air, water, and chloride ion permeability, relative to the plain Portland cement concrete when cured beyond 91 days. Bai *et al.* (2002) showed in their study that increasing metakaolin (MK) content of Portland cement - pulverised fuel ash - metakaolin (PC-PFA-MK) system in a water-cured concrete mix reduced the sorptivity value compared to control mix of PC only. Also, Schwarz *et al*. (2008) concluded that concrete mixes incorporating 10 % glass powder and 10 % fly ash had lower moisture intake compared to plain concrete. The results were obtained from mix samples subjected to the one-dimensional moisture intake test after moist- curing for 90 days.

Researchers have given attention to developing index tests that could be used to quantify potential durability of concrete. Such tests include oxygen permeability and water sorptivity tests. Different methods had been adopted in evaluating the oxygen permeability and water sorptivity of concrete (Hall, 1986; Banthia, 1989; Tsivilis *et al*., 2003; Nambair and Ramamurthy, 2007; Schwarz *et al*., 2008). Despite the existence of different methods, the concept is still the same.

A gas permeability test involves the forceful passage of gas through the mortar and concrete samples such that it passes through the continuous pores of the samples. The sorptivity test, on the other hand, involves the absorption and transmission of water by the samples, through capillary action. The rate of this capillary sorption depends on the degree of saturation of samples. This is an important test because the primary transport mechanisms through which chloride and sulphate ions ingress concrete are diffusion and capillary action (Martys and Ferraris, 1997). Factors that affect concrete permeability and sorptivity are discussed below:

2.5.2.1.1 Curing

It has been observed that curing condition is critical to durability properties of concrete (Gopalan, 1996). Water-cured concrete exhibits lower sorptivity and permeability than air-cured and steam-cured concrete (Soroka, 1979; Neville, 1981; Bai *et al*., 2002). The longer the curing period, the smaller the sorptivity and permeability. This indicates that the additional curing reduces the pore size and volume (Soroka, 1979; Martys and Ferraris, 1997). Sufficient curing is needed for complete cement hydration, which is responsible for reduction of pore size and improvement of concrete durability. Extenders require longer curing period than cement for complete pozzolanic reaction.

2.5.2.1.2 Pore structure

The pore size distribution of a concrete influences the rate of ionic transport (Gonen and Yaziioglu, 2007). Continuous pore structure of cement paste will lead to high porosity and high permeability. Interconnectivity of microcracks and pores in the paste matrix as well as at the interfacial transition zone are responsible for pore continuity. Sufficient hydration is important in reducing continuous pore system.

2.5.2.1.3 Water/cement ratio

Porosity of concrete which is central to permeability and sorptivity tests is a function of the water/cement ratio of the mixture. Figure 2.7 shows the relation between the water/cement ratio and the coefficient of permeability of cement paste. At high W/C ratio, the coefficient of permeability increases due to the continuity of capillary pores within the cement paste. These capillary pores are discontinuous at low W/C ratio, specifically, less than 0.6 W/C ratio.

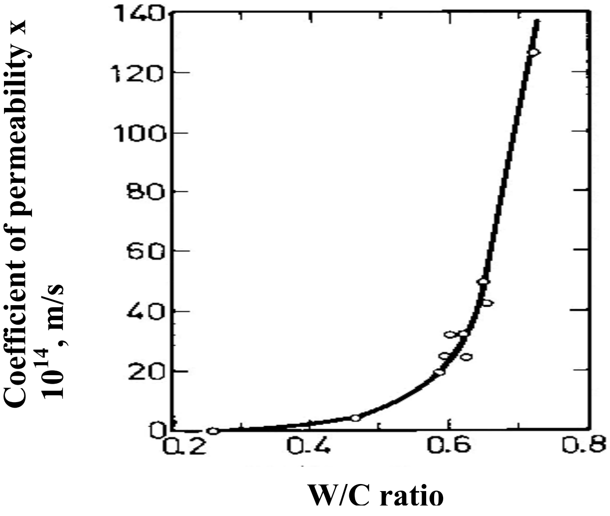

Figure 2.7: The relation between the water/cement ratio and the coefficient of permeability of cement paste (Soroka, 1979).

2.5.2.1.4 Extenders

Addition of extenders in concrete mix helps in refining the pore structure and reducing permeability and sorptivity. According to Banthia (1989) silica fume caused a decrease in permeability in concrete mix due to pore refinement by the extender. The finer the extender grain size, the higher the tendency to serve as filler in concrete matrix and help in refining concrete pore structure. In addition to pozzolanic effect, the filler effect of extenders results in blockage of pore channels and consequence reduction of concrete permeability and sorptivity.

2.5.2.1.5 Degree of hydration

The degree to which hydration has taken place during a particular time interval will determine the pore structure of concrete at that time. Hydration reduces the typical pore size in the cement paste matrix and slows down sorption of water (Martys and Ferraris, 1997). The coefficient of permeability decreases with increase in the degree of hydration (Banthia, 1989).

2.5.2.2 Sulphate attack

Sulphate attack is one of the most aggressive environmental factors that affect long term durability of concrete structures. It can result in cracking, expansion and deterioration of concrete structures (Nabil, 2006). Sulphate attack is the reaction of sulphate ions with calcium hydroxide and calcium aluminate hydrate to form ettringite and gypsum, these products are voluminous and lead to expansion, cracking, deterioration, and deformation of concrete structures (Torri *et al*., 1995; Nabil, 2006; Sideris *et al*., 2006; Salah, 2007) when formed after concrete has hardened.

Sulphate attack can also lead to leaching of calcium compounds, degradation of calcium silicate hydrate (C-S-H), and overall deterioration of cement paste matrix (Nabil, 2006). One of the most severe conditions for durability of concrete is the sulphate or acid environment caused by industrial wastes or chemical residues at re-claimed grounds (Hanifi and Orhan, 2006). Quite a number of studies have been done on investigating ways of increasing concrete resistance to sulphate attack through incorporation of extenders (pozzolans) in mortars and concrete mixes (Torri *et al*., 1995; Osborne, 1999; Rodriguez-Camacho and Uribe-Afif, 2002; Courard *et al.*, 2003; Nabil, 2006).

Consumption of calcium hydroxide produce during hydration by cement extenders and less presence of C_3A due to reduced quantity of cement content when extender is incorporated (Rodriguez-Camacho and Uribe-Afif, 2002; Salah, 2007), can help in increasing the resistance of concrete to sulphate attack. This emanates from reduction in gypsum and ettringite formation within the cementitious system.

Deterioration of concrete as a result of sulphate attack can be in form of internal attack due to sulphate content of the cement, and external attack due to exposure of concrete to sulphate environment. Both forms of sulphate attack are manifested by expansion and cracking of concrete. According to Omar (2002), formation of gypsum and ettringite are function of sulphate attack. Gypsum formation resulted in eating away of hydrated cement paste, which is characterized by softening of cement matrix and causes reduction in cross-sectional area of the structural component and strength, due to loss of cohesiveness of the cement hydration products. Also, ettringite product, tricalcium-sulfo-aluminate hydrate formation results in expansion and cracking, when reactive hydrated aluminate phases are attacked by sulphate ions.

Some of the factors that affect sulphate attack are discussed below:

2.5.2.2.1 Cement type

The different forms of sulphate attack can be affected by the cement type. Sulphate ions can be introduced to concrete mix from internal sources. Cement type with high content of tricalcium aluminate (C_3A) will exhibit low resistance to sulphate attack. If the C_3A content of cement is more than 5 %, most of the alumina it contained will be in form of monosulfate hydrate, $C_3A.CS.H_{18}$ or $C_3A.CS.H_{12}$. If the C_3A content is more than 8 %, the hydration product will also contain hydrogarnet, $C_3A.CH.H_{18}$ or $C_3A.CH.H_{12}$. Alumina containing hydrates will be converted to ettringite, which generates excessive expansion in hardened concrete, when cement paste comes in contact with sulphate ions in the presence of moisture. The reactions that result are shown in equations (2.7) and (2.8).

$C_4ASH_{12} + 2CSH_2 + 16H \longrightarrow C_6AS_3H_{32}$ (ettringite) -------------------------(2.7)

$C_4AH_{13} + 3CSH_2 + 14H \longrightarrow C_6AS_3H_{32}$ (ettringite) + CH ----------------------(2.8)

High content of C_3S in cement is essential for early strength development. It also produces high quantities of calcium hydroxide as a by-product of hydration. CH in concrete will aid gypsum formation when exposed to sulphate ions (Al-Dulaijan *et al.*, 2003).

2.5.2.2.2 Sulphate type and concentration

In experimental studies, concrete deterioration due to sulphate attack tends to increase with increase in the concentration of sulphate solution to some extent (Omar, 2002) but beyond 0.5 % of $MgSO_4$ or 1 % of Na_2SO_4, the rate of increase in intensity of the attack becomes smaller (Neville, 1981). In the case of Na_2SO_4 attack, formation of sodium hydroxide, a by-product of the reaction, causes continuation of high alkalinity in the system. This is essential for the stability of the ettringite and reduces sulphate attack. On the other hand, in the case of $MgSO_4$ attack, gypsum formation is accompanied by the simultaneous formation of magnesium hydroxide, which is insoluble and causes reduction in the alkalinity of the system. In the absence of hydroxyl ions in the solution, C-S-H is no longer stable and is also attacked by the sulphate solution (Kumar *et al*, 1993). The attack by magnesium sulphate is therefore more severe on concrete.

2.5.2.2.3 Effect of water/cement ratio on sulphate attack

W/C ratio has great influence on the permeability of concrete as explained earlier under Section 2.5.2.1 by affecting the ingress of sulphate ions into concrete. Low W/C ratio leads to dense and less porous concrete when sufficiently cured. The resulting more refined pore structure decreases the diffusion of sulphate ions and other deleterious agents into concrete. The cement content affects sulphate resisting properties of concrete mainly through its effect on the W/C ratio, such that increase in cement content reduces W/C ratio and leads to dense less permeable concrete with improved sulphate resisting properties. Figure 2.8 shows the effect of W/C ratio on rate of deterioration of concrete exposed to sulphate–bearing soils.

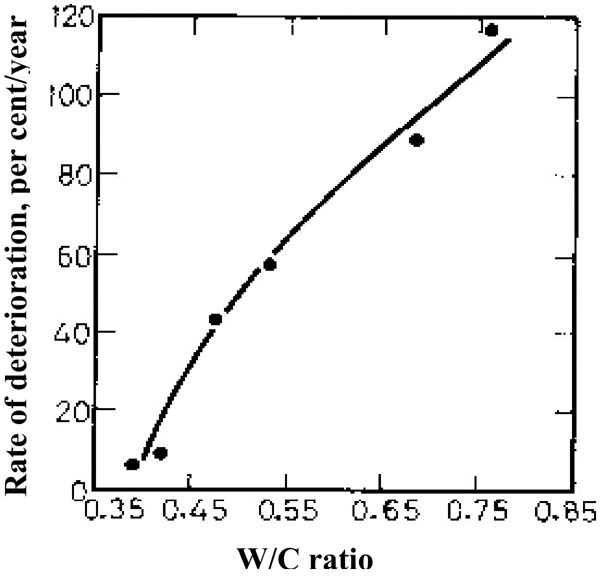

Figure 2.8: The effect of W/C ratio on rate of deterioration of concrete exposed to sulphate–bearing soils. (Soroka, 1979).

2.5.2.2.4 Effect of pozzolans on sulphate attack

Pozzolanic reaction between calcium hydroxide and pozzolans to form secondary calcium-silicate-hydrate (C-S-H) helps in increasing resistance of structure to sulphate attack in the following ways (Omar, 2002; Al-Dulaijan *et al.*, 2003; Sideris *et al.*, 2006):

- Consumption of calcium hydroxide reduces the formation of gypsum
- Reduction in the quantity of cement used by replacing part of it with pozzolan, leads to reduction in C_3A content.

- Formation of secondary C-S-H produces a coating around the reactive phases, thereby hindering formation of secondary ettringite.
- Formation of secondary C-S-H results in a more dense and impermeable concrete, reducing the ingress of sulphate ions.

2.5.2.3 Alkali-aggregate reaction

Expansion and cracking of concrete can also result from chemical reactions involving alkali and hydroxyl ions from the cement paste and certain reactive siliceous minerals that are often present in certain aggregates. The most common form is the alkali-silicate reaction (ASR), by silica-based reactive phases. Other form of alkali-aggregate reaction is alkali-carbonate reaction. The mode of attack in concrete involves the breakdown of the silica structure of the aggregate by hydroxyl ions derived from the alkalis (Na_2O and K_2O) in the cement (Neville, 1981; Kumar *et al.*, 1993) followed by the formation of the alkali-silicate gel and alteration of the borders of the aggregate. Alkali-silicate gel imbibes water, which accounts for its mobility from the interior of the aggregate particles to the micro-cracked part of the aggregate and the concrete, leading to cracking and expansion of the concrete. The typical crack pattern of ASR is irregular, characterized by map cracking.

According to Juengera *et al.* (2004), the alkali-silica reaction involves diffusion of anions and cations into the aggregate. The diffusion process is slow and occurs after much of the available Ca^{2+} ions are already bound into the cement hydration product, therefore, free Na^+ and K^+ ions are more readily available than Ca^{2+} ions to balance out SiO^- groups. The resulting alkali–silica gel is loosely structured and can imbibe water easily, causing expansion. The extent of the expansion depends on the amount, size, and type of the reactive aggregate present and the chemical composition of the alkali-silicate gel formed. The presence of both hydroxyl ions and alkali-metal ions is necessary for the expansive phenomenon.

The effect of cement extenders on alkali-silicate reaction has been reviewed by some researchers (Chen *et al*., 1993; Sibbick, 1995; Quanlin and Naiqian, 2005; *I*lker *et al.*, 2008). Chen *et al.* (1993), in their study show that the effective replacement levels of supplementing cementing materials in reducing expansion due to ASR are 15 %, or possibly greater, for the condensed silica fumes; 20-30 % for the natural pozzolans; 40-50 % for the fly ashes; and 50-65 % for the slags. Quanlin and Naiqian (2005) concluded in their study that modified zeolite derived from immersion of natural zeolite in $2NH_4Cl$ solution, reduces expansion due to alkali-silicate reaction by decreasing the concentration of soluble alkalis in pore solution. Authors (Quanlin and Naiqian, 2005) suggested that alkali ions (Na + K) could be exchanged by NH_4^+ existing in the modified zeolite forming $NH_3.H_2O$ rather than participate in ASR.

According to *I*lker *et al.* (2008), the alkaline content of fly ash is lower than CEM 1, therefore, ASR occurs slowly and expansion can also be prevented by reduction of soluble alkaline concentration and the pH of the pore solution due to pozzolanic reaction between fly ash and $Ca(OH)_2$. They concluded that usage of more than 20 % fly ash is required to improve ASR resistance. The following measures can be taken to control harmful ASR expansion of concrete structures: avoiding reactive aggregate, use of low-alkali cement, use of chemical additive, and partially replacement of high-alkali cement by supplementary cementing material (Chen *et al*., 1993). Factors controlling expansion due to alkali-aggregate reaction are discussed below:

2.5.2.3.1 Alkali content in cement

Cement that contains more than 0.6 % Na_2O_e, when used in combination with an alkali-reactive aggregate, can exhibit significant expansion due to the alkali-aggregate reaction (Kumar, 1993; Addis, 2001). The case will be worse if very high content of cement is used in the concrete mix. It is the alkali content of the cement and the cement content of the concrete that determine the alkalinity of the pore solution and to what extent the reaction with a reactive aggregate will occur. The higher the alkali contents in the cement, the greater the expansion when used with a given reactive aggregate.

2.5.2.3.2 Admixtures

The alkalis present in most slags and natural pozzolans are acid–insoluble and probably are not available for reaction with aggregate (Kumar, 1993). Pozzolans can be added to the concrete mix to reduce the alkali content in cement. The use of pozzolanic admixtures can also result in the formation of less expansive alkali-silicate products with high silica/alkali ratio (Kumar, 1993). However, some certain pozzolans promote ASR. Studies on Ugandan volcanic ash and tuff by Ekolu *et al*. (2006) showed that volcanic ash reduced mortar ASR to 0.02 % when used at 20 % replacement of cement and cured for 14 days. The expansion value was much less than the required expansion of 0.06 % according to ASTM C-618. It was also observed from the same study that Ugandan tuff increased ASR expansion, notwithstanding the proportion of tuff used in the mixtures.

2.5.2.3.3 Aggregate type

Deleterious expansion is aided by dense aggregate with sufficient alkali-reactive constituent. Porous aggregate will have enough void space to accommodate expansive gel that develops (Addis, 1994). The reactivity of aggregates from different geological formations is different; each aggregate source should be ascertained individually before use.

2.5.2.3.4 Exposure of concrete

High temperatures, continual dampness, and exposure of concrete to moisture aids expansive ASR. If leaking joints in concrete structures are left unrepaired, deleterious ASR expansion may be promoted. Any environmental condition that will prevent concrete from drying out and the internal humidity dropping below the critical value will create room for deleterious ASR expansion to take place (Addis, 1994).

2.5.2.4 Carbonation

Carbonation process involves the reaction of dissolved calcium hydroxide ($Ca(OH)_2$) in the concrete pore solution with the atmospheric carbon dioxide (CO_2) to form calcium carbonate ($CaCO_3$) and water as shown in equation (2.9).

$Ca(OH)_2 + CO_2 \longrightarrow CaCO_3 + H_2O$ -- (2.9)

This reaction causes reduction in the pH of concrete pore solution from 12.6 to less than 9 (Lo and Lee, 2002; Sideris *et al*., 2006; Gonen and Yaziioglu, 2007; Ha-Won *et al*., 2007), and leads to corrosion of steel in carbonated concrete by destroying the passivation layer of the steel (Atis, 2003). This happens progressively as the carbonation front moves through the concrete until it reaches steel. Good cover thickness is therefore needed for protection over reinforcing steel. The effect of carbonation on concrete is mainly affected by change in capillary pore structure due to consumed hydrates and $CaCO_3$ formation (Ha-Won and Seung-Jun, 2007).

The carbonation rate depends on the concentration gradient of CO_2 that is being diffused into the concrete pore system, which is affected by the concrete porosity, time of curing, type and amount of cement, type and quantity of pozzolanic additions (Gonen and Yaziioglu, 2007). Carbonation depth also increases with increase in water-cement ratio (Neville, 1981; Lo and Lee, 2002). A series of studies have been carried out on carbonation of ordinary concrete and blended concrete (Ceukelaire and Nieuwenburg, 1993; Balayssac *et al*., 1995; Lo and Lee, 2002; Atis, 2003; Xiong *et al*., 2004; Sideris *et al*., 2006; Kritsada and Lutz, 2007), and some of them are reviewed below:

Investigation done by Ceukelaire and Nieuwenburg (1993) on the accelerated carbonation of blast-furnace cement concrete showed that relative humidity is very important in studying carbonation of concrete. The maximum carbonation rate was observed at relative humidity level of 50 %. The effect of curing on concrete carbonation was investigated by Balayssac *et al.* (1995), using cement with fillers

(CPJ 45), containing 75 % of clinker and 25 % of limestone fillers to produce concrete samples. Water/cement ratios, 0.48, 0.53, 0.61, and 0.65 were used. The concrete samples were water-cured for 1, 3, and 28 days before being exposed to 3 % carbon dioxide for 90, 180, 360, and 540 days. It was observed that the effect of curing on concrete carbonation depends on the water/cement ratio. The lower the water/cement ratio, the shorter may be the curing period for reduced carbonation. Concrete with water/cement ratio, 0.65 showed more significant carbonated depths than others, for 3 and 28 day curing periods. At 18 months, one-day curing period gives carbonated depths of between 10 and 15 mm, relating to cement content. Based on their results, increasing the curing period from 1 day to 3 days was sufficient for concretes with cement content higher than 380 kg/m^3, that is concrete with water/cement ratio below 0.53; for others, curing must be longer.

Also, Lo and Lee (2002) studied the effects of initial curing on the depth of carbonation using concrete of water/cement ratios 0.38, 0.48 and 0.54, water-cured and air-cured for 28 days before being exposed to 2 % concentration of carbon dioxide for 30, 60, and 90 days. In the investigation, water-cured samples were found to exhibit lower carbonation depth than air-cured concrete sample at early ages, but the difference diminishes and became stable after 3 months regardless the water/cement ratio used. They recorded that concrete under low humidity does not react with carbon dioxide because there is no sufficient water for it to dissolve, while penetration of carbon dioxide into saturated concrete under a condition of high humidity is difficult. It was stated that the diffusion of carbon dioxide into concrete depends on the pressure differential when the concentration of carbon dioxide outside the concrete is high. The optimum conditions for the carbonation reaction process are said to be in the humidity range of 50-70 %.

The carbonation property of hardened binder pastes containing super-pulverized blast-furnace slag was also examined by Xiong *et al* (2004). The binder materials used were pulverized blast-furnace slag, original blast-furnace slag, and OPC. Two paste samples were prepared by replacing OPC with 50 % pulverized blast-furnace slag, and original blast-furnace slag respectively. Constant water/cement ratio of 0.4 was used for all samples. The samples were exposed to 20 % carbon dioxide after being water-cured for 27 days and later cured in saturated NaBr solution for another 5 days. The study showed the carbonation-resistance properties of super-pulverized blast–furnace slag binder pastes to be superior to paste made with original blast-furnace slag. The behaviour was attributed to the formation of dense paste structure and production of lower $Ca(OH)_2$, observed with super-pulverized blast–furnace slag binder pastes. Both of these effects reduced the diffusion of CO_2 and extent of its reaction in hardened binder paste containing super-pulverized blast–furnace slag.

A study carried out by Sideris *et al.* (2006) on carbonation of plain and blended cements showed that carbonation depth of all blended cement mixtures was greater than that of the plain cement mixture at all test ages. The pozzolanic materials used are: two Greek natural pozzolans of volcanic origin, Milo's Earth (ME) and Skydras' Earth (SkE), and two lignite fly ashes, Megalopoli fly ash (MFA) and Ptolemaida treated fly ash (PFA). Cements were produced for the study by mixing cement clinker, pozzolanic material and gypsum, except for PFA where gypsum was not added. Proportions of the pozzolanic materials used are 10 %, 20 %, and 30 % of the cement mixture. Different proportions of 30 %, 40 %, 50 % and 60 % were used for PFA. Water/binder ratio used was different in each case so as to keep the mixture's fluidity constant. Mortar samples were cured in a room with relative humidity 95-98 % and temperature 21 ± 2 ^{o}C for 28 days; they were later exposed to CO_2 concentration of 354 ppm in a laboratory environment with relative humidity of 50-60 %, and temperature of 21 ± 2 ^{o}C. Mortar samples were tested for carbonation at 6, 12 and 24 months after exposure to CO_2. The authors (Sideris *et al.,* 2006) reported that the rate of carbonation was greater with the plain concrete mixture and reduced as the pozzolanic content in the mixture increased. It was also stated that among the pozzolanic materials used, PFA had the smallest carbonation depth at all test ages, this was attributed to the internal source of CaO in the material, and the increased fineness of the material. The general behaviour of the pozzolanic materials used was attributed to the consumption of $Ca(OH)_2$ available in the pore solution by the pozzolanic reaction, yielding a smaller pH value and resulted in higher carbonation depth at the early stages of hydration.

The effect of pozzolanic materials on concrete carbonation was also studied by Kritsada and Lutz (2007). The concrete samples used include Portland cement concrete (CEM I 42,5 R), blast-furnace slag concrete (CEM III-B), and fly ash blended concrete. Fly ash was used in proportion of 25 % and 50 % of cement weight. Effective water/binder ratios of 0.42 and 0.6 were used, the hardened concrete samples were water-cured for 3, 7, and 28 days. The samples were later subjected to accelerated carbonation with 3 % carbon dioxide after they had aged 5 months. The authors (Kritsada and Lutz, 2007) observed that carbonation resistance of pozzolanic mixtures in the case of fly ash and slag was lower than pure concrete without pozzolan at early curing age (3 days). However, carbonation depth increased with corresponding increase of fly ash in concrete mixtures. Generally, carbonation resistance can be improved by increasing concrete cover to 25-30 mm from the conventional cover of 20 mm, and also by extending the submerged curing period. They also stated that if the curing period was extended from 3 days to 28 days, the carbonation depth of fly ash blended concrete would be comparable to those of concrete made with CEM 1, cured 3 days in water.

In summary, the rate and depth of carbonation depends on the following factors:

- Concentration of CO_2
- Moisture content of the concrete and relative humidity of the ambient medium
- Porosity of concrete
- Time of curing
- Type and amount of cement
- Type and quantity of pozzolanic addition
- Water/cement ratio

2.6 SOUTH AFRICA'S DURABILITY INDEX APPROACH

Deterioration of concrete structures has been of immense concern to contractors, structures designers, engineers and researchers for years. The cause of most structural deterioration may be linked to non-durable concrete. According to Alexander (2004) durability may be defined as "the ability of a material or structure to withstand the service conditions for which it is designed over a prolonged period without significant deterioration". The most important form of deterioration, within the context of concrete durability is the corrosion of reinforcement in the reinforced concrete structure rather than the deterioration of the concrete fabric itself (Alexander, 2004; Ballim and Alexander, 2005). Protection of steel against aggressive agents such as chloride ions by the concrete cover layer is therefore very important.

Some research (Hall, 1986; Banthia, 1989; Tsivilis *et al*., 2003; Nambair and Ramamurthy, 2007; Schwarz *et al*., 2008) done towards combating durability problems have used different approaches, but most of the methods involved the use of highly sophisticated equipment, and lengthy testing periods. In addition, the information from most of the tests techniques is useful only for research purposes and not for site use. Therefore, in meeting the need for more practical durability tests, the durability index test methods have been formulated in South Africa. The approach has been described in some publications (Alexander *et al*., 2001; Gouws *et al*., 2001) and was developed in response to the need for practical durability tests that could be site-applicable.

2.6.1 Philosophy

The durability indexing technique was based on the fact that, improvement of concrete durability can be achieved if some relevant concrete durability characteristics can be accurately determined (Olorunsogo and Padayachee, 2002). South Africa's durability indexes approach attempts to characterize concrete using quantifiable physical or engineering parameters. The indexes are sensitive to material, processing, and environmental factors such as water/binder ratio, method and duration of curing, and binder type (Alexander *et al.,* 2008). Alexander *et al*. (2001) used the concept of characterizing the quality of concrete cover by parameters related with the transport mechanisms, such as gaseous and ionic diffusion, and water absorption. These parameters quantify the engineering properties of concrete like permeability and water sorptivity. According to Alexander *et al*. (2008), the approach has been advanced to such a level that both rational durability design and performance–based durability specifications are being developed, also being applied to actual construction in some cases.

The philosophy of durability index testing is given below (Alexander, 2004):

- The use of strength parameter is not sufficient in characterizing the durability quality of concrete cover layer because it only measures the response of the material to stress, therefore there is need to characterize the quality of concrete cover layer using parameters that are related to deterioration processes acting on the concrete.
- Concrete surface layer is vulnerable to the effect of curing and transport mechanism (gaseous and ionic diffusion, water absorption and ingress of chemical agents). Thus, there is need for a series of index tests to cover the broad range of durability problems.
- There is need for quantifiable physical or engineering parameters to characterize concrete at early ages in terms of its ability to resist the ingress of aggressive agents, and give reproducible measures of microstructure and durability properties.
- For quality control purposes, the usefulness of index tests should be assessed by reference to the actual durability performance of structures built using the indexes.

2.6.2 Techniques

According to Ballim *et al*. (2004), “Potential durability of concrete is defined as the resistance of the cover concrete to the conduction of chlorides, permeation of oxygen and absorption of water, indexed by specific tests”. The three Index tests that have been developed in South Africa are the oxygen permeability test, the water sorptivity test, and the chloride conductivity test (Ballim, 1991; Streicher and Alexander, 1995; Streicher and Alexander, 1999; Alexander *et al*., 2001). These index tests were developed to aid in the control of concrete quality and prediction of the long-term performance of reinforced concrete subjected to aggressive environments (Stanish *et al*., 2006).

Each test has its significance in measuring parameters related to the transportation mechanisms of oxygen permeability for permeation, water sorptivity for absorption, and chloride conductivity for diffusion. These transportation mechanisms are the main mechanisms leading to concrete deterioration. These index tests have advanced to the level of regular use and the performance of structures built using the index approach are under monitoring to validate the approach and implement improvements (Alexander, 2004).

2.6.3 Durability index test methods

Durability index test methods are sensitive to important material, processing and environmental factors such as cement type, water/binder ratio, method and duration of curing. Specimens are 68 mm diameter, 25 mm thick discs, and core drilled from cover zone of the actual structure (lab or in-situ concrete). The same sample can be used for the oxygen permeability and water sorptivity tests and a separate sample is needed for the chloride conductivity test. The tests can be applied either on lab specimens or on as-built structures to characterize concrete. Brief description of the test methods was done by Ballim and Alexander (2005) as follows:

The water sorptivity test measures the rate of movement of a water front through the concrete under capillary suction. It is particularly sensitive to the micro-structural properties of the near-surface zone of concrete and therefore reflects the nature and effectiveness of curing. The lower the water sorptivity index, the better is the potential durability of the concrete. Sorptivity values vary from approximately 5 mm/√h for well-cured grade 30-50 concretes to 15–20 mm/√h for poorly cured grade 20 concretes. A schematic diagram of the test is shown in Figure 2.9.

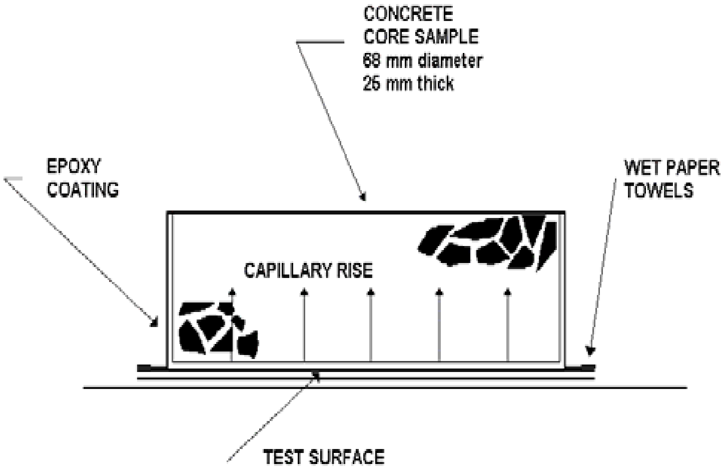

Figure 2.9: Schematic diagram of water sorptivity test (Ballim and Alexander, 2005).

The oxygen permeability index test (OPI) is sensitive to the amount and continuity of larger pores and voids where most of the flow will occur, and which are likely to be caused by poor compaction and bleeding. The OPI is the negative logarithm of the Darcy coefficient of permeability and values generally range from 8 to 11. The higher the permeability index, the less permeable the concrete. An illustration of the test apparatus is shown in Figure 2.10.

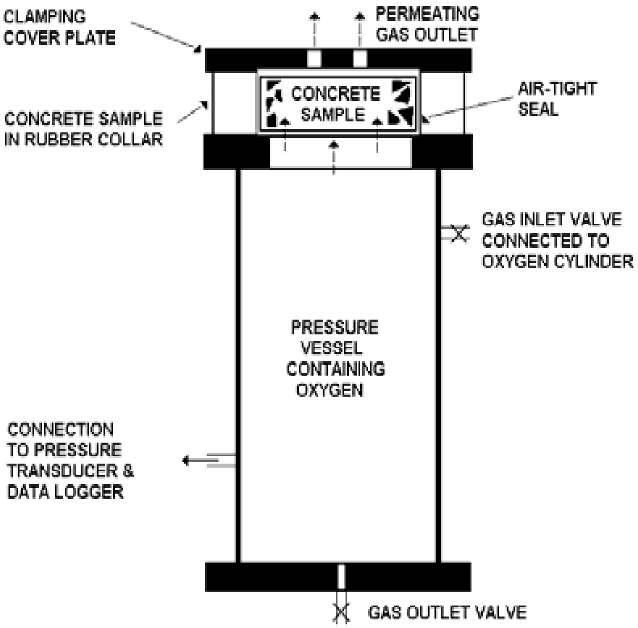

Figure 2.10: Schematic diagram of oxygen permeability apparatus (Ballim and Alexander, 2005).

The chloride conductivity test measures the conductive ionic flux through a concrete disc under a potential difference, and is related to the chloride diffusion properties of the concrete. The apparatus consists of a two-cell conduction rig, each cell containing a 5 M NaCl solution so that there is no concentration gradient across the sample and chloride migration is due to conduction from the applied potential difference as shown in Figure 2.11. The concrete disc is pre-conditioned by vacuum saturation with a 5 M NaCl solution.

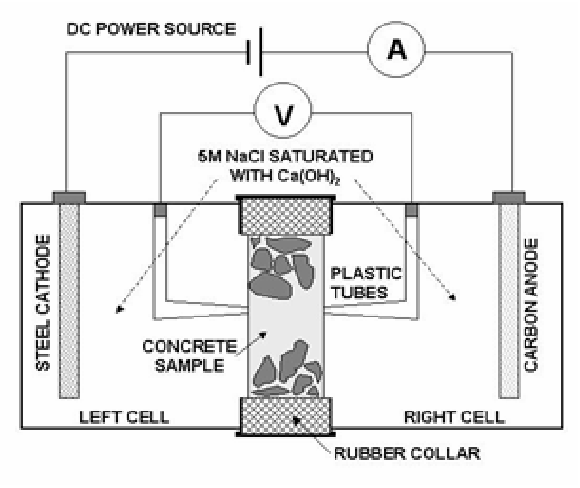

Figure 2.11: Schematic diagram of chloride conductivity apparatus (Ballim and Alexander, 2005).

Detailed test procedures based on the South Africa durability index approach are described in Section 3.3.4 for oxygen permeability and water sorptivity. This approach was used in this study.

2.6.4 Implications

According to Alexander *et al.*, 2001, the suggested ranges of index values for durability classification of concrete are shown in Table 2.5.

Table 2.5: Suggested ranges of index values for concrete durability classification (Alexander *et al.*, 2001)

Durability	OPI (log scale)	Sorptivity	Chloride conductivity
Excellent	> 10.0	< 6.0	< 0.75
Good	9.5–10.0	6.0–10.0	0.75–1.50
Poor	9.0–9.5	10.0–15.0	1.50–2.50
Very poor	< 9.0	>15.0	> 2.50

2.7 SUMMARY AND CONCLUSION

The quality and characteristics of mortar and concrete go a long way in determining the life time of a structure. A lot of research has been conducted to improve the quality of mortar and concrete. Concrete of high quality is needed, if the structure is to be exposed to aggressive environmental conditions. Lots of studies have been done in incorporating extenders into concrete mix. Most extenders improve concrete properties, especially durability. In most cases, early strength is reduced but high replacement contents are used within optimal proportions. In order to improve concrete strength and its durability at the same time, preferably with little content of extender, the use of an artificially modified zeolite admixture (PowerCem) may be investigated. From the literature, it is evident that modified pozzolans may have significant effect on concrete properties, especially concrete strength and durability. However, the literature survey showed that little work has been carried out on the effect of modified pozzolans on mortar and concrete properties. In response to this, the present study investigates the effect of an artificially modified zeolite admixture (PowerCem) on mortar and concrete properties.

CHAPTER THREE

3.0 MATERIALS AND EXPERIMENTAL METHODS

The experimental work was done in two phases. The first phase dealt with studies on mortar properties, which included workability, flexural and compressive strength, oxygen permeability, sorptivity, porosity, sulphate attack resistance, and alkali silica reaction. The second phase dealt with studies on concrete properties, which included workability, split tensile strength, compressive strength, oxygen permeability, sorptivity, porosity, and carbonation. Tests procedures and materials used are therefore described in this chapter.

3.1 MATERIALS

3.1.1 Binders

The binding materials used for this study consisted of modified zeolite, ordinary Portland cement, and fly ash. Modified zeolite additive was obtained from PowerCem Technologies, described as ConcreCem, micronized. The Portland cement used was the CEM 1 42.5N, produced by the Afrisam cement (formerly Holcim), South Africa.

3.1.2 Aggregates

The different aggregates used consisted of coarse aggregate (stone), silica sand, granite crusher sand, and greywacke crusher sand from different sources. Coarse aggregate of size 19 mm were used in concrete mixes. All the coarse aggregate, granite crusher sand, and greywacke crusher sand were obtained from Afrisam, South Africa, while the silica sand produced by Rolfes silica, South Africa was used in mortar mixes.

3.1.3 Reagents

Reagents used throughout the experimental work are: Ordinary portable water, distilled water, water reducing agent admixture, calcium hydroxide ($Ca(OH)_2$), sodium sulphate (Na_2SO_4), ethanol, and phenolphthalein. Others include the gases, oxygen, and carbon dioxide.

3.2 TESTS SCHEDULE

Tables 3.1 and 3.2 are the test schedule tables of phase 1 and 2 respectively, showing the total number of samples prepared for the project, the test methods, and the mould sizes.

Table 3.1: Test schedule of phase 1 (Mortar)

Tests	Sample sizes	Test ages	No of samples	Total	Test methods
Flow	Fresh mortar	After mixing	--	--	ASTM C 1437
Flexural and compressive strength	40x40x160 mm prisms	3, 7, 14, 28, 90, and180 days	16 prisms/mix	96 prisms	SABS EN-196
Accelerated compressive strength	50x50x50 mm cubes	3, 14, 28, and 45 days	8 cubes/mix	56 cubes	Accelerated curing
Oxygen permeability, sorptivity and porosity	100 mm cubes	7, 28, 115, and 180 days	12 cubes/mix	72 cubes	Method described by Alexander *et al* (1999)
Internal sulphate resistance	25x25x280 mm prisms	1, 14, 28, 60, 90, 120, 180, and 295 days	4 prisms/mix	16 prisms	ASTM C 1038
External sulphate resistance	25x25x280 mm prisms, 50mm cubes	1, 7, 14, 28, 60, 90, 120, 180, and 260 days	3 prisms/mix 6 cubes/mix	12 prisms 24 cubes	ASTM C 1012
Alkali silicate reaction	25x25x280 mm prisms	1, 14, 28, 45, 60, and 150 days	3 prisms/mix	24 prisms	ASTM C 227
Thermal analysis	Pulverized paste (passing 90µm sieve)	115 days	--	--	TGA and DTA

Total Samples: 96 (40x40x160mm prisms), 52 (25x25x280mm prisms),

80 (50mm cubes), and 72 (100mm cubes)
-- (not required)

Table 3.2: Test schedule of phase 2 (Concrete)

Tests	Sample sizes	Test ages	No of samples	Total	Test methods
Workability	Fresh concrete	After mixing	---	---	ASTM C 143
Split tensile strength	100 mm cubes	28 and 180 days	4 cubes/mix	28 cubes	ASTM C 496
Compressive strength	100 mm cubes	7,28, 90, and 180 days	11 cubes/mix	77 cubes	SABS 863
Oxygen permeability, sorptivity and porosity	100 mm cubes	28 and 180 days	3 cubes/mix	21 cubes	Method described by Alexander et al (1999)
Carbonation	100 mm cubes	28 days	4 cubes/mix	28 cubes	Accelerated carbonation

Total Samples: 154 (100mm cubes)

3.3 MORTAR PROPERTIES STUDY

Studies on the effects of PWC on mortar properties were carried out using flow test, flexural strength test, compressive strength test, oxygen permeability test, sorptivity test, sulphate attack tests, and alkali silica reaction test.

3.3.1 Standard silica sand preparation

Standard silica sand locally prepared in accordance with the SABS EN 196-1 was used for mortar production, using the available sand sizes ranges of 0.8-1.8 mm (coarse), 0.4–0.85 mm (medium) and 600 µm (fine). Sieve analysis was performed on different proportions of available sand sizes so as to meet standard sand specification.

Graphs were plotted to asses which of the proportions will fit within the lower and upper limit of the specified grading for standard sand. Proportion ratio 14:15:8 (coarse:medium:fine) was adopted and used to prepare standard silica sand. The prepared standard sand was used to prepare mortars for flexural and compressive strength tests as well as oxygen permeability and sorptivity tests. Silica sand of size 0.4-0.85 mm was used for sulphate resistance tests, while greywacke aggregate crushed and specially graded to ASTM C 227 was used for alkali silicate reaction test.

3.3.2 Flexural and compressive strength tests

Flexural and compressive strength tests were performed on mortar samples according to SABS EN 196-1. The detailed mix proportions used for the mortar production are as shown in Table 3.3. Constant water/binder (w/b) ratio of 0.5 was used.

3.3.2.1 Moulds preparation

40 x 40 x 160 mm prism moulds were cleaned and sparingly covered with a lubricant, before mortar mixing operation. The lubricant was used as a releasing agent, so as to allow easy removal of hardened samples.

Table 3.3: Mixture proportions for 1m^3 of mortar for flexural and compressive strength tests

Samples	Cement (Kg)	Silica sand (Kg)	PowerCem (Kg)	Water (Kg)	w/b	Flow (mm)
Control	586.00	1758.00	0.00	293.00	0.5	112.97
0.4 % PWC + Cement	586.00	1758.00	2.34	294.17	0.5	112.46
0.6 % PWC + Cement	586.00	1758.00	3.52	294.76	0.5	112.55
0.8 % PWC + Cement	586.00	1758.00	4.69	295.35	0.5	113.48
1.0 % PWC + Cement	586.00	1758.00	5.86	295.93	0.5	119.06
2.5 % PWC + Cement	586.00	1758.00	14.65	300.33	0.5	135.03

3.3.2.2 Mixing Procedure

OPC, PWC, and prepared standard silica sand were weigh batched and mixed according to SABS EN 196-1 using HOBART mortar mixer for 3 minutes. Water and binder were mixed for 30 seconds at low speed, after which standard silica sand was then added over another 30 seconds. The mix was then allowed to stand for another one minute, while rubber scraper was used to remove the mortar adhering to the wall of the mixing bowl into the main mortar at the middle of the mixing bowl. The mixer was then adjusted to a medium speed and mixing run for another 1 minute. A flow test was then conducted according to ASTM C 1437.

3.3.2.3 Casting and compaction

Casting of mortar samples was done using 40 x 40 x 160 mm prism moulds. The prisms were loosely filled with mortar and hand-pressed on a mechanical vibrating table for 10 seconds. Sufficient mortar was added to fill the mould, and then held on the vibrating table for further period of 10 seconds.

3.3.2.4 Curing

After compacting, the moulds were covered with moist cloth for 24 hours to preserve the initial moisture condition of the sample, after which the hardened prisms were removed from their moulds and placed in a water curing tank. The temperature of curing water was maintained at $23 \pm 2\ ^{o}C$ with a built in thermostat and a small circulation pump. All the samples were stored in the curing tank until testing period. The tank was periodically filled with water to cater for the loss of water which occurred as a result of evaporation and removal of samples.

3.3.2.5 Testing

3.3.2.5.1 Flow test of mortar

The flow test was conducted on mortars according to ASTM C 1437 immediately after mixing. The flow table top was carefully wiped clean and dry. The flow mould was placed at the center. A layer of mortar about 25 mm thickness was placed in the mould and tamped 20 times with the tamper. The second layer of mortar was added and tamped as specified for the first layer. The mortar was cut off to a plane surface, and leveled with the edge of the trowel. The mould was lifted away from the mortar one minute after completion of the filling operation. Immediately the table was dropped 25 times in 15 seconds. The diameters of the mortar were measured along the flow lines scribed at the table top using vernier calipers. The average of the 4 readings was taken. Two runs of flow test were conducted for each mix and the average result was recorded. Figure 3.1 shows the flow table with a sample during testing.

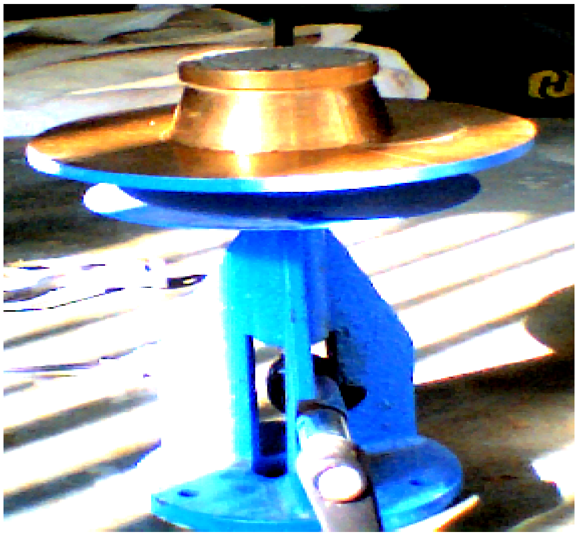

Figure 3.1: Flow table and sample during testing.

3.3.2.5.2 Flexural strength test of mortar

The flexural strength test of mortar was carried out according to SABS EN 196 -1. A center-point loading method was used as described in the standard. During testing, a 40 x 40 x 160 mm mortar prism sample was placed in the testing machine with one side face on the supporting roller and its longitudinal axis normal to the supports as shown in Figure 3.2. Load was applied vertically by means of the loading roller to the opposite side face of the prism and it was increased smoothly at the rate of 50 ±

10 N/s until failure. The flexural strengths were determined at curing ages of 7, 28, 90, 120 and 180 days. The flexural strength (R_f) was calculated from:

$$R_f = \frac{1.5F.L}{b^3} \text{ -- } (3.1)$$

where:

R_f is the flexural strength, in Newtons per square millimeter (N/mm^2)

b is the side of the square section of the prism, in millimeters (mm)

F is the ultimate load applied to the middle of the prism at fracture, in Newton (N)

L is the distance between the supports, in millimeters (mm)

Results recorded are average of two samples.

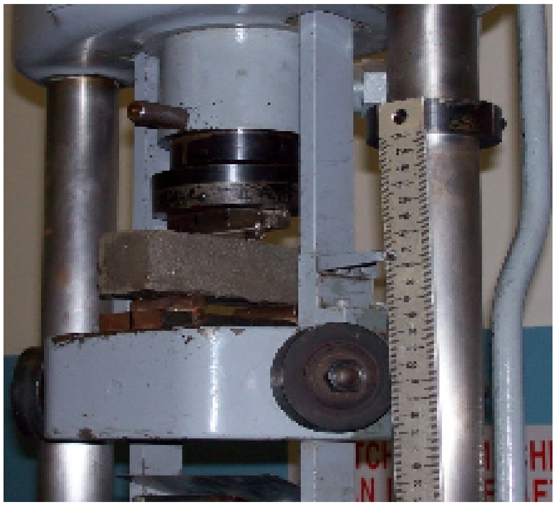

Figure 3.2: Placement of sample in flexural testing machine

3.3.2.5.3 Compressive strength test of mortar

The prism halves obtained from 40 x 40 x 160 mm mortar prisms after flexural test were used for compressive strength test of mortar according to SABS EN 196 -1. The prism halves were kept damp after flexural test until tested in compression. The test was done on the side faces of the prism halves in a Tinus Olsen compression testing machine, which has a load capacity of 600 kN. The prism halves were centre placed, laterally to the auxiliary plate of the machine within ± 0.5 mm as shown in Figure 3.3 and longitudinally such that the end face of the prism overhangs the auxiliary plates by 10 mm. The load was smoothly increased at the rate of 2400 ± 200 N/s over the entire load application until failure. The compressive strengths were determined at curing ages of 7, 28, 90, 120 and 180 days. Compressive strength (R_c) measured was calculated in N/mm^2 from:

$$R_c = \frac{F_c}{A} \quad \text{---} \quad (3.2)$$

where:

R_c is the compressive strength in N/mm^2

F_c is the maximum load at fracture, in N

A is the area of the load bearing plates, in mm^2

Results recorded are average of four samples.

Figure 3.3: Placement of sample in compression testing machine

3.3.3 Accelerated compressive strength test

Accelerated compressive strength test was carried out on mortar samples as a confirmatory test, using 50 mm cube moulds. Mortar samples were prepared based on the detailed mix proportions showed in Table 3.4. Constant water/binder (w/b) ratio of 0.5 was used.

Table 3.4: Mixture proportions for 1m^3 of mortar for accelerated compressive strength test

Samples	Cement (Kg)	Silica sand (Kg)	PowerCem (Kg)	Fly ash (Kg)	Water (Kg)	w/b
Control	586.00	1758.00	0.00	-	293.00	0.5
0.6% PWC + Cement	586.00	1758.00	3.52	-	294.76	0.5
1.0% PWC + Cement	586.00	1758.00	5.86	-	295.93	0.5
2.5% PWC + Cement	586.00	1758.00	14.65		300.33	0.5
0.6% PWC + 30 % FA + Cement	410.20	1758.00	3.52	175.80	294.76	0.5
1.0% PWC+ 30 % FA + Cement	410.20	1758.00	5.86	175.80	295.93	0.5
2.5% PWC + 30 % FA + Cement	410.20	1758.00	14.65	175.80	300.33	0.5

3.3.3.1 Mould preparation, mixing, casting, and compaction

These operations were performed as explained in Sections 3.3.2.1, 3.3.2.2, and 3.3.2.3. The mould type used was 50 mm cube moulds instead of 40 x 40 x 160 mm prism moulds.

3.3.3.2 Curing

The moulds were placed in the oven at 50 ^{o}C immediately after casting for 8 hours, after which the hardened cubes were removed from their moulds and placed in an accelerated water curing tank. The temperature of curing water was maintained at 50 ± 2 ^{o}C with a built in thermostat and a small circulation pump. Samples were stored in the curing tank until testing period.

3.3.3.3 Testing

At testing age, the samples were removed from the curing tank and left for two hours to cool down, after which they were centrally placed in a Tinus Olsen compression testing machine , which has a load capacity of 600 KN. The uniaxial load was applied perpendicular to the direction of casting at the rate of 2400 ± 200 N/s until failure. The compressive strengths were determined at curing ages of 3, 14, 28, and 45 days. Compressive strength (R_c) measured was calculated in N/mm^2 as shown in equation 3.2. Results recorded are average of two samples.

3.3.4 Oxygen permeability, sorptivity, and porosity tests

3.3.4.1 Samples preparation

Mortars were prepared for oxygen permeability and sorptivity tests following the procedure explained in Section 3.3.2.2 in a 50 L pan mixer. The same mix proportions (Table 3.3) used for flexural and compressive strength tests were also used in preparing 100 mm cubes mortar samples. The samples were water-cured for 7, 28, 115, and 180 days. The temperature of curing water was maintained at 23 ± 2 ^{o}C with a built in thermostat and a small circulation pump.

3.3.4.2 Testing for oxygen permeability

Permeability of mortars was measured using a falling head gas permeameter (Ballim, 1991). The method is based on Darcy coefficient of permeability determined by monitoring a falling pressure head. The samples consisted of discs of diameter 68 ± 2 mm and thickness 25 ± 2 mm. At testing age, these were core drilled from 100 mm cubes (parallel to the casting direction) after being water-cured for required testing days. Discs samples cored from the cubes were then oven dried at 50 ^{o}C for 7 days prior to testing.

The samples were then removed from the oven and allowed to cool for 2 hours in a room maintained at 23 ^{o}C. The thickness of each sample was measured with vernier caliper at 4 points equally spaced around the perimeter of the specimen, while the diameter was measured at 2 points. After the thickness and diameter of samples had been recorded, the samples were placed in a compressible collar with the test face (outer face) facing the bottom. The collar was placed in a PVC sheath to form a unit as shown in Figure 3.4 (a). This unit was placed in the permeameter chamber, covered with a wooden ring and tightened. The complete experimental set up is shown in Figure 3.4 (b).

The oxygen pressure in the permeameter chamber was increased to 100 kPa and then the inlet valve was closed. Time and pressure were then recorded. Pressure decay was recorded at intervals of approximately 5 kPa and test stopped when pressure reaches approximately 60 kPa or 6 hours from start of test. After the permeability test, the disc samples were removed from the collar and later used for sorptivity test.

The coefficient of permeability (m/s) is calculated using the equation:

$$K = \frac{WVg}{RA}\left(\frac{d}{\theta . t}\right)\ln\left(\frac{P_o}{P}\right) \text{ -- } (3.3)$$

where:

K = coefficient of permeability in m/s

W = molecular mass of oxygen, 32 g/mol

V = volume of oxygen under pressure in permeameter (m^3)

g = acceleration due to gravity, 9.81 m/s^2

R = universal gas constant, 8.313 Nm/Kmol

A = superficial cross- sectional area of sample (m^3)

d = average sample thickness (m)

θ = absolute temperature (K)
t = time (s) for pressure to decrease from P_o to P
P_o = pressure at the beginning of test (KPa)
P = pressure at the end of test

Results recorded are average of three samples

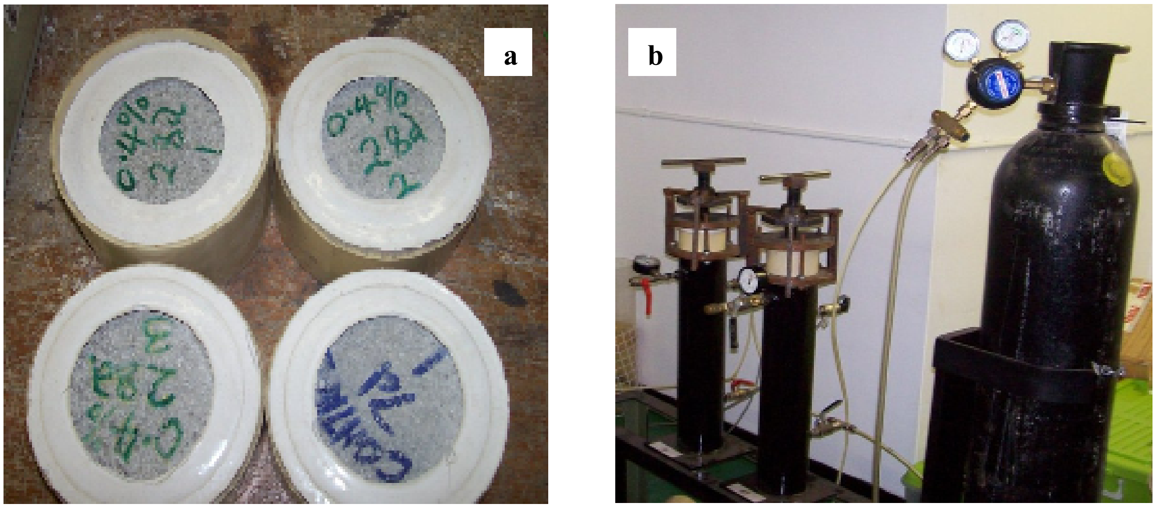

Figure 3.4: (a) Oxygen permeability sample unit. (b) Oxygen permeability experimental set up.

3.3.4.3 Testing for Sorptivity and Porosity

The same disc samples used for permeability test were then used for the water sorptivity test. In this test, the curved surface of the disc samples was sealed with tape up to 5 mm above test face. This was to allow only one directional capillary flow of water to occur. The test face of disc samples was placed in lime-saturated solution contained in a tray such that the final level of solution was slightly above the edge of sample. These samples were weighed at regular intervals of 3, 5, 7, 9, 12 for a period of up to 25 mins. This was followed by vacuum saturation of samples done by applying -75 KPa suction. Vacuum was applied for 3 hours to samples placed in an empty dessicator followed by five hours of vacuum suction while samples are submerged in $Ca(OH)_2$ saturated water. After a further 18 hours of soaking, the samples were weighed. Porosity was calculated using equation 3.4.

$$n = \frac{M_{sv} - M_{so}}{A.d.\rho_w} \text{ -- } (3.4)$$

where:

M_{sv} = vacuum saturated mass of the samples to the nearest 0.01 g
M_{so} = initial mass of the specimen to the nearest 0.01 g
A = cross- sectional area of the samples to the nearest 0.02 m^2
d = average samples thickness to the nearest 0.02 mm
P_w = density of water

Then the mass of the water absorbed at each weighing period was calculated using:

$$M_{wt} = M_{st} - M_{so} \text{ --- } (3.5)$$

where:

M_{st} = mass to the nearest 0.01 g of the sample at time t

Sorptivity was calculated from the slope of graph of water absorbed (M_{wt}) versus the square root of time (in hr).

$$S = \frac{F.d}{M_{sv} - M_{so}} \text{ -- } (3.6)$$

where:

F = the slope of the best fit line obtained by plotting M_{wt} against $t^{½}$
S = sorptivity

Results recorded are average of three samples.

3.3.5 Sulphate resistance tests

3.3.5.1 Sulphate resistance according to ASTM C 1038

Expansion of samples due to their internal sulphate content was examined based on ASTM C 1038. The purpose of the test is to determine the amount of expansion of mortar bar samples when stored in water. PowerCem was used as additive to cement in the following proportions 0 %, 0.4 %, 0.6 % and 2.5 % by weight of cement. Details of all the mixes are shown in Table 3.5.

Table 3.5: Mixture proportions for 1m^3 of mortar for sulphates resistance test to C 1038

Samples	Cement (Kg)	Silica sand (Kg)	PowerCem (Kg)	Water (Kg)	w/b	Flow (mm)
Control	714.00	1964.00	0.00	350.00	0.49	110.02
0.4% PWC + Cement	714.00	1964.00	2.86	351.00	0.49	110.04
0.6% PWC + Cement	714.00	1964.00	4.28	352.00	0.49	111.24
2.5% PWC + Cement	714.00	1964.00	17.85	358.00	0.49	115.90

3.3.5.1.1 Moulds preparation

25 x 25 x 280 mm prism moulds were cleaned and sparingly covered with a lubricant, before mortar mixing operation. The lubricant was used as a releasing agent, so as to allow easy removal of hardened samples. The studs were attached at ends of 25 x 25 x 280 mm prisms moulds as shown in Figure 3.5.

Figure 3.5: 25 x 25 x 280 mm prism mould with attached studs.

3.3.5.1.2 Mixing Procedure

OPC, PWC and silica sand of size 0.4 – 0.85 mm (medium), were weigh batched and mixed in a HOBART mortar mixer for 3 minutes according to SABS EN 196-1. The mixing procedure used was the same as described for flexural and compressive strength test in Section 3.3.2.2. The water content of the mixtures was adjusted to maintain a flow of 110 ± 5 mm according to ASTM C 1038. A flow test was conducted according to ASTM C 1437; the detailed procedure has been described in Section 3.3.2.5.1.

3.3.5.1.3 Casting and compaction

Mortar was cast by filling the already prepared 25 x 25 x 280 mm prism moulds in two layers and hand-compacted with tamping wooden plate of size 10 x 25 x 150 mm.

3.3.5.1.4 Curing

After casting, the moulds were covered with moist cloth for 24 hours to preserve the initial moisture condition of the sample, after which the hardened prisms were removed from their moulds and properly labeled. The samples were then placed in saturated lime solution for 30 minutes prior to making the initial measurement. After the initial measurement, the samples were immersed in a saturated lime solution placed in a storage container. Bottom of the container was lined with plastic mesh to allow for easy expansion measurement. The container was covered tightly with a lid during sample storage. Periodically, the calcium hydroxide solution was re-filled to cater for the loss of solution which occurred as a result of evaporation or during removal of samples.

3.3.5.1.5 Testing

Expansion was measured at different curing ages using length comparator as shown in Figure 3.6. The initial measurement was recorded after one day of casting, while other expansions were measured at 14, 28, 60, 90, 120, 180, and 295 days curing period.

3.3.5.1.6 Expansion calculation

The change in length of the samples at any age was calculated as follows:

$$\Delta L = \frac{L_x - L_i}{L_g} .100 \quad \text{---} \quad (3.7)$$

where:

ΔL = change in length at any age, %

L_x = comparator reading of samples at any age

L_i = initial comparator reading of samples (reading at day 1)

L_g = nominal gage length, 250 mm

The change in length at any age was recorded as the expansion of the samples at that age. Results recorded are average of four samples.

Figure 3.6: Length comparator

3.3.5.2 Sulphate resistance according to C 1012

Expansion of samples when exposed to sulphate environment was examined based on ASTM C 1012. This test method provides a means of assessing the external sulphate resistance of mortars made using Portland cement, blends of Portland cement with pozzolans, and blended hydraulic cement. PowerCem was used as additive to OPC in the proportions of 0 %, 0.4 %, 0.6 % and 2.5 % by weight of cement. Details of all the mixes are shown in Table 3.6.

3.3.5.2.1 Moulds preparation

25 x 25 x 280 mm prism moulds and 50 mm cubes moulds were cleaned and sparingly covered with a lubricant, before mortar mixing operation. The lubricant was used as a releasing agent, so as to allow easy removal of hardened samples. The studs were attached to 25 x 25 x 280 mm prisms moulds as shown in Figure 3.5.

Table 3.6: Mixture proportions for 1m^3 of mortar for sulphates resistance test to C 1012

Samples	Cement (Kg)	Silica sand (Kg)	PowerCem (Kg)	Water (Kg)	w/b	Compressive Strength (N/mm^2) At day 1
Control	714.000	1964.000	0.000	346.300	0.485	24.200
0.4 % PWC + Cement	714.000	1964.000	2.860	347.700	0.485	23.040
0.6 % PWC + Cement	714.000	1964.000	4.280	348.400	0.485	22.800
2.5 % PWC + Cement	714.000	1964.000	17.840	354.900	0.485	20.160

3.3.5.2.2 Mixing Procedure

OPC, PWC, and silica sand of size 0.4 – 0.85 mm (medium) were weigh batched, and mixed in HOBART mortar mixer for 3 minutes according to SABS EN 196-1. The mixing procedure was the same as described for flexural and compressive strength test in Section 3.3.2.2. Constant water/binder (w/b) ratio of 0.485 was used as stipulated in ASTM C 1012.

3.3.5.2.3 Casting and compaction

Mortar was cast by filling the already prepared 25 x 25 x 280 mm prisms moulds in two layers and compacting with tamping wooden plate of size 10 x 25 x 150 mm. 50 mm cube moulds were also filled and hand-held on a mechanical vibrating table for 10 seconds. Sufficient mortar was added to fill the 50 mm cubes mould, held on the vibrating table for further period of 10 seconds.

3.3.5.2.4 Curing

Immediately after molding, the filled mortar moulds were covered with a rigid plastic plate, and placed in a water curing tank. The temperature of curing water was maintained at 38 ± 2 ^{o}C with a built in thermostat and a small circulation pump, until the mortar cube strength reached a value of 20 MPa. This strength value was reached after one day of curing for all cube samples tested. Initial measurement was then recorded, after which the bar samples were immersed in 5 % Na_2SO_4 solution in a storage plastic container. The samples rested on plastic mesh placed at the bottom of container to allow for free expansion movement. The container was covered tightly with a lid during samples storage period. The storage container was periodically re-filled with 5 % Na_2SO_4 solution to maintain constant volume of solution.

3.3.5.2.5 Testing

Expansion was measured at different curing ages using length comparator as shown in Figure 3.6. The initial measurement was recorded after compressive strength value of 20 MPa has been confirmed. Other expansions were measured after 7, 14, 28, 60, 90, 120, and 180 days curing period.

3.3.5.2.6 Expansion calculation

Expansion was calculated using equation (3.7), explained in Section 3.3.5.1.6. Results recorded are average of three samples.

3.3.6 Alkali-silica reaction test

Resistance of samples to alkali-silica reaction was tested based on ASTM C 227. PowerCem was used as additive to Cement in the proportions of 0 %, 0.4 %, 0.6 %, 1.0 %, and 2.5 % by weight of cement. A highly reactive aggregate, greywacke, supplied by Afrisam, South Africa was used for the test. Greywacke aggregate was crushed in a laboratory crusher to the desired sizes. The crushed greywacke aggregate was graded as specified in ASTM C 227. The grading requirement is shown in Table 3.7. Details of all the mixes are shown in Table 3.8.

Table 3.7: Grading requirements (ASTM C 227)

Sieve Size		
Passing	**Retained on**	**Mass %**
4.75 mm	2.36 mm	10
2.36 mm	1.18 mm	25
1.18 mm	600 µm	25
600 µm	300 µm	25
300 µm	150 µm	15

Table 3.8: Mixture proportions for 1m^3 of mortar for alkali silica reaction

Samples	Cement (Kg)	Fly ash (Kg)	Graded sand (Kg)	PowerCem (Kg)	Water (Kg)	w/b	Flow (mm)
Control	857.00	-	1928.25	0.00	342.80	0.40	105.88
0.4 % PWC + Cement	857.00	-	1928.25	3.43	344.17	0.40	106.12
0.6 % PWC + Cement	857.00	-	1928.25	5.14	344.86	0.40	109.75
1.0 % PWC + Cement	857.00	-	1928.25	8.57	346.23	0.40	112.51
2.5 % PWC + Cement	857.00	-	1928.25	21.43	351.37	0.40	120.22
0.6 % PWC + 30 % FA + Cement	599.90	257.10	1928.25	5.14	344.86	0.40	110.60
1.0 % PWC + 30 % FA + Cement	599.90	257.10	1928.25	8.57	346.23	0.40	115.24
2.5 % PWC+ 30 % FA + Cement	599.90	257.10	1928.25	21.43	351.37	0.40	120.12

3.3.6.1 Moulds preparation, Casting, Compaction and Expansion calculation

Moulds (25 x 25x 280 mm prism) preparation, casting, and compaction were done as explained in Sections 3.3.5.2.1 and 3.3.5.2.3. Expansion was calculated using equation (3.7), explained in Section 3.3.5.1.6.

3.3.6.2 Mixing Procedure

OPC, PWC and graded crushed greywacke aggregates were weigh batched and mixed in a HOBART mortar mixer for 3 minutes according to SABS EN 196-1. The mixing procedure used was the same as described in Section 3.3.2.2 for flexural and compressive strength test. The water content of the mixtures was adjusted to maintain a flow of 105 to 120 according to ASTM C 227 requirement. A flow test was conducted according to procedure specified in ASTM C 1437 and also described in Section 3.3.2.5.1.

3.3.6.3 Curing

After casting, the moulds were covered with moist cloth for 24 hours, to preserve the initial moisture condition of the sample, after which the hardened prisms were removed from their moulds and properly labeled. The initial length measurement was then taken. Thereafter, samples were placed on plastic mesh in the storage container such that they were not in contact with the storage container. This was achieved by raising the plastic mesh to two-third of the storage container by means of four 50 mm concrete cubes. The storage container was sealed and placed in a water bath maintained at 38 ± 2 ^{o}C.

3.3.6.4 Testing

Expansion was measured at different curing ages using length comparator as shown in Figure 3.6. The initial measurement was recorded after one day of casting, while other expansions were measured at 14, 28, 45, 60, and 150 days curing period. Results recorded are average of three samples.

3.3.7 Hydration study

Hydration study was done on pulverized hydrated mortar samples. These samples were cured for 115 days and then kept in the oven maintained at 50 ^{o}C for 24 hours. The samples were pulverized after being removed from oven and sieved through 90 μm sieve to obtain only pastes powder for use in thermal studies. The thermal decomposition behaviour of powder samples was studied by tracing mass and heat changes using a Setaram TG92 thermogravimetric analyzer coupled to a Setaram differential analyzer. The analysis was carried out at the School of Chemical and Metallurgical Engineering, University of the Witwatersrand.

Specimen weighing 20 to 40 mg were loaded into a 4 mm internal diameter and 8 mm height, alumina crucible and heated from ambient temperature to 1000 ^{o}C at a scanning rate of 10 ^{o}C/minute in an inert atmosphere. Argon was used as the furnace gas to provide an inert atmosphere. This is to ensure that all the changes observed are strictly due to pyrolysis with no interferences from atmosphere. The various temperatures at which various reactions of the hydrated samples occurred were determined by this technique. Mass losses and peaks on the heat flow curve were used to mark these temperatures. Peak areas of DTA endothermic peak were calculated using Microsoft Excel software.

3.4 CONCRETE PROPERTIES STUDY

The tests performed to study the behaviour of concrete properties with or without PWC additive were: slump test, split tensile strength test, compressive strength test, oxygen permeability test, sorptivity test, and carbonation test. Table 3.9 shows detailed mix proportions used for concrete production. A constant water/binder ratio of 0.5 was used for all the mixtures.

3.4.1 Moulds preparation

100 mm cube moulds were cleaned and sparingly covered with a lubricant, before concrete mixing operation. The lubricant was used as a releasing agent, so as to allow easy removal of hardened samples.

Table 3.9: Mixture proportions for $1m^3$ of concrete samples

Samples	Cement	FA (Kg)	Premix (Kg)	Crusher sand (Kg)	PWC (Kg)	Coarse aggregate (Kg)	WRA (L)	Water (Kg)	w/ b	Slump (mm)
Control	410	0	0	788	0.00	980	1.25	205	0.5	105
0.6 % PWC + cement	410	0	0	788	2.46	980	1.25	205	0.5	90
1.0 % PWC + cement	410	0	0	788	4.10	980	1.25	205	0.5	80
30 % FA + cement	287	123	0	788	0.00	980	0.75	205	0.5	105
0.6% PWC + 30 % FA + cement	287	123	0	788	2.46	980	0.75	205	0.5	102
1.0% PWC + 30 % FA + cement	287	123	0	788	4.10	980	0.75	205	0.5	98
Premix	0	0	410	788	0.00	980	0.75	205	0.5	120

*Premix --- 1.0 % PWC + 59 % FA + 40 % OPC

3.4.2 Mixing Procedure

Cementitious materials, coarse aggregate, granite crusher sand, and water were weigh batched on a laboratory balance to an accuracy of 100 g. The water reducing agent was volume batched using a measuring cylinder graduated in 20 ml intervals. PWC and water reducing agent were mixed into the weighed water using it as a medium to effectively disperse the materials during concrete mixing. The materials were added into 50 L pan mixer in the order of crusher sand, OPC with or without fly ash, and coarse aggregate. These materials were then mixed in their dry state for 1 minute. Water with added PWC and water reducing agent, were then introduced into the mix over a period of 1 minute. Mixing was then continued for another 1 minute. A slump test was performed to ensure that the mix fell within the desired slump range.

3.4.3 Casting and compaction

Casting of concrete samples was done by using 100 mm cube moulds. The cube moulds were loosely filled with concrete and hand-pressed on a mechanical vibrating table for 10 seconds. Sufficient concrete was added to fill the mould, and then held on the vibrating table for further period of 10 seconds.

3.4.4 Curing

Concrete samples were cured as described in Section 3.3.2.4 for mortars.

3.4.5 Testing

3.4.5.1 Workability

Workability was measured by slump test according to ASTM C 143. The slump mould is a cone, which is 300 mm high with open base of 203 mm diameter and a smaller opening of 102 mm diameter at the top. The tools used consisting of slump mould, steel tamping rod, and flat steel plate, were wiped with a damp cloth. A steel base plate was placed on a level surface. The slump mould was placed on the steel plate and held firmly, by standing on its footpieces. The slump mould was then filled with concrete in three layers of about equal depth. Each layer was tamped 25 times with the rounded end of the tamping rod. After tamping the final layer, excess concrete was struck off by means of a trowel and by rolling motion of the tamping rod, such that the mould is completely filled and leveled.

The mould was firmly held down by its handles, keeping it steady while stepping off the footpieces. The mould was then lifted carefully away from the concrete. Cone mould was inverted near slumped concrete. The slump was measured by determining the vertical difference between the top rim of the mould and the average highest point of the surface of slumped concrete as shown in Figure 3.7.

Figure 3.7: Slump measurement.

3.4.5.2 Split tensile strength test

Split tensile test was carried out on concretes based on ASTM C 496 using 100 mm cubes. A center line was drawn on the opposite sides of the cube samples. During testing, the cube sample was placed in position in the Tinus Olsen testing machine, which has a loading capacity of 600 kN. Steel bars of 16 mm diameter, sealed on steel plates were placed on the center line drawn on the opposite sides of the cube samples. Compressive forces were applied along the two opposite center line, such that the splitting along these lines was caused by the principal tensile stress in the plane joining the loaded lines as shown in Figure 3.8 (a and b). Loading was applied continuously at the rate of 150 KN/minute over the entire load application until fracture. The split tensile strengths were determined at curing ages of 28 and 180 days, and were calculated from:

$$F = \frac{2P}{\pi . a^2} \text{ -- } (3.8)$$

where:

$F =$ tensile strength (N/mm^2)

$P =$ compressive load at fracture (N)

$a =$ size of cube (mm)

Results recorded are average of two samples.

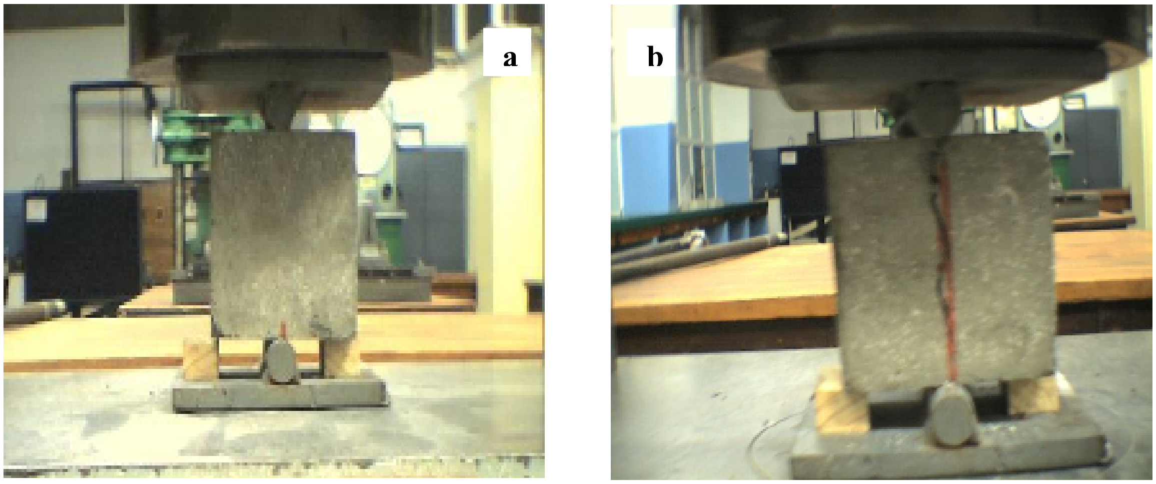

Figure 3.8: (a) Loaded split tensile strength sample. (b) Failed split tensile strength sample.

3.4.5.3 Compressive strength test

The compressive strength test was carried out on concrete samples based on SABS Method 863. At testing age, samples were removed from the curing tank and weighed after excess water had been wiped off the surface. The mass of sample was recorded to the nearest gram. During testing, the samples were then put in a bowl of water, to keep them wet for testing. The samples were centrally placed in a compression testing machine and load was applied at a rate of 150 kN/minute. The uniaxial load was applied perpendicular to the direction of casting. Failure load was recorded to the nearest one kN. Cubes were tested using Amsler type 103 compression testing machine, which has a load capacity of 2000 kN. Figure 3.9 (a and b) show the loading to failure of samples during testing.

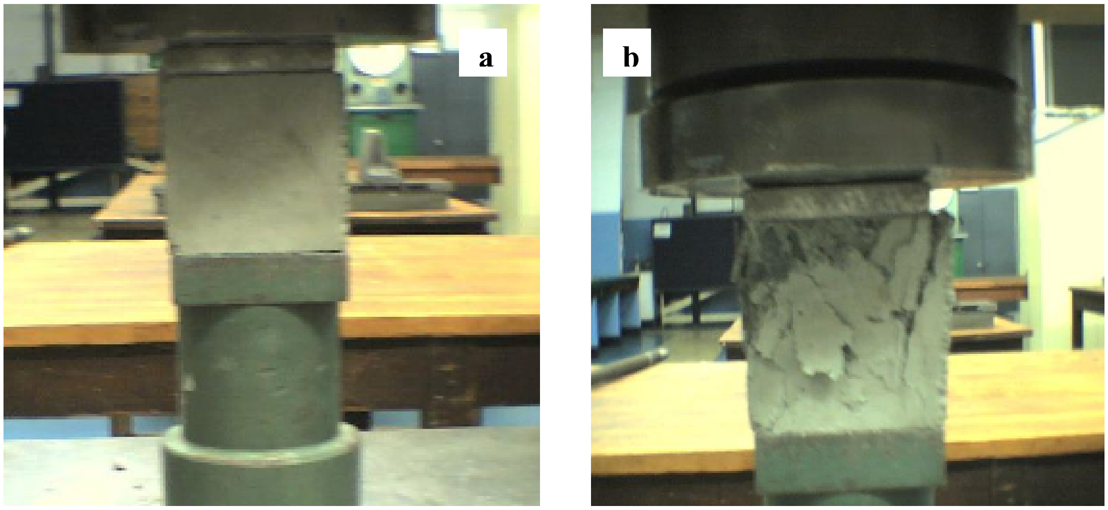

Figure 3.9: (a) Loaded compressive strength sample. (b) Failed compressive strength sample.

Compressive strengths were determined at curing ages of 3, 28, 90 and 180 days, and were calculated in N/mm^2 from:

$$R_c = \frac{F_c}{A} \quad \text{--} \quad (3.9)$$

where:

R_c is the compressive strength in Newtons per square millimeter (N/mm^2);

F_c is the maximum load at fracture, in Newtons (N);

A is the area of the load bearing plates, in square millimeter (mm^2).

Results recorded are average of three samples.

3.4.5.4 Oxygen permeability, sorptivity and porosity tests

Oxygen permeability, sorptivity, and porosity tests were performed on concrete samples. The procedure followed is the same as explained in Section 3.3.4. Samples were tested at 28 and 180 days curing ages. Results recorded are average of three samples.

3.4.5.5 Carbonation

Carbonation test was carried out on concrete by exposing the samples to accelerated carbonation in a 10 % CO_2 environment. The carbonation chamber used was constructed in such a way that the CO_2 concentration can be maintained at a chosen concentration between 5 % and 25 % using a commercial CO_2 gas control module. CO_2 was supplied to the chamber from a CO_2 gas cylinder that connected through a pressure regulating valve. The air within the chamber was continuously agitated by a small electric fan. This ensured a uniform distribution of CO_2 within the chamber.

Samples were removed from the curing tank after they had been cured for 28 days. After removal, they were surface-dried and coated with a water-based epoxy on all four contiguous surfaces. This ensured that carbonation could only proceed through the two opposite uncoated faces. Coated samples were left in laboratory air for 24 hours, to allow epoxy coating to dry, after which they were put in the oven maintained at 50 ^{o}C for two weeks. The samples were then placed in the carbonation chamber and exposed to 10 % CO_2 for three weeks. Thereafter, the samples were split into halves, in a plane parallel to the uncoated surface and sprayed with a phenolphthalein solution. The uncarbonated part of the samples showed pink to purple colour upon spraying with phenolphthalein solution, while the carbonated parts remained colourless as shown in Figure 3.10. Carbonation depth was then measured with a vernier caliper and recorded. Results recorded are average of eight readings.

Phenolphthalein solution was prepared by mixing 1 g of phenolphthalein with 99 ml of ethanol to give 100 ml phenolphthalein solution. A labeled container fitted with a nozzle was used to give a fine spray of the phenolphthalein solution onto samples.

Figure 3.10: Partly carbonated sample

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 PHYSICAL PROPERTIES OF BINDERS

As shown in Table 4.1, Fly ash additive was observed to be finer than CEM 1 42.5N. The loose and relative densities of CEM 1 42.5N were higher than FA and PowerCem additives. According to equation (4.1) stated by Dally (1994), it is seen that absolute volume is inversely proportional to relative density.

$$Absolute\ volume\ (m^3) = \frac{\text{Mass of materials (kg)}}{\text{Re}\mathit{lative}\ \text{density x 1000}} \text{ ------------------------------------ } (4.1)$$

This observed trend could indicate that the PWC additive is more voluminous than CEM 1 42.5N and FA additive.

Table 4.1: Physical properties of binders

Binders	**Fineness, (% retained on 90 µm sieve)**	**Loose Density (kg/m^3)**	**Relative density (g/cm^3)**
CEM 1 42.5N	5.81	1037	3.12
PowerCem	8.22	664	1.92
Fly ash	2.42	792	2.78

4.2 SILICA STANDARD SAND

The grading analysis of locally prepared silica standard sand (PSSS) and commercially available European silica standard sand (ESSS) shows similar trend as shown in Figure 4.1. Mortar cubes of 50 mm size were prepared using both types of standard sands and tested to compare their results.

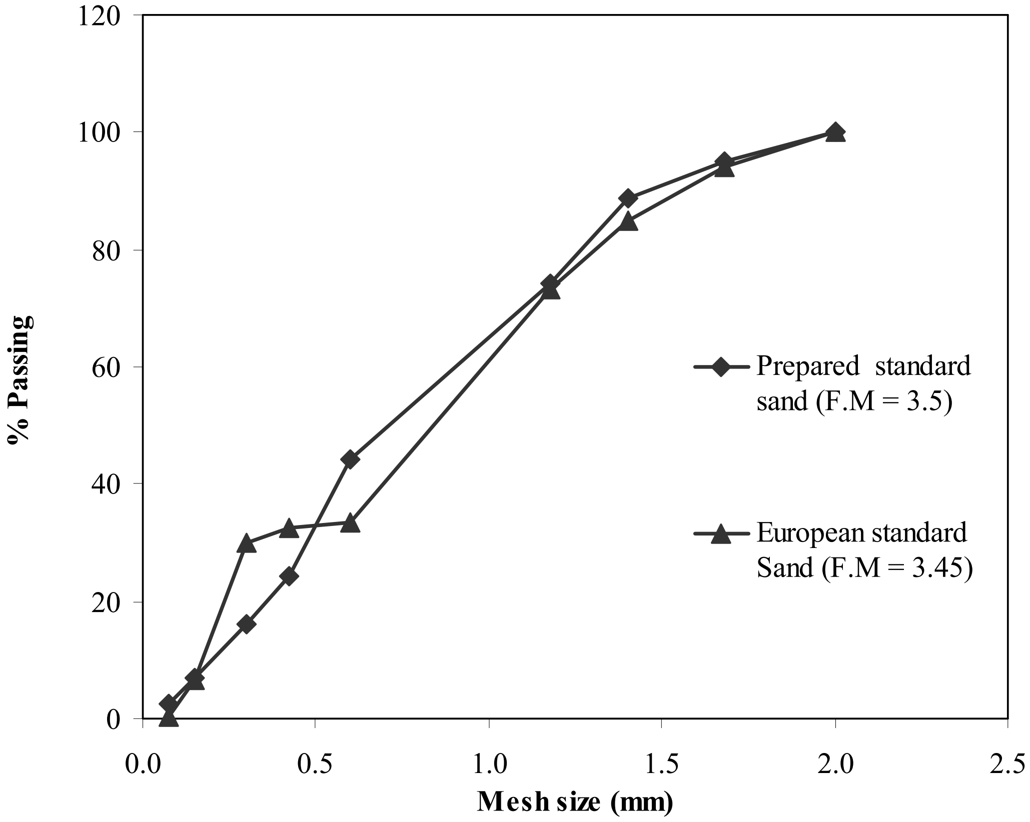

Figure 4.1: Grading curve for prepared standard sand and European standard sand.

The compressive mortar strength results for the two types of standard sand showed relatively the same trend (Figure 4.2) when cured for 3, 7, 28, and 90 days. It was observed that the prepared standard silica sand grading analysis fits in the range specified in SABS EN 196-1. Comparison of the grading analysis and compressive strengths of PSSS and ESSS gave similar results. It was inferred from the results, based on the trends observed that PSSS can be locally used in laboratory testing in lieu of commercially imported and expensive ESSS. The use of PSSS is an advantage over ESSS because the former is prepared locally and is cost effective.

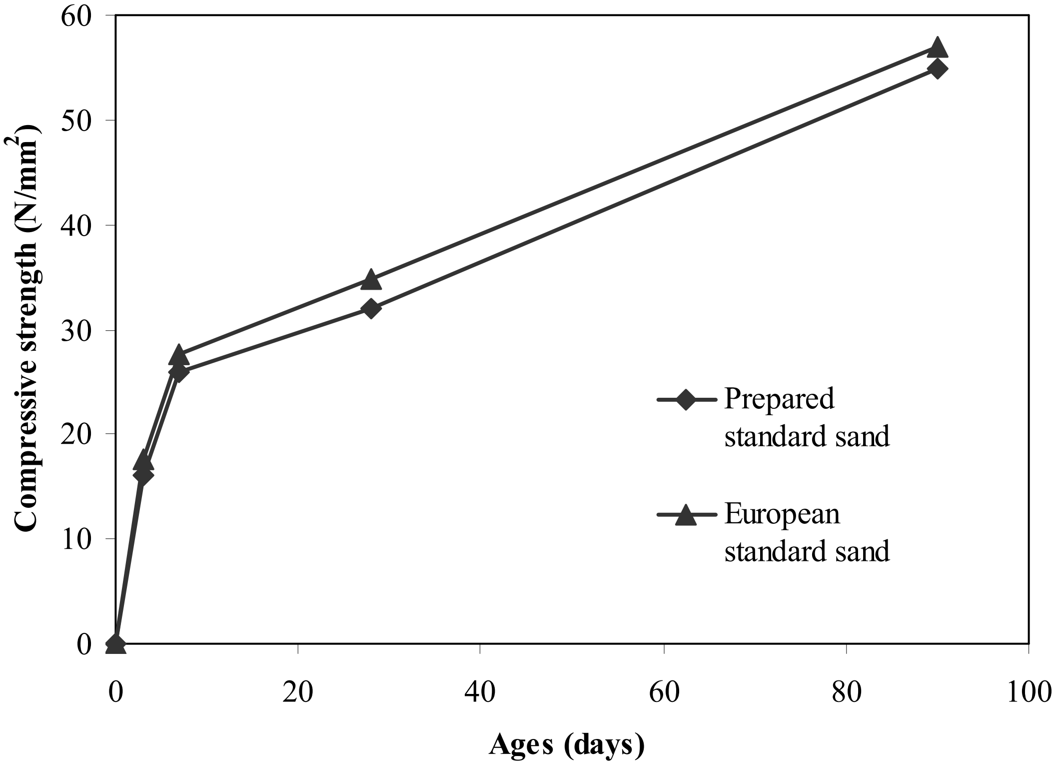

Figure 4.2: Compressive strength of mortar prepared with standard sand and with European standard sand.

4.3 HYDRATION STUDY

Different temperature peaks were observed in the differential thermal analysis curves of all samples as seen in Figure 4.3. These different temperature peaks represent the dehydration temperature of CSH gel, de-hydroxylation temperature of $Ca(OH)_2$ and the decomposition temperature of $CaCO_3$ (de-carbonation). Various mass variations determined are also shown from the thermogravimetric analysis curves in Figures 4.4 to 4.8.

DTA curves for all the samples showed similar trend as illustrated in Figure 4.3. They indicate that the hydration characteristics and products are almost identical. Small differences were in the peak areas at different temperatures.

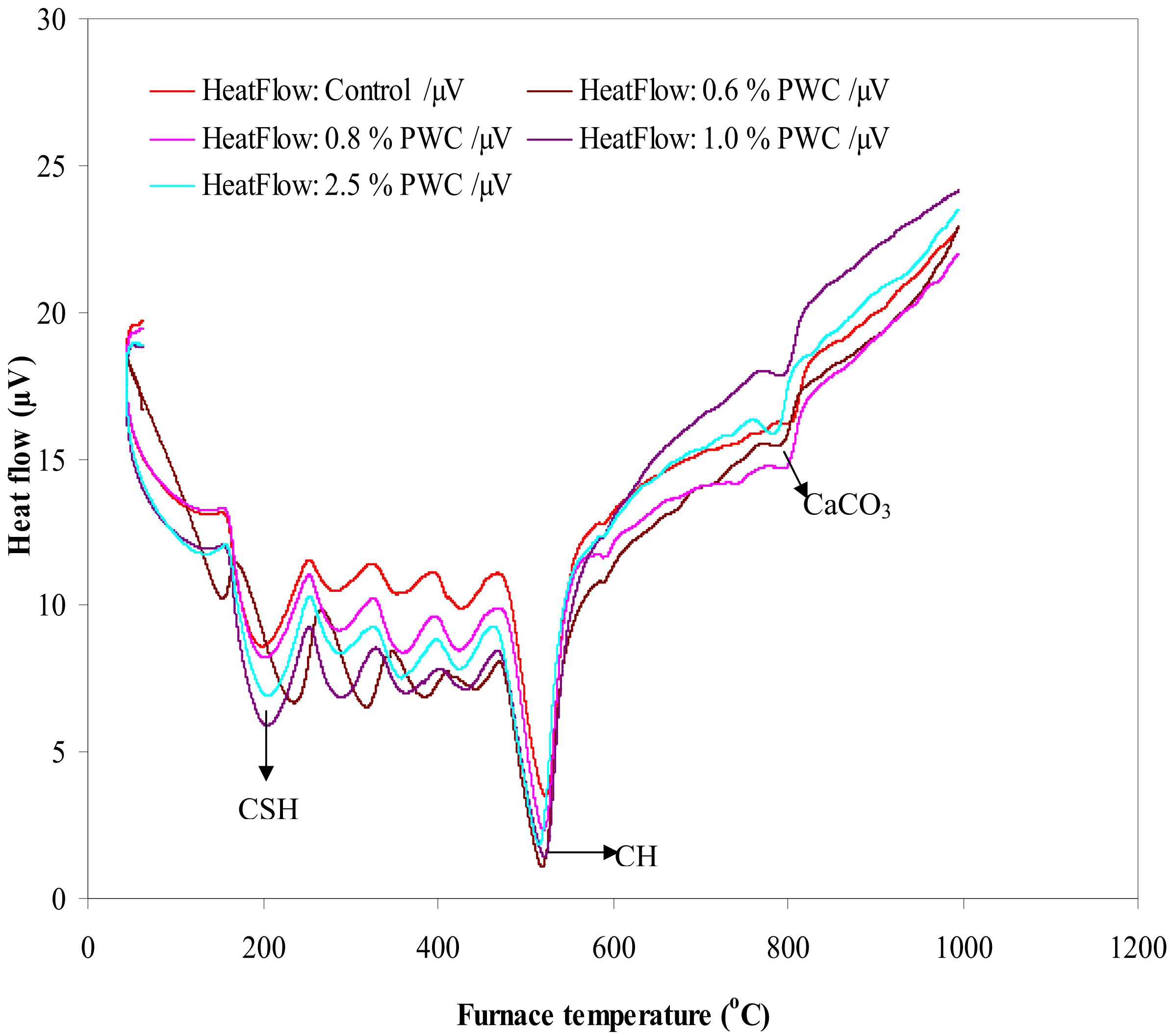

Figure 4.3: Superimposed DTA curves of hydrated OPC with and without PWC additive.

The dehydration temperature peak of CSH for the control sample was 211 °C, the de-hydroxylation temperature peak of CH was 522 °C, and the de-carbonation temperature peak of $CaCO_3$ was 807 °C as shown in Figure 4.4 for OPC. There was 6.803 % mass loss between 200 °C and 1000 °C, the glass transition zone was at 534 °C.

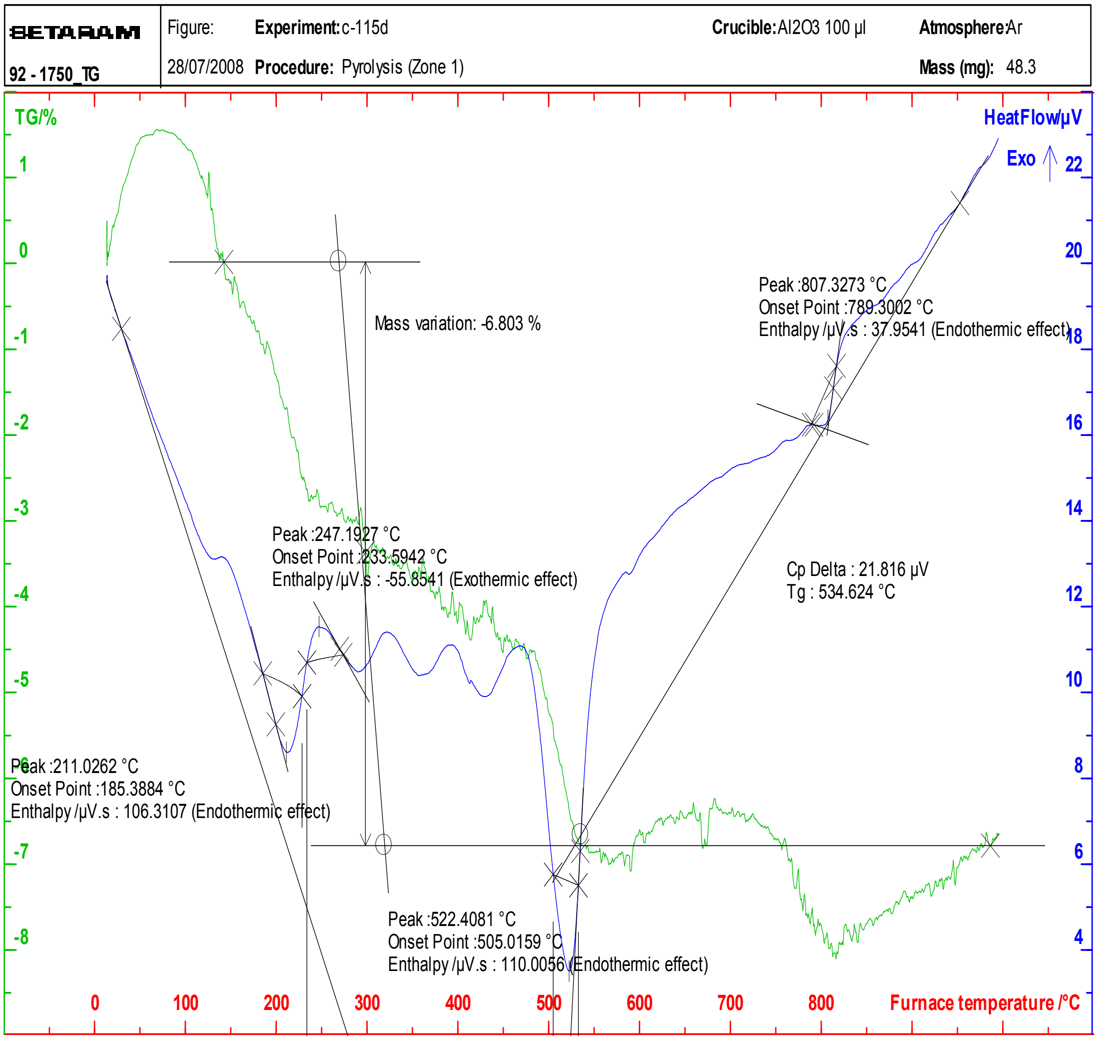

Figure 4.4: DTA and TGA curves of hydrated OPC without additive (control).

The 0.6 % PWC sample had dehydration temperature peak of CSH at 232 ^{o}C, de-hydroxylation temperature peak of CH at 517 ^{o}C, and de-carbonation temperature peak of $CaCO_3$ at 776 ^{o} C as shown in Figure 4.5. There was 6.154 % mass loss between 200 ^{o}C and 1000 ^{o}C, the glass transition zone was at 529 ^{o}C.

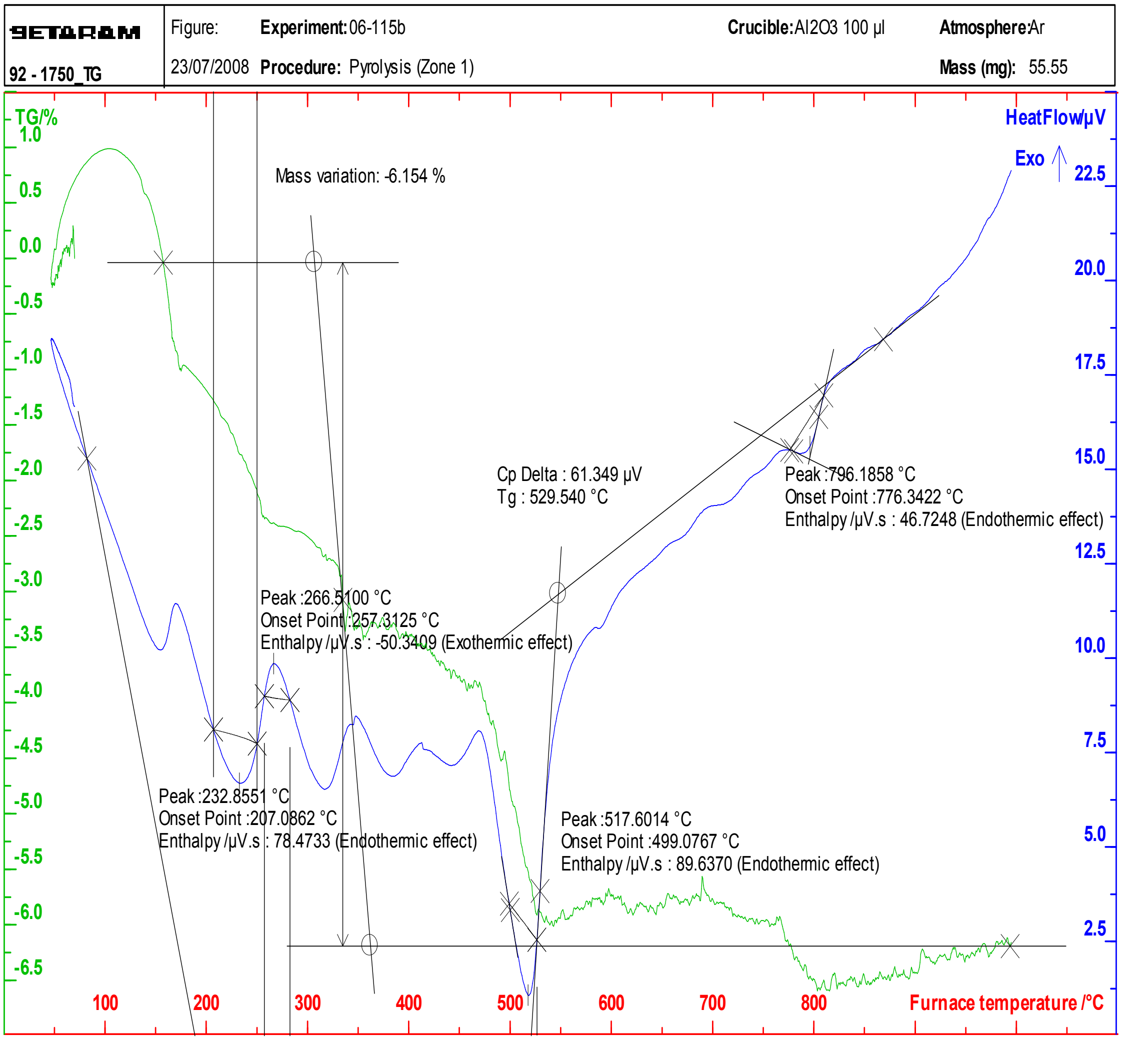

Figure 4.5: DTA and TGA curves of hydrated OPC in the presence of 0.6 % PWC additive.

In the case of 0.8 % PWC sample, the dehydration temperature peak of CSH was 213 °C, the de-hydroxylation temperature peak of CH was 520 °C, and de-carbonation temperature peak of $CaCO_3$ was 801 °C as shown in Figure 4.6. There was 7.792 % mass loss between 200 °C and 1000 °C, the glass transition zone was at 533 °C.

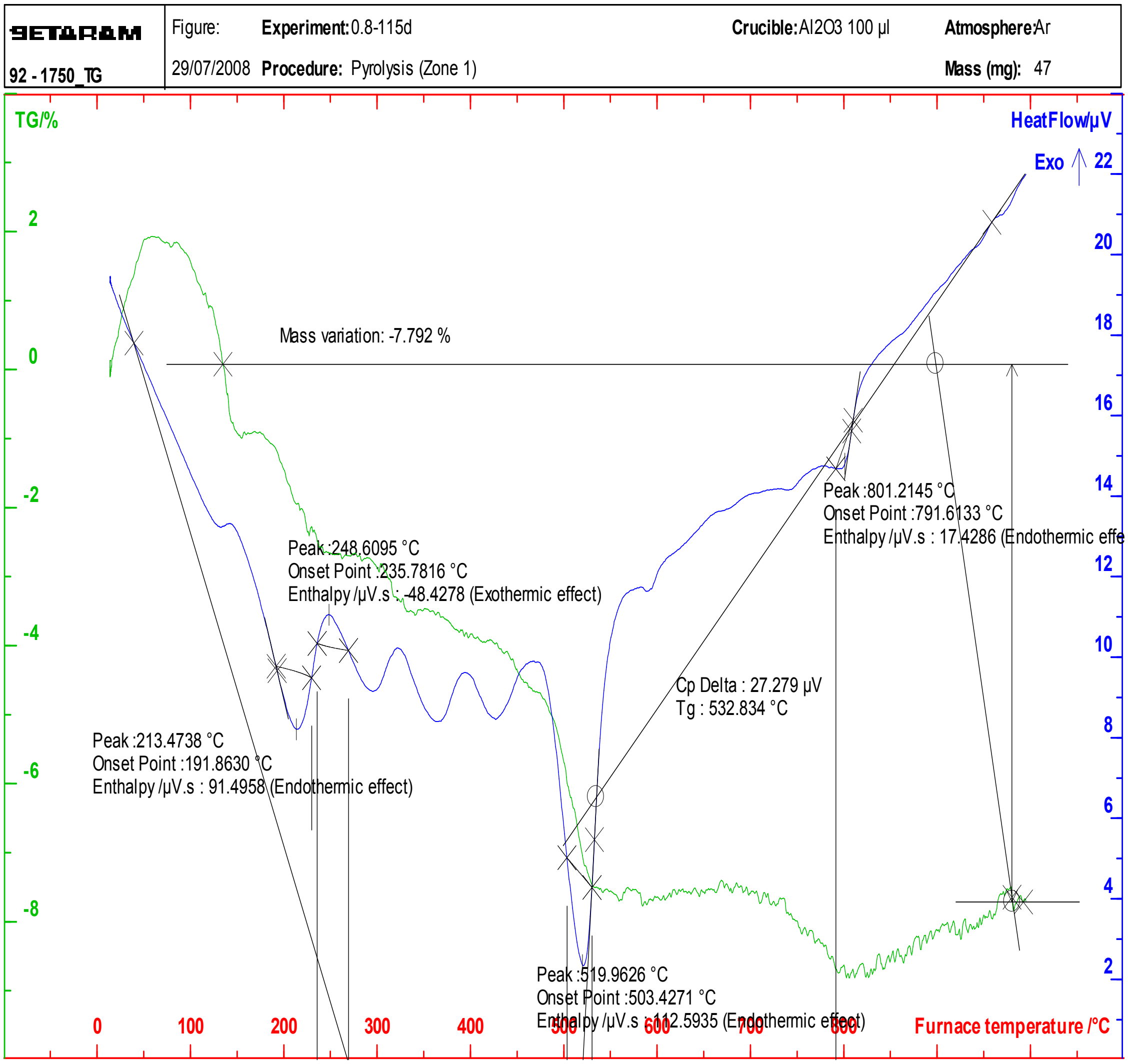

Figure 4.6: DTA and TGA curves of hydrated OPC in the presence of 0.8 % PWC additive.

When 1.0 % PWC sample was studied, the dehydration temperature peak of CSH was 215 ^{o}C, the de-hydroxylation temperature peak of CH was 521 ^{o}C, and de-carbonation temperature peak of $CaCO_3$ was 798 ^{o}C as shown in Figure 4.7. There was 6.915 % mass loss between 200 ^{o}C and 1000 ^{o}C, the glass transition zone was at 533 ^{o}C.

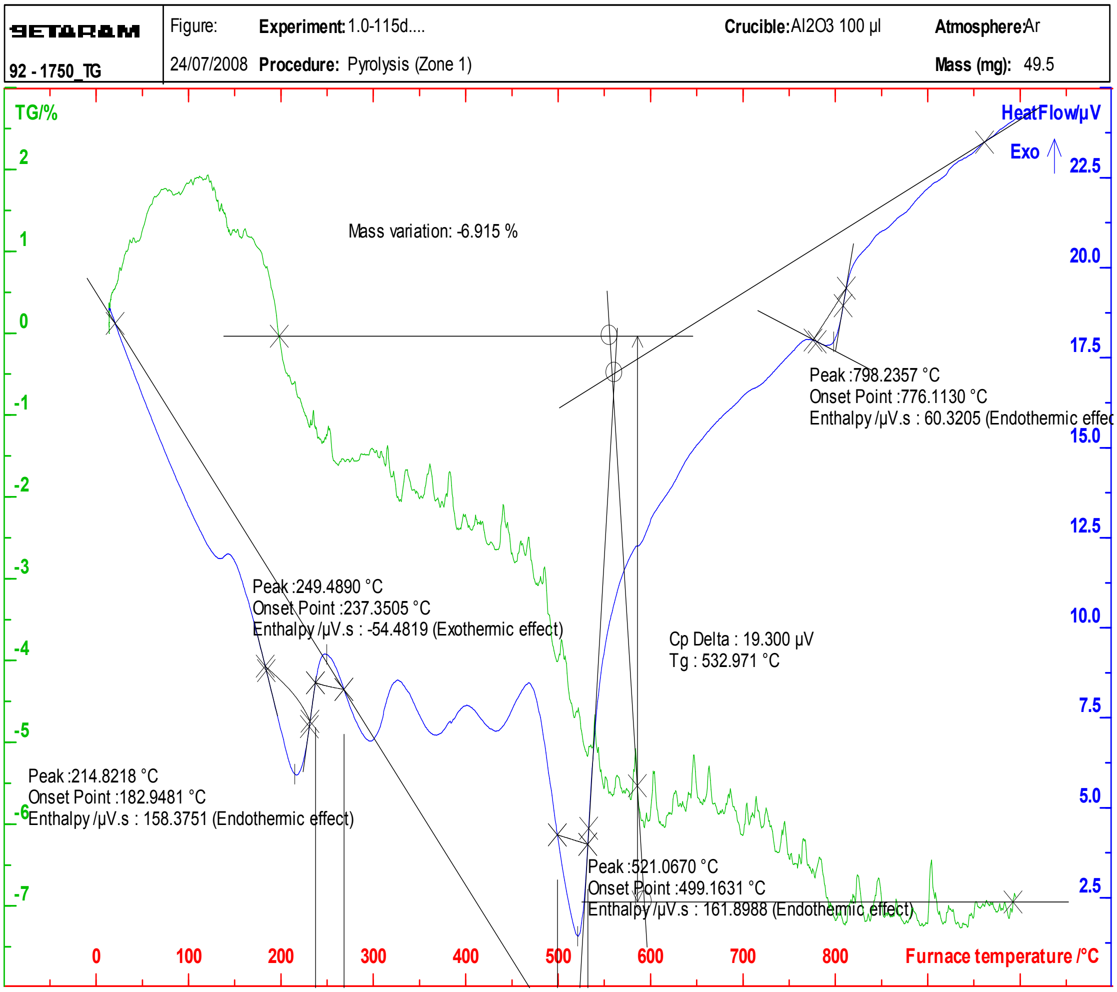

Figure 4.7: DTA and TGA curves of hydrated OPC in the presence of 1.0 % PWC additive.

Also, for 2.5 % PWC sample, the dehydration temperature peak of CSH was observed at 216 ^{o}C, the de-hydroxylation temperature peak of CH was observed at 515 ^{o}C, and de-carbonation temperature peak of $CaCO_3$ was observed at 786 ^{o}C as shown in Figure 4.8. There was 8.803 % mass loss between 200 ^{o}C and 1000 ^{o}C, the glass transition zone was at 527 ^{o}C.

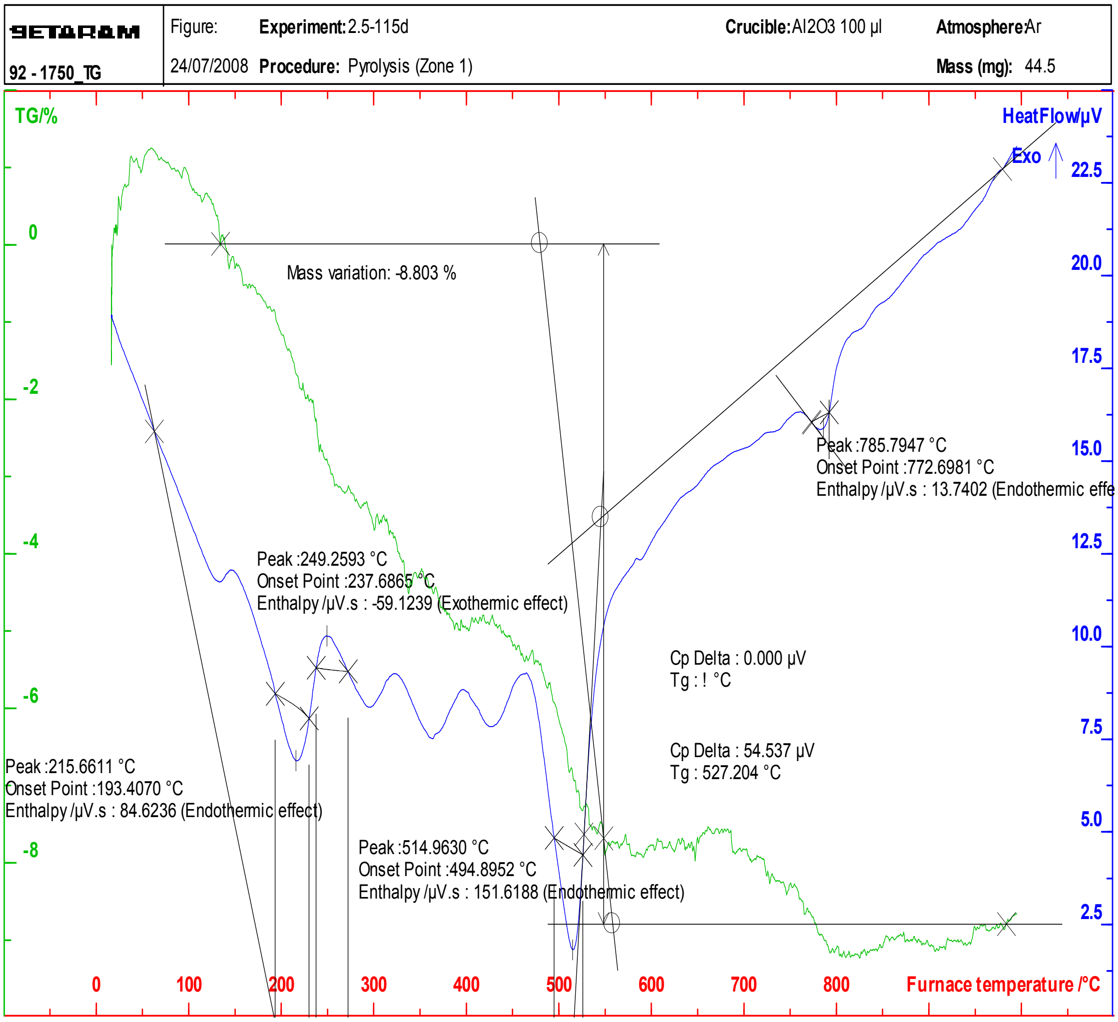

Figure 4.8: DTA and TGA curves of hydrated OPC in the presence of 2.5 % PWC additive.

The three major temperature peaks occurred at approximately the same temperature for all samples. The observed peak areas given in Table 4.2 for dehydration of CSH at approximately 200 ^{o}C indicate that more CSH was formed with increase in PWC additive compared to control, except for 0.8 % PWC sample. In 0.8 % PWC sample reduction in CSH content was observed when compared to control. The reason for this observation is quite unclear.

The decrease in peak areas (Table 4.2) due to decomposition of $Ca(OH)_2$ at approximately 500 ^{o}C in samples with PWC additive compared to that of control sample may indicate the occurrence of a pozzolanic reaction. Consumption of CH in pozzolanic reaction gives secondary CSH, hence, corresponding increase of CSH observed at 200 ^{o}C for PWC additive samples. Caputo *et al.* (2008), explains that zeolite reactivity is related to its large external specific surface, which favors its dissolution into the saturated lime solution and the subsequent precipitation of CSH (hydrated calcium silicate) and CAH (hydrated calcium aluminate) phases.

The reduced intensity of $CaCO_3$ peak in all samples, especially samples with PWC additive indicated the dissolution of $CaCO_3$ during the formation of hydration products. There was reduction in the peak areas due to de-carbonation of $CaCO_3$ at approximately 800 ^{o}C in samples with PWC additive compared to control sample. This is consistent with relatively low amount of CH present in the system containing PWC additive.

In summary, a notable decrease in the amount of $Ca(OH)_2$ was observed with sample incorporating PWC additive especially with 0.6 % PWC sample compared to control sample. According to Perraki *et al.* (2003) natural zeolite shows remarkable decrease in $Ca(OH)_2$ content when used at 10 % proportion of cement. Hence, the use of PWC additive enhanced pozzolanic reaction at the low proportion used.

Table 4.2: Peak areas of DTA endothermic peak

Materials (115 days hydration period)	**Peak area (unit ^{2}) of DTA endothermic peak at ≈200 ^{o}C for C-S-H.**	**Peak area (unit ^{2}) of DTA endothermic peak at ≈500 ^{o}C for CH.**	**Peak area (unit ^{2}) of DTA endothermic peak at ≈800 ^{o}C for $CaCO_3$.**
Control	81.93	228.80	1.60
0.6 % PWC + Cement	89.32	195.72	1.54
0.8 % PWC + Cement	79.89	196.99	1.36
1.0 % PWC + Cement	90.03	198.32	1.57
2.5 % PWC + Cement	98.17	201.76	0.84

4.4 MORTAR PROPERTIES

4.4.1 Effect of PWC additive on mortar workability

The flow test results given in Figure 4.9 revealed the effect of PWC additive on workability property of mortar. It was observed that differences between results of control samples, 0.4 % PWC proportion and 0.6 % PWC proportion were not remarkable.

The results indicated that at PWC proportion of 0.4 % and 0.6 %, the mortar workability may remain unaffected. However, beyond 0.6 % there is increase in workability with increase in proportion of PWC added. PWC additive therefore, may improve mortar workability when used at a percentage beyond 0.6 %. This helps to enhance easy flow and compaction of mortar.

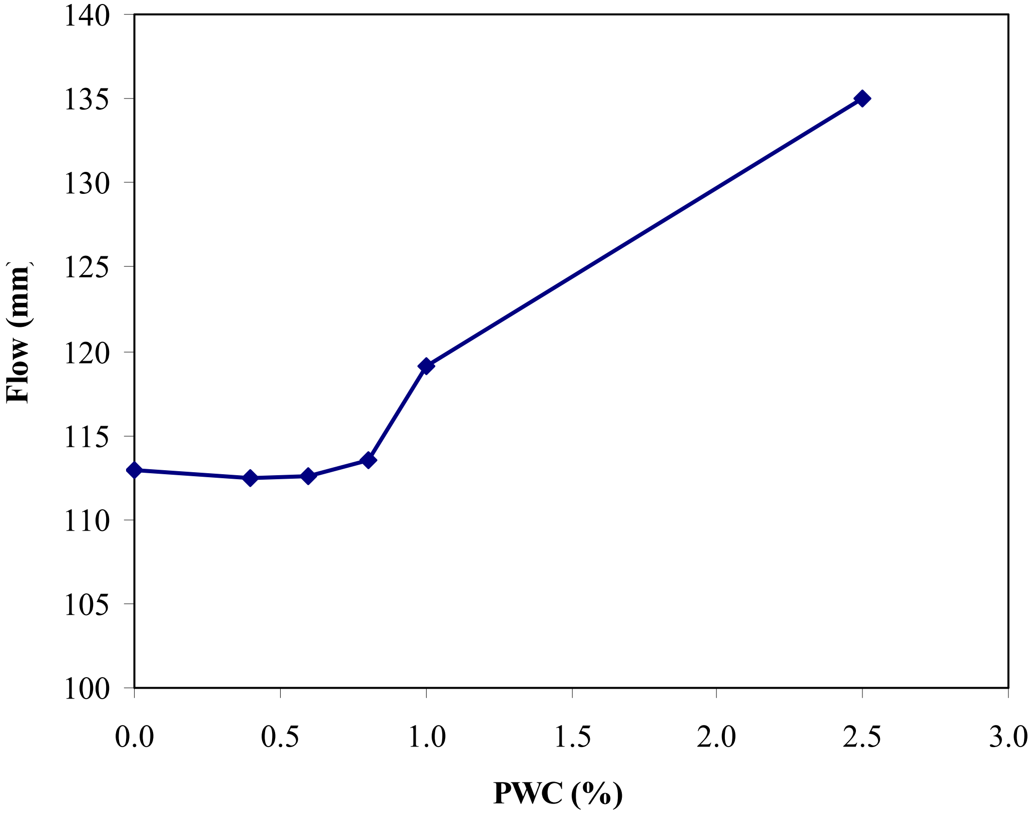

Figure 4.9: Flow chart of samples.

Increase in workability beyond 0.6 % PWC proportion was contrary to the general behaviour of natural zeolite. It was recorded by Caputo *et al*. (2008) that replacement of Portland clinker by zeolitic tuff, reduced workability and increased water demand. This was also reported by Habert *et al.* (2008) who found that increase in zeolite and clay mineral content in mortar, resulted in increase of water demand and decrease in workability. The contrary behaviour of PWC additive may be related to the nature and quantity of modifying ingredients used.

4.4.2 Effect of test age and PWC additive on mortar flexural strength

As shown in Figure 4.10, flexural strength was observed to increase with increasing test age (curing period) for all mixes except for the control samples. For the control samples, reduction in flexural strength was observed between 90 and 120 days.

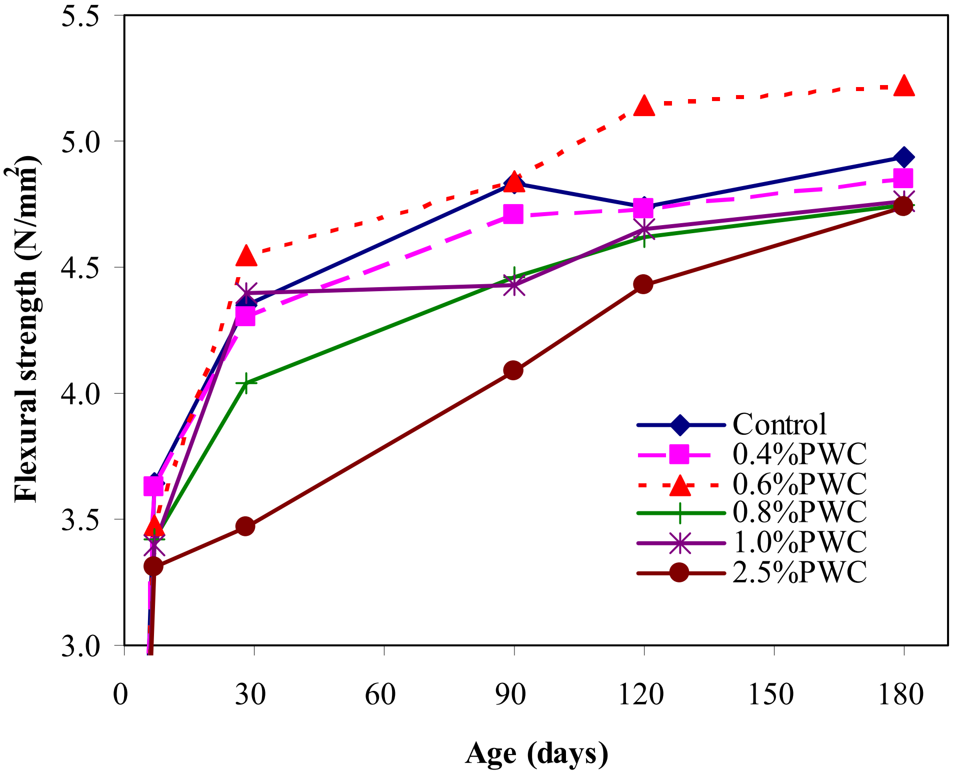

Figure 4.10: Flexural strength against test age of mortar samples.

In all the mixes, the rate of increase in flexural strength was however lower at the later age than early age. Except for 0.6 %, all the other PWC additive samples showed a lower strength relative to strength of control at all test ages. It can be seen in Figures 4.10 and 4.11 that highest values and proportional increase in flexural strength were observed in 0.6 % PWC mortar samples when compared to the rest samples for all ages after 28 days. The increase in additive dosage beyond 0.6 % generally showed a decrease in flexural strength relative to control.

Table 4.3 shows that PWC additive reduces the flexural strength of mortar to maximum percentage of 20.2 % observed at 28 days with 2.5 % PWC proportion. On the other hand, the PWC additive increases flexural strength to a maximum percentage of 8.4 % observed at 120 days for 0.6 % PWC proportion. As already mentioned, the adverse effect of strength reduction was observed with PWC dosages beyond 0.6 %.

It can be inferred from the results that curing improves flexural strength. Adequate curing is needed for complete hydration and pozzolanic reactions to take place. The higher flexural strength relative to control that was observed with 0.6 % PWC samples may be attributed to the pozzolanic reaction. As shown in this study and confirmed by Kumar *et al*. (1993), the pozzolanic reaction consumes $Ca(OH)_2$ and produces more CSH, which is responsible for strength development.

Table 4.3: % Change in mortar flexural strength relative to control

Samples	**Curing age (days)**		
	28 days	**120 days**	**180 days**
Control	Datum	Datum	Datum
0.4 % PWC + cement	-1.2	-0.2	-1.8
0.6 % PWC + cement	4.4	8.4	5.7
0.8 % PWC + cement	-7.1	-2.5	-3.9
1.0 % PWC + cement	1.1	-1.9	-3.9
2.5 % PWC + cement	-20.2	-6.5	-4.1

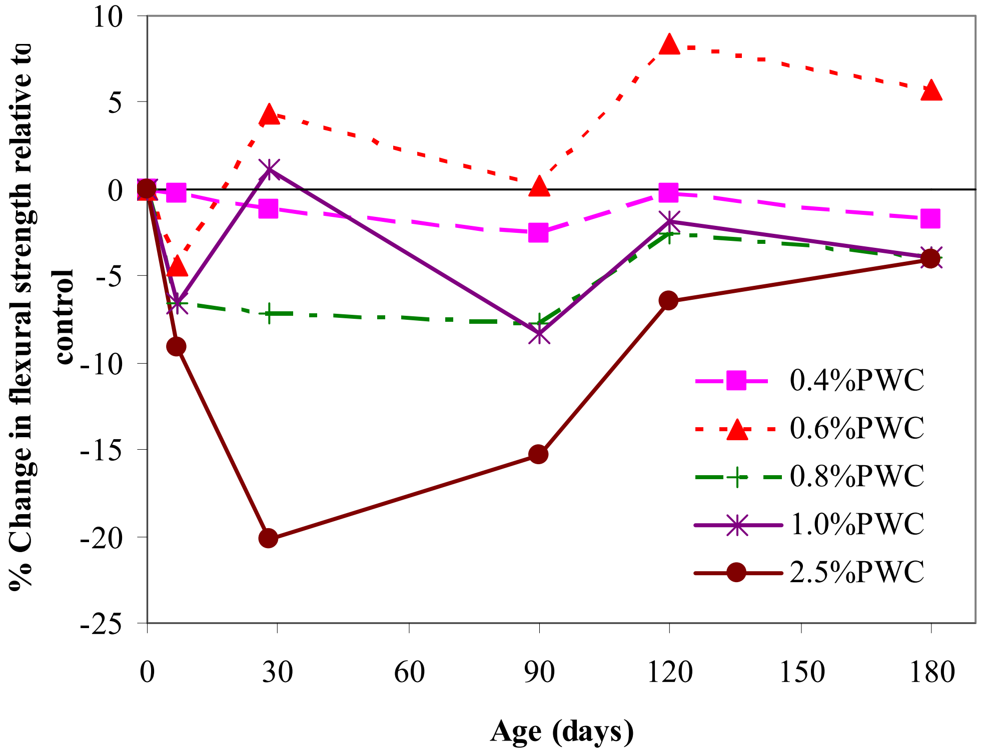

Figure 4.11: Percentage decrease or increase in flexural strength relative to control.

A proper explanation for the reduction in flexural strength due to dosages of PWC higher than 0.6 % is not clear but may be related to artificial modifying agents used in the material. It was shown in Section 4.3 of this study that PWC additive beyond 0.6 % does not contribute to the enhancement of pozzolanic reaction.

4.4.3 Effect of test age and PWC additive on mortar compressive strength

Figure 4.12 gives results of mortar compressive strength against age. Increase in compressive strength was observed with increasing test age for all mixes. This trend is similar with results observed for flexural strength. Reduction in early compressive strength was also observed for all PWC samples compared to control samples.

Compressive strengths higher than results for control were observed for 0.4 % PWC samples at the later ages of 90 days and 120 days. Also, 0.6 % PWC samples showed higher compressive strengths than control at 120 days and 180 days. Samples with PWC proportions greater than 0.6 % generally showed decrease in compressive strength compared to control. Compressive strength increase for samples with 0.8 % PWC and 1.0 % PWC was not consistent. The differences between the compressive strength results at 120 days and 180 days for control, 0.4 % PWC and 0.6 % PWC were not remarkable, though with 0.4 % PWC samples having highest value of 46.7 N/mm^2 at 120 days and 0.6 % PWC samples having highest value of 52.5 N/mm^2 at 180 days.

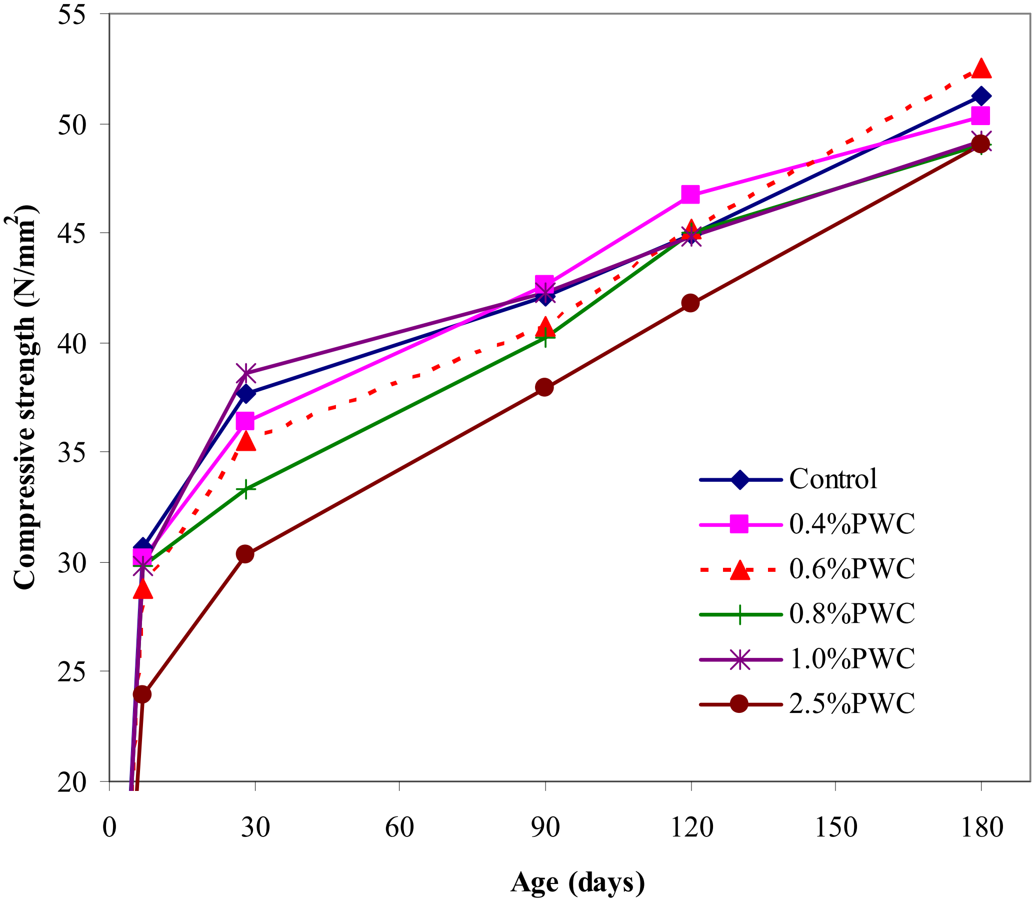

Figure 4.12: Compressive strength against test age of mortar samples

Samples with 0.6 % PWC show relatively steady strength gain compared to other mixes. The increase gain in strength of the 0.6 % PWC samples at all ages was steady as seen in Figure 4.13. PWC additive reduced the compressive strength of mortar by a maximum percentage of 22 % at 7 days when used at 2.5 % PWC proportion. However, increase in compressive strength by a maximum percentage of 2.5 % was observed at 180 days when used at 0.6 % PWC proportion as shown in Table 4.4. Generally an adverse effect leading to strength reduction was observed with PWC dosages exceeding 0.6 %.

The strength results of 0.6 % PWC additive makes PWC to have advantage over natural zeolite (not modified), which was reported to improve strength when used at proportions between 10 % and 15 % (Poon *et al.*, 1999; Quanlin and Naiqian, 2005). As stated earlier, an increase in additive dosage beyond 0.6 % results showed a general decrease in compressive strength compared to control. This confirms the results for flexural strength, which may be presumably related to the action of modifying artificial agents used.

Table 4.4: % Change in mortar compressive strength relative to control

Samples	**Curing age (days)**		
	28 days	**120 days**	**180 days**
Control	Datum	Datum	Datum
0.4 % PWC + cement	-3.2	4.0	-1.8
0.6 % PWC + cement	-5.6	0.6	2.5
0.8 % PWC + cement	-11.6	0.1	-4.3
1.0 % PWC + cement	2.6	-0.2	-4.0
2.5 % PWC + cement	-19.5	-7.0	-4.4

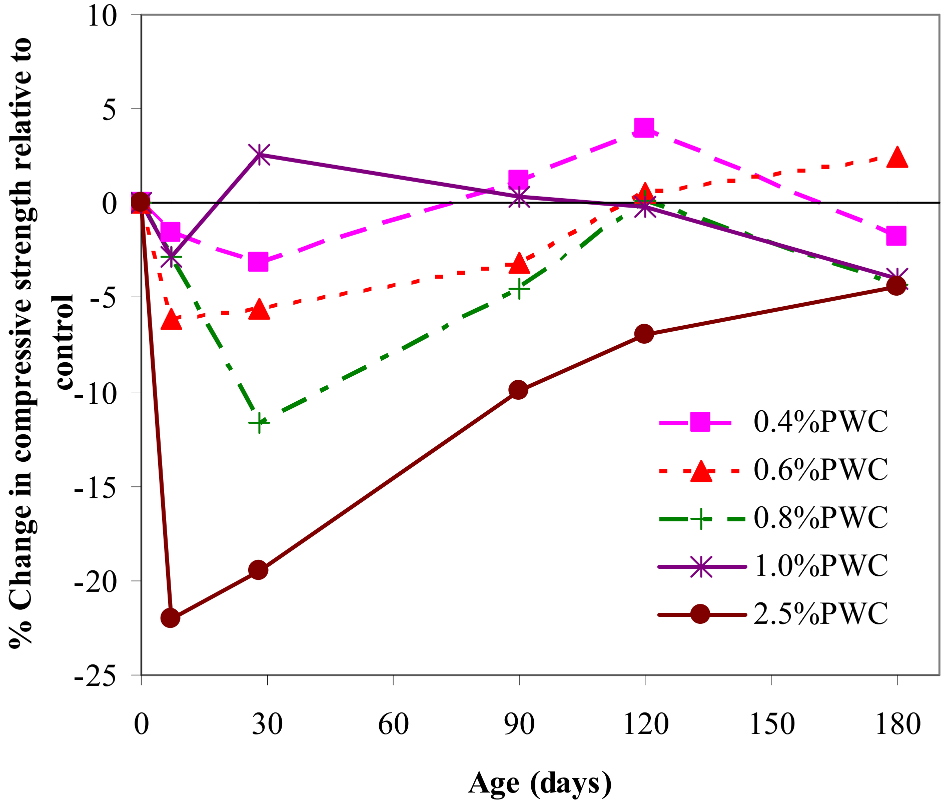

Figure 4.13: Percentage decrease or increase in compressive strength of mortar samples relative to control.

4.4.4 Effect of PWC additive on mortar oxygen permeability, sorptivity, and porosity

A reduction in permeability was observed from 28 days age onwards for mortars of low dosages consisting of 0.4 %, 0.6 %, and 0.8 % PWC when compared to the control mortar as seen in Figure 4.14. However, an increase in the dosage of PWC additive beyond 0.8 % increased permeability. It is clear that permeability increases with increase in PWC dosage above 0.8 %. It was also observed that at 180 days the differences in permeability between control, 0.4 % PWC, 0.6 % PWC, and 0.8% PWC samples were not remarkable.

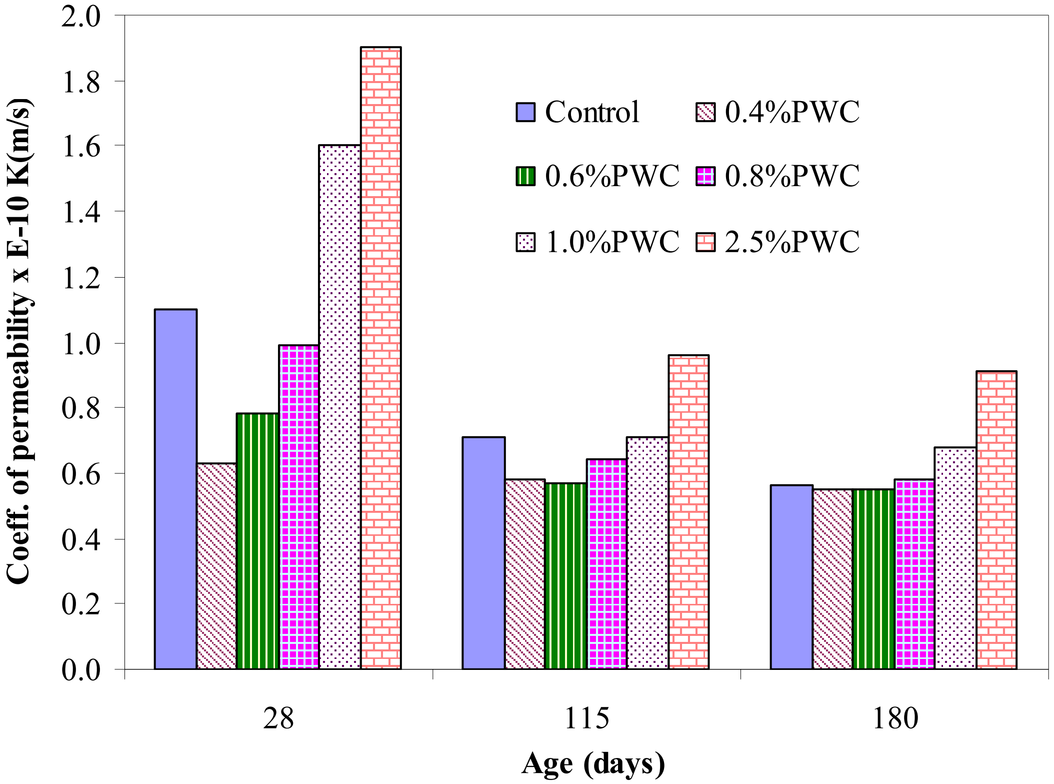

Figure 4.14: Permeability of mortars samples.

Results given in Table 4.5 showed that the PWC additive reduced the permeability of mortar to maximum percentage of 42.7 % at 28 days when used at 0.4 % PWC proportion. This is illustrated graphically in Figure 4.15.

Table 4.5: % Change in mortar permeability relative to control

Samples	Curing age (days)		
	28 days	120 days	180 days
Control	Datum	Datum	Datum
0.4 % PWC + cement	-42.7	-18.3	-1.8
0.6 % PWC + cement	-29.1	-19.7	-1.8
0.8 % PWC + cement	-10.0	-9.9	3.6
1.0 % PWC + cement	45.5	0.0	21.4
2.5 % PWC + cement	72.7	35.2	62.5

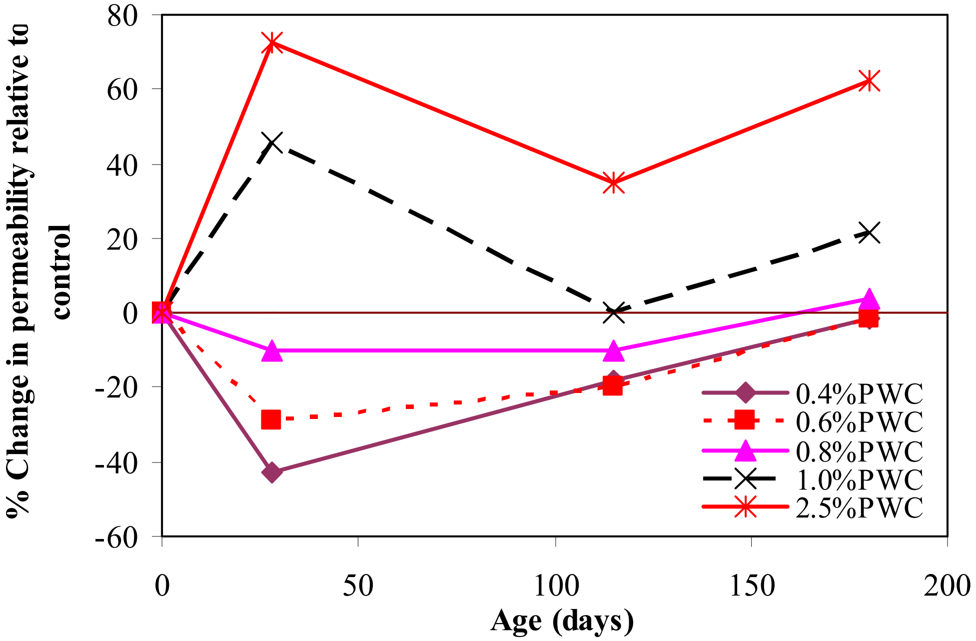

Figure 4.15: Percentage decrease or increase in permeability of mortar samples relative to control.

Also, PWC additive was seen in Table 4.5 to increase mortar permeability to maximum percentage of 72.7 % at 28 days when used at a dosage level of 2.5 % PWC. Again, adverse effect on permeability was observed with PWC dosages greater than 0.8 %.

The sorptivity of control mortar samples can be seen in Figure 4.16 to be higher than that of PWC mortars at all ages for all dosages. Variations between the sorptivity values of all PWC additive samples at 115 days and 180 days were similar. The reduction of sorptivity due to use of PWC additive was remarkable as shown in Figure 4.17.

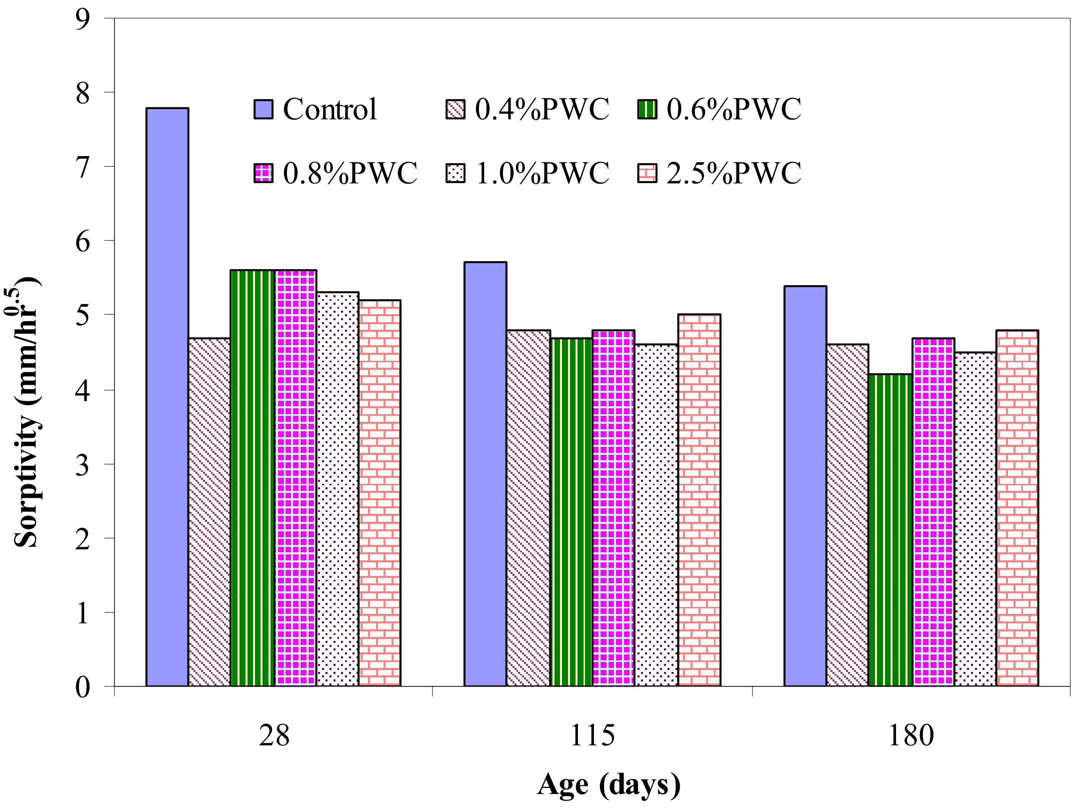

Figure 4.16: Sorptivity of mortars samples.

It was observed in Table 4.6 that the PWC additive reduces sorptivity of mortar to maximum percentage of 39.7 % at 28 days when used at 0.4 % PWC proportion. At 180 days, 0.6 % PWC samples showed the highest percentage reduction in sorptivity compared to control samples. This is shown graphically in Figure 4.17.

Table 4.6: % Change in mortar sorptivity relative to control

Samples	**Curing age (days)**		
	28 days	**120 days**	**180 days**
Control	Datum	Datum	Datum
0.4 % PWC + cement	-39.7	-15.8	-14.8
0.6 % PWC + cement	-28.2	-17.5	-22.2
0.8 % PWC + cement	-28.2	-15.8	-13.0
1.0 % PWC + cement	-32.1	-19.3	-16.7
2.5 % PWC + cement	-33.3	-12.3	-11.1

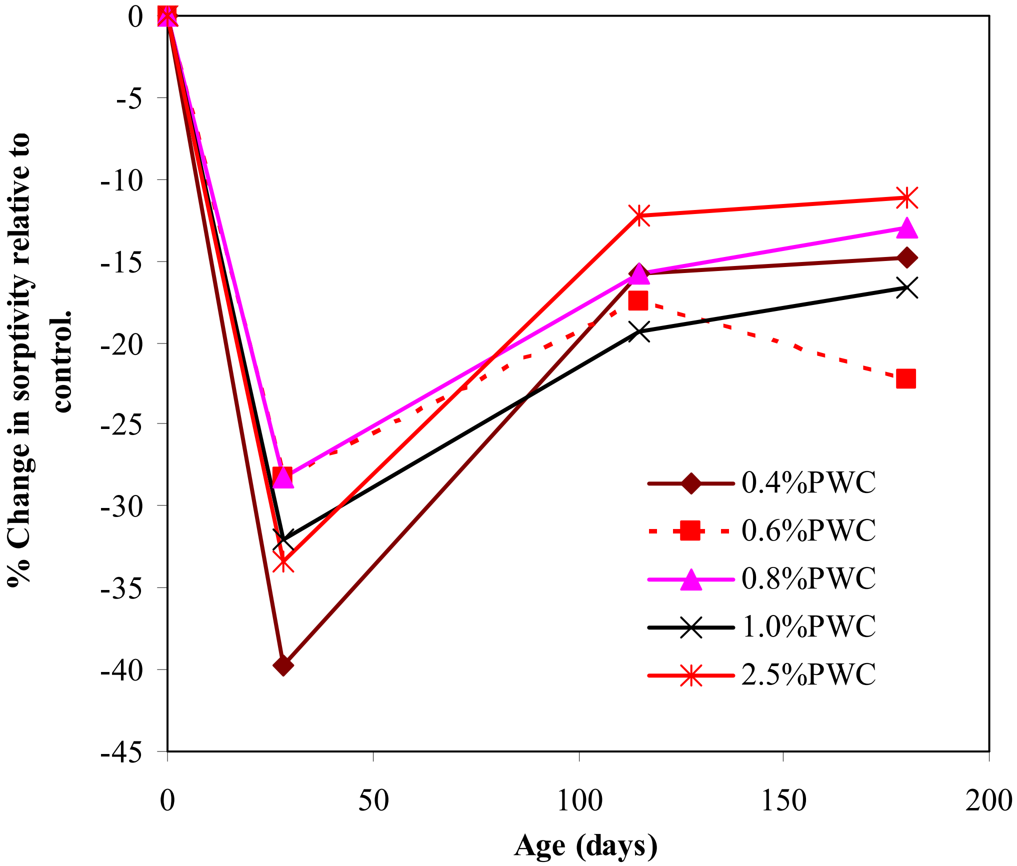

Figure 4.17: Percentage decrease or increase in sorptivity of mortar samples relative to control.

Figure 4.18 shows reduction in porosity of mortar samples containing PWC additive when used at 0.4 %, 0.6 %, and 0.8 % proportions, compared to control mortar from 28 days onwards. It was observed that samples with higher dosages of PWC beyond 0.8 % reduced porosity only at 115 days, while an increase in porosity was observed at 28 days and similar porosity to that of control samples was observed at 180 days. This trend is similar to the observed trend for permeability results.

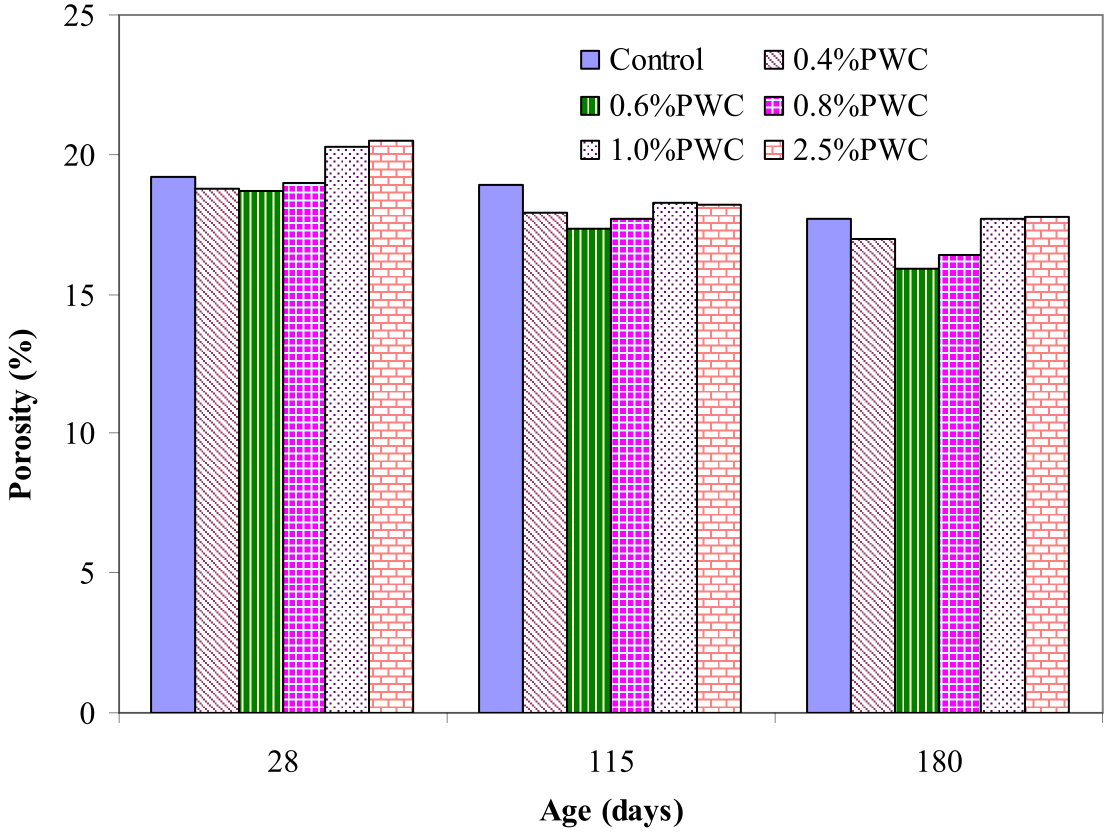

Figure 4.18: Porosity of mortars samples.

As shown in Table 4.7, porosity was reduced by maximum percentage of 10.2 % at 180 days when the PWC additive was used at 0.6 %. PWC dosages above 0.8 % increased porosity by maximum percentage of 6.8 % at 28 days when used at 2.5 % as seen in Figure 4.19. It was also observed that the reduction in porosity of samples containing 0.6 % and 0.8 % PWC additive was steady from 28 days onwards. Through the process of pozzolanic reaction, PWC additive caused reduction in the volume of pores present in the mortar samples. As a result of pore volume reduction, the sorptivity of samples also decreased. This observation was in conformity with the statement made by Soroka (1979), which states that "sorptivity measures the volume of open pores accessible to water". Therefore, the higher the volume of open pores accessible to water, the higher the sorptivity.

Table 4.7: % Change in mortar porosity relative to control

Samples	Curing age (days)		
	28 days	120 days	180 days
Control	Datum	Datum	Datum
0.4 % PWC + cement	-2.1	-5.3	-4.0
0.6 % PWC + cement	-2.6	-8.5	-10.2
0.8 % PWC + cement	-1.0	-6.3	-7.3
1.0 % PWC + cement	5.7	-3.2	0.0
2.5 % PWC + cement	6.8	-3.7	0.6

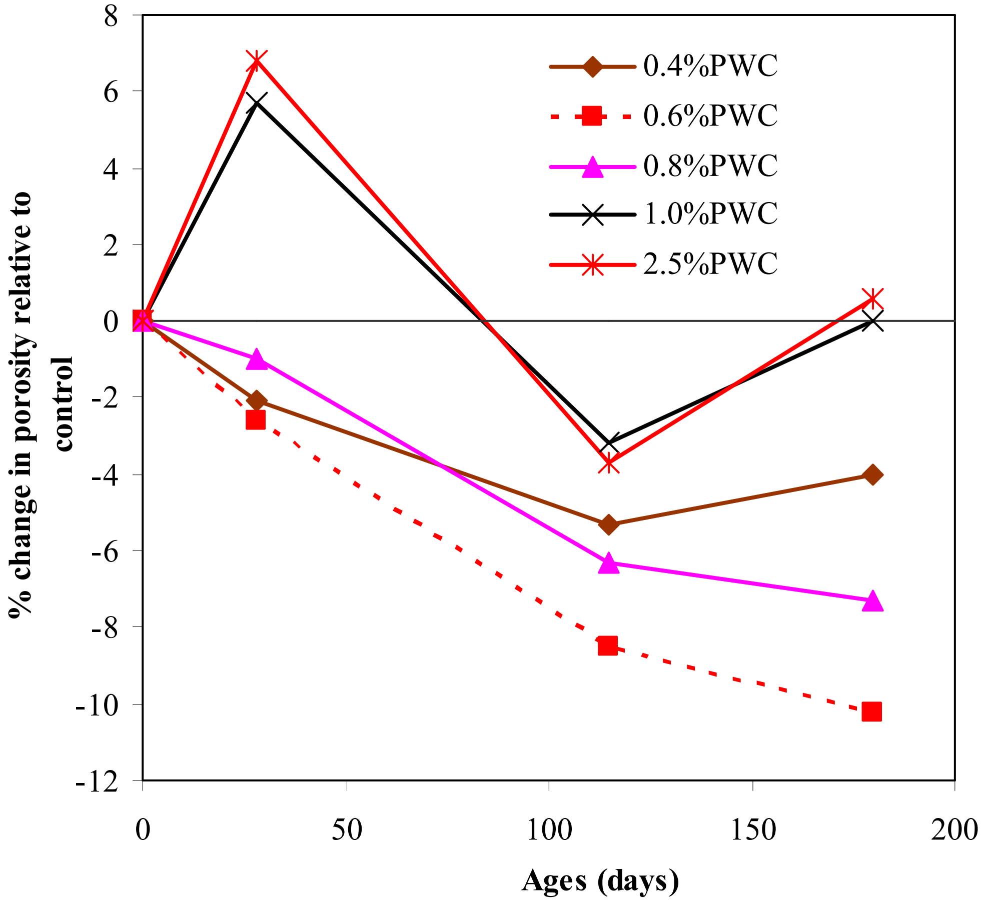

Figure 4.19: Percentage decrease or increase in porosity of mortar samples relative to control.

Durability is significantly influenced by permeability and sorptivity characteristics. The reduction of these properties in mortars due to use of the PWC additive suggests improvement in durability as a result of reduced ingress of chlorides, sulphates, carbon-dioxide, moisture, and other deleterious ions responsible for concrete deterioration.

4.4.5 Effect of sulphate content and PWC additive on internal sulphate attack of mortar

Mortar samples that were left to harden for one day after casting were slightly pulverized and sieved in a 90 μm sieve size such that only paste samples were sieved out. Sulphate content of the paste samples was analyzed. The results obtained are shown in Table 4.8. The sulphate content appears to decrease with an increase in PWC additive, but there was some notable increase observed for 0.6 % PWC.

Table 4.8: Sulphate content of samples paste

Sample	Sulphate content (SO_3, %)
Control	1.64
0.6 % PWC + Cement	1.84
1.0 % PWC + Cement	1.57
2.5 % PWC + Cement	1.32

Figure 4.20 shows the percentage expansion of samples due to sulphate attack when immersed in lime solution according to ASTM C 1038. A similar expansion trend was observed for all samples at all ages. Samples containing 0.6 % PWC have highest expansion value of 0.033 % at 28 days. Relatively moderate expansion was however observed for 0.6 % PWC paste between 60 and 120 days.

Expansion of the samples when stored in lime water is directly related to the amount of sulphate in the cement according to ASTM C 1038. Expansion may become excessive when the cement contains too much sulphate.

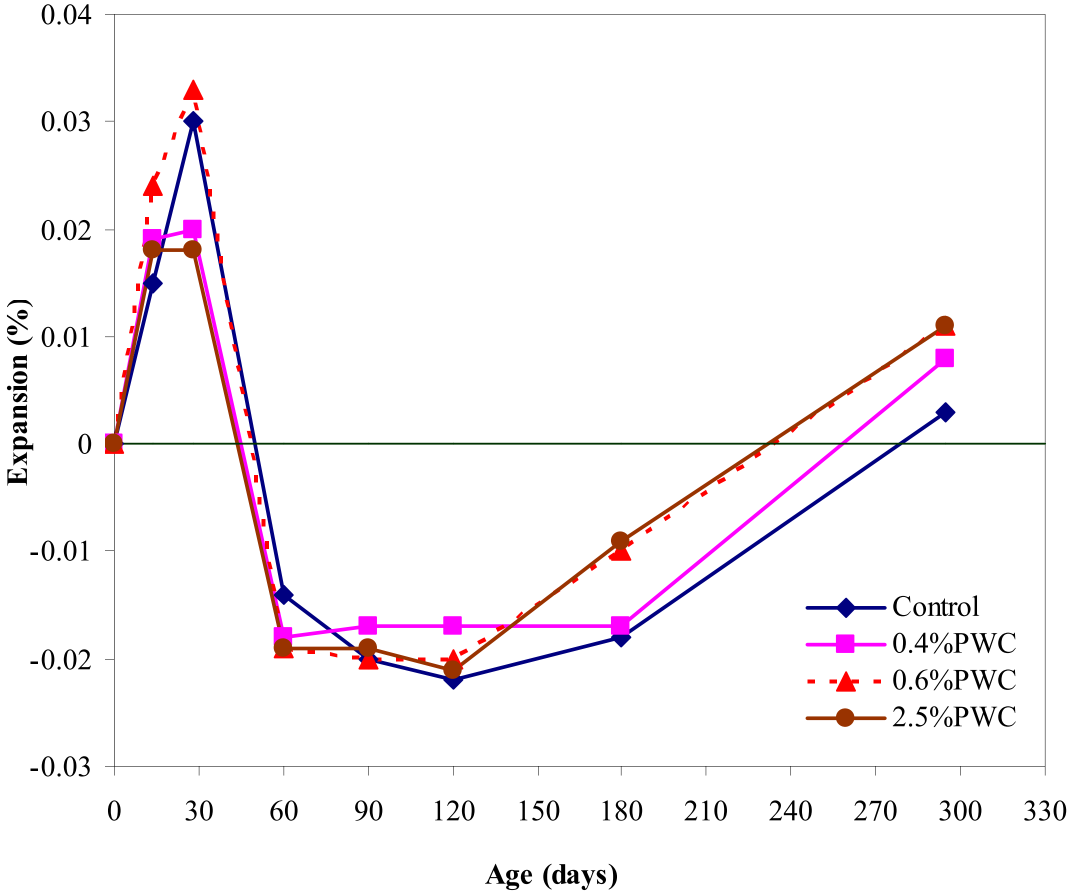

Figure 4.20: Expansion due to internal sulphate attack as per ASTM C 1038.

4.4.6 Effect of PWC additive on external sulphate attack of mortar.

Figure 4.21 shows the percentage expansion of samples due to sulphate attack when immersed in 5 % Na_2SO_4 solution according to ASTM C 1012. At all ages observed, the expansion of 0.4 % PWC and 0.6 % PWC samples were less than the expansion observed in control samples. It was also observed that the higher dosage of 2.5 % PWC additive resulted in a higher expansion.

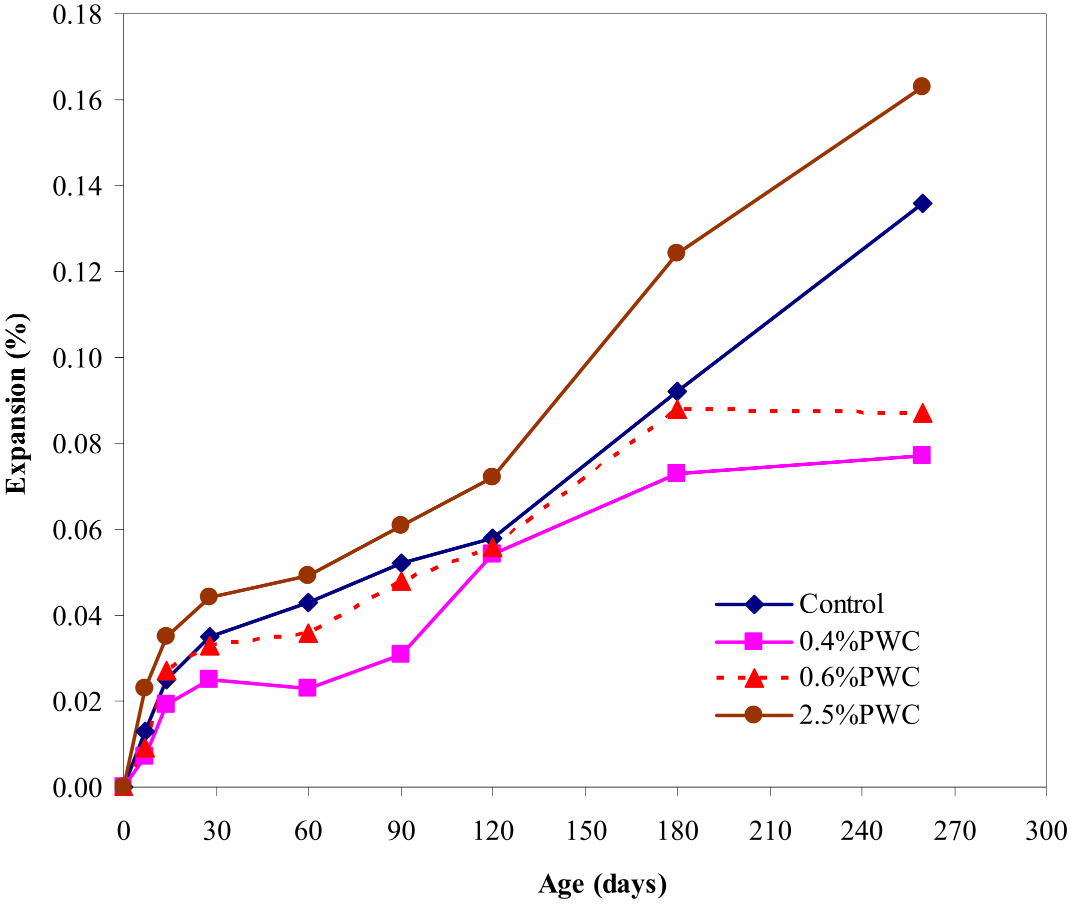

Figure 4.21: Expansion due to external sulphate attack as per ASTM C 1012

In Figure 4.22, expansion is seen to decrease for 0.4 % PWC and 0.6 % PWC samples at ages 28, 60, and 90 days. Further relative decrease in expansion was also observed for 0.4 % PWC and 0.6 % PWC samples at the late ages of 120, 180, and 260 days.

The influence of PWC additive on sulphate attack may partially be attributed to the pozzolanic reaction between the additive and $Ca(OH)_2$ formed during hydration process. This reaction results into secondary C-S-H and forms more dense mortar and pores of similar diameter. Consumption of excess calcium hydroxide due to pozzolanic reaction is reported by Sideris *et al.* (2006) to render it unavailable for the formation of ettringite and gypsum compounds. The formation of these compounds in hardened cementitious systems is responsible for expansion.

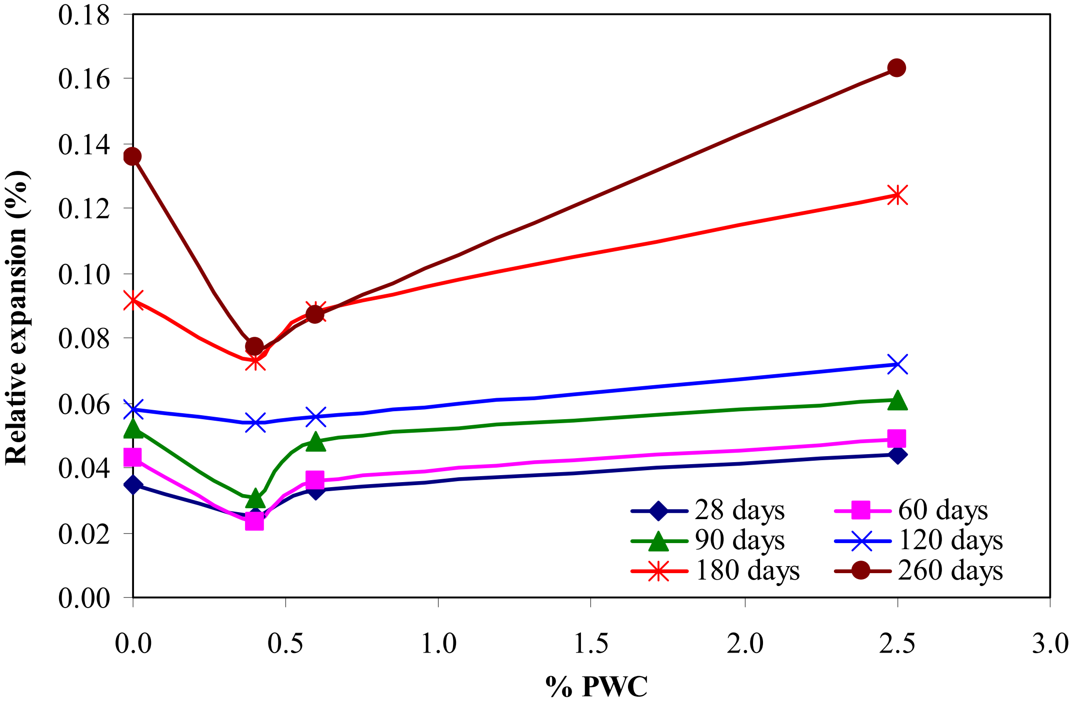

Figure 4.22: Relative expansion due to external sulphate attack between curing days for all samples.

In this study, increased dosage levels of 2.5 % PWC enhanced sulphate expansion. This aspect is beyond the scope of this investigation but may be related to the nature and quantity of modifying ingredients used.

4.4.7 Effect of PWC additive on the alkali silica reaction of mortar.

The alkali contents of the cement, PWC additive, and FA used were chemically analyzed. Results of the chemical analysis are shown in Table 4.9. The results show that PWC additive has higher alkali content than that of CEM 1 42.5N, while the alkali content of FA is lower than that of CEM 1 42.5N. The alkali content of PWC additive is higher than the recommended value of 0.6 % for ASR prevention (Neville, 1981).

Table 4.9: Alkali content of binders used

Binders	**Total alkali (%)**		
	Na_2O	K_2O	Na_2O_e
CEM 1 42.5N	Nil	0.43	0.3
FA	Nil	0.02	0.01
PWC	14.2	10.2	20.9

$$Na_2O_e = \%\ Na_2O + 0.658 \times \%\ K_2O$$

Figure 4.23 shows that the expansion of the control samples and the samples with 0.4 % PWC additive are similar. Expansion values of samples containing 0.6 % or more of PWC additive are higher than values for control samples. When PWC additive was used together with FA, similar expansion of -0.009 % was observed at 14 days for control, 0.6 % PWC + 30 % FA, and 1.0 % PWC + 30 % FA samples.

Table 4.10: % Reduction in expansion due to ASR of combined PWC and FA samples

Samples	**Curing age (days)**		
	14 days	**28 days**	**45 days**
Control	Datum	Datum	Datum
0.6 % PWC + 30 % FA + cement	0.0	-228.6	-150.0
1.0 % PWC + 30 % FA + cement	0.0	-200.0	-133.3
2.5 % PWC + 30 % FA + cement	55.0	-142.9	-75.0

Expansion was highly reduced when PWC additive was used together with FA in mixes. At 28 days, ASR expansion was reduced by a maximum percentage of 228.6 %, when 0.6 % PWC + 30 % FA proportions were used as shown in Table 4.10.

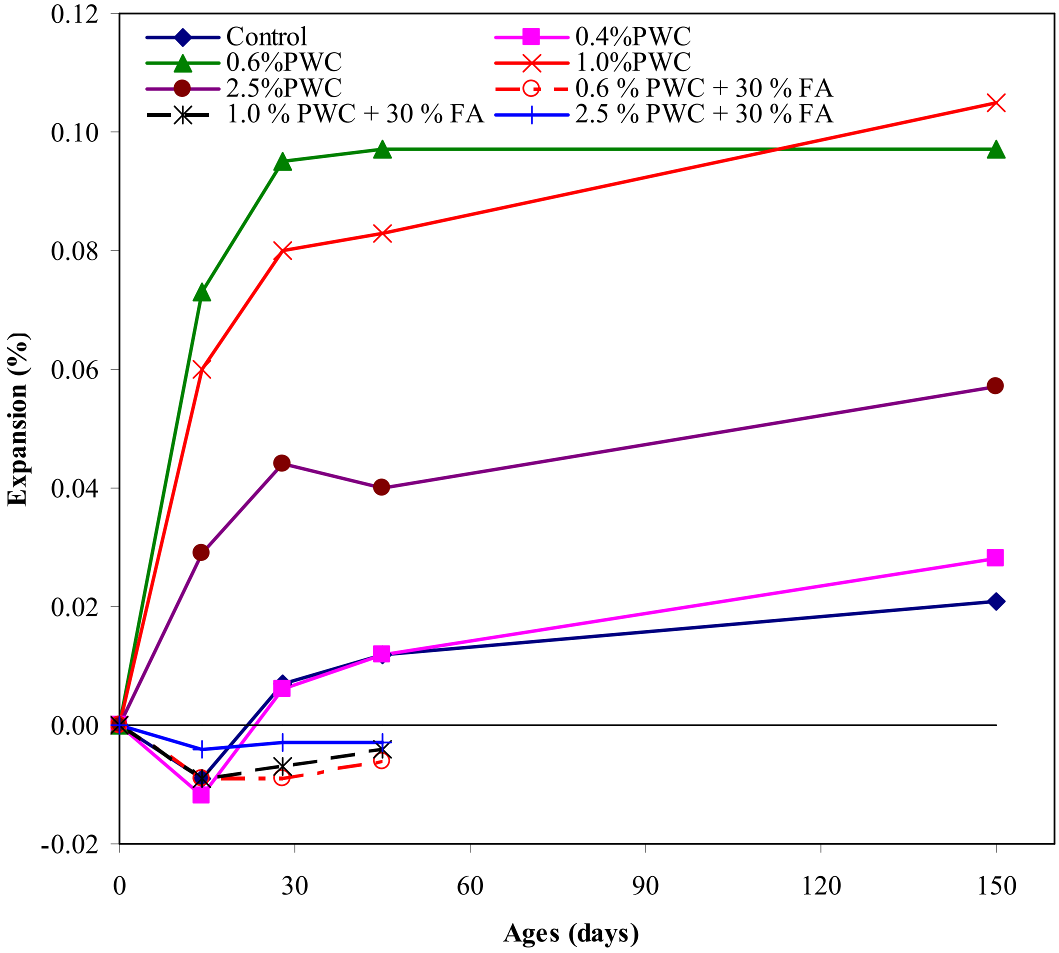

Figure 4.23: Expansion due to alkali silica reaction.

The greywacke aggregate used is highly reactive. It was the first aggregate to be recognized as exhibiting alkali reactivity in South Africa (Grieve, 1994). The Higher expansion observed with samples containing PWC additive only, with exception of 0.4 % PWC, may be as a result of the high content of alkali oxides in PWC additive compared to alkali content of CEM 1 42.5N and FA as shown in Table 4.9. In pozzolanic additives that are effective against ASR, the pozzolanic reaction between the additive and $Ca(OH)_2$ is expected to cause reduction in pH of the mortar pore solution (Quanlin and Naiqian, 2005; *I*lker *et al.*, 2008). This reduction in pH should then result in a decrease of expansion due to ASR (Quanlin and Naiqian, 2005). In the case of PWC, effect on ASR is adverse enhancing rather than reducing expansion.

4.5 CONCRETE PROPERTIES

4.5.1 Densities of concrete samples

The densities of 100 mm cube concrete samples prior to testing are recorded in Table 4.11. Results show that the compaction of the cubes was reasonably uniform, since the average densities do not differ greatly within each mix type. Samples with fly ash have lower densities than PWC samples and control for all test ages.

Table 4.11: Densities of concretes (Kg/m^3)

Curing days	**Binder**						
	Control	0.6 % PWC + Cement	1.0 % PWC + Cement	30 % FA + Cement	0.6 % PWC + 30 % FA + Cement	1.0 % PWC + 30 % FA + Cement	Premix
3	2672.1	2625.5	2658.6	2599.4	2627.2	2595.4	2556.2
28	2639.8	2631.7	2625.2	2584.7	2632.9	2587.0	2546.4
90	2658.4	2668.5	2641.8	2632.3	2582.7	2616.8	2557.1
180	2662.2	2682.8	2649.0	2605.2	2601.1	2602.8	2564.8

4.5.2 Effect of test age and PWC additive on concrete split tensile strength

Increase in split tensile strength between 28 and 180 days was observed for all samples, except control and 1.0 % PWC samples as shown in Figure 4.24. Control samples have higher strength at 28 days than other samples with PWC and FA additive. However, strength values of samples containing PWC and FA were higher at 180 days than the control samples, except premix samples. Premix samples, which contain 1 % PWC, 59 % FA and 40 % CEM 1 42.5N show relatively very low strength at both 28 and 180 days. Emphasis will not be laid on this sample because its results are unsatisfactory and may be of little value.

Samples with PWC additive only, showed higher strength at 28 days than samples containing FA additive. However, samples containing FA additive showed higher strength than samples containing only PWC additive at 180 days. The highest strength was observed with 1.0 % PWC +30 % FA samples at 180 days. The results given in Figure 4.24 also show that 0.6 % PWC samples exhibited higher strength than control and 1.0 % PWC samples at 180 days, which is a reverse trend to observations at 28 days.

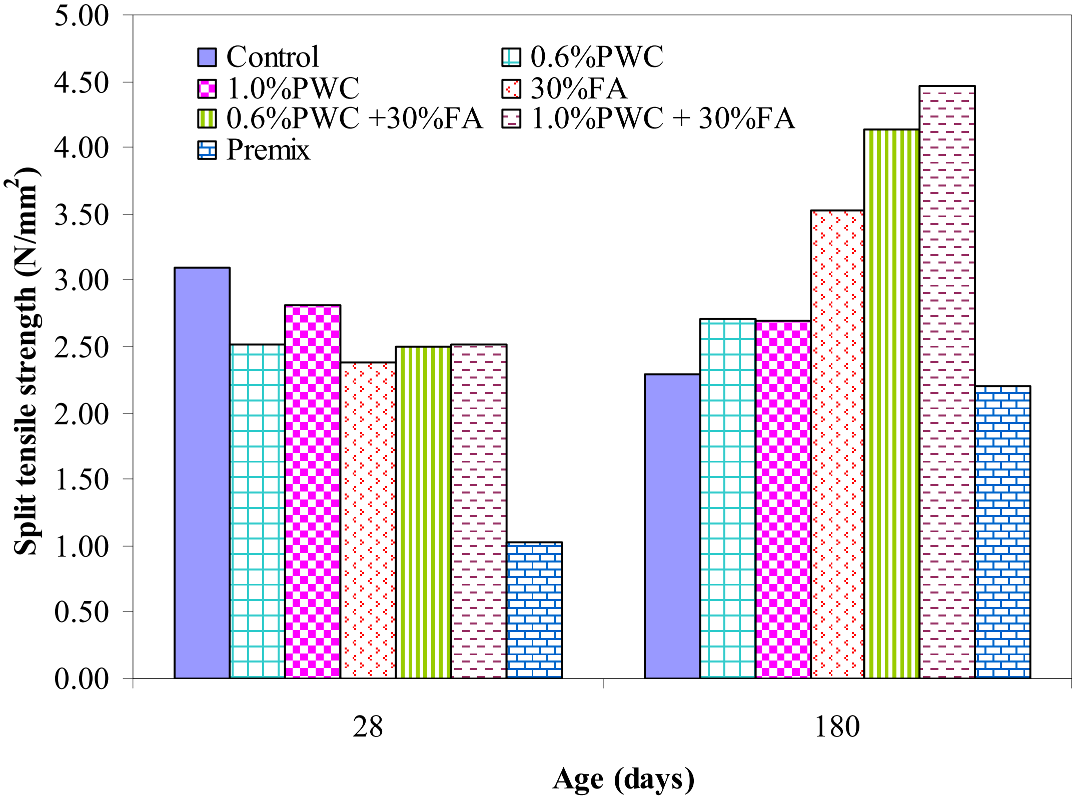

Figure 4.24: Split tensile strength against test age of concrete samples.

The strength gains at 180 days are 54.2 %, 80.8 % and 95.2 % for 30 % FA, 0.6 % PWC + 30 % FA and 1.0 % PWC + 30 % FA samples respectively. These results are represented in Figure 4.25. It can be inferred from the results that PWC additive enhanced the strength behaviour of FA additive. It was also shown in Figure 4.25 that PWC additive reduced the split tensile strength of concrete by a maximum percentage of 18.5 % at 28 days with 0.6 % PWC proportion, and increased it to maximum percentage of 18.3 % at 180 days with 0.6 % PWC.

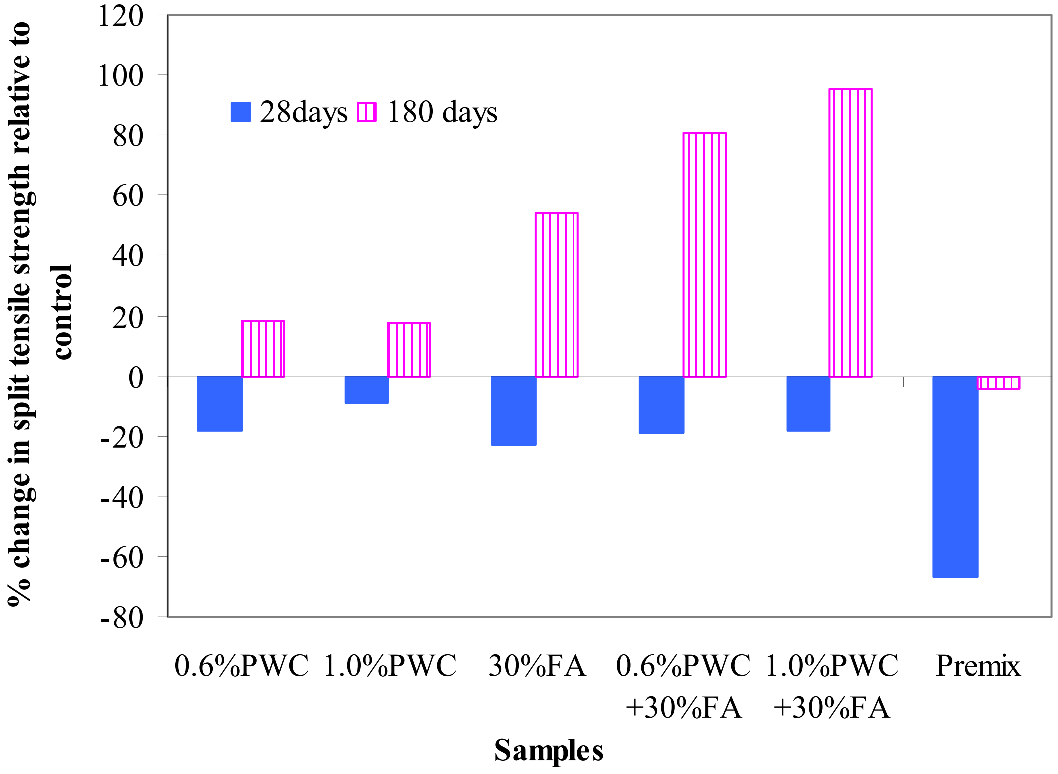

Figure 4.25: Percentage decrease or increase in split tensile strength relative to control.

In the case of FA additive, the split tensile strength of concrete was reduced by maximum percentage of 23 % at 28 days with 30 % FA proportion, and increased to maximum percentage of 54.2 % at 180 days with 30 % FA proportion. When PWC and FA additives were both used in a mix, the combination reduced the split tensile strength of concrete to a maximum percentage of 19.1 % at 28 days with 0.6 % PWC + 30 % FA proportion and increased it to a maximum percentage of 95.2 % at 180 days with 1.0 % PWC + 30 % FA proportion.

The reduction in early strength of PWC and FA additives samples compared to control samples is a characteristic trend for most pozzolanic material (Habert *et al.*, 2008). Higher split tensile strength of all samples containing additives beyond control samples was an evidence of pozzolanic reaction. PWC additive exhibited excellent result when used with FA additive.

4.5.3 Effect of test age and PWC additive on concrete compressive strength

Increase in compressive strength was observed in all samples as the curing period increases as seen in Figure 4.26. Premix samples, made of 1 % PWC + 59 % FA + 40 % OPC gave compressive strength results that were unsatisfactory throughout the testing period, as was the case for split tensile strength of the samples. Reduction in early strength was observed for samples containing FA additive while early strengths higher than those of control were observed with samples having PWC as the only additive. Higher strengths than for control samples were observed with samples containing FA additive when cured for at least 90 days.

It is clear in Figure 4.26 that the PWC additive improved both early and late compressive strength of concrete. FA additive has the effect of reducing the early compressive strength and increasing the late strength compared to control. Strength improvement was highly enhanced when both PWC and FA additives were used. This confirms the fact that PWC additive enhanced the strength behaviour of FA additive, as observed for split tensile strength. Highest strength was observed with 1.0 % PWC +30 % FA samples, followed by 0.6 % PWC +30 % FA samples from 90 days.

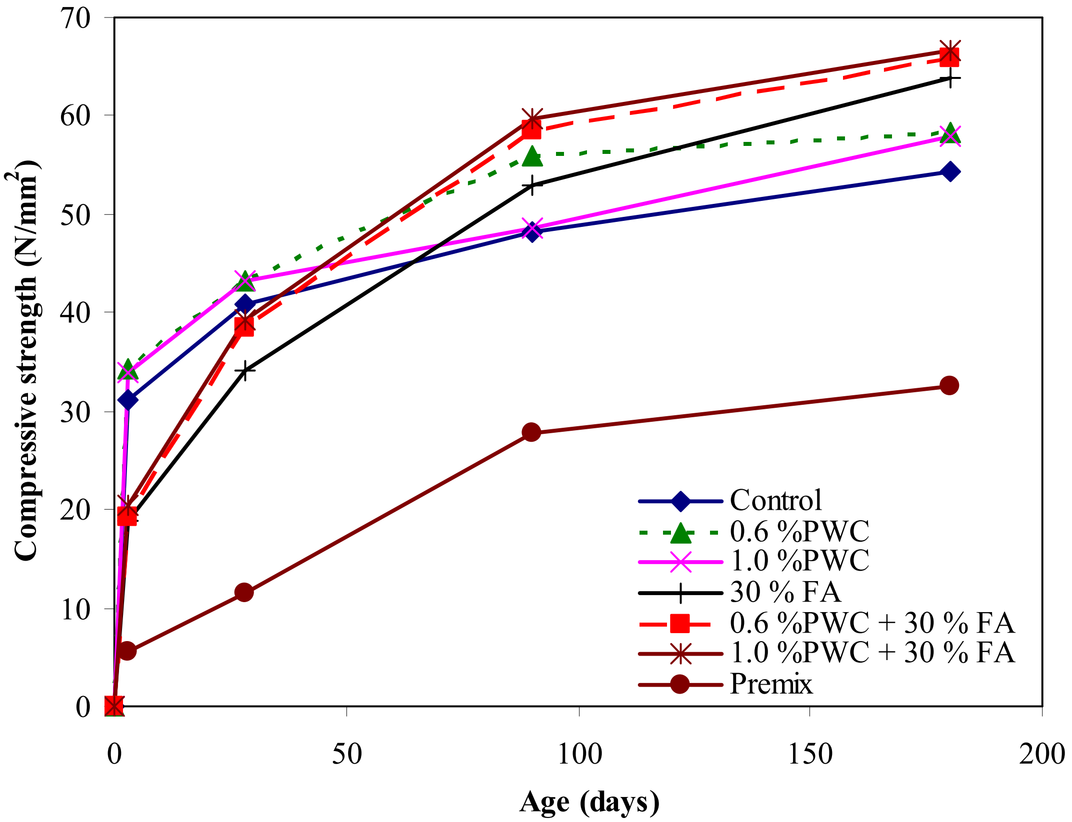

Figure 4.26: Compressive strength against test age of concrete samples.

Table 4.12 gives change in concrete compressive strength and corresponding percentage relative to control. Increased compressive strength of concrete by a maximum percentage of 15.8 % at 90 days was observed when only PWC additive was used with 0.6 % PWC proportion. Relative to control, 30 % FA additive reduced the compressive strength of concrete by maximum percentage of 39.7 % at 3 days with 30 % FA proportion and increased it by maximum percentage of 17.9 % at 180 days.

It was also observed that when the PWC and FA additives were used together, the combination reduced the compressive strength of concrete by maximum percentage of 38.4 % at 3 days with 0.6 % PWC + 30 % FA proportion, and increases it to maximum percentage of 22.7 % at 180 days with 1.0 % PWC + 30 % FA proportion.

Table 4.12: Change and % change in concrete compressive strength

Samples	Change in compressive strength (N/mm^2)				% Change in compressive strength			
	Age (days)				Age (days)			
	3	28	90	180	3	28	90	180
Control	Datum	Datum	Datum	Datum	Datum	Datum	Datum	Datum
0.6 % PWC	3.09	2.35	7.62	4.07	9.9	5.8	15.8	7.5
1.0 % PWC	2.77	2.24	0.32	3.74	8.9	5.5	0.7	6.9
30 % FA	-12.37	-6.85	4.74	9.69	-39.7	-16.78	9.8	17.9
0.6 % PWC + 30 % FA	-11.99	-2.51	10.29	11.59	-38.4	-6.1	21.3	21.4
1.0 % PWC + 30 % FA	-10.86	-17.20	11.35	12.34	-34.8	-4.2	23.5	22.7
Premix	-25.66	-29.34	-20.42	-21.81	-82.3	-71.7	-42.3	-40.2

The increase and decrease trends are represented in Figure 4.27. A similar trend of increase or decrease in strength for additives samples, compared to those for control samples was observed for both split tensile and compressive strength. Samples with 1.0 % PWC + 30 % FA proportion have the highest strength value for both split tensile and compressive strength at 180 days.

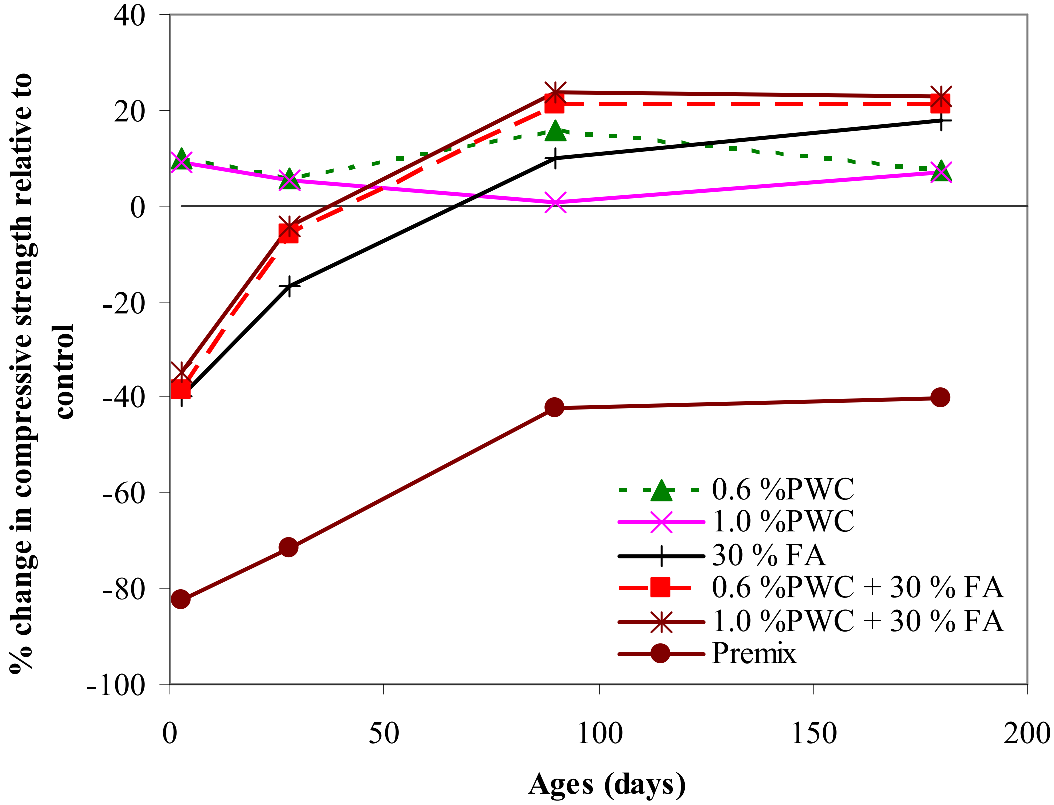

Figure 4.27: Percentage decrease or increase in compressive strength of concrete samples relative to control.

The observed results in this study agree with observations made by Poon *et al*. (1999) where the pozzolanic activity of natural zeolite was reported to be higher than that of fly ash. It was further explained that mortars and concrete blended with natural zeolite tend to have higher early strength compared to fly ash blended mortars and concretes due to the higher pozzolanic activity of zeolites. The PWC additive is a modified zeolite and improved pozzolanic activity may be expected with PWC additive. This may explain the increased early strength observed in PWC concrete samples compared to the lower early strengths for FA additive samples. With reference to split tensile and compressive strength results of concrete, 0.6 % PWC and 1.0 % PWC samples showed satisfactory results. The performance of PWC additive can be highly enhanced when used in conjunction with FA additive. Accelerated compressive strength test was performed on mortar samples to confirm this observation.

4.5.4 Effect of Test Age and PWC Additive on Mortar Accelerated Compressive Strength (Comparison to Concrete).

Figure 4.28 shows reduction in compressive strength of samples containing PWC and FA additives when compared to control samples at 3 days curing period. Improvement in strength was observed for samples containing both PWC additive and FA from 14 days onwards.

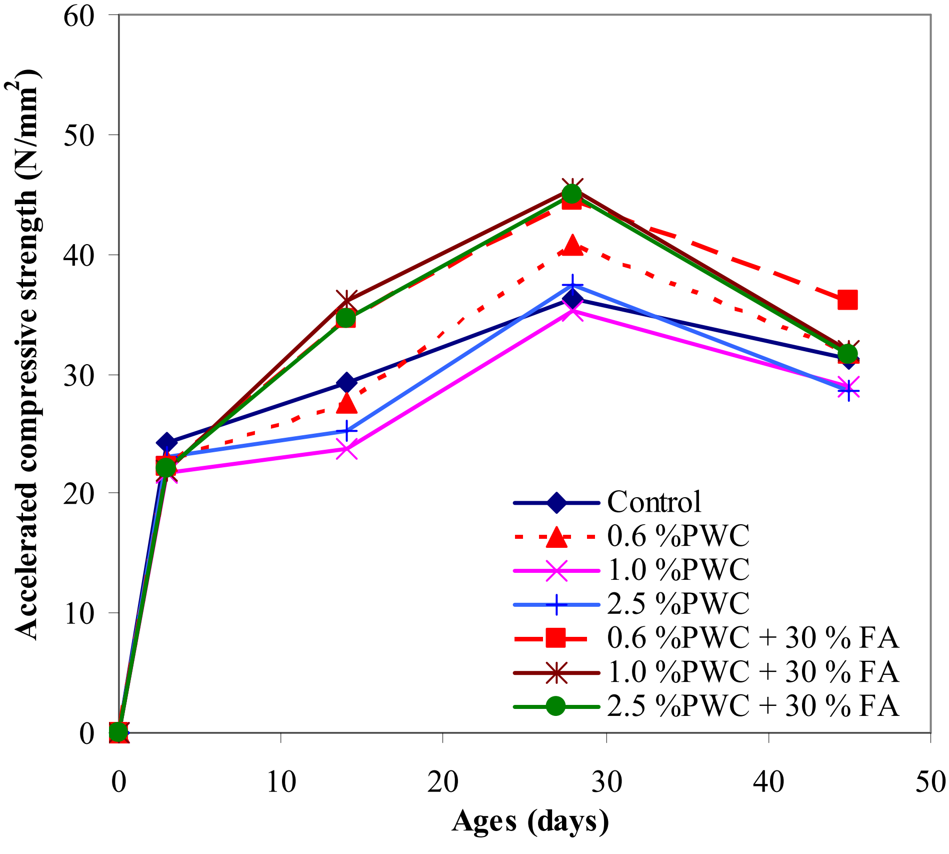

Figure 4.28: Accelerated compressive strength against test age of mortar samples.

The early strength improvement of PWC and FA additives combined samples may be as a result of higher curing temperature of 50 ^{o}C used. With only PWC additive, compressive strength was increased by a maximum percentage of 12.6 % at 28 days when used at 0.6 % PWC proportion. For PWC and FA additives combined samples, there was maximum of 25.6 % increase in compressive strength at 28 days with 1.0 % PWC + 30 % FA sample as shown in Table 4.13. This observation confirms that FA additive enhanced the strength behaviour of PWC additive. Reduction in strength at 45 days was observed for all the samples, which may be as a result of the accelerated curing done at 50 ^{0}C.

Table 4.13: % Change in mortar accelerated compressive strength relative to control

Samples	**Curing age (days)**		
	14 days	**28 days**	**45 days**
Control	Datum	Datum	Datum
0.6 % PWC + cement	-5.7	12.6	1.6
1.0 % PWC + cement	-18.9	-2.8	-7.7
2.5 % PWC + cement	-13.4	3.3	-9.0
0.6 % PWC + 30 % FA + cement	18.2	22.7	15.4
1.0 % PWC + 30 % FA + cement	23.6	25.6	1.8
2.5 % PWC + 30 % FA + cement	18.3	24.2	0.8

The strength results obtained for mortar samples and concrete samples indicated that PWC additive has the ability to improve mortar and concrete strength when used at proportion as low as 0.6 %. These results were compared with the findings of Naiqian *et al*., (1993), who investigated a modified zeolite, named FMA. It was reported from their findings that FMA improves concrete strength when used to replace 5 to 10 % of the ordinary Portland cement at water-cement ratio of about 0.35. Low dosages of PWC additive in improving mortar and concrete strength at water-cement ratio of 0.4 can be a significant advantage over other types of modified zeolites such as FMA.

4.5.5 Effect of PWC additive on concrete oxygen permeability, sorptivity, and porosity.

As shown in Figure 4.29, reduction in permeability was observed for all samples between 28 and 180 days. Premix samples (1 % PWC + 59 % FA + 40 % OPC) showed a highly remarkable decrease in permeability between 28 and 180 days. The PWC additive, when used as the only additive, did not seem to reduce permeability of concrete to an extent lower than the permeability of control samples.

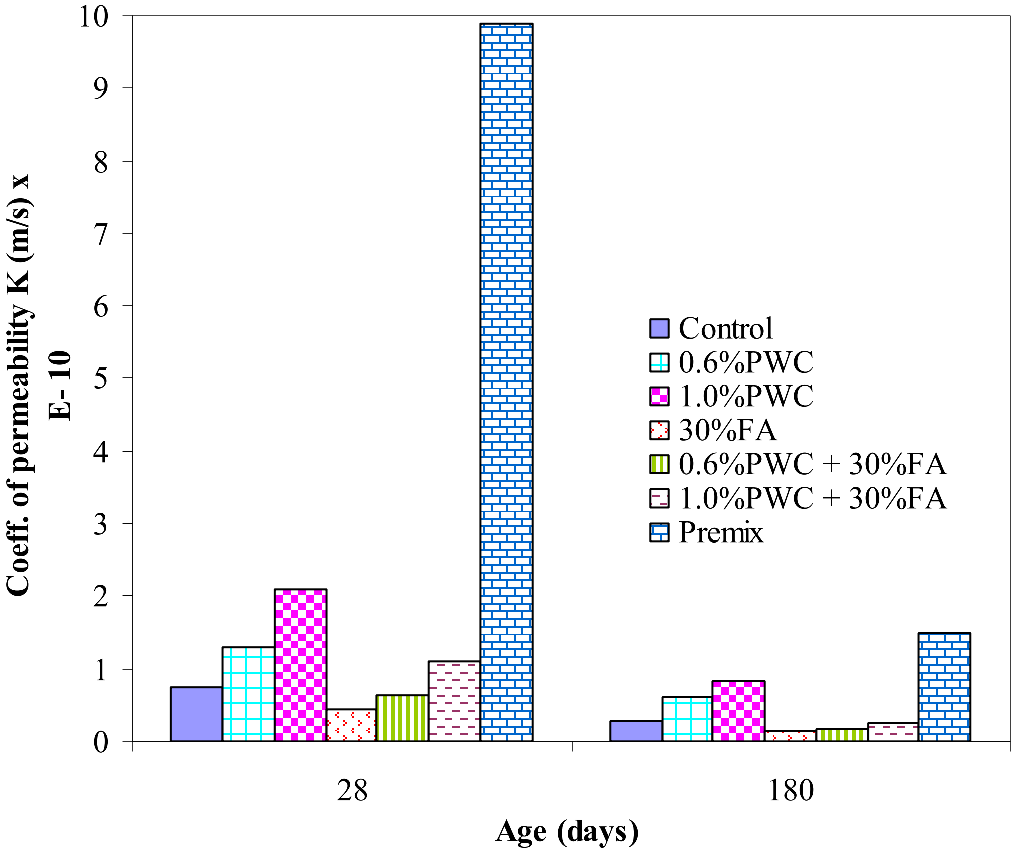

Figure 4.29: Coefficient of permeability of concrete samples.

When used in conjunction with FA additive, PWC additive performs excellently by reducing the permeability of concrete samples by up to 37.0 % at 180 days for 0.6 % PWC + 30 % FA proportion. FA additive reduced permeability of concrete when used as the only additive by up to 39.2 % at 28 days and up to 51.9 % at 180 days for the 30 % FA proportion as seen in Figure 4.30.

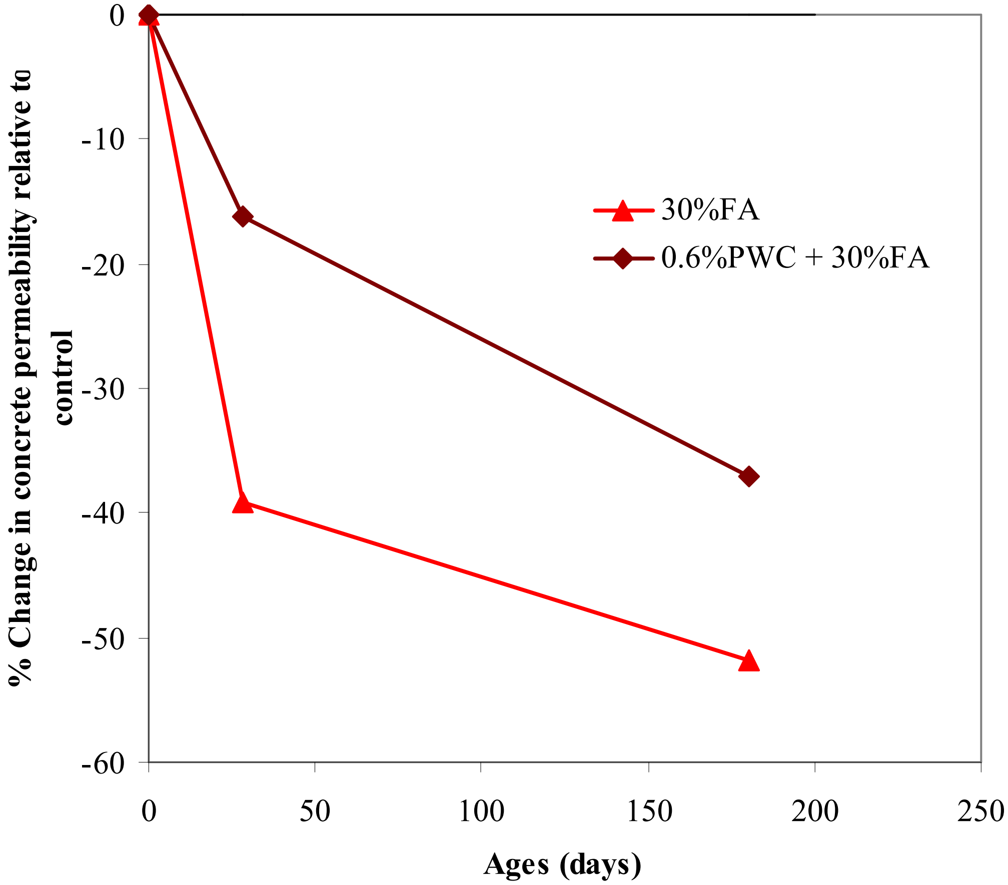

Figure 4.30: Percentage decrease or increase in permeability of concrete samples relative to control.

The sorptivity of control concrete was higher than that of all other samples, including premix samples (1 % PWC + 59 % FA + 40 % CEM 1 42.5N) at both 28 and 180 days. This trend was the same as results for mortar samples discussed in Section 4.4.4 and shown in Figure 4.16. Figure 4.31 shows that FA additive improved sorptivity property of concrete more than PWC additive.

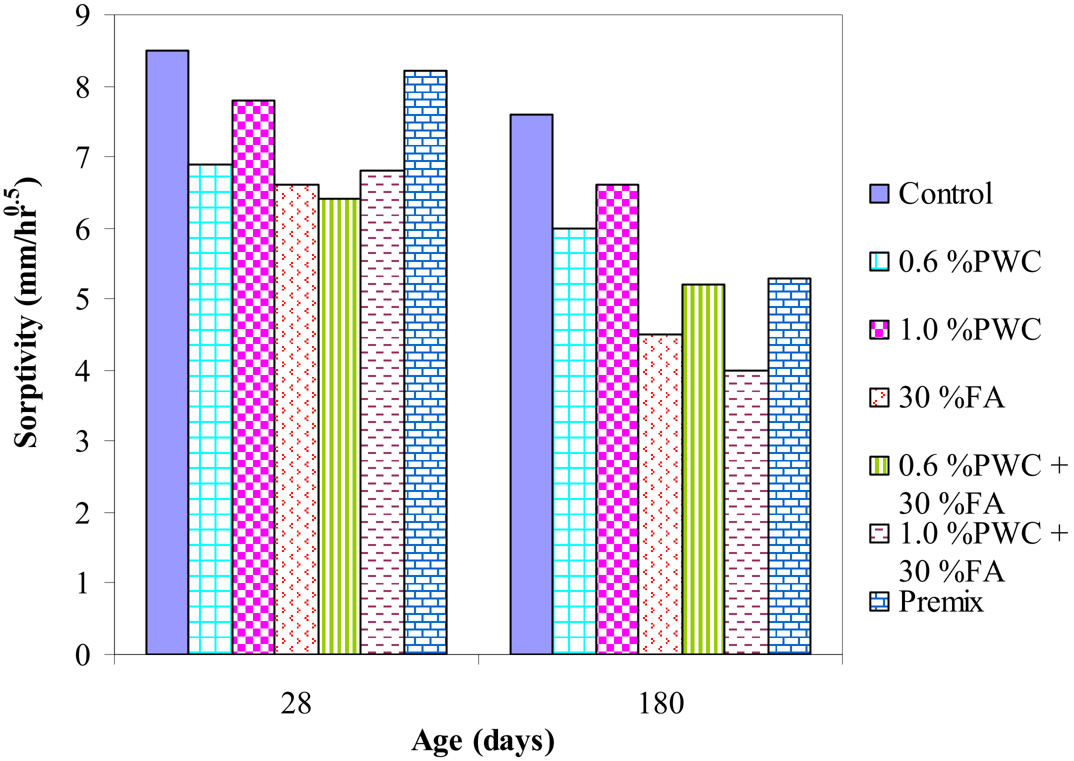

Figure 4.31: Sorptivity of concrete samples.

The 30 % FA additive reduced sorptivity of concrete by a maximum percentage of 40.8 % at 180 days, while 0.6 % PWC additive reduced sorptivity of concrete by a maximum percentage of 21.1 % at 180 days as given in Table 4.14. When both PWC and FA additives were used, sorptivity of concrete was further reduced by a maximum percentage of 47.4 % at 180 days for 1.0 % PWC + 30 % FA proportion; this is represented in Figure 4.32.

Table 4.14: % Change in concrete sorptivity relative to control

Samples	**Curing days**	
	28	**180**
Control	Datum	Datum
0.6 % PWC + cement	-18.9	-21.1
1.0 % PWC + cement	-18.9	-13.2
30 % FA + cement	-22.4	-40.8
0.6 % PWC + 30 % FA + cement	-24.7	-31.6
1.0 % PWC + 30 % FA + cement	-20.0	-47.4

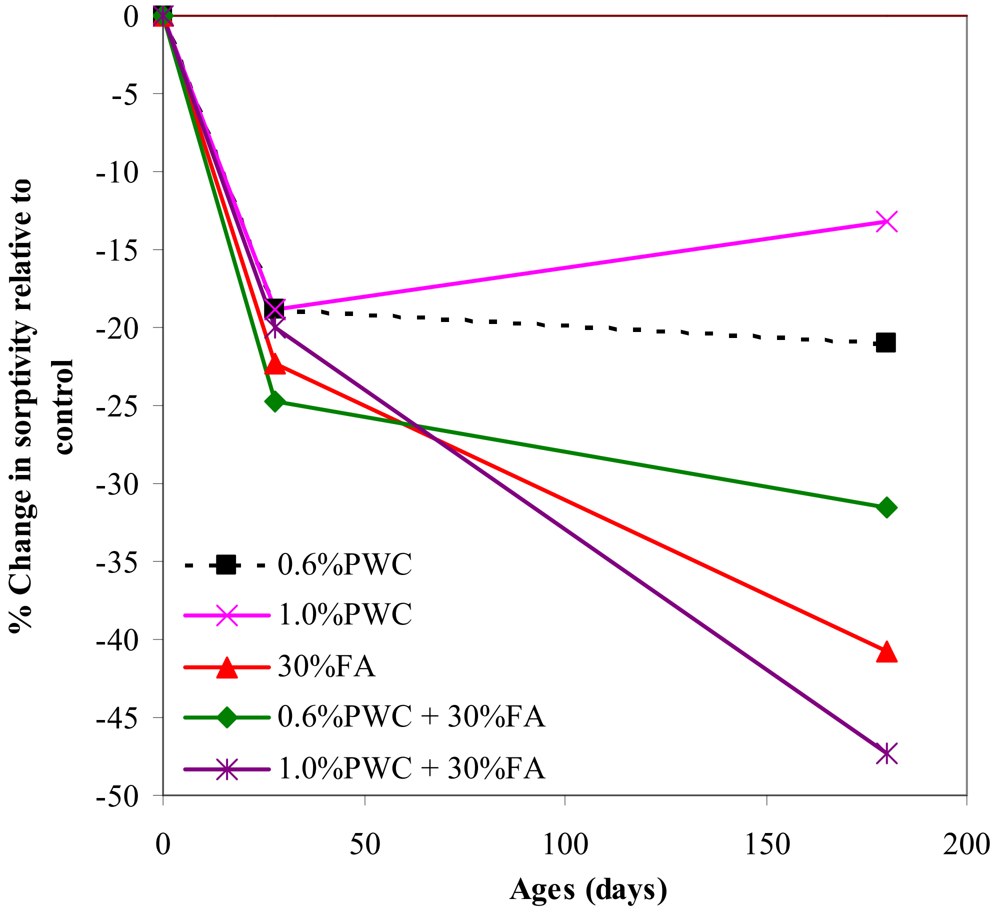

Figure 4.32: Percentage decrease and increase in sorptivity of concrete samples relative to control.

Porosity of control samples was seen in Figure 4.33 to be higher than all other samples at both 28 and 180 days. Samples prepared with both PWC and FA additives in their mixes exhibited lower porosity than samples with only PWC additive. Reduction in porosity by PWC additive was also observed for mortar samples as explained in Section 4.4.4 and shown in Figure 4.18. FA was seen to help in reducing the porosities of PWC samples.

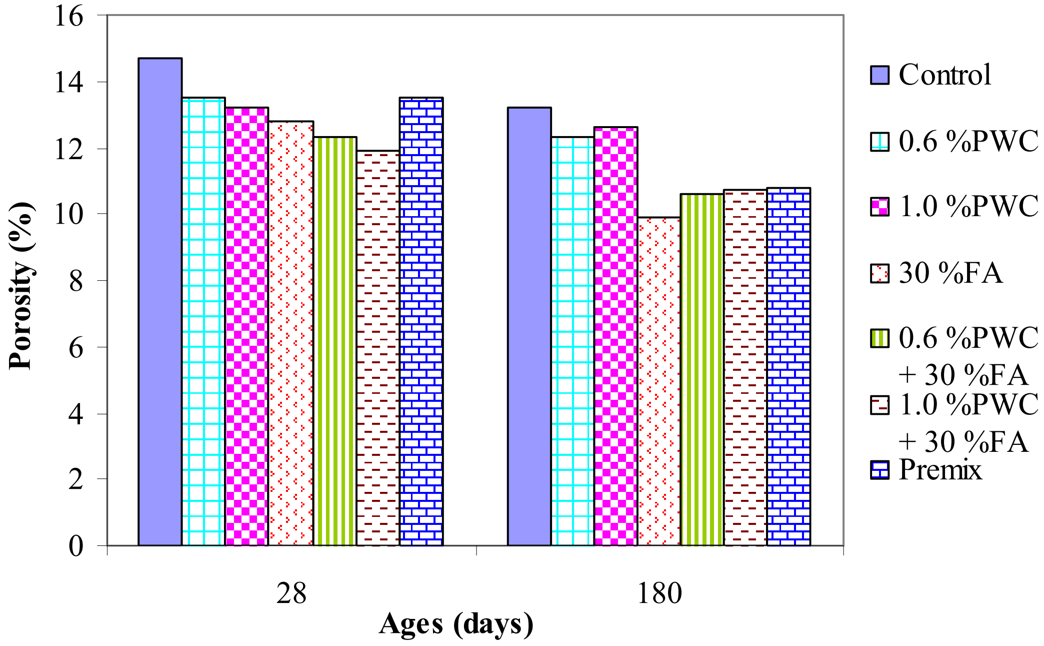

Figure 4.33: Porosity of concrete samples.

Table 4.15 shows that, when only PWC additive was used, porosity of control samples was reduced by a maximum percentage of 10.2 % at 28 days for 1.0 % PWC proportion. In the case of combined use of PWC and FA additives, porosity was reduced by a maximum percentage of 19.7 % at 180 days for 0.6 % + 30 % FA samples. Figure 4.34 shows the trend in porosity reduction relative to control.

Table 4.15: % Change in concrete porosity relative to control

Samples	**Curing days**	
	28	**180**
Control	Datum	Datum
0.6 % PWC + cement	-8.2	-6.8
1.0 % PWC + cement	-10.2	-4.6
30 % FA + cement	-12.9	-25.0
0.6 % PWC + 30 % FA + cement	-16.3	-19.7
1.0 % PWC + 30 % FA + cement	-19.1	-18.9

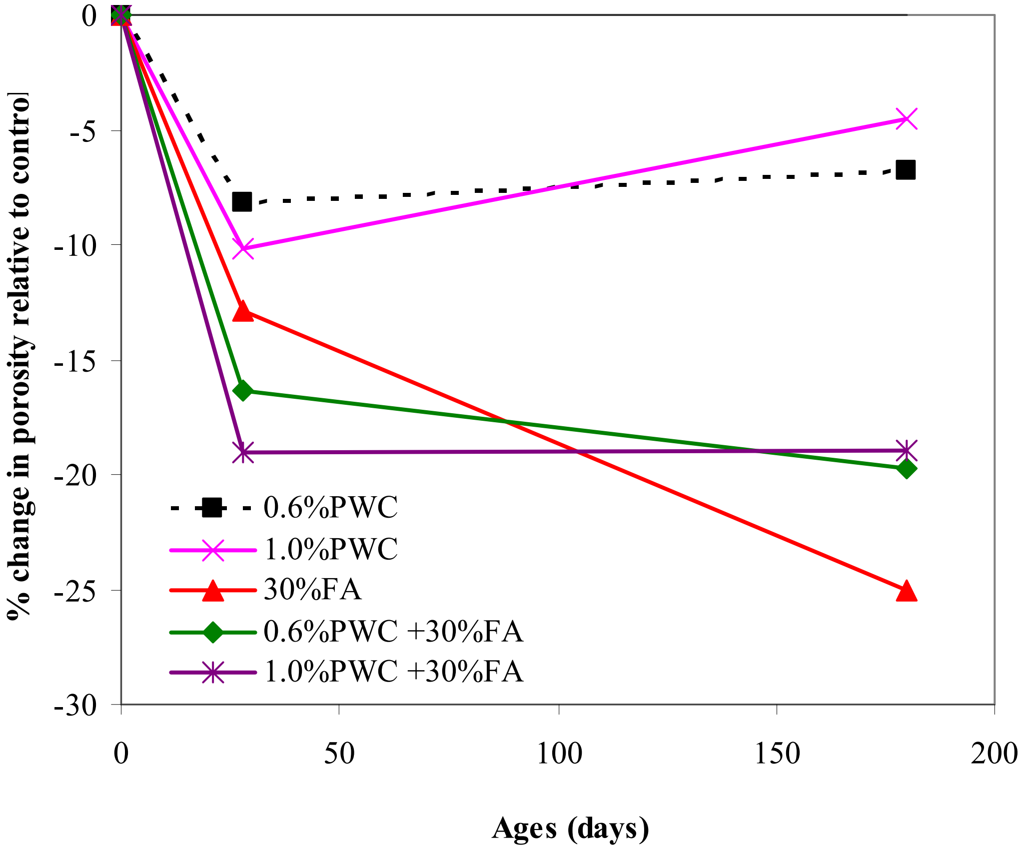

Figure 4.34: Percentage decrease or increase in porosity of concrete samples relative to control.

Reduction in permeability between 28 and 180 days for all samples confirmed that the coefficient of permeability decreases with an increase in the degree of hydration or curing time (Nemkumar, 1989; Tarun *et al.*, 1994). The same trend was also observed for mortar samples. Hydration and pozzolanic reactions reduced the continuous pore distribution of the samples making them less permeable.

FA additive was finer than PWC additive and OPC used, as earlier shown in Table 4.1. This and other factors makes FA additive more effective as a pore refiner. The reduced permeability and porosity caused by FA additive may be a consequence of pore refinement due to FA additive addition. It was stated by Gopalan (1996) that sorptivity of properly cured concrete can be reduced by up to 37 % if part of the cement used is replaced by 40 % FA. In this study, the enhancement of FA by PWC additive improved sorptivity by up to 47.4 %.

4.5.6 Effect of PWC additive on concrete carbonation.

The carbonation test was performed at only 28 days age of curing. The test could not be performed at later age(s) due to problems with equipment. Therefore, this discussion is limited to the comparison of the carbonation depth of concrete with, and without additive at 28 days curing period. It is recognized that this age may be quite early for certain additives to make effect on concrete properties.

The results given in Figure 4.35 show that the use of PWC additive as the only additive resulted in a reduction of carbonation depth when compared to the control. However, the use of FA additive increased the carbonation depth when used as the only additive and also when used in conjunction with PWC additive. Premix samples (1 % PWC + 59 % FA+ 40 % CEM 1 42.5N) showed full carbonation at 28 days, so no carbonation depth was recorded. Use of the PWC additive reduced carbonation depth when compared by up to 21.2 % with 0.6 % PWC proportion.

Increase in carbonation depth of samples containing FA additive at 28 days may be as a result of the slow pozzolanic reactivity of FA and also the proportion of FA additive used. In this study, the strength results suggest that PWC reacts rapidly giving effect as early as 28 days, unlike FA. The proportion of FA may also affect carbonation depth as stated by Kritsada and Lutz (2007) that carbonation depth increases with corresponding increase of fly ash in concrete mixtures at early ages. This statement is evidence with premix samples where FA additive content was 59 % and as a result full carbonation was observed at 28 days.

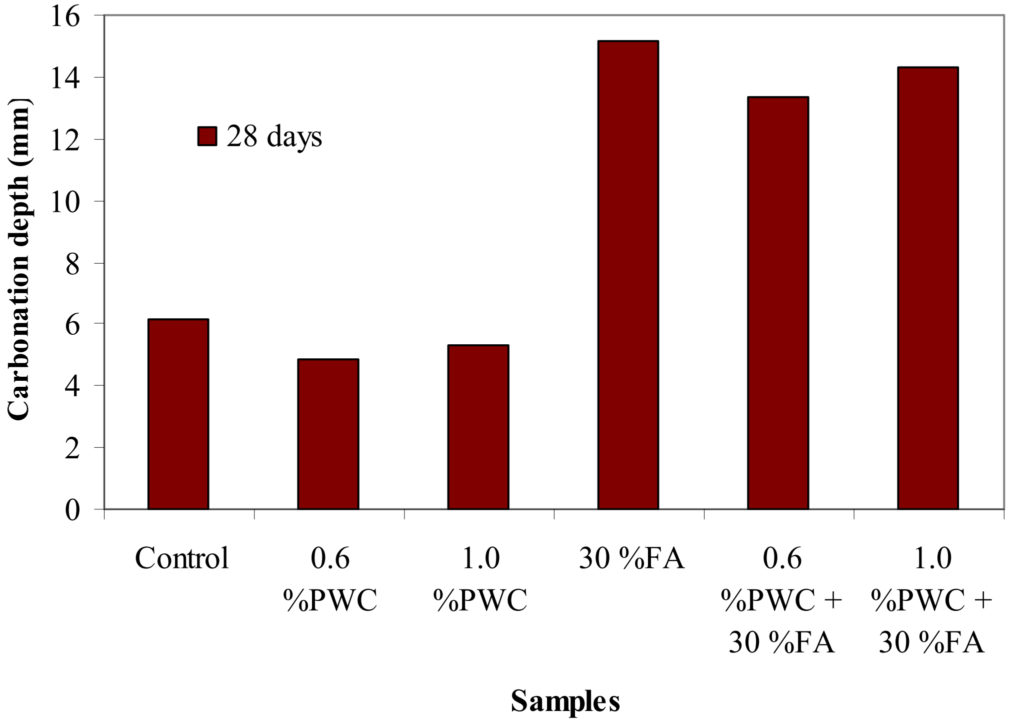

Figure 4.35: Carbonation depth of concrete samples.

The behaviour of PWC additive was different from the behaviour of the FA additive in that it reduced carbonation depth at 28 days. This may be as a result of the higher pozzolanic reactivity of PWC additive than FA and the small quantities of 0.6 % and 1.0 % PWC proportions of PWC additive used. There is possibility of reduction in carbonation depth of FA additive samples at later curing ages, due to reduced permeability, reduced sorptivity and improved pore structure.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

In this study, the effect of the use of PowerCem additive in improving mortar and concrete properties was investigated. The PWC additive was added to several mortar or concrete samples in varying proportions. As a control, a mortar or concrete sample with no additive was prepared. Properties of the control were evaluated and compared to the corresponding properties of samples in which PWC additive was used. The properties of mortars and concretes that were evaluated included workability, flexural strength, split tensile strength, compressive strength, resistance to sulphate attack, alkali-silica reaction resistance, oxygen permeability, sorptivity, porosity, and carbonation. Thermal analysis utilizing DTA/TGA was employed to determine changes in hydration products developed in pastes. Based on observations and trends determined from the results of this evaluation, the following conclusions were made:

1. The thermal analysis results indicate that PWC additive is a pozzolanic material and aids the consumption of $Ca(OH)_2$. Its usage in proportions beyond 0.6 % of cement did not seem to enhance the pozzolanic reaction.

2. The workability (flow test) test showed that PWC additive improves the workability of mortar when used at proportions beyond 0.8 %. Below this dosage, PWC additive did not affect the workability of mortar.

3. An increase in flexural strength beyond that of the control sample was observed with 0.6 % PWC additive samples at late ages after 28 days. On contrary, a decrease in flexural strength of mortar occurs when PWC additive is at dosages greater than 0.6 %. The same trend occurs for compressive strength. Increase in compressive strength beyond that of the control was observed at late ages after 90 days curing period with 0.4 % PWC and 0.6 %

PWC additive samples. PWC samples with proportions greater than 0.6 % PWC gave decrease in compressive strength when compared to corresponding strength of the control.

4. Split tensile strength of concrete with PWC additive exhibits a similar trend as the flexural strength of mortars. At 28 days curing period, PWC concrete samples exhibited a decrease in split tensile strength compared to control, but at 180 days their split tensile strength increased to values higher than that of control samples.

5. The use of PWC in concrete generally increases both early and late compressive strengths when compared to the strengths of the control.

6. Based on strength results, the optimum proportion lies between 0.4 % and 0.6 % PWC. Long-term curing is needed for PWC for proper strength development in systems containing PWC.

7. It was found that the effect of PWC additive on mortar and concrete strength improves significantly when it is used in conjunction with FA. When 30 % FA was used with 0.6 % PWC additive in concrete, there was 21.3 % increase in compressive strength at 180 days when compared to the control. With 0.6 % PWC additive alone, a small increase of 7.5 % in compressive strength was observed at 180 days. Accelerated compressive strength test on mortar samples also showed 25.6 % increase in compressive strength with 1.0 % PWC + 30 % FA sample at 28 days and 12.6 % increase in compressive strength with only 0.6 % PWC additive without FA at 28 days.

8. PWC additive improves mortar permeability when used at proportions below 0.8 %. At higher contents exceeding 0.8 %, the PWC additive increases mortar permeability. The same trend as in mortar permeability was observed

for mortar porosity. This suggests that the optimum proportion should be below 0.8 %. PWC reduces the sorptivity of mortars and concretes regardless of PWC dosage.

9. Concrete permeability improved only when PWC additive was used in conjunction with FA. PWC additive improves concrete porosity, but further reduction in porosity was observed when used together with FA. Results show that PWC additive is most effective when used in the presence of FA.

10. It was found that when PWC additive is used at low dosages of 0.4 % and 0.6 % PWC, it causes reduction in expansion due to sulphate attack. At higher dosages of PWC additive, greater expansion occurs when compared to control samples. Again this result indicates that the optimum proportion of PWC additive to be used may lie in the range between 0.4 % and 0.6 %.

11. The use of PWC additive in reducing expansion due to alkali-silica reaction might be adverse. Higher expansions than for control were observed with PWC additive samples. This is explained by the very high alkali contents of PWC of 21 % Na_2O_e. When PWC additive was used together with FA in mixes, lower ASR expansions than for control were observed, this further confirms that PWC is most effective in the presence of FA.

12. PWC use in concrete reduces carbonation. Carbonation depth was reduced by up to 21 % in concrete of 28 days age due to use of 0.6 % PWC additive. When PWC additive was used in conjunction with 30 % FA, there was an increase in carbonation as a direct result of using FA.

In general, this study shows that the optimum proportion for use of PWC additive in mortars and concrete lies between 0.4 % and 0.6 %. Within this range of proportions, PWC additive increases late flexural strength, split tensile strength, and compressive strength of mortars and concretes. It also decreases permeability, sorptivity, porosity, and expansion due to sulphate attack. Addition of the modified zeolite (PWC additive) beyond these optimum proportions might be adverse. Where ASR is involved, use of PWC should be done cautiously. The effect of PWC additive on mortar and concrete can be enhanced in the presence of FA when combined.

A clear distinction observed from this study was that modified zeolite (PWC additive) can be used in remarkably low proportions compared to natural zeolite that requires high proportions of up to 15 % to improve concrete properties. The low optimum proportions favor economic considerations.

5.2 RECOMMENDATIONS

The following further researches are recommended:

1. Further investigation is needed on the proportion of FA to be used together with PWC additive, because only 30 % FA proportion was considered in this study.

2. There is need to study the behaviour of PWC additive in the presence of other pozzolans apart from fly ash (FA).

3. Further research is required to understand the resistance to sulphate attack behaviour of PWC additive in conjunction with other pozzolans.

4. Concrete carbonation depths need to be observed after a long term curing period before a final conclusion can be made on the effect of PWC on concrete carbonation.

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APPENDIX A: DETAILED EXPERIMENTAL RESULTS

Table A-1: Tests matrix of phase 1 (Mortar)

TESTS	MIX (additives)						W/B
	Control	0.4 % PWC	0.6 % PWC	0.8 % PWC	1.0 % PWC	2.5 % PWC	
Compressive strength	X	X	X	X	X	X	0.5
Flexural strength	X	X	X	X	X	X	0.5
Flow	X	X	X	X	X	X	0.5
ASR expansion	X	X	X	-	X	X	0.4
External sulfate resistance	X	X	X	-	-	X	0.485
Internal sulfate resistance	X	X	X	-	-	X	0.49
Oxygen permeability	X	X	X	X	X	X	0.5
Sorptivity	X	X	X	X	X	X	0.5
Porosity	X	X	X	X	X	X	0.5
Chemical analysis (DTA)	X	X	X	X	X	X	0.5

PWC -------------------------- PowerCem
X --------------------------- Test required
W/B ------------------- Water/ Binder ratio
- --------------------- Test not required

Table A-2: Tests matrix of phase 2 (Concrete)

TESTS	**MIX (additives)**							**W/B**
	Control	0.6 % PWC	1.0 % PWC	30 % PFA	0.6% PWC + 30 % PFA	1.0 % PWC + 30 % PFA	40 % OPC + 59 % PFA + 1 % PWC	
Compressive strength	X	X	X	X	X	X	X	0.5
Split tensile strength	X	X	X	X	X	X	X	0.5
Workability (slump)	X	X	X	X	X	X	X	0.5
Oxygen permeability	X	X	X	X	X	X	X	0.5
Sorptivity	X	X	X	X	X	X	X	0.5
Porosity	X	X	X	X	X	X	X	0.5
Carbonation	X	X	X	X	X	X	X	0.5

PWC -------------------------- PowerCem
OPC ------------------------- Ordinary Portland cement (CEM 1 42.5N)
PFA ------------------------- Pulverized fuel ash
X --------------------------- Test required
W/B -------------------Water/Binder ratio

Table A-3: Grading analysis of prepared silica standard sand

Sieve Size (µm)	% Retained	% passing	Cumulative % Retained
2000	0	100	0
1680	4.8	95.2	4.8
1400	6.5	88.7	11.3
1180	14.4	74.3	25.7
600	30.1	44.2	55.8
425	19.8	24.4	75.6
300	8.3	16.1	83.9
150	9.0	7.1	92.9
75	4.7	2.4	-
< 75	2.4	0	-
	100	-	350.0

Fineness modulus = 3.5

Table A-4: Grading analysis of European silica standard sand

Sieve Size (µm)	% Retained	% passing	Cumulative % Retained
2000	0.00	100.00	0.00
1680	6.02	93.98	6.02
1400	8.98	85.00	15.00
1180	11.63	73.37	26.63
600	39.81	33.56	66.44
425	1.00	32.56	67.44
300	2.44	30.12	69.88
150	23.51	6.61	93.39
75	6.19	0.42	-
< 75	0.42	0	-
	100	-	344.8

Fineness modulus = 3.45

Table A-5: Compressive strength values of silica standard sand

Sample	Curing days	Compressive strength (N/mm^2) 1	2	3	Average value (N/mm^2)
Mortar with Prepared silica standard sand	3	15.68	15.24	17.28	16.07
	7	25.96	24.48	27.16	25.87
	28	31.44	32.76	32.08	32.09
	90	55.40	53.72	55.68	54.93
Mortar with European silica standard sand	3	18.44	16.2	18.00	17.55
	7	26.80	25.88	30.08	27.59
	28	36.04	32.64	35.80	34.83
	90	55.60	57.04	58.16	56.93

Table A-6: Flow test results of mortar samples

	Control		0.4 % PWC + Cement		0.6 % PWC + Cement		0.8 % PWC + Cement		1.0 % PWC + Cement		2.5 % PWC + Cement	
Reading	**Run 1**	**Run 2**	**Run 1**	**Run 2**	**Run 1**	**Run 2**	**Run 1**	**Run 2**	**Run 1**	**Run 2**	**Run 1**	**Run 2**
1	112.10	112.40	111.39	112.8	110.10	113.40	111.90	114.20	119.45	120.02	136.02	134.60
2	112.34	112.60	111.14	113.42	112.43	112.90	112.53	113.92	115.64	119.90	133.68	136.40
3	114.20	113.80	111.62	113.2	112.21	113.60	112.20	113.80	119.58	120.20	129.62	137.20
4	113.12	113.20	112.96	113.00	112.52	113.20	112.00	114.40	118.14	119.50	134.68	138.00
Average 1	112.94	113.00	111.78	113.11	111.82	113.28	112.15	114.08	118.20	119.91	133.50	136.55
Average 2	112.97		112.46		112.55		113.48		119.06		135.03	

Table A-7: Flexural strength results of mortars

Materials	Days	Load (Kg)	Load (Kg)	Average Strength (N/mm^2)
Control	7	350	342	3.64
	28	402	422	4.35
	90	442	474	4.83
	120	442	456	4.74
	180	458	479	4.94
0.4 % PWC + Cement	7	346	342	3.63
	28	416	400	4.30
	90	428	466	4.71
	120	440	456	4.73
	180	444	476	4.85
0.6 % PWC + Cement	7	340	320	3.48
	28	442	420	4.55
	90	462	456	4.84
	120	482	494	5.14
	180	500	490	5.22
0.8 % PWC + Cement	7	322	326	3.42
	28	382	384	4.04
	90	418	428	4.46
	120	428	448	4.62
	180	448	453	4.75
1.0 % PWC + Cement	7	334	310	3.40
	28	424	410	4.40
	90	418	422	4.43
	120	430	452	4.65
	180	457	444	4.76
2.5 % PWC + Cement	7	316	312	3.31
	28	322	336	3.47
	90	378	398	4.09
	120	424	416	4.43
	180	459	440	4.74

Table A-8: Compressive strength results of mortars

Materials	Days	Load (KN)	Load (KN)	Load (KN)	Load (KN)	Average Strength (N/mm^2)
Control	7	51.3	47.7	48.0	49.2	30.66
	28	59.7	58.6	60.9	61.6	37.63
	90	64.3	67.8	63.3	74.0	42.09
	120	67.7	72.1	74.8	72.8	44.91
	180	84.0	80.4	82.0	81.6	51.25
0.4 % PWC + Cement	7	48.0	48.4	47.6	49.1	30.17
	28	57.6	58.4	58.0	59.0	36.41
	90	71.9	70.6	64.2	72.3	42.59
	120	75.6	73.1	77.4	72.8	46.70
	180	79.2	82.1	80.2	80.5	50.31
0.6 % PWC + Cement	7	45.9	48.3	45.1	45.0	28.80
	28	58.0	56.7	57.0	55.7	35.53
	90	63.2	62.6	71.8	63.1	40.73
	120	72.3	71.7	75.2	69.9	45.17
	180	83.0	84.5	81.4	87.1	52.50
0.8 % PWC + Cement	7	49.5	46.5	45.7	49.0	29.80
	28	53.4	54.0	54.6	51.0	33.28
	90	68.5	59.1	60.5	69.1	40.19
	120	72.6	71.6	69.4	74.2	44.97
	180	77.1	79.4	76.6	80.9	49.06
1.0 % PWC + Cement	7	40.4	39.2	42.9	38.3	29.80
	28	63.0	64.0	61.0	59.2	38.63
	90	70.5	67.5	60.1	72.4	42.26
	120	73.5	66.7	73.9	72.6	44.80
	180	78.2	77.9	80.4	78.3	49.19
2.5 % PWC + Cement	7	38.2	41.2	36.5	37.2	23.92
	28	49.0	47.7	48.0	49.2	30.30
	90	59.4	63.7	57.5	62.0	37.91
	120	62.6	70.3	63.7	70.8	41.78
	180	81.0	78.6	77.0	77.1	49.02

Table A-9: Grading analysis of crusher sand

Sieve Size (μm)	% Retained	% passing	Cumulative % Retained
4750	0.96	99.04	0.96
2360	22.44	76.6	23.4
1180	25.18	51.42	48.58
600	17.68	33.74	66.26
425	4.68	29.06	70.94
300	7.54	21.52	78.48
150	10.89	10.63	89.37
< 150	10.60	0.03	-
			377.99

Fineness modulus = 3.78

Table A-10: Split tensile strength results of concrete

Materials	Days	Load (KN)	Load (KN)	Average Strength (N/mm^2)
Control	28	49.7	47.5	3.09
	180	35.5	36.3	2.29
0.6 % PWC + Cement	28	38.3	41.0	2.52
	180	41.7	43.5	2.71
1.0 % PWC + Cement	28	43.6	44.8	2.81
	180	42.9	41.6	2.69
30 % FA+ Cement	28	40.5	34.3	2.38
	180	55.2	55.6	3.53
0.6 % PWC + 30 % FA + Cement	28	44.0	34.6	2.50
	180	66.2	63.8	4.14
1.0 % PWC + 30 % FA + Cement	28	37.1	42.0	2.52
	180	71.9	68.5	4.47
Premix	28	17.3	15.2	1.03
	180	31.3	37.9	2.20

Table A-11: Compressive strength of concrete

Materials	Days	Load (KN)	Load (KN)	Load (KN)	Average Strength (N/mm^2)
Control	3	309.5	314.3	-	31.19
	28	422.6	410.1	394.2	40.9
	90	479.7	485.2	-	48.25
	180	517.5	567.7	-	54.26
0.6 % PWC + Cement	3	341.7	343.8	-	34.28
	28	424.4	450.4	422.8	43.25
	90	560.3	557.1	-	55.87
	180	597.0	570.0	-	58.35
1.0 % PWC + Cement	3	345.5	333.7	-	33.96
	28	440.7	414.0	439.5	43.14
	90	474.7	496.6	-	48.57
	180	563.0	597.0	-	58.00
30 % FA+ Cement	3	189.6	186.8	-	18.82
	28	332.0	337.4	352.1	34.05
	90	518.9	541.0	-	52.99
	180	634.0	645.0	-	63.95
0.6 % PWC + 30 % FA + Cement	3	195.1	188.8	-	19.2
	28	384.6	381.4	385.8	38.39
	90	589.3	581.4	-	58.54
	180	673.0	644.0	-	65.85
1.0 % PWC + 30 % FA + Cement	3	199.5	207	-	20.33
	28	398.8	397.3	379.2	39.18
	90	590.0	602.0	-	59.6
	180	694.0	638.0	-	66.60
Premix	3	57.9	52.6	-	5.53
	28	115.1	115.3	116.4	11.56
	90	283.7	272.9	-	27.83
	180	331.0	318.0	-	32.45

Table A-12: Accelerated compressive strength of mortar

Materials	**Days**	**Load (KN)**	**Load (KN)**	**Average Strength (N/mm^2)**
Control	3	61.5	59.4	24.18
	14	71.6	74.6	29.24
	28	90.8	90.3	36.22
	45	77.2	79.4	31.32
0.6 % PWC + Cement	3	53.4	60.6	22.80
	14	72.4	65.5	27.58
	28	100.3	103.6	40.78
	45	78.9	80.2	31.82
1.0 % PWC + Cement	3	55.3	53.6	21.78
	14	60.2	58.3	23.70
	28	85.3	90.7	35.20
	45	70.0	74.5	28.90
2.5 % PWC + Cement	3	61.3	54.2	23.10
	14	66.5	60.1	25.32
	28	98.1	88.9	37.40
	45	72.3	70.2	28.50
0.6 % PWC + 30 % FA + Cement	3	59.5	51.3	22.16
	14	91.7	81.1	34.56
	28	111.5	110.7	44.44
	45	91.4	89.3	36.14
1.0 % PWC + 30 % FA + Cement	3	53.9	55.4	21.86
	14	93.2	87.5	36.14
	28	114.1	113.4	45.50
	45	78.9	80.5	31.88
2.5 % PWC + 30 % FA + Cement	3	59.4	51.1	22.1
	14	88.6	84.3	34.58
	28	112.2	112.7	44.98
	45	78.8	79.1	31.58

Table A-13: Sulphate resistance results of mortar according to ASTM C 1038

Materials	Age (Days)	Length(mm)				Expansion (%)				Average (%)
Control	initial reading	15.56	22.35	21.23	17.20	0.000	0.000	0.000	0.000	0.000
	14	15.61	22.38	21.27	17.23	0.020	0.012	0.016	0.012	0.015
	28	15.63	22.42	21.31	17.28	0.028	0.028	0.032	0.032	0.030
	60	15.51	22.31	21.22	17.16	-0.020	-0.016	-0.004	-0.016	-0.014
	90	15.49	22.30	21.20	17.15	-0.028	-0.020	-0.012	-0.020	-0.020
	120	15.47	22.31	21.20	17.14	-0.036	-0.016	-0.012	-0.024	-0.022
	180	15.50	22.34	21.22	17.19	-0.024	-0.004	-0.004	-0.004	-0.018
	295	15.56	22.38	21.26	17.21	0.000	-0.004	0.012	0.004	0.003
0.4 % PWC + Cement	initial reading	20.26	19.70	20.06	19.26	0.000	0.000	0.000	0.000	0.000
	14	20.27	19.81	20.07	19.32	0.004	0.044	0.004	0.024	0.019
	28	20.30	19.79	20.12	19.27	0.016	0.036	0.024	0.004	0.020
	60	20.20	19.69	20.02	19.19	-0.024	-0.004	-0.016	-0.028	-0.018
	90	20.20	19.64	20.02	19.19	-0.024	-0.024	-0.016	-0.028	-0.023
	120	20.21	19.66	20.03	19.21	-0.020	-0.016	-0.012	-0.020	-0.017
	180	20.23	19.66	20.03	19.19	-0.012	-0.016	-0.012	-0.028	-0.017
	295	20.28	19.72	20.09	19.27	0.008	0.008	0.012	0.004	0.008
0.6 % PWC + Cement	initial reading	15.02	19.43	20.08	19.67	0.000	0.000	0.000	0.000	0.000
	14	15.15	19.48	20.09	19.72	0.052	0.020	0.004	0.020	0.024
	28	15.16	19.49	20.14	19.74	0.056	0.024	0.024	0.028	0.033
	60	15.00	19.39	20.01	19.61	-0.008	-0.016	-0.028	-0.024	-0.019
	90	14.98	19.39	20.00	19.61	-0.016	-0.016	-0.032	-0.024	-0.022
	120	14.98	19.39	20.01	19.62	-0.016	-0.016	-0.028	-0.020	-0.020
	180	15.01	19.40	20.07	19.62	-0.004	-0.012	-0.004	-0.020	-0.010
	295	15.09	19.47	20.08	19.67	0.028	0.016	0.000	0.000	0.011
2.5 % PWC + Cement	initial reading	20.08	19.47	20.11	19.48	0.000	0.000	0.000	0.000	0.000
	14	20.14	19.47	20.22	19.49	0.024	0.000	0.044	0.004	0.018
	28	20.15	19.48	20.20	19.49	0.028	0.004	0.036	0.004	0.018
	60	20.04	19.37	20.09	19.45	-0.016	-0.040	-0.008	-0.012	-0.019
	90	20.04	19.37	20.09	19.44	-0.016	-0.040	-0.008	-0.016	-0.020
	120	20.04	19.38	20.08	19.43	-0.016	-0.036	-0.012	-0.020	-0.021
	180	20.07	19.42	20.10	19.46	-0.004	-0.020	-0.004	-0.008	-0.009
	295	20.14	19.48	20.14	19.49	0.024	0.004	0.012	0.004	0.011

Table A-14: Sulphate resistance results of mortar according to ASTM C 1012

Materials	Age (Days)	Length(mm)			Expansion (%)			Average (%)
Control	initial reading	21.85	19.49	21.22	0.000	0.000	0.000	0.000
	7	21.89	19.52	21.25	0.016	0.012	0.012	0.013
	14	21.92	19.55	21.28	0.028	0.024	0.024	0.025
	28	21.94	19.57	21.31	0.036	0.032	0.036	0.035
	60	21.96	19.60	21.32	0.044	0.044	0.040	0.043
	90	21.98	19.62	21.35	0.052	0.052	0.052	0.052
	120	22.00	19.64	21.36	0.060	0.058	0.056	0.058
	180	22.10	19.68	21.47	0.100	0.076	0.100	0.092
	260	22.22	19.76	21.60	0.148	0.108	0.152	0.136
0.4 % PWC + Cement	initial reading	20.76	20.18	21.34	0.000	0.000	0.000	0.000
	7	20.78	20.20	21.35	0.008	0.008	0.004	0.007
	14	20.81	20.23	21.38	0.020	0.020	0.016	0.019
	28	20.82	20.24	21.41	0.024	0.024	0.028	0.025
	60	20.79	20.24	21.42	0.012	0.024	0.032	0.023
	90	20.81	20.26	21.44	0.020	0.032	0.040	0.031
	120	20.90	20.31	21.48	0.056	0.052	0.056	0.055
	180	20.91	20.37	21.55	0.060	0.076	0.084	0.073
	260	20.92	20.36	21.58	0.064	0.072	0.096	0.077
0.6 % PWC + Cement	initial reading	22.20	21.00	22.53	0.000	0.000	0.000	0.000
	7	22.23	21.02	22.55	0.012	0.008	0.008	0.009
	14	22.30	21.04	22.59	0.040	0.016	0.024	0.027
	28	22.32	21.06	22.60	0.048	0.023	0.028	0.033
	60	22.30	21.09	22.61	0.040	0.036	0.032	0.036
	90	22.32	21.12	22.65	0.048	0.048	0.048	0.048
	120	22.35	21.12	22.68	0.060	0.048	0.060	0.056
	180	22.43	21.20	22.76	0.092	0.080	0.092	0.088
	260	22.38	21.26	22.74	0.072	0.104	0.084	0.087
2.5 % PWC + Cement	initial reading	18.62	21.94	21.78	0.000	0.000	0.000	0.000
	7	18.67	22.02	21.82	0.020	0.032	0.016	0.023
	14	18.70	22.05	21.85	0.032	0.044	0.028	0.035
	28	18.73	22.08	21.86	0.044	0.056	0.032	0.044
	60	18.74	22.04	21.93	0.048	0.040	0.060	0.049
	90	18.75	22.13	21.92	0.052	0.076	0.056	0.061
	120	18.80	22.14	21.94	0.072	0.080	0.064	0.072
	180	18.96	22.26	22.05	0.136	0.128	0.108	0.124
	260	18.85	22.17	21.94	0.172	0.172	0.144	0.163

Table A-15: Alkali silica reaction results of mortars

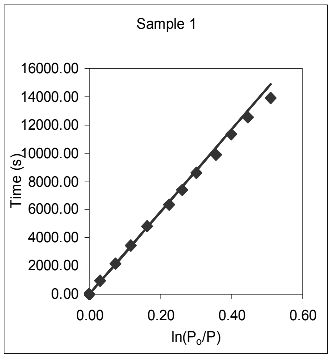
Materials	Age (Days)	Length (mm)			Expansion (%)			Average (%)
Control	initial reading	27.95	20.47	25.91	0.000	0.000	0.000	0.000
	14	27.92	20.46	25.88	-0.012	-0.004	-0.012	-0.009
	28	27.96	20.48	25.94	0.004	0.004	0.012	0.007
	45	27.98	20.49	25.95	0.012	0.008	0.016	0.012
	60	27.99	20.49	25.94	0.016	0.008	0.012	0.012
	150	28.02	20.51	25.96	0.028	0.016	0.020	0.021
0.4 % PWC + Cement	initial reading	18.58	18.76	19.02	0.000	0.000	0.000	0.000
	14	18.54	18.74	18.99	-0.016	-0.008	-0.012	-0.012
	28	18.58	18.77	19.04	0.000	0.004	0.008	0.006
	45	18.60	18.80	19.05	0.008	0.016	0.012	0.012
	60	18.60	18.78	19.06	0.008	0.008	0.016	0.011
	150	18.64	18.83	19.10	0.024	0.028	0.032	0.028
0.6 % PWC + Cement	initial reading	26.10	18.02	25.20	0.000	0.000	0.000	0.000
	14	26.30	18.16	25.41	0.080	0.056	0.084	0.073
	28	26.36	18.22	25.45	0.104	0.080	0.100	0.095
	45	26.37	18.24	25.44	0.108	0.088	0.096	0.097
	60	26.33	18.19	25.39	0.092	0.068	0.076	0.079
	150	26.36	18.26	25.43	0.104	0.096	0.092	0.097
1.0 % PWC + Cement	initial reading	19.41	26.59	29.17	0.000	0.000	0.000	0.000
	14	19.55	26.75	29.32	0.056	0.064	0.060	0.060
	28	19.63	26.78	29.36	0.088	0.076	0.076	0.080
	45	19.63	26.78	29.38	0.088	0.076	0.084	0.083
	60	19.60	26.74	29.34	0.076	0.060	0.068	0.068
	150	19.65	26.83	29.48	0.096	0.096	0.124	0.105
2.5 % PWC + Cement	initial reading	26.38	27.16	18.47	0.000	0.000	0.000	0.000
	14	26.42	27.24	18.57	0.016	0.032	0.040	0.029
	28	26.50	27.25	18.59	0.048	0.036	0.048	0.044
	45	26.46	27.28	18.57	0.032	0.048	0.040	0.040
	60	26.43	27.24	18.57	0.020	0.032	0.040	0.031
	150	26.53	27.30	18.61	0.060	0.056	0.056	0.057
0.6 % + 30 % FA + Cement	initial reading	37.37	36.78	36.55	0.000	0.000	0.000	0.000
	14	37.34	36.77	36.52	-0.012	-0.004	-0.012	-0.009
	28	37.34	36.77	36.52	-0.012	-0.004	-0.012	-0.009
	45	37.35	36.77	36.53	-0.008	-0.004	-0.008	-0.006
1.0 % + 30 % FA + Cement	initial reading	37.19	38.76	37.84	0.000	0.000	0.000	0.000
	14	37.16	38.74	37.82	-0.012	-0.008	-0.008	-0.009
	28	37.17	38.74	37.83	-0.008	-0.008	-0.004	-0.007
	45	37.18	38.75	37.84	-0.004	-0.004	-0.004	-0.004
2.5 % + 30 % FA + Cement	initial reading	39.35	39.25	39.00	0.000	0.000	0.000	0.000
	14	39.35	39.23	38.99	0.000	-0.008	-0.004	-0.004
	28	39.35	39.23	39.00	0.000	-0.008	0.000	-0.003
	45	39.35	39.23	39.00	0.000	-0.008	0.000	-0.003

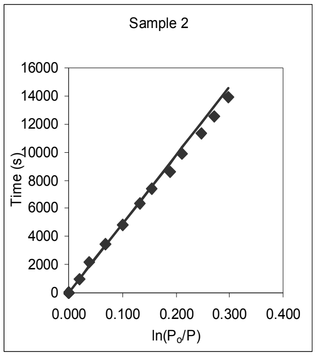
Table A-16: Concrete carbonation depth results

Materials	Age (Days)	Carbonation depth (mm)								Average Carbonation depth (mm)
		1	2	3	4	5	6	7	8	
Control	28	5.98	5.64	5.18	6.48	7.00	5.56	4.76	8.40	6.13
0.6 % PWC + Cement	28	5.26	6.98	3.12	3.90	3.48	5.16	3.70	7.04	4.83
1.0 % PWC + Cement	28	3.96	4.20	2.82	1.62	7.08	8.76	7.70	6.36	5.31
30 % FA+ Cement	28	13.16	13.66	16.38	14.74	15.46	17.92	16.12	13.62	15.13
0.6 % PWC + 30 % FA + Cement	28	13.40	14.28	14.58	11.98	11.58	13.74	14.08	12.94	13.32
1.0 % PWC + 30 % FA + Cement	28	13.74	13.62	15.28	13.46	14.70	14.82	14.60	13.66	14.34
Premix	28	Full Carbonation								-

Table A-17: Control mortar samples 28 days permeability results

Average k (m/s): 1.1 E-10 COV: 27.0 % OPI: 9.97					
SAMPLE 1		SAMPLE 2		SAMPLE3	
Diameter (mm)	69.75	Diameter (mm)	70.28	Diameter (mm)	70.13
Thickness (mm)	23.86	Thickness (mm)	27.64	Thickness (mm)	25.59
k (m/s)	1.39E-10	k (m/s)	9.53E-11	k (m/s)	8.491E-11
r^2	0.9927	r^2	0.9908	r^2	0.9971
Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)
1.52	100.0	1.52	105.0	1.52	100.0
2.08	97.0	2.08	103.0	2.08	98.0
2.28	93.0	2.28	101.0	2.28	96.0
2.50	89.0	2.50	98.0	2.50	93.0
3.13	85.0	3.13	95.0	3.13	90.0
3.38	80.0	3.38	92.0	3.38	88.0
3.55	77.0	3.55	90.0	3.55	86.0
4.16	74.0	4.16	87.0	4.16	84.0
4.37	70.0	4.37	85.0	4.37	81.0
5.01	67.0	5.01	82.0	5.01	79.0
5.21	64.0	5.21	80.0	5.21	77.0
5.44	60.0	5.44	78.0	5.44	76.0





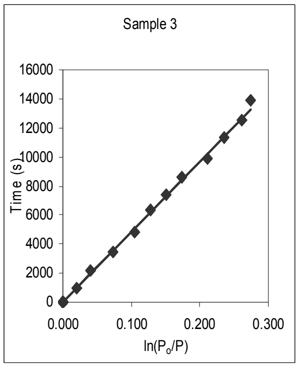
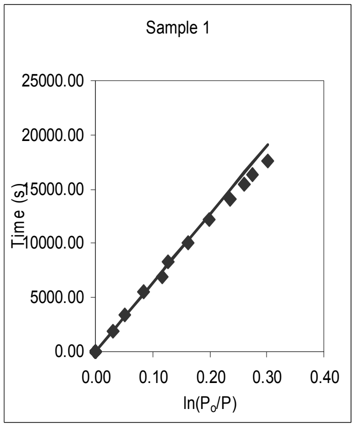
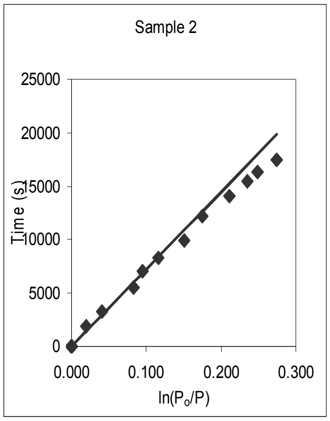


Table A-18: 0.4 % PWC mortar samples 28 days permeability results

Average k (m/s): 6.3 E-11 COV: 26.8 % OPI: 10.20					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	70.20	Diameter (mm)	69.94	Diameter (mm)	69.83
Thickness (mm)	28.54	Thickness (mm)	27.74	Thickness (mm)	22.86
k (m/s)	7.68E-11	k (m/s)	6.79E-11	k (m/s)	4.411E-11
r^2	0.9834	r^2	0.9661	r^2	0.9707
Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)
1.27	100.0	1.28	100.0	1.29	100.0
1.58	97.0	1.59	98.0	1.59	99.0
2.23	95.0	2.23	96.0	2.24	97.0
3.00	92.0	3.01	92.0	3.01	94.0
3.23	89.0	3.25	91.0	3.22	93.0
3.46	88.0	3.47	89.0	3.47	91.0
4.14	85.0	4.14	86.0	4.14	89.0
4.51	82.0	4.52	84.0	4.52	87.0
5.21	79.0	5.22	81.0	5.22	85.0
5.45	77.0	5.45	79.0	5.46	83.0
6.00	76.0	6.00	78.0	6.00	82.0
6.20	74.0	6.20	76.0	6.21	81.0





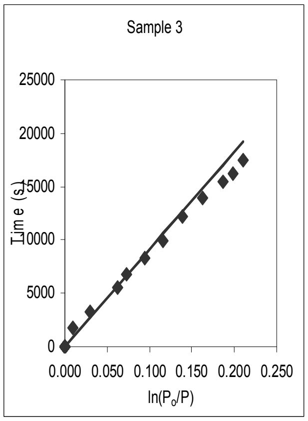
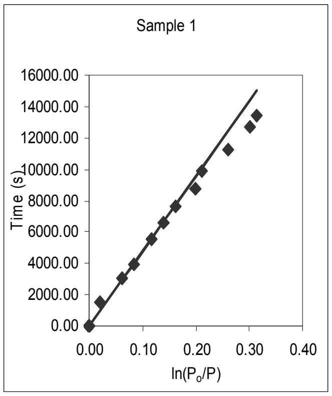
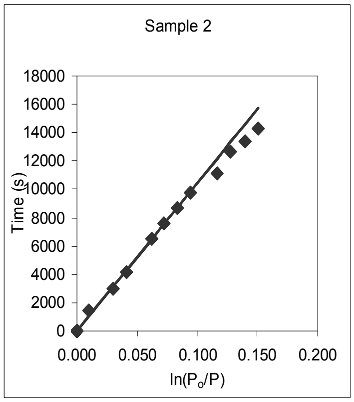


Table A-19: 0.6 % PWC mortar samples 28 days permeability results

Average k (m/s): 7.8 E-11 COV: 45.7 % OPI: 10.11					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	70.26	Diameter (mm)	70.45	Diameter (mm)	70.79
Thickness (mm)	30.96	Thickness (mm)	26.00	Thickness (mm)	26.87
k (m/s)	1.13E-10	k (m/s)	4.23E-11	k (m/s)	7.716E-11
r^2	0.9638	r^2	0.9796	r^2	0.9839
Time	Pressure	Time	Pressure	Time	Pressure
(hh.min)	(kPa)	(hh.min)	(kPa)	(hh.min)	(kPa)
2.53	100.0	2.54	100.0	2.54	100.0
3.18	98.0	3.18	99.0	3.18	98.0
3.44	94.0	3.44	97.0	3.43	96.0
3.58	92.0	4.04	96.0	3.56	94.0
4.25	89.0	4.43	94.0	4.15	92.0
4.43	87.0	5.00	93.0	4.42	89.0
5.00	85.0	5.19	92.0	5.00	87.0
5.19	82.0	5.37	91.0	5.19	86.0
5.38	81.0	6.00	89.0	5.37	84.0
6.00	77.0	6.25	88.0	6.00	82.0
6.25	74.0	6.37	87.0	6.25	79.0
6.37	73.0	6.52	86.0	6.37	78.0





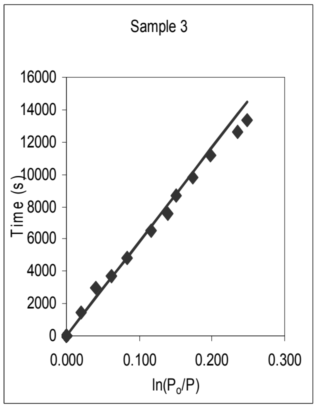
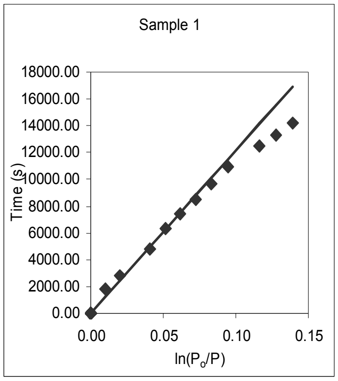
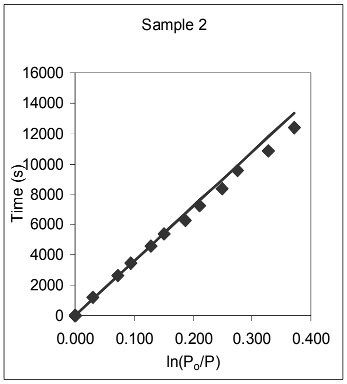


Table A-20: 0.8 % PWC mortar samples 28 days permeability results

Average k (m/s): 9.9 E-11 COV: 50.8 % OPI: 10.00					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	70.09	Diameter (mm)	70.34	Diameter (mm)	69.94
Thickness (mm)	27.81	Thickness (mm)	27.83	Thickness (mm)	27.39
k (m/s)	4.12E-11	k (m/s)	1.32E-10	k (m/s)	1.252E-10
r^2	0.9301	r^2	0.9828	r^2	0.9975
Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)
2.56	100.0	2.58	100.0	2.57	100.0
3.26	99.0	3.18	97.0	3.17	96.0
3.43	98.0	3.42	93.0	3.42	93.0
4.16	96.0	3.56	91.0	3.56	90.0
4.41	95.0	4.14	88.0	4.14	88.0
4.59	94.0	4.28	86.0	4.28	86.0
5.18	93.0	4.43	83.0	4.43	83.0
5.37	92.0	4.58	81.0	4.58	81.0
5.59	91.0	5.18	78.0	5.18	79.0
6.24	89.0	5.37	76.0	5.36	76.0
6.38	88.0	5.59	72.0	5.59	74.0
6.52	87.0	6.24	69.0	6.24	71.0





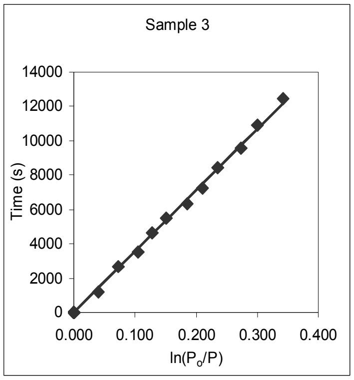
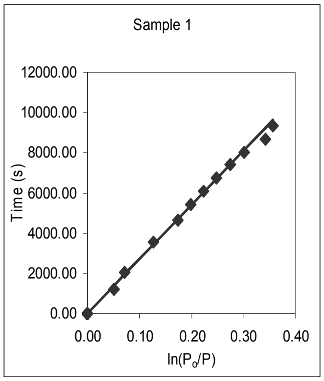
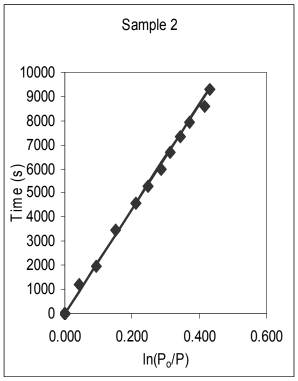


Table A-21: 1.0 % PWC mortar samples 28 days permeability results

Average k (m/s): 1.6 E-10 COV: 27.5 % OPI: 9.80					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	70.32	Diameter (mm)	69.94	Diameter (mm)	68.77
Thickness (mm)	24.98	Thickness (mm)	26.65	Thickness (mm)	24.83
k (m/s)	1.51E-10	k (m/s)	2.04E-10	k (m/s)	1.177E-10
r^2	0.9955	r^2	0.9948	r2	0.9978
Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)
1.44	100.0	1.45	100.0	1.46	100.0
2.04	95.0	2.05	96.0	2.06	97.0
2.18	93.0	2.18	91.0	2.18	95.0
2.43	88.0	2.43	86.0	2.46	90.0
3.01	84.0	3.01	81.0	3.02	88.0
3.14	82.0	3.13	78.0	3.14	86.0
3.26	80.0	3.25	75.0	3.26	84.0
3.37	78.0	3.36	73.0	3.38	83.0
3.48	76.0	3.47	71.0	3.48	81.0
3.58	74.0	3.57	69.0	3.58	80.0
4.09	71.0	4.08	66.0	4.10	79.0
4.20	70.0	4.20	65.0	4.20	77.0





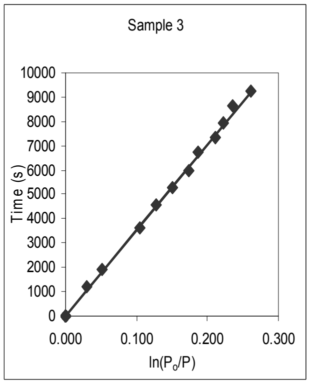
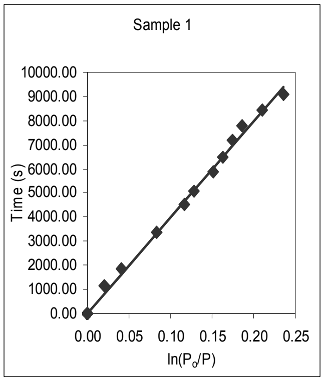
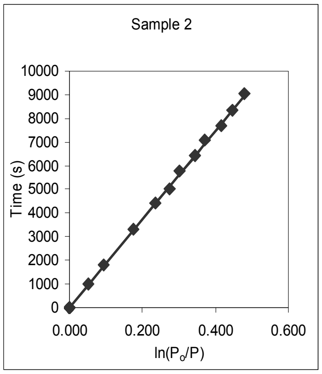


Table A-22: 2.5 % PWC mortar samples 28 days permeability results

Average k (m/s): 1.9 E-10 COV: 40.2 % OPI: 9.71					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	69.85	Diameter (mm)	70.65	Diameter (mm)	69.94
Thickness (mm)	26.10	Thickness (mm)	25.87	Thickness (mm)	28.00
k (m/s)	1.06E-10	k (m/s)	2.19E-10	k (m/s)	2.553E-10
r^2	0.9950	r^2	0.9991	r^2	0.9985
Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)
1.48	100.0	1.49	100.0	1.50	100.0
2.07	98.0	2.06	95.0	2.06	95.0
2.19	96.0	2.19	91.0	2.19	91.0
2.44	92.0	2.44	84.0	2.44	84.0
3.03	89.0	3.03	79.0	3.03	78.0
3.13	88.0	3.13	76.0	3.13	75.0
3.26	86.0	3.25	74.0	3.26	72.0
3.36	85.0	3.36	71.0	3.36	70.0
3.48	84.0	3.47	69.0	3.47	67.0
3.58	83.0	3.57	66.0	3.57	65.0
4.09	81.0	4.08	64.0	4.09	63.0
4.20	79.0	4.20	62.0	4.20	61.0





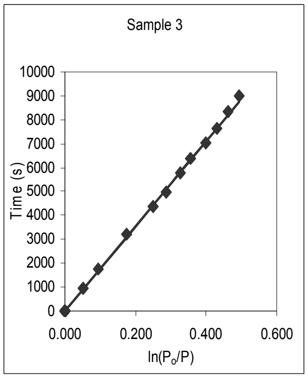
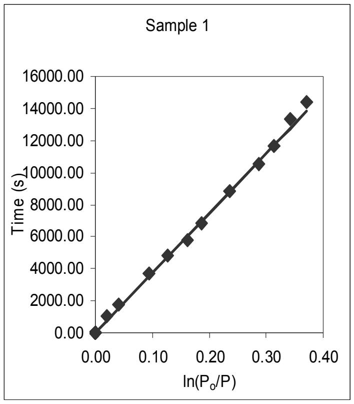
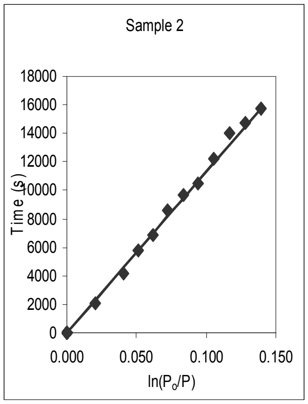


Table A-23: Control mortar samples 115 days permeability results

Average k (m/s): 7.1 E-11 COV: 52.6 % OPI: 10.15					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	69.93	Diameter (mm)	70.04	Diameter (mm)	69.83
Thickness (mm)	25.89	Thickness (mm)	26.58	Thickness (mm)	26.14
k (m/s)	1.11E-10	k (m/s)	3.75E-11	k (m/s)	6.426E-11
r^2	0.9962	r^2	0.9950	r^2	0.9427
Time	Pressure	Time	Pressure	Time	Pressure
(hh.min)	(kPa)	(hh.min)	(kPa)	(hh.min)	(kPa)
12.08	100.0	13.27	100.0	9.55	100.0
12.26	98.0	14.02	98.0	10.28	99.0
12.37	96.0	14.36	96.0	10.45	96.0
13.09	91.0	15.04	95.0	11.09	94.0
13.28	88.0	15.22	94.0	11.33	92.0
13.45	85.0	15.50	93.0	11.53	91.0
14.02	83.0	16.08	92.0	12.14	89.0
14.36	79.0	16.22	91.0	12.33	86.0
15.04	75.0	16.50	90.0	12.50	84.0
15.22	73.0	17.21	89.0	13.25	82.0
15.50	71.0	17.33	88.0	14.01	80.0
16.08	69.0	17.49	87.0	14.41	78.0





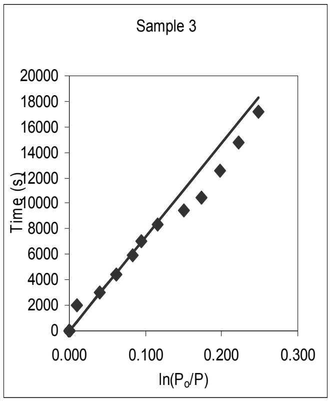
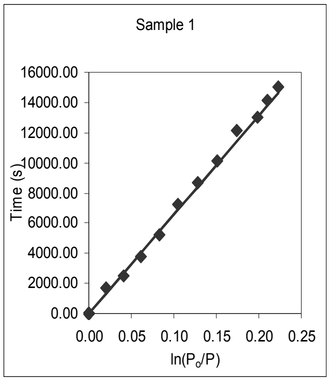
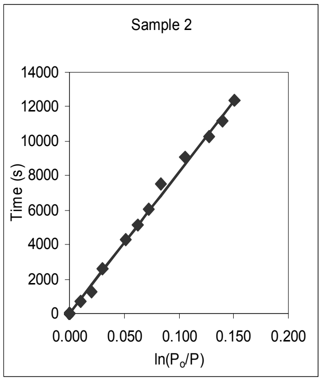


Table A-24: 0.4 % PWC mortar samples 115 days permeability results

Average k (m/s): 5.8 E-11 COV: 11.1 % OPI: 10.24					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	70.86	Diameter (mm)	70.73	Diameter (mm)	70.16
Thickness (mm)	27.50	Thickness (mm)	26.98	Thickness (mm)	25.79
k (m/s)	6.48E-11	k (m/s)	5.2E-11	k (m/s)	5.752E-11
r^2	0.9954	r^2	0.9950	r^2	0.8686
Time	Pressure	Time	Pressure	Time	Pressure
(hh.min)	(kPa)	(hh.min)	(kPa)	(hh.min)	(kPa)
11.23	100.0	11.39	100.0	9.56	100.0
11.51	98.0	11.51	99.0	10.15	99.0
12.05	96.0	12.00	98.0	10.27	98.0
12.26	94.0	12.22	97.0	10.46	97.0
12.50	92.0	12.50	95.0	11.09	95.0
13.24	90.0	13.05	94.0	11.33	93.0
13.48	88.0	13.20	93.0	11.53	91.0
14.12	86.0	13.45	92.0	12.14	89.0
14.45	84.0	14.10	90.0	12.34	87.0
15.00	82.0	14.30	88.0	12.50	85.0
15.19	81.0	14.45	87.0	13.10	83.0
15.34	80.0	15.05	86.0	14.41	82.0





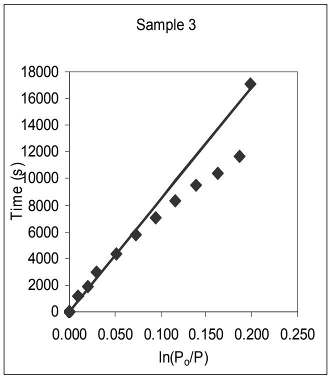
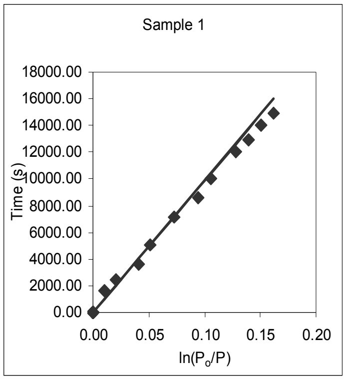
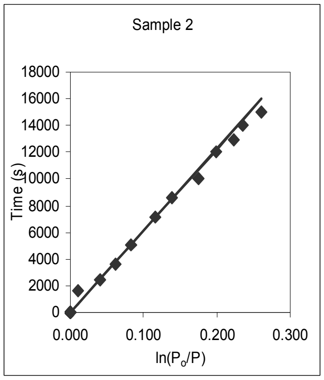


Table A-25: 0.6 % PWC mortar samples 115 days permeability results

Average k (m/s): 5.7 E-11 COV: 20.8 % OPI: 10.24					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	71.20	Diameter (mm)	71.13	Diameter (mm)	70.68
Thickness (mm)	27.00	Thickness (mm)	25.99	Thickness (mm)	26.41
k (m/s)	4.53E-11	k (m/s)	6.92E-11	k (m/s)	5.757E-11
r^2	0.9852	r^2	0.9898	r^2	0.9189
Time	Pressure	Time	Pressure	Time	Pressure
(hh.min)	(kPa)	(hh.min)	(kPa)	(hh.min)	(kPa)
11.25	100.0	11.25	100.0	9.58	100.0
11.52	99.0	11.52	99.0	10.28	99.0
12.05	98.0	12.05	96.0	10.46	97.0
12.26	96.0	12.26	94.0	11.09	95.0
12.50	95.0	12.50	92.0	11.33	93.0
13.24	93.0	13.24	89.0	11.53	91.0
13.48	91.0	13.48	87.0	12.15	89.0
14.13	90.0	14.13	84.0	12.34	88.0
14.45	88.0	14.45	82.0	12.50	86.0
15.00	87.0	15.01	80.0	13.23	85.0
15.19	86.0	15.19	79.0	12.58	83.0
15.34	85.0	15.35	77.0	14.42	82.0





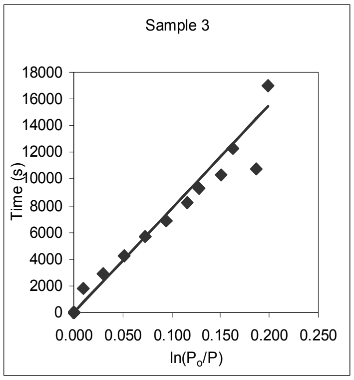
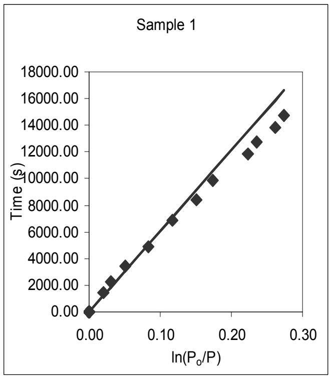
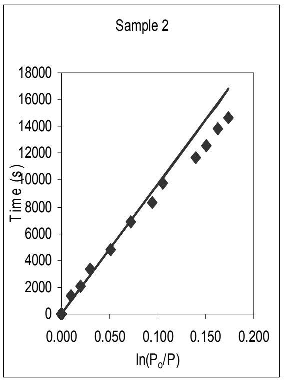


Table A-26: 0.8 % PWC mortar samples 115 days permeability results

Average k (m/s): 6.4 E-11 COV: 22.4 % OPI: 10.20					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	70.88	Diameter (mm)	70.74	Diameter (mm)	70.85
Thickness (mm)	26.97	Thickness (mm)	27.04	Thickness (mm)	25.91
k (m/s)	7.84E-11	k (m/s)	5E-11	k (m/s)	6.243E-11
r^2	0.9505	r^2	0.9435	r^2	0.9833
Time	Pressure	Time	Pressure	Time	Pressure
(hh.min)	(kPa)	(hh.min)	(kPa)	(hh.min)	(kPa)
11.29	100.0	11.31	100.0	10.00	100.0
11.53	98.0	11.53	99.0	10.27	98.0
12.06	97.0	12.06	98.0	10.46	96.0
12.26	95.0	12.27	97.0	11.10	94.0
12.51	92.0	12.51	95.0	11.33	92.0
13.24	89.0	13.25	93.0	11.53	90.0
13.49	86.0	13.49	91.0	12.15	88.0
14.14	84.0	14.14	90.0	12.35	86.0
14.46	80.0	14.46	87.0	12.51	84.0
15.01	79.0	15.01	86.0	13.26	82.0
15.20	77.0	15.21	85.0	14.02	81.0
15.35	76.0	15.35	84.0	14.42	79.0





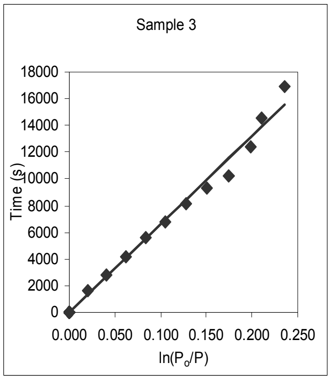
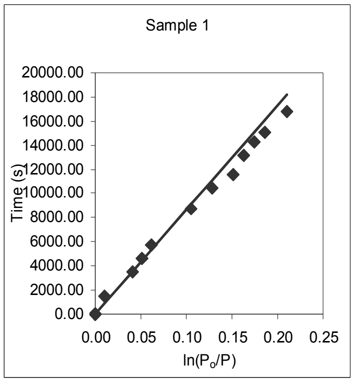
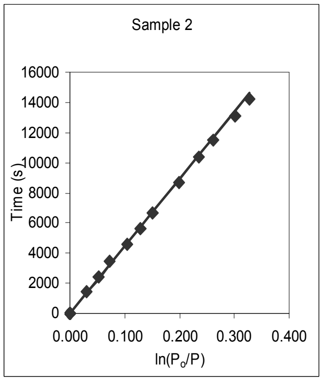


Table A-27: 1.0 % PWC mortar samples 115 days permeability results

Average k (m/s): 8.8 E-11 COV: 41.4 % OPI: 10.05					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	70.35	Diameter (mm)	70.68	Diameter (mm)	70.42
Thickness (mm)	24.99	Thickness (mm)	25.49	Thickness (mm)	25.32
k (m/s)	4.97E-11	k (m/s)	9.28E-11	k (m/s)	1.225E-10
r^2	0.9771	r^2	0.9982	r^2	0.9975
Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)
12.11	100.0	12.12	100.0	10.02	100.0
12.36	99.0	12.36	97.0	10.15	98.0
13.09	96.0	12.52	95.0	10.28	96.0
13.28	95.0	13.09	93.0	10.47	92.0
13.46	94.0	13.28	90.0	11.10	89.0
14.37	90.0	13.46	88.0	11.34	84.0
15.05	88.0	14.03	86.0	11.54	81.0
15.23	86.0	14.37	82.0	12.15	78.0
15.50	85.0	15.05	79.0	12.35	75.0
16.09	84.0	15.23	77.0	12.51	74.0
16.22	83.0	15.50	74.0	13.11	71.0
16.50	81.0	16.09	72.0	14.42	61.0





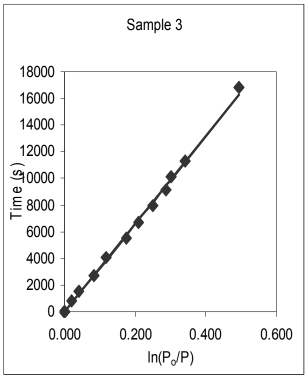
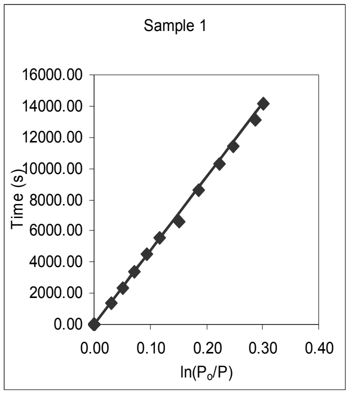
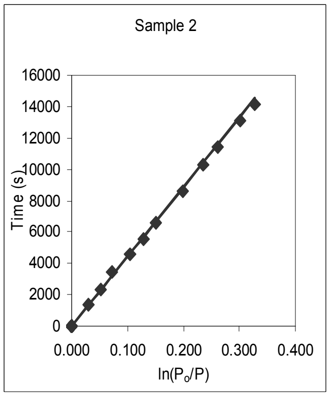


Table A-28: 2.5 % PWC mortar samples 115 days permeability results

Average k (m/s): 9.6 E-11 COV: 6.1 % OPI: 10.02					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	70.21	Diameter (mm)	69.62	Diameter (mm)	70.89
Thickness (mm)	25.86	Thickness (mm)	25.38	Thickness (mm)	25.53
k (m/s)	9.04E-11	k (m/s)	9.57E-11	k (m/s)	1.021E-10
r^2	0.9967	r^2	0.9987	r^2	0.9952
Time	Pressure	Time	Pressure	Time	Pressure
(hh.min)	(kPa)	(hh.min)	(kPa)	(hh.min)	(kPa)
12.13	100.0	12.13	100.0	10.03	100.0
12.36	97.0	12.36	97.0	10.28	96.0
12.52	95.0	12.52	95.0	10.47	93.0
13.09	93.0	13.10	93.0	11.10	90.0
13.28	91.0	13.29	90.0	11.34	88.0
13.46	89.0	13.46	88.0	11.54	85.0
14.03	86.0	14.03	86.0	12.16	82.0
14.37	83.0	14.37	82.0	12.36	80.0
15.05	80.0	15.05	79.0	12.51	77.0
15.23	78.0	15.23	77.0	13.11	75.0
15.51	75.0	15.51	74.0	13.31	72.0
16.09	74.0	16.09	72.0	14.42	66.0





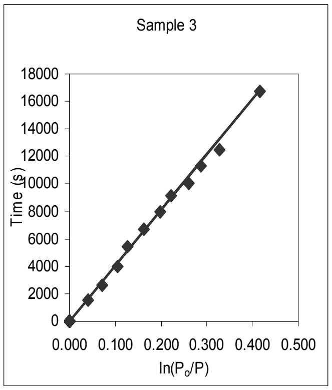
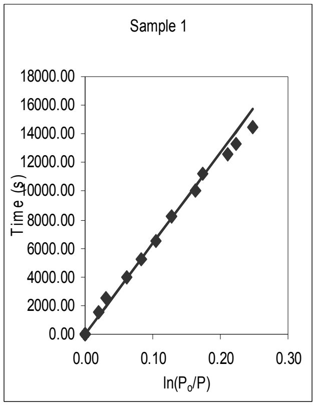
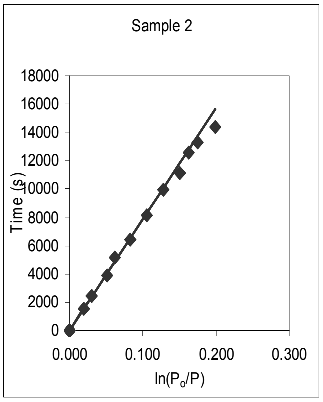


Table A-29: Control mortar samples 180 days permeability results

Average k (m/s): 5.6 E-11 COV: 13.7 % OPI: 10.25					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	70.77	Diameter (mm)	70.66	Diameter (mm)	70.21
Thickness (mm)	23.52	Thickness (mm)	27.70	Thickness (mm)	27.67
k (m/s)	6.15E-11	k (m/s)	5.84E-11	k (m/s)	4.701E-11
r^2	0.9864	r^2	0.9910	r^2	0.8229
Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)
11.55	100.0	11.56	100.0	11.57	100.0
12.21	98.0	12.21	98.0	12.21	99.0
12.37	97.0	12.37	97.0	13.37	98.0
13.01	94.0	13.01	95.0	13.01	96.0
13.22	92.0	13.22	94.0	13.22	95.0
13.43	90.0	13.43	92.0	13.44	94.0
14.12	88.0	14.12	90.0	14.12	92.0
14.42	85.0	14.42	88.0	14.42	90.0
15.02	84.0	15.02	86.0	15.02	89.0
15.24	81.0	15.25	85.0	15.25	88.0
15.37	80.0	15.37	84.0	15.37	87.0
15.56	78.0	15.56	82.0	15.56	85.0





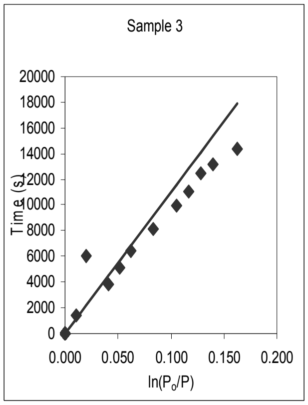
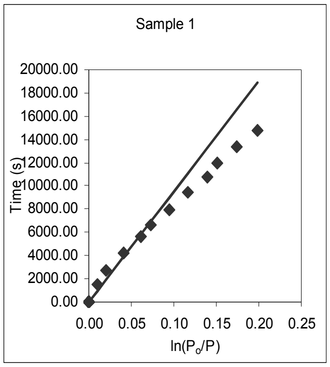
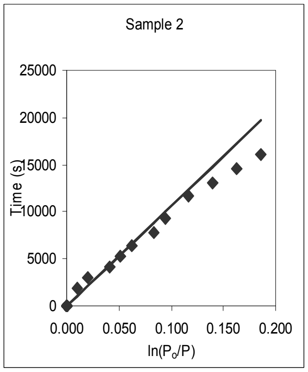


Table A-30: 0.4 % PWC mortar samples 180 days permeability results

Average k (m/s): 5.5 E-11 COV: 32.0 % OPI: 10.26					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	72.15	Diameter (mm)	72.31	Diameter (mm)	70.22
Thickness (mm)	25.92	Thickness (mm)	24.95	Thickness (mm)	26.49
k (m/s)	5.02E-11	k (m/s)	4.1E-11	k (m/s)	7.53E-11
r^2	0.8288	r^2	0.9115	r^2	0.9605
Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)
12.03	100.0	17.35	100.0	12.06	100.0
12.28	99.0	18.06	99.0	12.25	99.0
12.49	98.0	18.26	98.0	12.32	98.0
13.13	96.0	18.44	96.0	12.49	96.0
13.37	94.0	19.02	95.0	13.14	94.0
13.53	93.0	19.22	94.0	13.37	91.0
14.16	91.0	19.45	92.0	13.53	90.0
14.40	89.0	20.10	91.0	14.16	88.0
15.02	87.0	20.50	89.0	14.41	86.0
15.23	86.0	21.13	87.0	15.02	84.0
15.45	84.0	21.38	85.0	15.24	80.0
16.10	82.0	22.03	83.0	15.45	78.0





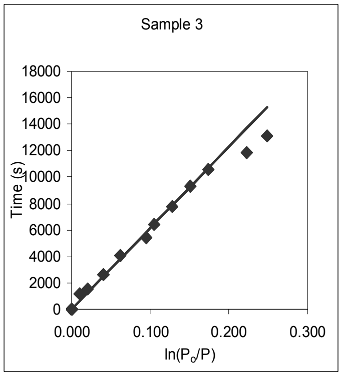
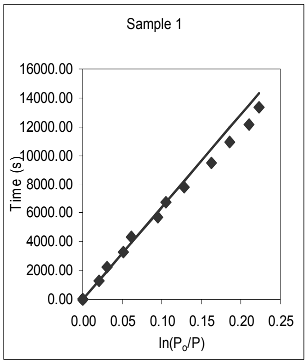
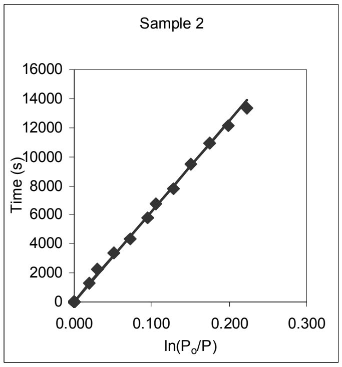


Table A-31: 0.6 % PWC mortar samples 180 days permeability results

Average k (m/s): 5.5 E-11 COV: 31.5 % OPI: 10.26					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	71.07	Diameter (mm)	70.07	Diameter (mm)	70.57
Thickness (mm)	24.86	Thickness (mm)	24.60	Thickness (mm)	24.88
k (m/s)	6.57E-11	k (m/s)	6.48E-11	k (m/s)	3.512E-11
r^2	0.9730	r^2	0.9968	r^2	0.9947
Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)
15.18	100.0	15.18	100.0	15.19	100.0
15.39	98.0	15.39	98.0	15.39	99.0
15.56	97.0	15.56	97.0	15.56	98.0
16.13	95.0	16.14	95.0	16.14	97.0
16.31	94.0	16.31	93.0	16.32	96.0
16.53	91.0	16.54	91.0	16.54	95.0
17.11	90.0	17.11	90.0	17.12	94.0
17.28	88.0	17.28	88.0	17.29	93.0
17.56	85.0	17.56	86.0	17.57	92.0
18.20	83.0	18.20	84.0	18.20	91.0
18.40	81.0	18.40	82.0	18.41	90.0
19.00	80.0	19.00	80.0	19.02	89.0





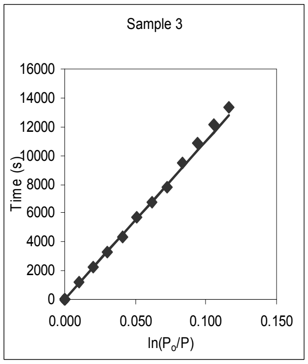
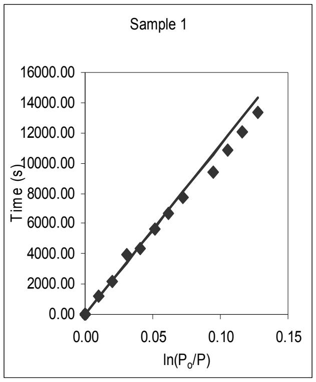
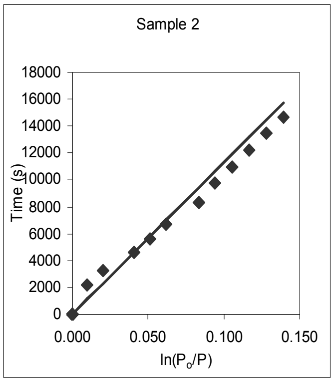


Table A-32: 0.8 % PWC mortar samples 180 days permeability results

Average k (m/s): 5.8 E-11 COV: 46.8 % OPI: 10.24					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	70.92	Diameter (mm)	70.20	Diameter (mm)	70.78
Thickness (mm)	27.81	Thickness (mm)	27.62	Thickness (mm)	27.47
k (m/s)	4.21E-11	k (m/s)	4.24E-11	k (m/s)	8.92E-11
r^2	0.9771	r^2	0.9648	r^2	0.9861
Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)
15.20	100.0	15.38	100.0	15.32	100.0
15.40	99.0	16.14	99.0	15.42	99.0
15.56	98.0	16.33	98.0	15.57	97.0
16.25	97.0	16.55	96.0	16.15	95.0
16.33	96.0	17.12	95.0	16.34	93.0
16.54	95.0	17.29	94.0	16.55	91.0
17.11	94.0	17.57	92.0	17.13	88.0
17.29	93.0	18.21	91.0	17.29	86.0
17.57	91.0	18.41	90.0	17.57	84.0
18.21	90.0	19.02	89.0	18.21	82.0
18.41	89.0	19.22	88.0	18.41	79.0
19.02	88.0	19.42	87.0	19.02	77.0





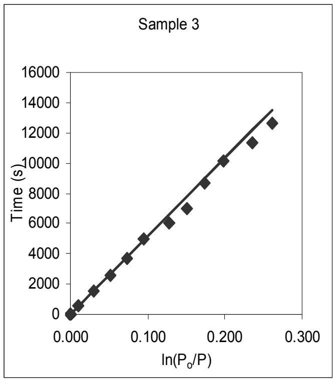
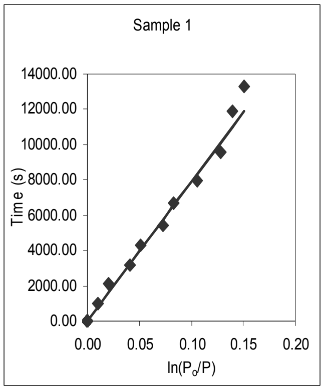
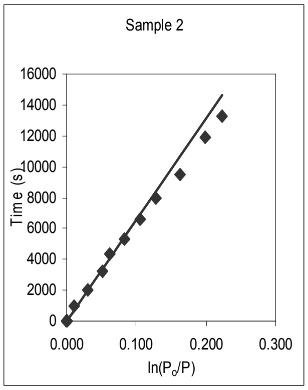


Table A-33: 1.0 % PWC mortar samples 180 days permeability results

Average k (m/s): 6.8 E-11 COV: 15.1 % OPI: 10.16					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	67.87	Diameter (mm)	67.32	Diameter (mm)	67.97
Thickness (mm)	28.37	Thickness (mm)	27.54	Thickness (mm)	27.52
k (m/s)	6E-11	k (m/s)	8E-11	k (m/s)	6.553E-11
r^2	0.9810	r^2	0.9735	r^2	0.9935
Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)
17.30	100.0	17.31	100.0	17.31	100.0
17.46	99.0	17.47	99.0	17.47	99.0
18.05	98.0	18.05	97.0	18.05	97.0
18.23	96.0	18.24	95.0	18.24	95.0
18.42	95.0	18.43	94.0	18.43	94.0
19.00	93.0	19.00	92.0	19.01	93.0
19.21	92.0	19.21	90.0	19.21	91.0
19.43	90.0	19.44	88.0	19.44	90.0
20.09	88.0	20.09	85.0	20.09	88.0
20.48	87.0	20.49	82.0	20.49	85.0
21.12	86.0	21.12	80.0	21.12	83.0





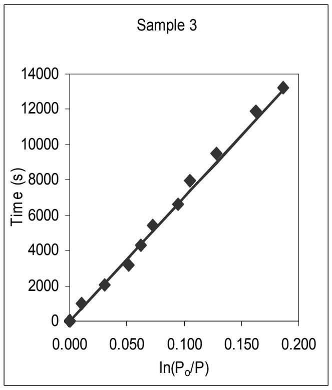
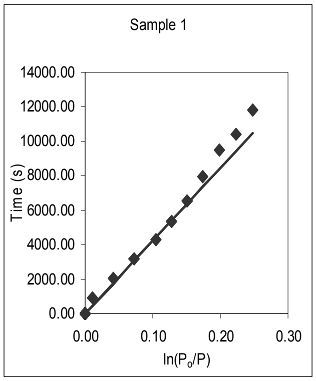
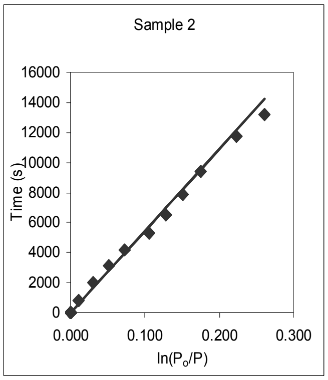


Table A-34: 2.5 % PWC mortar samples 180 days permeability results

Average k (m/s): 9.1 E-11 COV: 14.4 % OPI: 10.04					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	67.06	Diameter (mm)	68.55	Diameter (mm)	67.93
Thickness (mm)	27.57	Thickness (mm)	26.50	Thickness (mm)	27.17
k (m/s)	1.06E-10	k (m/s)	8.6E-11	k (m/s)	8.143E-11
r^2	0.9702	r^2	0.9892	r^2	0.8709
Time	Pressure	Time	Pressure	Time	Pressure
(hh.min)	(kPa)	(hh.min)	(kPa)	(hh.min)	(kPa)
17.32	100.0	17.33	100.0	17.34	100.0
17.47	99.0	17.47	99.0	17.47	98.0
18.06	96.0	18.06	97.0	18.06	96.0
18.25	93.0	18.25	95.0	18.25	94.0
18.43	90.0	18.43	93.0	18.44	92.0
19.01	88.0	19.01	90.0	19.01	89.0
19.21	86.0	19.22	88.0	19.22	88.0
19.44	84.0	19.44	86.0	19.45	87.0
20.10	82.0	20.10	84.0	20.10	85.0
20.25	80.0	20.49	80.0	20.50	83.0
20.49	78.0	21.13	77.0	21.13	81.0





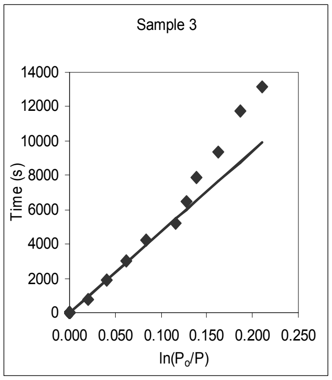
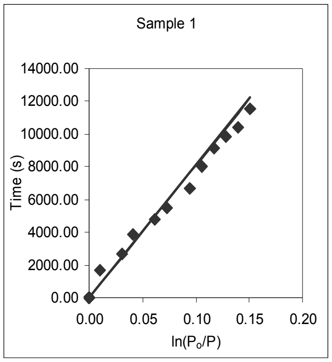
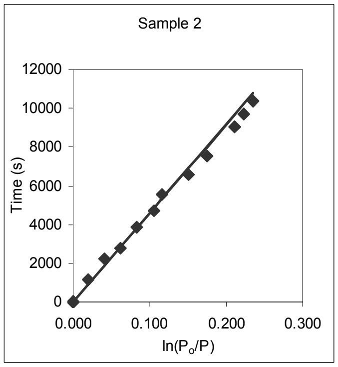


Table A-35: Control concrete samples 28 days permeability results

Average k (m/s): 7.4E-11 COV: 34.5 % OPI: 10.13					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	70.60	Diameter (mm)	70.30	Diameter (mm)	70.19
Thickness (mm)	27.00	Thickness (mm)	28.23	Thickness (mm)	27.39
k (m/s)	5.63E-11	k (m/s)	1.03E-10	k (m/s)	6.247E-11
r^2	0.9726	r^2	0.9900	r^2	0.9265
Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)
13.27	100.0	13.28	100.0	13.29	100.0
13.55	99.0	13.47	98.0	13.55	99.0
14.12	97.0	14.05	96.0	14.13	97.0
14.32	96.0	14.14	94.0	14.32	96.0
14.47	94.0	14.32	92.0	14.47	94.0
14.59	93.0	14.46	90.0	15.00	93.0
15.18	91.0	15.00	89.0	15.18	91.0
15.41	90.0	15.18	86.0	15.36	90.0
16.00	89.0	15.34	84.0	15.59	88.0
16.11	88.0	15.59	81.0	16.10	87.0
16.21	87.0	16.10	80.0	16.21	86.0
16.39	86.0	16.21	79.0	16.39	85.0





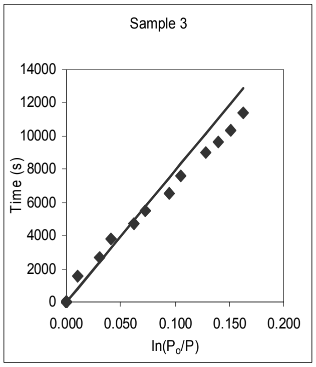
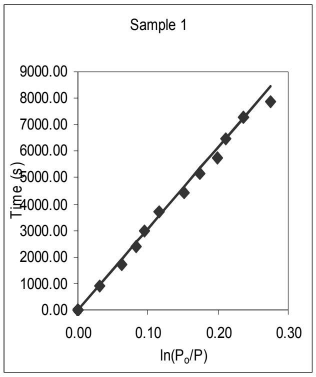
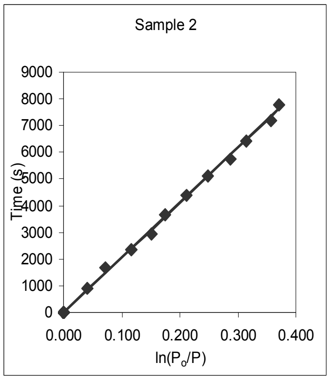


Table A-36: 0.6 % PWC concrete samples 28 days permeability results

Average k (m/s): 1.3 E-10 COV: 35.3 % OPI: 9.87					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	70.18	Diameter (mm)	70.61	Diameter (mm)	70.47
Thickness (mm)	27.41	Thickness (mm)	22.33	Thickness (mm)	25.66
k (m/s)	1.49E-10	k (m/s)	1.74E-10	k (m/s)	8.169E-11
r^2	0.9912	r^2	0.9979	r^2	0.8457
Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)
13.48	100.0	13.49	100.0	13.50	100.0
14.03	97.0	14.04	96.0	14.17	98.0
14.17	94.0	14.17	93.0	14.28	96.0
14.28	92.0	14.28	89.0	14.38	95.0
14.38	91.0	14.38	86.0	14.51	94.0
14.50	89.0	14.50	84.0	15.02	93.0
15.02	86.0	15.02	81.0	15.15	91.0
15.14	84.0	15.14	78.0	15.25	90.0
15.24	82.0	15.25	75.0	15.36	88.0
15.36	81.0	15.36	73.0	15.50	86.0
15.49	79.0	15.49	70.0	16.00	85.0
15.59	76.0	15.59	69.0	16.10	84.0





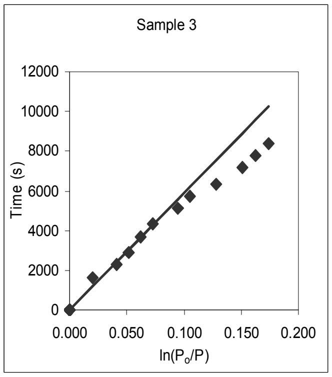
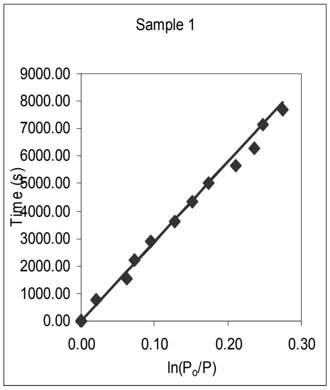
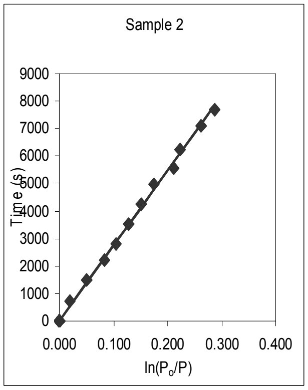


Table A-37: 1.0 % PWC concrete samples 28 days permeability results

Average k (m/s): 2.1 E-10 COV: 38.3 % OPI: 9.67					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	70.75	Diameter (mm)	70.35	Diameter (mm)	70.63
Thickness (mm)	28.18	Thickness (mm)	29.12	Thickness (mm)	26.11
k (m/s)	1.6E-10	k (m/s)	1.72E-10	k (m/s)	3.067E-10
r^2	0.9900	r^2	0.9970	r^2	0.9991
Time	Pressure	Time	Pressure	Time	Pressure
(hh.min)	(kPa)	(hh.min)	(kPa)	(hh.min)	(kPa)
13.51	100.0	13.52	100.0	14.41	100.0
14.04	98.0	14.04	98.0	14.52	96.0
14.17	94.0	14.17	95.0	15.03	91.0
14.28	93.0	14.29	92.0	15.15	86.0
14.39	91.0	14.39	90.0	15.25	82.0
14.51	88.0	14.51	88.0	15.32	80.0
15.03	86.0	15.03	86.0	15.37	78.0
15.15	84.0	15.15	84.0	15.44	76.0
15.25	81.0	15.25	81.0	15.50	74.0
15.36	79.0	15.36	80.0	15.58	71.0
15.50	78.0	15.50	77.0	16.07	68.0
15.59	76.0	16.00	75.0	16.12	67.0





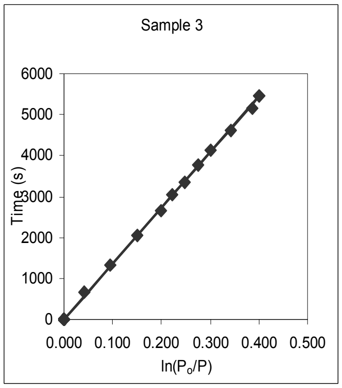
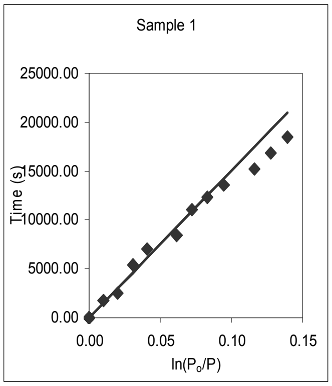
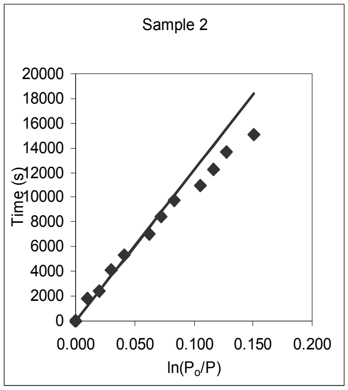


Table A-38: 30 % FA concrete samples 28 days permeability results

Average k (m/s): 4.5E-11 COV: 46.8 % OPI: 10.34					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	70.63	Diameter (mm)	70.54	Diameter (mm)	70.48
Thickness (mm)	24.93	Thickness (mm)	25.34	Thickness (mm)	27.08
k (m/s)	2.89E-11	k (m/s)	3.78E-11	k (m/s)	6.928E-11
r^2	0.9513	r^2	0.9171	r^2	0.9966
Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)
14.02	100.0	14.03	100.0	14.05	100.0
14.31	99.0	14.33	99.0	14.27	98.0
14.43	98.0	14.43	98.0	14.42	96.0
15.31	97.0	15.11	97.0	15.11	94.0
16.00	96.0	15.32	96.0	15.32	92.0
16.23	94.0	16.00	94.0	16.00	90.0
17.06	93.0	16.23	93.0	16.23	88.0
17.28	92.0	16.46	92.0	16.46	86.0
17.49	91.0	17.06	90.0	17.06	84.0
18.15	89.0	17.28	89.0	17.29	82.0
18.42	88.0	17.50	88.0	17.50	80.0
19.10	87.0	18.15	86.0	18.15	79.0





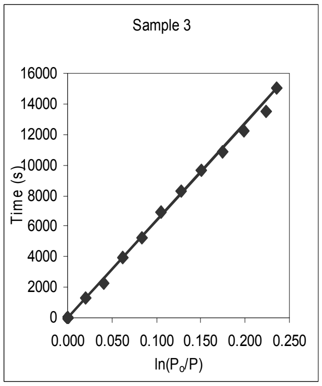
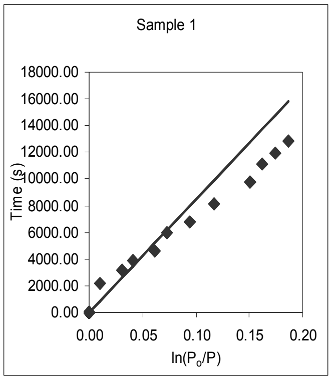
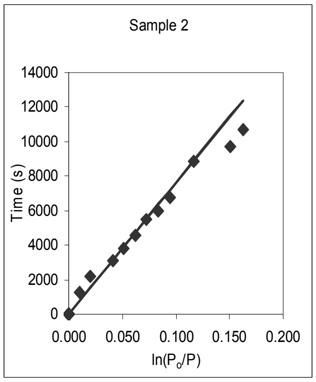


Table A-39: 0.6 % PWC + 30 % FA concrete samples 28 days permeability results

Average k (m/s): 6.2 E-11 COV: 3.7 % OPI: 10.21					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	69.91	Diameter (mm)	69.42	Diameter (mm)	69.83
Thickness (mm)	25.60	Thickness (mm)	27.07	Thickness (mm)	25.91
k (m/s)	5.98E-11	k (m/s)	6.43E-11	k (m/s)	6.296E-11
r^2	0.7860	r^2	0.9418	r^2	0.9237
Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)
11.36	100.0	11.37	100.0	11.38	100.0
12.12	99.0	11.58	99.0	12.13	98.0
12.29	97.0	12.13	98.0	12.29	96.0
12.41	96.0	12.29	96.0	12.40	95.0
12.53	94.0	12.40	95.0	12.53	94.0
13.16	93.0	12.53	94.0	13.09	93.0
13.29	91.0	13.08	93.0	13.17	92.0
13.52	89.0	13.17	92.0	13.29	91.0
14.19	86.0	13.29	91.0	13.52	89.0
14.41	85.0	14.05	89.0	14.05	87.0
14.55	84.0	14.19	86.0	14.19	86.0
15.10	83.0	14.35	85.0	14.35	85.0





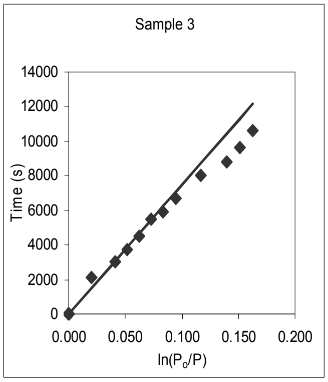
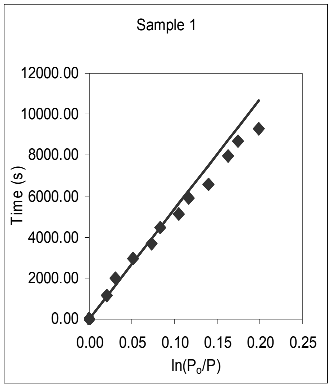
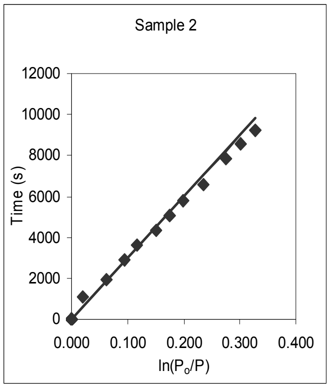


Table A-40: 1.0 % PWC + 30 % FA concrete samples 28 days permeability results

Average k (m/s): 1.1 E-10 COV: 28.3 % OPI: 9.95					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	70.97	Diameter (mm)	71.15	Diameter (mm)	71.21
	25.91	Thickness (mm)	26.65	Thickness (mm)	27.94
k (m/s)	8.35E-11	k (m/s)	1.46E-10	k (m/s)	1.07E-10
r^2	0.9562	r^2	0.9868	r^2	0.9905
Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)
11.39	100.0	11.40	100.0	11.41	100.0
11.58	98.0	11.58	98.0	11.58	98.0
12.12	97.0	12.12	94.0	12.12	96.0
12.28	95.0	12.28	91.0	12.28	94.0
12.40	93.0	12.40	89.0	12.40	92.0
12.53	92.0	12.52	86.0	12.53	90.0
13.04	90.0	13.04	84.0	13.04	89.0
13.17	89.0	13.16	82.0	13.16	87.0
13.29	87.0	13.30	79.0	13.30	85.0
13.52	85.0	13.51	76.0	13.51	83.0
14.04	84.0	14.03	74.0	14.03	81.0
14.14	82.0	14.14	72.0	14.18	79.0





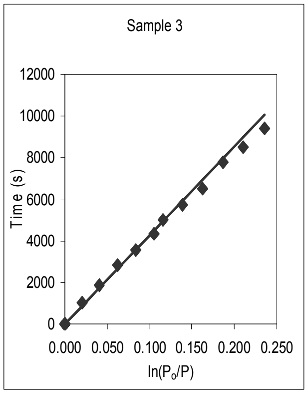
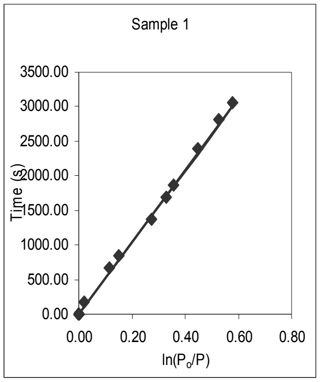
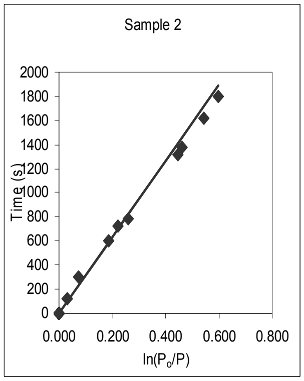


Table A-41: Premix concrete 28 days permeability results

Average k (m/s): 9.9 E-10 COV: 39.5 % OPI: 9.01					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	71.02	Diameter (mm)	71.05	Diameter (mm)	71.32
	26.91	Thickness (mm)	27.34	Thickness (mm)	27.68
k (m/s)	8.03E-10	k (m/s)	1.43E-09	k (m/s)	7.204E-10
r^2	0.9966	r^2	0.9893	r^2	0.9978
Time	Pressure	Time	Pressure	Time	Pressure
(hh.min)	(kPa)	(hh.min)	(kPa)	(hh.min)	(kPa)
11.57	100.0	11.58	100.0	11.59	100.0
12.00	98.0	12.00	97.0	12.08	92.0
12.08	89.0	12.03	93.0	12.10	90.0
12.11	86.0	12.08	83.0	12.20	81.0
12.20	76.0	12.10	80.0	12.25	77.0
12.25	72.0	12.11	77.0	12.29	74.0
12.28	70.0	12.20	64.0	12.37	69.0
12.37	64.0	12.21	63.0	12.44	64.0
12.44	59.0	12.25	58.0	12.48	62.0
12.48	56.0	12.28	55.0	12.50	59.0





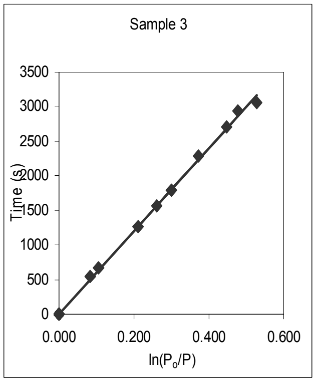
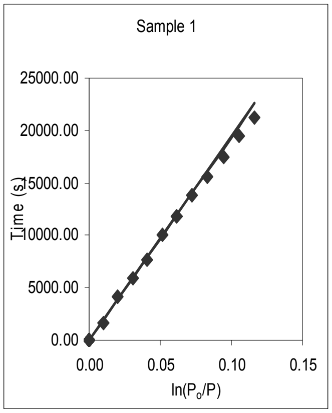
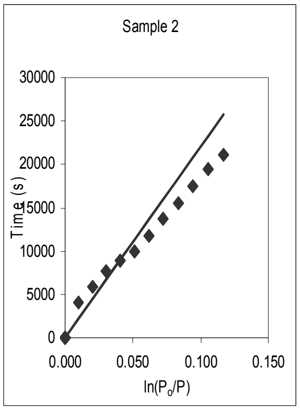


Table A-42: Control concrete samples 180 days permeability results

Average k (m/s): 2.7 E-11 COV: 8.7 % OPI: 10.57					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	67.30	Diameter (mm)	67.22	Diameter (mm)	67.49
Thickness (mm)	27.40	Thickness (mm)	26.84	Thickness (mm)	27.97
k (m/s)	2.58E-11	k (m/s)	2.5E-11	k (m/s)	2.942E-11
r^2	0.9930	r^2	0.8407	r^2	0.9572
Time	Pressure	Time	Pressure	Time	Pressure
(hh.min)	(kPa)	(hh.min)	(kPa)	(hh.min)	(kPa)
14.58	100.0	14.59	100.0	15.00	100.0
15.26	99.0	16.08	99.0	15.39	99.0
16.08	98.0	16.37	98.0	16.09	98.0
16.37	97.0	17.06	97.0	16.37	97.0
17.06	96.0	17.27	96.0	17.06	96.0
17.45	95.0	17.45	95.0	17.27	95.0
18.15	94.0	18.15	94.0	17.45	94.0
18.48	93.0	18.48	93.0	18.15	93.0
19.18	92.0	19.18	92.0	18.48	92.0
19.50	91.0	19.50	91.0	19.18	91.0
20.22	90.0	20.22	90.0	19.50	90.0
20.52	89.0	20.52	89.0	20.22	89.0





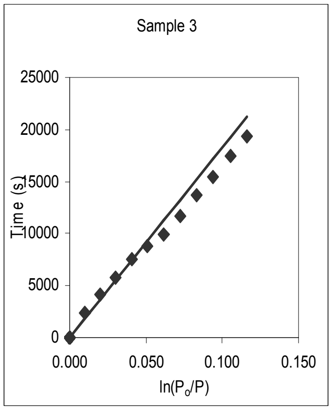
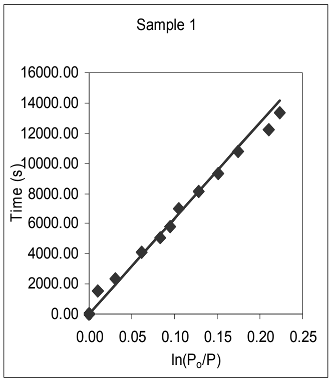
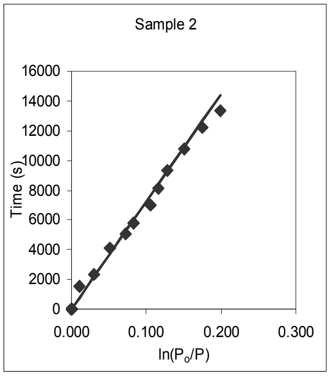


Table A-43: 0.6 % PWC concrete samples 180 days permeability results

Average k (m/s): 6.1E-11 COV: 34.1 % OPI: 10.22					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	67.18	Diameter (mm)	67.45	Diameter (mm)	70.06
Thickness (mm)	26.81	Thickness (mm)	26.51	Thickness (mm)	29.30
k (m/s)	7.75E-11	k (m/s)	6.65E-11	k (m/s)	3.761E-11
r^2	0.9839	r^2	0.9857	r^2	0.9877
Time	Pressure	Time	Pressure	Time	Pressure
(hh.min)	(kPa)	(hh.min)	(kPa)	(hh.min)	(kPa)
15.01	100.0	15.01	100.0	15.03	100.0
15.26	99.0	15.26	99.0	15.41	99.0
15.40	97.0	15.40	97.0	16.10	97.0
16.09	94.0	16.10	95.0	16.26	96.0
16.26	92.0	16.26	93.0	16.58	95.0
16.38	91.0	16.38	92.0	17.16	94.0
16.58	90.0	16.58	90.0	17.45	93.0
17.16	88.0	17.16	89.0	18.00	92.0
17.36	86.0	17.36	88.0	18.25	91.0
18.00	84.0	18.00	86.0	18.43	90.0
18.25	81.0	18.25	84.0	19.02	89.0
18.43	80.0	18.43	82.0	19.25	88.0





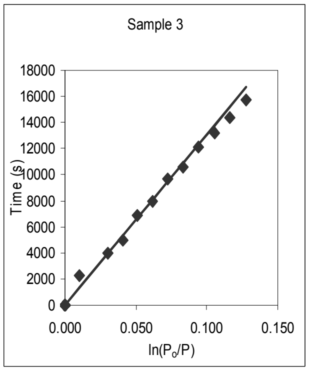
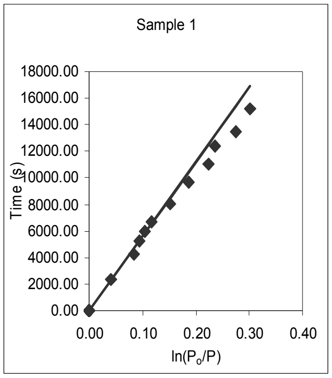
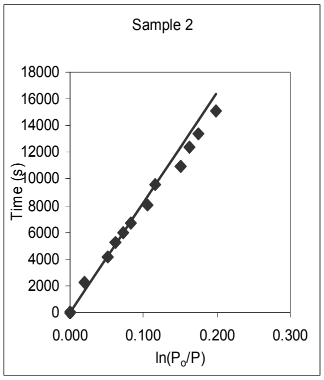


Table A-44: 1.0 % PWC concrete samples 180 days permeability results

Average k (m/s): 8.2 E-11 COV: 25.9 % OPI: 10.08					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	67.33	Diameter (mm)	67.57	Diameter (mm)	67.15
Thickness (mm)	26.57	Thickness (mm)	25.70	Thickness (mm)	25.58
k (m/s)	9.09E-11	k (m/s)	5.81E-11	k (m/s)	9.806E-11
r^2	0.9561	r^2	0.9730	r^2	0.9955
Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)
15.41	100.0	15.42	100.0	15.43	100.0
16.20	96.0	16.20	98.0	16.20	96.0
16.52	92.0	16.52	95.0	16.52	91.0
17.09	91.0	17.09	94.0	17.09	90.0
17.21	90.0	17.21	93.0	17.21	89.0
17.33	89.0	17.33	92.0	17.33	86.0
17.55	86.0	17.56	90.0	17.56	84.0
18.22	83.0	18.22	89.0	18.22	81.0
18.45	80.0	18.45	86.0	18.45	79.0
19.08	79.0	19.08	85.0	19.08	76.0
19.25	76.0	19.25	84.0	19.25	75.0
19.54	74.0	19.54	82.0	19.37	74.0





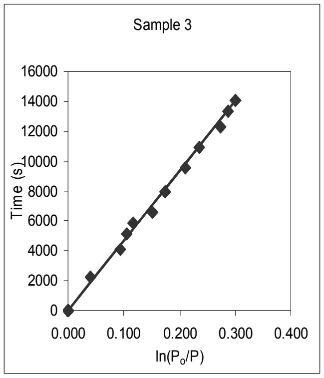
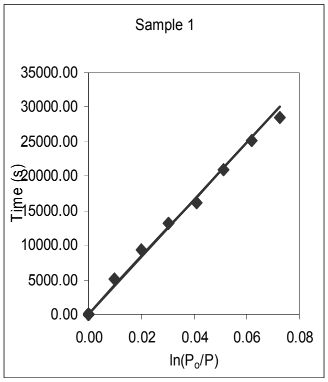
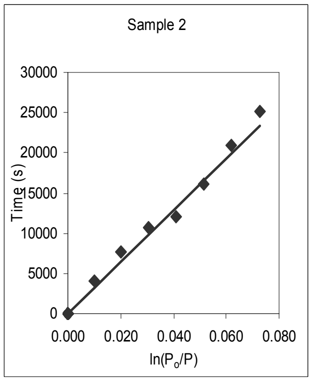


Table A-45: 30 % FA concrete samples 180 days permeability results

Average k (m/s): 1.3 E-11 COV: 20.8 % OPI: 10.88					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	67.59	Diameter (mm)	68.11	Diameter (mm)	67.30
Thickness (mm)	24.63	Thickness (mm)	24.85	Thickness (mm)	25.14
k (m/s)	1.06E-11	k (m/s)	1.27E-11	k (m/s)	1.6E-11
r^2	0.9921	r^2	0.9837	r^2	0.9450
Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)	Time (hh.min)	Pressure (kPa)
15.45	100.0	15.46	100.0	15.47	100.0
17.09	99.0	16.53	99.0	16.54	98.0
18.21	98.0	17.55	98.0	17.55	97.0
19.24	97.0	18.44	97.0	18.45	96.0
20.16	96.0	19.08	96.0	19.09	95.0
21.35	95.0	20.16	95.0	20.16	94.0
22.45	94.0	21.35	94.0	21.36	93.0
23.40	93.0	22.45	93.0	22.45	92.0





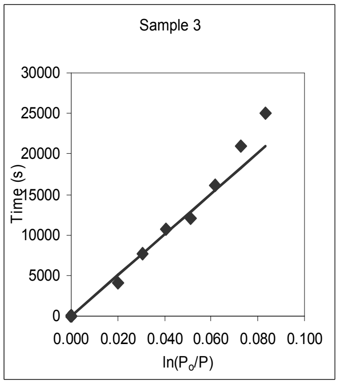
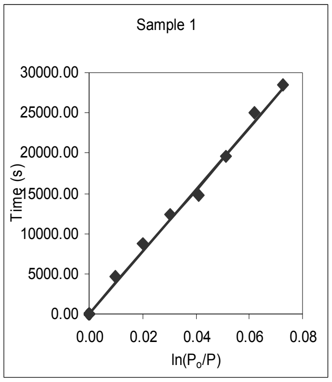
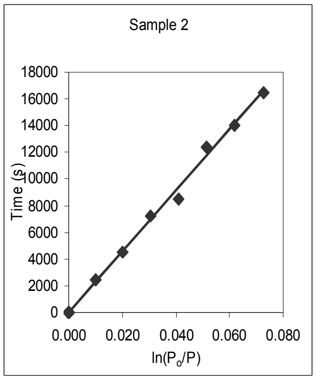


Table A-46: 0.6 % PWC + 30 % FA concrete samples 180 days permeability results

Average k (m/s): 1.7 E-11 COV: 29.4 % OPI: 10.78					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	67.61	Diameter (mm)	67.60	Diameter (mm)	67.54
Thickness (mm)	24.88	Thickness (mm)	24.89	Thickness (mm)	23.00
k (m/s)	1.1E-11	k (m/s)	1.9E-11	k (m/s)	1.991E-11
r^2	0.9937	r^2	0.9948	r^2	0.9811
Time	Pressure	Time	Pressure	Time	Pressure
(hh.min)	(kPa)	(hh.min)	(kPa)	(hh.min)	(kPa)
11.43	100.0	11.45	100.0	11.45	100.0
13.00	99.0	12.25	99.0	12.25	99.0
14.08	98.0	13.00	98.0	13.00	98.0
15.10	97.0	13.46	97.0	13.46	97.0
15.50	96.0	14.07	96.0	14.07	96.0
17.10	95.0	15.11	95.0	14.34	95.0
18.40	94.0	15.39	94.0	15.11	94.0
19.38	93.0	16.20	93.0	15.39	93.0





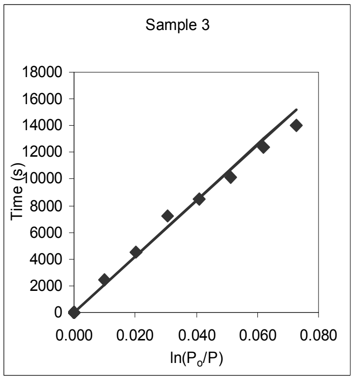
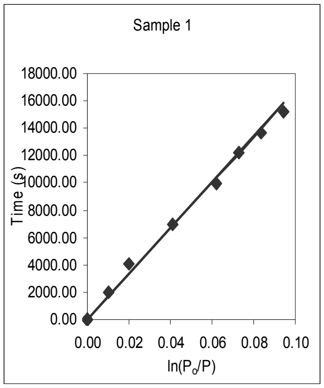
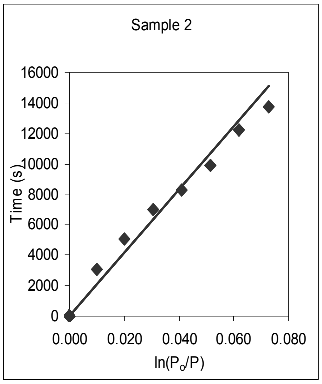


Table A-47: 1.0 % PWC + 30 %FA concrete samples 180 days permeability results

Average k (m/s): 2.4 E-11 COV: 7.1 % OPI: 10.63					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	67.89	Diameter (mm)	66.88	Diameter (mm)	68.07
	22.81	Thickness (mm)	24.43	Thickness (mm)	24.09
k (m/s)	2.39E-11	k (m/s)	2.19E-11	k (m/s)	2.52E-11
r^2	0.9949	r^2	0.9658	r^2	0.9920
Time	Pressure	Time	Pressure	Time	Pressure
(hh.min)	(kPa)	(hh.min)	(kPa)	(hh.min)	(kPa)
11.47	100.0	11.48	100.0	11.49	100.0
12.20	99.0	12.39	99.0	12.26	99.0
12.55	98.0	13.13	98.0	12.59	98.0
13.43	96.0	13.45	97.0	13.45	96.0
14.33	94.0	14.06	96.0	14.33	94.0
15.10	93.0	14.33	95.0	15.12	93.0
15.35	92.0	15.12	94.0	15.37	92.0
16.01	91.0	15.37	93.0	16.01	91.0





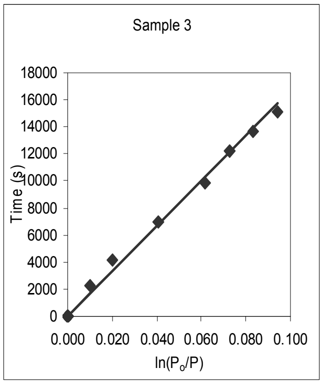
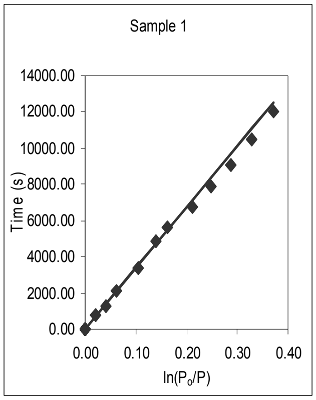
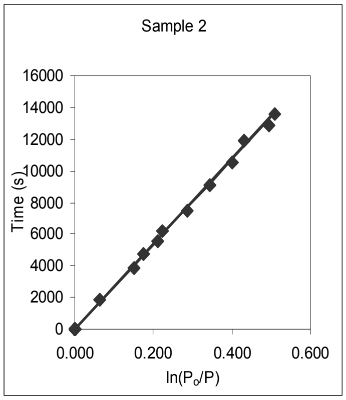


Table A-48: Premix concrete samples 180 days permeability results

Average k (m/s): 1.5 E-10 COV: 13.5 % OPI: 9.82					
SAMPLE 1		SAMPLE 2		SAMPLE 3	
Diameter (mm)	67.63	Diameter (mm)	67.76	Diameter (mm)	68.04
	23.93	Thickness (mm)	25.90	Thickness (mm)	24.78
k (m/s)	1.29E-10	k (m/s)	1.69E-10	k (m/s)	1.577E-10
r^2	0.9913	r^2	0.9973	r^2	0.9911
Time	Pressure	Time	Pressure	Time	Pressure
(hh.min)	(kPa)	(hh.min)	(kPa)	(hh.min)	(kPa)
15.04	100.0	15.49	100.0	11.51	100.0
15.17	98.0	16.20	94.0	12.07	96.0
15.25	96.0	16.53	86.0	12.24	93.0
15.39	94.0	17.08	84.0	12.38	90.0
16.00	90.0	17.21	81.0	12.59	86.0
16.25	87.0	17.32	80.0	13.10	83.0
16.38	85.0	17.54	75.0	13.19	80.0
16.57	81.0	18.21	71.0	13.44	77.0
17.15	78.0	18.44	67.0	14.06	74.0
17.35	75.0	19.07	65.0	14.31	71.0
17.59	72.0	19.23	61.0	14.46	68.0
18.24	69.0	19.36	60.0	15.11	65.0





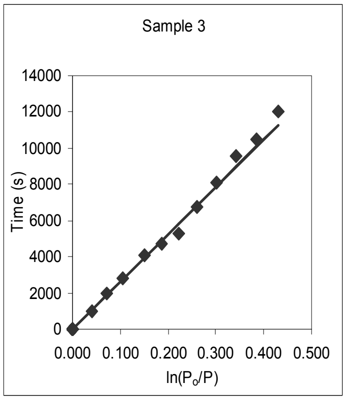
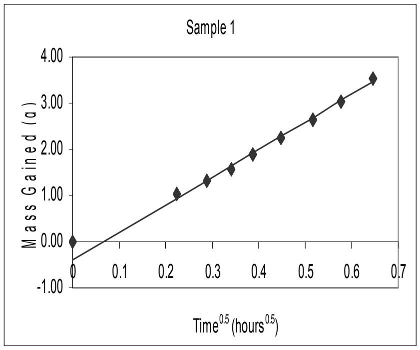
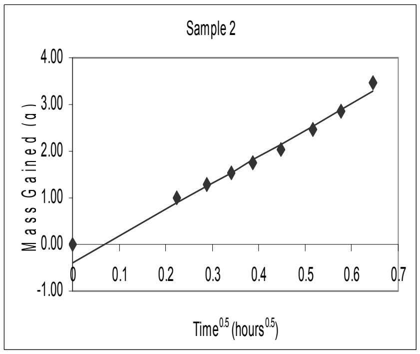


Table A-49: Control mortar samples 28 days sorptivity results

Av. Sorptivity:	7.8	COV:	1.0
Av. Porosity:	19.2	COV:	4.8
	1	2	3
Diameter (mm)	69.75	70.28	70.13
Thickness (mm)	23.86	27.64	25.59
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	178.41	211.44	196.14
3	179.43	212.43	197.02
5	179.74	212.72	197.25
7	179.98	212.96	197.48
9	180.31	213.20	197.76
12	180.65	213.46	198.20
16	181.04	213.90	198.53
20	181.46	214.30	198.93
25	181.96	214.9	199.29
Saturated Mass (g)	196.86	231.86	214.34
R^2 (Must be >0.98)	0.9953	0.9847	0.9938
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	7.8	7.7	7.9
Porosity (%)	20.2	19.0	18.4





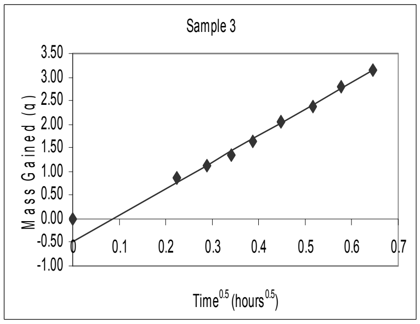
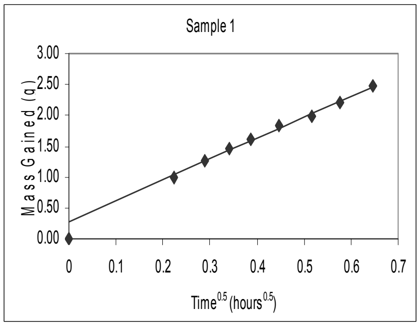
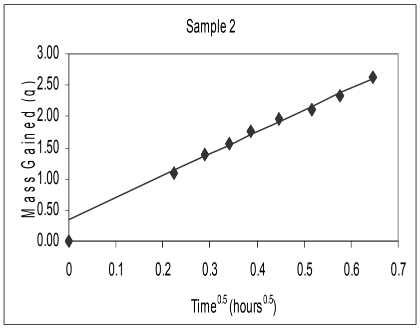


Table A-50: 0.4 % PWC mortar samples 28 days sorptivity results

Av. Sorptivity:	4.7	COV:	4.2
Av. Porosity:	18.8	COV:	1.9
	1	2	3
Diameter (mm)	70.20	69.94	69.83
Thickness (mm)	28.54	27.74	22.86
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	217.26	210.93	171.89
3	218.26	212.01	172.92
5	218.52	212.31	173.18
7	218.72	212.49	173.34
9	218.88	212.68	173.50
12	219.10	212.90	173.71
16	219.24	213.04	173.91
20	219.46	213.27	174.12
25	219.74	213.55	174.37
Saturated Mass (g)	238.34	230.57	188.53
R^2 (Must be >0.98)	0.9949	0.9936	0.9990
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	4.6	4.9	4.6
Porosity (%)	19.1	18.4	19.0





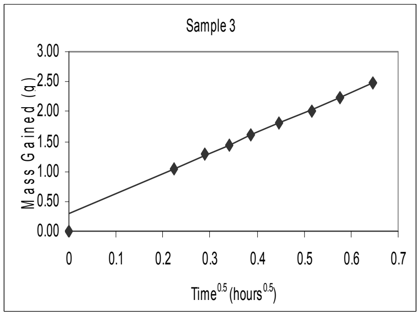
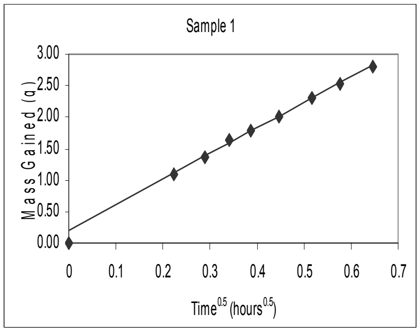
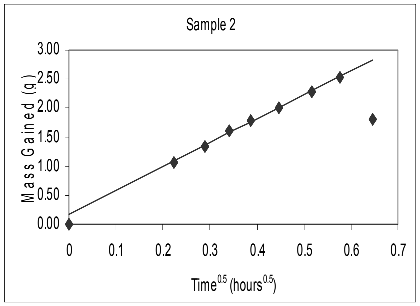


Table A-51: 0.6 % PWC mortar samples 28 days sorptivity results

Av. Sorptivity:	5.7	COV:	2.0
Av. Porosity:	18.7	COV:	3.0
	1	2	3
Diameter (mm)	70.26	70.45	70.79
Thickness (mm)	30.96	26.00	26.87
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	233.93	200.59	203.08
3	235.01	201.66	204.15
5	235.30	201.94	204.46
7	235.56	202.20	204.66
9	235.72	202.37	204.84
12	235.94	202.60	205.10
16	236.24	202.87	205.37
20	236.47	203.13	205.66
25	236.73	202.39	205.94
Saturated Mass (g)	255.9	219.20	223.5
R^2 (Must be >0.98)	0.9985	0.9986	0.9994
Range	3-25 min	3-20 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	5.7	5.7	5.5
Porosity(%)	18.3	18.4	19.3





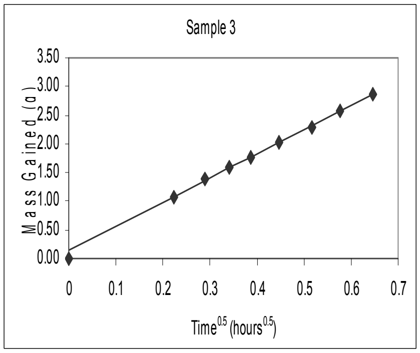
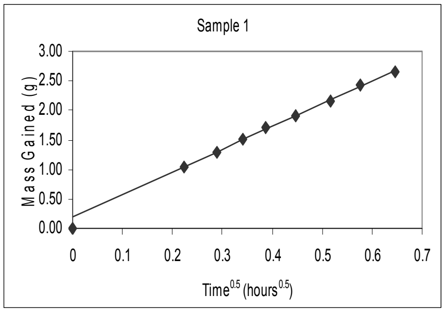
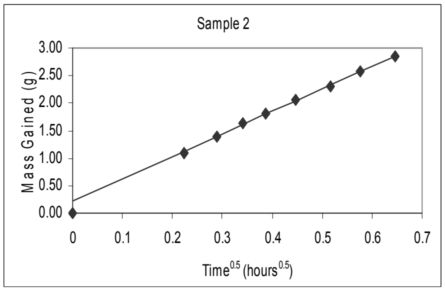


Table A-52: 0.8 % PWC mortar samples 28 days sorptivity results

Av. Sorptivity:	5.6	COV:	4.2
Av. Porosity:	19.0	COV:	6.7
	1	2	3
Diameter (mm)	70.09	70.34	69.94
Thickness (mm)	27.81	27.83	27.39
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	215.77	215.65	208.53
3	216.80	216.75	209.67
5	217.07	217.05	209.98
7	217.29	217.29	210.21
9	217.47	217.45	210.40
12	217.68	217.70	210.64
16	217.93	217.96	210.96
20	218.20	218.23	211.24
25	218.43	218.5	211.52
Saturated Mass (g)	235.7	235.20	230.1
R^2 (Must be >0.98)	0.9991	0.9992	0.9996
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	5.4	5.8	5.5
Porosity(%)	18.6	18.1	20.5





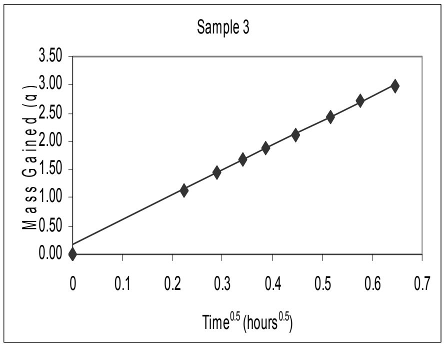
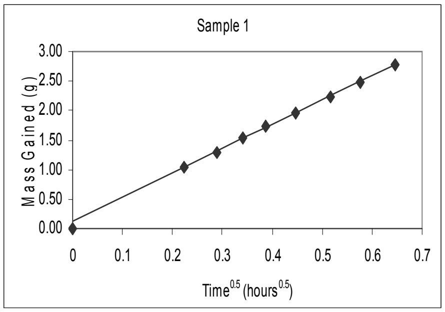
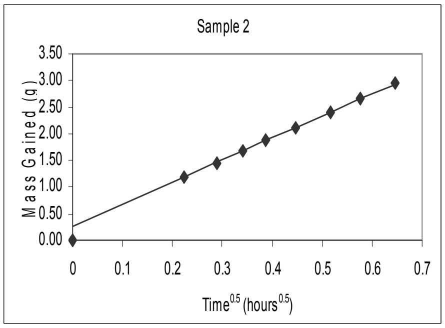


Table A-53: 1.0 % PWC mortar samples 28 days sorptivity results

Av. Sorptivity:	5.3	COV:	5.6
Av. Porosity:	20.3	COV:	6.6
	1	2	3
Diameter (mm)	70.32	69.94	68.77
Thickness (mm)	24.98	26.65	24.88
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	203.69	200.22	182.71
3	204.73	201.42	183.85
5	204.99	201.68	184.11
7	205.23	201.90	184.32
9	205.43	202.09	184.47
12	205.66	202.33	184.73
16	205.93	202.61	185.00
20	206.18	202.87	185.27
25	206.47	203.16	185.54
Saturated Mass (g)	222.5	220.40	202.9
R^2 (Must be >0.98)	0.9996	0.9999	0.9994
Range	3-25 min	3-25 min	3-25 min
Sorptivity ($mm/hr^{0.5}$)	5.5	5.4	4.9
Porosity(%)	19.4	19.7	21.8





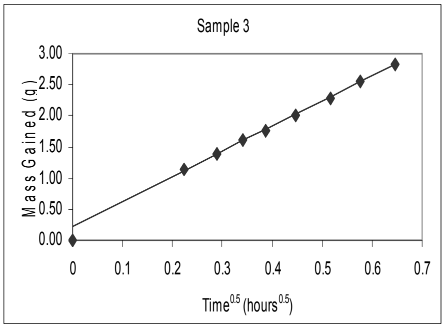
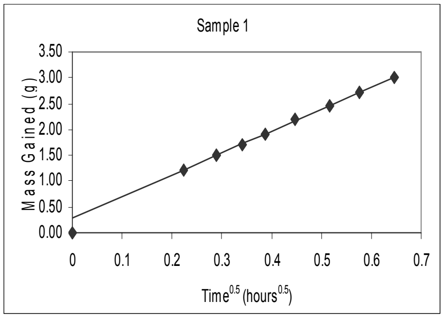
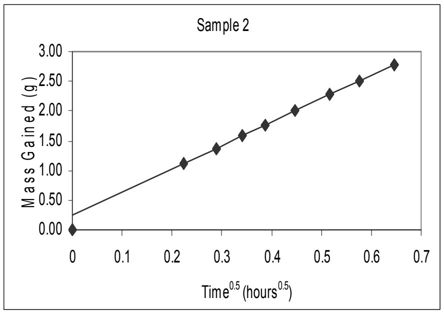


Table A-54: 2.5 % PWC mortar samples 28 days sorptivity results

Av. Sorptivity:	5.2	COV:	9.0
Av. Porosity:	20.5	COV:	4.5
	1	2	3
Diameter (mm)	69.85	70.65	69.94
Thickness (mm)	26.10	25.87	28.00
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	201.09	187.81	204.69
3	202.31	188.92	205.90
5	202.60	189.18	206.20
7	202.80	189.40	206.42
9	203.00	189.58	206.60
12	203.28	189.83	206.82
16	203.54	190.08	207.09
20	203.81	190.32	207.36
25	204.10	190.59	207.67
Saturated Mass (g)	220.6	209.40	227.1
R^2 (Must be >0.98)	0.9997	0.9998	0.9990
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	5.7	4.7	5.1
Porosity(%)	19.5	21.3	20.8





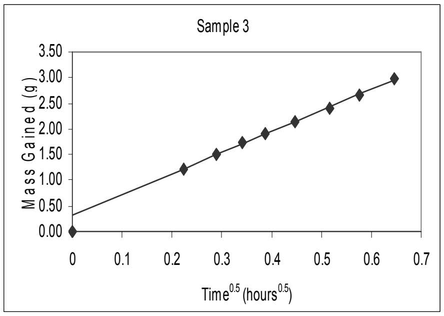
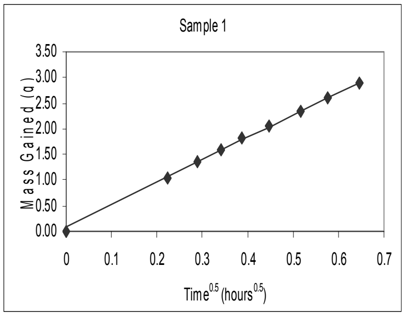
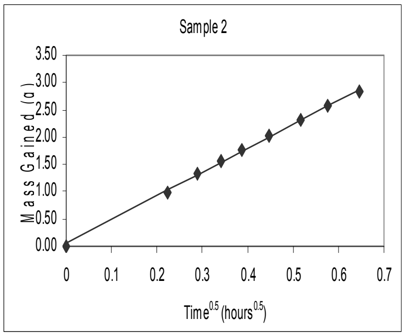


Table A-55: Control mortar samples 115 days sorptivity results

Av. Sorptivity:	5.7	COV:	2.2
Av. Porosity:	18.9	COV:	8.4
	1	2	3
Diameter (mm)	69.93	70.04	69.83
Thickness (mm)	25.89	26.58	26.14
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	195.98	200.41	200.05
3	197.01	201.39	201.02
5	197.33	201.73	201.28
7	197.58	201.98	201.49
9	197.79	202.18	201.64
12	198.04	202.43	201.85
16	198.32	202.71	202.12
20	198.57	202.98	202.34
25	198.86	203.25	202.62
Saturated Mass (g)	216.06	220.23	217.18
R^2 (Must be >0.98)	0.9986	0.9982	0.9995
Range	3-25 min	3-25 min	3-25 min
Sorptivity ($mm/hr^{0.5}$)	5.6	5.8	5.7
Porosity(%)	20.2	19.4	17.1





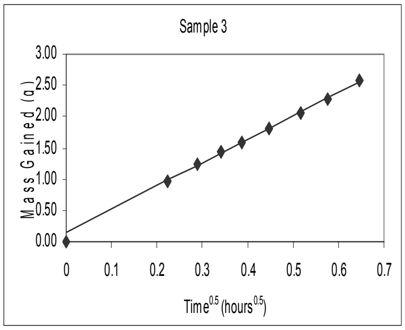
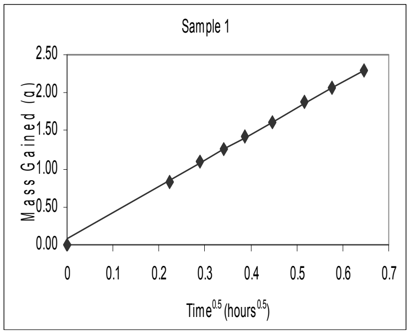
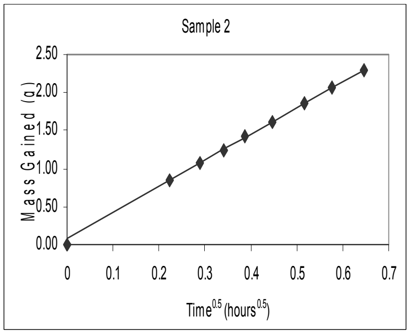


Table A-56: 0.4 % PWC mortar samples 115 days sorptivity results

Av. Sorptivity:	4.8	COV:	2.5
Av. Porosity:	17.9	COV:	6.3
	1	2	3
Diameter (mm)	70.86	70.73	70.16
Thickness (mm)	27.50	26.98	25.79
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	208.98	202.95	194.06
3	209.81	203.80	194.89
5	210.07	204.02	195.10
7	210.24	204.19	195.26
9	210.41	204.37	195.40
12	210.60	204.56	195.59
16	210.85	204.81	195.82
20	211.04	205.02	196.00
25	211.27	205.25	196.22
Saturated Mass (g)	228.75	223	210.7
R^2 (Must be >0.98)	0.9993	0.9998	0.9999
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	4.8	4.6	4.9
Porosity(%)	18.2	18.9	16.7





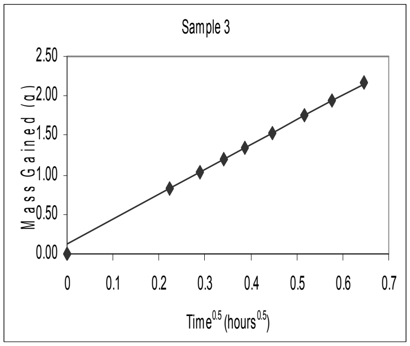
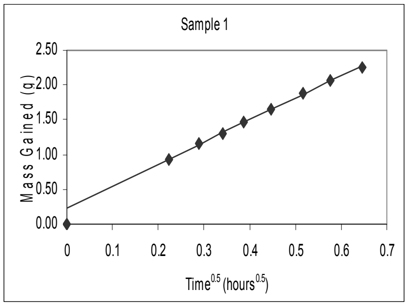
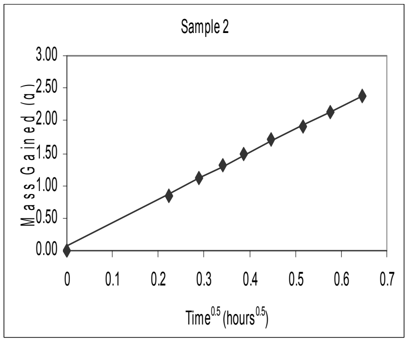


Table A-57: 0.6 % PWC mortar samples 115 days sorptivity results

Av. Sorptivity:	4.7	COV:	5.8
Av. Porosity:	17.3	COV:	7.5
	1	2	3
Diameter (mm)	71.20	71.13	70.68
Thickness (mm)	27.00	25.99	26.41
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	211.50	197.40	200.89
3	212.42	198.25	201.67
5	212.65	198.51	201.91
7	212.81	198.71	202.05
9	212.97	198.88	202.18
12	213.15	199.10	202.35
16	213.38	199.32	202.55
20	213.57	199.54	202.72
25	213.76	199.77	202.93
Saturated Mass (g)	230.89	216.09	217.28
R^2 (Must be >0.98)	0.9993	0.9990	0.9988
Range	3-25 min	3-25 min	3-25 min
Sorptivity ($mm/hr^{0.5}$)	4.4	5.0	4.7
Porosity(%)	18.0	18.1	15.8





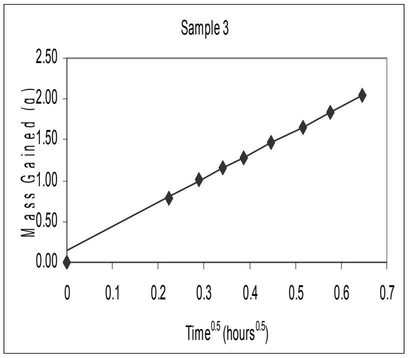
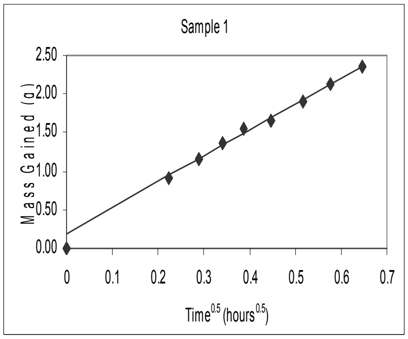
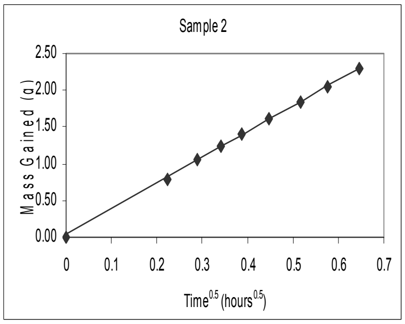


Table A-58: 0.8% PWC mortar samples 115 days sorptivity results

Av. Sorptivity:	4.8	COV:	5.9
Av. Porosity:	17.7	COV:	2.6
	1	2	3
Diameter (mm)	70.88	70.74	70.85
Thickness (mm)	26.97	27.04	25.91
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	205.49	207.58	196.48
3	206.40	208.37	197.31
5	206.65	208.63	197.52
7	206.86	208.83	197.70
9	207.03	208.99	197.86
12	207.14	209.20	198.05
16	207.40	209.42	198.26
20	207.62	209.63	198.46
25	207.84	209.87	198.69
Saturated Mass (g)	224	226.17	215.1
R^2 (Must be >0.98)	0.9961	0.9989	0.9998
Range	3-25 min	3-25 min	3-25 min
Sorptivity ($mm/hr^{0.5}$)	4.9	5.1	4.5
Porosity (%)	17.4	17.5	18.2





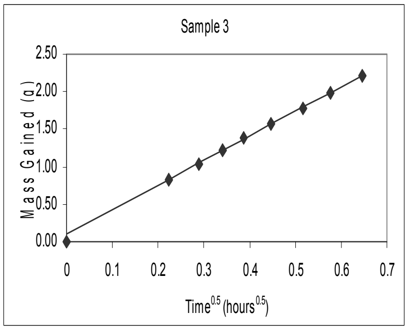
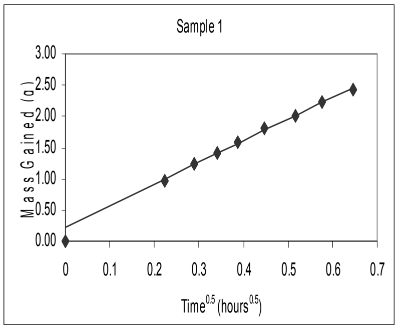
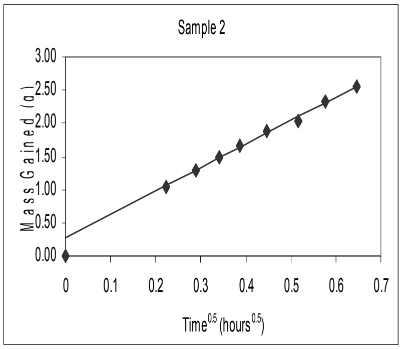


Table A-59: 1.0 % PWC mortar samples 115 days sorptivity results

Av. Sorptivity:	4.6	COV:	4.7
Av. Porosity:	18.3	COV:	6.2
	1	2	3
Diameter (mm)	70.35	70.68	70.42
Thickness (mm)	24.99	25.49	25.32
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	185.19	186.68	189.70
3	186.16	187.72	190.64
5	186.42	187.98	190.91
7	186.61	188.17	191.07
9	186.78	188.34	191.23
12	186.99	188.57	191.41
16	187.21	188.71	191.53
20	187.42	189.01	191.64
25	187.63	189.24	191.96
Saturated Mass (g)	203.66	205.48	206.43
R^2 (Must be >0.98)	0.9985	0.9961	0.9837
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	4.7	4.8	4.4
Porosity (%)	19.0	18.8	17.0





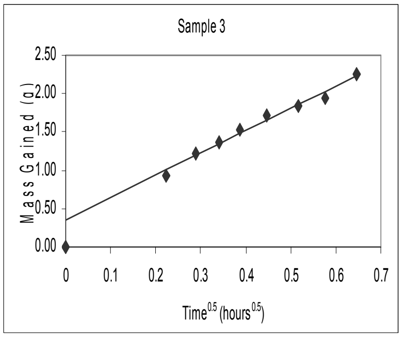
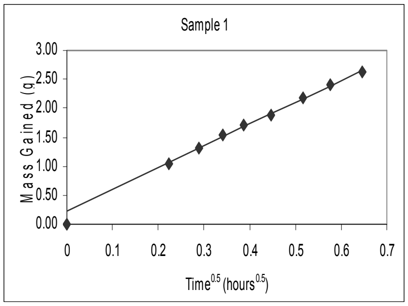
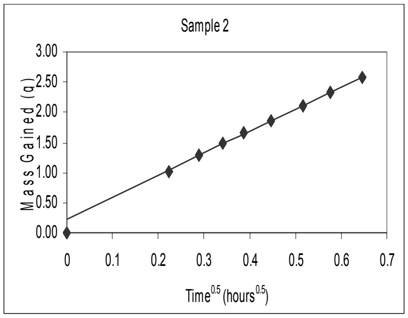


Table A-60: 2.5 % PWC mortar samples 115 days sorptivity results

Av. Sorptivity:	5.0	COV:	5.9
Av. Porosity:	18.2	COV:	11.8
	1	2	3
Diameter (mm)	70.21	69.62	70.86
Thickness (mm)	25.86	25.38	25.53
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	199.42	190.75	197.36
3	200.46	191.76	198.27
5	200.73	192.03	198.48
7	200.95	192.25	198.66
9	201.12	192.42	198.80
12	201.31	192.62	199.00
16	201.59	192.86	199.21
20	201.82	193.09	199.41
25	202.05	193.32	199.64
Saturated Mass (g)	217.68	210.43	213.54
R^2 (Must be >0.98)	0.9990	0.9985	0.9999
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	5.3	4.7	5.1
Porosity (%)	18.2	20.4	16.1





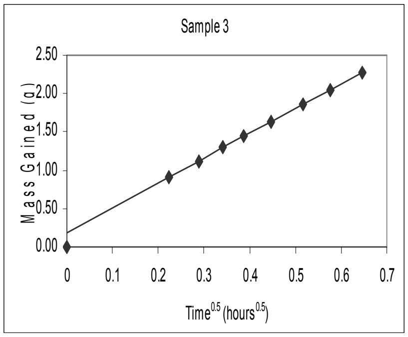
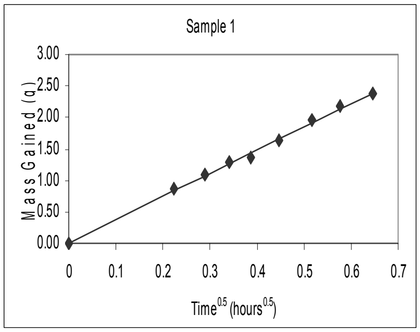
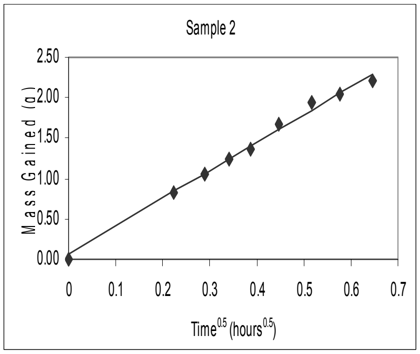


Table A-61: Control mortar samples 180 days sorptivity results

Av. Sorptivity:	5.4	COV:	11.4
Av. Porosity:	17.7	COV:	3.3
	1	2	3
Diameter (mm)	70.77	70.66	70.21
Thickness (mm)	23.52	27.70	27.67
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	176.24	217.18	216.72
3	177.10	218.00	217.55
5	177.32	218.23	217.83
7	177.52	218.42	218.05
9	177.60	218.54	218.24
12	177.87	218.85	218.47
16	178.20	219.13	218.76
20	178.41	219.22	218.99
25	178.61	219.4	219.26
Saturated Mass (g)	193.17	236.41	235.06
R^2 (Must be >0.98)	0.9945	0.9876	0.9997
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	5.1	5.0	6.1
Porosity (%)	18.3	17.7	17.1





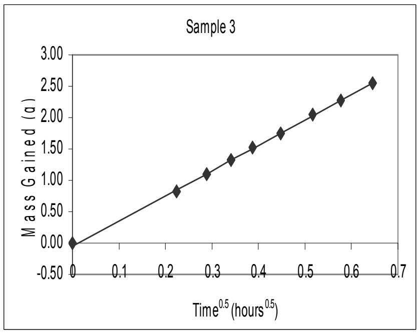
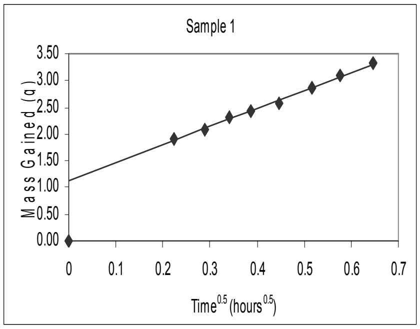
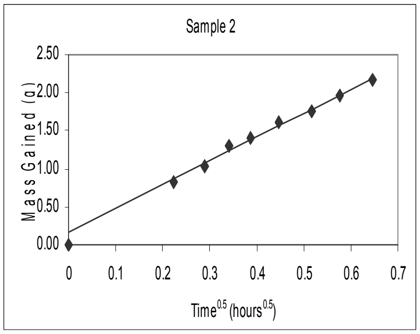


Table A-62: 0.4 % PWC mortar samples 180 days sorptivity results

Av. Sorptivity:	4.6	COV:	2.5
Av. Porosity:	17.0	COV:	2.2
	1	2	3
Diameter (mm)	72.15	72.31	70.22
Thickness (mm)	24.92	24.95	25.49
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	207.68	205.70	202.57
3	209.60	206.52	204.31
5	209.75	206.74	204.48
7	210.00	207.00	204.67
9	210.12	207.10	204.83
12	210.25	207.32	205.10
16	210.54	207.45	205.21
20	210.78	207.67	205.46
25	211.00	207.86	205.52
Saturated Mass (g)	225.45	223	219.1
R^2 (Must be >0.98)	0.9944	0.9915	0.9838
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	4.7	4.5	4.7
Porosity (%)	17.4	16.9	16.7





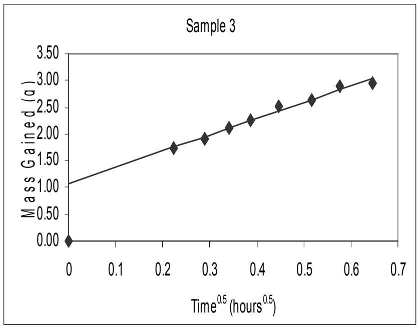
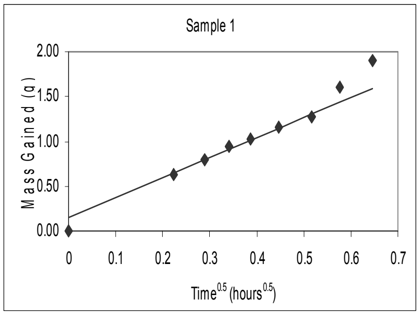
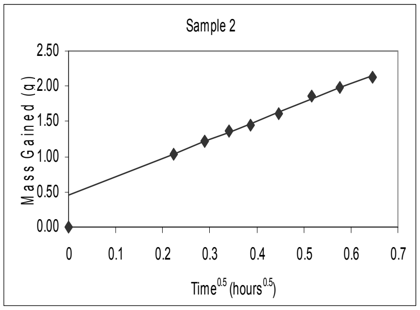


Table A-63: 0.6 % PWC mortar samples 180 days sorptivity results

Av. Sorptivity:	4.2	COV:	6.0
Av. Porosity:	15.9	COV:	8.5
	1	2	3
Diameter (mm)	71.07	70.37	70.57
Thickness (mm)	24.86	25.60	24.88
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	192.74	247.81	197.22
3	193.36	248.84	198.25
5	193.53	249.03	198.44
7	193.68	249.17	198.65
9	193.76	249.26	198.74
12	193.89	249.42	198.80
16	194.02	249.66	199.04
20	194.35	249.80	199.30
25	194.64	249.94	199.54
Saturated Mass (g)	206.9	264.17	213.67
R^2 (Must be >0.98)	0.9927	0.9968	0.9833
Range	3-16 min	3-25 min	3-25 min
Sorptivity ($mm/hr^{0.5}$)	3.9	4.1	4.4
Porosity (%)	14.4	16.4	16.9





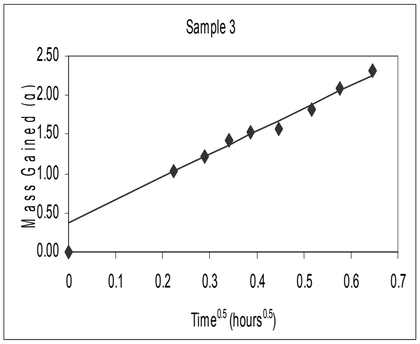
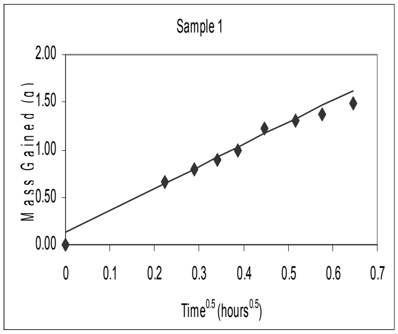
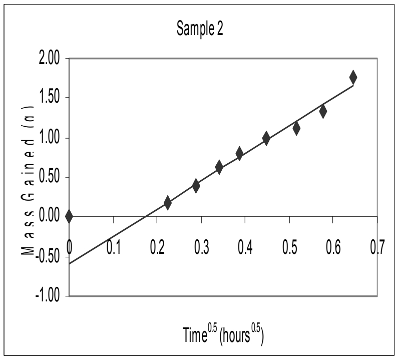


Table A-64: 0.8 % PWC mortar samples 180 days sorptivity results

Av. Sorptivity:	4.7	COV:	10.9
Av. Porosity:	16.4	COV:	12.2
	1	2	3
Diameter (mm)	71.00	70.20	70.78
Thickness (mm)	27.81	27.62	27.47
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	236.74	220.15	213.81
3	237.40	220.33	213.98
5	237.54	220.55	214.19
7	237.64	220.78	214.41
9	237.74	220.95	214.57
12	237.96	221.15	214.76
16	238.05	221.27	214.87
20	238.11	221.48	215.07
25	238.23	221.92	215.50
Saturated Mass (g)	252.4	239.52	232.1
R^2 (Must be >0.98)	0.9853	0.9825	0.9806
Range	3-16 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	4.1	5.0	5.0
Porosity (%)	14.2	18.1	16.9





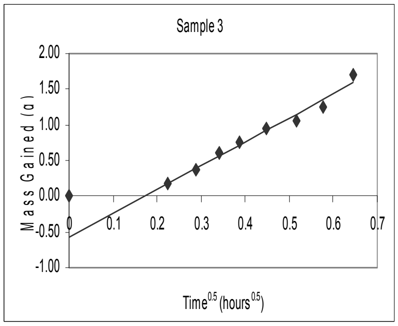
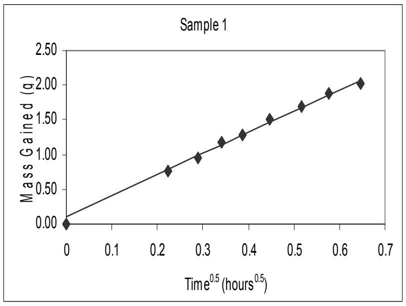
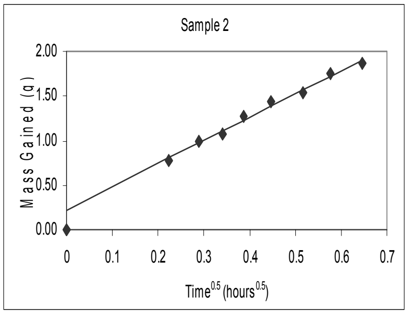


Table A-65: 1.0 % PWC mortar samples 180 days sorptivity results

Av. Sorptivity:	4.5	COV:	5.7
Av. Porosity:	17.7	COV:	2.0
	1	2	3
Diameter (mm)	67.87	67.32	67.97
Thickness (mm)	28.37	27.54	27.52
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	199.82	197.73	188.92
3	200.58	198.50	189.32
5	200.78	198.72	189.45
7	201.00	198.80	189.55
9	201.11	199.00	189.65
12	201.32	199.16	189.89
16	201.51	199.27	190.12
20	201.70	199.48	190.34
25	201.85	199.59	190.46
Saturated Mass (g)	218.39	214.87	206.4
R^2 (Must be >0.98)	0.9959	0.9904	0.9864
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	4.7	4.2	4.6
Porosity (%)	18.1	17.5	17.5





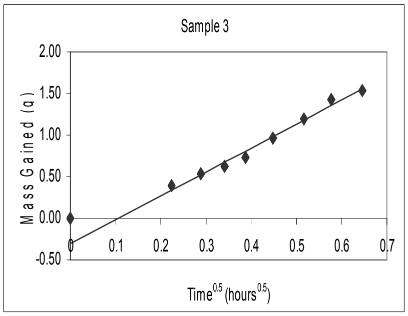
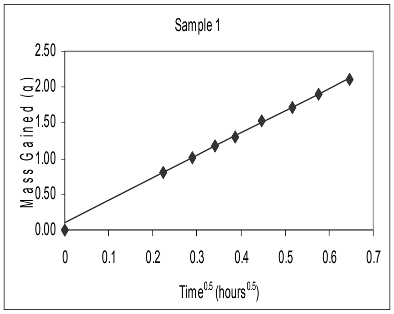
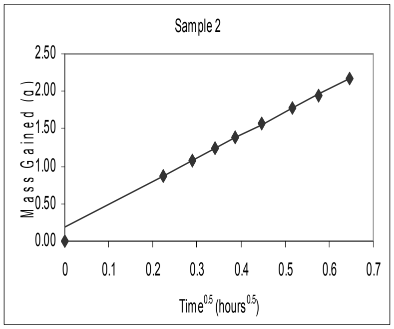


Table A-66: 2.5% PWC mortar samples 180days sorptivity results

Av. Sorptivity:	4.8	COV:	0.7
Av. Porosity:	17.8	COV:	3.4
	1	2	3
Diameter (mm)	67.06	68.55	67.93
Thickness (mm)	27.57	26.50	27.17
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	190.53	183.36	188.25
3	191.33	184.23	189.12
5	191.54	184.43	189.33
7	191.70	184.60	189.49
9	191.84	184.74	189.62
12	192.06	184.92	189.83
16	192.25	185.13	190.02
20	192.43	185.31	190.22
25	192.64	185.53	190.43
Saturated Mass (g)	208.39	200.11	205.84
R^2 (Must be >0.98)	0.9993	0.9999	0.9997
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	4.8	4.8	4.8
Porosity (%)	18.3	17.1	17.9





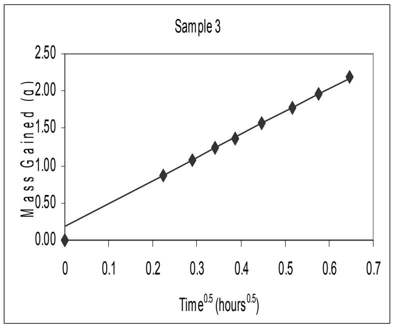
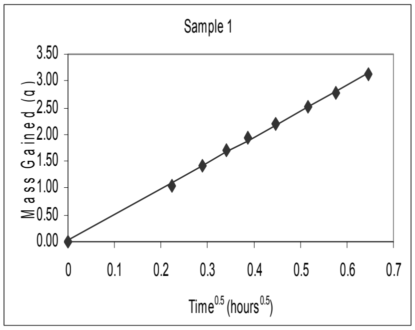
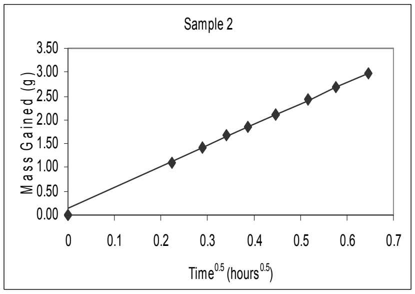


Table A-67: Control concrete samples 28 days sorptivity results

Av. Sorptivity:	8.5	COV:	10.4
Av. Porosity:	14.7	COV:	8.9
	1	2	3
Diameter (mm)	70.60	70.30	70.19
Thickness (mm)	27.00	28.23	27.39
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	238.77	260.28	249.49
3	239.82	261.37	250.02
5	240.19	261.69	250.54
7	240.47	261.95	250.87
9	240.70	262.14	251.15
12	240.97	262.39	251.48
16	241.29	262.70	251.78
20	241.56	262.96	251.98
25	241.89	263.25	252.29
Saturated Mass (g)	255.86	275.20	264.74
R^2 (Must be >0.98)	0.9982	0.9992	0.9814
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	7.6	8.4	9.4
Porosity (%)	16.2	13.6	14.4





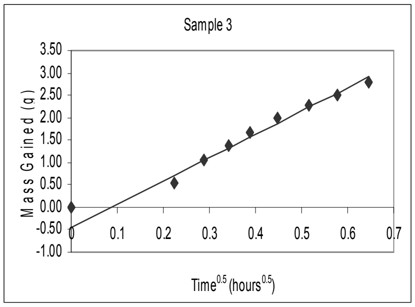
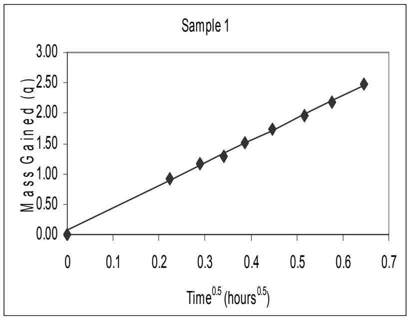
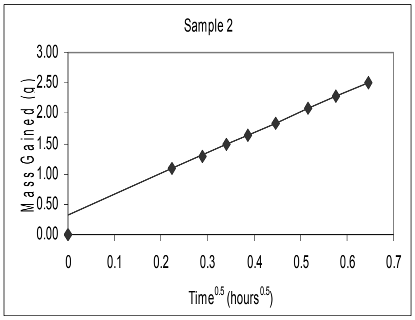


Table A-68: 0.6 % PWC concrete samples 28 days sorptivity results

Av. Sorptivity:	6.9	COV:	5.8
Av. Porosity:	13.5	COV:	1.8
	1	2	3
Diameter (mm)	70.18	70.61	70.47
Thickness (mm)	27.41	22.23	25.66
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	253.61	206.08	234.15
3	254.52	207.17	235.59
5	254.77	207.37	235.87
7	254.91	207.56	236.11
9	255.13	207.72	236.29
12	255.34	207.92	236.51
16	255.57	208.17	236.76
20	255.78	208.35	236.97
25	256.09	208.59	237.24
Saturated Mass (g)	268.23	217.65	247.7
R^2 (Must be >0.98)	0.9980	0.9996	0.9980
Range	3-25 min	3-25 min	3-25 min
Sorptivity ($mm/hr^{0.5}$)	6.9	6.5	7.3
Porosity (%)	13.8	13.3	13.5





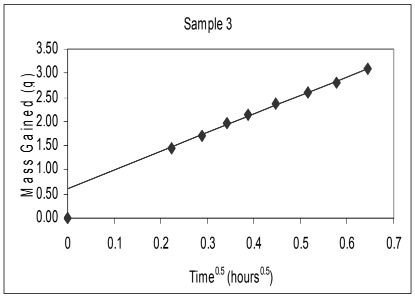
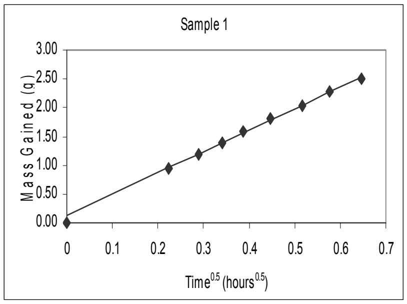
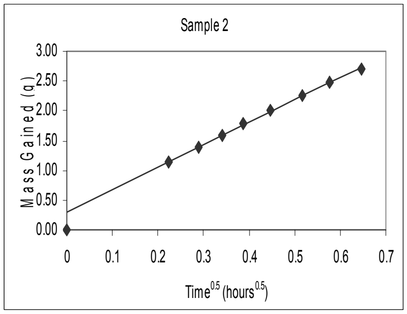


Table A-69: 1.0 % PWC concrete samples 28 days sorptivity results

Av. Sorptivity:	7.8	COV:	9.4
Av. Porosity:	13.2	COV:	4.0
	1	2	3
Diameter (mm)	70.75	70.35	70.63
Thickness (mm)	28.18	29.15	26.11
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	263.74	274.41	239.60
3	264.67	275.54	240.91
5	264.93	275.79	241.19
7	265.14	276.00	241.41
9	265.33	276.20	241.64
12	265.55	276.42	241.93
16	265.78	276.67	242.23
20	266.01	276.90	242.50
25	266.24	277.11	242.81
Saturated Mass (g)	277.67	289.69	253.42
R^2 (Must be >0.98)	0.9988	0.9985	0.9997
Range	3-25 min	3-25 min	3-25 min
Sorptivity ($mm/hr^{0.5}$)	7.5	7.2	8.6
Porosity (%)	12.6	13.5	13.5





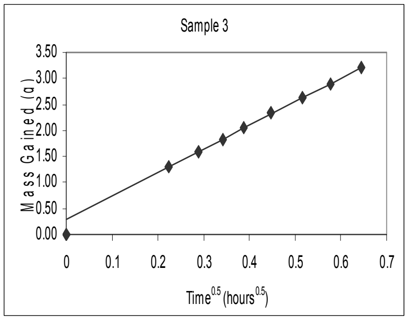
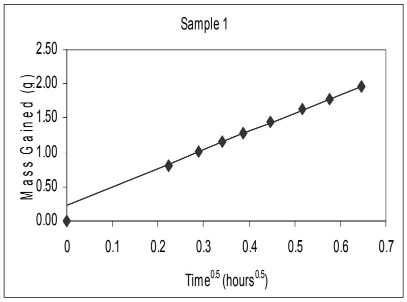
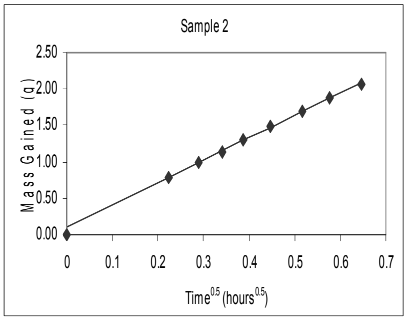


Table A-70: 30 % FA concrete samples 28 days sorptivity results

Av. Sorptivity:	6.6	COV:	14.7
Av. Porosity:	12.8	COV:	9.5
	1	2	3
Diameter (mm)	70.63	70.54	70.48
Thickness (mm)	24.93	25.34	27.08
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	233.80	238.13	245.69
3	234.61	238.91	246.90
5	234.81	239.13	247.21
7	234.95	239.27	247.43
9	235.08	239.44	247.63
12	235.24	239.61	247.88
16	235.43	239.83	248.17
20	235.57	240.00	248.39
25	235.77	240.2	248.68
Saturated Mass (g)	245.81	249.85	260.62
R^2 (Must be >0.98)	0.9993	0.9993	0.9991
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	5.6	6.6	7.6
Porosity (%)	12.3	11.8	14.1





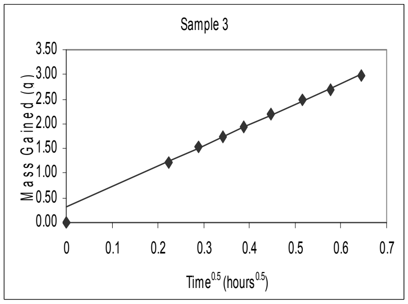
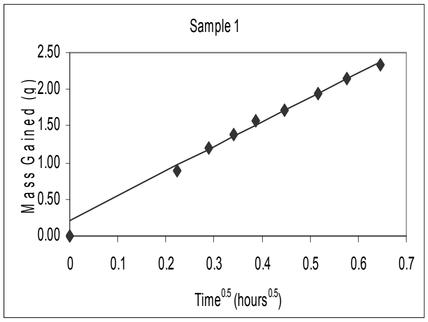
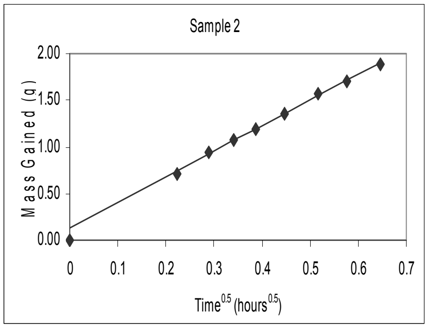


Table A-71: 0.6 % PWC + 30 % FA concrete samples 28 days sorptivity results

Av. Sorptivity:	6.4	COV:	8.0
Av. Porosity:	12.3	COV:	7.1
	1	2	3
Diameter (mm)	69.91	69.42	69.83
Thickness (mm)	25.60	27.07	25.91
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	234.55	249.59	232.16
3	235.43	250.30	233.01
5	235.75	250.53	233.25
7	235.94	250.67	233.41
9	236.12	250.78	233.57
12	236.26	250.95	233.73
16	236.50	251.16	233.92
20	236.69	251.30	234.10
25	236.88	251.47	234.29
Saturated Mass (g)	246.79	261.22	245.14
R^2 (Must be >0.98)	0.9917	0.9977	0.9975
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	7.0	6.4	6.0
Porosity (%)	12.5	11.4	13.1





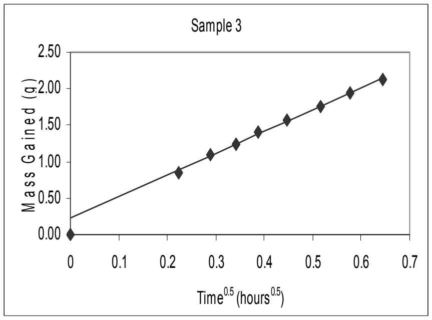
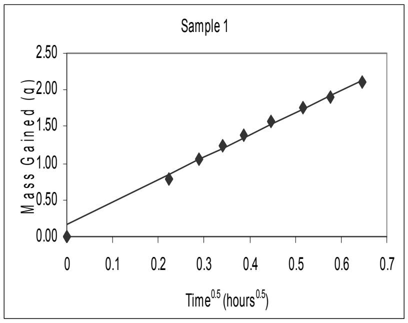
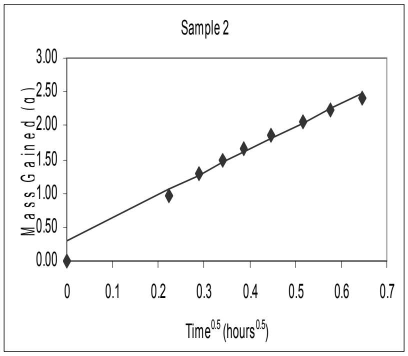


Table A-72: 1.0 % PWC + 30 % FA concrete samples 28 days sorptivity results

Av. Sorptivity:	6.8	COV:	11.6
Av. Porosity:	11.9	COV:	13.4
	1	2	3
Diameter (mm)	70.97	71.15	71.21
Thickness (mm)	25.91	26.65	27.94
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	243.84	249.19	228.03
3	244.62	250.16	228.88
5	244.89	250.47	229.11
7	245.08	250.68	229.27
9	245.22	250.84	229.42
12	245.40	251.04	229.61
16	245.59	251.26	229.81
20	245.74	251.43	229.99
25	245.94	251.6	230.18
Saturated Mass (g)	256.61	263.03	239.22
R^2 (Must be >0.98)	0.9931	0.9896	0.9989
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	6.2	6.5	7.7
Porosity (%)	12.5	13.1	10.1





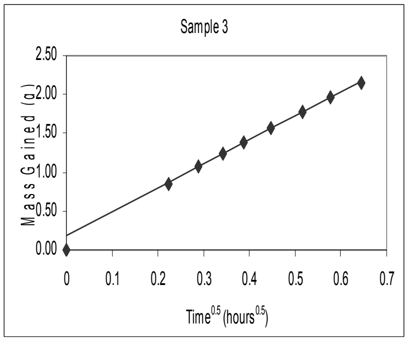
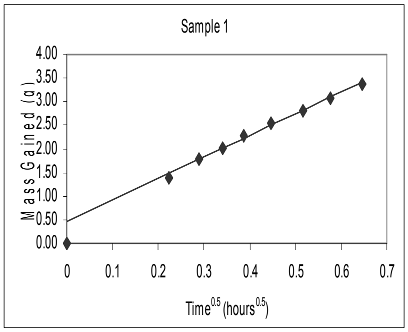
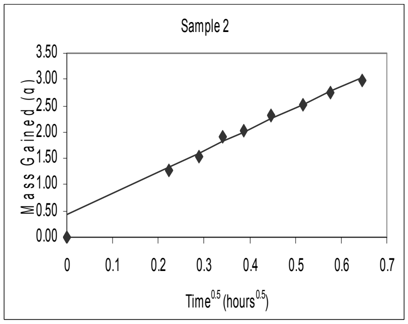


Table A-73: Premix concrete samples 28 days sorptivity results

Av. Sorptivity:	8.2	COV:	4.0
Av. Porosity:	13.5	COV:	3.3
	1	2	3
Diameter (mm)	71.02	71.05	71.32
Thickness (mm)	26.91	27.34	27.68
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	240.37	250.92	251.87
3	241.77	252.20	253.49
5	242.16	252.46	253.86
7	242.40	252.83	254.14
9	242.65	252.95	254.36
12	242.92	253.22	254.63
16	243.18	253.45	254.93
20	243.44	253.68	255.18
25	243.74	253.9	255.45
Saturated Mass (g)	254.94	265.00	267.16
R^2 (Must be >0.98)	0.9956	0.9899	0.9958
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	8.4	7.8	8.3
Porosity (%)	13.7	13.0	13.8





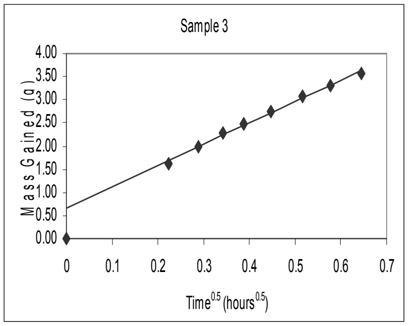
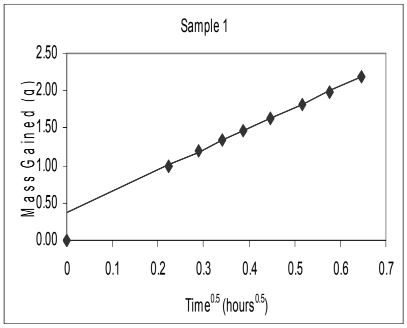
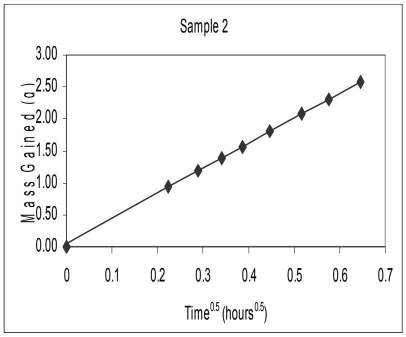


Table A-74: Control concrete samples 180 days sorptivity results

Av. Sorptivity:	7.6	COV:	7.5
Av. Porosity:	13.2	COV:	12.1
	1	2	3
Diameter (mm)	67.30	67.22	67.49
Thickness (mm)	27.40	26.84	27.97
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	238.54	228.04	235.30
3	239.54	228.98	236.43
5	239.73	229.23	236.73
7	239.88	229.43	236.93
9	240.01	229.61	237.14
12	240.17	229.85	237.37
16	240.36	230.12	237.65
20	240.53	230.35	237.90
25	240.74	230.63	238.16
Saturated Mass (g)	249.65	241.47	249.56
R^2 (Must be >0.98)	0.9997	0.9999	0.9995
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	6.9	7.8	8.0
Porosity (%)	11.4	14.1	14.3





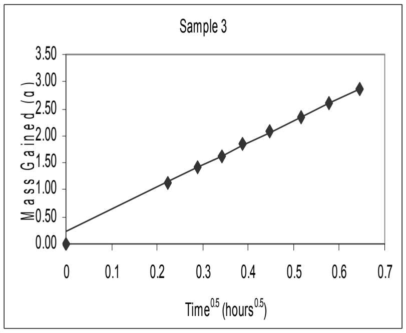
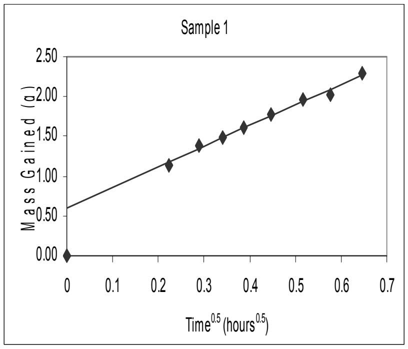
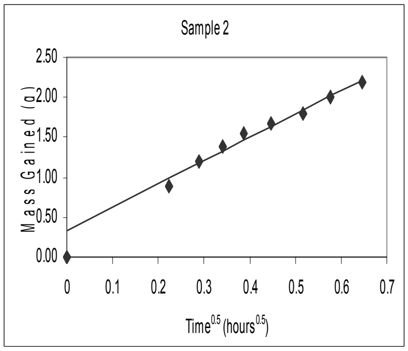


Table A-75: 0.6 % PWC concrete samples 180 days sorptivity results

Av. Sorptivity:	6.0	COV:	7.4
Av. Porosity:	12.3	COV:	6.6
	1	2	3
Diameter (mm)	67.18	67.45	70.06
Thickness (mm)	26.81	26.51	29.30
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	234.93	228.75	273.82
3	236.07	229.64	274.57
5	236.31	229.94	274.74
7	236.42	230.13	274.89
9	236.55	230.30	275.01
12	236.70	230.42	275.16
16	236.90	230.55	275.33
20	236.96	230.75	275.49
25	237.22	230.95	275.63
Saturated Mass (g)	246	241.26	287.41
R^2 (Must be >0.98)	0.9913	0.9824	0.9988
Range	3-25 min	3-25 min	3-25 min
Sorptivity ($mm/hr^{0.5}$)	6.3	6.2	5.5
Porosity (%)	11.6	13.2	12.0





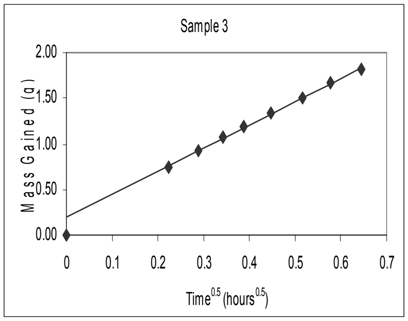
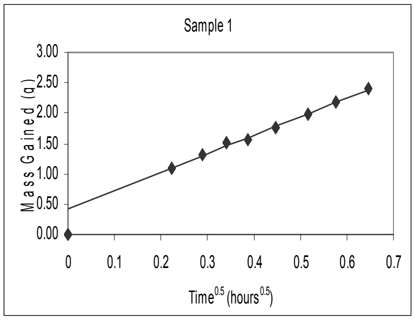
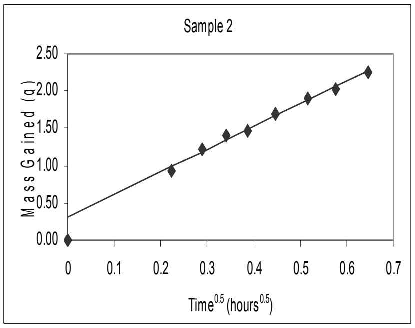


Table A-76: 1.0 % PWC concrete samples 180 days sorptivity results

Av. Sorptivity:	6.6	COV:	4.0
Av. Porosity:	12.6	COV:	0.8
	1	2	3
Diameter (mm)	67.33	67.57	67.15
Thickness (mm)	26.57	25.70	25.58
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	232.31	224.26	225.71
3	233.39	225.18	226.74
5	233.63	225.47	226.97
7	233.82	225.66	227.15
9	233.87	225.73	227.29
12	234.07	225.96	227.38
16	234.29	226.17	227.59
20	234.49	226.29	227.77
25	234.72	226.51	228.00
Saturated Mass (g)	244.22	235.82	237.24
R^2 (Must be >0.98)	0.9956	0.9914	0.9941
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	6.8	6.8	6.3
Porosity (%)	12.6	12.5	12.7





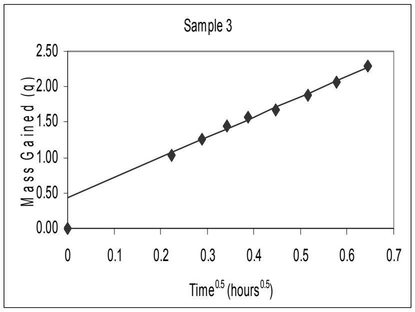
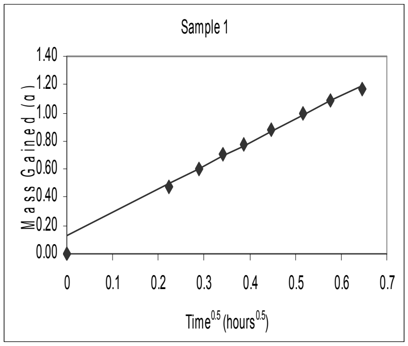
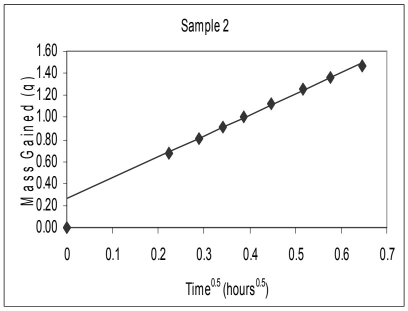


Table A-77: 30 % FA concrete samples 180 days sorptivity results

Av. Sorptivity:	4.5	COV:	13.7
Av. Porosity:	9.9	COV:	6.8
	1	2	3
Diameter (mm)	67.59	68.11	67.30
Thickness (mm)	24.63	24.85	25.14
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	215.23	218.35	221.18
3	215.71	219.02	221.64
5	215.83	219.16	221.72
7	215.93	219.26	221.82
9	216.01	219.36	221.89
12	216.11	219.48	221.95
16	216.22	219.60	222.02
20	216.32	219.71	222.10
25	216.40	219.82	222.17
Saturated Mass (g)	223.76	227.95	229.5
R^2 (Must be >0.98)	0.9964	0.9978	0.9912
Range	3-25 min	3-25 min	3-25 min
Sorptivity ($mm/hr^{0.5}$)	4.8	4.9	3.8
Porosity (%)	9.7	10.6	9.3





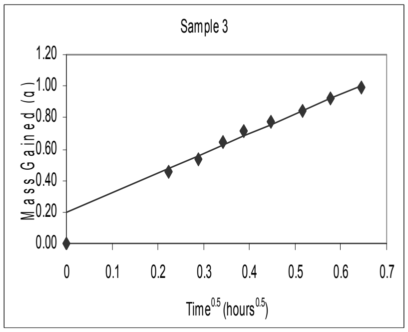
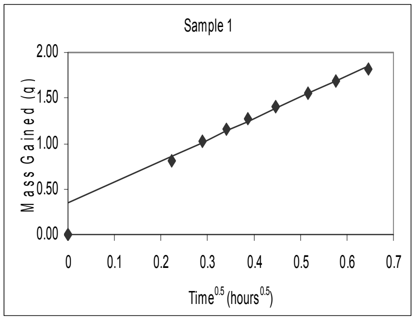
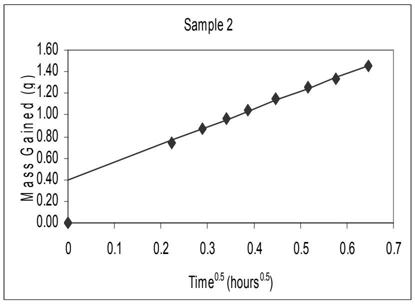


Table A-78: 0.6 % PWC + 30 % FA concrete samples 180 days sorptivity results

Av. Sorptivity:	5.2	COV:	4.5
Av. Porosity:	10.6	COV:	12.6
	1	2	3
Diameter (mm)	67.61	67.50	67.54
Thickness (mm)	24.88	24.89	23.00
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	215.13	221.42	203.95
3	215.94	222.16	204.75
5	216.16	222.29	204.91
7	216.29	222.39	205.03
9	216.40	222.46	205.12
12	216.53	222.57	205.25
16	216.69	222.67	205.37
20	216.81	222.76	205.49
25	216.95	222.87	205.61
Saturated Mass (g)	225.67	229.58	212.95
R^2 (Must be >0.98)	0.9934	0.9971	0.9968
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	5.5	5.1	5.2
Porosity (%)	11.8	9.2	10.9





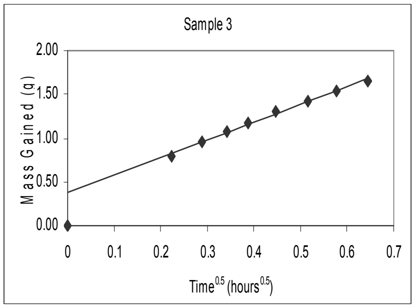
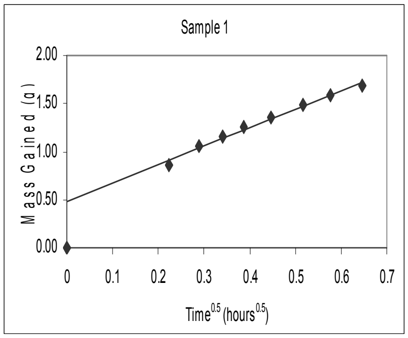
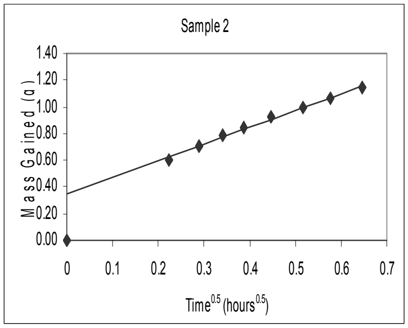


Table A-79: 1.0 % PWC + 30 % FA concrete samples 180 days sorptivity results

Av. Sorptivity:	4.0	COV:	5.5
Av. Porosity:	10.7	COV:	14.8
	1	2	3
Diameter (mm)	67.89	66.88	68.07
Thickness (mm)	22.81	24.43	24.09
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	201.63	216.45	212.39
3	202.49	217.05	213.04
5	202.68	217.16	213.16
7	202.79	217.24	213.24
9	202.89	217.30	213.31
12	202.99	217.37	213.41
16	203.11	217.44	213.50
20	203.22	217.52	213.58
25	203.32	217.59	213.68
Saturated Mass (g)	211.91	224.45	221.54
R^2 (Must be >0.98)	0.9893	0.9927	0.9973
Range	3-25 min	3-25 min	3-25 min
Sorptivity (mm/hr$^{0.5}$)	4.2	3.8	3.9
Porosity (%)	12.4	9.3	10.4





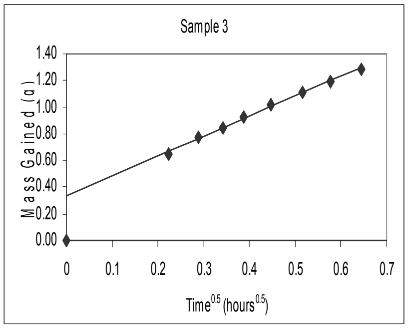
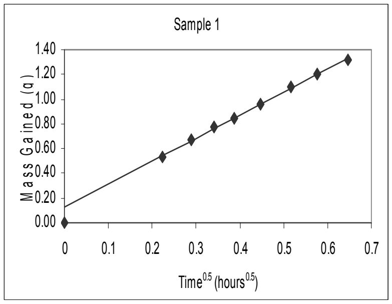
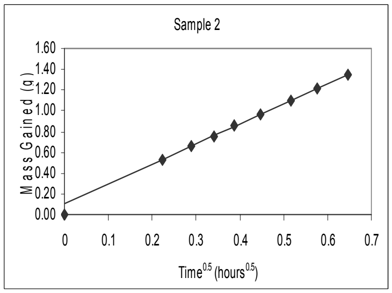
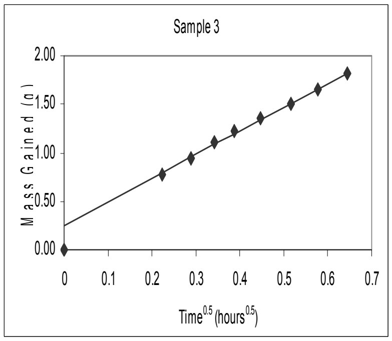


Table A-80: premix concrete samples 180 days sorptivity results

Av. Sorptivity:	5.3	COV:	15.0
Av. Porosity:	10.8	COV:	3.2
	1	2	3
Diameter (mm)	67.63	67.76	68.04
Thickness (mm)	23.93	25.90	24.78
Time (min)	Mass (g)	Mass (g)	Mass (g)
0	203.51	219.69	213.97
3	204.04	220.22	214.74
5	204.18	220.35	214.92
7	204.28	220.45	215.07
9	204.36	220.55	215.19
12	204.47	220.65	215.33
16	204.61	220.79	215.48
20	204.71	220.91	215.62
25	204.83	221.04	215.78
Saturated Mass (g)	212.54	230.13	223.62
R^2 (Must be >0.98)	0.9991	0.9997	0.9975
Range	3-25 min	3-25 min	3-25 min
Sorptivity ($mm/hr^{0.5}$)	4.9	4.8	6.3
Porosity (%)	10.5	11.2	10.7





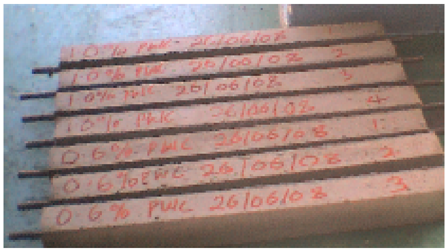


APPENDIX B: SAMPLES SEQUENCE

PWC additive

CEM 1 42.5N

Mortar bars immersed in Na_2SO_4 solution



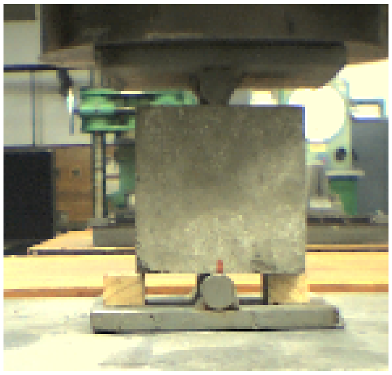
Mortar bars samples with studs in place

Discs samples

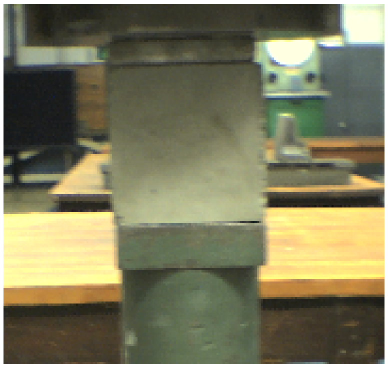
Partly carbonated sample

Sample covered with epoxy
before carbonation test

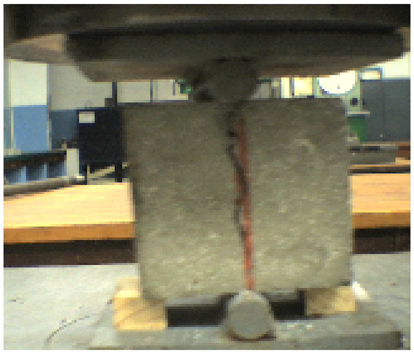
Silica sand



Loaded sample during split
tensile strength test



Loaded sample during concrete
compressive strength test



Failed sample after split tensile
strength test

Failed sample after compressive
strength test

Samples in the moulds

Loaded sample during flexural strength test

Loaded sample during mortar compressive strength test

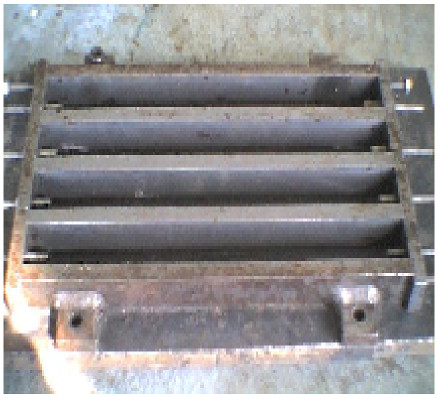
Failed sample after compressive strength test

Discs samples in PVC sheath

Mortar sample on vibrator

APPENDIX C: EQUIPMENT SEQUENCE

Oven



25 x 25 x 280 mm prism mould with attached studs

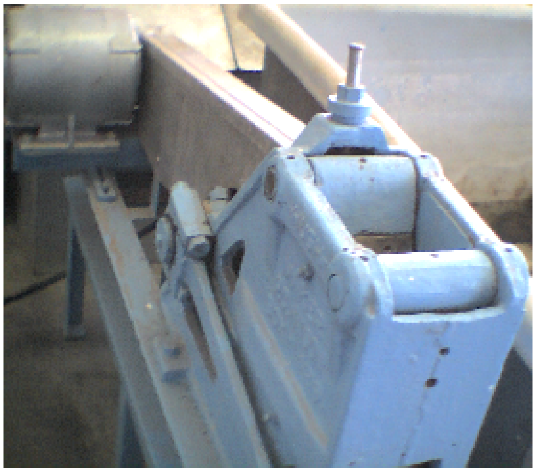
Oxygen permeability experimental set up

Flow table

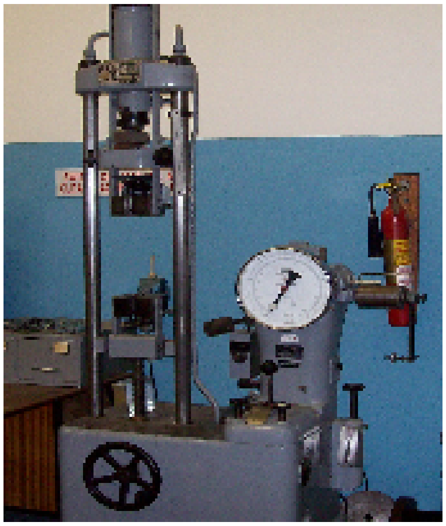
Length comparator

Set of sieves

Diamond grit cutter



Aggregate crusher



Tensile strength testing machine

40 x 40 x 160 mm prism mould

Amsler compressive strength testing machine

Sorptivity test set up

Vibrator

Pan mixer

Core driller

Slump cone